

# **Exploring Acute Low Back Pain: Connections Between Neuroscience, Biomechanics, and Psychology.**

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## **Dedications**

Deus.

*“Cristo Jesus sua mão me dá,  
Nada, portanto, me faz parar,  
Nada aqui pode me abalar,  
Com meu Jesus, passo a passo vou...”*

Ao meu esposo Rafael Parolini.

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## List of Publications

This doctoral thesis is based on the following scientific publications, referred in the text with Arabic and Roman numerals (respectively):

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1. ARTICLE 1. Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain
2. ARTICLE 2. Beyond low back pain! The influence of physical activity intensity on mental health, reflected in the functionality of people with low back pain – a canonical model.
3. ARTICLE 3. Precision and Reliability of a Dynamometer for Trunk Extension Strength and Steadiness Assessment.
4. ARTICLE 4. Acute Low Back Pain and Its Effects on Motor Control: An Analysis of Adaptations in Force Steadiness and Motor Unit Recruitment
5. ARTICLE 5. From Central for Peripheral Neural Adaptations in Force Steadiness During Acute Low Back Pain
6. ARTICLE 6. The face of low back pain.

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$$VAR = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2$$

Equation 2. 112

$$MAD = \frac{1}{N} \sum_{k=1}^N |x_k - \bar{x}|$$

Equation 3. 112

$$SampEn = -\log\left(\frac{\sum A_i}{\sum B_i}\right) = -\log(A/B)$$

Equation 3. 113

$$Int = \int_a^b f(x) dx \approx (b-a) \frac{f(a) + f(b)}{2}$$

Equation 4. 113

$$SP_c(f) = \frac{1}{n} \sum_{i=1}^n c_i(f) c_i^*(f)$$

Equation 5. 114

$$CMC \text{ or } CCC_{c1,c2}(f) = \frac{|S_{c1,c2}(f)|^2}{|SP_{c1}(f)| |SP_{c2}(f)|}$$

Equation 6. 114

$$S_{c1,c2}(f) = \frac{1}{n} \sum_{i=1}^n C_{1i}(f) C_{2i}^*(f)$$

Chapter 7 Equation 1.

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$$ii(x, y) = \sum_{(x' \leq x, y' \leq y)} i(x', y')$$

Equation 2.

147

$$\begin{aligned} & reprLBPH_{neutral} \\ &= \frac{(\sum \text{frames with faces}) * (reprLBPH_{frame})}{\text{number of frames with faces}} \end{aligned}$$

Equation 3.

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$$\text{diffLBPHframe} = \text{reprLBPHframe} - \text{reprLBPHneutral}$$

## **Abstract**

This thesis explores low back pain through a multidimensional approach, considering physical, psychological, and social factors, and employs artificial neural network to investigate non-linear interactions between physical and psychological variables. The study highlights the importance of physical activity as a key factor in modulating low back pain, demonstrating that regular exercise improves mental health and spinal functionality. However, exercise intensity plays a crucial role: while low-intensity exercise helps reduce stress and anxiety, high-intensity activities may alleviate pain but also increase pain perception, particularly in individuals with chronic conditions.

Additionally, the interaction between physical activity and psychological factors directly impacts functional capacity. Muscle weakness and trunk instability are central components of low back pain, affecting motivation and the ability to exercise. The research validated an instrumented dynamometer to precisely quantify trunk extension force and force steadiness, with excellent comparability to commercial reference devices. It also used this tool alongside electromyography to analyze neuromuscular responses to experimentally induced acute low back pain. The results revealed a dynamic and lateralized neuromuscular reorganization, with activation adjustments in muscles both ipsilateral and contralateral to the pain site, suggesting compensatory strategies by the central nervous system to maintain force steadiness.

These neuromuscular responses were accompanied by changes in electromyographic signal complexity, reflecting neurophysiological adaptations aimed at optimizing motor control in response to nociceptive stress. However, these adaptations were insufficient to sustain long-term force steadiness, highlighting the disruption of motor control caused by pain. Reduced corticomuscular coherence in the beta and gamma bands in the motor cortex

ipsilateral to pain induction revealed pain's direct interference in motor cortex-lumbar muscle communication, impairing synchronization between cortical commands and force generation. These findings suggest that targeted interventions addressing both neural control and biomechanical dimensions of low back pain are essential for improving motor control and functional recovery, addressing the complex interplay between pain, neural control, and force steadiness.

## Résumé

Cette thèse explore la douleur lombaire à travers une approche multidimensionnelle, prenant en compte les facteurs physiques, psychologiques et sociaux, et utilise des réseaux de neurones artificiels pour étudier les interactions non linéaires entre les variables physiques et psychologiques. L'étude souligne l'importance de l'activité physique en tant que facteur clé dans la modulation de la douleur lombaire, démontrant que l'exercice régulier améliore la santé mentale et la fonctionnalité spinale. Cependant, l'intensité de l'exercice joue un rôle : tandis que les exercices de faible intensité contribuent à réduire le stress et l'anxiété, les activités de haute intensité peuvent soulager la douleur, mais aussi augmenter la perception de la douleur, notamment chez les individus souffrant de conditions chroniques.

De plus, l'interaction entre l'activité physique et les facteurs psychologiques influence directement la capacité fonctionnelle. La faiblesse musculaire et l'instabilité du tronc sont des composantes centrales de la douleur lombaire, affectant la motivation et la capacité à pratiquer de l'exercice. La recherche a validé un dynamomètre instrumenté pour quantifier avec précision la force d'extension du tronc et la stabilité de la force, avec une excellente comparabilité aux dispositifs de référence commerciaux. Cet outil a également été utilisé en combinaison avec l'électromyographie pour analyser les réponses neuromusculaires à la douleur lombaire aiguë induite expérimentalement. Les résultats ont révélé une réorganisation neuromusculaire dynamique et latéralisée, avec des ajustements d'activation des muscles ipsilatéraux et controlatéraux au site de la douleur, suggérant des stratégies compensatoires par le système nerveux central pour maintenir la stabilité de la force.

Ces réponses neuromusculaires ont été accompagnées de changements dans la complexité du signal électromyographique, reflétant des adaptations neurophysiologiques visant à optimiser le contrôle moteur en réponse au stress

nociceptif. Cependant, ces adaptations se sont avérées insuffisantes pour maintenir la stabilité de la force à long terme, soulignant la perturbation du contrôle moteur causée par la douleur. La réduction de la cohérence corticomusculaire dans les bandes beta et gamma du cortex moteur ipsilatéral à l'induction de la douleur a révélé l'interférence directe de la douleur dans la communication entre le cortex moteur et les muscles lombaires, compromettant la synchronisation entre les commandes corticales et la génération de force. Ces résultats suggèrent que des interventions ciblées, abordant à la fois le contrôle neural et les dimensions biomécaniques de la douleur lombaire, sont essentielles pour améliorer le contrôle moteur et la récupération fonctionnelle, en tenant compte de l'interaction complexe entre la douleur, le contrôle neural et la stabilité de la force.

## Resumo

Esta tese explora a dor lombar através de uma abordagem multidimensional, considerando fatores físicos, psicológicos e sociais, e utiliza redes neurais artificiais para investigar as interações não-lineares entre variáveis físicas e psicológicas. O estudo destaca a importância da atividade física como um fator-chave na modulação da dor lombar, demonstrando que a prática regular de exercício melhora a saúde mental e a funcionalidade espinal. A intensidade da atividade física, no entanto, desempenha um papel crucial: enquanto exercícios de baixa intensidade ajudam a reduzir o estresse e a ansiedade, atividades de alta intensidade podem aliviar a dor, mas também aumentar a percepção da dor, especialmente em indivíduos com condições crônicas.

Além disso, a interação entre a atividade física e os fatores psicológicos afeta diretamente a capacidade funcional. Fraqueza muscular e instabilidade do tronco são componentes centrais da dor lombar, impactando a motivação e a capacidade de realizar exercícios. A pesquisa validou um dinamômetro instrumentado para quantificar com precisão a força de extensão do tronco e a estabilidade da força, com excelente comparabilidade com dispositivos de referência comerciais, e utilizou essa ferramenta juntamente com a eletromiografia para analisar as respostas neuromusculares à dor lombar aguda induzida experimentalmente. Os resultados mostraram uma reorganização neuromuscular dinâmica e lateralizada, com ajustes na ativação muscular tanto ipsilateral quanto contralateral ao local da dor, sugerindo estratégias compensatórias do sistema nervoso central para manter a estabilidade da força.

Essas respostas neuromusculares foram acompanhadas por alterações na complexidade do sinal eletromiográfico, refletindo adaptações neurofisiológicas para otimizar o controle motor em resposta ao estresse nociceptivo. No entanto, essas adaptações não foram suficientes para sustentar a estabilidade da força a longo prazo, evidenciando a perturbação do controle motor causada pela dor. A

redução da coerência corticomuscular nas bandas beta e gama no córtex motor ipsilateral à dor revelou a interferência direta da dor na comunicação entre o córtex motor e os músculos lombares, comprometendo a sincronização entre os comandos corticais e a geração de força. Esses achados sugerem que intervenções direcionadas tanto ao controle neural quanto às dimensões biomecânicas da dor lombar são essenciais para melhorar o controle motor e a recuperação funcional, abordando a complexa interação entre dor, controle neural e estabilidade da força.

## Abbreviation List

LBP	Low back pain
EEG	electroencephalograph
CCC	Cortico coherence cortical
d	cohen's d criteria
dEMG	electromyography signal decomposition
CMC	Coherence cortico muscular
EMG	surface electromyography
FR	Firing rate
RT	Recruitment threshold
MUAP	motor unit action potential amplitude
MVC	maximal voluntary contraction
SMVC	Submaximal maximal voluntary contraction
p-value	significance level
m	median
vs	versus
IASP°	International Association for the Study of Pain

### General introduction

Pain is an essential biological signal, functioning as a primary protective mechanism, though approximately 95% of the global population still experiences some form of pain (Basbaum et al., 2009; Raja et al., 2020). Historically, one-dimensional models of pain have prioritized its sensory nature, assuming that its intensity was directly related to the degree of tissue injury (Melzack & Wall, 1965). However, decades of research have demonstrated that the painful experience is highly modulated by biopsychosocial factors. Individuals with similar injuries may have very different levels of pain and disability (Gatchel et al., 2007; Vlaeyen & Linton, 2012).

Currently defined by the International Association for the Study of Pain (IASP) as an unpleasant sensory and emotional experience, potentially associated with actual or potential tissue damage, pain is a multifaceted phenomenon that significantly impacts quality of life (Raja et al., 2020). Low back pain (LBP) stands out, with a lifetime prevalence of approximately 84%, affecting a large portion of the population (Balagué et al., 2012; Von Korff & Dunn, 2008). Characterized by pain and stiffness localized in the lower back region, with or without radiation to the legs, LBP is one of the leading causes of disability and resource consumption in healthcare systems (Carvalho et al., 2016). However, due to the biomechanical complexity of the lumbar spine, a specific injury is identified in only about 20% of cases (Widmer et al., 2020)

Recent advancements in neuroimaging and neuroscience have facilitated a deeper understanding of the neurophysiological mechanisms underlying pain perception (Viseux et al., 2022). These findings demonstrate that pain is modulated by neural circuits and central nervous system plasticity and influenced by both genetic and environmental factors (Apkarian et al., 2005; Viseux et al., 2022). This integrated approach has driven the identification of new therapeutic targets, highlighting the importance of personalized strategies for pain management. This context has stimulated investigations exploring the alterations

in motor control associated with the presence of pain (Ervilha et al., 2004). Furthermore, psychosocial factors such as stress, anxiety, and depression have been recognized as modulators of pain, amplifying its experience and influencing the response to treatment (Hill & Fritz, 2011).

Experimental pain induction in research models has become an essential tool for elucidating the physiological and behavioral mechanisms underlying pain. These models allow for the controlled application of painful stimuli, facilitating the systematic investigation of neurophysiological and behavioral responses in a standardized manner (Hodges & Tucker, 2011). Additionally, pain can be induced locally in specific muscles, providing partial control over its intensity and enabling paired analyses, which enhances the precision of experimental outcomes (Canestri et al., 2021; Ervilha et al., 2004; Hirata et al., 2015). These experimental paradigms are vital for advancing our understanding of alterations in motor control and for exploring the complex interactions between central and peripheral systems, contributing significantly to the development of more refined approaches in the management of acute low back pain (Kantak et al., 2022).

The multifaceted assessment of low back pain, which includes anatomical, functional, and physiological aspects, provides a more comprehensive understanding of the motor and psychological adaptations associated with this condition (Hegmann et al., 2019). While the effects of pain on voluntary motor tasks are well-documented, the underlying mechanisms responsible for maintaining force steadiness under painful conditions, particularly in postural tasks, remain less explored (Arvanitidis et al., 2025; Tsao et al., 2008; Viseux et al., 2022; Xiao et al., 2023). Surface electromyography (sEMG) has played a key role in studying neuromuscular control, providing valuable data on the impact of pain on force production, particularly in submaximal force tasks essential for daily activities (Dieën et al., 2019; Ortega-Auriol et al., 2023).

Pain not only reduces the force generated but also affects its stability and precision, impairing motor control and increasing the risk of postural dysfunction (Hirata et al., 2015; Salomoni et al., 2016). In this context, electroencephalography (EEG) emerges as a promising tool, enabling the

assessment of brain activity associated with pain, in conjunction with surface electromyography (sEMG). The analysis of the synchrony between brain and muscular signals may reveal specific patterns of neural adaptation to pain, providing insights into the central and peripheral mechanisms involved (Becker et al., 2022; Poortvliet et al., 2015).

However, pain assessment faces challenges, as subjective measures, such as self-reports, can be influenced by individual and contextual factors. In this context, facial expression analysis has emerged as a promising objective tool. The Facial Action Coding System (FACS) has been widely used to identify facial patterns associated with pain, although it requires training (Koelstra et al., 2010; Schneider et al., 2024). Nevertheless, technological advancements have enabled the transition from static images to continuous monitoring of dynamic videos, enhancing the accuracy of detecting pain-induced changes (Ahonen et al., 2004; Schneider et al., 2024; Zhang & Ji, 2005). Modern facial recognition methods, such as Haar Cascade and Local Binary Pattern Histogram (LBPH) algorithms, allow for automated analysis of facial expressions, reducing reliance on subjective pain assessments such as visual or numerical pain scales (Viola & Jones, 2001; Zhang & Ji, 2005).

This thesis aims to analyze the effects of experimentally induced acute low back pain on motor control and neuromuscular activity, focusing on the interaction between the central and peripheral systems during spinal extension movements. The research concentrates on the changes in muscle activation patterns, assessed through surface decomposition electromyography (dEMG), and brain activity, measured via EEG. Furthermore, it will explore the influence of emotional factors, such as anxiety and stress, on the modulation of pain perception and motor control. By integrating biomechanical, neuromuscular, and psychological variables, the study seeks to propose novel approaches for the diagnosis and clinical management of acute low back pain.

This thesis is structured into **10 chapters**, with **Chapter 1** dedicated to the general introduction. In this chapter, we provide a contextualization of low back pain, addressing its interrelationships with mental health, physical functionality,

and the underlying neural mechanisms. By integrating advancements in artificial intelligence, objective assessment methods, and behavioral analyses, the studies presented here aim to offer a holistic approach that could enhance the management of low back pain. Additionally, the objectives and contents of each chapter of the thesis are outlined. **Chapters 2 through 7** present the experimental studies that form the basis of this doctoral work. In **Chapter 8**, titled "General Discussion," we compare the main findings with the most relevant evidence from the literature, linking them to the advances in scientific knowledge in the field. The final two chapters (**Chapter 9 and Chapter 10**) present the conclusions of this thesis and suggestions for future research directions.

Aiming to systematically validate the IASP definition of pain, **Chapter 2**, with the article "*Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain*," investigates the application of artificial intelligence algorithms to identify patterns linking mental disorders to the experience of pain. This pioneer work demonstrates how the integration of clinical data and computational techniques can reveal subtle and relevant interactions, enhancing the understanding of the mechanisms underpinning pain, and rigorously validating the IASP definition of pain.

In **Chapter 3**, the study "*Beyond Low Back Pain! The Influence of Physical Activity Intensity on Mental Health, Reflected in the Functionality of People with Low Back Pain – A Canonical Model*" explores the impact of physical activity intensity on mental health and functionality in individuals suffering from low back pain. By proposing a canonical model, this investigation highlights the modulating role of physical exercise, suggesting intervention strategies that may improve quality of life and reduce disability associated with pain.

In **Chapter 4**, the study "*Precision and Reliability of a Dynamometer for Trunk Extension Strength and Steadiness Assessment*" presents the validation of an innovative dynamometer capable of accurately measuring the strength and stability of trunk muscles. This tool is essential for the objective assessment of

muscle function, providing critical parameters for clinical monitoring and the development of more effective rehabilitation programs.

In **Chapter 5**, the study "*Acute Low Back Pain is a Prevalent Musculoskeletal Disorder That Can Disrupt Motor Control and Compromise Functional Steadiness*" investigates neuromuscular adaptations in acute low back pain. Thirty-three healthy participants performed a sustained spinal extension task under different experimental conditions. The results revealed lateralized changes in the firing rate of motor units in the longissimus muscle, highlighting a neuroplastic compensatory mechanism that preserves functional stability despite pain. These findings provide new insights into neuromuscular adaptations in acute low back pain.

In **Chapter 6**, the study "*From Central to Peripheral - Neural Adaptations in Force Steadiness During Acute Low Back Pain*" investigates the neural adaptations occurring during episodes of acute low back pain. By elucidating the mechanisms of corticomuscular and cortical modulation, this study provides important insights into how central processes influence stability and motor control, contributing to a deeper understanding of pain mechanisms. This integration of multidisciplinary approaches not only enhances the understanding of the mechanisms involved in low back pain but also paves the way for the development of more precise and personalized therapeutic strategies, significantly advancing scientific knowledge and improving clinical care in this field.

In **Chapter 7**, the article "*The Face of Low Back Pain*" employs advanced image processing techniques using machine learning methods, such as Haar Cascade and Local Binary Pattern Histogram to analyze facial expressions associated with low back pain. This study demonstrates the efficacy of automated facial recognition in identifying pain, enabling objective and continuous assessment of facial reactions during episodes of experimentally induced acute low back pain.

Finally, **Chapter 8** of this thesis will present an integrated analysis of the main findings from **Chapters 2, 3, 4, 5, 6, and 7**, exploring how low back pain affects individuals both psychologically and physically. The use of advanced techniques such as artificial intelligence, facial expression analysis, EMG, and EEG has

expanded the understanding of the neurophysiological correlates of low back pain, enabling more accurate diagnoses. **Chapters 9 and 10** will synthesize the key findings and contributions of this thesis, highlighting the adaptive mechanisms involved in low back pain and providing valuable insights for future research and the enhancement of therapeutic strategies targeting this condition.

## Reference

- Ahonen, T., Hadid, A., & Pietikäinen, M. (2004). Face Recognition with Local Binary Patterns. In T. Pajdla & J. Matas, *Computer Vision - ECCV 2004* Berlin, Heidelberg.
- Apkarian, A. V., Bushnell, M. C., Treede, R. D., & Zubieta, J. K. (2005). Human brain mechanisms of pain perception and regulation in health and disease. *Eur J Pain*, 9(4), 463-484. <https://doi.org/10.1016/j.ejpain.2004.11.001>
- Balagué, F., Mannion, A. F., Pellisé, F., & Cedraschi, C. (2012). Non-specific low back pain. *Lancet*, 379(9814), 482-491. [https://doi.org/10.1016/s0140-6736\(11\)60610-7](https://doi.org/10.1016/s0140-6736(11)60610-7)
- Basbaum, A. I., Bautista, D. M., Scherrer, G., & Julius, D. (2009). Cellular and Molecular Mechanisms of Pain. *Cell*, 139, 267-284.
- Becker, K., Goethel, M., Fonseca, P., Vilas-Boas, J. P., & Ervilha, U. (2022). The Strategy of the Brain to Maintain the Force Production in Painful Contractions—A Motor Units Pool Reorganization. *Cells*, 11(20), 3299. <https://www.mdpi.com/2073-4409/11/20/3299>
- Canestri, R., Franco-Alvarenga, P. E., Brietzke, C., Vinícius, Í., Smith, S. A., Mauger, A. R., Goethel, M. F., & Pires, F. O. (2021). Effects of experimentally induced muscle pain on endurance performance: A proof-of-concept study assessing neurophysiological and perceptual responses. *Psychophysiology*, 58(6), e13810. <https://doi.org/https://doi.org/10.1111/psyp.13810>
- Carvalho, C., Caetano, J. M., Cunha, L., Rebouta, P., Kaptchuk, T. J., & Kirsch, I. (2016). Open-label placebo treatment in chronic low back pain: a randomized controlled trial. *Pain*, 157(12), 2766-2772. <https://doi.org/10.1097/j.pain.0000000000000700>

- Dieën, J., Reeves, N., Kawchuk, G., Kawchuk, G., Dillen, L., & Hodges, P. (2019). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *The Journal of orthopaedic and sports physical therapy*, 49(6), 370-379. <https://doi.org/10.2519/jospt.2019.7917>
- Ervilha, U. F., Arendt-Nielsen, L., Duarte, M., & Graven-Nielsen, T. (2004). The effect of muscle pain on elbow flexion and coactivation tasks. *Exp Brain Res*, 156(2), 174-182. <https://doi.org/10.1007/s00221-003-1781-1>
- Hegmann, K. T., Travis, R., Belcourt, R. M., Donelson, R., Eskay-Auerbach, M., Galper, J., Haldeman, S., Hooper, P. D., Lessenger, J. E., Mayer, T., Mueller, K. L., Murphy, D. R., Tellin, W. G., Thiese, M. S., & Weiss, M. S. (2019). Diagnostic Tests for Low Back Disorders. *J Occup Environ Med*, 61(4), e155-e168. <https://doi.org/10.1097/jom.0000000000001551>
- Hill, J. C., & Fritz, J. M. (2011). Psychosocial Influences on Low Back Pain, Disability, and Response to Treatment. *Physical Therapy*, 91, 712 - 721.
- Hirata, R. P., Salomoni, S. E., Christensen, S. W., & Graven-Nielsen, T. (2015). Reorganised motor control strategies of trunk muscles due to acute low back pain. *Hum Mov Sci*, 41, 282-294. <https://doi.org/10.1016/j.humov.2015.04.001>
- Hodges, P. W., & Tucker, K. (2011). Moving differently in pain: a new theory to explain the adaptation to pain. *Pain*, 152(3 Suppl), S90-S98. <https://doi.org/10.1016/j.pain.2010.10.020>
- Kantak, S., Johnson, T., & Zarzycki, R. (2022). Linking Pain and Motor Control: Conceptualization of Movement Deficits in Patients with Painful Conditions. *Physical Therapy*.
- Koelstra, S., Pantic, M., & Patras, I. (2010). A dynamic texture-based approach to recognition of facial actions and their temporal models. *IEEE Trans Pattern Anal Mach Intell*, 32(11), 1940-1954. <https://doi.org/10.1109/tpami.2010.50>
- Ortega-Auriol, P., Byblow, W. D., Besier, T., & McMorland, A. J. C. (2023). Muscle synergies are associated with intermuscular coherence and cortico-synergy coherence in an isometric upper limb task. *Exp Brain Res*, 241(11-12), 2627-2643. <https://doi.org/10.1007/s00221-023-06706-6>

- Poortvliet, P. C., Tucker, K. J., Finnigan, S., Scott, D., Sowman, P., & Hodges, P. W. (2015). Cortical activity differs between position-and force-control knee extension tasks. *Experimental brain research*, 233, 3447-3457.
- Raja, S. N., Carr, D. B., Cohen, M., Finnerup, N. B., Flor, H., Gibson, S., Keefe, F. J., Mogil, J. S., Ringkamp, M., Sluka, K. A., Song, X. J., Stevens, B., Sullivan, M. D., Tutelman, P. R., Ushida, T., & Vader, K. (2020). The revised International Association for the Study of Pain definition of pain: concepts, challenges, and compromises. *Pain*, 161(9), 1976-1982. <https://doi.org/10.1097/j.pain.0000000000001939>
- Salomoni, S., Tucker, K., Hug, F., McPhee, M., & Hodges, P. (2016). Reduced Maximal Force during Acute Anterior Knee Pain Is Associated with Deficits in Voluntary Muscle Activation. *PLoS One*, 11(8), e0161487. <https://doi.org/10.1371/journal.pone.0161487>
- Schneider, P., Lautenbacher, S., & Kunz, M. (2024). Sex differences in facial expressions of pain: results from a combined sample. *Pain*, 165(8), 1784-1792. <https://doi.org/10.1097/j.pain.0000000000003180>
- Viola, P., & Jones, M. (2001). *Rapid Object Detection using a Boosted Cascade of Simple Features* (Vol. 1). <https://doi.org/10.1109/CVPR.2001.990517>
- Viseux, F. J. F., Simoneau, M., & Billot, M. (2022). A Comprehensive Review of Pain Interference on Postural Control: From Experimental to Chronic Pain. *Medicina*, 58(6), 812. <https://www.mdpi.com/1648-9144/58/6/812>
- Von Korff, M., & Dunn, K. M. (2008). Chronic pain reconsidered. *Pain*, 138(2), 267-276. <https://doi.org/10.1016/j.pain.2007.12.010>
- Widmer, J., Cornaz, F., Scheibler, G., Spirig, J. M., Snedeker, J. G., & Farshad, M. (2020). Biomechanical contribution of spinal structures to stability of the lumbar spine - Novel biomechanical insights. *The spine journal : official journal of the North American Spine Society*.
- Zhang, Y., & Ji, Q. (2005). Active and dynamic information fusion for facial expression understanding from image sequences. *IEEE Trans Pattern Anal Mach Intell*, 27(5), 699-714. <https://doi.org/10.1109/tpami.2005.93>

### **Breaking barriers: artificial intelligence interpreting the interplay between mental illness and pain as defined by the international association for the study of pain**

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## **Abstract**

Low back pain is one of the main causes of motor disabilities and psychological stress, with the painful process encompassing sensory and affective components. Noxious stimuli originate on the periphery, however the stimuli are recombined in the brain and therefore subjected to be processed differently due to the emotional environment. To better understand this process, our objective was to develop a mathematical representation of the International Association for the Study of Pain (IASP) model of pain, covering the multidimensional representation of this phenomenon. Data from Oswestry disability index, depression anxiety stress scales short form and pain catastrophizing daily questionnaires were collected through online completion, available from June 8, 2022 to April 8, 2023 (1021 cases). Using the information collected, an artificial neural network structure was trained (based on anomaly detection methods) to identify the patterns that emerge from the relationship between the variables. The developed model proved to be robust and able to show the patterns and the relationship between the variables, as well as allowed to differentiate the groups with altered patterns in the context of low back pain. The distinct groups behave all according to the main finding that psychological and pain events are directly associated. We conclude that our proposal is effective, being possible to test and confirm the definition of the IASP for the study of pain. Here we show that the fiscal and mental dimensions of pain are directly associated, meaning that mental illness can be an enhancer of pain episodes and functionality.

**Keywords:** lower back pain; mental illness; pain catastrophizings; AI (artificial intelligence); motor disability; pain perception; affective components, central nervous system; emotions; peripheral nervous system; sensation.

## 1. Introduction

In several countries, low back pain is referred to as the major source of musculoskeletal complaints, with a high impact on health and economy due to the limitations and disability it imposes on individuals, and seek for health care and absenteeism from work ("Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019," ; Vos et al., 2012). The process that leads to the perception of pain is a complex succession of peripheral and central neural system activities, including modulation at different levels. Despite the essentially peripheral origin of low back pain, its cause is not identified in 85% of the cases (Gatchel, Peng, Peters, Fuchs, & Turk, 2007; Hooten, 2016). Pain process encompasses sensory, cognitive, and affective components (Paulus & Stein, 2010), with this last component including feelings of annoyance, sadness, anxiety and depression in response to a harmful stimulus (Lumley et al., 2017; Paulus & Stein, 2010). Brain activity in patients with low back pain for two months showed activation in the insular cortex, thalamus, anterior cingulate cortex, and prefrontal cortex.

For over a decade, it has been noted that those who suffer from long-term lower back pain exhibit activity in certain areas of the brain, specifically the perigenual anterior cingulate and medial prefrontal cortexes, as well as the amygdala (Paulus & Stein, 2010). This implies that as acute pain becomes chronic, there may be a shift towards emotional pathways instead of just sensory ones. Furthermore, the experience of pain, as well as anxiety and depression, is often intertwined with the idea of suffering (Mescouto, Olson, Hodges, & Setchell, 2022). The association of pain with the subjects' psychological state has been investigated (Edwards, Dworkin, Sullivan, Turk, & Wasan, 2016; Mescouto et al., 2022), and it seems consensual that psychological and social factors are fused in biopsychosocial processes that characterizes chronic pain (Gutiérrez, Écija, Catalá, & Peñacoba).

In recent years, there has been a growing recognition of the close relationship between pain and mental illness (Nagireddi, Vyas, Sanapati, Soin, & Manchikanti). It has become increasingly clear that mental health conditions,

such as depression, anxiety, and stress, can significantly influence the experience and perception of pain (Raja et al., 2020; Rajkomar, Dean, & Kohane, 2019). Conversely, chronic pain can also have a profound impact on mental well-being, leading to increased levels of psychological distress and impairment (Ashar et al.). Recent studies elucidate those different types of chronic pain conditions such fibromyalgia and low-back pain, and chronic pain conditions from underlying medical condition such post-trauma, neuropathic, musculoskeletal pain and so on, have distinct pathogenic pathways (Baliki & Apkarian, 2015; Olango & Finn, 2014). So perhaps chronic back pain is best understood in the framework of pain perception, including cognitive, emotional, and social components, therefore the association of mental health and pain perception appears to be a logical association (Okafor et al., 2023; Tanaka, Török, Tóth, Szabó, & Vécsei, 2021). Understanding and addressing this intricate relationship between mental illness and pain is crucial for providing comprehensive and effective care to individuals experiencing pain.

As of 2020, the meaning of pain has been redefined by the International Association for the Study of Pain (IASP). According to the latter definition, pain is an unpleasant sensory and emotional experience associated with or similar to that associated with actual or potential tissue damage (Raja et al.). Those who have extensive knowledge in pain-related fields, including clinical and fundamental science, decided on the model by examining existing definitions and annotations and deciding whether they still apply or need modification. Although it seems to be very well accepted in the community, a global multivariate model can provide more robust support for what is currently the most accepted definition. If such a model considers, with the respective weights, the interaction of a set of variables involved, this multivariate phenomenon will certainly better understand and, consequently, develop more accurate and adequate diagnostic and therapeutic tools.

To access a deeper understanding of the complex interplay between mental illness and low back pain, researchers have turned to mathematical modelling and artificial intelligence as powerful tools (Bair, Wu, Damush, Sutherland, & Kroenke, 2008; Doan, Manders, & Wang, 2015; Park, Lee, Kim, Park, & Kim,

2019; Sanz-Baños et al., 2016). Machine learning and deep learning algorithms offers the ability to analyze few and large amounts of data and discover hidden patterns and associations that may not be evident through traditional statistical approaches(Kuner & Kuner, 2021; Pastor-Mira et al., 2019). One of the main advantages of using artificial intelligence to study the relationship between mental ill-health and low back pain, is its ability to capture and analyze multiple dimensions of pain (Popescu, Burdea, Bouzit, & Hentz, 2000). Traditional research methods often focus only on the physiological aspects of pain, such as measuring pain intensity or identifying biomarkers. While these aspects are undeniably important, they provide only a partial understanding of the pain experience (Quartana, Campbell, & Edwards, 2009; Sanz-Baños et al., 2016).

Mathematical modeling can provide a more comprehensive representation of pain by integrating functional, psychological, and emotional factors into the analysis, and artificial intelligence algorithms allow researchers to analyze complex and heterogeneous data and can help identify patterns and relationships between variables, determining the relationship between low back pain and its interaction with mental illness (Graham et al., 2019; Nagireddi et al., 2022; Okafor et al., 2023; Singh, Kumar, & Gupta, 2022). Pain is a subjective experience, the evaluation of which depends largely on self-reported measures. These measures often include questionnaires, surveys, and diaries to capture people's perceptions, emotions, and behaviors related to pain. AI algorithms can process and analyze these data sources, generating meaningful insights and identifying patterns that help understand how pain and mental illness relate to and affect an individual's quality of life (Crombez, Eccleston, Van Damme, Vlaeyen, & Karoly).

In order to improve understanding of the link between low back pain and psychological conditions, and to aid in better assessment and decision-making by healthcare professionals, artificial intelligence have shown great efficacy (Kuner & Kuner). Artificial intelligence algorithms can analyse behavioural, language, and emotional functional patterns captured in digital data, such as text messages, social media, or electronic health records, and identify indicators of emotional pain and distress (Park et al.). This information can be used to develop

low back pain tracking tools and continuous monitoring for more timely and individualized interventions.

Therefore, the aim of the current study was two-fold: (i) to develop a mathematical representation based on multivariate model to elucidate the relation between low back pain and biopsychosocial aspects and (ii) to identify subpopulations that present deviations from the pattern emerged. We hypothesize that it is possible to test the IASP concept of pain through a mathematical representation (evidencing its coherence) and that there is a strong relationship between mental health and the way the subject copes with the experience of pain and its functional consequences.

## **2. Materials and Methods**

Details of the study design are presented, including methodological approaches that we use to analyze the complex interactions of low back pain phenomena and try to understand the underlying patterns and relationships, with the auxilium of mathematical modeling and the algorithms of artificial intelligence (Gatchel et al., 2007; Park et al., 2019; Vlaeyen & Linton, 2000). The methodological design of our study allows us to provide a comprehensive view of the research process and aims to ensure the validity and reliability of the results obtained. With targeted methods, we intend to expand our knowledge in this field, advancing our understanding of the interaction between low back pain and mental illness (Kuner & Kuner).

This was a cross-sectional observational study approved by the ethics committee of the School of Health of the Polytechnique of Porto (CE0092B) and the study objectives and procedures were conducted in accordance with the guidelines of the Declaration of Helsinki. Volunteers consented to participate in the study through their informed consent form. The sample consisted of 1.021 young adults (73% females), aged between 18 and 35 years ( $24.68 \pm 1.5$  years, height  $167.9 \pm 0.1$  m and weight  $65.8 \pm 3.5$  kg). The exclusion criteria were  $< 18$  years old or  $> 35$  years old or have not completed the survey. The research involved the center for rehabilitation and research (CIR) of the higher school of health of

the polytechnic of Porto and laboratory of biomechanics of university of Porto (LABIOMEPE).

### *2.1 Data Collection.*

The survey focusing on the relation of low back pain with psychological variables in young adults was created with Lime Survey version 3.28.56+230404, an online survey application software written in pre-processed Python text. Data were collected through online auto-completion on the Lime platform in the period from June 8, 2022 to April 8, 2023. The link to access the survey was disseminated through the institutional emails of the Polytechnic of Porto the University of Porto to the entire academic population and in social networks. Participants provided information related to gender, mass, age, height, sociodemographic information, the existence of medical diagnosis of psychiatric disorder and frequency of episodes of low back pain in six weeks.

### *2.2 Instruments.*

The Oswestry disability index I (ODI) (Davidson; Keating, 2002), was used in the survey as a specific instrument that measures the impact of back pain on daily living activities (particularly regarding pain intensity, lifting weights, social interaction, sitting, standing, traveling, sex life, sleeping, walking and caring). It is composed of 10 questions with six alternatives (each ranging in scores from 0 to 5). The first question assesses the intensity of pain, while the others score the pain impact on daily activities (such as personal care, lifting weights, walking, sitting, standing, sleeping, social activities and mobility). The total score is multiplied by the number of questions answered and, again, multiplied by five, with the result expressed as a percentage ( $[\text{score} \div (\text{number of questions answered} \times 5)] \times 100$ ). It is classified as minimal, moderate and severe disabilities (0-20, 21-40 and 41-60%, respectively), disabled (61-80%) and bedridden (81-100%).

The depression anxiety stress scales short form (DASS) (Marijanović; Kraljević; Buhovac; Cerić *et al.*, 2021) was also used (including 21 items) and was designed to assess depression, anxiety and stress domains (each one being represented by seven items). Participants rated each item on a 0 ("did not apply to me at all")

to 3 (“applied to me very much or most of the time”) scale. Each domain is represented by a subscale score (the sum of the item responses for that subscale multiplied by two to be comparable with the original 42 item Depression Anxiety Stress Scales). This instrument was previously validated and considered reliable (Ong et al.), with a high score representing worse depression, anxiety or stress. Cut points normal, mild, moderate, severe and extremely severe scores classification, based on population norms, are provided in its manual. Classification symptoms are rated as 0-10 (normal), 11-18 (mild), 19-26 (moderate), 27-34 (severe) and 35-42 (extremely severe) for stress, 0-6 (normal), 7-9 (mild), 10- 14 (moderate), 15-19 (severe) and 20-42 (extremely severe) for anxiety and 0-9 (normal), 10-12 (mild), 13-20 (moderate), 21-17 (severe) and 28-42 (extremely) severe for depression.

Pain catastrophizing daily (Darnall; Sturgeon; Cook; Taub *et al.*, 2017) is a questionnaire with 14 points that aims to assess disasters in the last 24 hours, whose items were also rated by our participants on a scale of 0 (“never”) to 4 (“always”). The total score was calculated as the sum of the item responses (range 0-56), with higher scores representing greater catastrophizing of pain. The use of the daily catastrophe questionnaire may lead to greater analytical accuracy in research, health tools and platforms, and studies of psychosocial diaries that seek to understand the adaptive mechanisms of pain.

### *2.3 Anomaly detection structure.*

Anomaly detection refers to the problem of finding data patterns that do not conform to the expected behaviour (Okafor et al.). In the current research it was used a dataset of 1.021 volunteers, to model the relationship patterns between the low back pain related variables. An artificial neural network structure with two hidden layers was trained, including tangent hyperbolic transfer and a logistic sigmoid with 20 neurons each and fully connected (Figure 1). The input layer was composed of socioanthropometric dimensions related variables (age, sex, body mass, height and body mass index) and data from the Oswestry disability index I (Lovelace et al.), depression anxiety stress scales (Ong et al.) and pain catastrophizing daily (Tanaka et al.) questionnaire scores. The output layer contained the same information, but with the randomized subjects order. The

output space consisted of a "1" or "2" binary classification, indicating "no change" and "change" in the general functional profile (respectively). The learning algorithm used was Bayesian regularization. The dataset was randomly split into 80% of samples for training and 20% for testing.

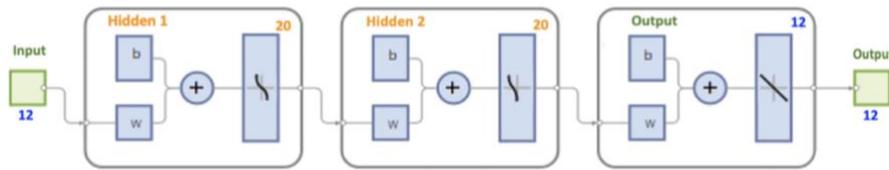


Figure 1. Used artificial neural network structure.

After 727 epochs, a mean square error performance value of 0.001 was obtained. The accuracy achieved after training equals  $R = 0.9903, 0.9625$  and  $0.9846$  in training, test and for all samples (respectively). Then, data of all subjects were simulated using the model obtained and the estimates were compared with the real data through a single linear regression, where the target was the dependent variable and the output was the independent variable.

Subsequently, three subgroups were created, determined by the position of the  $R$  in relation to the 25 and 75th percentiles (the first formed by subjects with values  $< 25$ th percentile, the second from 25-75th percentiles and the third  $> 75$ th percentile). Since data did not show a normal distribution, the between groups comparison was made through the Kruskal-Wallis test (with the pairwise comparison conducted with Mann-Whitney U test adjusted with the Bonferroni correction).

### 3. Results

The model seems to capture some interesting differences between the groups (Fig. 2), showing a relationship between the variables of number of lower back pain events in the 6-week period ( $p = 0.001$ ), medical diagnosis of lower back pathology ( $p = 0.002$ ), ODI ( $p = 0.001$ ), age ( $p = 0.030$ ), anthropometric data, and correlated with the psychological variables, stress ( $p = 0.001$ ), anxiety ( $p = 0.001$ ), depression ( $p = 0.001$ ) and catastrophizing in the last 24 hours in episodes of low back pain ( $p = 0.001$ ). The results are expressed as the multiplication factor (MF)

of each condition that is multiplied by the constant value (as mean) of each variable.

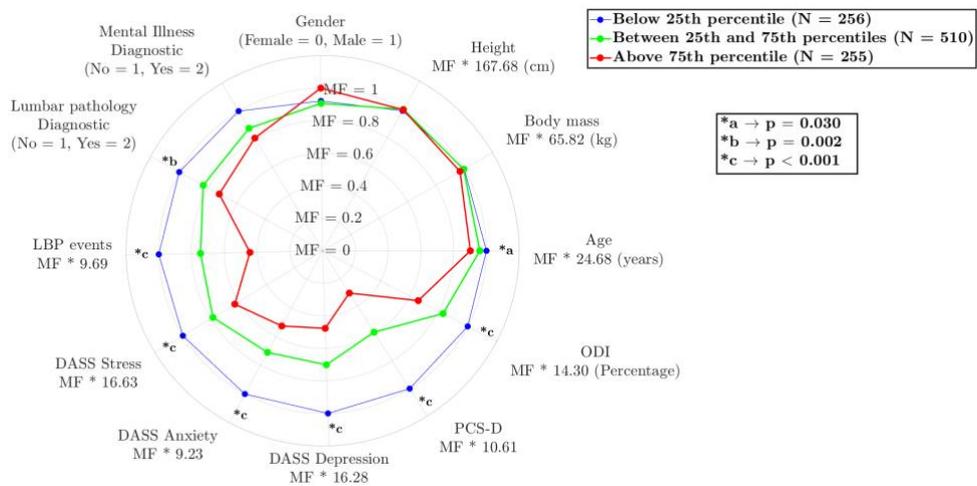


Figure 2. Comparison of different variables among the three subgroups, with the variables names being followed by the value to be multiplied by the multiplication factor. Legend: stress (DASS Stress), anxiety (DASS Anxiety), depression (DASS Depression) scales short, pain catastrophizing daily (PCS-D) and form Oswestry disability index (ODI).

### Statistical analysis

Table 1 shows the difference between groups and effect size regarding each variable, followed by median and interquartile range values. The GPower 3.1.7 software (University of Kiel, Kiel, Germany) was used to calculate the effect size (ES) and determine the power of analysis using the Mann-Whitney-U, followed by the Cohen’s d criteria (small: > 0.2; moderate: > 0.50; large: > 0.80) (Cohen 1988). No differences were found between groups regarding body mass, height, gender or mental illness diagnostic. Lumbar pathology was higher in groups 1 vs 3 ( $p < 0.001$ ) and in groups 2 vs 3 ( $p = 0.039$ ), and low back pain events presented a similar behaviour, i.e., groups 1 > 2 ( $p = 0.001$ ) and groups 1 > 3 ( $p = 0.003$ ). The psychological variables differed between groups, with stress being higher in groups 1 vs 2 and in groups 1 vs 3 (both for a  $p < 0.001$ ), anxiety showing to be higher in groups 1 vs 3 ( $p < 0.001$ ), in groups 1 vs 2 ( $p < 0.001$ ) and in groups 2 vs 3 ( $p = 0.031$ ), depression displaying higher values in groups 2 vs 3 ( $p = 0.019$ ), in groups 1 vs 3 ( $p < 0.001$ ) and in groups 1 vs 2 ( $p < 0.001$ ) and Pain Catastrophizing Daily in groups 1 > 2 and groups 1 > 3 (both for a  $p < 0.001$ ) due to its epistemological proximity. Given that psychological variables are factors that can exacerbate pain, the Oswestry disability index I higher values in groups 1 > 3 ( $p = 0.050$ ), showing mild difficulty of lumbar functionality, are not surprising.

Variables	comparison	group	p	d- cohen
Age	G1 - 22 (8)	G2	0.322	1.494
		G3	<b>0.000</b>	0.212
	G2 – 22 (8)	G1	0.322	1.494
		G3	0.008	0.179
	G3 – 21 (5)	G1	<b>0.000</b>	0.212
		G2	0.008	0.179
Body mass	G1 – 62 (21)	G2	0.012	1.503
		G3	<b>0.001</b>	0.301
	G2 – 63 (16)	G1	0.012	1.503
		G3	0.437	0.191
	G3 – 60 (12)	G1	<b>0.001</b>	0.301
		G2	0.437	0.191
Height	G1 – 167 (11)	G2	0.801	1.403
		G3	1.000	0.177
	G2 – 165 (12)	G1	0.801	1.403
		G3	1.000	0.054
	G3 – 165 (12)	G1	1.000	0.177
		G2	1.000	0.054
Gender	G1*	G2	1.000	0.041

		G3	1.000	0.138
	G2*	G1	1.000	0.041
		G3	1.000	0.034
	G3*	G1	1.000	0.138
		G2	1.000	0.034
Mental Illness diagnosis	G1*	G2	0.054	0.111
		G3	0.060	0.158
	G2*	G1	0.054	0.111
		G3	1.000	0.033
	G3*	G1	0.060	0.158
		G2	1.000	0.033
Lumbar pathology Diagnosis	G1*	G2	0.041	1.421
		G3	<b>0.000</b>	0.200
	G2*	G1	0.041	1.421
		G3	0.142	0.136
	G3*	G1	0.000	0.200
		G2	0.142	0.136
LBP events	G1 – 4 (9)	G2	<b>0.000</b>	1.469
		G3	<b>0.000</b>	0.260
	G2 – 4 (4)	G1	<b>0.000</b>	1.469
		G3	0.028	0.280

		G1	<b>0.000</b>	0.260
	G3 – 4 (4)	G2	0.028	0.280
		G2	<b>0.000</b>	1.686
	G1 – 14 (16)	G3	<b>0.000</b>	0.517
Dass - stress		G1	<b>0.000</b>	1.686
	G2 – 10 (10)	G3	0.015	0.424
		G1	<b>0.000</b>	0.517
	G3 – 10 (8)	G2	0.015	0.424
		G2	<b>0.000</b>	1.677
	G1 – 8 (12)	G3	<b>0.000</b>	0.506
Dass - anxiety		G1	<b>0.000</b>	1.677
	G2 – 4 (6)	G3	0.021	0.413
		G1	<b>0.000</b>	0.506
	G3 – 2 (8)	G2	0.021	0.413
		G2	<b>0.000</b>	1.757
	G1 – 12 (20)	G3	<b>0.000</b>	0.596
Dass - depression		G1	<b>0.000</b>	1.757
	G2 – 6 (10)	G3	<b>0.001</b>	0.510
		G1	<b>0.000</b>	0.596
	G3 – 6 (8)	G2	<b>0.001</b>	0.510
PCS-D	G1 – 2 (15)	G2	<b>0.000</b>	1.523

		G3	<b>0.000</b>	0.326
	G2 – 1 (8)	G1	<b>0.000</b>	1.523
		G3	<b>0.000</b>	0.218
	G3 – 1 (5)	G1	<b>0.000</b>	0.326
		G2	<b>0.000</b>	0.218
	G1 – 10 (18)	G2	0.015	1.416
		G3	<b>0.000</b>	0.193
ODI	G2 – 10 (16)	G1	0.015	1.416
		G3	0.036	0.072
	G3 – 8 (10)	G1	<b>0.000</b>	0.193
		G2	0.036	0.072

Table 1: comparison of different variables among the three subgroups. Legend Cohen's D test value, stress (DASS Stress), anxiety (DASS Anxiety), depression (DASS Depression) scales short, pain catastrophizing daily (PCS-D) , form Oswestry disability index (ODI), group 1 (G1), group2 (G2), group 3 (G3), \*have binary values described in the results session, p-value and Cohen's D test value.

These findings provide valuable information about the factors that contribute to low back pain in young adults and emphasize the importance of considering physiological and psychological aspects in understanding and managing this condition.

#### 4. Discussion

Pain and mental illness together should be part of an integrated treatment approach. It should involve a multi-professional team, with a combination of physical interventions, such as exercise, physical therapy, medication to manage pain, and psychological interventions, to address the mental and improve the functional (Quartana et al.). Therefore, research in this area, with the aid of multivariate models, is of great importance, as it allows the identification of risk and protection factors associated with pain and mental illness. This includes

genetic, environmental, psychosocial and behavioral factors that may influence the development of these conditions. Understanding these factors enables the implementation of more effective preventive strategies and the development of targeted interventions, playing an important role in reducing the stigma associated with these conditions (Bair et al., 2008; Veehof, Oskam, Schreurs, & Bohlmeijer, 2011).

The mathematical modeling we used in our study can lead to advances in the delivery of care from all areas of healthcare. Using effective screening artificial intelligence algorithms, unusual patterns in the frequency, intensity, or duration of low back pain over time can be identified and is useful for identifying episodes of severe acute pain or significant changes in pain pattern. It can be applied to identify specific activities, postures or movements that lead to a significant increase in pain (Doan et al., 2015). This information can help identify behaviours or situations that should be avoided or changed to improve pain management, and thus identify triggers associated with low back pain episodes and their physical and mental functions.

We found evidence of a relationship between the repetition of traumatic events and physical and mental functioning, particularly stress, anxiety, and ultimately depression. According to the literature and the data obtained in this study, the repeated experience of pain can have a significant impact on a person's daily functioning and can also increase the risk of developing or worsening depressive symptoms (Cohen, 2013; Nickinson, Board, & Kay, 2009). Recurrent or persistent pain can limit a person's ability to carry out daily activities, such as work, exercise, socializing, and self-care. In the case of persistent pain, it can affect sleep, energy, mood, and quality of life, leading to symptoms of depression (Kuner & Kuner, 2021; Vlaeyen & Linton, 2000). Mental and emotional health play a significant role in the experience and perception of pain, and addressing these aspects can bring substantial benefits to patients (Doan et al., 2015; Singh et al., 2022), thus this study has significant potential by exploring the direct relationship between musculoskeletal pain and mental ill-health.

Considering that pain is an unpleasant sensory and emotional experience associated with (or resembling to) actual/potential tissue damage, there should

be quantifiable emotional variables that allow transcribing it into a mathematical model. Moreover, due to the sensory-motor nature of this phenomenon, movement measures or scores should be included in the model. Data from human movement biomechanical variables are commonly heterogeneous and form a large volume of information, making it difficult to treat them, using inferential statistics. However, advanced analytical techniques used to evaluate informative data features and model underlying relationships that cannot be treated with traditional statistics can increase the research quality (Gatchel et al., 2007; Wager et al., 2013). For a more global understanding of low back pain multivariate phenomena, widely used artificial intelligence tools (Dworkin et al., 2009; Wager et al., 2013), should be employed. Aiming to mathematically represent the IASP (Raja et al., 2020) definition of pain using an artificial neural network approach, based on the current study results, we advocate that it is possible to mathematically model and represent it.

The mathematical model that we have presented processed information from 1.021 volunteers allowing us to access the linear and non-linear relationships between variables that construct the phenomenon. It was shown a very robust final performance and identified the sub-populations that presented deviations from the pattern in the context of low back pain and biopsychosocial aspects (Dworkin et al., 2009; Gatchel et al., 2007). The relationships between the variables that emerged from this model can be seen in the group profiles. An interesting fact in the group < 25th percentile is that the lumbar pathology diagnosis is closely linked to the depression anxiety stress scales related variables (Ong et al., 2019)], pain catastrophizing daily (Tanaka et al., 2021) and low back pain events, promoting a slight functional incapacity of the individual. It seems that this functional incapacity makes it difficult for the individuals to carry out their usual activities (Graham et al., 2019), eventually leading to social isolation and having a major negative effect on individual well-being.

The current study results show an interdependence of variables, meaning that, for example, our oldest group also has higher prevalence of diagnosis of lumbar problems and low back pain flairs, as well as scored worse on depression anxiety

stress scales, pain catastrophizing daily and Oswestry disability index I surveys. However, our data cannot give a good explanation about the underlying mechanism, i.e., if the low back pain flares lead to worse psychological variables or if the psychological impairment leads to perception and aggravation of the pain (leading to seek medical diagnosis).

The relationship between low back pain, psychological distress and mild functional disability observed by us is in line with previous data that identified high levels of pain intensity associated with poor psychological and physiological capacity and high levels of anxiety and depression (Baron, Binder, & Wasner, 2010). Based on the current study results and on the literature, it is possible that the mental disorder in low back pain may be a predictor of reduced functionality (Bair et al., 2008; Lovelace et al., 2016) and to hypothesize that individuals with a medical diagnosis of lower back pathology have a higher number of lower back pain episodes over a six weeks period and higher levels of pain catastrophizing.

Our data are in line with a study with 84 patients with rotator cuff tears that were evaluated for the presence of differences in pain, function and/or psychological distress associated with pain, as well as analysed for the association between psychological distress with shoulder pain and function during adjustment for cuff tears severity (Bair, Robinson, Katon, & Kroenke, 2003). Results demonstrated that baseline psychological distress relates with patients pain and shoulder function more than the diagnosis of rotator cuff tears, suggesting that the size and severity of the lesion do not fully relate with symptoms (e.g. pain and functional limitation) but rather with psychological distress (Bair et al., 2008; Silva, Fassa, & Valle, 2004; Sun, Wang, Zhang, & Wang, 2023). Anxiety and avoidance can cause an inflated sense of pain (Goethel et al., 2020; Taherdoost & Madanchian, 2023), while fear of pain influences short-term pleasure seeking (Nagireddi et al., 2022) due to pain's catastrophic aftermath (Malhotra et al., 2016; Samariya, Ma, Aryal, & Zhao, 2023). These behavioural patterns aren't connected to the disease at hand.

Based on these statements, a study in mice examines whether long-term associations with remembering fear stored in neural engrams in the prefrontal cortex can determine how painful episodes evolve into later-life painful

experiences (Doan et al., 2015; Écija, Luque-Reca, Suso-Ribera, Catala, & Peñacoba, 2020). It was evidenced that long-term fear memory has been shown to be associated with pathological changes in nociceptive sensitivity following tissue injury, a key feature of pathological pain disorders and known to be regulated by the cortex (Davidson & Keating, 2002). Pain and fear are independent behavioural states that are interrelated (Doan et al., 2015; Hooten, 2016), with fear acutely potentiating the perception of pain that is fundamental to survival. It was concluded that a painful experience could encode a memory of fear (that will be stored in a discrete and specific cohort of prefrontal cortical neurons). This will be subjected to reactivation after exposure to a new painful stimulus in future life events and, as a result, it will produce an intensification on pain perception (Davidson & Keating, 2002; Marijanović et al., 2021).

According to the above-referred approach and the data from our study, it can be underlined that the catastrophizing of pain leads to excessive fear of pain, with the associative long-term memory of fear induced by previous exposure to pain may also be a critical predisposing factor for pain chronicity (Darnall et al., 2017; Hooten, 2016). Thus, the fear of pain can provoke avoidance of motion behaviours and exacerbate pain in the long term, implying an increase in the functional disability of the individual. It is important to address that the relationship between pain, functionality and depression is bidirectional.

This study has some limitations. Data from self-completion questionnaires rely on the accuracy and honesty of participants' responses. However, these responses may be subject to self-report bias, where participants may provide inaccurate or biased responses. This may occur due to memory problems, lack of understanding of the questions, desire to please the researcher or hide certain information, besides not having a face-to-face and objective verification of the data provided by the participants. We take these limitations into consideration when constructing the survey, applying, and interpreting study results. We understood the possible sources of bias, which helped us to assess the validity and reliability of the results obtained. In addition, we combined different methods of complementary analysis which allowed us to strengthen the conclusion of our study.

## **5. Conclusions**

In view of the above we conclude that it is possible to validate and confirm the definition of pain by IASP through mathematical modelling. The identified subpopulations showed a direct relationship between pain and mental illness, with these two inducing greater disabilities. Even if these results may help to improve the understanding between mental illness as a possible enhancer of pain episodes and functionality, future studies evaluating other variables, like the level of physical activity and the sedentary behaviour of the subjects, are required to better understand the referred association.

**Author Contributions:** conceptualization, F.P., K.B., U.E., M.G.; R.S; and J.P.V.B.; methodology F.P; M.G; C.F; R.F and K.B.; formal analysis F.P., K.B., U.E., C.F; M.G.; R.F; R.S and J.P.V.B; resources, F.P; K.B; M.G; R.F and R.S; writing—original draft preparation, F.P, M.G; K.B; U.E; C.F; R.F; J.P.V.B and R.S. ; writing—review and editing, F.P., U.E, R.F; C.F; K.B., J.P.V.B., M.G and R.S.; supervision J.P. V.B., R.S and M.G.; project administration, F.P; K.B; M.G; U.E; C.F; R.F and R.S. All authors have read and agreed to the published version of the manuscript.

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### **Institutional Review Board Statement:**

The study was conducted in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Committee School of Health of the Polytechnic of Porto (CE0092B).

### **Informed Consent Statement:**

Informed consent was obtained from all the participants involved in the study.

### **Data Availability Statement:**

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

## Conflicts of Interest:

The authors declare no conflict of interest.

## References

- Ashar, Y. K., Gordon, A., Schubiner, H., Uipi, C., Knight, K., Anderson, Z., . . . Wager, T. D. (2022). Effect of Pain Reprocessing Therapy vs Placebo and Usual Care for Patients With Chronic Back Pain: A Randomized Clinical Trial. *JAMA Psychiatry*, 79(1), 13-23. doi:10.1001/jamapsychiatry.2021.2669
- Bair, M. J., Robinson, R. L., Katon, W., & Kroenke, K. (2003). Depression and pain comorbidity: a literature review. *Arch Intern Med*, 163(20), 2433-2445. doi:10.1001/archinte.163.20.2433
- Bair, M. J., Wu, J., Damush, T. M., Sutherland, J. M., & Kroenke, K. (2008). Association of depression and anxiety alone and in combination with chronic musculoskeletal pain in primary care patients. *Psychosom Med*, 70(8), 890-897. doi:10.1097/PSY.0b013e318185c510
- Baliki, M. N., & Apkarian, A. V. (2015). Nociception, Pain, Negative Moods, and Behavior Selection. *Neuron*, 87(3), 474-491. doi:10.1016/j.neuron.2015.06.005
- Baron, R., Binder, A., & Wasner, G. (2010). Neuropathic pain: diagnosis, pathophysiological mechanisms, and treatment. *Lancet Neurol*, 9(8), 807-819. doi:10.1016/s1474-4422(10)70143-5
- Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*: routledge.
- Crombez, G., Eccleston, C., Van Damme, S., Vlaeyen, J. W., & Karoly, P. (2012). Fear-avoidance model of chronic pain: the next generation. *Clin J Pain*, 28(6), 475-483. doi:10.1097/AJP.0b013e3182385392
- Darnall, B. D., Sturgeon, J. A., Cook, K. F., Taub, C. J., Roy, A., Burns, J. W., . . . Mackey, S. C. (2017). Development and Validation of a Daily Pain Catastrophizing Scale. *J Pain*, 18(9), 1139-1149. doi:10.1016/j.jpain.2017.05.003

- Davidson, M., & Keating, J. L. (2002). A comparison of five low back disability questionnaires: reliability and responsiveness. *Phys Ther*, *82*(1), 8-24. doi:10.1093/ptj/82.1.8
- Doan, L., Manders, T., & Wang, J. (2015). Neuroplasticity underlying the comorbidity of pain and depression. *Neural Plast*, *2015*, 504691. doi:10.1155/2015/504691
- Dworkin, R. H., Turk, D. C., McDermott, M. P., Peirce-Sandner, S., Burke, L. B., Cowan, P., . . . Sampaio, C. (2009). Interpreting the clinical importance of group differences in chronic pain clinical trials: IMMPACT recommendations. *Pain*, *146*(3), 238-244. doi:10.1016/j.pain.2009.08.019
- Écija, C., Luque-Reca, O., Suso-Ribera, C., Catala, P., & Peñacoba, C. (2020). Associations of Cognitive Fusion and Pain Catastrophizing with Fibromyalgia Impact through Fatigue, Pain Severity, and Depression: An Exploratory Study Using Structural Equation Modeling. *J Clin Med*, *9*(6). doi:10.3390/jcm9061763
- Edwards, R. R., Dworkin, R. H., Sullivan, M. D., Turk, D. C., & Wasan, A. D. (2016). The Role of Psychosocial Processes in the Development and Maintenance of Chronic Pain. *J Pain*, *17*(9 Suppl), T70-92. doi:10.1016/j.jpain.2016.01.001
- Gatchel, R. J., Peng, Y. B., Peters, M. L., Fuchs, P. N., & Turk, D. C. (2007). The biopsychosocial approach to chronic pain: scientific advances and future directions. *Psychol Bull*, *133*(4), 581-624. doi:10.1037/0033-2909.133.4.581
- Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. (2020). *Lancet*, *396*(10258), 1204-1222. doi:10.1016/s0140-6736(20)30925-9
- Goethel, M. F., Gonçalves, M., Brietzke, C., Cardozo, A. C., Vilas-Boas, J. P., & Ervilha, U. F. (2020). A global view on how local muscular fatigue affects human performance. *Proc Natl Acad Sci U S A*, *117*(33), 19866-19872. doi:10.1073/pnas.2007579117
- Graham, S., Depp, C., Lee, E. E., Nebeker, C., Tu, X., Kim, H. C., & Jeste, D. V. (2019). Artificial Intelligence for Mental Health and Mental Illnesses: an

- Overview. *Curr Psychiatry Rep*, 21(11), 116. doi:10.1007/s11920-019-1094-0
- Gutiérrez, L., Écija, C., Catalá, P., & Peñacoba, C. (2023). Sedentary Behavior and Pain after Physical Activity in Women with Fibromyalgia—The Influence of Pain-Avoidance Goals and Catastrophizing. *Biomedicines*, 11(1), 154. Retrieved from <https://www.mdpi.com/2227-9059/11/1/154>
- Hooten, W. M. (2016). Chronic Pain and Mental Health Disorders: Shared Neural Mechanisms, Epidemiology, and Treatment. *Mayo Clin Proc*, 91(7), 955-970. doi:10.1016/j.mayocp.2016.04.029
- Kuner, R., & Kuner, T. (2021). Cellular Circuits in the Brain and Their Modulation in Acute and Chronic Pain. *Physiol Rev*, 101(1), 213-258. doi:10.1152/physrev.00040.2019
- Lovelace, M. D., Varney, B., Sundaram, G., Franco, N. F., Ng, M. L., Pai, S., . . . Brew, B. J. (2016). Current Evidence for a Role of the Kynurenine Pathway of Tryptophan Metabolism in Multiple Sclerosis. *Front Immunol*, 7, 246. doi:10.3389/fimmu.2016.00246
- Lumley, M. A., Schubiner, H., Lockhart, N. A., Kidwell, K. M., Harte, S. E., Clauw, D. J., & Williams, D. A. (2017). Emotional awareness and expression therapy, cognitive behavioral therapy, and education for fibromyalgia: a cluster-randomized controlled trial. *Pain*, 158(12), 2354-2363. doi:10.1097/j.pain.0000000000001036
- Malhotra, P., Ramakrishnan, A., Anand, G., Vig, L., Agarwal, P., & Shroff, G. (2016). LSTM-based encoder-decoder for multi-sensor anomaly detection. *arXiv preprint arXiv:1607.00148*.
- Marijanović, I., Kraljević, M., Buhovac, T., Cerić, T., Mekić Abazović, A., Alidžanović, J., . . . Sokolović, E. (2021). Use of the Depression, Anxiety and Stress Scale (DASS-21) Questionnaire to Assess Levels of Depression, Anxiety, and Stress in Healthcare and Administrative Staff in 5 Oncology Institutions in Bosnia and Herzegovina During the 2020 COVID-19 Pandemic. *Med Sci Monit*, 27, e930812. doi:10.12659/msm.930812
- Mescouto, K., Olson, R. E., Hodges, P. W., & Setchell, J. (2022). A critical review of the biopsychosocial model of low back pain care: time for a new

- approach? *Disabil Rehabil*, 44(13), 3270-3284.  
doi:10.1080/09638288.2020.1851783
- Nagireddi, J. N., Vyas, A. K., Sanapati, M. R., Soin, A., & Manchikanti, L. (2022). The Analysis of Pain Research through the Lens of Artificial Intelligence and Machine Learning. *Pain Physician*, 25(2), E211-e243.
- Nickinson, R. S., Board, T. N., & Kay, P. R. (2009). Post-operative anxiety and depression levels in orthopaedic surgery: a study of 56 patients undergoing hip or knee arthroplasty. *J Eval Clin Pract*, 15(2), 307-310.  
doi:10.1111/j.1365-2753.2008.01001.x
- Okafor, C., Levin, J. M., Boadi, P., Cook, C., George, S., Klifto, C., & Anakwenze, O. (2023). Pain associated psychological distress is more strongly associated with shoulder pain and function than tear severity in patients undergoing rotator cuff repair. *JSES Int*, 7(4), 544-549.  
doi:10.1016/j.jseint.2023.02.010
- Olango, W. M., & Finn, D. P. (2014). Neurobiology of stress-induced hyperalgesia. *Curr Top Behav Neurosci*, 20, 251-280.  
doi:10.1007/7854\_2014\_302
- Ong, W. Y., Stohler, C. S., & Herr, D. R. (2019). Role of the Prefrontal Cortex in Pain Processing. *Mol Neurobiol*, 56(2), 1137-1166. doi:10.1007/s12035-018-1130-9
- Park, I., Lee, H. J., Kim, S. K., Park, M. S., & Kim, Y. S. (2019). Factors Related to Preoperative Shoulder Pain in Patients with Atraumatic Painful Rotator Cuff Tears. *Clin Shoulder Elb*, 22(3), 128-134.  
doi:10.5397/cise.2019.22.3.128
- Pastor-Mira, M. A., López-Roig, S., Martínez-Zaragoza, F., León, E., Abad, E., Lledó, A., & Peñacoba, C. (2019). Goal Preferences, Affect, Activity Patterns and Health Outcomes in Women With Fibromyalgia. *Front Psychol*, 10, 1912. doi:10.3389/fpsyg.2019.01912
- Paulus, M. P., & Stein, M. B. (2010). Interoception in anxiety and depression. *Brain structure and Function*, 214(5), 451-463.
- Popescu, V. G., Burdea, G. C., Bouzit, M., & Hentz, V. R. (2000). A virtual-reality-based telerehabilitation system with force feedback. *IEEE transactions on Information Technology in Biomedicine*, 4(1), 45-51.

- Quartana, P. J., Campbell, C. M., & Edwards, R. R. (2009). Pain catastrophizing: a critical review. *Expert Rev Neurother*, 9(5), 745-758. doi:10.1586/ern.09.34
- Raja, S. N., Carr, D. B., Cohen, M., Finnerup, N. B., Flor, H., Gibson, S., . . . Vader, K. (2020). The revised International Association for the Study of Pain definition of pain: concepts, challenges, and compromises. *Pain*, 161(9), 1976-1982. doi:10.1097/j.pain.0000000000001939
- Rajkomar, A., Dean, J., & Kohane, I. (2019). Machine Learning in Medicine. *N Engl J Med*, 380(14), 1347-1358. doi:10.1056/NEJMra1814259
- Samariya, D., Ma, J., Aryal, S., & Zhao, X. (2023). Detection and explanation of anomalies in healthcare data. *Health Information Science and Systems*, 11(1), 20.
- Sanz-Baños, Y., Pastor, M., Velasco, L., López-Roig, S., Peñacoba, C., Lledo, A., & Rodríguez, C. (2016). To walk or not to walk: insights from a qualitative description study with women suffering from fibromyalgia. *Rheumatol Int*, 36(8), 1135-1143. doi:10.1007/s00296-016-3459-6
- Silva, M. C., Fassa, A. G., & Valle, N. C. (2004). [Chronic low back pain in a Southern Brazilian adult population: prevalence and associated factors]. *Cad Saude Publica*, 20(2), 377-385. doi:10.1590/s0102-311x2004000200005
- Singh, V., Kumar, A., & Gupta, S. (2022). Mental health prevention and promotion—A narrative review. *Frontiers in psychiatry*, 13, 898009.
- Sun, L., Wang, Z., Zhang, Y., & Wang, G. (2023). A Feature-Trajectory-Smoothed High-Speed Model for Video Anomaly Detection. *Sensors*, 23(3), 1612. Retrieved from <https://www.mdpi.com/1424-8220/23/3/1612>
- Taherdoost, H., & Madanchian, M. (2023). Artificial intelligence and sentiment analysis: A review in competitive research. *Computers*, 12(2), 37.
- Tanaka, M., Török, N., Tóth, F., Szabó, Á., & Vécsei, L. (2021). Co-Players in Chronic Pain: Neuroinflammation and the Tryptophan-Kynurenine Metabolic Pathway. *Biomedicines*, 9(8). doi:10.3390/biomedicines9080897
- Veehof, M. M., Oskam, M. J., Schreurs, K. M. G., & Bohlmeijer, E. T. (2011). Acceptance-based interventions for the treatment of chronic pain: a

- systematic review and meta-analysis. *Pain*, 152(3), 533-542.  
doi:10.1016/j.pain.2010.11.002
- Vlaeyen, J. W. S., & Linton, S. J. (2000). Fear-avoidance and its consequences in chronic musculoskeletal pain: a state of the art. *Pain*, 85(3), 317-332.  
doi:10.1016/s0304-3959(99)00242-0
- Vos, T., Flaxman, A. D., Naghavi, M., Lozano, R., Michaud, C., Ezzati, M., . . . Memish, Z. A. (2012). Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet*, 380(9859), 2163-2196.  
doi:10.1016/s0140-6736(12)61729-2
- Wager, T. D., Atlas, L. Y., Lindquist, M. A., Roy, M., Woo, C.-W., & Kross, E. (2013). An fMRI-Based Neurologic Signature of Physical Pain. *New England Journal of Medicine*, 368(15), 1388-1397.  
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## Chapter 3

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*Article*

### **Beyond low back pain! The influence of physical activity intensity on mental health, reflected in the functionality of people with low back pain – a canonical model.**

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## **Abstract**

Health problems, such as low back pain, can negatively affect both the psychological and physical aspects of life, significantly influencing quality of life.

**Methods:** data from Oswestry disability index, depression anxiety stress scales short form, International Physical Activity Questionnaire – short term and pain catastrophizing daily questionnaires were collected through online completion, available from June 8, 2022 to April 8, 2023 (1.021 cases). A canonical correlation analysis was performed to examine the overall linear correlation between the two sets of variables. **Results:** The canonical correlation of the variables between the mental health and functionality of the individual with low back pain was significant  $p < 0.05$ , as well as in the levels of stress, anxiety and depression between the different groups of physical activity (light and intense). **Conclusion:** These results highlight the beneficial role of physical activity, especially at higher intensities, in mental health and consequently in the functionality of the lumbar spine.

**Keywords:** Physical activity, Mental Health, Young Adults, low back pain, canonical correlation.

## 1. Introduction

Low back pain is recognized in many countries as the leading cause of musculoskeletal complaints, with significant health and economic impacts due to the limitations and disabilities it imposes on individuals (Vos et al., 2020). This condition leads to increased healthcare use and high rates of absenteeism due to pain, adversely affecting patient quality of life, burdening healthcare systems, and reducing their productivity (Davidson & Keating, 2002; Vos et al., 2020). The pain process encompasses sensory, cognitive, and affective components, the latter including feelings of annoyance, sadness, anxiety, and depression in response to a harmful stimulus (De Ridder et al., 2021; Doan et al.; Wiech & Tracey, 2009).

This is corroborated by the revised definition of the International Association for the Study of Pain (IASP), which conceptualizes pain as "an unpleasant sensory and emotional experience associated with, or similar to, actual or potential tissue injury" (Raja et al., 2020). The IASP definition was tested with a mathematical model that used data on functionality, symptoms of depression, anxiety, stress, and pain catastrophizing, using an artificial neural network to identify patterns (Parolini et al., 2023). The results showed that psychological events and pain are directly associated, demonstrating that mental aspects can intensify pain and affect an individual's functionality. In this context, it is possible to state that pain is closely related to people's biopsychosocial context (Abbott et al., 2011; Darnall et al., 2017).

In contemporary society, psychological factors have become increasingly prevalent (Liu et al., 2024; Mun et al., 2015; Selzler et al., 2023). The mental health of people with low back pain is likely to vary as a result of daily fluctuations in symptom intensity and other contextual pain-related characteristics (Campbell et al., 2010). In this scenario, there has been a growing interest in exploring the potential therapeutic effects of physical activity on physical and psychological well-being in low back pain, since it has recently become a priority to emphasize

the psychosocial approach in the prescription of low back pain treatment (Wun et al., 2021).

Physical activity is a multifaceted intervention that can influence the body through various biological, psychological, and social mechanisms (Ferreira et al., 2010). It is known that regular physical activity is associated with a lower risk of depression, but this association was not sustained when anxiety symptoms were analyzed (Liu et al., 2024). However, little is known about the specific influence of physical activity intensity, and several studies are still needed to define its doses and intensities that might influence psychological factors (Paolucci et al., 2018; Polli et al., 2019). Therefore, it is necessary to identify goals that modulate the intensity of physical activity according to the psychosocial characteristics of patients (Contreras-Osorio et al., 2022; Marshall et al., 2017; Selzler et al., 2023; Wood et al., 2021).

Although numerous studies have investigated the relationship between exercise and psychological factors as applied to low back pain and, consequently, individual functionality (Heneweer et al., 2009; Lin et al., 2011; Polli et al., 2019; Rahman et al., 2022; Vlaeyen & Linton, 2000; Wood et al., 2021; Wun et al., 2021), further exploration is needed to understand how different intensities of physical activity can influence various aspects of the physical and psychological health of these individuals (Ferreira et al., 2010; Liu et al., 2024; Parolini et al., 2023; Wood et al., 2021; Wun et al., 2021; Xu et al., 2024). The fear-avoidance model has also been widely used to understand how chronic low back pain is associated with activity limitation and increased psychological distress, suggesting that the way individuals perceive pain may be mediated by concern and fear that pain may lead to further damage (Vlaeyen & Linton, 2000).

However, there is a significant gap in the literature in understanding the interaction between psychological factors, functionality, and physical activity in the context of acute low back pain, which is distinct from the chronic condition (Chou & Huffman, 2007; Ijzelenberg et al., 2024; Meilleur-Durand et al., 2024; Qaseem et al., 2017). While most research has focused on chronic pain, the

acute phase presents unique challenges and possibly different dynamics that may influence recovery and psychosocial factors. Therefore, the aim of this study is to analyze the correlation between psychological factors and individual functionality in the presence of acute low back pain, considering different intensities of physical activity, and contribute to filling this important gap in the literature.

## **2. Materials and methods**

This was a cross-sectional observational study approved by the ethics committee of the School of Health of the Polytechnique of Porto (CE0092B). The study objectives and procedures were conducted in accordance with the guidelines of the Declaration of Helsinki. Volunteers consented to participate in the study through their written informed consent form. The sample consisted of 1.208 young adults. The inclusion criteria were: being between 18 and 35 years old and having low back pain as the main complaint, practicing physical activity, completing the four questionnaires in the survey, as well as understanding the instructions for filling in the questionnaires. The research involved the Center for Rehabilitation and Research (CIR) of the Higher School of Health of the Polytechnic Institute of Porto and the Biomechanics Laboratory of the University of Porto (LABIOMEPE).

### **2.1 Data Collection.**

The survey focusing on the relationship of low back pain with psychological variables in young adults was created with Lime Survey version 3.28.56+230404, an online survey application software written in pre-processed Python text. The survey consisted of four different questionnaires: The Oswestry Disability Index was used to assess the functional impact of low back pain; The Depression, Anxiety, and Stress Test allowed for the assessment of psychological symptoms among the participants; The Daily Pain Catastrophizing questionnaire investigated how intensely participants interpret their painful experiences; and, finally, the International Physical Activity Questionnaire - Short Form was used to

measure the frequency and intensity of physical activity carried out by the participants. Data were collected through online auto-completion on the Lime platform between June 8, 2022 and April 8, 2023. The link to access the survey was disseminated through the institutional emails of the Polytechnic Institute of Porto and the University of Porto to the entire academic population and in social media networks. Volunteers provided information related to gender, body mass, age, height, sociodemographic status, existence of any medical diagnosis of psychiatric disorder and frequency of episodes of low back pain in the previous 42 days.

## **2.2 Sample and low back pain**

The sample consisted of 1.021 young adults, aged between 18 and 35 years, with 63% women and 37% men, selected from a total of 1.208 participants. These 1.021 individuals were selected based on meeting the inclusion criteria. Regarding spinal health, 20% of participants reported diagnosed spinal pathologies, with the following prevalences: scoliosis (15%), disc protrusion (3%), herniated disc (1%), and anterolisthesis (1%). All participants reported at least one episode of acute low back pain in the past 6 weeks, with the distribution of episodes as follows: 10% reported 1 episode (102 participants), 20% reported 10 episodes (204 participants), 30% reported 14 episodes (306 participants), 15% reported 20 episodes (153 participants), 10% reported 25 episodes (102 participants), 5% reported 30 episodes (51 participants), and 10% reported more than 30 episodes (102 participants). Recruitment was conducted with a broad approach to ensure a comprehensive understanding of the relationship between low back pain episodes and psychosocial and functional factors.

## **2.3 Instruments.**

### **The Oswestry disability index - ODI (Fairbank & Pynsent, 2000)**

It was used in the survey as a specific instrument that measures the impact of back pain on daily living activities (particularly regarding pain intensity, lifting

weights, social interaction, sitting, standing, traveling, sex life, sleeping, walking, and caring)(Davidson & Keating, 2002; Fairbank & Pynsent, 2000). It is composed of 10 questions with six alternatives (each ranging in scores from 0 to 5). The first question assesses the intensity of pain, while the others score the pain impact on daily activities (such as personal care, lifting weights, walking, sitting, standing, sleeping, social activities, and mobility). The total score is obtained by multiplying the sum of the scores by 5, and then dividing the result by the total number of questions answered. The score is classified a minimal, moderate, and severe disabilities (0-20, 21-40, and 41-60%, respectively), disabled (61-80%), and bedridden (81-100%).

### **Depression anxiety stress scales – short form – DASS-21**

The depression anxiety stress scales short form (Martins et al., 2019) was also used (including 21 items) and was designed to assess depression, anxiety, and stress domains (each one being represented by seven items). Participants rated each item on a 0 (“did not apply to me at all”) to 3 (“applied to me very much or most of the time”) scale. Each domain is represented by a subscale score (the sum of the item responses for that subscale multiplied by two to be comparable with the original 42 item Depression Anxiety Stress Scales). This instrument was previously validated and considered reliable (Martins et al., 2019), with a high score representing worse depression, anxiety, or stress. Cut points for normal, mild, moderate, severe, and extremely severe scores classification, based on population norms, are provided. Classification symptoms are rated as 0-10 (normal), 11-18 (mild), 19-26 (moderate), 27-34 (severe) and 35-42 (extremely severe) for stress, 0-6 (normal), 7-9 (mild), 10- 14 (moderate), 15-19 (severe) and 20-42 (extremely severe) for anxiety and 0-9 (normal), 10-12 (mild), 13-20 (moderate), 21-17 (severe) and 28-42 (extremely) severe for depression.

### **Pain catastrophizing daily – PCS-D**

The pain catastrophizing daily – PCS-D – (Darnall et al., 2017) is a questionnaire with 14 points that aims to assess disasters in the last 24 hours, whose items

were also rated by our participants on a scale of 0 (“never”) to 4 (“always”). The total score was calculated as the sum of the item responses (range 0-56), with higher scores representing greater catastrophizing of pain. The use of the daily catastrophe questionnaire may lead to greater analytical accuracy in research, health tools and platforms, and studies of psychosocial diaries that seek to understand the adaptive mechanisms of pain.

### **International Physical Activity Questionnaire - Short Form (IPAQ)**

The IPAQ-sf consists of 7 questions and is easy to apply in clinical practice. It provides information on the number of days/week and the average time/day spent on moderate and vigorous intensity walking activities, as well as sitting, based on the previous 7 days. The IPAQ-sf categorical score classifies the patient's level of physical activity as ‘low’, ‘moderate’ or ‘high’ (IPAQ, 2004; Lee et al., 2011).

### **Canonical Correlation Analysis- CCA**

The choice of CCA for this study was based on its strength as a multivariate statistical tool capable of identifying and quantifying complex relationships between multiple sets of variables. CCA is widely recognized for its ability to explore multidimensional interactions, providing a detailed understanding of the links between factors such as physical activity, psychological health, and functionality, particularly in the context of low back pain (Hwang et al., 2011; Li et al., 2023). By applying CCA, it was possible to investigate how different dimensions of mental health, such as stress, anxiety, and depression, are associated with functional disability in individuals with low back pain (Li et al., 2023). While CCA involves challenges related to statistical significance and model assumptions, its application enables an in-depth analysis of the interrelationships between complex variables, making it an appropriate and effective approach for this study (Friman et al., 2001; Zhuang et al., 2020).

## **2.4 Statistical analysis**

The participants were divided into three physical activity groups, according to the criteria established by the IPAQ-SF, based on the volume of MET-minutes per week, which already includes both the intensity and duration of the activity (Lee et al., 2011). The cut-off criteria for each level of physical activity were as follows: participants who reached between 600 and 1499 MET-minutes per week were classified as performing light physical activity, those who reached between 1500 and 2999 MET-minutes per week were classified as performing moderate physical activity, and participants who reached 3000 or more MET-minutes per week were classified as performing intense physical activity (Fan et al., 2014; Wolin et al., 2008). The cut-off points were selected based on international recommendations for adequate levels of physical activity, as outlined by the IPAQ (Fan et al., 2014; IPAQ, 2004).

All analyses were performed using SPSS 27 and the significance level was set at  $p \leq 0.05$  (two-tailed). Means, standard deviations, and counts for demographic characteristics were calculated using descriptive statistics. CCA was used to identify pairs of variables with statistical significance, using their correlation coefficients to assess the degree of interrelationship between them (Hotelling, 1992; Li et al., 2023; Zhuang et al., 2020). In addition, the individual contribution of each variable to its ipsilateral canonical variables was examined and quantified through their loads. This approach allows not only to determine the intensity of the relationship between sets of variables, but also to understand the relevance of each variable within the canonical context (Li et al., 2023).

To analyze the relationship between mental illnesses (stress, anxiety, and depression) and the intensity of physical activity, the MANOVA (multivariate analysis of variance) test was performed. MANOVA was chosen due to its ability to analyze multiple dependent variables simultaneously, allowing to assess whether there are significant differences in stress, anxiety, and depression levels between groups.

To assess whether psychological symptoms mediate the relationship between physical activity intensity and pain-related outcomes, mediation analyses were conducted using the PROCESS macro for SPSS. Indirect effects were tested with bootstrapping (5.000 samples) to generate bias-corrected confidence intervals. The independent variable was physical activity intensity, the mediators were stress, anxiety, and depression, and the dependent variable was functional disability related to low back pain. Significant indirect effects would suggest that psychological factors partially explain the association between physical activity and pain-related outcomes, providing further insight into potential underlying mechanisms. The G-Power 3.1.7 software (University of Kiel, Kiel, Germany) was used to calculate the effect size and determine the power of analysis using Cohen's d criterion (small: > 0.2; moderate: > 0.50; large: > 0.80) (Cohen 1988).

### 3. Results

Participants in group 1, light intensity, had an average age of  $23.5 \pm 6.19$  years. Their average body mass was  $64.8 \pm 13.5$  kg, while their average height was  $166.8 \pm 8.4$  cm. For group 2, moderate intensity, the average age was  $23.5 \pm 5.0$  years, body mass  $65.4 \pm 14.4$  kg, height  $166.3 \pm 12.8$  cm. Finally, group 3, vigorous intensity, with an average age of  $23.5 \pm 5.9$  years, body mass of  $65.2 \pm 15.4$  kg, and average height of  $167.5 \pm 12.8$  cm. Regarding episodes of low back pain, the average for the light group was  $7.9 \pm 9.6$  days, for the moderate group  $6.9 \pm 9.1$  days, and for the vigorous group  $6.9 \pm 8.7$  days over a period of 42 days.

The results of the mediation analysis indicate that the total number of days of activity does not have a statistically significant association with psychological health ( $\beta = -0.2547$ ,  $p = 0.234$ ) or with functional disability measured by the ODI ( $\beta = 0.0621$ ,  $p = 0.459$ ). The confidence intervals for these estimates include a value of zero, which reinforces the absence of statistical significance. On the other hand, "psychological factors" (DASS stress, anxiety, and depression) demonstrated a significant positive association with disability ( $\beta = 0.0466$ ,  $p <$

0.001), suggesting that higher levels of psychological impairment are associated with a higher degree of functional disability in acute low back pain.

### 3.1 Relationship between psychological symptoms and the level of intensity of physical activity practiced.

Table 1 shows the results of the MANOVA test, which made possible to simultaneously assess the differences in levels of stress, anxiety and depression between the different physical activity groups. The results indicate significant differences between all groups for the three variables: stress, anxiety and depression, regarding the different levels of physical activity intensity (light, moderate and intense).

The light physical activity group had the highest levels of stress, followed by the moderate physical activity group, while the rigorous physical activity group had the lowest levels. In the anxiety variable, the group with light physical activity also showed the highest levels, followed by the group with moderate physical activity. The depression variable showed a similar pattern: the group with light physical activity showed the highest levels of depression, followed by the group with moderate physical activity, while the group with rigorous physical activity showed the lowest levels of depression. These results suggest an inverse relationship between the intensity of physical activity and levels of stress, anxiety and depression.

**Table 1.** Results obtained from MANOVA considering the variables DASS, DASS Anxiety, DASS Depression scales short, and the variable physical activity group.

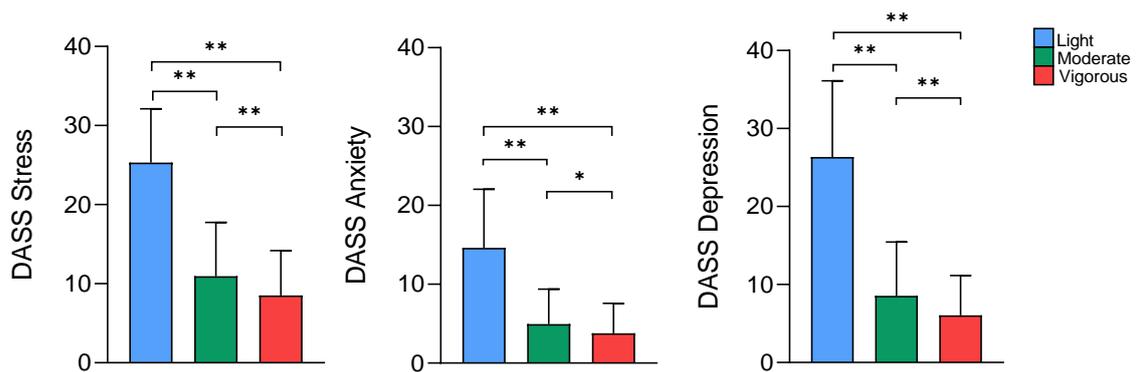
Variables	Group / N° / Mean	Comparison	<i>p</i>	d-Cohen's
<b>Stress</b>	G1 (256) (25.30)	G2	.001	2.10
		G3	.001	2.77
	G2 (236) (10.97)	G1	.001	2.10
		G3	.001	0.06
	G3 (529) (8.51)	G1	.001	2.77
		G2	.001	0.06
<b>Anxiety</b>	G1 (256)	G2	.001	1.59

	(14.63)	G3	.001	2.08
	G2 (236)	G1	.001	1.59
	(4.97)	G3	.009	0.29
	G3 (529)	G1	.001	2.08
	(3.78)	G2	.009	0.29
<b>Depression</b>	G1 (236)	G2	.001	2.00
	(26.34)	G3	.001	2.80
	G2 (256)	G1	.001	2.00
	(8.55)	G3	.001	0.43
	G3 (529)	G1	.001	2.80
	(6.04)	G2	.001	0.43
<b>Diagnosis of lumbar pathologies</b>	G1 (256)	G2	1	1.00
	(0.75)	G3	.032	5.69
	G2 (236)	G1	1	1.00
	(0.77)	G3	1	4.32
	G3 (529)	G1	.032	5.69
	(0.83)	G2	1	4.32

**Legend:** group physical activity-PA (0 – no physical activity, 1 light physical activity, 2 moderate physical activity, 3 vigorous physical activity), number of samples in each group (N°), stress (DASS Stress), anxiety (DASS Anxiety), depression (DASS Depression) scales short, and *Cohen's D test value*. Depression Anxiety Stress Scales (DASS).

Figure 1 shows the significant differences in levels of stress, anxiety, and depression between three groups with different levels of physical activity. The group that practiced vigorous physical activity consistently showed the lowest levels of stress, anxiety, and depression, while the group with light physical activity recorded the highest levels in all three dimensions assessed. Although the practice of moderate physical activity showed intermediate effects, there was still a significant difference compared to the group with rigorous physical activity

**Figure 1.** Comparison of symptoms of DASS stress, anxiety, depression with different levels of physical activity (N = 1021). Depression Anxiety Stress Scales (DASS).



**Legend:** group physical activity-PA (0 – no physical activity, 1 light physical activity, 2 moderate physical activity, 3 vigorous physical activity), \*\*  $p < 0.001$ , \*  $p < 0.005$ .

### 3.2 Canonical correlation of psychological symptoms and functionality of individuals with low back pain in different physical activity intensity groups.

Canonical correlation analysis was used to explore the relationship between the two groups of dimensions of mental health and functionality of the individual with low back pain, divided into three groups according to light, moderate and intense physical activity based on IPAQ values (Fan et al., 2014; IPAQ, 2004), shown in Table 2. Three pairs of canonical variables were extracted from each group. This suggests that physical activity intensity may be associated with different sets of variables, since the canonical correlations vary between physical activity intensity groups.

In the group that performed light physical activity, the first pair of canonical variables proved to be significant ( $p=0.017$ ), and the canonical correlation coefficient was 0.266, in which case they were included in the follow-up analysis. In the group that performed moderate physical activity, the p-value was not significant ( $p=0.092$ ), and this was the case for the three pairs of canonical variables, which were excluded from the follow-up analysis. In the group that performed vigorous physical activity, only the first pair of canonical variables showed a significant value ( $p= 0.013$ ), and the canonical correlation coefficient was 0.177, also included in the analysis afterwards, suggesting that the

relationships between physical activity and other variables may vary depending on the intensity of the physical activity.

The first pair of canonical variables was called mental illness (MI), and the second was called low back pain (LBP), where MI was mainly used to extract information from all the dimensions of depressive symptoms, anxiety, and depression, and LBP was mainly used to extract information from all the dimensions of the functionality of the individual with low back pain.

**Table 2.** Physical activity groups with pairs of canonical correlations, and significance test.

Group AF	Canonical Correlation Pair	Canonical correlation coefficient	Significance test		
			Wilks	f Value	p Value
Light	1	0.266	0.923	2.254	<b>0.017</b>
	2	0.078	0.994	0.389	0.816
Moderate	1	0.237	0.937	1.674	0.092
	2	0.079	0.993	0.403	0.807
Vigorous	1	0.177	0.961	2.340	<b>0.013</b>
	2	0.084	0.992	1.084	0.363

**Legend:** group activity physical (group AF).

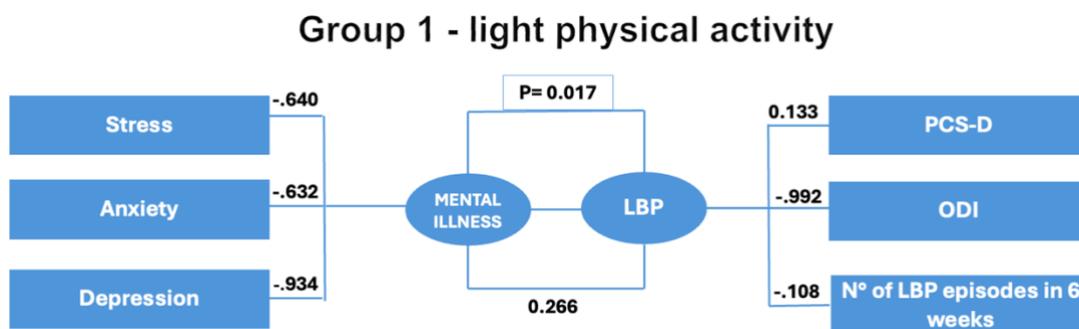
The results of the canonical correlation analysis presented in Figure 2 reveal significant differences between the two physical activity groups (light and vigorous) in terms of associations between mental health and low back pain at different physical activity intensities. In the light physical activity group, depression emerged as the most influential mental health variable, with an extremely strong impact of -0.934. This result indicates that depression is a critical factor in the mental health of these individuals. Anxiety also had a moderate negative impact, with a coefficient of -0.632, suggesting a significant association, although less intense than depression.

Stress showed a moderate negative impact, with a coefficient of -0.640, demonstrating that stress contributes negatively to mental health in this group. In addition to the mental health variables, PCS-D had an extremely strong negative

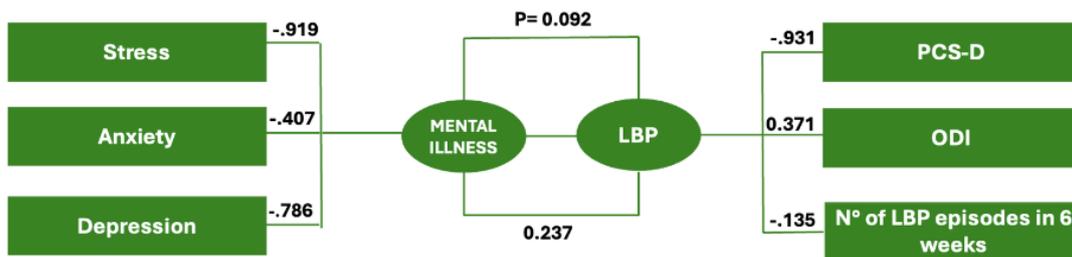
impact on the mild group, with a coefficient of -0.992. This result indicates that pain catastrophizing is a key factor in the perception of low back pain for these individuals. The ODI had a weak positive impact, with a coefficient of 0.133, suggesting a lower association with functional disability. The number of low back pain episodes in 6 weeks had a weak negative impact, with a coefficient of -0.108, indicating a limited association with the frequency of low back pain episodes.

In the vigorous physical activity group, depression remained the most influential mental health variable, with a significant impact of -0.894. This result suggests that depression is an important determinant, although slightly less impactful than in the light physical activity group. Anxiety had a moderate negative impact of -0.313, indicating a less intense association than in the light group. Stress, on the other hand, had almost zero impact, with a coefficient of 0.013, suggesting that stress is not a significant factor for this group. PCS-D had a moderate positive impact on the intense group, with a coefficient of 0.461, suggesting that catastrophizing pain increases the canonical variable LBP. The ODI had a significant negative impact, with a coefficient of -0.825, indicating that functional incapacity is more relevant for individuals who perform vigorous physical activity. The number of low back pain episodes in 6 weeks had a positive and more significant impact, with a coefficient of 0.364, indicating that the frequency of low back pain episodes is associated with an increase in the LBP canonical variable.

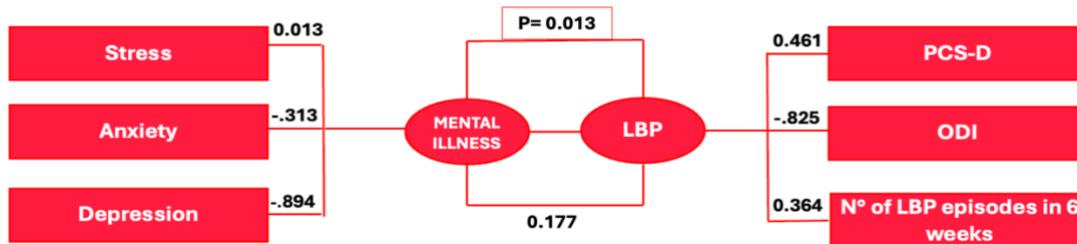
**Figure 2.** Canonical correlation analysis load coefficient (N = 1021).



### Group 2 - moderate physical activity



### Group 3 - vigorous physical activity



**Legend:** low back pain (LBP), p-value, Pain catastrophizing daily (PCS-D), The Oswestry disability index (ODI), number of low back pain episodes in six weeks (N° of LBP episodes in 6 weeks).

The results presented in Table 3 show that "Mental Illness" captured most of the joint variability, while the subsequent variables contributed less to explaining the variations. This reflects the robustness of the first canonical variable in representing the relationship between mental health and the individual's functionality in the presence of low back pain.

The variability explained by mental illness varies from 29.9 % to 56.1 %, depending on the level of physical activity. This suggests that the presence of mental illness has a significant influence on all levels of physical activity, with a greater influence at the lighter and more moderate levels of physical activity. The influence of mental illness is considerably less at the intense physical activity level. The explanatory power of low back pain is relatively constant, ranging from 33.2 to 33.8 %. This suggests that low back pain has a consistent influence on all levels of physical activity, regardless of the level of physical activity intensity.

**Table 3.** Explanatory power of typical variables (%) (N = 1021).

Level of physical activity	Mental illness	Low back pain
Light	56.1	33.8

Moderate	54.1	34.2
Vigorous	29.9	34.3

**Legend:** low back pain (LBP), mental illness (M.I), activity physical (AF).

#### 4. Discussion

The results of the canonical correlation analysis identified significant associations between the intensity of physical activity, psychological symptoms, and functionality in individuals with acute low back pain, a prevalent and debilitating condition in the studied population. All participants reported at least one episode of low back pain in the past six weeks, and the findings of this study provide a more detailed understanding of how psychosocial factors, and the intensity of physical activity interact to shape the clinical experience of acute low back pain.

##### **Impact of psychological symptoms on functionality**

In the group that engaged in light physical activity, depression showed a significant association with functionality, suggesting that individuals with more intense depressive symptoms perceive greater functional impairment. This finding is noteworthy as it reinforces the idea that depression can not only exacerbate pain but also impair an individual's ability to perform daily tasks, which is critical in the management of acute low back pain (McMahon et al., 2017; Meilleur-Durand et al., 2024). While the literature on chronic pain already suggests this relationship (Meilleur-Durand et al., 2024; Qaseem et al., 2017; Wiech & Tracey, 2009; Wun et al., 2021), the results of this study provide new evidence on how psychological factors can influence functionality in acute episodes of low back pain. Anxiety and stress, though with a lesser impact, also played significant roles, indicating that psychological symptoms are not merely a reflection of pain but can directly influence the degree of functional impairment experienced. This finding is crucial for the interdisciplinary management of pain, but further research is needed to investigate whether a causal relationship exists.

## **Distinguishing between levels of physical activity and psychological factors**

A key innovation of this study lies in the differentiation of groups based on physical activity intensity for acute low back pain. In the high-intensity physical activity group, depression remained a significant variable, though with a moderate effect. This finding indicates that among individuals engaging in more intense physical activity, the association between psychological symptoms and functionality appears less pronounced (Heneweer et al., 2009; Noetel et al., 2024; Powell et al., 2011).

Additionally, an analysis of pain catastrophizing (PCS-D) in the high-intensity activity group revealed a positive association, suggesting that, among individuals engaging in vigorous physical activity, catastrophizing may be linked to an increased perception of pain-related disability (Heneweer et al., 2009). This finding aligns with existing literature indicating that catastrophizing can be an important mediating factor in the relationship between pain and functionality, regardless of physical activity intensity in this population (Campbell et al., 2010; Weissman-Fogel et al., 2008; Zhou et al., 2023).

These results contribute to a broader understanding of the complex interplay between physical activity, psychological factors, and disability perception. While higher-intensity physical activity may be associated with certain benefits, it may also coincide with an amplification of pain perception in individuals with a tendency toward catastrophizing. This underscores the necessity of a comprehensive, biopsychosocial assessment for individuals experiencing pain.

### **Volume X intensity of physical activity in acute low back pain.**

The mediation analysis revealed a significant finding: the total number of days of physical activity was not significantly associated with either psychological health (DASS-21) or lumbar spine functionality, as assessed by the ODI index (Davidson & Keating, 2002). This result challenges the notion that merely increasing the

frequency of physical activity is sufficient to improve psychological health and functionality in individuals experiencing acute low back pain episodes.

Another key aspect of our study is the suggestion that the intensity of physical activity, including its intensity, may have a more substantial impact on pain and functionality in acute low back pain episodes, rather than simply focusing on the total amount of physical activity. While previous research has addressed this issue in other clinical contexts, its relevance to acute low back pain remains underexplored (Law & Sluka, 2017; Varongot-Reille et al., 2023). This distinction is important, as it implies that a more personalized approach, considering the type, intensity, and adherence to an exercise regimen, may be essential for optimizing therapeutic outcomes in patients with acute low back pain.

### **Relevance of psychosocial factors in the intensity of exercises in acute low back pain**

The significant association between psychological symptoms (stress, anxiety, and depression) and functional disability in this study reinforces the relevance of psychosocial factors in the experience of acute low back pain. Previous studies have highlighted the predominant role of psychological factors in chronic pain (Heneweer et al., 2009; Marshall et al., 2017; Vlaeyen & Linton, 2000; Wun et al., 2021), but this study also emphasizes the importance of these factors in acute episodes, where effective management requires an integrated, guided, and personalized approach (Chang et al., 2024; Meilleur-Durand et al., 2024). The more significant impact of psychological symptoms in the group with light physical activity suggests that, in individuals with low levels of physical activity, psychological support may play a crucial role in pain management (Chang et al., 2024). This reinforces the idea that, in the context of acute low back pain, treatment should go beyond simple physical activity prescription, incorporating psychological interventions as a central strategy (Qaseem et al., 2017). The absence of significant impact in the moderate and intense physical activity groups may suggest that the intensity of physical activity could attenuate the negative effects of psychological factors (Füzéki & Banzer, 2018; Lin et al., 2011; Naugle

et al., 2017; Paolucci et al., 2018; Pascoe et al., 2020), a finding that could open new avenues for the development of more effective therapeutic interventions for this population (Karlsson et al., 2020).

### **Clinical implications and future directions**

Although this study does not allow for causal inferences, it provides important insights into how psychological factors, physical activity volume, and intensity interact in patients with acute low back pain. The combination of psychological interventions with personalized physical activity appears to be a promising strategy for managing acute low back pain. The attenuated impact of intense physical activity on psychological symptoms suggests that more intense interventions may be beneficial for some individuals (Heneweer et al., 2009; Noetel et al., 2024; Powell et al., 2011), but attention must be given to catastrophizing behavior to avoid pain amplification (Wiech & Tracey, 2009; Zhou et al., 2023). Furthermore, the absence of a significant association between the volume of physical activity, psychological health, and lumbar spine functionality suggests that future studies should explore how different types of exercise and intensities (aerobic, resistance, flexibility) interact with psychological factors in modulating pain and functional capacity in acute low back pain, as the literature still presents gaps in this area (Chou & Huffman, 2007; Ijzelenberg et al., 2024; Rubinstein et al., 2012).

### **Limitations**

This study has several limitations. Its cross-sectional and observational design prevents the establishment of causal relationships between the analyzed variables. Additionally, the use of self-reported data through questionnaires may introduce response and perception biases. The sample, consisting of individuals with acute low back pain, may not fully capture the complexities of chronic pain, where the interactions between psychological symptoms and pain tend to be more dynamic and multifaceted. Future longitudinal studies and randomized clinical trials will be essential to more robustly examine the impact of psychosocial

factors and physical activity intensity, as well as to explore how these elements can be effectively integrated into the management of acute low back pain, not only to promote recovery but also to reduce the recurrence of future pain episodes.

## **5. Conclusion**

Therefore, this study reinforces the complex interaction between physical activity, psychological factors, and functionality in acute low back pain, as demonstrated by canonical correlation analysis. The findings highlight that the total amount of physical activity alone is not directly associated with improvements in functionality or psychological well-being. Instead, the intensity and intensity of physical activity appear to play a more significant role, particularly in individuals who exhibit pain catastrophizing behavior. These results suggest that personalized therapeutic approaches, which consider not only physical activity levels but also psychological and individual factors, are essential for optimizing the rehabilitation of patients with low back pain.

### **Data availability**

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

### **Declaration of competing interest**

The authors declare no conflict of interest.

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## 6. References

- Abbott, A. D., Tyni-Lenné, R., & Hedlund, R. (2011). Leg pain and psychological variables predict outcome 2-3 years after lumbar fusion surgery. *Eur Spine J*, 20(10), 1626-1634. <https://doi.org/10.1007/s00586-011-1709-6>
- Campbell, C. M., Quartana, P. J., Buenaver, L. F., Haythornthwaite, J. A., & Edwards, R. R. (2010). Changes in situation-specific pain catastrophizing precede changes in pain report during capsaicin pain: a cross-lagged panel analysis among healthy, pain-free participants. *J Pain*, 11(9), 876-884. <https://doi.org/10.1016/j.jpain.2009.12.007>
- Chang, W., Jenkins, L., Humburg, P., & Schabrun, S. (2024). The influence of pain hypersensitivity and psychological factors on pain and disability in the transition from acute to chronic low back pain: a longitudinal exploratory investigation and cluster analysis. *The journal of pain*, 104584. <https://doi.org/10.1016/j.jpain.2024.104584>
- Chou, R., & Huffman, L. (2007). Nonpharmacologic Therapies for Acute and Chronic Low Back Pain: A Review of the Evidence for an American Pain Society/American College of Physicians Clinical Practice Guideline. *Annals of internal medicine*, 147, 492-504. <https://doi.org/10.7326/0003-4819-147-7-200710020-00007>
- Contreras-Osorio, F., Ramirez-Campillo, R., Cerda-Vega, E., Campos-Jara, R., Martínez-Salazar, C., Reigal, R. E., Hernández-Mendo, A., Carneiro, L., & Campos-Jara, C. (2022). Effects of Physical Exercise on Executive Function in Adults with Depression: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health*, 19(22). <https://doi.org/10.3390/ijerph192215270>
- Darnall, B. D., Sturgeon, J. A., Cook, K. F., Taub, C. J., Roy, A., Burns, J. W., Sullivan, M., & Mackey, S. C. (2017). Development and Validation of a

- Daily Pain Catastrophizing Scale. *J Pain*, 18(9), 1139-1149.  
<https://doi.org/10.1016/j.jpain.2017.05.003>
- Davidson, M., & Keating, J. L. (2002). A comparison of five low back disability questionnaires: reliability and responsiveness. *Phys Ther*, 82(1), 8-24.  
<https://doi.org/10.1093/ptj/82.1.8>
- De Ridder, D., Adhia, D., & Vanneste, S. (2021). The anatomy of pain and suffering in the brain and its clinical implications. *Neurosci Biobehav Rev*, 130, 125-146. <https://doi.org/10.1016/j.neubiorev.2021.08.013>
- Doan, L., Manders, T., & Wang, J. (2015). Neuroplasticity underlying the comorbidity of pain and depression. *Neural Plast*, 2015, 504691.  
<https://doi.org/10.1155/2015/504691>
- Fairbank, J. C., & Pynsent, P. B. (2000). The Oswestry Disability Index. *Spine (Phila Pa 1976)*, 25(22), 2940-2952; discussion 2952.  
<https://doi.org/10.1097/00007632-200011150-00017>
- Fan, M., Lyu, J., & He, P. (2014). Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ).2005. URL: <http://www.IPAQ.ki.se>. *Zhonghua liu xing bing xue za zhi = Zhonghua liuxingbingxue zazhi*, 35, 961-964.
- Ferreira, M. L., Smeets, R. J., Kamper, S. J., Ferreira, P. H., & Machado, L. A. (2010). Can we explain heterogeneity among randomized clinical trials of exercise for chronic back pain? A meta-regression analysis of randomized controlled trials. *Physical therapy*, 90(10), 1383-1403.
- Friman, O., Cedefamn, J., Lundberg, P., Borga, M., & Knutsson, H. (2001). Detection of neural activity in functional MRI using canonical correlation analysis. *Magnetic Resonance in Medicine*, 45.  
[https://doi.org/10.1002/1522-2594\(200102\)45:2<323::AID-MRM1041>3.0.CO;2-#](https://doi.org/10.1002/1522-2594(200102)45:2<323::AID-MRM1041>3.0.CO;2-#)
- Füzéki, E., & Banzer, W. (2018). Physical Activity Recommendations for Health and Beyond in Currently Inactive Populations. *Int J Environ Res Public Health*, 15(5). <https://doi.org/10.3390/ijerph15051042>
- Heneweer, H., Vanhees, L., & Picavet, H. S. (2009). Physical activity and low back pain: a U-shaped relation? *Pain*, 143(1-2), 21-25.  
<https://doi.org/10.1016/j.pain.2008.12.033>

- Hotelling, H. (1992). Relations between two sets of variates. In *Breakthroughs in statistics: methodology and distribution* (pp. 162-190). Springer.
- Hwang, H., Jung, K., Takane, Y., & Woodward, T. (2011). Functional Multiple-Set Canonical Correlation Analysis. *Psychometrika*, 77, 48-64. <https://doi.org/10.1007/s11336-011-9234-4>
- Ijzelenberg, W., Oosterhuis, T., Hayden, J., Koes, B., Van Tulder, M., Rubinstein, S., & De Zoete, A. (2024). Exercise therapy for treatment of acute non-specific low back pain: a Cochrane systematic review and meta-analysis of randomised controlled trials. *Archives of physical medicine and rehabilitation*. <https://doi.org/10.1016/j.apmr.2024.02.732>
- IPAQ, R. (2004). Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ)-short form. In: Version.
- Karlsson, M., Bergenheim, A., Larsson, M., Nordeman, L., Van Tulder, M., & Bernhardsson, S. (2020). Effects of exercise therapy in patients with acute low back pain: a systematic review of systematic reviews. *Systematic Reviews*, 9. <https://doi.org/10.1186/s13643-020-01412-8>
- Law, L., & Sluka, K. (2017). How does physical activity modulate pain? *Pain*. <https://doi.org/10.1097/j.pain.0000000000000792>
- Lee, P., Macfarlane, D., Lam, T., & Stewart, S. (2011). Validity of the international physical activity questionnaire short form (IPAQ-SF): A systematic review. *The International Journal of Behavioral Nutrition and Physical Activity*, 8, 115-115. <https://doi.org/10.1186/1479-5868-8-115>
- Li, L., Wang, P., Li, S., Liu, Q., Yu, F., Guo, Z., Jia, S., & Wang, X. (2023). Canonical correlation analysis of depression and anxiety symptoms among college students and their relationship with physical activity. *Scientific Reports*, 13(1), 11516. <https://doi.org/10.1038/s41598-023-38682-w>
- Lin, C. C., McAuley, J. H., Macedo, L., Barnett, D. C., Smeets, R. J., & Verbunt, J. A. (2011). Relationship between physical activity and disability in low back pain: a systematic review and meta-analysis. *Pain*, 152(3), 607-613. <https://doi.org/10.1016/j.pain.2010.11.034>
- Liu, S., Mei, Y., Huang, L., Liu, X., & Xi, Y. (2024). Association of habitual physical activity with depression and anxiety: a multicentre cross-sectional study.

*BMJ Open*, 14(1), e076095. <https://doi.org/10.1136/bmjopen-2023-076095>

- Marshall, P. W. M., Schabrun, S., & Knox, M. F. (2017). Physical activity and the mediating effect of fear, depression, anxiety, and catastrophizing on pain related disability in people with chronic low back pain. *PLoS One*, 12(7), e0180788. <https://doi.org/10.1371/journal.pone.0180788>
- Martins, B. G., Silva, W. R. d., Maroco, J., & Campos, J. A. D. B. (2019). Escala de Depressão, Ansiedade e Estresse: propriedades psicométricas e prevalência das afetividades. *Jornal Brasileiro de Psiquiatria*, 68.
- McMahon, E. M., Corcoran, P., O'Regan, G., Keeley, H., Cannon, M., Carli, V., Wasserman, C., Hadlaczky, G., Sarchiapone, M., Apter, A., Balazs, J., Balint, M., Bobes, J., Brunner, R., Cozman, D., Haring, C., Iosue, M., Kaess, M., Kahn, J. P., . . . Wasserman, D. (2017). Physical activity in European adolescents and associations with anxiety, depression and well-being. *Eur Child Adolesc Psychiatry*, 26(1), 111-122. <https://doi.org/10.1007/s00787-016-0875-9>
- Meilleur-Durand, M., Dubé, M.-O., Hébert, L., Mercier, C., Léonard, G., & Roy, J.-S. (2024). Conditioned pain modulation, kinesiophobia, and pain catastrophizing as prognostic factors for chronicity in a population with acute low back pain: An exploratory prospective study. *Musculoskeletal science & practice*, 70, 102920. <https://doi.org/10.1016/j.msksp.2024.102920>
- Mun, C. J., Karoly, P., & Okun, M. A. (2015). Effects of daily pain intensity, positive affect, and individual differences in pain acceptance on work goal interference and progress. *Pain*, 156(11), 2276-2285. <https://doi.org/10.1097/j.pain.0000000000000278>
- Naugle, K. M., Ohlman, T., Naugle, K. E., Riley, Z. A., & Keith, N. R. (2017). Physical activity behavior predicts endogenous pain modulation in older adults. *Pain*, 158(3), 383-390. <https://doi.org/10.1097/j.pain.0000000000000769>
- Noetel, M., Sanders, T., Gallardo-Gómez, D., Taylor, P., Del Pozo Cruz, B., van den Hoek, D., Smith, J. J., Mahoney, J., Spathis, J., Moresi, M., Pagano, R., Pagano, L., Vasconcellos, R., Arnott, H., Varley, B., Parker, P., Biddle,

- S., & Lonsdale, C. (2024). Effect of exercise for depression: systematic review and network meta-analysis of randomised controlled trials. *Bmj*, 384, e075847. <https://doi.org/10.1136/bmj-2023-075847>
- Paolucci, E. M., Loukov, D., Bowdish, D. M. E., & Heisz, J. J. (2018). Exercise reduces depression and inflammation but intensity matters. *Biol Psychol*, 133, 79-84. <https://doi.org/10.1016/j.biopsycho.2018.01.015>
- Parolini, F., Goethel, M., Becker, K., Fernandes, C., Fernandes, R. J., Ervilha, U. F., Santos, R., & Vilas-Boas, J. P. (2023). Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain. *Biomedicines*, 11(7). <https://doi.org/10.3390/biomedicines11072042>
- Pascoe, M., Bailey, A. P., Craike, M., Carter, T., Patten, R., Stepto, N., & Parker, A. (2020). Physical activity and exercise in youth mental health promotion: a scoping review. *BMJ Open Sport Exerc Med*, 6(1), e000677. <https://doi.org/10.1136/bmjsem-2019-000677>
- Polli, G., Falqueto, H., Czarnobai, I., Giulliano, D., & Guerra, P. (2019). Atividade física e dor lombar em brasileiros: uma revisão sistemática.
- Powell, K. E., Paluch, A. E., & Blair, S. N. (2011). Physical activity for health: What kind? How much? How intense? On top of what? *Annu Rev Public Health*, 32, 349-365. <https://doi.org/10.1146/annurev-publhealth-031210-101151>
- Qaseem, A., Wilt, T., McLean, R., & Forciea, M. (2017). Noninvasive Treatments for Acute, Subacute, and Chronic Low Back Pain: A Clinical Practice Guideline From the American College of Physicians. *Annals of internal medicine*, 166 7, 514-530. <https://doi.org/10.7326/M16-2367>
- Rahman, N. A. A., Li, S., Schmid, S., & Shaharudin, S. (2022). Biomechanical factors associated with non-specific low back pain in adults: A systematic review. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine*, 59, 60-72. <https://doi.org/10.1016/j.ptsp.2022.11.011>
- Raja, S. N., Carr, D. B., Cohen, M., Finnerup, N. B., Flor, H., Gibson, S., Keefe, F. J., Mogil, J. S., Ringkamp, M., Sluka, K. A., Song, X. J., Stevens, B., Sullivan, M. D., Tutelman, P. R., Ushida, T., & Vader, K. (2020). The

- revised International Association for the Study of Pain definition of pain: concepts, challenges, and compromises. *Pain*, 161(9), 1976-1982. <https://doi.org/10.1097/j.pain.0000000000001939>
- Rubinstein, S., Terwee, C., Assendelft, W., De Boer, M., & Van Tulder, M. (2012). Spinal manipulative therapy for acute low-back pain. *The Cochrane database of systematic reviews*, 9. <https://doi.org/10.1002/14651858.CD008880.pub2>
- Selzler, A. M., Ellerton, C., Ellerton, L., Habash, R., Nikolaichuk, E., Goldstein, R., & Brooks, D. (2023). The Relationship between Physical Activity, Depression and Anxiety in People with COPD: A Systematic Review and Meta-analyses. *Copd*, 20(1), 167-174. <https://doi.org/10.1080/15412555.2023.2200826>
- Varongot-Reille, C., Barrero-Santiago, L., Cuenca-Martínez, F., Paris-Alemany, A., La Touche, R., & Herranz-Gómez, A. (2023). Effectiveness of exercise on pain intensity and physical function in patients with knee and hip osteoarthritis: an umbrella and mapping review with meta-meta-analysis. *Disability and rehabilitation*, 1-15. <https://doi.org/10.1080/09638288.2023.2252742>
- Vlaeyen, J. W. S., & Linton, S. J. (2000). Fear-avoidance and its consequences in chronic musculoskeletal pain: a state of the art. *Pain*, 85(3), 317-332. [https://doi.org/10.1016/s0304-3959\(99\)00242-0](https://doi.org/10.1016/s0304-3959(99)00242-0)
- Vos, T., Lim, S. S., Abbafati, C., Abbas, K. M., Abbasi, M., Abbasifard, M., Abbasi-Kangevari, M., Abbastabar, H., Abd-Allah, F., Abdelalim, A., Abdollahi, M., Abdollahpour, I., Abolhassani, H., Aboyans, V., Abrams, E. M., Abreu, L. G., Abrigo, M. R. M., Abu-Raddad, L. J., Abushouk, A. I., . . . Murray, C. J. L. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990&#x2013;2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396(10258), 1204-1222. [https://doi.org/10.1016/S0140-6736\(20\)30925-9](https://doi.org/10.1016/S0140-6736(20)30925-9)
- Weissman-Fogel, I., Sprecher, E., & Pud, D. (2008). Effects of catastrophizing on pain perception and pain modulation. *Experimental Brain Research*, 186, 79-85. <https://doi.org/10.1007/s00221-007-1206-7>

- Wiech, K., & Tracey, I. (2009). The influence of negative emotions on pain: behavioral effects and neural mechanisms. *Neuroimage*, 47(3), 987-994. <https://doi.org/10.1016/j.neuroimage.2009.05.059>
- Wolin, K. Y., Heil, D. P., Askew, S., Matthews, C. E., & Bennett, G. G. (2008). Validation of the International Physical Activity Questionnaire-Short among Blacks. *J Phys Act Health*, 5(5), 746-760. <https://doi.org/10.1123/jpah.5.5.746>
- Wood, L., Bishop, A., Lewis, M., Smeets, R. J., Bronfort, G., Hayden, J. A., & Foster, N. E. (2021). Treatment targets of exercise for persistent non-specific low back pain: a consensus study. *Physiotherapy*, 112, 78-86.
- Wun, A., Kollias, P., Jeong, H., Rizzo, R. R., Cashin, A. G., Bagg, M. K., McAuley, J. H., & Jones, M. D. (2021). Why is exercise prescribed for people with chronic low back pain? A review of the mechanisms of benefit proposed by clinical trialists. *Musculoskeletal Science and Practice*, 51, 102307.
- Zhou, Y., Gao, W., Gao, S., Guo, X., Liu, M., & Cao, C. (2023). Pain Catastrophizing, Kinesiophobia and Exercise Adherence in Patients After Total Knee Arthroplasty: The Mediating Role of Exercise Self-Efficacy. *Journal of Pain Research*, 16, 3993-4004. <https://doi.org/10.2147/JPR.S432106>
- Zhuang, X., Yang, Z., & Cordes, D. (2020). A technical review of canonical correlation analysis for neuroscience applications. *Human Brain Mapping*, 41, 3807-3833. <https://doi.org/10.1002/hbm.25090>

## Chapter 4

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### **Precision and Reliability of a Dynamometer for Trunk Extension Strength and Steadiness Assessment**

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## **Abstract**

Low back pain is a major cause of disability worldwide, often associated with deficits in trunk extensor strength control. Accurate assessment of trunk extension strength control is crucial for diagnosing impairments and monitoring interventions. This study evaluated the reliability of a dynamometry-based protocol for isometric trunk extension strength control assessment. Twenty-eight healthy volunteers (9 females, 19 males) completed two sessions, seven days apart. A single-point load cell system, encapsulated within a 3D-printed structure and connected to a Delsys<sup>®</sup> system at a sampling frequency of 2000 Hz, was used for data acquisition. Participants performed maximal voluntary contractions (MVC) and submaximal isometric contractions (SMVC) guided by trapezoidal visual feedback. Key outcome variables included peak force, mean force, and force steadiness. Calibration demonstrated high accuracy ( $R^2 = 1$ ) with a low root mean square error (0.55 N). Test-retest analysis showed excellent reliability for peak force (ICC = 0.81, SEM = 0.50, MDC = 1.39), mean force (ICC = 0.93, SEM = 0.17, MDC = 1.08), and steadiness (ICC = 0.87, SEM = 0.85, MDC = 2.36), with no significant intersession differences ( $p > 0.05$ ). This study demonstrates the high reliability of using dynamometry to assess trunk extension strength during MVC and SMVC, endorsing the dynamometer as a tool for functional assessment and the development of personalized rehabilitation and training strategies.

**Keywords:** low back pain, maximal voluntary contractions, handheld dynamometry, muscle function.

## 1. Introduction

Low back pain (LBP) remains one of the leading causes of disability worldwide, with approximately 85% of cases lacking a specific peripheral etiology (Vos et al., 2012). Despite the uncertainty surrounding its origin, recurrence rates of 60% to 80% are observed after the initial episode (da Silva et al., 2017). It has been hypothesized that weakness and poor endurance of the paravertebral muscles lead to increased loading on passive spinal structures, such as intervertebral discs and ligaments, thus contributing to the persistence and chronicity of pain (Alaranta, Luoto, Heliövaara, & Hurri, 1995; Arins et al., 2016; Larsen, Hirata, & Graven-Nielsen, 2018; McGill, 1997; van Dieën, Reeves, Kawchuk, van Dillen, & Hodges, 2019). Among the muscles involved, trunk extensors play a particularly critical role in both locomotion and postural control. Dysfunction in these muscles not only impairs motor capacity but also significantly impacts quality of life, with profound physical and psychological implications (Cholewicki & McGill, 1996; Neufuss et al., 2014; Hicks, 2005).

Motor function impairment, characterized by reduced strength and muscle performance, can substantially limit autonomy in activities of daily living (Brill, Macera, Davis, Blair, & Gordon, 2000; Camposo & Pereira, 2015; Brill, 200; Ruiz et al., 2008). As such, the accurate assessment of trunk extensor strength becomes vital across various populations, including older adults (Vlažná et al., 2021; Yang et al., 2020), individuals with LBP (Althobaiti & Falla, 2023; Gruther et al., 2009), and healthy subjects (Essendrop, Schibye, & Hansen, 2001; Moreland, Finch, Stratford, Balsor, & Gill, 1997), as a means of preventing further musculoskeletal dysfunctions (Kell, Bell, & Quinney, 2001; Larivière, Gagnon, & Loisel, 1999). Understanding key variables such as maximal force production capacity, mean force, and steadiness during muscle contraction is essential for effectively monitoring therapeutic responses and ensuring accurate interpretation of functional changes (De Vet, Terwee, Mokkink, & Knol, 2011; Steele et al., 2019). These assessments provide invaluable insight into the factors driving the persistence of LBP and the functional limitations that accompany it (Chou & Shekelle, 2010; Pincus, Burton, Vogel, & Field, 2002).

Different methods have been employed to assess trunk extensor strength, though their reliability remains variable (Eichinger et al., 2016; Freitas & Greve, 2008; Gonçalves & Barbosa, 2005; Jain et al., 2022; Müller, Machado de Brito, Pereira, & Brusamarello, 2010; Valentin & Maribo, 2014). The Lafayette isometric handheld dynamometer (HHD) is widely regarded as the gold standard for isometric muscle strength evaluation (Althobaiti & Falla, 2023; Althobaiti, Rushton, Aldahas, Falla, & Heneghan, 2022; Guilhem, Giroux, Couturier, & Maffiuletti, 2014). However, previous studies have reported intraclass correlation coefficients (ICC) for different HHD models ranging from 0.67 to 0.93, with considerable variability attributed to factors such as participant posture and differing measurement protocols (Althobaiti & Falla, 2023; Barros et al., 2021; Bonhof-Jansen, van Ham, Kroon, Winter, & Brink, 2023; De Blaiser, De Ridder, Willems, Danneels, & Roosen, 2018). Despite its widespread use, the HHD has notable limitations, including high cost, the requirement for specialized personnel, and stringent control conditions, which can hinder its broader clinical application (Yang et al.). Moreover, the HHD's inability to synchronize with other data acquisition systems limits its utility for real-time feedback during assessments, particularly when evaluating submaximal isometric contractions (SMVC). In such cases, maintaining consistent force is crucial for assessing variables such as steadiness.

In contrast, load cell systems offer higher sampling frequencies, which are essential for detecting minute variations in force output and improving the precision of strength assessments. However, questions remain about the test-retest reliability of these methods, as results may be influenced by factors like subject posture during evaluation (prone, seated, or standing), the type of equipment used, and the fixation methodology of the dynamometer, which can complicate cross-study comparisons (Althobaiti & Falla, 2023; Barros et al., 2021; De Blaiser et al., 2018; Jubany, Busquets, Marina, Cos, & Angulo-Barroso, 2015; Martínez-Romero et al., 2020). The lack of standardization in measurement protocols, along with the influence of gravitational force, can also introduce biases in the obtained values, further complicating result interpretation. Despite recent advancements in the reliability of portable dynamometers, uncertainties remain regarding the impact of posture and testing conditions on the assessment of

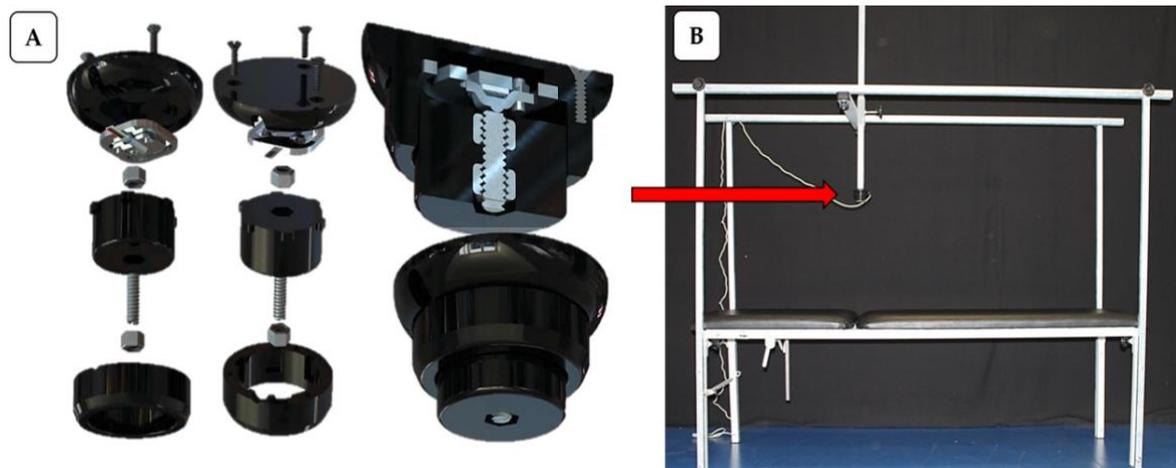
maximal and submaximal isometric strength, as well as muscle steadiness during trunk extension (Althobaiti & Falla, 2023; Arvanitidis, Falla, Sanderson, & Martinez-Valdes, 2025; Bonhof-Jansen et al., 2023; De Blaiser et al., 2018; Guilhem et al., 2014; Valentin & Maribo, 2014).

Given these challenges, the implementation of fixation structures designed to minimize inertial effects could significantly enhance the accuracy and reliability of measurements, addressing a critical gap in current strength assessment practices. Therefore, the aim of the present study is to evaluate the reliability and precision of a dynamometer system in measuring both maximal and submaximal isometric strength, as well as muscle steadiness, during trunk extension. Our hypothesis is that the implementation of these fixation structures will demonstrate high reliability in the measurements of maximal contraction volunteer (MVC) and SMVC, as well as muscle steadiness during trunk extension.

## **2. Materials and Methods**

### **2.1 Force Measurement System**

A single-point load cell (Figure 1A) with a maximum reading capacity of 1000 N was used, and its signal was amplified using an AD620 amplifier. The amplified signal was then transmitted to the analog input of the Delsys system (Delsys, Natick, MA, USA), enabling real-time data visualization and recording at a sampling frequency of 2000 Hz. The load cell was encapsulated into a 3D-printed structure (Figure 1A) and secured with a screw to ensure unidirectional force transmission. The system operated through a probe with a metal rod that efficiently conveyed the applied force to the load cell. After encapsulation, the load cell was fixed within a rigid structure (Figure 1B), designed to ensure proper participant positioning within the force measurement system. This configuration provided stability during the test.



**Figure 1.** (A) Load cell encapsulation; (B) Final assembled structure.

## 2.2 Calibration

The calibration of the described dynamometer was conducted using a universal testing machine for compression, INSTRON® model 4507, yielding a calibration equation (Volts-Newtons) and ensuring compliance with the ASTM E8/E8M-09 (2010) standard.

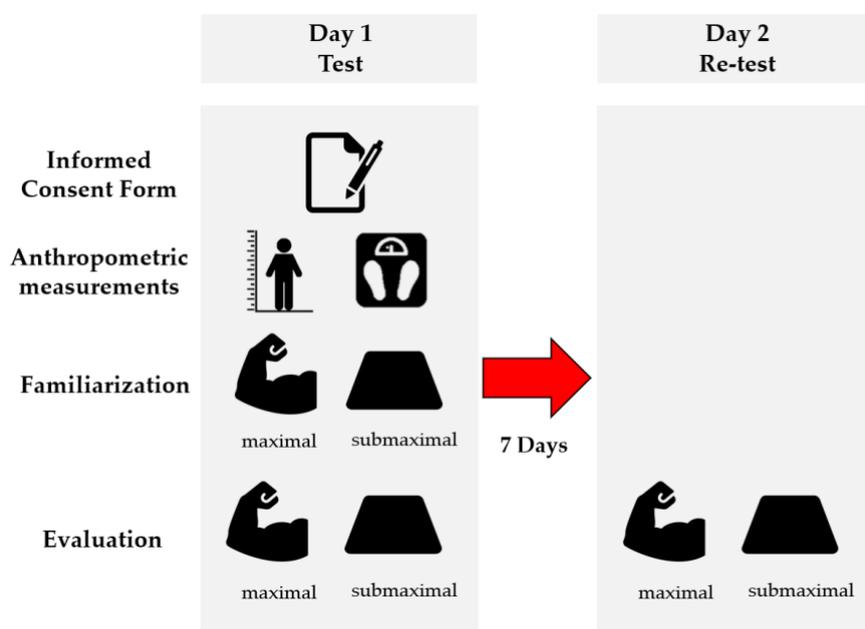
During the calibration procedure, the INSTRON® system was programmed to apply a gradually increasing load up to 1000 N, maintain it for a brief period, and then systematically release it. A total of 14 calibration trials were performed: five in the 0–100 N range with 20 N increments and nine in the 100–1000 N range with 100 N increments. Each trial was repeated ten times to establish a robust correlation between the voltage readings and the applied mechanical load.

## 2.3 Reliability Experimental Procedures

The study involved two laboratory visits, separated by a seven-day interval. All procedures were conducted in accordance with the guidelines of the Declaration of Helsinki, and all participants provided written informed consent before enrollment. During the first visit, anthropometric measurements, including height with seca 213 portable stadiometer (seca GmbH & Co. KG, Hamburg, Germany) and body mass, were obtained using a bioimpedance system (InBody 230, InBody Co., Ltd., Korea) following the manufacturer's guidelines. Subsequently, participants underwent a familiarization session, followed by the evaluation

protocol. The evaluation consisted of a MVC assessment, followed by a SMVC for further familiarization and data collection.

The second visit, replicated the procedures performed during the first session to ensure consistency and reliability of the measurements as shown in figure 2. All participants underwent a structured familiarization process before testing. The assessments were carried out by a physiotherapist with expertise in the field. The study was approved by the Ethics Committee of the Faculty of Sport, University of Porto (CEFADE 28-2023).



**Figure 2.** Experimental Procedures

## 2.4 Sample

The study sample comprised 28 healthy volunteers (9 females, 19 males) with a mean age of  $29.50 \pm 6.50$  years. Their anthropometric characteristics included a mean height of  $171.13 \pm 7.47$  cm, body mass of  $74.93 \pm 11.44$  kg, and body fat percentage of  $23.06 \pm 8.01\%$ . Inclusion criteria required healthy individuals aged 18 to 40 years with no history of musculoskeletal disorders or recurrent pain in the past six weeks. Participants were also required to abstain from anti-

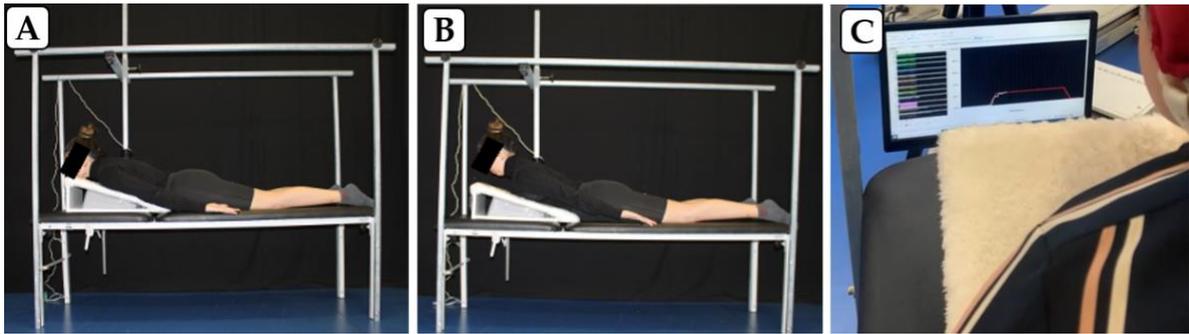
inflammatory drugs or analgesics in the 24 hours prior to testing. Exclusion criteria encompassed a history of lumbar injury or surgery, chronic conditions such as disc degeneration, lumbar osteoarthritis, herniated disc, ankylosing spondylitis, or any other pathology affecting muscle function, as well as pregnancy. These criteria ensured a homogeneous and clinically healthy sample, reducing potential confounding factors in the study outcomes.

## **2.5 Familiarization and Evaluation**

During the familiarization phase, participants were instructed to perform five repetitions of trunk extension, as shown in Figure 3 (A), while maintaining a MVC for five seconds. After a one-minute rest period, three additional repetitions of a SMVC were conducted (Valentin & Maribo). The submaximal isometric contractions were guided by visual feedback from a trapezoidal reference signal, which was displayed on a monitor using Delsys<sup>®</sup> EMG Works 4.8.0 software (Delsys, Natick, MA, USA) at a sampling frequency of 2000 Hz. This software allowed for real-time monitoring of the generated force patterns. The trapezoidal signal involved a progressive increase in force from zero to the target value over five seconds, followed by a sustained phase at 20% of the MVC for 20 seconds, and a gradual reduction to zero over the final five seconds (Nawab, Chang, & De Luca).

The evaluation protocol included performing the MVC, followed by a SMVC at 20% of the MVC, mirroring the procedures from the familiarization phase.

Figure 3 (B) illustrates the volunteer performing the spine extension, highlighting the required posture for the task. Figure 3 (C) presents the trapezoidal reference signal on the screen, which was used to guide the SMVC during the experimental procedures.



**Figure 3.** Experimental Setup: (A) Initial position of the volunteer, (B) Volunteer performing trunk extension, and (C) Screen display of the trapezoidal model using Delsys® EMG Works 4.8.0 software (Delsys, Natick, MA, USA).

## 2.6 Data processing

Data processing was performed using Matlab® software (The MathWorks Inc., Natick, MA, USA). During MVC, the peak force, considered the maximum force point during this evaluation, was manually extracted using the Delsys system and normalized to body mass.

During SMVC, the variables mean force and force steadiness were derived from a 20-second duration. For the analysis of mean force and steadiness, the central five seconds of the task were considered for data extraction. Mean force values were expressed as percentages relative to the MVC peak using the following formula:  $[(SMVC \mu \div MVC peak) \cdot 100]$ . Force steadiness was calculated by determining the coefficient of variation (CV) using the formula:  $[(SMVC \sigma \div SMVC \mu) \cdot 100]$ .

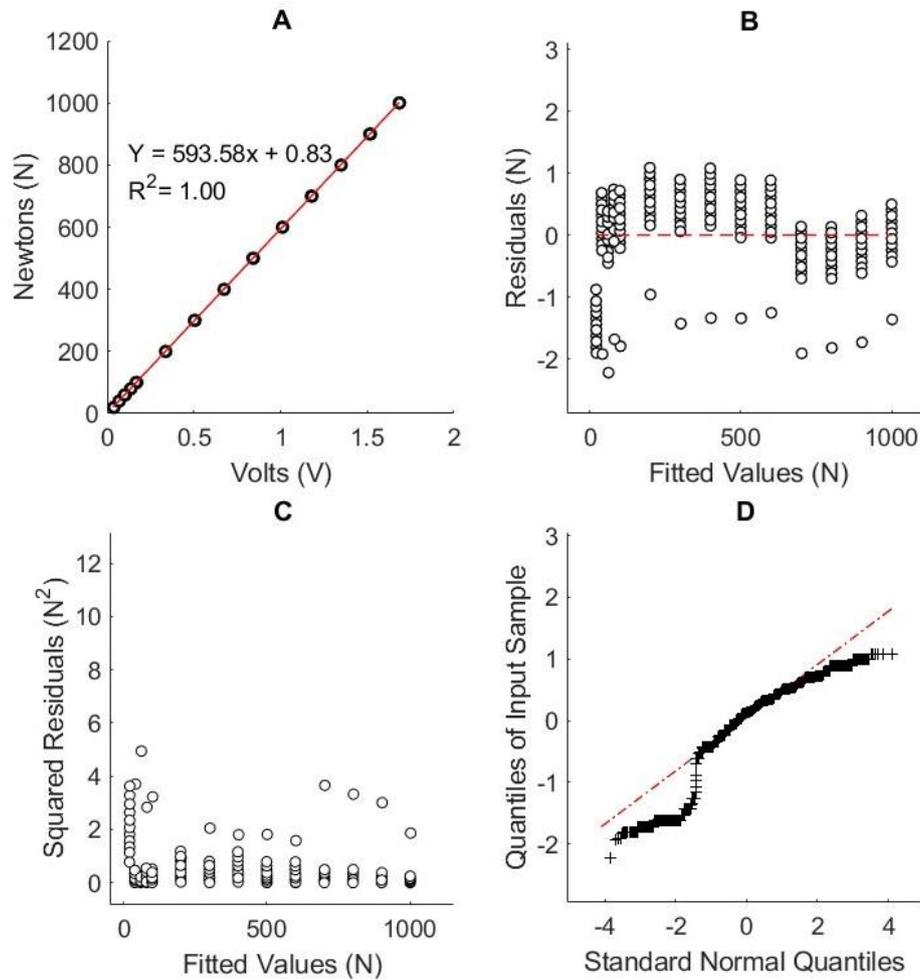
## 2.7 Statistical Analysis

For the statistical analysis, descriptive statistics were computed for the force measurements obtained in each session. The Shapiro-Wilk test was performed to assess data normality. For the calibration data, normality was confirmed, and Pearson's correlation was used to analyse the relationship between volts and newtons. Additionally, a residuals analysis was conducted, including Residuals vs. Fitted Values, Heteroscedasticity Assessment, and Q-Q Plot of Residuals.

For the reliability experimental procedures, the data did not follow a normal distribution. Therefore, the non-parametric Wilcoxon signed-rank test for paired samples was applied to evaluate significant differences between mean measurements across the two sessions (test-retest). The standard error of measurement (SEM) was calculated to quantify random variation using the formula:  $SEM = \sigma \cdot \sqrt{(1 - r)}$ . Furthermore, the minimal detectable change (MDC), representing the smallest change that exceeds random variation, was determined using the formula:  $MDC = SEM \cdot 1.96 \cdot \sqrt{2}$ . The intra-class correlation coefficient (ICC) (2,1) was calculated to assess measurement consistency across both sessions, with values ranging from 0 (no agreement) to 1 (perfect agreement) (Koo & Li). Agreement between sessions was further examined using Bland-Altman plots to visualize potential bias or systematic trends. Additionally, linear regression analysis was conducted to identify trends in force measurements over the test sessions. The effect size of the analyses was determined using Cohen's  $d$  criteria, with thresholds defined as small ( $d > 0.2$ ), moderate ( $d > 0.50$ ), and large ( $d > 0.80$ ) (Lipovšek, Kacin, & Puh). All statistical analyses were performed using SPSS Statistics software (IBM Corporation, Version 27), with the significance level set at  $p < 0.05$ .

### 3. Results

Figure 4 presents the calibration of the load cell, accompanied by residual analysis, which demonstrated linearity with a coefficient of determination ( $R^2 = 1$ ), and the applied linear regression yielded a mean square error of 0.55 N and a sum of squared errors of 7318.3 N<sup>2</sup>. Furthermore, the integration of a High-Resolution Digital Extensometer (HRDE) ensured precise strain measurements, contributing to uniform load distribution and enhancing the overall reliability of the experimental setup. Minimal data variations over time indicated high stability, and the near-zero mean of residuals, alongside a variance of 0.30 N and a standard deviation of 0.55 N, suggests no significant bias in the model.



**Figure 4.** Correlation and Residuals Analysis: A) Correlation; B) Residuals vs. Fitted Values; C) Heteroscedasticity Assessment; D) Q-Q Plot of Residuals.

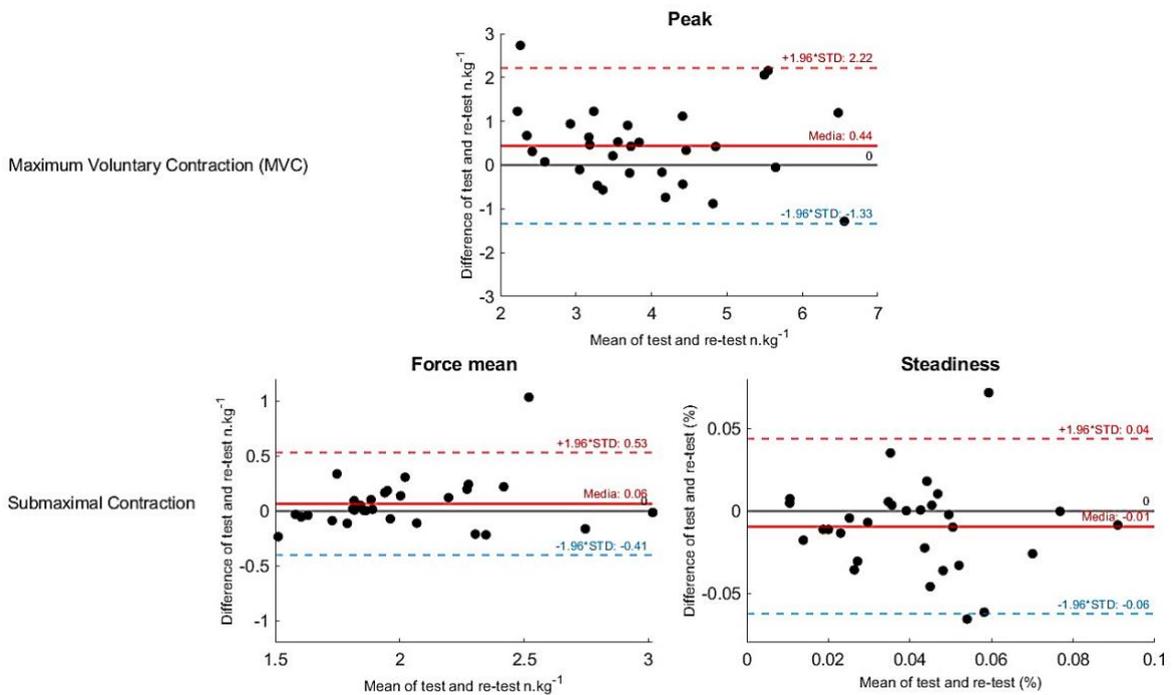
Table 1. presents the test-retest reliability results for MVC and submaximal voluntary contraction of the trunk extensors during spinal extension.

Test/Retest	Day 1	Day 2	<i>p</i>	Cohen's <i>d</i>	MDC	SEM	ICC (95% IC)	<i>R</i> <sup>2</sup>
<b>Maximal voluntary contractions (MVC)</b>								
Peak force (N.kg <sup>-1</sup> )	4.07 (1.18)	3.88 (1.23)	0.22	0.58	1.39	0.5	0.81 (0.62, 0.91)	0.71
<b>Submaximal voluntary contraction (SMV)</b>								
Mean Force (N.kg <sup>-1</sup> )	1.88 (0.39)	2.07 (0.34)	0.24	0.45	1.08	0.17	0.93 (0.84, 0.97)	0.88
Steadiness (%)	1.88 (1.22)	2.46 (1.37)	0.83	0.44	2.36	0.85	0.87 (0.78, 0.90)	0.40

Legend: Data are presented as mean (SD), Day 1–Day 2 (test/retest), *p*-value, minimal detectable change (MDC), standard error of measurement (SEM),

intraclass correlation coefficient (ICC) with 95% confidence intervals (CI), and linear regression coefficient of determination ( $R^2$ ).

Figure 5 presents the Bland–Altman plots for MVC and SMVC, assessing agreement between test and retest conditions within a 95% confidence interval. For peak force, the results were  $t=2.7$ ,  $df=29$ ,  $p=0.01$ , with 96.42% of samples within the limits of agreement. For mean force, the results were  $t=1.4$ ,  $df=29$ ,  $p=0.20$ , with 96.42% of samples within the limits of agreement. For steadiness, the analysis reported  $t=-1.9$ ,  $df=29$ ,  $p=0.06$ , with 92.85% of samples within the limits of agreement.



**Figure 5.** Bland–Altman plots comparing test and retest conditions for peak force, mean force, and steadiness during maximum voluntary contraction (MVC) and submaximal contraction.

#### 4. Discussion

This study aimed to evaluate the reliability and precision of a dynamometry in measuring both maximal and submaximal isometric strength, as well as muscle steadiness, during trunk extension. The results demonstrated high reliability across all maximal and submaximal tests for peak force, mean force, and force steadiness under both test and re-test conditions, thus confirming our initial hypothesis.

The calibration results validated that the single-point load cell meets research standards, ensuring that the sensor does not deform within our measurement range. This guarantees accuracy for both current and future studies involving loads up to 1000 N. The perfect fit of the linear regression model ( $R^2 = 1$ ) confirms precise calibration, while the low root means square error (0.55 N) and sum of squared errors underscore data consistency. These findings indicate that the dynamometer operates within an acceptable margin of error, comparable to commercial reference devices with an accuracy of  $\pm 1\%$  (Shrout & Fleiss), as well as previous studies that have successfully employed similar devices (Althobaiti & Falla, 2023; De Blaiser et al., 2018; Lipovšek et al., 2021; Park, Baek, Kim, Park, & Kang, 2017; Stark, Walker, Phillips, Fejer, & Beck, 2011; Yang et al., 2020). Additionally, the low heteroscedasticity observed in the analysis suggests that when a constant mass is applied, the voltage readings from the device remain stable without significant variations, further supporting the device's reliability. The Q-Q Plot of the residuals confirmed that the errors are normally distributed, further validating the model's assumptions. Consequently, this transducer can be considered a calibrated tool for assessing isometric trunk strength in practical and research settings.

The reliability analysis showed high agreement between sessions for maximum strength, average strength, and force steadiness, with no significant differences between the two assessment days ( $p > 0.05$ ), indicating consistent performance across sessions. ICC values ranged from 0.81 to 0.93, reflecting good to excellent reliability, with SMVC showing the highest reliability (ICC = 0.93). This suggests that lower-intensity efforts produce more consistent results than maximal efforts. Compared to previous studies, our results demonstrate superior reliability in maximum trunk extension strength. For example, Moreland et al. (ICC = 0.24) reported low reliability, likely due to improper dynamometer placement, while Valentin et al. achieved an ICC of 0.90 with a fixed dynamometer similar to our study. This confirms that fixing the dynamometer to a stable structure, yields reliable and consistent results, consistent with previous findings.

The values of MDC, SEM, and  $R^2$  further confirm the system's capability to detect differences that exceed random variability in peak and mean force variables, enhancing its sensitivity and utility in performance assessment. The reliability of the measurements, reflected by an SEM of 0.85% for force steadiness, indicates high precision with a reduced margin of error. However, the MDC of 2.36% suggests some degree of variability, highlighting the potential influence of external factors such as effort replicability, fluctuations in muscle activation, and motor unit recruitment (Guilhem et al., 2014; Hodges & Tucker, 2011; Silva et al., 2017). Bland-Altman analyses confirmed that most measurements fell within the limits of agreement between test and retest, indicating acceptable reproducibility without significant systematic bias. Nonetheless, factors such as neuromuscular noise, simultaneous execution of motor tasks, and variations in concentration could affect trunk force steadiness, emphasizing the importance of comprehensive evaluations of the system's reliability (Arvanitidis et al., 2025; Bouisset & Zattara, 1987; Hodges & Tucker, 2011; van Dieën et al., 2019).

In the literature, various protocols have been identified for evaluating the isometric strength of the trunk. For instance, (De Blaiser et al., 2018) utilized a protocol using a handheld dynamometer to measure maximal lumbar extensor strength during trunk flexion at 30° and prone extension at 0°. This is similar to our choice of 20° inclination, as increased gravitational force at 0° may create a mechanical disadvantage for force production (Bouisset & Zattara, 1987; Hunt, 1998). Our findings align with previous research validating the use of dynamometers to assess extensors. Unlike standing positions, which may introduce support-related variations, the 20° inclination accounts for biomechanical factors (De Blaiser et al., 2018). Controlled inclinations during isometric strength evaluations have been shown to reduce gravitational effects and muscular discomfort, thereby improving measurement accuracy (Barros et al., 2021; Juan-Recio, Barbado, Vaquero, & López-Plaza, 2017). Standardization is particularly crucial for patients with chronic LBP, enabling safer and more precise spinal extensor assessments (Althobaiti & Falla, 2023) Adopting a reliability position such as the 20° inclination ensures reliable and clinically

relevant outcomes, even for healthy individuals and with mobility restrictions (De Blaiser et al., 2018; Gruther et al., 2009)

The assessment of force steadiness is fundamental to understanding motor performance, especially in the muscles involved in postural control and affecting movement efficiency (Arvanitidis et al., 2025; Hamed, Hamed, Bohm, Mersmann, & Arampatzis, 2018; Kollmitzer, Ebenbichler, Sabo, Kerschan, & Bochsansky, 2000; Zemková & Zapletalová, 2022). Clinically, trunk strength and force steadiness deficits are impaired quality of life. In individuals with LBP, muscle instability often contributes to persistent pain and functional limitations (da Silva et al., 2017; Jain et al., 2022; McGill, 2001; van Dieën et al., 2019). Dynamometer systems provide a precise evaluation of muscle force steadiness, identifying motor control deficits and supporting the development of more effective rehabilitation strategies. Additionally, the device's ability to provide real time-force curve feedback can enhance neuromuscular re-education, minimizing compensatory patterns that exacerbate injuries or lead to new ones (Eichinger et al., 2016; Soares, Júnior, Silva, Domenech, & Gomes, 2013; Steele et al., 2019). The reliability demonstrated by this device for trunk force steadiness assessment has significant implications for tracking functional progress and tailoring therapeutic interventions. It offers healthcare professionals including physical therapists, physicians, and sports educators a practical and reliable tool to optimize clinical decision-making.

This study acknowledges certain limitations, including the absence of a gold-standard device for validating variables such as steadiness across different testing protocols and postures. Although standardized instructions and consistent verbal encouragement were provided to minimize external influences, psychological factors like anxiety and stress may have impacted participants' performance (Burton, Turrell, Oldenburg, & Sallis, 2005; Parolini et al., 2023). Additionally, variations in physical activity levels were not strictly controlled. Future research should focus on longitudinal studies to assess the dynamometer's effectiveness in tracking therapeutic progress and explore its application in diverse populations, including older adults, athletes, and individuals

with specific musculoskeletal conditions, while validating its performance against reference methods. interventions.

## 5. Conclusions

This study demonstrates the precision and reliability of using dynamometry to assess trunk extension strength during both MVC and SMVC. Calibration results validate the device's accuracy, showing high comparability to reference commercial equipment. Test-retest analysis confirms excellent reliability for both maximal and submaximal efforts across different days. Furthermore, the findings support the viability of evaluating muscular steadiness using a dynamometer system. The standardization of the protocol minimizes gravitational effects and muscular discomfort, thereby enhancing measurement precision. These results endorse the dynamometer as a valuable tool for functional assessment and the development of personalized rehabilitation and training strategies.

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**Ethical approval:** The study was conducted in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Sport of the University of Porto (CEFADE 28-2023).

**Informed Consent Statement:** Informed consent was obtained from all the participants involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

**Competing interests:** The authors declare no conflict of interest.

## References

- Alaranta, H., Luoto, S., Heliövaara, M., & Hurri, H. (1995). Static back endurance and the risk of low-back pain. *Clin Biomech (Bristol, Avon)*, 10(6), 323-324. doi:10.1016/0268-0033(95)00002-3
- Althobaiti, S., & Falla, D. (2023). Reliability and criterion validity of handheld dynamometry for measuring trunk muscle strength in people with and without chronic non-specific low back pain. *Musculoskeletal Science and Practice*, 66, 102799. doi:<https://doi.org/10.1016/j.msksp.2023.102799>
- Althobaiti, S., Rushton, A., Aldahas, A., Falla, D., & Heneghan, N. R. (2022). Practicable performance-based outcome measures of trunk muscle strength and their measurement properties: A systematic review and narrative synthesis. *Plos one*, 17(6), e0270101.
- Arins, M. R., Murara, N., Bottamedi, X., Ramos, J. d. S., Woellner, S. S., & Soares, A. V. (2016). Physiotherapeutic treatment Schedule for chronic low back pain: influence on pain, quality of life and functional capacity. *Revista Dor*, 17.
- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2025). Does pain influence control of muscle force? A systematic review and meta-analysis. *Eur J Pain*, 29(2), e4716. doi:10.1002/ejp.4716
- Barros, M., Clemente, N., Rezende, F., Cardoso, T., Thomaz, S. R. T., Garcia, P., . . . Martins, W. (2021). Reliability of the handheld dynamometer in the evaluation of the muscle strength of trunk extensors in healthy adults. *Motricidade*, 17. doi:10.6063/motricidade.20784
- Bonhof-Jansen, E. D. J., van Ham, A., Kroon, G. J., Winter, R. W., & Brink, S. M. (2023). Validity and reliability of a portable handheld dynamometer compared to a fixed isokinetic dynamometer to assess forearm torque strength. *Hand Surgery and Rehabilitation*, 42(2), 147-153. doi:<https://doi.org/10.1016/j.hansur.2022.12.003>
- Bouisset, S., & Zattara, M. (1987). Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *J Biomech*, 20(8), 735-742. doi:10.1016/0021-9290(87)90052-2

- Brill, P. A., Macera, C. A., Davis, D. R., Blair, S. N., & Gordon, N. (2000). Muscular strength and physical function. *Med Sci Sports Exerc*, 32(2), 412-416. doi:10.1097/00005768-200002000-00023
- Burton, N. W., Turrell, G., Oldenburg, B., & Sallis, J. F. (2005). The relative contributions of psychological, social, and environmental variables to explain participation in walking, moderate-, and vigorous-intensity leisure-time physical activity. *Journal of Physical Activity and Health*, 2(2), 181-196.
- Camposo, L., & Pereira, R. (2015). Correlação entre os testes de dinamometria de preensão manual, escapular e lombar com o desempenho no Special Judo Fitness Test. *Revista de Educação Física / Journal of Physical Education*, 84. doi:10.37310/ref.v84i1.111
- Cholewicki, J., & McGill, S. M. (1996). Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech (Bristol, Avon)*, 11(1), 1-15. doi:10.1016/0268-0033(95)00035-6
- Chou, R., & Shekelle, P. (2010). Will this patient develop persistent disabling low back pain? *JAMA*, 303 13, 1295-1302. doi:10.1001/jama.2010.344
- da Silva, T., Mills, K., Brown, B. T., Herbert, R. D., Maher, C. G., & Hancock, M. J. (2017). Risk of Recurrence of Low Back Pain: A Systematic Review. *J Orthop Sports Phys Ther*, 47(5), 305-313. doi:10.2519/jospt.2017.7415
- De Blaiser, C., De Ridder, R., Willems, T., Danneels, L., & Roosen, P. (2018). Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population. *Physical Therapy in Sport*, 34, 180-186.
- De Vet, H. C., Terwee, C. B., Mokkink, L. B., & Knol, D. L. (2011). *Measurement in medicine: a practical guide*: Cambridge university press.
- Eichinger, F., Soares, A., Júnior, J., Gevaerd, M., Domenech, S., & Júnior, N. (2016). Dinamometria lombar: um teste funcional para o tronco. *Revista Brasileira de Medicina do Trabalho*, 14, 120-126. doi:10.5327/Z1679-443520162415
- Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength tests for the trunk, hands and shoulders. *International Journal of*

*Industrial Ergonomics*, 28(6), 379-387. doi:[https://doi.org/10.1016/S0169-8141\(01\)00044-0](https://doi.org/10.1016/S0169-8141(01)00044-0)

- Freitas, C. D. d., & Greve, J. M. D. A. (2008). Estudo comparativo entre exercícios com dinamômetro isocinético e bola terapêutica na lombalgia crônica de origem mecânica. *Fisioterapia e Pesquisa*, 15.
- Gonçalves, M., & Barbosa, F. S. S. (2005). Análise de parâmetros de força e resistência dos músculos eretores da espinha lombar durante a realização de exercício isométrico em diferentes níveis de esforço. *Revista Brasileira de Medicina do Esporte*, 11.
- Gruther, W., Wick, F., Paul, B., Leitner, C., Posch, M., Matzner, M., . . . Ebenbichler, G. (2009). Diagnostic accuracy and reliability of muscle strength and endurance measurements in patients with chronic low back pain. *Journal of rehabilitation medicine : official journal of the UEMS European Board of Physical and Rehabilitation Medicine*, 41, 613-619. doi:10.2340/16501977-0391
- Guilhem, G., Giroux, C., Couturier, A., & Maffiuletti, N. A. (2014). Validity of trunk extensor and flexor torque measurements using isokinetic dynamometry. *Journal of Electromyography and Kinesiology*, 24(6), 986-993.
- Hamed, A., Hamed, A., Bohm, S., Mersmann, F., & Arampatzis, A. (2018). Exercises of dynamic stability under unstable conditions increase muscle strength and balance ability in the elderly. *Scandinavian Journal of Medicine & Science in Sports*, 28, 961-971. doi:10.1111/sms.13019
- Hodges, P. W., & Tucker, K. (2011). Moving differently in pain: a new theory to explain the adaptation to pain. *Pain*, 152(3 Suppl), S90-s98. doi:10.1016/j.pain.2010.10.020
- Hunt, A. (1998). *A guide to the Measurement of Force*.
- Jain, S., Shetty, G., Munje, P., Bhan, A., Linjhara, S., & Ram, C. S. (2022). Gender-based Variations in Trunk Motion and Isometric Strength in Young Adults with Low Back Pain: A Prospective Case-control Study. *Revista Brasileira de Ortopedia*, 57.
- Juan-Recio, C., Barbado, D., Vaquero, M. P., & López-Plaza, D. (2017). Reliability assessment and correlation analysis of three protocols to

- measure trunk muscle strength and endurance. *Journal of Sports Sciences*, 36. doi:10.1080/02640414.2017.1307439
- Jubany, J., Busquets, A., Marina, M., Cos, F., & Angulo-Barroso, R. (2015). Reliability and validity of a custom-made instrument including a hand-held dynamometer for measuring trunk muscle strength. *Journal of Back and Musculoskeletal Rehabilitation*, 28(2), 317-326.
- Kell, R. T., Bell, G., & Quinney, A. (2001). Musculoskeletal fitness, health outcomes and quality of life. *Sports Med*, 31(12), 863-873. doi:10.2165/00007256-200131120-00003
- Kollmitzer, J., Ebenbichler, G., Sabo, A., Kersch, K., & Bochsansky, T. (2000). Effects of back extensor strength training versus balance training on postural control. *Medicine and science in sports and exercise*, 32 10, 1770-1776. doi:10.1097/00005768-200010000-00017
- Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*, 15(2), 155-163. doi:10.1016/j.jcm.2016.02.012
- Larivière, C., Gagnon, D., & Loisel, P. (1999). *The effect of load on the coordination of the trunk for subjects with and without chronic low back pain during flexion-extension & lateral bending tasks.*
- Larsen, L. H., Hirata, R. P., & Graven-Nielsen, T. (2018). Experimental Low Back Pain Decreased Trunk Muscle Activity in Currently Asymptomatic Recurrent Low Back Pain Patients During Step Tasks. *J Pain*, 19(5), 542-551. doi:10.1016/j.jpain.2017.12.263
- Lipovšek, T., Kacin, A., & Puh, U. (2021). Reliability and validity of hand-held dynamometry for assessing lower limb muscle strength. *Isokinetics and Exercise Science*, 30, 1-10. doi:10.3233/IES-210168
- Martínez-Romero, M. T., Ayala, F., De Ste Croix, M., Vera-Garcia, F. J., Sainz de Baranda, P., Santonja-Medina, F., & Sánchez-Meca, J. (2020). A Meta-Analysis of the Reliability of Four Field-Based Trunk Extension Endurance Tests. *International Journal of Environmental Research and Public Health*, 17(9), 3088. Retrieved from <https://www.mdpi.com/1660-4601/17/9/3088>
- McGill, S. M. (1997). Distribution of tissue loads in the low back during a variety of daily and rehabilitation tasks. *J Rehabil Res Dev*, 34(4), 448-458.

- McGill, S. M. (2001). Low back stability: from formal description to issues for performance and rehabilitation. *Exerc Sport Sci Rev*, 29(1), 26-31. doi:10.1097/00003677-200101000-00006
- Moreland, J., Finch, E., Stratford, P., Balsor, B., & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *J Orthop Sports Phys Ther*, 26(4), 200-208. doi:10.2519/jospt.1997.26.4.200
- Müller, I., Machado de Brito, R., Pereira, C., & Brusamarello, V. (2010). Load cells in force sensing analysis - Theory and a novel application. *Instrumentation & Measurement Magazine, IEEE*, 13, 15-19. doi:10.1109/MIM.2010.5399212
- Nawab, S. H., Chang, S. S., & De Luca, C. J. (2010). High-yield decomposition of surface EMG signals. *Clin Neurophysiol*, 121(10), 1602-1615. doi:10.1016/j.clinph.2009.11.092
- Neufuss, J., Hesse, B., Thorpe, S. K., Vereecke, E. E., D'Aout, K., Fischer, M. S., & Schilling, N. (2014). Fibre type composition in the lumbar perivertebral muscles of primates: implications for the evolution of orthogrady in hominoids. *J Anat*, 224(2), 113-131. doi:10.1111/joa.12130
- Park, H. W., Baek, S., Kim, H. Y., Park, J. G., & Kang, E. K. (2017). Reliability and Validity of a New Method for Isometric Back Extensor Strength Evaluation Using A Hand-Held Dynamometer. *Ann Rehabil Med*, 41(5), 793-800. doi:10.5535/arm.2017.41.5.793
- Parolini, F., Goethel, M., Becker, K., Fernandes, C., Fernandes, R. J., Ervilha, U. F., . . . Vilas-Boas, J. P. (2023). Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain. *Biomedicines*, 11(7). doi:10.3390/biomedicines11072042
- Pincus, T., Burton, A., Vogel, S., & Field, A. (2002). A Systematic Review of Psychological Factors as Predictors of Chronicity/Disability in Prospective Cohorts of Low Back Pain. *Spine*, 27. doi:10.1097/00007632-200203010-00017
- Ruiz, J. R., Sui, X., Lobelo, F., Morrow, J. R., Jr., Jackson, A. W., Sjöström, M., & Blair, S. N. (2008). Association between muscular strength and mortality

- in men: prospective cohort study. *Bmj*, 337(7661), a439. doi:10.1136/bmj.a439
- Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychol Bull*, 86(2), 420-428. doi:10.1037//0033-2909.86.2.420
- Silva, M. F., Dias, J. M., Pereira, L. M., Mazuquin, B. F., Lindley, S., Richards, J., & Cardoso, J. R. (2017). Determination of the motor unit behavior of lumbar erector spinae muscles through surface EMG decomposition technology in healthy female subjects. *Muscle Nerve*, 55(1), 28-34. doi:10.1002/mus.25184
- Soares, A., Júnior, J., Silva, L., Domenech, S., & Gomes, N. (2013). *VALORES NORMATIVOS DA DINAMOMETRIA LOMBAR: UM TESTE FUNCIONAL PARA O TRONCO*.
- Stark, T., Walker, B., Phillips, J. K., Fejer, R., & Beck, R. (2011). Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *Pm r*, 3(5), 472-479. doi:10.1016/j.pmrj.2010.10.025
- Steele, J., Fisher, J., Perrin, C., Conway, R., Bruce-Low, S., & Smith, D. (2019). Does change in isolated lumbar extensor muscle function correlate with good clinical outcome? A secondary analysis of data on change in isolated lumbar extension strength, pain, and disability in chronic low back pain. *Disability and rehabilitation*, 41(11), 1287-1295.
- Valentin, G., & Maribo, T. (2014). Hand-held dynamometry fixated with a tripod is reliable for assessment of back extensor strength in women with osteoporosis. *Osteoporos Int*, 25(8), 2143-2149. doi:10.1007/s00198-014-2743-0
- van Dieën, J. H., Reeves, N. P., Kawchuk, G., van Dillen, L. R., & Hodges, P. W. (2019). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *J Orthop Sports Phys Ther*, 49(6), 370-379. doi:10.2519/jospt.2019.7917
- Vlažná, D., Krkoška, P., Kuhn, M., Dosbaba, F., Bařalík, L., Vlčková, E., . . . Adamová, B. (2021). Assessment of Lumbar Extensor Muscles in the Context of Trunk Function, a Pilot Study in Healthy Individuals. *Applied Sciences*. doi:10.3390/app11209518

- Vos, T., Flaxman, A. D., Naghavi, M., Lozano, R., Michaud, C., Ezzati, M., . . . Memish, Z. A. (2012). Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet*, *380*(9859), 2163-2196. doi:10.1016/s0140-6736(12)61729-2
- Yang, S., Wu, W., Zhang, C., Wang, D., Chen, C., Tang, Y., . . . Luo, F. (2020). Reliability and validity of three isometric back extensor strength assessments with different test postures. *J Int Med Res*, *48*(2), 300060519885268. doi:10.1177/0300060519885268
- Zemková, E., & Zapletalová, L. (2022). The Role of Neuromuscular Control of Postural and Core Stability in Functional Movement and Athlete Performance. *Frontiers in Physiology*, *13*. doi:10.3389/fphys.2022.796097

*Article*

### **Acute Low Back Pain and Its Effects on Motor Control: An Analysis of Adaptations in Force Steadiness and Motor Unit Recruitment.**

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## **Abstract**

**Introduction/Aims:** Acute low back pain is a prevalent musculoskeletal disorder that can disrupt motor control and compromise functional stability. Recent evidence indicates that pain may alter motor unit discharge characteristics and the temporal organization of muscle activation. However, the precise neuromuscular adaptations remain inadequately understood. **Methods:** Thirty-three healthy participants (aged 18–40 years) performed a sustained spinal extension task at 20% of their maximum voluntary contraction under two conditions: pre and during pain (hypertonic injection) and pre and during-isotonic injection into the lumbar region. Electromyography signals were recorded from the right and left longissimus muscles. Electromyography signals were decomposed into individual motor unit action potentials using advanced algorithms and subsequently clustered via a K-means method. Key parameters, including firing rate, recruitment threshold, and motor unit action potential amplitude were analyzed in the identified clusters, under pain and control conditions. **Results:** In the pain condition, significant lateralized changes were observed. The contralateral longissimus exhibited an increased firing rate ( $p = 0.020$ ) with no significant changes in the recruitment threshold or motor unit action potential amplitude, whereas the ipsilateral side showed subtle modulations in recruitment threshold. In the isotonic control condition, motor unit parameters remained stable, indicating that the observed changes were specific to the pain state. **Conclusions:** These findings demonstrate that acute low back pain induces a dynamic, lateralized reorganization of motor unit recruitment, reflecting a compensatory neuroplastic mechanism that preserves functional stability despite impaired motor coordination. This study provides novel insights into the neuromuscular adaptations underlying acute low back pain.

**Key Words:** Electromyography, force steadiness, motor units, low back pain, neuromuscular adaptation, isometric contraction

**Running Head:** Acute Low Back Pain & Motor Control.

## 1. Introduction

Low back pain is a highly prevalent musculoskeletal condition that compromises motor control and functionality (Dieën et al., 2019a, 2019b). Evidence suggests that pain increases variability in muscle force control during painful contractions, highlighting the importance of these adaptations for functional performance (Arvanitidis et al., 2025; Schabrun et al., 2016). However, the neural mechanisms underlying these changes have not been fully elucidated, particularly concerning the lateralization of neuromuscular adjustments in response to acute low back pain (Farina et al., 2004; Hodges & Richardson, 1999; Martinez-Valdes et al., 2020). However, the neural mechanisms underlying these changes have not been fully elucidated, particularly concerning the lateralization of neuromuscular adjustments in response to acute low back pain (Porcaro et al., 2021; Wang et al., 2023).

Despite advancements, there remains a significant gap in understanding how changes induced by low back pain manifest in force steadiness and motor unit pool organization during submaximal tasks (Arvanitidis et al., 2025). Previous investigations have reported divergent mechanisms in motor control in individuals with low back pain (Meier et al., 2018; van Dieën et al., 2019), but the role of selective motor unit reorganization has not been fully explored. Recent advances in electromyographic signal decomposition have enabled precise analysis of individual motor unit behavior during dynamic contractions, providing detailed insights into central nervous system strategies for force production modulation (De Luca et al., 2006; De Luca & Contessa, 2015; Nawab et al., 2010). However, the interpretation of these data can vary significantly depending on the methodological approach used. It is essential to apply techniques that ensure greater precision in characterizing the motor unit pools (Farina et al., 2004; Martinez-Valdes et al., 2020). When analysing superficially, without proper depth or refinement, oversimplification of results can lead to limited conclusions or even the absence of reliable conclusions (Silva et al., 2017). The method described by Becker et al. (2022, 2024) allows for more precise and detailed analysis of motor units by segmenting neuromuscular activity data, separating critical events, and

providing a clearer view of the interactions between recruitment, firing rate, and synchronization of action potentials.

Thus, our hypothesis is that experimentally induced acute low back pain triggers dynamic changes in force steadiness, reflecting a neuromuscular reconfiguration. The aim of this study is to investigate the effects of acute low back pain on motor control during a sustained isometric trunk extension task performed at 20% of maximal force. To do so, we applied advanced EMG decomposition and clustering techniques, aiming to outline changes in motor unit recruitment and discharge properties, providing a more comprehensive understanding of the mechanisms that maintain force steadiness in the presence of acute low back pain.

## **2. Methods**

### **2.1 Study design**

This is an experimental study that involved participants attending two visits, with a seven-day interval between them. The research protocol received ethical approval from the ethics committee of the Faculty of Sport of the University of Porto (CEFADE 28-2023). All objectives and methodologies were meticulously developed and executed following the guidelines established by the Declaration of Helsinki. Before participation, all volunteers provided informed consent by signing an Informed Consent Form, ensuring their understanding of the objectives and procedures of the study.

### **2.2 Volunteers**

Thirty-three individuals participated in this study. The inclusion criteria required participants to be healthy individuals aged between 18 and 40 years, with no history of musculoskeletal disorders or recurrent pain in the preceding six weeks. Moreover, they should not have taken anti-inflammatory or analgesic medication within 24 hours before the experiment. Exclusion criteria encompassed individuals with a history of lumbar injury or surgery, pre-existing chronic conditions such as disc degeneration, or other disorders that could affect muscle function. Pregnant women were also excluded. These criteria were established

to ensure a homogeneous sample, thereby reducing the influence of confounding factors on the study outcomes.

The participants ranged in age from 18 to 40 years (mean:  $29.06 \pm 5.96$  years). Among them, eight were women, with an average height of  $164.66 \pm 6.3$  cm, an age of  $29.77 \pm 6.2$  years, and a body mass of  $65.14 \pm 6.20$  kg. The remaining 25 participants were men, with a mean height of  $175.20 \pm 5.5$  cm, an age of  $28.79 \pm 5.9$  years, and a body mass of  $80.00 \pm 9.3$  kg. Height and body mass were assessed using a bioimpedance system (InBody 230, InBody Co., Ltd., Korea).

### **2.3 Electromyography (EMG) signals**

EMG signals from the right and left longissimus muscles in the lower back, were collected using dEMG Galileo sensor (Delsys, Natick, MA, USA) electrodes, sizes  $23 \times 30$  mm with four electrodes (5 mm of inter-electrode distance), 19 g of mass, and placed on dry skin. All the gears were plugged into an uninterruptible power supply with an external battery to isolate all the possible noise from the net wire. The active site of the sensor placement was cleaned and shaved, and the electrode was placed in the middle of the muscle belly, according to the SENIAM recommendations (Hermens et al., 2000). Further, the quality of the signal was checked based on two principles: the minimal offset amplitude accepted was around 20 and no more than 40 microvolts and the other caution was to check the signal-to-noise ratio, to ensure the quality of the signal collected. Galileo sensors were placed over the longissimus right and left muscles. Data collection was performed using the Delsys<sup>®</sup> EMGWorks 4.8.0 software (Delsys, USA) with a sampling frequency of 2000 Hz. The EMG signal was decomposed using the algorithm developed by De Luca et al. (De Luca et al., 2006) and refined by Nawab et al. (2010), utilizing the NeuroMap System software (Delsys, USA). A minimum accuracy of 80% was set for motor unit detection.

### **2.4 Experimental Setup**

### 2.4.1 Force test

Five familiarization repetitions of the maximal voluntary contraction (MVC) test and three repetitions of the submaximal (20% of maximal) test with a trapezoidal signal were performed (steadiness) (Arvanitidis et al., 2024; Valentin & Maribo, 2014). After a 2-minute rest period, one MVC repetition was conducted, followed by 1 minute of rest, and subsequently, one repetition of the trapezoidal force signal was performed. The trapezoidal shape of the force curve is illustrated in Figure 1. Visual feedback of the curve was provided throughout the trials. At the first visit, a MVC was performed, and then a submaximal isometric contraction was performed at 20% of the MVC. On the second visit, after 7 days, the same participant performed the same procedure as in the first visit. Familiarization with the tests was carried out with all volunteers. The dynamometer was attached to a metal structure mounted on a treatment table to keep it stable in both tests. For the performance of trunk extensor muscle strength tests, volunteers were positioned in prone. The dynamometer was positioned in the midline between the two upper angles of the scapulae, and volunteers were asked to perform spinal extension, maintaining isometry for 30 seconds. Figure 1 shows the experimental setup.



Figure 1. Experimental Setup: (A) Initial position of the volunteer, (B) Volunteer performing trunk extension, and (C) Screen display of the trapezoidal model using Delsys® EMG Works 4.8.0 software (Delsys, Natick, MA, USA).

### 2.4.2 Experimentally induced acute low back pain

Experimental acute low back pain and a control condition were obtained, respectively, by intramuscular injections of hypertonic and isotonic saline solution, administered 7 days apart (Kellgren, 1938). During the injections, the participants were positioned in the prone position on a trunk wedge with a 20° incline, as illustrated in Figure 1. The inclination was measured in the cephalocaudal direction, while the spine was extended, which helped to promote muscle relaxation. The study employed a randomized crossover design, where each participant received a single 2.5 mL dose (Canestri et al., 2021) of either hypertonic saline solution (6.0%) to induce pain, or isotonic saline solution (0.9%) (Graven-Nielsen, 2006), as a placebo, ensuring the test was conducted during the pain phase.

The injections were administered in the intervertebral space between L3 and L4, at the level of the spinous process, located approximately 2 to 3 cm from the midline (Hermens et al., 2000). The injection was performed in the multifidus muscle due to its stabilizing role and its tendency to reflex inhibition under nociceptive conditions (Devecchi et al., 2022; MacDonald et al., 2006). On the other hand, the longissimus was monitored with EMG because it is a superficial muscle, highly involved in the extension of the spine and frequently recruited in a compensatory manner when there is dysfunction in the deep muscles (Raabe & Chaudhari, 2018).

After cleaning the area with 70% alcohol, the solution was injected into the dominant side of the body using a 25 × 28 mm needle, at a depth of 30 mm from the skin surface. The participants were assessed in three different conditions: baseline, experimentally induced pain (hypertonic solution), and control condition (isotonic solution) while performing a spinal extension task in the prone position.

### *2.5 Data Analysis - clustering, EMG and analyses force steadiness*

The method used for clustering (Becker et al., 2022) involved the variables FR (firing rate), RT (recruitment threshold), and MUAP<sub>AMP</sub> (motor unit action potential

amplitude) to group the motor units (MUs) using the K-means algorithm. This algorithm assigns data points to the nearest of k randomly selected centers, then recalculates each center as the center of mass of the assigned points (Sarabon et al., 2021). A signal processing routine was developed in MATLAB (R2022a, Natick, MA, USA) to group the MUs into two predefined clusters, labeled G1 (red) and G2 (blue), roughly analogous to the fiber types described by Becker et al. (2022).

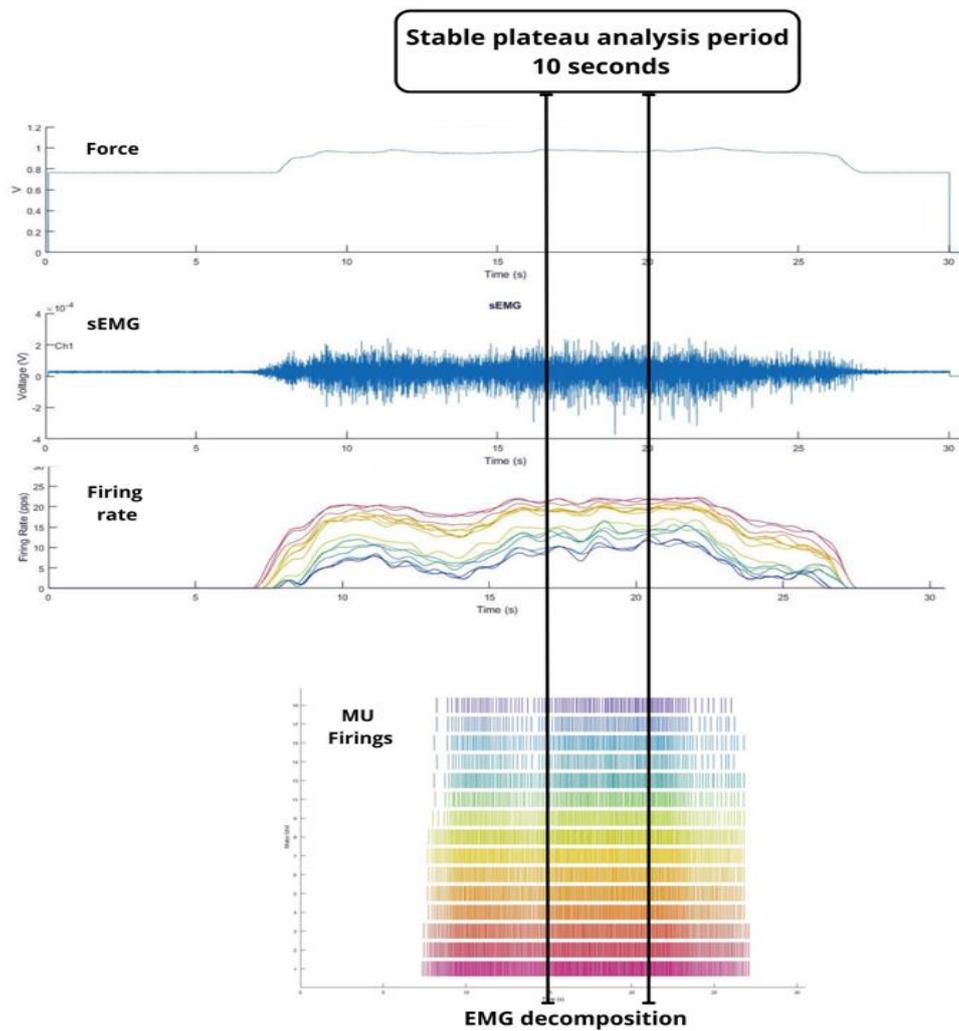


Figure 2: Schematic representation of data analysis workflow adopted in the current work.

The force steadiness was analyzed from the extracted and normalized data. Ten seconds of the plateau phase of the trapezoidal signal were analyzed during the sustained submaximal test (Figure 2). This period allowed for an accurate assessment of sustained strength.

## 2.6 Statistical analysis

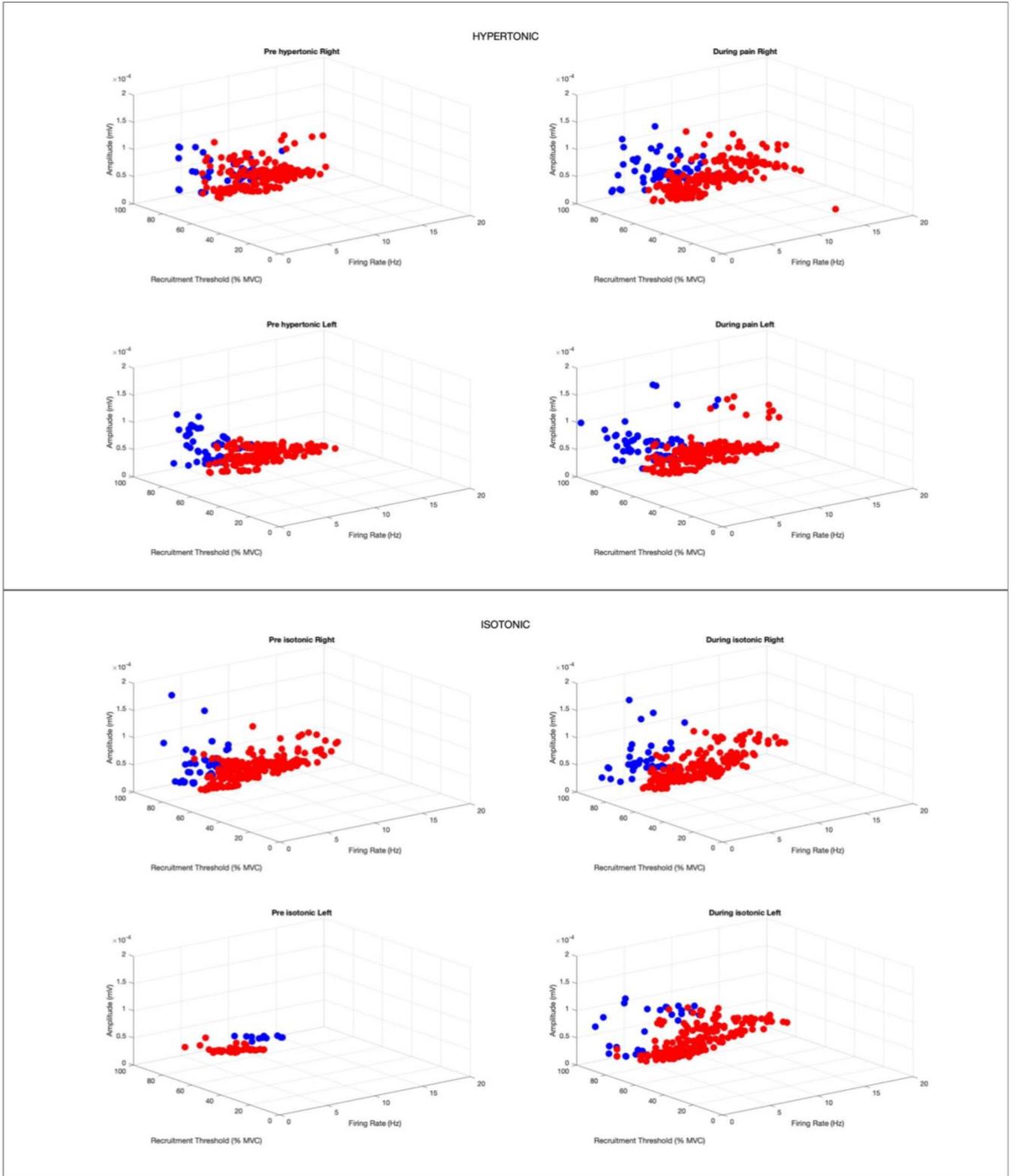
The Shapiro-Wilk test was used to assess the normality of the data, and since the assumption of normality was not met, non-parametric tests were used for statistical analysis. The Friedman test was applied to compare the four experimental conditions (pre-hypertonic, during pain, pre-isotonic, and during-

isotonic) regarding changes in motor unit behavior (FR, RT, and MUAP<sub>AMP</sub>). Additionally, the Wilcoxon signed-rank test was used to assess intra-group differences for G1 and G2 under each experimental condition. Effect size and statistical power of the analysis, using Cohen's d criteria (small: > 0.2; moderate: > 0.50; large: > 0.80) (Cohen, 1988). The statistical power of the analysis was estimated using G\*Power 3.1.7 (University of Kiel, Germany). All statistical analyses were conducted using SPSS Statistics (IBM Corporation, Version 27), with a significance level set at  $\alpha = 0.05$ . Data are presented as medians and interquartile ranges (parentheses), as they did not follow a normal distribution.

### **3. Results**

#### *3.1 Clustering of Motor Units*

RT was the most significant variable for the clustering of motor units, as shown in Figure 3. Since the clustering method used three variables, we employed a three-dimensional plot to visualize their interaction in both conditions, hypertonic and isotonic.



*Figure 3:* Three-dimensional plots of the three variables considered in the clustering analyses. (a) Clusters of MUs in hypertonic condition. (b) Clusters of MUs in Isotonic condition. Each point represents a motor unit, identified as belonging to group 1 (red) or group 2 (blue), according to the recruitment threshold value. Pre- and post-injection values are shown.

### 3.2 The Effect of Pain in force steadiness

Force steadiness showed a median of 0.65 (0.51) in the pre-hypertonic condition and 0.55 (0.72) during acute induced low back pain. This suggests a reduction ( $p < 0.011$ ) in force steadiness during low back pain (Figure 4). In the isotonic protocol wasn't possible to find the same effect.

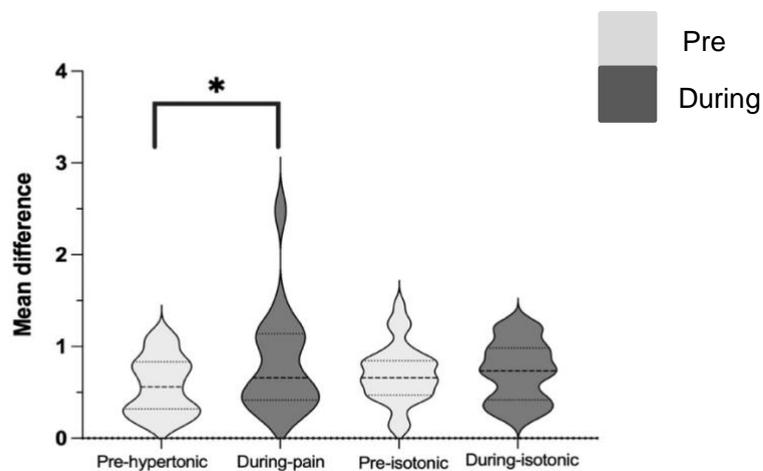


Figure 4: Graph of the median difference in force steadiness, pre-hypertonic, during pain, pre- and during isotonic.

### 3.3 Pain effect on motor units' pool

In G1, when comparing the conditions before and during the induced pain, statistically significant differences were observed in the left longissimus muscle (contralateral to the injection) for FR ( $p = 0.020$ ,  $d = 0.516$ ) (Figure 5). However, no significant differences were found for RT recruitment threshold ( $p = 0.151$ ,  $d = 0.889$ ) or  $MUAP_{AMP}$  amplitude ( $p = 0.345$ ,  $d = 0.334$ ). In the right longissimus muscle (injection site), none of the variables analyzed showed statistically significant differences: RT ( $p = 0.783$ ,  $d = 0.096$ ), FR ( $p = 0.709$ ,  $d = 0.13$ ), and  $MUAP_{AMP}$  ( $p = 0.437$ ,  $d = 0.273$ ). In the pre- and during-isotonic condition, on the left side, only  $MUAP_{AMP}$  showed significant differences ( $p = 0.003$ ,  $d = 1.235$ ), while RT and FR showed no relevant changes (RT:  $p = 0.156$ ,  $d = 0.510$ ; FR:  $p =$

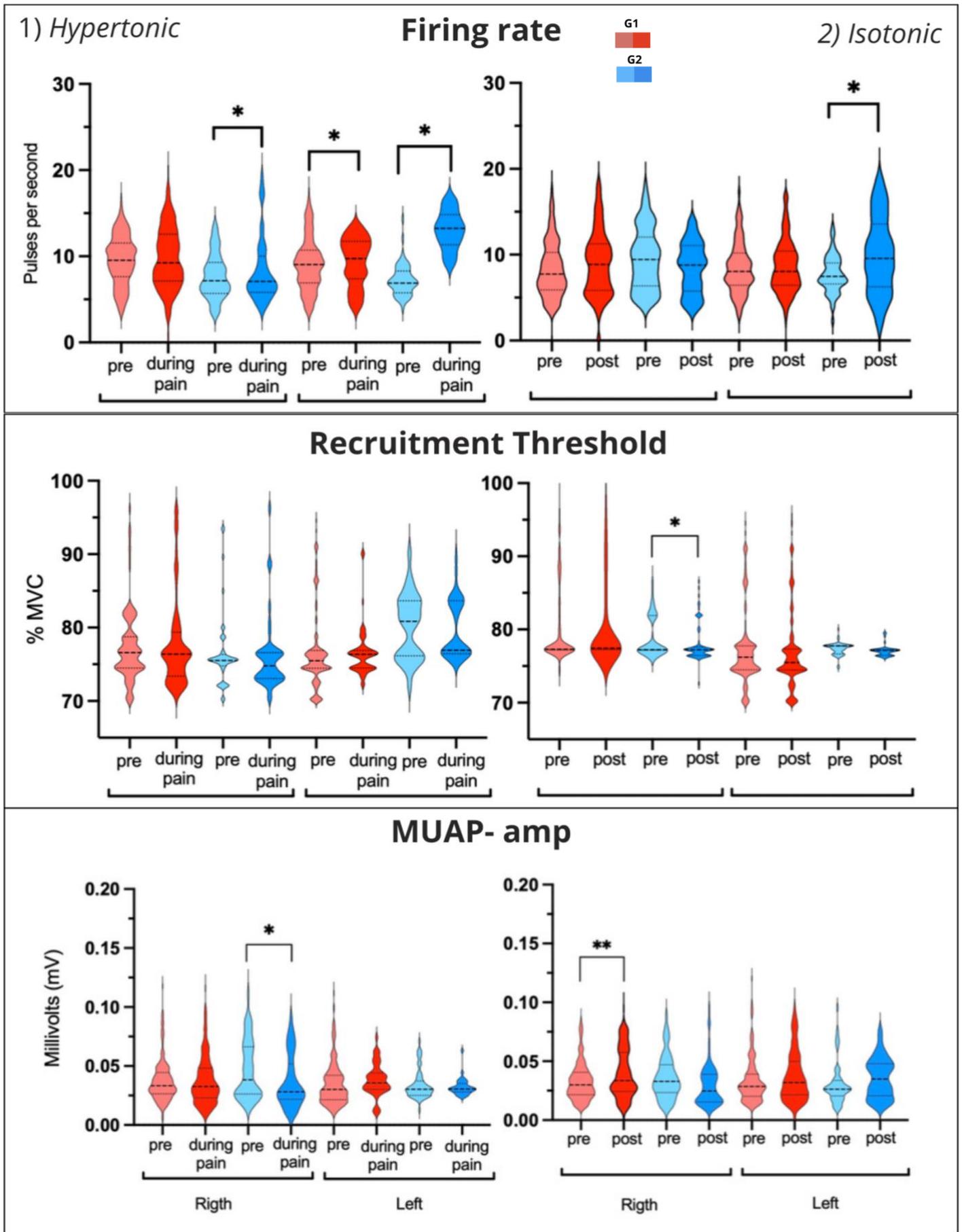


Figure 5. Median and interquartile range of the variables of the motor units identified in thirty-three subjects during 10 seconds of plateau of the trapezoidal sign of sustained spine extension, stratified by groups of motor units and hypertonic (1) and isotonic (2) condition in the right and left longissimus muscles. (a) Firing rate, (b) recruitment threshold, (c) amplitude of motor unit action potential (MUAP<sub>AMP</sub>). Statistical significance was tested using the Wilcoxon test for nonparametric data between time points in the same condition (\*p < 0.01, \*\*p < 0.001).

#### 4. Discussion

The results of this study provide substantial support for our hypothesis that experimentally induced acute low back pain triggers a dynamic and lateralized neuromuscular reconfiguration, reflected in the modulation of force steadiness during a trunk extension task performed at 20% of MVC. Even under a low-intensity challenge, the presence of pain induces specific alterations in neuromuscular activity, with distinct responses in the ipsilateral and contralateral muscles relative to the pain induction site. Analysis of clustered groups G1 and G2 revealed significant changes in electrophysiological parameters, particularly in the FR and the MUAP<sub>AMP</sub>.

In the left longissimus muscle (contralateral to pain induction), an increase in FR was observed in the G1 group, suggesting that the central nervous system adopts a compensatory strategy by intensifying activation of the muscles on the unaffected side (Martinez-Valdes et al., 2020; van Dieën et al., 2019; Zhang et al., 2024). This response may be related to the predominance of type 1 fibers in the lumbar musculature, which are known for their stabilizing function and gradual recruitment (Agten et al., 2020; Širca & Kostevc, 1985). Contralateral activation pattern FR suggests an adaptive reorganization of motor control: a possible change in synchronicity (Meier et al., 2018; Tsao et al., 2008). The central nervous system appears to prioritize functional stability by selectively increasing the activation of both groups of Mus on the contralateral side, elucidating again a compensatory strategy to preserve neuromuscular function (Wang et al., 2023; Zhang et al., 2024).

The observed changes in FR and MUAP<sub>AMP</sub> together indicate a dynamic process of neuroplasticity in which the reorganization of neural activation aims to preserve motor execution (Brumagne et al., 2019). The differential modulation of muscle

activity between the ipsilateral and contralateral sides suggests a refined adaptive mechanism within the central nervous system (Heming et al., 2019). The redistribution of motor unit activation may reflect adjustments in motor control in response to pain, thereby maintaining functional stability (Brumagne et al., 2019; Schmid et al., 2021). This differential response may result from both peripheral influences, such as changes in motor unit excitability, and central mechanisms involved in motor control reorganization (Cheung et al., 2005; Corti et al., 2022; Meier et al., 2018).

On the ipsilateral side to pain induction (right longissimus muscle), the changes were more subtle, with no major variations in FR or MUAP<sub>AMP</sub> amplitude, but with adjustments in recruitment latency. This finding suggests that although FR modulation was less pronounced than on the contralateral side, the central nervous system adjusts the muscular response to local nociceptive input (Farina et al., 2004; Martinez-Valdes et al., 2020; Sterling et al., 2001). The absence of substantial FR modifications suggests that the central nervous system maintains a baseline level of ipsilateral motor regulation, possibly to prevent interference that could compromise overall movement coordination (Porcaro et al., 2021; Tazoe & Perez, 2014).

The observed lateralized reorganization has important implications for understanding motor control mechanisms in the presence of pain. Previous studies have shown that pain is often associated with functional deficits and reduced force-generation capacity (Becker et al., 2022; Hodges & Richardson, 1999; van Dieën et al., 2019). However, our results indicate that pain not only affects force steadiness, but also induces an asymmetric reorganization of muscle activation, reflecting a neurophysiological adaptation aimed at preserving functional stability despite the limitations imposed by pain (Arvanitidis et al., 2025).

Thus, even during submaximal contractions, acute low back pain significantly impacts force steadiness and variability. These changes are dynamic and affect not only the ability to generate force, but also its accuracy and consistency over time. Our findings suggest that experimentally induced acute low back pain promotes a reorganization of muscle activation, resulting in a lateralized

modulation of force steadiness control. This directly affects the neural mechanisms involved in motor control and the maintenance of postural stability.

### **Applicability**

The results of this study may contribute to the personalization of treatments for acute low back pain. Identifying changes in the recruitment and synchronization of motor units can help adapt rehabilitation programs, allowing healthcare professionals to create more effective strategies to restore strength stability and motor control. Understanding changes in firing rate provides a basis for targeted interventions focused on modulating motor recruitment and optimizing muscle function, helping to reduce the impact of pain and promoting faster recovery.

### **Limitations**

The limitations of this study include the cross-sectional nature of the experimental design, which does not allow the evolution of neural responses over time to be assessed, and the fact that the results were obtained in a controlled environment, which may limit generalization to natural conditions of acute low back pain. Furthermore, the evaluation was restricted to a single experimental pain model, which may not reflect the full complexity of acute and chronic low back pain in clinical populations.

### **Future research**

Future studies could investigate how the chronicity of pain modifies the adaptations observed in acute pain, as well as examining the temporal modulation and intensity of pain. It would also be relevant to explore compensatory motor recruitment strategies and postural adjustments to mitigate pain. The longitudinal analysis of therapeutic interventions and the impact of visual and proprioceptive feedback on neuromuscular recovery are also promising areas.

## **5. Conclusion**

This study demonstrated that experimentally induced acute low back pain triggers a lateralized and adaptive reorganization of motor control, as evidenced by alterations in the firing rate of the musculature contralateral to pain induction. The asymmetric modulation of motor unit recruitment reflects a compensatory mechanism of the central nervous system, aimed at preserving functional stability. These findings provide new insights into the neural dynamics of pain, emphasizing the complexity of motor control adaptations under acute low back pain conditions.

### **Conflict of interest statement**

The authors have no conflicts of interest to declare.

### **Data availability**

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

### **Informed consent statement**

Informed consent was obtained from all participants for the publication of identifiable information and images included in this manuscript.

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### **References**

- Agten, A., Stevens, S., Verbrugge, J., Eijnde, B. O., Timmermans, A., & Vandenabeele, F. (2020). The lumbar multifidus is characterised by larger type I muscle fibres compared to the erector spinae. *Anatomy & Cell Biology*, 53, 143 - 150.
- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2024). Does pain influence control of muscle force? A systematic review and meta-analysis. *European journal of pain (London, England)*. <https://doi.org/10.1002/ejp.4716>
- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2025). Does pain influence control of muscle force? A systematic review and meta-analysis. *Eur J Pain*, 29(2), e4716. <https://doi.org/10.1002/ejp.4716>
- Becker, K., Goethel, M., Fonseca, P., Vilas-Boas, J. P., & Ervilha, U. (2022). The Strategy of the Brain to Maintain the Force Production in Painful Contractions-A Motor Units Pool Reorganization. *Cells*, 11(20). <https://doi.org/10.3390/cells11203299>
- Becker, K., Goethel, M., Sousa, M., De, I., Batista, S., Vilas-Boas, J. P., Ervilha, U., & Paulo, J. (2024). The importance of analysing a single common window of a concentric and eccentric dynamic muscle contraction: unveiling the components of EMG data and motor unit pool. *Computer Methods in Biomechanics and Biomedical Engineering Imaging & Visualization*. <https://doi.org/10.1080/10255842.2024.2422900>
- Brumagne, S., Diers, M., Danneels, L., Moseley, G. L., & Hodges, P. W. (2019). Neuroplasticity of Sensorimotor Control in Low Back Pain. *The Journal of orthopaedic and sports physical therapy*, 49 6, 402-414.
- Canestri, R., Franco-Alvarenga, P. E., Brietzke, C., Vinícius, Í., Smith, S. A., Mauger, A. R., Goethel, M. F., & Pires, F. O. (2021). Effects of experimentally induced muscle pain on endurance performance: A proof-of-concept study assessing neurophysiological and perceptual responses. *Psychophysiology*, 58(6), e13810. <https://doi.org/10.1111/psyp.13810>
- Cheung, V. C. K., d'Avella, A., Tresch, M. C., & Bizzi, E. (2005). Central and Sensory Contributions to the Activation and Organization of Muscle Synergies during Natural Motor Behaviors. *The Journal of Neuroscience*, 25, 6419 - 6434.

- Corti, E. J., Marinovic, W., Nguyen, A. T., Gasson, N., & Loftus, A. M. (2022). Motor cortex excitability in chronic low back pain. *Experimental Brain Research*, 240, 3249 - 3257.
- De Luca, C. J., Adam, A., Wotiz, R., Gilmore, L. D., & Nawab, S. H. (2006). Decomposition of surface EMG signals. *Journal of neurophysiology*, 96(3), 1646-1657.
- De Luca, C. J., & Contessa, P. (2015). Biomechanical benefits of the Onion-Skin motor unit control scheme. *J Biomech*, 48(2), 195-203. <https://doi.org/10.1016/j.jbiomech.2014.12.003>
- Devecchi, V., Falla, D., Cabral, H., & Gallina, A. (2022). NEUROMUSCULAR ADAPTATIONS TO EXPERIMENTALLY INDUCED PAIN IN THE LUMBAR REGION: SYSTEMATIC REVIEW AND META-ANALYSIS. *Pain*. <https://doi.org/10.1097/j.pain.0000000000002819>
- Dieën, J. H. v., Reeves, N. P., Kawchuk, G. N., Kawchuk, G. N., Dillen, L. R. v., & Hodges, P. W. (2019a). Analysis of Motor Control in Patients With Low Back Pain: A Key to Personalized Care? *The Journal of orthopaedic and sports physical therapy*, 49 6, 380-388.
- Dieën, J. H. v., Reeves, N. P., Kawchuk, G. N., Kawchuk, G. N., Dillen, L. R. v., & Hodges, P. W. (2019b). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *The Journal of orthopaedic and sports physical therapy*, 49 6, 370-379.
- Farina, D., Arendt-Nielsen, L., Merletti, R., & Graven-Nielsen, T. (2004). Effect of Experimental Muscle Pain on Motor Unit Firing Rate and Conduction Velocity. *Journal of Neurophysiology*, 91(3), 1250-1259. <https://doi.org/10.1152/jn.00620.2003>
- Graven-Nielsen, T. (2006). Fundamentals of muscle pain, referred pain, and deep tissue hyperalgesia. *Scandinavian Journal of Rheumatology*, 35(sup122), 1-43. <https://doi.org/10.1080/03009740600865980>
- Heming, E. A., Cross, K. P., Takei, T., Cook, D. J., & Scott, S. H. (2019). Independent representations of ipsilateral and contralateral limbs in primary motor cortex. *eLife*, 8.
- Hermens, H., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures.

*Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 10, 361-374.  
[https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/10.1016/S1050-6411(00)00027-4)

- Hodges, P. W., & Richardson, C. A. (1999). Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. *Archives of Physical Medicine and Rehabilitation*, 80(9), 1005-1012.  
[https://doi.org/10.1016/S0003-9993\(99\)90052-7](https://doi.org/10.1016/S0003-9993(99)90052-7)
- Kellgren, J. H. (1938). Referred Pains from Muscle. *Br Med J*, 1(4023), 325-327.  
<https://doi.org/10.1136/bmj.1.4023.325>
- MacDonald, D. A., Lorimer Moseley, G., & Hodges, P. W. (2006). The lumbar multifidus: Does the evidence support clinical beliefs? *Manual Therapy*, 11(4), 254-263. <https://doi.org/https://doi.org/10.1016/j.math.2006.02.004>
- Martinez-Valdes, E., Negro, F., Farina, D., & Falla, D. (2020). Divergent response of low- versus high-threshold motor units to experimental muscle pain. *The Journal of Physiology*, 598.
- Meier, M. L., Vrana, A., & Schweinhardt, P. (2018). Low Back Pain: The Potential Contribution of Supraspinal Motor Control and Proprioception. *The Neuroscientist*, 25, 583 - 596.
- Nawab, S. H., Chang, S.-S., & De Luca, C. J. (2010). High-yield decomposition of surface EMG signals. *Clinical neurophysiology*, 121(10), 1602-1615.
- Porcaro, C., Mayhew, S. D., & Bagshaw, A. P. (2021). Role of the Ipsilateral Primary Motor Cortex in the Visuo-Motor Network During Fine Contractions and Accurate Performance. *International journal of neural systems*, 2150011.
- Raabe, M., & Chaudhari, A. (2018). Biomechanical consequences of running with deep core muscle weakness. *Journal of biomechanics*, 67, 98-105.  
<https://doi.org/10.1016/j.jbiomech.2017.11.037>
- Sarabon, N., Kozinc, Ä., & Perman, M. (2021). Establishing Reference Values for Isometric Knee Extension and Flexion Strength. *Frontiers in Physiology*, 12, Article 767941. <https://doi.org/10.3389/fphys.2021.767941>
- Schabrun, S. M., Christensen, S. W. M., Mrachacz-Kersting, N., & Graven-Nielsen, T. (2016). Motor Cortex Reorganization and Impaired Function in

- the Transition to Sustained Muscle Pain. *Cerebral cortex*, 26 5, 1878-1890.
- Schmid, S., Bangerter, C., Schweinhardt, P., & Meier, M. L. (2021). Identifying Motor Control Strategies and Their Role in Low Back Pain: A Cross-Disciplinary Approach Bridging Neurosciences With Movement Biomechanics. *Frontiers in Pain Research*, 2.
- Silva, M. F., Dias, J. M., Pereira, L. M., Mazuquin, B. F., Lindley, S., Richards, J., & Cardoso, J. R. (2017). Determination of the motor unit behavior of lumbar erector spinae muscles through surface EMG decomposition technology in healthy female subjects. *Muscle Nerve*, 55(1), 28-34. <https://doi.org/10.1002/mus.25184>
- Širca, A., & Kostevc, V. (1985). The fibre type composition of thoracic and lumbar paravertebral muscles in man. *Journal of anatomy*, 141, 131-137.
- Sterling, M., Jull, G., & Wright, A. (2001). The effect of musculoskeletal pain on motor activity and control. *J Pain*, 2(3), 135-145. <https://doi.org/10.1054/jpai.2001.19951>
- Tazoe, T., & Perez, M. A. (2014). Selective Activation of Ipsilateral Motor Pathways in Intact Humans. *The Journal of Neuroscience*, 34, 13924 - 13934.
- Tsao, H., Galea, M. P., & Hodges, P. W. (2008). Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain : a journal of neurology*, 131 Pt 8, 2161-2171.
- Valentin, G., & Maribo, T. (2014). Hand-held dynamometry fixated with a tripod is reliable for assessment of back extensor strength in women with osteoporosis. *Osteoporos Int*, 25(8), 2143-2149. <https://doi.org/10.1007/s00198-014-2743-0>
- van Dieën, J. H., Reeves, N. P., Kawchuk, G., van Dillen, L. R., & Hodges, P. W. (2019). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *J Orthop Sports Phys Ther*, 49(6), 370-379. <https://doi.org/10.2519/jospt.2019.7917>
- Wang, X., Luo, Z., Zhang, M., Zhao, W., Xie, S., Wong, S. F., Hu, H., & Li, L. (2023). The interaction between changes of muscle activation and cortical network dynamics during isometric elbow contraction: a sEMG and fNIRS

study [Original Research]. *Frontiers in Bioengineering and Biotechnology*, 11. <https://doi.org/10.3389/fbioe.2023.1176054>

Zhang, C., Li, Y., Zhang, Z., Fu, R., Yin, Y., Wang, H., Li, N., Feng, C., Yu, Q., Jiang, G., & Wang, C.-h. (2024). Motor Control Exercise Modulates the Neural Plasticity of the Default Mode Network in Patients with Chronic Low Back Pain. *Pain physician*, 27 1, E55-E64.

*Article*

### **From Central for Peripheral - Neural Adaptations in Force Steadiness During Acute Low Back Pain**

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## **Abstract**

This study investigated the effects of experimentally induced acute low back pain on force steadiness and cortical activity. Thirty-three healthy adults (25 men and 8 women) performed a sustained spinal extension task at 20% of their maximum voluntary contraction under two conditions: pre- and during pain (hypertonic injection) and pre- and post-isotonic injection into the lumbar region. Electromyography signals were recorded from the right and left longissimus muscles, and electroencephalography signals were collected from motor cortical areas. Spectral power in the alpha, beta, and gamma bands, as well as corticomuscular and cortico-cortical coherence, were analyzed. Results showed a significant reduction in force steadiness during pain. Beta and gamma spectral power increased in the prefrontal cortex, while alpha power decreased in the motor cortex. No significant changes were observed in corticomuscular or cortico-cortical coherence. However, increased electromyography entropy on the non-painful side suggested compensatory neuromuscular adaptations. Acute low back pain disrupts motor control by reducing force steadiness and altering cortical activity patterns. These findings highlight the need for therapeutic strategies addressing both neuromuscular and cortical adaptations to pain during motor tasks.

## **Perspective**

This study reveals how the central nervous system adapts motor control of force steadiness during acute low back pain, with distinct modulations in the pre-motor and motor regions. Results indicate that, despite the pain, the system adjusts its responses to maintain muscle stability, highlighting the complex interaction between the sensorimotor and cognitive systems. These findings offer new perspectives for the development of personalized therapeutic strategies in the management of low back pain.

**Keywords:** Acute induced low back pain, encephalography, submaximal extensor force, electromyography.

## 1. Introduction

Low back pain is one of the most prevalent and disabling musculoskeletal conditions, significantly affecting motor control, functional and emotional steadiness (Dieën et al., 2019; Jenkins et al., 2022; Parolini et al., 2023). Acute pain can alter neuromuscular coordination and strength steadiness, interfering with the interaction between the central nervous system and the muscles (Farina et al., 2003; Graven-Nielsen, 2006). However, the impact of these changes depends on the type of task performed (Dieën et al., 2019). Voluntary tasks, which require precise cortical control, are more susceptible to these interferences, while postural tasks, which involve a greater contribution from subcortical and spinal circuits, seem to be less affected (Hauck et al., 2007; Kristeva-Feige et al., 2002).

Force Steadiness is an essential marker of motor control, representing the ability to produce and maintain force consistently during sustained muscle contractions (Arvanitidis et al., 2024). This ability is relevant in submaximal tasks that require postural control, such as spinal extension, where variability in force production can compromise functionality and motor efficiency (Meier et al., 2018; Rohel et al., 2022). In pain conditions, such as acute low back pain, steadiness can be affected by alterations in the neural mechanisms that regulate motor control (Martinez-Valdes et al., 2020; Rohel et al., 2022). The available results suggest that acute pain induces changes in the recruitment of motor units and in the coupling between cortical and muscular activity, which can increase force variability and impair motor performance (Becker et al., 2022; Farina et al., 2003; Tucker & Hodges, 2010).

In the neurophysiology of motor control, the mechanisms that support force maintenance under painful conditions remain unexplored. Although the literature has advanced in understanding the effects of pain on voluntary motor tasks, most studies focus on actions that do not fully capture the neural demands of everyday postural tasks (Poortvliet et al., 2019; Poortvliet et al., 2015; Tsao et al., 2008;

Viseux et al., 2022; Xiao et al., 2023). Recent studies, such as the systematic review by Arvanitidis et al. (2024), show that force steadiness plays a fundamental role in neuromuscular adaptation in response to pain. The studies suggest that postural tasks may employ distinct neural strategies, with less dependence on cortical activation, which may attenuate the effects of pain compared to tasks that require high voluntary motor control (Brown, 2000; Mima & Hallett, 1999; Poortvliet et al., 2019).

Corticomuscular coherence (CMC) has been widely recognized as a robust and reliable approach to investigating the effects of acute low back pain on the neural mechanisms involved in motor control (Mehrkanoon et al., 2014; Mima & Hallett, 1999; Perez et al., 2006; Poortvliet et al., 2019). This coupling between cortical and muscular activity is modulated by several factors, including task demands, movement dynamics, and pain (Tsao et al., 2008; Viseux et al., 2022). The relationship between acute pain and the ability to maintain steadiness in isometric tasks remains insufficiently explored (Arvanitidis et al., 2024). This limits the understanding of the mechanisms by which the central nervous system adapts its motor behavior to preserve performance in the presence of pain. (Dieën et al., 2019; Jenkins et al., 2022; Xiao et al., 2023).

In order to deepen the understanding of these pain adaptations, our study integrates, in an innovative way, the junction of CMC and cortical modulation (CCC), intending to investigate the adaptations of the central and peripheral systems during the execution of submaximal tasks in strength steadiness. This approach will allow us to reveal how pain influences the neural strategies responsible for force control, challenging existing models of motor regulation in painful conditions and providing new insights into neuromechanical adaptation. We hypothesize that acute pain reduces force steadiness and weakens connectivity between cortical and muscular activity, reflecting impairments in neuromuscular coordination and the activation of compensatory strategies in postural tasks.

## **2. Methods**

### **2.3 Study design**

This is an experimental study that involved participants attending two visits, with a seven-day interval between them. The research protocol received ethical approval from the ethics committee of the Faculty of Sport of the University of Porto (CEFADE 28-2023). All objectives and methodologies were meticulously developed and executed following the guidelines established by the Declaration of Helsinki. Before participation, all volunteers provided informed consent by signing an Informed Consent Form, ensuring their understanding of the objectives and procedures of the study.

### **2.4 Participant**

Thirty-three individuals took part in this study. The inclusion criteria were defined as healthy individuals aged between 18 and 40, with no history of musculoskeletal diseases or recurrent pain in the past six weeks. Additionally, participants should not have used anti-inflammatory or analgesic medication in the 24 hours prior to the experiment. Exclusion criteria included individuals with a history of lumbar injury or surgery, existing chronic pathologies such as disc degeneration, osteoarthritis of the lumbar spine, facial paralysis, disc herniation, ankylosing spondylitis, and other conditions that could affect muscle function, as well as pregnant women. These criteria were established to ensure that the participants represented a homogeneous population, thereby minimizing the impact of confounding variables on the study results.

Among the subjects, aged between 18 and 40 years (average  $29.06 \pm 5.96$  years), 8 were women, with a height of  $164.66 \pm 6.3$  cm, an age of  $29.77 \pm 6.2$  years, and a body mass of  $65.14 \pm 6.20$  kg. The other 25 participants were men, with a height of  $175.20 \pm 5.5$  cm, an age of  $28.79 \pm 5.9$  years, and a body mass of  $80.00 \pm 9.3$  kg. Height and body mass were measured using a bioimpedance system (Inbody 230, InBody Co., Ltd., Korea).

### **2.3. Electromyography (EMG) signals**

EMG signals from the right and left longissimus muscles in the lower back, were collected using dEMG Galileo sensor (Delsys, Natick, MA, USA) electrodes, sizes 23 × 30 mm with four electrodes (5 mm of inter-electrode distance), 19 g of mass, and placed on dry skin. All the gears were plugged into an uninterruptible power supply with an external battery, to isolate all the possible noise from the net wire. The active site of the sensor placement was cleaned and shaved, and the electrode was placed in the middle of the muscle belly, according to the SENIAM recommendations (Hermens et al., 2000). Further, the quality of the signal was checked based on two principles: the minimal offset amplitude accepted was around 20uV and no more than 40uV, and the other caution was to check the signal-to-noise ratio, to ensure the quality of the signal collected. Galileo sensors were placed over the longissimus right and left muscles, oriented in the same direction of the muscle fibers. Data collection was performed using the Delsys® EMGWorks 4.8.0 software (Delsys, USA) with a sampling frequency of 2000 Hz.

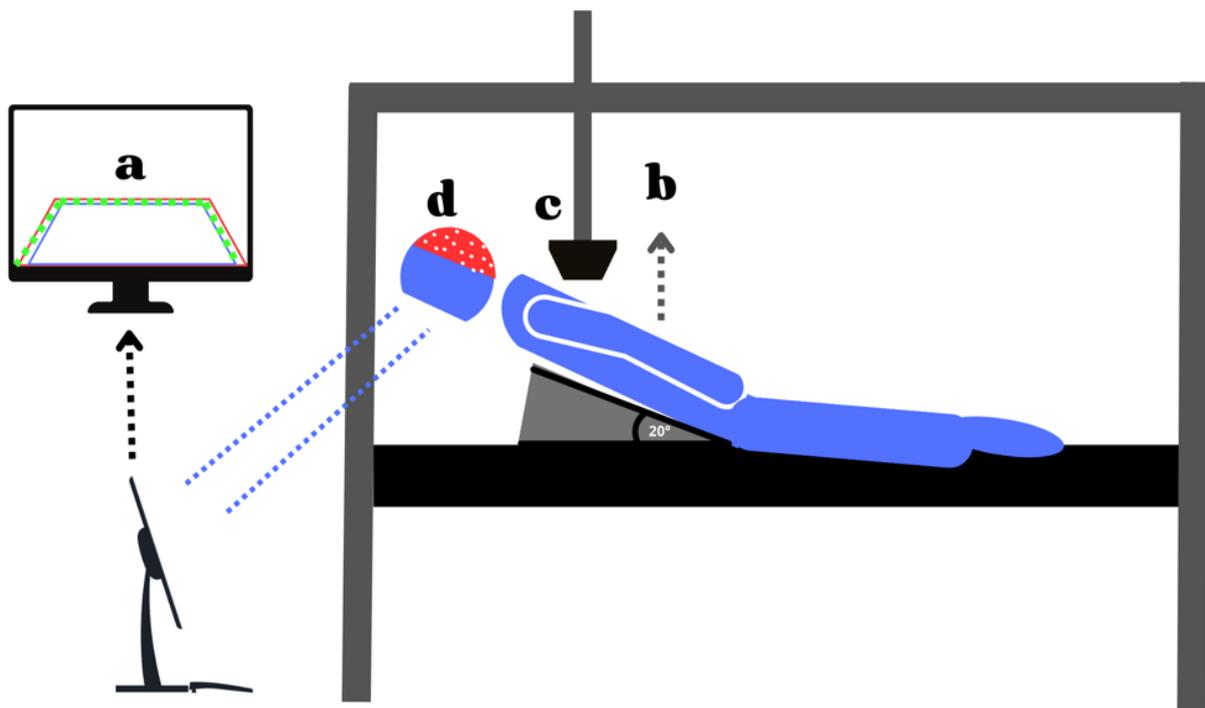
#### **2.4. Electroencephalography (EEG) signals**

All the recordings were acquired using Biopac Systems MP150 hardware with the following modules: MP150A.CE data acquisition unit, UIM100C universal interface module, and three EEG100C electroencephalogram amplifier modules. The software used for acquisition was AcqKnowledge 5.0. Participants wore a cap with a center on the vertex (point 0.0), determined by the International System 10/20 (Hermens et al., 2000; Herwig et al., 2003) The fit was regularly monitored to ensure the accuracy of the positioning. The impedances of the sensors were monitored using Netstation software (Electrical Geodesics, Inc., USA), considering a limit of 10 kΩ. Between tests, the impedances were checked and adjusted when necessary. EEG activity was amplified, sampled at 1000 Hz, and filtered with a bandpass filter (3-70 Hz). Subsequent analyses were carried out using MATLAB® R2024a software.

#### **2.5 Experimental Setup and Protocol**

### 2.5.1 Force test

Five familiarization repetitions of the maximal voluntary contraction (MVC) test and three repetitions of the submaximal (20% of maximal) test with a trapezoidal signal were performed (steadiness) (Arvanitidis et al., 2024; Valentin & Maribo, 2014). After a 2-minute rest period, one MVC repetition was conducted, followed by 1 minute of rest, and subsequently, one repetition of the trapezoidal force



signal was performed. The trapezoidal shape of the force curve is illustrated in Figure 1. Experimental Setup: (a) Screen display of the trapezoidal (20% of MVC), the trace is plotted as red line, and dashed green line is the real time signal performed by the volunteer using Delsys® EMG Works 4.8.0 software, (b) Volunteer performing trunk extension at 20°, (Delsys, Natick, MA, USA), (c) dynamometer, (d) EEG cap, and then a submaximal isometric contraction performed at 20% of the MVC.

On the second visit, after 7 days, the same participant performed the same procedure as in the first visit. Familiarization with the tests was carried out with all volunteers. The dynamometer was attached to a metal structure mounted on a treatment table to keep it stable in both tests. For the performance of trunk

extensor muscle strength tests, volunteers were positioned in prone. The dynamometer was positioned in the midline between the two upper angles of the scapulae, and volunteers were asked to perform spinal extension, maintaining isometry for 30 seconds. Figure 1 shows the experimental setup.

### *2.5.2 Experimentally induced acute low back pain*

Experimental acute low back pain and a control condition were obtained, respectively, by intramuscular injections of hypertonic and isotonic saline solution, administered 7 days apart (Kellgren, 1938). During the injections, the participants were positioned in the prone position on a wedge with a 20° incline, as illustrated in Figure 1. The inclination was measured in the cephalocaudal direction, while the spine was extended, which helped to promote muscle relaxation. The study employed a randomized crossover design, where each participant received a single 2.5 mL dose (Canestri et al., 2021) of either hypertonic saline solution (6.0%) to induce pain, or isotonic saline solution (0.9%) (Graven-Nielsen, 2006), as a placebo, ensuring the test was conducted during the pain phase. The injections were administered in the intervertebral space between L3 and L4, at the level of the spinous process, located approximately 2 to 3 cm from the midline. After cleaning the area with 70% alcohol, the solution was injected into the dominant side of the body using a 25 × 28 mm needle, at a depth of 30 mm from the skin surface. The participants were assessed in three different conditions: baseline, experimentally induced pain (hypertonic solution), and control condition (isotonic solution) while performing a spinal extension task in the prone position.

## **2.6 Data Analysis**

### Preprocessing Force Signal

The force analysis was performed from the extracted and normalized data. Ten seconds of the plateau (stable phase) of the trapezoidal signal were analyzed during the sustained submaximal test. The period analyzed corresponded to the force stabilization phase, allowing an accurate assessment of sustained strength.

## Preprocessing Electromyography Signal

The signal was digitally filtered using a fourth-order, zero-phase-lag Butterworth filter with a 10 Hz low-pass cutoff frequency. Velocity and acceleration were derived through differentiation. EMG signals were Butterworth band-pass filtered between 20 and 400 Hz and low pass filtered at 50 Hz. Peak and integral EMG data were normalized to the maximum voluntary isometric contraction. Parameter extraction from individual trials followed a standardized sequence (Vonsevych et al., 2019):

- a. Variance (VAR) and Mean Absolute Deviation (MAD) are statistical measures that assess data dispersion relative to the mean. Their calculations followed the following equation:

$$VAR = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2$$

- b. MAD was calculated by the following equation:

$$MAD = \frac{1}{N} \sum_{k=1}^N |x_i - \bar{x}|$$

- c. EMG entropy was computed using the sample entropy (SampEn) algorithm, as defined by the following equation (Bank et al., 2013):

$$SampEn = -\log\left(\frac{\sum Ai}{\sum Bi}\right) = -\log(A / B)$$

- d. Full-wave rectification was applied to the EMG data, transforming all negative values into positive equivalents to generate a unidirectional representation of signal intensity.

- e. The Integral of EMG (Int), quantifying the accumulated EMG signal, was computed using the trapezoidal rule, which approximates the area under the curve, providing a measure of the signal's overall magnitude (Farina et al.):

$$Int = \int_a^b f(x)dx \approx (b - a) \frac{f(a)+f(b)}{2}$$

- f. Peak EMG was considered the maximum value of the filtered and rectified amplitude measured for the sample.

### Coherence Analysis

Coherence analysis was performed using the discrete Fourier transform applied to successive segments of unprocessed EEG and EMG data, covering the entire frequency range. A Hanning window filter was applied to 1024 ms windows for spectral smoothing. Spectre Power (SP) was calculated using the following formula:

$$SP_c(f) = \frac{1}{n} \sum_{i=1}^n c_i(f)c_i^*(f)$$

Cortico-cortical coherence (CCC) was calculated between the CZ and Fp1 regions of the EEG signals recorded from the prefrontal and central areas of the motor cortex, as illustrated in Figure 2 (Homan et al., 1987; Poortvliet et al., 2015; Steinmetz et al., 1989). The analyses were performed on the two regions, Fp1 and Cz.

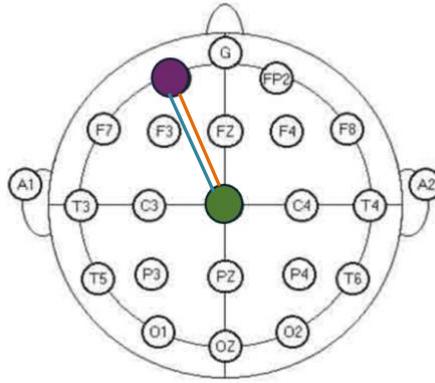


Figure 2: Measuring System EEG, 10-20 (Herwig et al., 2003)

The muscle-cortical coherence (CMC) was calculated between the unrectified EMG signals from the trunk extensor muscles in the lumbar region, specifically the right and left longissimus, and the EEG signals recorded from two electrodes located in the cortical motor area (Cz) and the premotor cortex (Fp1). The linear association between the cortical-cortical coherence (CCC) recordings between Fp1 and Cz, and between the EMG and EEG recordings (CMC) from the lumbar extensor muscles, at the selected cortical electrode sites, in the 13 to 45 Hz frequency range (including alpha, beta, and gamma bands), was assessed through coherence using the following equations (Halliday et al., 1995):

$$\text{CMC or CCC}_{c1,c2}(f) = \frac{|S_{c1,c2}(f)|^2}{|SP_{c1}(f)| |SP_{c2}(f)|}$$

where,

$$S_{c1,c2}(f) = \frac{1}{n} \sum_{i=1}^n C_{1i}(f) C_{2i}^*(f)$$

The cross-spectrum between an EEG signal (C1) and a second EEG signal (CCC) or an EMG signal (CMC) as C2 at frequency  $f$  was calculated. Additionally,  $i$  represents the segment number, with a total of  $n$  segments, and the symbol  $*$  denotes the complex conjugate. This calculation returns a real value between 0

(no coherence) and 1 (maximum coherence). The confidence level was set at 95%. Coherence was considered significantly different from zero when the resulting value exceeded the desired confidence level (0.05) (Rosenberg et al., 1989).

The CCC and CMC were quantified as the area under the coherence curve, separately for the alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-45 Hz) frequency bands. This calculation was performed for each electrode combination (Cz and Fp1) and for each of the two trunk extensor muscles. The EEG power for both electrode locations was quantified as the area under the spectral power curve, also separately for the same frequency bands.

## **2.7 Statistical analysis**

A descriptive analysis of electromyography (EMG) variables was performed, including measurements of variance, MAD, integral, entropy, and peak for the right and left longissimus muscles under both isotonic and hypertonic conditions. Additionally, the alpha, beta, and gamma bands of EEG activity were analyzed at the FP1 and CZ positions under the same experimental conditions. Initially, the Shapiro-Wilk normality test was conducted to assess the data distribution.

The Wilcoxon signed-rank test was applied to all variables under isotonic and hypertonic conditions, comparing the pre- and post-condition measurements for each muscle group and each EEG band. The G\*Power 3.1.7 software (University of Kiel, Kiel, Germany) was used to determine the effect size and statistical power of the analysis, using Cohen's d criteria (small: > 0.2; moderate: > 0.50; large: > 0.80) (Cohen, 1988). All tests were performed using SPSS Statistics software (IBM Corporation, Version 27), with a significance level set at  $\alpha = 0.05$ . Data are presented as median and interquartile range (IQ) in both text and figures, once data did not follow a normal distribution.

## **3.0 Results**

Force steadiness showed a median of 0.65 (IQ 0.51) in the pre-hypertonic condition and 0.55 (IQ 0.72) during acute induced low back pain in the

submaximal task, with  $p < 0.011$ , suggesting a reduction in force steadiness control during low back pain (Figure 3). In contrast, in the isotonic protocol, force steadiness showed no significant differences, in force steadiness control following the isotonic protocol.

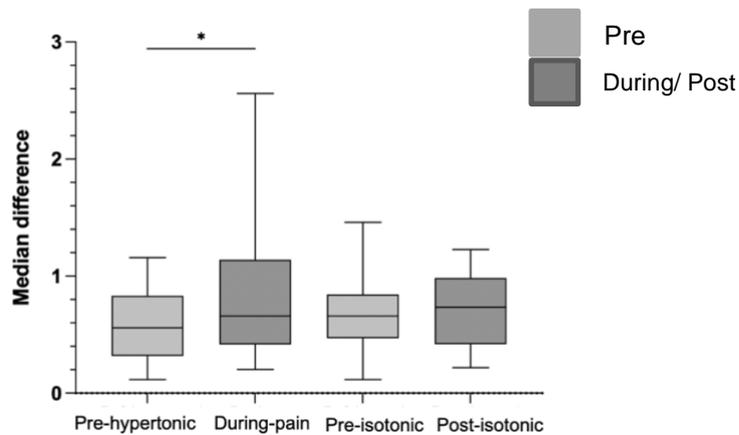


Figure 3: Graph of the median difference in force steadiness, pre-hypertonic, during pain, pre- and post-isotonic.

Legend: \* $<0.05$ .

### Electromyography

In the electromyography analysis, the variance, MAD, integral and peak of the right and left longissimus muscles did not show statistically significant differences between the pre- and post-isotonic condition. Similarly, these variables did not differ between the pre-hypertonic conditions and during acute induced low back pain for both the right and left longissimus muscles. However, only entropy showed a statistically significant difference in the hypertonic condition during pain in the left longissimus (Figure 4), pre-hypertonic (1.09 (IQ 0.28-1.09)) and during low back pain (1.13 (IQ 0.21-1.09) with  $p$ -value = 0.032), suggesting changes in the complexity of the EMG signal associated with pain.

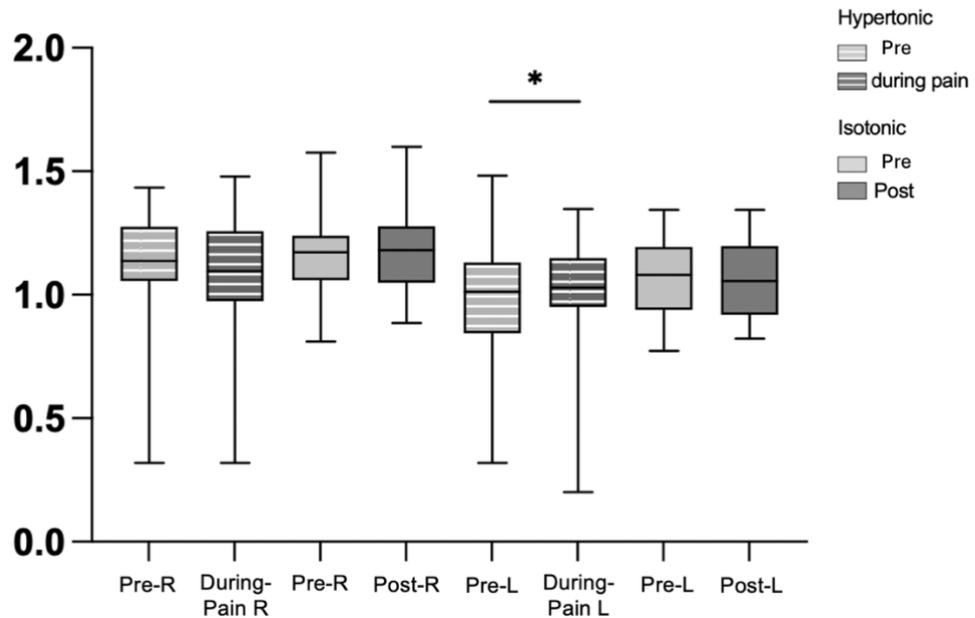


Figure 4: Graph of entropy in force steadiness, pre-hypertonic, during pain, pre- and post-isotonic, in the right and left longissimus muscles.

Legend: \* $<0.05$ . right longissimus muscle (R), left longissimus muscle (L).

### Cortical-cortical coherence

In the hypertonic condition before and during pain, as well as in the pre- and post-isotonic condition, there were no significant changes in cortical coherence between FP1 and CZ in the three frequency bands analyzed on both sides (right and left longissimus) with  $p > 0.05$ , with no substantial changes in cortical activity in these conditions.

### Corticomuscular coherence

The  $p$ -values for the CMC analysis in the isotonic and hypertonic conditions in the right and left longissimus muscles were analyzed in different frequency bands (alpha, beta and gamma) in two specific regions: FP1 and CZ, for both the right and left of the longissimus muscle (Figure 5). On both sides, right and left in FP1, no significant differences were observed between the hypertonic conditions, in the alpha ( $p = 0.40$ ), beta ( $p = 0.45$ ) and gamma ( $p = 0.53$ ), as well as in the pre- and post-isotonic conditions (alpha,  $p = 0.86$ ; beta,  $p = 0.69$ ; gamma,  $p = 0.79$  on the right side and alpha,  $p = 0.86$ ; beta,  $p = 0.85$ ; gamma,  $p = 0.83$  on the left

side), maintaining CMC during the task. At Cz, there were significant differences only in the right longissimus muscle in the beta ( $p = 0.018$ ) and gamma ( $p = 0.07$ ) bands, during the induced pain.

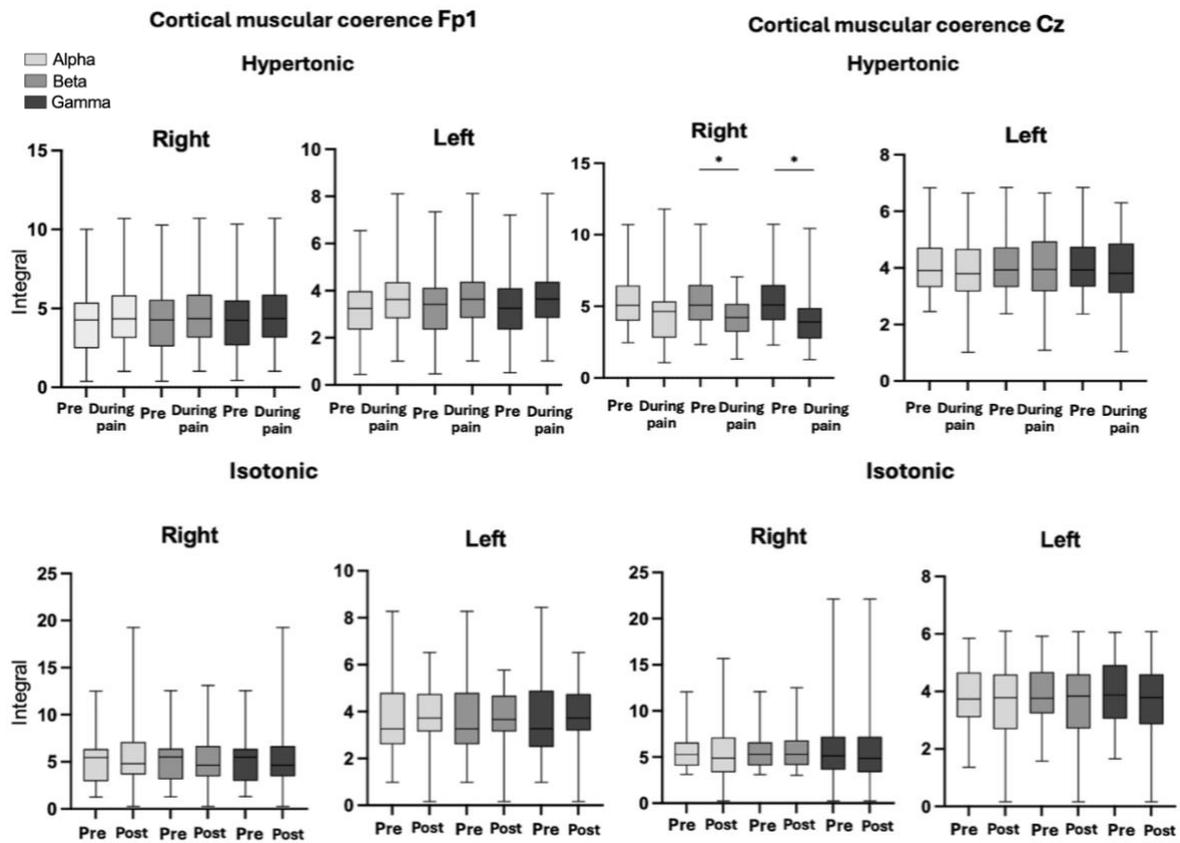


Figure 5: Graph of CMC, in conditions hypertonic (pre- and during pain), pre- and post-isotonic, in the right and left longissimus muscles, in FP1 and Cz regions in band Alfa, Beta, and Gamma. Legend: \* $<0.05$ . Band Alfa, Beta and Gamma.

## EEG Power Spectra

The results indicate variations in alpha, beta, and gamma frequency bands in the FP1 and Cz regions across the different experimental conditions, as presented in Table 1. In the FP1 region, alpha band power significantly increased during pain compared to the pre-hypertonic condition, followed by a reduction in the pre- and post-isotonic conditions. Beta band power also showed a substantial increase during pain, followed by a sharp decrease in the post-isotonic condition. Gamma band power exhibited a decreasing trend across conditions, reaching its lowest

values in the post-isotonic condition.

VARIABLE	Pre-hypertonic	During of pain	Pre-isotonic	Post-isotonic
	<b>FP1</b>			
ALFA*	0.04e-3 (IQ- 0.09e-3)	5,87 (IQ- 1.0)	1.71 (IQ-0,08)	1.87 (IQ- 0, 11E-6)
BETA*	0,07e-3 (IQ- 0,21e-4)	8,23 (IQ- 1.0)	1.35 (IQ- 0.02)	7.86E-09 (IQ- 1.10e-10)
GAMA*	7.88e-06 (IQ-1.00e-06)	2,12e-08 (IQ- 0.1e-7)	1.82e-09 (IQ-9.4e-11)	6.23e-12 (IQ-1.23e-13)
	<b>Cz</b>			
ALFA*	6.78e-07 (IQ- 1.00e-07)	3.21e-08 (IQ- 0.1e-8)	7.42e-09 (IQ- 4.49e-10)	2.31e-10 (IQ- 1.23e-11)
BETA*	1.23e-06 (IQ- 4.8E-10)	2.98e-11 (IQ- 6.66e-12)	1.26e-11 (IQ- 6.03e-13)	9.85e-10 (IQ- 1.22e-11)
GAMA**	3.01e-09 (IQ- 1.01e-12)	3.34e-09 (IQ-4.69e-10)	3.80e-11 (IQ- 1.47e-11)	2.04e-12 (IQ- 9e-15)

*Table 1:* The table shows the inhibition or excitation of the bands in the Fp1 and Cz regions, in the alpha, beta, and gamma bands, in the pre-hypertonic, during pain, and pre- and post-isotonic conditions. Legend: median (IQ - interquartile range), \*\*p<0.01, \*p<0.05, in both conditions: hypertonic before and during pain, and pre- and post-isotonic.

In the Cz region, alpha band power progressively decreased across conditions, reaching its lowest value in the post-isotonic condition. Beta band power showed a marked reduction during pain, followed by a slight recovery in the post-isotonic condition. Gamma band power remained relatively stable during pain but decreased significantly in the post-isotonic condition. These findings indicate changes in cortical activity across the different experimental phases.

## **4. Discussion**

This study offers a new perspective on the neurophysiological adaptations underlying motor control during experimentally induced acute low back pain, with a focus on force steadiness. Pain significantly compromised motor accuracy, increasing force production variability and suggesting an adverse impact on the neural regulation of fine motor skills (Arvanitidis et al., 2024). The significant reduction in CMC in Cz during pain indicates nociceptive modulation of the functional connectivity between the motor cortex and the muscles involved in the task (Barnes et al., 2021; Liu et al., 2019; Mima & Hallett, 1999; Poortvliet et al., 2019).

At the same time, EEG spectral analysis revealed cortical reorganization patterns, with increased alpha and beta band activity in FP1, suggesting compensatory recruitment of cortical networks associated with sensorimotor integration and fine motor control. Concurrently, the suppression of alpha band power in Cz reinforces a specific neural adaptation to nociceptive processing. These findings highlight a highly dynamic interaction between motor regulation and nociceptive processing, challenging classical models of voluntary motor control and emphasizing the need for approaches that integrate the influence of nociception on movement biomechanics.

### **EMG entropy**

The changes in the entropy of the electromyographic signal indicate neurophysiological adaptations in motor control, especially in the left longissimus muscle (since this is the side contralateral to the injection) during pain, suggesting a process of cortical compensation in motor control on this side. This increase in entropy means an increase in signal complexity, due to greater heterogeneity of patterns. These changes may reflect a functional reorganization, in which the brain seeks to improve neurofunctional efficiency and postural stability in response to the painful stress experienced on the affected side. (Tucker & Hodges, 2010; Zurcher et al., 2007). These results are consistent with the idea that pain activates compensatory mechanisms, which include both cortical recruitment of motor areas and areas associated with executive control (Mouraux

& Plaghki, 2004; Poortvliet et al., 2015). This can be interpreted as an attempt by the neuromuscular system to compensate for pain or to respond to changes in the motor demands of the submaximal task (Smith et al., 2021). These changes are associated with the nervous system's adaptation to pain, with implications for motor control and force steadiness, possibly leading to increased inefficiency in muscle control during task execution (Zurcher et al., 2007).

### **Modulation of CMC in steadiness During low back Pain**

Analyzing the CMC associated with the alpha, beta, and gamma frequency bands reveals how the cortical system adapts to a demanding task, maintaining submaximal contraction in the force steadiness. The reduction in CMC in the beta and gamma band, in the motor cortex, indicates a dysfunction in the transmission of information between the motor cortex and the muscles, possibly due to the increased cognitive load involved in the task affected by pain (Poortvliet et al., 2019; Poortvliet et al., 2015; Schulz et al., 2011). The fact that the right longissimus muscle (where pain was induced) showed a decrease in CMC, particularly in the beta and gamma bands, while the left side showed an increase in entropy, reveals a lateralized cortical response to pain. This decrease in CMC reflects a challenge in motor coordination, which suggests that pain not only affects motor control but also overloads the cognitive processes needed to sustain the motor task (Tucker & Hodges, 2010; Viseux et al., 2022; Xiao et al., 2023).

### **Comparison of CCC pain and placebo**

According to Poortvliet et al. (2019), CCC is particularly sensitive to variations in the type of motor control required by a given task. In our study, the submaximal task may not have been sufficient to robustly activate the cortical networks responsible for coherence at specific frequencies. Studies suggest that during submaximal efforts, cognitive and neuromuscular demands do not reach the intensity necessary to elicit a significant increase in CCC, particularly in the alpha, beta, and gamma bands (Gross et al., 2007; Liu et al., 2019; Mima & Hallett, 1999; Poortvliet et al., 2015). From a similar perspective Schulz et al., (2011) indicate that under painful conditions, the brain prioritizes motor protection

mechanisms by redistributing control to subcortical networks or altering cortical activation patterns, thereby limiting detectable changes in CCC (Barnes et al., 2021; Mehrkanon et al., 2014). The overall lack of statistical significance across the investigated conditions may reflect the complex interaction between task type, the nature of experimentally induced pain, and the adaptive dynamics of cortical motor control, as suggested by the current literature (Liu et al., 2019; Mima & Hallett, 1999; Poortvliet et al., 2015).

### **Low back Pain Adaptations in EEG**

One of the interesting findings is the differentiated modulation of cortical activity in the premotor (FP1) and motor (Cz) regions, highlighting the multifaceted neural strategies employed to maintain force steadiness under painful conditions. Increased alpha and beta activity in FP1 suggests greater involvement of the prefrontal cortex in sensory-motor integration, possibly reflecting the cognitive demand required to regulate movement in the face of nociceptive interference (Dieën et al., 2019; Franciotti et al., 2009; Gross et al., 2007; Hauck et al., 2007). At the same time, the suppression of alpha and beta oscillations at Cz, accompanied by increased gamma activity, indicates intracortical inhibition and increased motor excitability, respectively, of the adaptive mechanism that probably facilitates force maintenance in the presence of pain (Gross et al., 2007; Hauck et al., 2007). These findings corroborate recent models suggesting that the motor cortex undergoes task-specific reorganization when faced with nociceptive stimuli, to guarantee functional stability even in adverse conditions (Chowdhury et al., 2022; Poortvliet et al., 2019).

Essentially, our findings challenge traditional conceptions about the impact of pain on motor performance, highlighting its influence on neuromuscular modulation and adaptation. Rather than causing a 'simple drop' in neuromuscular function, acute low back pain appears to trigger a remodeling of motor control, characterized by targeted cortical adaptations and a strategic redistribution of neuromuscular resources (Ecsy et al., 2018). This is evidenced by the modulation of CMC, where changes in connectivity between the motor cortex and the lumbar muscles suggest a refined compensatory mechanism that enables force

steadiness despite sensory disturbance (Tan et al., 2019). This pattern of cortical modulation that we found aligns with one of the neurophysiological biomarkers described by (Chowdhury et al., 2022) as part of the cortical signature predictive of individual pain sensitivity, which reinforces the importance of alpha oscillation dynamics in regulating motor behavior in pain contexts (Dieën et al., 2019; Franciotti et al., 2009).

The contralateral response observed, with differential adaptations between muscle groups (right and left longissimus), highlights the specificity and complexity of these regulatory processes (Chowdhury et al., 2022; Gross et al., 2007; Poortvliet et al., 2019). These neurophysiological adaptations go beyond the immediate motor response and have significant implications for clinical practice. The nervous system's ability to dynamically reconfigure its control strategies in response to acute pain suggests that rehabilitation approaches must overcome simplistic models of motor inhibition. Instead, interventions should take advantage of this adaptive potential, promoting neuromuscular strategies that optimize strength stability and posture. Furthermore, by identifying individualized cortical signatures of pain-related motor adaptation, as highlighted in recent literature (Chowdhury et al., 2025; Chowdhury et al., 2022), it becomes possible to improve therapeutic protocols by tailoring interventions to target specific neural mechanisms involved in movement efficiency in painful conditions.

Lastly, this study elevates our understanding of the relationship between pain, strength stability, and neural control, in how we conceive motor adaptation in acute musculoskeletal pain. The evidence presented not only fills a critical gap in the literature but also paves the way for innovative therapeutic strategies that exploit neuroplasticity to mitigate the functional impact of low back pain. The treatment of acute low back pain, based on neurophysiological adaptations, can promote recovery and postural stability of the lumbar muscles and, when combined with biopsychosocial factors (Parolini et al., 2023), can decrease the risk of recurrence of low back pain (Baliki et al., 2012; Jenkins et al., 2022). These findings represent a significant advance in the field, reinforcing the urgency of integrating strength stability assessments into both research and clinical practice,

unlocking new opportunities for optimizing motor function in individuals facing acute pain.

### **Limitations**

Although this study has made important contributions to understanding the neurophysiological adaptations in motor control during experimentally induced acute low back pain, as reflected in force steadiness, some limitations should be acknowledged. The sample consisted of only healthy individuals, which may limit the results for populations with chronic low back pain or other clinical conditions. Additionally, the lack of a longitudinal assessment prevents the analysis of the persistence or adaptation of cortical patterns over time, limiting the understanding of pain dynamics and the evolution of cortical adaptation mechanisms.

### **Future research**

Future studies involving more diverse samples and assessing adaptations over time could expand the applicability of the findings and provide a more comprehensive understanding of cortical modulation in low back pain and force steadiness.

## **5. Conclusion**

This study provided insights into the neurophysiological adaptations in force steadiness control during acute low back pain, focusing on changes in cortical modulation in the pre-motor and motor regions. The research reveals how the central nervous system adjusts its responses to maintain muscle stability and movement execution despite pain, indicating a complex interaction between the sensorimotor and cognitive systems. Thus, we offer a new understanding of how low back pain affects motor control ability for the preservation of muscle function, essential for postural stability.

### **Conflict of interest statement**

The authors have no conflicts of interest to declare.

### **Data availability**

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

### **Informed consent statement**

Informed consent was obtained from all participants for the publication of identifiable information and images included in this manuscript.

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### **Reference**

- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2024). Does pain influence control of muscle force? A systematic review and meta-analysis. *European journal of pain (London, England)*. <https://doi.org/10.1002/ejp.4716>
- Baliki, M. N., Petre, B., Torbey, S., Herrmann, K. M., Huang, L., Schnitzer, T. J., Fields, H. L., & Apkarian, A. V. (2012). Corticostriatal functional connectivity predicts transition to chronic back pain. *Nat Neurosci*, *15*(8), 1117-1119. <https://doi.org/10.1038/nn.3153>
- Bank, P. J., Peper, C. E., Marinus, J., Beek, P. J., & van Hilten, J. J. (2013). Motor consequences of experimentally induced limb pain: a systematic review.

*Eur J Pain*, 17(2), 145-157. <https://doi.org/10.1002/j.1532-2149.2012.00186.x>

- Barnes, K., McNair, N., Harris, J., Sharpe, L., & Colagiuri, B. (2021). In anticipation of pain: expectancy modulates corticospinal excitability, autonomic response, and pain perception. *Pain*, 162 8, 2287-2296. <https://doi.org/10.1097/J.PAIN.0000000000002222>
- Becker, K., Goethel, M., Fonseca, P., Vilas-Boas, J. P., & Ervilha, U. (2022). The Strategy of the Brain to Maintain the Force Production in Painful Contractions-A Motor Units Pool Reorganization. *Cells*, 11(20). <https://doi.org/10.3390/cells11203299>
- Brown, P. (2000). Cortical drives to human muscle: the Piper and related rhythms. *Progress in neurobiology*, 60(1), 97-108.
- Canestri, R., Franco-Alvarenga, P. E., Brietzke, C., Vinícius, Í., Smith, S. A., Mauger, A. R., Goethel, M. F., & Pires, F. O. (2021). Effects of experimentally induced muscle pain on endurance performance: A proof-of-concept study assessing neurophysiological and perceptual responses. *Psychophysiology*, 58(6), e13810. <https://doi.org/10.1111/psyp.13810>
- Chowdhury, N. S., Bi, C., Furman, A. J., Chiang, A. K. I., Skippen, P., Si, E., Millard, S. K., Margerison, S. M., Spies, D., Keaser, M. L., Da Silva, J. T., Chen, S., Schabrun, S. M., & Seminowicz, D. A. (2025). Predicting Individual Pain Sensitivity Using a Novel Cortical Biomarker Signature. *JAMA Neurology*. <https://doi.org/10.1001/jamaneurol.2024.4857>
- Chowdhury, N. S., Chang, W. J., Millard, S. K., Skippen, P., Bilska, K., Seminowicz, D. A., & Schabrun, S. M. (2022). The Effect of Acute and Sustained Pain on Corticomotor Excitability: A Systematic Review and Meta-Analysis of Group and Individual Level Data. *J Pain*, 23(10), 1680-1696. <https://doi.org/10.1016/j.jpain.2022.04.012>
- Dieën, J., Reeves, N., Kawchuk, G., Kawchuk, G., Dillen, L., & Hodges, P. (2019). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *The Journal of orthopaedic and sports physical therapy*, 49 6, 370-379. <https://doi.org/10.2519/jospt.2019.7917>

- Ecsy, K., Brown, C., & Jones, A. (2018). Cortical nociceptive processes are reduced by visual alpha-band entrainment in the human brain. *European Journal of Pain*, 22. <https://doi.org/10.1002/ejp.1136>
- Farina, S., Tinazzi, M., Le Pera, D., & Valeriani, M. (2003). Pain-related modulation of the human motor cortex. *Neurol Res*, 25(2), 130-142. <https://doi.org/10.1179/016164103101201283>
- Franciotti, R., Ciancetta, L., Della Penna, S., Belardinelli, P., Pizzella, V., & Romani, G. L. (2009). Modulation of alpha oscillations in insular cortex reflects the threat of painful stimuli. *NeuroImage*, 46(4), 1082-1090. <https://doi.org/https://doi.org/10.1016/j.neuroimage.2009.03.034>
- Graven-Nielsen, T. (2006). Fundamentals of muscle pain, referred pain, and deep tissue hyperalgesia. *Scandinavian Journal of Rheumatology*, 35(sup122), 1-43. <https://doi.org/10.1080/03009740600865980>
- Gross, J., Schnitzler, A., Timmermann, L., & Ploner, M. (2007). Gamma oscillations in human primary somatosensory cortex reflect pain perception. *PLoS Biol*, 5(5), e133. <https://doi.org/10.1371/journal.pbio.0050133>
- Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P., Conway, B. A., & Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data--theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Prog Biophys Mol Biol*, 64(2-3), 237-278. [https://doi.org/10.1016/s0079-6107\(96\)00009-0](https://doi.org/10.1016/s0079-6107(96)00009-0)
- Hauck, M., Lorenz, J., & Engel, A. K. (2007). Attention to painful stimulation enhances gamma-band activity and synchronization in human sensorimotor cortex. *J Neurosci*, 27(35), 9270-9277. <https://doi.org/10.1523/jneurosci.2283-07.2007>
- Hermens, H., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 10, 361-374. [https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/10.1016/S1050-6411(00)00027-4)

- Herwig, U., Satrapi, P., & Schönfeldt-Lecuona, C. (2003). Using the international 10-20 EEG system for positioning of transcranial magnetic stimulation. *Brain Topogr*, 16(2), 95-99. <https://doi.org/10.1023/b:brat.0000006333.93597.9d>
- Homan, R. W., Herman, J., & Purdy, P. (1987). Cerebral location of international 10-20 system electrode placement. *Electroencephalogr Clin Neurophysiol*, 66(4), 376-382. [https://doi.org/10.1016/0013-4694\(87\)90206-9](https://doi.org/10.1016/0013-4694(87)90206-9)
- Jenkins, L. C., Chang, W. J., Buscemi, V., Liston, M., Skippen, P., Cashin, A. G., McAuley, J. H., & Schabrun, S. M. (2022). Low Somatosensory Cortex Excitability in the Acute Stage of Low Back Pain Causes Chronic Pain. *J Pain*, 23(2), 289-304. <https://doi.org/10.1016/j.jpain.2021.08.003>
- Kellgren, J. H. (1938). Referred Pains from Muscle. *Br Med J*, 1(4023), 325-327. <https://doi.org/10.1136/bmj.1.4023.325>
- Kristeva-Feige, R., Fritsch, C., Timmer, J., & Lücking, C. H. (2002). Effects of attention and precision of exerted force on beta range EEG-EMG synchronization during a maintained motor contraction task. *Clin Neurophysiol*, 113(1), 124-131. [https://doi.org/10.1016/s1388-2457\(01\)00722-2](https://doi.org/10.1016/s1388-2457(01)00722-2)
- Liu, J., Sheng, Y., & Liu, H. (2019). Corticomuscular Coherence and Its Applications: A Review. *Front Hum Neurosci*, 13, 100. <https://doi.org/10.3389/fnhum.2019.00100>
- Martinez-Valdes, E., Negro, F., Farina, D., & Falla, D. (2020). Divergent response of low- versus high-threshold motor units to experimental muscle pain. *The Journal of physiology*, 598. <https://doi.org/10.1113/JP279225>
- Mehrkanoon, S., Breakspear, M., & Boonstra, T. (2014). The reorganization of corticomuscular coherence during a transition between sensorimotor states. *NeuroImage*, 100, 692-702. <https://doi.org/10.1016/j.neuroimage.2014.06.050>
- Meier, M., Vrana, A., & Schweinhardt, P. (2018). Low Back Pain: The Potential Contribution of Supraspinal Motor Control and Proprioception. *The Neuroscientist*, 25, 583-596. <https://doi.org/10.1177/1073858418809074>

- Mima, T., & Hallett, M. (1999). Corticomuscular coherence: a review. *J Clin Neurophysiol*, 16(6), 501-511. <https://doi.org/10.1097/00004691-199911000-00002>
- Mouraux, A., & Plaghki, L. (2004). Single-trial detection of human brain responses evoked by laser activation of Adelta-nociceptors using the wavelet transform of EEG epochs. *Neurosci Lett*, 361(1-3), 241-244. <https://doi.org/10.1016/j.neulet.2003.12.110>
- Parolini, F., Goethel, M., Becker, K., Fernandes, C., Fernandes, R. J., Ervilha, U. F., Santos, R., & Vilas-Boas, J. P. (2023). Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain. *Biomedicines*, 11(7), 2042. <https://www.mdpi.com/2227-9059/11/7/2042>
- Perez, M. A., Lundbye-Jensen, J., & Nielsen, J. B. (2006). Changes in corticospinal drive to spinal motoneurons following visuo-motor skill learning in humans. *The Journal of physiology*, 573(3), 843-855.
- Poortvliet, P. C., Tucker, K. J., Finnigan, S., Scott, D., & Hodges, P. W. (2019). Experimental Pain Decreases Corticomuscular Coherence in a Force- But Not a Position-Control Task. *The Journal of Pain*, 20(2), 192-200. <https://doi.org/https://doi.org/10.1016/j.jpain.2018.08.012>
- Poortvliet, P. C., Tucker, K. J., Finnigan, S., Scott, D., Sowman, P., & Hodges, P. W. (2015). Cortical activity differs between position- and force-control knee extension tasks. *Experimental Brain Research*, 233(12), 3447-3457. <https://doi.org/10.1007/s00221-015-4404-8>
- Rohel, A., Desmons, M., Léonard, G., Desgagnés, A., Da Silva, R., Simoneau, M., Mercier, C., & Massé-Alarie, H. (2022). The influence of experimental low back pain on neural networks involved in the control of lumbar erector spinae muscles. *Journal of neurophysiology*. <https://doi.org/10.1152/jn.00030.2022>
- Rosenberg, J. R., Amjad, A. M., Breeze, P., Brillinger, D. R., & Halliday, D. M. (1989). The Fourier approach to the identification of functional coupling between neuronal spike trains. *Prog Biophys Mol Biol*, 53(1), 1-31. [https://doi.org/10.1016/0079-6107\(89\)90004-7](https://doi.org/10.1016/0079-6107(89)90004-7)

- Schulz, E., Tiemann, L., Schuster, T., Gross, J., & Ploner, M. (2011). Neurophysiological Coding of Traits and States in the Perception of Pain. *Cerebral Cortex*, 21(10), 2408-2414. <https://doi.org/10.1093/cercor/bhr027>
- Smith, S. A., Micklewright, D., Winter, S. L., & Mager, A. R. (2021). Muscle pain from an intramuscular injection of hypertonic saline increases variability in knee extensor torque reproduction. *Journal of Applied Physiology*, 130(1), 57-68.
- Steinmetz, H., Fürst, G., & Meyer, B. U. (1989). Craniocerebral topography within the international 10-20 system. *Electroencephalogr Clin Neurophysiol*, 72(6), 499-506. [https://doi.org/10.1016/0013-4694\(89\)90227-7](https://doi.org/10.1016/0013-4694(89)90227-7)
- Tan, L., Oswald, M., Heintz, C., Romero, O. A. R., Kaushalya, S., Monyer, H., & Kuner, R. (2019). Gamma oscillations in somatosensory cortex recruit prefrontal and descending serotonergic pathways in aversion and nociception. *Nature Communications*, 10. <https://doi.org/10.1038/s41467-019-08873-z>
- Tsao, H., Galea, M., & Hodges, P. (2008). Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain : a journal of neurology*, 131 Pt 8, 2161-2171. <https://doi.org/10.1093/brain/awn154>
- Tucker, K., & Hodges, P. (2010). Changes in motor unit recruitment strategy during pain alters force direction. *European Journal of Pain*, 14. <https://doi.org/10.1016/j.ejpain.2010.03.006>
- Valentin, G., & Maribo, T. (2014). Hand-held dynamometry fixated with a tripod is reliable for assessment of back extensor strength in women with osteoporosis. *Osteoporos Int*, 25(8), 2143-2149. <https://doi.org/10.1007/s00198-014-2743-0>
- Viseux, F., Simoneau, M., & Billot, M. (2022). A Comprehensive Review of Pain Interference on Postural Control: From Experimental to Chronic Pain. *Medicina*, 58. <https://doi.org/10.3390/medicina58060812>
- Vonsevych, K., Goethel, M. F., Mrozowski, J., Awrejcewicz, J., & Bezuglyi, M. (2019). Fingers Movements Control System Based on Artificial Neural

Network Model. *Radioelectronics and Communications Systems*, 62(1), 23-33. <https://doi.org/10.3103/S0735272719010047>

Xiao, W., Yang, H., Wang, Z., Mao, H., Wang, H., Hao, Z., Zu, Y., & Wang, C.-H. (2023). Postural Control of Patients with Low Back Pain Under Dual-Task Conditions. *Journal of Pain Research*, 16, 71-82. <https://doi.org/10.2147/JPR.S392868>

Zurcher, U., Kaufman, M., Vyhnalek, B., & Sung, P. (2007). Entropy measures of back muscles EMG for subjects with and without pain. *Bulletin of the American Physical Society*. <https://consensus.app/papers/entropy-measures-of-back-muscles-emg-for-subjects-with-and-zurcher-kaufman/226a6d0bfe565a39aebdd127b2c4321c/>

### *Article*

#### **The face of low back pain.**

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## **Abstract**

Facial expressions of pain are essential for pain assessment, yet subjective pain reports often vary between sexes. This study examined sex differences in facial expressions and subjective pain reports using a newly developed tool employing Haar Cascade and LBPH algorithms to detect and quantify facial expressions associated with experimentally induced acute low back pain. Thirty healthy participants (22 males, 8 females) received hypertonic saline injections during a spinal extension task, with facial expressions recorded and pain levels self-assessed using the visual analogue scale. The tool demonstrated high efficacy in detecting facial expression variations across conditions (pain, placebo, and pain free), with increased expressions during pain in both sexes. However, males reported higher pain intensities than females, despite no significant sex differences in facial expressions. Additionally, pain significantly reduced the stability of isometric contractions (steadiness) during the pain condition for both groups. These findings suggest that, while facial expressions of pain appear similar between sexes, males tend to report higher pain intensities. Our results underscore the tool's precision and value as an objective biomarker for pain assessment, indicating that integrating facial analysis with subjective reports may enhance accuracy in pain evaluation.

**Keywords:** facial expression of pain, acute low back pain, force, artificial intelligence.

## 1. Introduction

Contemporary theories of pain communication emphasize the diversity of manifestations associated with this phenomenon, encompassing multiple channels such as verbal reports, vocal complaints, postural changes and facial expressions (Schneider et al., 2024). From an evolutionary perspective, these diverse manifestations seem to have been conserved over time, reflecting different adaptive functions associated with preserving the integrity of the organism in the face of harmful stimuli (Sneddon, 2019; Zheng et al., 2020). In clinical practice, verbal reports of pain intensity are considered the gold standard for pain assessment (Lynch, 2001). However, this method faces limitations inherent to inter-individual variability and the influence of psychological factors, introducing significant biases in the interpretation and management of pain (Hadjistavropoulos et al., 2011; Tavakolian & Hadid, 2018).

Although facial expressions of pain are often underestimated as valid indicators of the painful experience, evidence pointed out by Tavakolian and Hadid (Tavakolian & Hadid) suggests that these expressions provide essential complementary information for assessing pain intensity. Functional magnetic resonance imaging studies have identified correlations between fluctuations in facial expression and changes in the activity of cortical areas involved in the spino-thalamo-cortical pathways (Picard et al., 2024). These fluctuations, however, have been shown to be independent of the intensity of the nociceptive stimulus and inversely correlated with activity in prefrontal regions, implying that facial expressions may represent a complex integration of activity in distributed brain networks, processing nociceptive information and modulating efferent motor outputs (Kunz et al., 2020; Kunz et al., 2006; Vachon-Presseau et al., 2016). This suggests that the facial expression of pain may reflect the integration of activity in distributed brain networks processing ascending nociceptive signals, determining action policy and controlling efferent facial motor outputs, highlighting the need to implement the assessment of facial expressions in clinical practice (Christe et al., 2021; Schneider et al., 2024; Zheng et al., 2020).

The automated assessment of pain by analyzing facial expressions, has advanced considerably (Prkachin, 1992). Initially approached as a binary classification, distinguishing only the presence or absence of pain, the field has evolved into a more refined understanding of pain as a continuous phenomenon, varying in intensity (Ashraf et al., 2007; Lucey et al., 2010; Prkachin, 1992). Studies such as those of Kaltwang et al. (Kaltwang et al., 2015) applied the local binary standard (Ahonen et al., 2004) to extract facial features from segmented images, while Florea et al. (Florea et al., 2015) explored histograms of topographic features using transfer learning to estimate pain intensity. Recent approaches in deep learning include the Recurrent Convolutional Neural Network focusing on the temporal progression of facial expressions, using ordinal data to capture nuances in pain intensity (Zhou et al., 2016), which models temporal patterns in time windows, and the integration of deep networks with artisanal characteristics (Egede et al., 2017).

However, most studies have investigated facial expressions in specific populations, such as individuals with cognitive impairments (Atee et al., 2022; Defrin et al., 2006; Symons et al., 2010), children (Moon et al., 2008) and babies (Stevens et al., 1994). We found only three studies in healthy adults (Kunz et al., 2006; Prkachin, 1992; Schneider et al., 2024) and two in patients with chronic pain, addressing low back pain and shoulder pain, respectively (Craig et al., 1991; Prkachin & Solomon, 2008). No study to date has been dedicated to the creation of a tool and analysis of facial expressions during a submaximal strength generation task in a context of experimental acute low back pain. In addition, the absence of studies that simultaneously integrate subjective and objective biomarkers limits the reach of more accurate clinical inferences (Kunz et al., 2020).

In this context, this study proposes the development of an innovative software based on the Haar Cascade and Local Binary Pattern Histogram (LBPH) algorithms for the detection and accurate quantification of variations in facial expressions associated with experimentally induced acute low back pain, and subjective and physical pain responses, in females and males

## **2. Materials and methods**

### **2.1 Study design**

This is an experimental study that involved participants attending two visits, with a seven-day interval between them. The research protocol received ethical approval from the ethics committee of the Faculty of Sport of the University of Porto (CEFADE 28-2023). All objectives and methodologies were meticulously developed and executed in accordance with the guidelines established by the Declaration of Helsinki. Prior to participation, all volunteers provided informed consent by signing the Informed Consent Form, ensuring their understanding of the objectives and procedures of the study.

### **2.2 Sample**

Thirty individuals took part in this study. The inclusion criteria were defined as healthy individuals aged between 18 and 40, with no history of musculoskeletal diseases or recurrent pain in the past six weeks. Additionally, participants should not have used anti-inflammatory or analgesic medication in the 24 hours prior to the experiment. Exclusion criteria included individuals with a history of lumbar injury or surgery, existing chronic pathologies such as disc degeneration, osteoarthritis of the lumbar spine, facial paralysis, disc herniation, ankylosing spondylitis, and other conditions that could affect muscle function and facial expression, as well as pregnant women. These criteria were established to ensure that the participants represented a homogeneous population, thereby minimizing the impact of confounding variables on the study results.

### **2.3 Method of measuring differences between facial expressions**

#### *2.3.1 Digital image representation*

In a digital system, such as a computer, an image is represented as an array of pixels (picture elements). A digital video can be treated as a series of frames,

each having this representation. When an image is in color, each pixel usually contains three numbers, to represent the levels of its color components. When an image is represented in grayscale, each pixel can be represented by a single number, proportional to its lightness. In grayscale, a commonly used system is one in which a completely dark pixel is represented by the number 0 and a pixel with maximum lightness by the number 255. Intermediate levels of lightness are represented between 0 and 255.(Gonzalez & Faisal, 2019)

### 2.3.2 Face Detection with Haar Cascade

Viola and Jones proposed a method for detecting objects in images, which they claimed was robust and very fast (Viola & Jones, 2001). The motivation for its development was face detection, but it has more general application. This method uses a type of calculation called by the author's integral image. It is performed on grayscale images. Using  $x$  and  $y$  to represent the coordinates of a pixel, with  $x$  increasing from left to right,  $y$  increasing from top to bottom in the image, and  $i(x, y)$  representing the intensity of the pixel at  $(x, y)$ , the value of the integral image  $ii(x, y)$  at coordinates  $(x, y)$  it is the value of the sum of all the pixel values that are in the rectangle whose diagonal runs from the upper leftmost pixel to the pixel at  $(x, y)$ .

$$ii(x, y) = \sum_{(x' \leq x, y' \leq y)} i(x', y') \quad (1)$$

The values of  $ii(x, y)$  can be calculated progressively for all pixels in an image, moving from left to right and top to bottom. In this calculation, on each advancement to the next pixel, previous results calculated for nearby pixels can be used, avoiding having to restart the sum from the top left corner.

Once all the values of  $ii(x, y)$  for an image have been calculated, the calculation of the sum of the pixel values for any rectangle in the same image is quick, using the known values of  $ii(x, y)$ , even if this new rectangle does not have one of its

ends in the upper left corner. Figure 1 provides an example of this. Considering the red rectangle, the sum of the values of its pixels is equal to the sum of those in the blue rectangle minus those in the green rectangle minus those in the white rectangle and replacing once those where the green overlaps with the white, since they were subtracted twice. In this example, using the previously calculated values of  $ii(x, y)$ , this calculation would be:

$$\text{total in the red rectangle} = ii(7, 4) - ii(7, 2) - ii(3, 4) + ii(3, 2)$$

where:

$ii(7, 4)$  is the sum in the blue rectangle,

$ii(7, 2)$  is the sum in the green rectangle,

$ii(3, 4)$  is the sum in the white rectangle,

$ii(3, 2)$  is the sum in the overlap of green and white.



Figure 1: Example of any rectangle in the image, in red. The sum of the values of its pixels is equal to the sum of those in the blue rectangle minus those in the green rectangle minus those in the white rectangle and replacing once those where the green overlaps with the white, since they were subtracted twice.

It can thus be seen that the sum of the pixel values in any rectangle can be quickly calculated from the previously calculated results for  $ii(x, y)$ . This fact is exploited in the Viola and Jones method, using ideas such as the following example. Each

Figure 2, (a) or (b), has a grayscale face, with a rectangle positioned over it. This is a detector rectangle for a particular feature of any face: the transition region between the forehead and the eyes. It is common in images of faces, due to lighting, for the forehead to appear lighter than the eyes region. The detector rectangle is divided in half by a horizontal line. It must slide across the image, traversing it step by step. At each step, the sum  $ssup$  of the pixel values under the upper half of the rectangle (marked with +) is calculated and, separately, the sum  $sinf$  of its lower half (marked with -) is calculated. Finally, the difference  $d = ssup - sinf$  is calculated. With the rectangle positioned over the forehead, the value of  $d$  will tend to be relatively small, because, since both halves are light, both  $ssup$  and  $sinf$  will have large, similar values. However, in Figure 2(b), the rectangle is in a position where  $ssup$  is much larger than  $sinf$ , since the upper part is much lighter than the lower part. This makes  $d$  relatively large, indicating that this feature of a face may have been detected there.

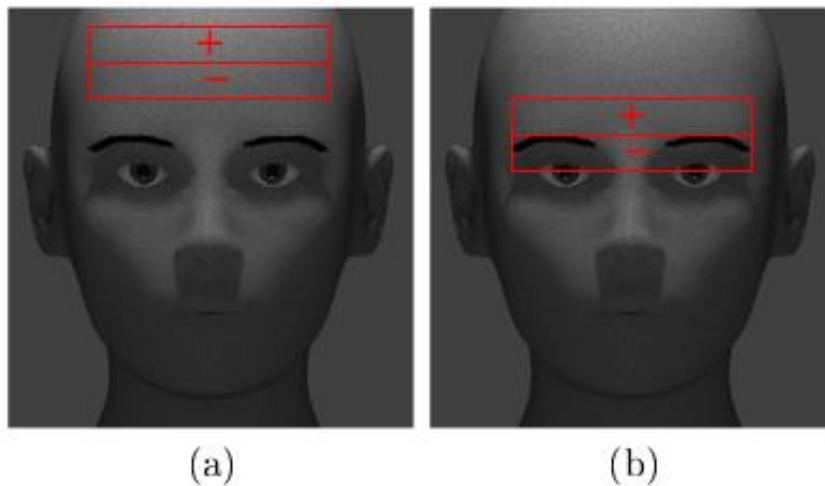


Figure 2: Example of a rectangle detecting a facial feature (transition from forehead to eyes).

Legend: (a) Rectangle in position without detecting the feature. (b) Rectangle in position detecting the feature.

However, this rectangle, in this process, is not capable of determining on its own whether what is underneath it is, in fact, a feature of a face. This simple pattern could be found in other objects in the image. Therefore, Viola and Jones' method uses many rectangles, each of which searches for a type of pattern. To detect a

nose, a rectangle divided into three parts by vertical lines can be used, as in Figure 3. The calculation associated with it is the sum of the values of the pixels under its central part (marked with +) minus the sums of the values of the pixels under its lateral parts (marked with -). This takes advantage of the fact that, normally, due to lighting, the central part of the image of a nose appears brighter than its lateral parts. The higher the result of this calculation, the greater the probability that there is a nose under the rectangle.

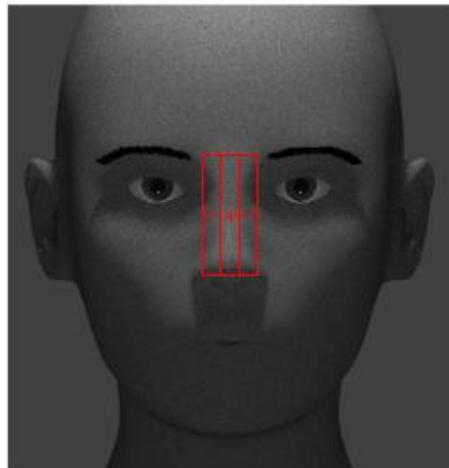


Figure 3: Example of using the nose detector rectangle.

The Viola and Jones (Viola & Jones, 2001) method applies several of these appropriate detector rectangles to each region of the image. The sequence of their application is planned so that first, in each region, rectangles are applied that are more reliable in declaring whether that region may contain the desired object. If high-confidence rectangles do not detect the pattern that they can detect in a region, it is decided that region does not contain the desired pattern, saving the time of applying the other rectangles. Otherwise, less reliable detector rectangles are applied successively. Finally, it is decided whether that region contains the desired pattern, considering the results obtained by all the detector rectangles applied.

The succession of rectangle applications described here, with evaluations of whether the process should continue in a region after each application, uses a strategy called “cascade”. The type of calculation performed under the rectangles

is similar to that of the so-called Haar functions. Therefore, this object detection process is called Haar Cascade. The Haar Cascade method is not specific to face detection; it is more generally applicable.

It can be adjusted to detect other types of objects. For each type of object to be detected, appropriate detector rectangles must be used in an arrangement adjusted to the specific case. In other words, the method is general purpose, but the rectangles to be used and their arrangement in the cascade are specific. For common use cases, such as face detection, specific arrangements of these rectangles and information about their application cascade are available and ready for use.

### *2.3.3 Feature extraction with LBPH (LBP)*

This subsection briefly describes the form of representation of face images presented in (Ahonen et al., 2004). Its basic element is the local binary pattern. Figure 4 shows a small region, containing nine pixels of a matrix that represents a grayscale image. In this set, the central pixel, with a value of 140, is taken as a reference. Then, each of its eight neighboring pixels receives a binary value (bit) associated with it, equal to 1 if this pixel has a value greater than the reference (140) and 0 otherwise. Finally, a number is formed, represented in the binary numbering system, by chaining those eight bits, as indicated by the arrows: 00011100. This value is 28 in the decimal numbering system. It is the LBP associated with the central pixel of that set. In the binary system, numbers with eight bits can be from 0 (00000000) to 255 (11111111) in the decimal system.

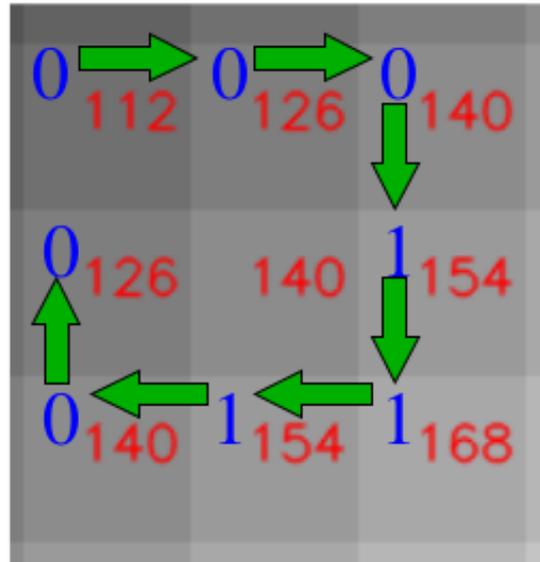


Figure 4: Example of LBP calculation for a pixel (the central one of the nine considered).

An important feature of this value is that it depends only on the results of comparing the brightness of the central pixel with its neighbors, not on these absolute values. If the image were equally brightened or darkened, this value would not change. For example, if the entire image were darkened so that each pixel value in it was reduced by 10 units, the LBP value of the central pixel would still be 28, because it would still be darker than its three neighbors below and to the right and lighter than (or as bright as) its other neighbors. The LBP is robust to variations in brightness. Another important feature is that this value is highly dependent on the relationships of the central pixel to its neighbors in terms of the pattern they form together. The brightness does not matter, but the pattern does. When applying LBP to a grayscale image, an LBP matrix with the same geometry as the image matrix is created. The LBP value is calculated for each pixel in the image. This value is placed in the LBP matrix in the position corresponding to the position of the pixel for which the LBP was calculated in the image. This creates a new matrix, containing values between 0 and 255, each element of which contains information about the image pattern in the small region around the corresponding pixel.

As an example, suppose that the hypothetical  $10 \times 10$  LBP matrix in Table 1 was obtained from a grayscale image of a face containing  $10 \times 10$  pixels. (This is a

very small number of pixels compared to real examples, but it is easier to present here.) Once such a matrix has been obtained, the next step in the representation method of (Ahonen et al., 2004) is to divide the matrix into regions. In this example, it has been divided into four regions (submatrices) of size  $5 \times 5$  each, with the boundaries between them marked by the lines in the matrix in Table 1. The division could be done into submatrices of different sizes, and they would not need to be square.

Table 1: Hypothetical example of LBP matrix.

78	40	133	135	167	176	217	50	166	38
241	227	246	190	161	96	118	145	237	5
133	31	86	174	21	52	2	216	74	252
219	171	227	119	127	80	173	72	61	122
157	113	214	1	180	0	5	112	17	182
105	2	128	190	30	173	54	112	87	132
204	113	202	133	99	92	151	36	54	37
179	1	71	236	145	126	42	9	98	60
145	118	84	45	198	176	133	43	241	105
219	234	51	92	45	89	68	168	19	185

After dividing the LBP matrix, a histogram of the values that appeared in it is assembled for each submatrix, as shown in Figure 5. The number of histogram classes and the limit values of each class are freely chosen. In this example, eight classes were used for each histogram. Each class of each histogram contains a band with an amplitude of 32. The first band, centered on the value 16, has the count of occurrences of the values from 0 to 31 in the corresponding submatrix. The second band is centered on 48 and contains the count of occurrences of the values from 32 to 63, and so on. In Figure 5, the histograms are in positions corresponding to the positions of the four submatrices in Table 1 from which they originated. Finally, the histograms are concatenated (placed side by side), as shown in Figure 6. Since each of the four histograms had eight classes, the result of the concatenation is a sequence containing  $4 \times 8 = 32$  numbers:

**(3, 1, 2, 3, . . . , 4, 0, 1)**

This is the result of the LBPH (Local Binary Pattern Histogram). This sequence of numbers (32, in this example) describes patterns of relationships between pixels in an image. It can then be used by machine learning algorithms, or other, as a representation of the image, bringing important information about it.

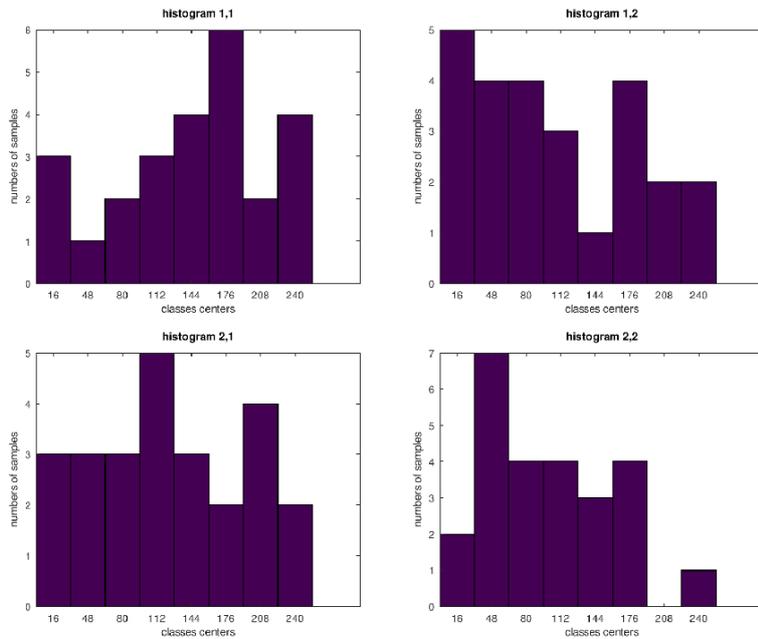


Figure 5: Histograms of the occurrences of values in the four submatrices of the Table 1.

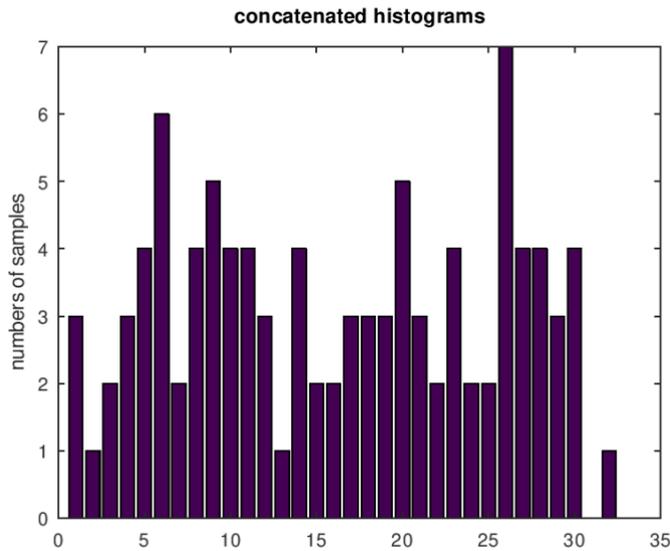


Figure 6: Result of concatenating the histograms in Figure 5.

### 2.3.4 Development of software for analysis of facial expressions with experimentally induced acute low back pain

A computer program was developed in Python language, using the OpenCV library. (Team, 2024) This has many algorithms implemented for image processing. The program must access two video files, in which the face of the person whose pain is to be assessed appears. In the first video, which is relatively short, the face should appear with a neutral expression. This is called the learning video by the program. It is used so that the program can learn what the neutral expression of that person is. In the second video, called the application video, the program measures, frame by frame, the difference between the facial expression in the frame and the average expression learned in the frames of the learning video. The program interface window is shown in Figure 7. It was developed using the Python package tkinter (NumPy, 2024).

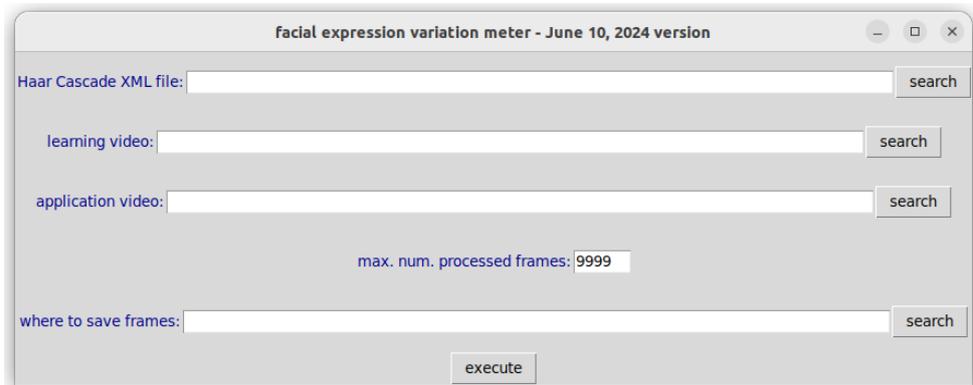


Figure 7: Program interface window.

The first information requested from the program user in this window is the name and location on the computer of a file in XML format that contains the details of the face detection by Haar Cascade, as discussed at the end of the section 2.3.2. Next, the files with the videos for learning and for application are requested. Then, the user is asked for the limit number of frames of the video for application to be processed. This number is useful when the user wants to do a quick test of the processing, by entering a small value there. Finally, the user is asked for the location on the computer where files with the results will be saved. One of these

files is an annotated video, frame by frame, with a number proportional to the difference between the expression detected in it and the average expression learned in the video for learning. The other is a file with a record, in plain text format, of the number of each frame next to the result of the measurement of the difference in expression between that of the face in it and the average learned. These numbers can then be entered into spreadsheets or provided to other programs for analysis and visualization of the evolution of the difference over time.

Face detection in video frames is performed by an object of the Cascade Classifier class of the OpenCV library (Team, 2024), named `face_cascade`, configured to use the XML file indicated by the user in the program interface window. In the learning phase, the program reads each frame of the first video, converts it to grayscale, and attempts to detect faces in it using the `face_cascade` detector. If no face is detected in a frame, processing continues to the next frame. If more than one face is detected in a frame, processing will continue only on the face that has the largest area in the image among the faces detected in it, because the smaller faces will probably be of people passing by the location in the background of the image, figures on the walls of the room, or other anomalies. Once a bounding rectangle has been isolated by `face_cascade` around the largest face detected in an image, it is divided into 9 rows and 8 columns, as depicted in green in Figure 8. These numbers for the division were chosen through empirical tests, previously carried out by the authors, on the JAFFE (Japanese Female Facial Expression) facial expression database (Lyons, 2021; Lyons et al., 2020). Since the leftmost column and the rightmost column have several rectangles that contain parts of the image that are not on the face, they are not used in the further processing, as they may suffer spurious effects from the scene background

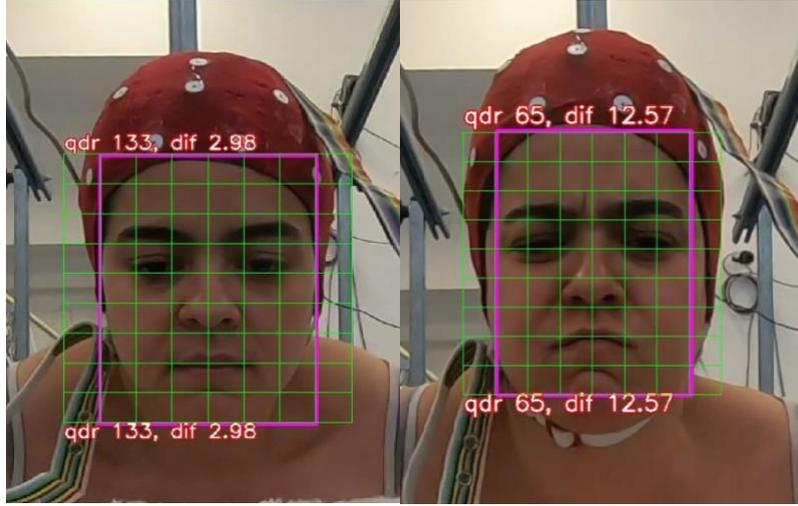


Figure 8: Rectangles containing faces detected by Haar Cascade divided into rows and columns (in green). Only the part delimited in violet is used in the following processing.

Legend: left picture pain free, right picture with low back pain.

Then, following the process described in section 2.3.3, the LBP is calculated for each of those remaining  $9 \times 6 = 54$  small rectangles. The implementation used for the LBP is the one available in the skimage package in the Python language.(Price et al., 1983) The LBP histogram of each small rectangle is assembled using the NumPy package in Python (NumPy, 2024). Each of these histograms has 30 classes and is normalized, so that the sum of their values is equal to 1, regardless of the area covered by the rectangle. After assembling and normalizing the LBP histogram of each small rectangle, the 54 histograms are concatenated, thus obtaining a sequence containing  $54 \times 30 = 1620$  numbers. This sequence is an LBPH representation of the largest face detected in the video frame.

Once the learning video is finished, the average LBPH representation of its frames is calculated, according to the expression:

$$\mathit{reprLBPH}_{neutral} = \frac{(\sum \mathit{frames\ with\ faces}) * (\mathit{reprLBPH}_{frame})}{\mathit{number\ of\ frames\ with\ faces}} \quad (2)$$

Thus, reprLBPHneutral is a sequence containing 1620 numbers and represents the average face of the video for learning, that is, it should represent the person's neutral face. In the application phase, for each frame of the video, steps similar to those in the learning phase are performed: conversion of the image to grayscale, detection of the largest face, division of it into small rectangles, assembly and concatenation of the histograms, obtaining a sequence containing 1620 numbers associated with the face in that frame, reprLBPHframe. The difference between this sequence and the reprLBPHneutral is then calculated to measure how much the face in this frame differs from the average neutral face:

$$\text{diffLBPHframe} = \text{reprLBPHframe} - \text{reprLBPHneutral} \quad (3)$$

This difference is calculated using the mean\_absolute\_error function from the Python sklearn package.(Pedregosa et al., 2012) To understand how this calculation works, here is a generic numerical example. Given the following sequences of numbers:

$$\mathbf{a} = (10, 20, 30, 40, 50)$$

and

$$\mathbf{b} = (1, 1, 2, 2, 3)$$

where  $\mathbf{a}$  is in the role of the sequence reprLBPHframe and  $\mathbf{b}$  is in the role of the sequence reprLBPHneutral, the difference between  $\mathbf{a}$  and  $\mathbf{b}$  will be:

$$\mathbf{d} = (9, 19, 28, 38, 47),$$

calculated position by position: the first element in  $\mathbf{d}$  is the difference between the first in  $\mathbf{a}$  and the first in  $\mathbf{b}$ , the second element in  $\mathbf{d}$  is the difference between the second in  $\mathbf{a}$  and the second in  $\mathbf{b}$ , and so on (The absolute values of the differences are used). Then, the average of the numbers in  $\mathbf{d}$  is calculated, which in this case is 28.2. This is the type of calculation done in the expression (3), providing, as a result, a number that reflects how much the face in a frame differs from the average neutral face. Experimentally, it was found that, when the

program was run, this number was in the order of thousandths or hundredths. Therefore, to make it more comfortable to read, the number recorded in the result video and in the text, file produced is the result of 1000 times difLBPHframe. Thus, the number shown to the user is in the order of units or tens, not thousandths or hundredths. It does not have a physical unit of measurement, such as meters or seconds, as it is an average of counting results, that is, of pure numbers.

## **2.4 Force test**

Five familiarization repetitions of the MVC test and three repetitions of the submaximal test with a trapezoidal signal were performed (steadiness) (Arvanitidis et al., 2024; Valentin & Maribo, 2014). After a 2-minute rest period, one MVC repetition was conducted, followed by 1 minute of rest, and subsequently, one repetition of the trapezoidal force signal was performed. Height and body mass were measured using a bioimpedance system (Inbody 230, InBody Co., Ltd., Korea). Then, two tests were performed by a physiotherapist experienced in the field; at the first visit, a maximal voluntary contraction (MVC) was performed (test 1), and then a submaximal isometric contraction performed at 20% of the MVC (test 2). On the second visit, after 7 days, the same participant performed the same procedure as in the first visit. Familiarization with the tests was carried out with all volunteers. The dynamometer was attached to a metal structure mounted on a treatment table to keep it stable in both tests. For the performance of trunk extensor muscle strength tests, volunteers were positioned in prone, with arms extended. The dynamometer was positioned in the midline between the two upper angles of the scapulae, and volunteers were asked to perform spinal extension, maintaining isometry for 5 seconds (test 1).

### **2.4.1 Experimentally induced acute low back pain**

Experimental acute low back pain was induced by intramuscular injections of hypertonic and isotonic saline solution, administered 7 days apart (Kellgren, 1938). During the injections, the participants were positioned in the prone position

with a 20° inclination, which helped to promote muscle relaxation. The study used a randomized crossover design, in which each participant received a single dose of 2.5 mL (Canestri et al., 2021) to ensure that the test was performed during the period of pain, of hypertonic saline solution (6.0%), designed to induce pain, or isotonic saline solution (0.9%) (Graven-Nielsen, 2006), used as a placebo. The injections were administered in the intervertebral space between L3 and L4, at the level of the spinous process, located approximately 2 to 3 cm from the midline. After cleaning the area with 70% alcohol, the solution was injected into the dominant side of the body using a 25 × 28 mm needle, at a depth of 30 mm from the skin surface, by a qualified professional. The participants were assessed in three different conditions: baseline, experimentally induced pain (hypertonic solution), and control condition (isotonic solution) while performing a spinal extension task in the prone position.

## **2.5 Evaluation of facial expressions**

Facial expressions were captured by a GoPro camera. The participant's faces were recorded in video frontal view while they performed a spinal extension in prone position, sustained for 20 seconds with a submaximal load corresponding to 20% of the maximum force. To ensure that the face remained aligned and visible during all experimental conditions, participants were instructed to fix their gaze on a computer screen positioned directly in front of them and to concentrate on maintaining the trapezoidal force signal projected on the screen for the entire 20-second period. In addition, participants were asked to remain silent throughout the procedure to avoid possible interference in analyzing facial expressions. All participants were informed in advance about the recording and provided written informed consent authorizing the capture and use of the images.

## **2.6 Evaluation of subjective responses to pain**

Pain intensity ratings were obtained immediately after each stimulus using the Visual analogue scale (VAS) (Karmann et al., 2014; Karmann et al., 2015), a widely validated and sensitive method for measuring the subjective perception of

pain (Price et al., 1983). The scale was standardized with the extreme points labeled: 0 = 'no pain' and 10 = 'extremely severe pain'. All participants were given detailed instructions to assess and record all painful sensations accurately. The assessments were conducted by the same researcher at regular 1-minute intervals over a total period of 7 minutes, ensuring the consistency and reliability of the data collected. The VAS is recognized for its simplicity and effectiveness in capturing subtle variations in pain perception over time, which contributed to the robustness of the results obtained in this study.

## **2.7 Statistical analysis**

The videos were analyzed using the OpenCV library in the Python programming language (van der Walt et al., 2014). Descriptive statistics were calculated for the VAS and facial expression measurements recorded during each experimental condition and session. To ensure the suitability of the analytical methods, a normality test Shapiro-Wilk was carried out to assess the distribution of the data, which indicated that it did not fulfil the normality assumption. As a result, non-parametric tests, which are more robust when normality is violated, were adopted for statistical analysis. The Friedmann test was applied to compare the three experimental conditions (pré, control and during of pain) in relation to changes in facial expression. In addition, the Wilcoxon test was used to assess intra-group differences in facial changes in males and females in each of the three conditions. To complement the analysis, Cohen's d criteria were applied to determine the effect size of the analyses, classified as small ( $d > 0.2$ ), moderate ( $d > 0.5$ ) and large ( $d > 0.8$ ). All tests were conducted using SPSS Statistics software (IBM Corporation, Version 27), with a significance level set at  $\alpha = 0.05$ . The combination of these methodological approaches ensures a rigorous and detailed analysis of the data collected.

## **3.0 Results**

The sample consisted of 30 young adults, aged between 18 and 40 years (average  $29.96 \pm 5.96$  years). Among the 30 volunteers, 8 were women, with an

average height of  $164.66 \pm 6.3$  cm, an average age of  $29.77 \pm 6.2$  years and an average body mass of  $65.14 \pm 6.2$  kg. The other 22 participants were men, with an average height of  $175.20 \pm 5.5$  cm, an average age of  $28.79 \pm 5.9$  years and an average body mass of  $80.00 \pm 9.3$  kg.

### 3.1 Measuring facial expressions.

The results (Figure 9) indicated statistically significant differences ( $p < 0.001$ ) between all conditions, confirming the effectiveness of the software in detecting variations in facial expressions. The analysis revealed that facial expression in men showed a greater mean difference during pain compared to the placebo and pain free conditions, with significant differences observed between all conditions ( $p < 0.01$ ). Women also showed an increase in facial expression during pain, although the effect was smaller than in men, with significant differences observed between the pain and pain free and placebo conditions ( $p < 0.05$ ). However, when directly comparing the male and female groups, no statistically significant differences were observed between the sexes in any condition. Furthermore, Cohen's  $d$  value of 0.588 suggests a moderate effect size, further emphasizing the robustness of the results given the sample size (Cohen, 2013).

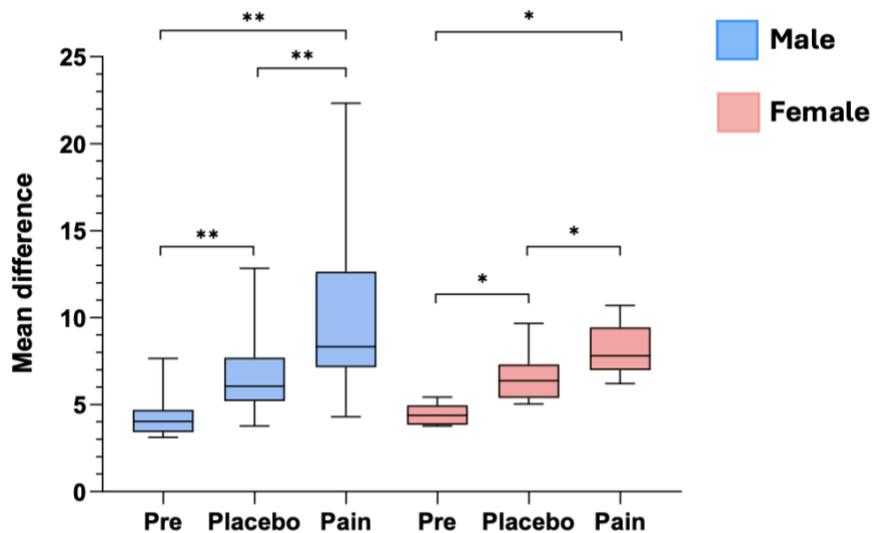


Figure 9: Graph of the mean difference in facial expressions at pain free, placebo, and during experimentally induced acute low back pain

Legend: \*\*  $< 0.001$ ; \*  $< 0.05$ .

### 3.1.1 Force teste

When maximal voluntary contraction (MVC) was analyzed, male and female participants showed significant intra-group differences between the experimental conditions (Figure 10 a). For women, the MVC was highest during preparation, followed by placebo and the pain period, with the Friedman test revealing a significant effect ( $\chi^2 = 16.00$ ,  $p < 0.001$ ). Among men (N=22), MVC was slightly higher during the placebo period compared to stimulation, being the lowest during the control period also showing significant differences ( $\chi^2 = 32.818$ ,  $p < 0.001$ ). In addition, more detailed analyses indicate that despite these intra-group variations, no significant differences were found between genders, suggesting that both sexes showed similar responses to experimental conditions in terms of changes in MVC

Analysis of the Steadiness figure (10 b) revealed distinct patterns of response to the experimental conditions. Friedman's test indicated statistically significant differences between the conditions ( $\chi^2 = 44.000$ ,  $p < 0.001$ ), suggesting robust variations in Steadiness under different experimental influences. Comparisons between conditions revealed that Steadiness was significantly lower during the pain condition compared to pre- and placebo for both sexes, indicating a pronounced impact of the pain condition on motor stability. For men, placebo steadiness was significantly higher than pre- and Steadiness with pain, while Steadiness with pain was the lowest value recorded. These results suggest that the experimental condition differentially affects the Steadiness of force production of the participants, with a consistent pattern of reduction in Steadiness during stimulation and pain conditions relative to placebo and baseline control.

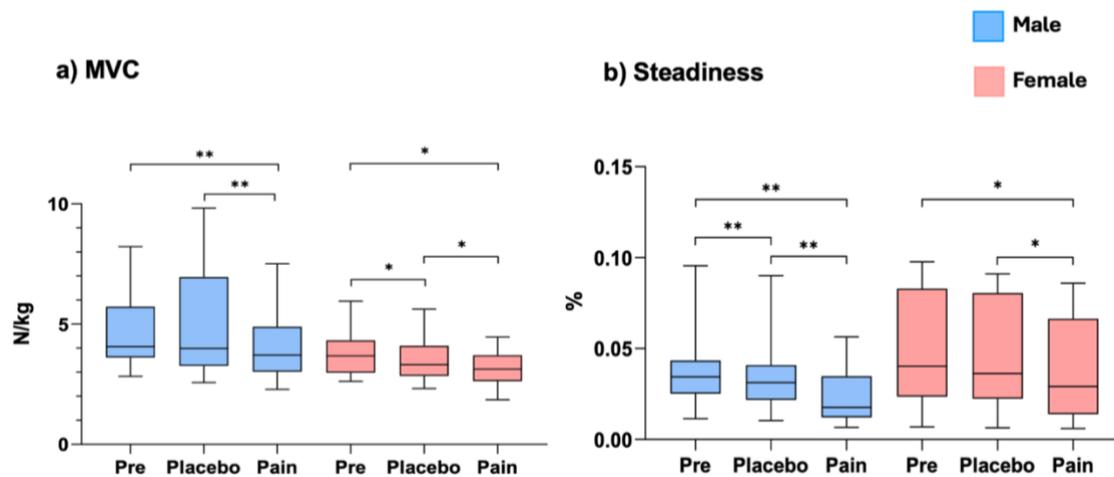


Figure10: Maximum strength and steadiness under pre, placebo and pain conditions in both men and women.

Legend: pain free, control and during of pain p\*\* <0.001; \* <0.05.

### 3.2 Gender Differences in VAS responses during acute low back pain

On the VAS, men reported pain as more intense compared to women, on a scale of 0 to 10. The standard deviation is low for both groups, but is lower for women, suggesting that there is less variation in pain ratings among women than among men as seen in figure 11. Analysis of the VAS revealed significant differences in pain perception between the experimental conditions and between sexes. For the total group of 30 participants, both men and women reported significantly greater pain during the pain condition compared to the placebo condition. However, a more detailed analysis showed significant differences between the sexes. For men, the average VAS with pain was 5.12, significantly higher than the placebo VAS average of 1.68 ( $Z = -4.108$ ,  $p < 0.001$ ). In contrast, for women, the mean VAS with pain was 3.75, while the mean VAS for placebo was 1.25 ( $Z = -2.58$ ,  $p = 0.01$ ). These results indicate not only that the intensity of perceived pain is higher during the pain condition compared to placebo, but also that there are significant differences in the way men and women report pain. Men's reported verbal pain perception was consistently higher than women's, suggesting that gender influences the intensity of reported pain. These results emphasize the importance of considering both experimental variables and gender differences when assessing and interpreting pain in clinical studies.

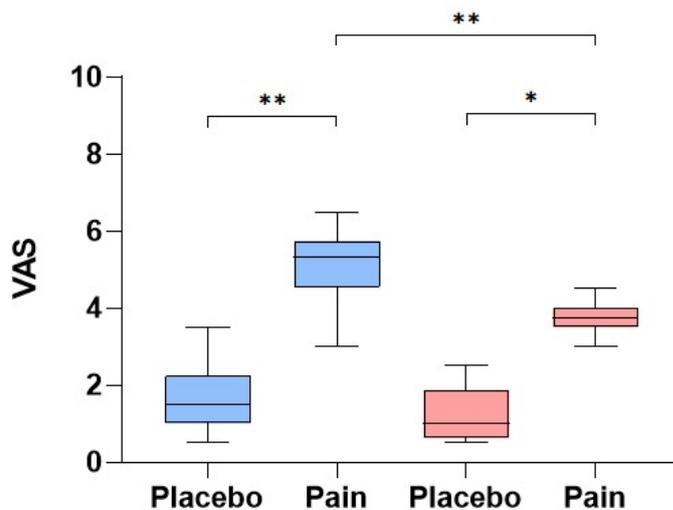


Figure 11: VAS results obtained under pre, placebo and pain conditions in both men and women.

Legend: visual analogue scale (VAS) 0-10, p\*\* <0.001; \* <0.05.

#### 4. Discussion

The innovation of this study lies in the combination of digital imaging techniques with machine learning algorithms for analyzing facial expressions, offering a more objective approach to the understanding of pain. The software developed can capture changes in facial expressions and create a robust method together with the physical (MVC and Steadiness) and subjective responses to pain (VAS) in both male and female subjects. With high efficacy and sensitivity, the software was able to ‘reveal the face of acute low back pain’, by distinguishing variations in facial expressions during episodes of acute low back pain compared to pre- and placebo conditions, in males and females, providing a comprehensive and detailed view of the pain experience.

The results revealed differences in the way pain is reported between the sexes. Despite men reported higher levels of subjective pain in the VAS compared to women, this perception was not consistently reflected in changes in facial expressions. Men and women were equally expressive during experimentally induced acute pain in the lower back, also in the pre- and placebo. These

observations are in line with previous findings that there are no sex differences in facial expressiveness of pain (Craig et al., 1991; Prkachin, 1992). Interestingly, men and women showed no differences in facial expressions during induced acute low back pain. However, men reported significantly higher pain levels on the VAS compared to women, contrasting with findings from previous studies (Kunz et al., 2006; Schneider et al., 2024). This result suggests that sex influences the relationship between self-reported pain and facial expression of emoticons (Brody, 1985; Kring & Gordon, 1998). Thus, gender may moderate how self-reports relate to facial responses to pain, indicating the need for different approaches in pain management for men and women (Merksey & Bogduk, 1994).

Another interesting point that was not previously addressed in literature (Karmann et al., 2015; Keogh, 2014; Kunz et al., 2006; Schneider et al., 2024) was the integration of changes in facial expressions during pain with reductions in muscle strength and steadiness. The expressive changes in facial dynamics captured by the software were often associated with a substantial decrease in both muscle strength and sustained contraction stability for both sexes. This association was particularly evident during the acute pain condition, where greater variability in Steadiness was observed, as well as statistically significant differences in MVC between the pain and placebo conditions ( $\chi^2 = 32.8$ ,  $p < 0.001$  for male;  $\chi^2 = 16.0$ ,  $p < 0.001$  for female). The data obtained support the hypothesis that the change in facial expressions during episodes of acute low back pain can function as a biomarker of the physiological component underlying the painful experience. This biomarker becomes especially significant when associated with a reduction in motor performance (Zheng et al., 2020).

The motor areas at the frontoparietal level are intrinsically associated with pain processing, integrating both sensory and affective aspects, highlighting the complex interaction between pain perception and motor response (Picard et al., 2024). These regions may suggest common mechanisms in prediction and emotional regulation of pain (Picard et al., 2024; Zheng et al., 2020). Recruitment of the frontoparietal network may also be involved in the conscious representation of the context of pain, making nociceptive information available for integration into

decision-making processes (Burt et al., 2020; Coll et al., 2022; Del Cul et al., 2007; Zheng et al., 2020). This link is reflected in the facial expression and subjective self-reports of individuals, indicating that motor areas not only contribute to the perception and physical response to pain, but also play a crucial role in emotional modulation (Burt et al., 2020; Pan et al., 2018).

Systematic analyses have consistently shown that high levels of pain-related fear, catastrophizing and depression are associated with a reduction in spinal range of motion and an increase in trunk muscle activity in individuals with low back pain, with these associations being independent of pain intensity (Burt et al., 2020; Christe et al., 2021; Del Cul et al., 2007). However, the small effect sizes question the relevance of these psychological factors as major determinants of a stiffer spinal motor behavior. Furthermore, the literature (Christe et al., 2021) has shown very small effect size associations between pain intensity and decreased spinal amplitudes and increased trunk muscle activity. These findings indicate that future research should adopt specific and individualized measures for psychological factors, pain intensity and spinal motor behavior (Christe et al., 2021). The detailed analysis of facial expressions captured through our software, subjective responses obtained and strength data, carried out in our study, are key factors for capturing subtle aspects of the pain experience that are not adequately represented by motor measures alone.

Therefore, it is crucial for health professionals to recognize that self-reporting in response to pain can vary substantially between individuals due to a combination of biopsychosocial factors, with gender being only one of the multiple determinants (Parolini et al., 2023; Sullivan et al., 2000). Although men and women exhibit similar facial expression patterns during episodes of acute induced low back pain, there are significant differences in subjective reports of pain. To develop innovative therapeutic approaches for individuals suffering from low back pain, it is essential to assess pain in multiple dimensions (Parolini et al., 2023). It is important to investigate the relationship between changes in facial expressions, psychological factors, and peripheral and central neural mechanisms in motor control through Steadiness during spinal movement in

individuals with low back pain (Arvanitidis et al., 2024). These elements can contribute to a better understanding and relief of symptoms, promoting improvements in patients' functional performance.

#### *4.1 Limitations*

An important limitation of this study is the relatively small sample size of 30 participants, which may limit the generalizability of the results to wider and more diverse populations. Furthermore, the sample was restricted to young, healthy individuals, with no history of chronic conditions or musculoskeletal pathologies, which reduces the applicability of the findings to clinical populations with chronic low back pain or other comorbidities. Another limitation refers to the experimental nature of the induced pain, which may not accurately replicate the complexity and variability of pain experienced in real clinical scenarios. Finally, despite the use of advanced software to detect facial expressions, automated analysis still depends on external factors, such as the positioning and quality of the camera (number of pixels), which can influence the accuracy of the data captured. Future studies with larger samples, more varied clinical populations and experimental conditions are needed to validate and expand our results.

#### *4.2 Future research*

Future research using the software developed in this study may explore several innovative directions to improve pain assessment and management. One promising possibility is to apply the software to clinical populations with chronic pain, such as persistent low back pain, to assess whether facial expressions captured in experimental acute pain situations are consistent with chronic pain patterns. In addition, the software can be adapted to monitor patients in real time in clinical settings, providing an automated tool to detect pain exacerbations or changes in pain status without the need for self-reporting. Future studies could also integrate other biomarkers, such as electromyography data, broadening the scope of the software to a multimodal pain assessment model. Improving facial recognition algorithms through deep learning techniques could also increase the

accuracy of expression detection, offering an even more detailed and sensitive analysis of pain in diverse and individualized contexts.

## **5. Conclusion**

The software developed demonstrated significant efficacy in accurately detecting and quantifying variations in facial expressions associated with experimentally induced acute low back pain in male and female participants. By capturing the subtle changes in expression in pain, placebo and baseline conditions, the tool offers a reliable approach to the assessment of low back pain, establishing a benchmark for research and clinical practice based on objective and reproducible biomarkers. The software's sensitivity to gender-based differences in self-reported pain intensity, together with its performance in distinguishing subtle variations in facial expression, highlights its potential as an accurate diagnostic aid.

## **Conflict of interest statement**

The authors have no conflicts of interest to declare.

## **Data availability**

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

## **Informed consent statement**

Informed consent was obtained from all participants for the publication of identifying information and images included in this manuscript.

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## REFERENCES

- Ahonen, T., Hadid, A., & Pietikäinen, M. (2004). *Face Recognition with Local Binary Patterns* (Vol. 3021). [https://doi.org/10.1007/978-3-540-24670-1\\_36](https://doi.org/10.1007/978-3-540-24670-1_36)
- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2024). Does pain influence control of muscle force? A systematic review and meta-analysis. *European journal of pain* (London, England). <https://doi.org/10.1002/ejp.4716>
- Ashraf, A. B., Lucey, S., Cohn, J. F., Chen, T., Ambadar, Z., Prkachin, K., Solomon, P., & Theobald, B. J. (2007). The painful face: Pain expression recognition using active appearance models. Proceedings of the 9th international conference on Multimodal interfaces,
- Atee, M., Hoti, K., Chivers, P., & Hughes, J. D. (2022). Faces of pain in dementia: learnings from a real-world study using a technology-enabled pain assessment tool. *Frontiers in Pain Research*, 3, 827551.
- Brody, L. R. (1985). Gender differences in emotional development: A review of theories and research. *Journal of personality*, 53(2), 102-149.
- Burt, J. B., Helmer, M., Shinn, M., Anticevic, A., & Murray, J. D. (2020). Generative modeling of brain maps with spatial autocorrelation. *NeuroImage*, 220, 117038. <https://doi.org/https://doi.org/10.1016/j.neuroimage.2020.117038>
- Canestri, R., Franco-Alvarenga, P. E., Brietzke, C., Vinícius, Í., Smith, S. A., Mager, A. R., Goethel, M. F., & Pires, F. O. (2021). Effects of experimentally induced muscle pain on endurance performance: A proof-of-concept study assessing neurophysiological and perceptual responses. *Psychophysiology*, 58(6), e13810. <https://doi.org/10.1111/psyp.13810>

- Christe, G., Crombez, G., Edd, S., Opsommer, E., Jolles, B. M., & Favre, J. (2021). Relationship between psychological factors and spinal motor behaviour in low back pain: a systematic review and meta-analysis. *Pain*, 162(3), 672-686. <https://doi.org/10.1097/j.pain.0000000000002065>
- Cohen, J. (2013). *Statistical Power Analysis for the Behavioral Sciences*. Elsevier Science.  
<https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=923159>
- Coll, M.-P., Slimani, H., Woo, C.-W., Wager, T. D., Rainville, P., Vachon-Presseau, É., & Roy, M. (2022). The neural signature of the decision value of future pain. *Proceedings of the National Academy of Sciences*, 119(23), e2119931119. <https://doi.org/10.1073/pnas.2119931119>
- Craig, K. D., Hyde, S. A., & Patrick, C. J. (1991). Genuine, suppressed and faked facial behavior during exacerbation of chronic low back pain. *Pain*, 46(2), 161-171. [https://doi.org/10.1016/0304-3959\(91\)90071-5](https://doi.org/10.1016/0304-3959(91)90071-5)
- Defrin, R., Lotan, M., & Pick, C. G. (2006). The evaluation of acute pain in individuals with cognitive impairment: a differential effect of the level of impairment. *Pain*, 124(3), 312-320.
- Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain Dynamics Underlying the Nonlinear Threshold for Access to Consciousness. *PLOS Biology*, 5(10), e260. <https://doi.org/10.1371/journal.pbio.0050260>
- Egede, J., Valstar, M., & Martinez, B. (2017). Fusing deep learned and hand-crafted features of appearance, shape, and dynamics for automatic pain estimation. 2017 12th IEEE international conference on automatic face & gesture recognition (FG 2017),
- Florea, C., Florea, L., & Vertan, C. (2015). Learning pain from emotion: transferred hot data representation for pain intensity estimation. Computer Vision-ECCV 2014 Workshops: Zurich, Switzerland, September 6-7 and 12, 2014, Proceedings, Part III 13,
- Gonzalez, R., & Faisal, Z. (2019). *Digital Image Processing Second Edition*.
- Graven-Nielsen, T. (2006). Fundamentals of muscle pain, referred pain, and deep tissue hyperalgesia. *Scandinavian Journal of Rheumatology*, 35(sup122), 1-43. <https://doi.org/10.1080/03009740600865980>

- Hadjistavropoulos, T., Craig, K. D., Duck, S., Cano, A., Goubert, L., Jackson, P. L., Mogil, J. S., Rainville, P., Sullivan, M. J. L., Williams, A. C. C., Vervoort, T., & Fitzgerald, T. D. (2011). A biopsychosocial formulation of pain communication. *Psychol Bull*, 137(6), 910-939. <https://doi.org/10.1037/a0023876>
- Kaltwang, S., Todorovic, S., & Pantic, M. (2015). Doubly sparse relevance vector machine for continuous facial behavior estimation. *IEEE transactions on pattern analysis and machine intelligence*, 38(9), 1748-1761.
- Karmann, A. J., Lautenbacher, S., Bauer, F., & Kunz, M. (2014). The influence of communicative relations on facial responses to pain: does it matter who is watching? *Pain Res Manag*, 19(1), 15-22. <https://doi.org/10.1155/2014/195286>
- Karmann, A. J., Lautenbacher, S., & Kunz, M. (2015). The role of inhibitory mechanisms in the regulation of facial expressiveness during pain. *Biol Psychol*, 104, 82-89. <https://doi.org/10.1016/j.biopsycho.2014.11.016>
- Kellgren, J. H. (1938). Referred Pains from Muscle. *Br Med J*, 1(4023), 325-327. <https://doi.org/10.1136/bmj.1.4023.325>
- Keogh, E. (2014). Gender differences in the nonverbal communication of pain: A new direction for sex, gender, and pain research? *Pain*, 155(10), 1927-1931.
- Kring, A. M., & Gordon, A. H. (1998). Sex differences in emotion: expression, experience, and physiology. *Journal of personality and social psychology*, 74(3), 686.
- Kunz, M., Chen, J.-I., & Rainville, P. (2020). Keeping an eye on pain expression in primary somatosensory cortex. *NeuroImage*, 217, 116885. <https://doi.org/https://doi.org/10.1016/j.neuroimage.2020.116885>
- Kunz, M., Gruber, A., & Lautenbacher, S. (2006). Sex differences in facial encoding of pain. *J Pain*, 7(12), 915-928. <https://doi.org/10.1016/j.jpain.2006.04.012>
- Lucey, P., Cohn, J. F., Matthews, I., Lucey, S., Sridharan, S., Howlett, J., & Prkachin, K. M. (2010). Automatically detecting pain in video through facial action units. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 41(3), 664-674.

- Lynch, M. (2001). Pain as the fifth vital sign. *Journal of intravenous nursing : the official publication of the Intravenous Nurses Society*, 24, 85-94.  
<https://doi.org/10.1111/j.1525-1497.2006.00415>
- Lyons, M. (2021). "Excavating AI" Re-Excavated: Debunking a Fallacious Account of the Jaffe Dataset. *SSRN Electronic Journal*.  
<https://doi.org/10.2139/ssrn.3900990>
- Lyons, M., Kamachi, M., & Gyoba, J. (2020). Coding Facial Expressions with Gabor Wavelets (IVC Special Issue).  
<https://doi.org/10.5281/zenodo.4029679>
- Merksey, H., & Bogduk, N. (1994). Classification of chronic pain. *Descriptions of Chronic Pain Syndromes and Definitions of Pain Term*, 59-71.
- Moon, E. C., Chambers, C. T., Larochette, A.-C., Hayton, K., Craig, K. D., & McGrath, P. J. (2008). Sex differences in parent and child pain ratings during an experimental child pain task. *Pain Research and Management*, 13(3), 225-230.
- NumPy. (2024). NumPy team.
- Pan, J., Zhan, L., Hu, C., Yang, J., Wang, C., Gu, L., Zhong, S., Huang, Y., Wu, Q., Xie, X., Chen, Q., Zhou, H., Huang, M., & Wu, X. (2018). Emotion Regulation and Complex Brain Networks: Association Between Expressive Suppression and Efficiency in the Fronto-Parietal Network and Default-Mode Network. *Front Hum Neurosci*, 12, 70.  
<https://doi.org/10.3389/fnhum.2018.00070>
- Parolini, F., Goethel, M., Becker, K., Fernandes, C., Fernandes, R. J., Ervilha, U. F., Santos, R., & Vilas-Boas, J. P. (2023). Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain. *Biomedicines*, 11(7). <https://doi.org/10.3390/biomedicines11072042>
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., Duchesnay, E., & Louppe, G. (2012). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, 12.

- Picard, M.-E., Kunz, M., Chen, J.-I., Coll, M.-P., Vachon-Preseu, É., Wager, T. D., & Rainville, P. (2024). A distributed brain response predicting the facial expression of acute nociceptive pain. In: eLife Sciences Publications, Ltd.
- Price, D. D., McGrath, P. A., Rafii, A., & Buckingham, B. (1983). The validation of visual analogue scales as ratio scale measures for chronic and experimental pain. *Pain*, *17*(1), 45-56. [https://doi.org/10.1016/0304-3959\(83\)90126-4](https://doi.org/10.1016/0304-3959(83)90126-4)
- Prkachin, K. M. (1992). The consistency of facial expressions of pain: a comparison across modalities. *Pain*, *51*(3), 297-306. [https://doi.org/10.1016/0304-3959\(92\)90213-u](https://doi.org/10.1016/0304-3959(92)90213-u)
- Prkachin, K. M., & Solomon, P. E. (2008). The structure, reliability and validity of pain expression: Evidence from patients with shoulder pain. *Pain*, *139*(2), 267-274.
- Schneider, P., Lautenbacher, S., & Kunz, M. (2024). Sex differences in facial expressions of pain: results from a combined sample. *Pain*, *165*(8), 1784-1792. <https://doi.org/10.1097/j.pain.0000000000003180>
- Sneddon, L. U. (2019). Evolution of nociception and pain: evidence from fish models. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*(1785), 20190290. <https://doi.org/10.1098/rstb.2019.0290>
- Stevens, B. J., Johnston, C. C., & Horton, L. (1994). Factors that influence the behavioral pain responses of premature infants. *Pain*, *59*(1), 101-109.
- Sullivan, M. J., Tripp, D. A., & Santor, D. (2000). Gender differences in pain and pain behavior: the role of catastrophizing. *Cognitive Therapy and Research*, *24*, 121-134.
- Symons, F. J., Harper, V., Shinde, S. K., Clary, J., & Bodfish, J. W. (2010). Evaluating a sham-controlled sensory-testing protocol for nonverbal adults with neurodevelopmental disorders: self-injury and gender effects. *The Journal of Pain*, *11*(8), 773-781.
- Tavakolian, M., & Hadid, A. (2018, 7-10 Oct. 2018). Deep Binary Representation of Facial Expressions: A Novel Framework for Automatic Pain Intensity Recognition. 2018 25th IEEE International Conference on Image Processing (ICIP),
- Team, O. (2024). OpenCV

- Vachon-Preseu, E., Roy, M., Woo, C.-W., Kunz, M., Martel, M.-O., Sullivan, M. J., Jackson, P. L., Wager, T. D., & Rainville, P. (2016). Multiple faces of pain: effects of chronic pain on the brain regulation of facial expression. *Pain*, 157(8), 1819-1830. <https://doi.org/10.1097/j.pain.0000000000000587>
- Valentin, G., & Maribo, T. (2014). Hand-held dynamometry fixated with a tripod is reliable for assessment of back extensor strength in women with osteoporosis. *Osteoporos Int*, 25(8), 2143-2149. <https://doi.org/10.1007/s00198-014-2743-0>
- van der Walt, S., Schönberger, J. L., Nunez-Iglesias, J., Boulogne, F., Warner, J. D., Yager, N., Gouillart, E., & Yu, T. (2014). scikit-image: image processing in Python. *PeerJ*, 2, e453. <https://doi.org/10.7717/peerj.453>
- Viola, P., & Jones, M. (2001, 8-14 Dec. 2001). Rapid object detection using a boosted cascade of simple features. Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. CVPR 2001,
- Zheng, W., Woo, C.-W., Yao, Z., Goldstein, P., Atlas, L. Y., Roy, M., Schmidt, L., Krishnan, A., Jepma, M., Hu, B., & Wager, T. D. (2020). Pain-Evoked Reorganization in Functional Brain Networks. *Cerebral Cortex*, 30(5), 2804-2822. <https://doi.org/10.1093/cercor/bhz276>
- Zhou, J., Hong, X., Su, F., & Zhao, G. (2016). Recurrent convolutional neural network regression for continuous pain intensity estimation in video. Proceedings of the IEEE conference on computer vision and pattern recognition workshops,

### General Discussion

Understanding low back pain requires a multidimensional approach that integrates biopsychosocial factors (parolini; goethel; becker; fernandes *et al.*, 2023). Within this context, this thesis used artificial neural networks to explore non-linear interactions between Biopsychosocial variables, addressing the underlying mechanisms of low back pain in an innovative way. The application of this technique made it possible to create a mathematic representation of the pain model and posteriorly test the interaction between factors, following the definition of the International Association for the Study of Pain (IASP). Based on this approach, it was possible to analyse the variables involved and offer new perspectives on the motor and emotional processes that modulate the experience of low back pain, providing a deeper and more precise understanding of its dynamics.

Among the factors that modulate low back pain, physical activity has emerged as a key element (Heneweer *et al.*, 2009; Huijnen *et al.*, 2010; Marshall *et al.*, 2017; Michaela *et al.*, 2020; Parolini *et al.*, 2023). The canonical correlation analysis carried out in this study, which involved the relationship between mental health and lumbar spine functionality, revealed that practising physical activities has a positive effect on mental health, which in turn directly influences spinal functionality. These findings corroborate previous studies showing that regular physical exercise not only improves physical aspects, such as muscle strength and range of motion, but also has beneficial effects on mental health, reducing symptoms of anxiety, depression and stress (Michaela *et al.*, 2020). The ability of physical activity to modulate emotional and psychological response can be attributed to the increased release of neurotransmitters such as endorphins, serotonin and dopamine, which act to reduce stress and improve general well-being (Van Dillen *et al.*, 2020; Zheng *et al.*, 2023).

In addition, the results indicate that the intensity of physical activity plays a fundamental role in psychological responses and functionality related to low back pain (Alzahrani et al., 2019; Huijnen et al., 2010; Verbrugghe et al., 2019; Zheng et al., 2023). It has been observed that while low-intensity activities have a positive impact on reducing stress and anxiety, high-intensity activities can, in some cases, promote a feeling of pain relief, but can also be associated with an increase in the perception of pain intensity, especially in individuals with a predisposition to chronic conditions (Han et al., 2022; Heneweer et al., 2009; Izquierdo-Alventosa et al., 2020)). The relationship between the intensity of physical activity and low back pain follows a U-shaped curve, where both a lack of exercise and excessive vigorous exercise can be detrimental to spinal health and increase pain perception (Heneweer et al., 2009; Marshall et al., 2017).

Studies show that regular physical activity can significantly contribute to the prevention of recurrent episodes of low back pain (Shiri & Falah-Hassani, 2017) by improving muscle strength, flexibility (Van Dillen et al., 2020) and postural control (Gordon & Bloxham, 2016; Paolucci et al., 2018). , which facilitates the reduction of pain associated with spinal overload However, it is important to note that while exercise can help relieve pain and improve mental health, it should not be excessive, especially in cases of acute low back pain, as the practice can eventually exacerbate it to the point of becoming a threat (Han et al., 2022; Lee & Park, 2017). The fear and avoidance model suggests that individuals who interpret pain as a threat may develop a fear of movement and avoid physical activity, leading to inactivity, physical deconditioning and perpetuation of pain (Han et al., 2022; Lee & Park, 2017; Marshall et al., 2017). In this way, the gradual introduction of physical activities at the appropriate intensity can help break this cycle, reducing fear and avoidance and improving functionality (Andrews et al., 2012; Christe et al., 2020). This bidirectional relationship suggests that while psychological factors can influence pain perception and physical activity, physical activity can also have a significant impact on modulating these factors (Van Dillen et al., 2020; Verbrugghe et al., 2019; Zheng et al., 2023).

The relationship between physical activity and psychological factors not only influences the perception of pain, but also directly impacts the functional capacity of individuals (Andrews et al., 2012; Izquierdo-Alventosa et al., 2020). Muscle weakness and loss of trunk stability are central components of low back pain and can directly affect motivation and the ability to exercise (Lee et al., 1999; Salamat et al., 2023). The literature shows that weakness of the extensor muscles of the spine is associated with reduced postural control and an increased risk of recurrence of low back pain (Kato et al., 2019; Salamat et al., 2023; Suzuki & Endo, 1983). Dysfunction in these muscles not only impairs motor capacity, but also significantly impacts quality of life, with profound physical and psychological implications (Cholewicki & McGill, 1996; Neufuss et al., 2014),

Thus, the use of the developed dynamometer, validated in this study, made it possible not only to quantify trunk extension force with high precision, but also to measure force steadiness, a fundamental aspect for understanding motor control in patients with low back pain, addressing one of the gaps in the literature (Arvanitidis et al., 2025). The calibration of the device showed high accuracy, with excellent comparability with commercial reference equipment (Althobaiti & Falla, 2023; Althobaiti et al., 2022; De Blaiser et al., 2018; Valentin & Maribo, 2014; Yang et al., 2020), validating its usability. In addition, the results reinforce the feasibility of using the dynamometer to assess the steadiness of muscle strength, one of the essential factors in understanding motor control during low back pain (Dieën et al., 2019a, 2019b; Gruther et al., 2009; Macedo et al., 2009).

The use of the developed dynamometer, together with decomposition electromyography, enabled a detailed analysis of the neuromuscular responses to experimentally induced acute low back pain during the maintenance of force steadiness in trunk extension at 20% of maximum force. In this context, a dynamic and lateralised neuromuscular reorganisation was identified, characterised by distinct activation patterns between the muscles ipsilateral and contralateral to the pain site (Dieën et al., 2019b; Heming et al., 2019; Schabrun et al., 2016).

In the right longissimus muscle (ipsilateral to the induction of pain), the changes were more subtle, with no significant variations in the firing rate or amplitude of the action potentials of the motor units, but with adjustments in the latency of recruitment, suggesting a modulation in the temporality of neuromuscular activation. On the other hand, in the left longissimus muscle (contralateral to the induction of pain), a significant increase in the firing rate of the motor units was observed in the G1 group, indicating a compensatory strategy of the central nervous system to intensify the activation of the unaffected side, possibly in order to preserve the force steadiness (Martinez-Valdes et al., 2020, Zhang et al., 2024).

This increase in the firing rate of the motor units was accompanied by changes in the complexity of the electromyographic signal, evidenced in the entropy of the signal, which may reflect neurophysiological adaptations to optimise motor control in the face of the challenge imposed by pain (Tucker & Hodges, 2010; Zurcher et al., 2007). This statement reinforces our hypothesis that induced pain not only alters muscle activation patterns locally, but also promotes systemic adjustments in motor control, highlighting the complexity of the interaction between pain, neural control and force steadiness.

This complexity in muscle activity represents one of the first compensatory mechanisms activated by the central nervous system to mitigate the effects of acute low back pain (Rohel et al., 2022; Viseux et al., 2022). This signal complexification may indicate an initial attempt to improve postural stability and neurofunctional efficiency in the face of nociceptive stress, possibly by recruiting more variable motor patterns to maintain functionality (Carvalho & Almeida, 2019; Tsao et al., 2008; Zhang et al., 2024). However, this adaptive response is not sufficient to sustain steadiness of force over time, showing that pain compromises not only the peripheral regulation of motor control, but also alters the interaction between cortical commands and muscle response (Poortvliet et al., 2019; Poortvliet et al., 2015; Tsao et al., 2008).

The reduction in cortico-muscular coherence (CMC) in the beta and gamma bands in the motor cortex ipsilateral to the induction of pain indicates a direct interference of pain in the communication between the motor cortex and the lumbar muscles, resulting in less synchronisation between cortical commands and force generation (Heming et al., 2019; Poortvliet et al., 2019). The decrease in CMC to pain reflects a reduction in efficiency in neural transmission, compromising the stability of isometric contraction, which is fundamental for postural maintenance and precise control of motor tasks (Tan et al., 2019; Wang et al., 2023). Previous studies (Liu et al., 2019; Poortvliet et al., 2019) have shown that pain significantly compromises CMC, impairing the central nervous system's ability to accurately modulate motor recruitment. These results are in line with our findings that pain not only alters sensory-motor processing, but also compromises dynamic force regulation, resulting in deterioration of force steadiness during submaximal contractions.

Therefore, the asymmetry in neural modulation, characterised by increased entropy in the contralateral muscle and reduced CMC in the muscle ipsilateral to the pain, suggests that the central nervous system redistributes motor control to minimise the nociceptive impact on task execution (Poortvliet et al., 2019; Poortvliet et al., 2015; Tucker & Hodges, 2010; Wang et al., 2023; Zhang et al., 2024). The increase in contralateral entropy may indicate an attempt to amplify motor recruitment variability to compensate for dysfunction on the affected side, while the reduction in ipsilateral CMC reflects the idea that pain not only modifies local corticomotor excitability, but also affects coordination between central nervous system and peripheral nervous system, impacting the distribution of motor control between the sides of the body (Poortvliet et al., 2019; Tsao et al., 2008; Viseux et al., 2022; Zhang et al., 2024; Zurcher et al., 2007).

At the same time, increased activity in the alpha and beta bands in the FP1 region indicates intensified activation of the prefrontal cortex, a phenomenon that may reflect a compensatory mechanism to modulate motor control in the face of nociceptive interference (Chowdhury et al., 2022; Franciotti et al., 2009; Gross et al., 2007). This additional cortical recruitment suggests that pain imposes an

increased cognitive demand for the maintenance of the motor task, requiring greater involvement of cortical areas responsible for sensory-motor integration and motor planning (Dieën et al., 2019b; Poortvliet et al., 2019; Schabrun et al., 2016; Tsao et al., 2008; Zhang et al., 2024). Although this adaptation may be functional in the short term, its long-term effectiveness is questionable, since it depends on the redistribution of neural resources, potentially resulting in less efficient strategies under prolonged pain conditions.

In this context, the modulation of cortical activity in the Cz region provides additional evidence about the adaptive strategies of the central nervous system in the face of low back pain. The suppression of alpha and beta oscillations, accompanied by an increase in gamma activity, suggests a reduction in intracortical inhibition and an increase in the excitability of the primary motor cortex (Chowdhury et al., 2025; Chowdhury et al., 2022; Poortvliet et al., 2019). While decreased alpha and beta oscillations facilitate motor activation, increased gamma activity may indicate a state of neural hyperexcitability, reflecting a compensatory mechanism to amplify motor output and mitigate the effects of pain on motor performance (Chowdhury et al., 2025; Poortvliet et al., 2019; Tan et al., 2019; Viseux et al., 2022). However, this strategy may come at a functional cost, since high gamma oscillations are often associated with less precise motor control, explaining why, despite central nervous system adaptations, force Steadiness remains impaired (Gross et al., 2007; Poortvliet et al., 2015; Tan et al., 2019)

Thus, central nervous system adaptation to nociceptive interference is partial and insufficient to completely restore force steadiness. Although compensatory mechanisms are employed, they do not fully normalise motor control, resulting in a strategic but ineffective modulation of neuromuscular activation (Macedo et al., 2009; Poortvliet et al., 2019; Schabrun et al., 2016; Tsao et al., 2008; Viseux et al., 2022; Zhang et al., 2024). Our results challenge traditional conceptions that associate pain only with reduced neuromuscular function. Instead, acute low back pain induces a dynamic reorganisation of motor control, characterised by cortical adaptations and redistribution of neuromuscular resources (Zhang et al.,

2024). This reorganisation is evidenced by the modulation of connectivity between the motor cortex and the lumbar muscles, suggesting a compensatory mechanism to preserve force steadiness, even under sensory interference and impaired force steadiness (Poortvliet et al., 2019). The suppression of alpha and beta oscillations at Cz, combined with increased gamma activity, reinforces the hypothesis of reduced intracortical inhibition and increased excitability of the primary motor cortex (Gross et al., 2007; Hauck et al., 2007). However, this strategy may not be sustainable in the long term, as the redistribution of neural resources may compromise the efficiency of motor control in prolonged pain scenarios (Ecsy et al., 2018; Tan et al., 2019).

This neural reorganization is not restricted to motor control, but also modulates facial expressions arising from pain, highlighting the interdependence between motor mechanisms and non-verbal communication of the painful experience. The modulation of connectivity between the motor cortex and the lumbar muscles discussed above suggests that acute pain induces neurophysiological changes that not only compromise force steadiness but can also influence the activation patterns of the structures involved in the facial expression of pain (Poortvliet et al., 2019; Zhang et al., 2024). In this sense, the software developed in this study was able to detect variations in facial expressions associated with pain in the pain-free and during pain conditions, in both sexes. These facial changes resulting from low back pain may be related to the neural reorganization that is induced by pain, impacting both the motor control of skeletal muscles and the processes underlying the perception and communication of pain (Pan et al., 2018; Picard et al., 2024; Prkachin, 1992; Zheng et al., 2023). Although facial expressions of pain did not differ significantly between men and women, subjective reports during pain, were higher in men, suggesting that distinct neural and psychological factors modulate these two aspects of the pain experience (Moon et al., 2008; Schneider et al., 2024).

The motor areas of the frontoparietal cortex play a central role in integrating the sensory and affective components of pain, contributing to its prediction and emotional regulation (Picard et al., 2024). These regions not only modulate the

motor response to pain, but also influence its facial expression, reflecting the interaction between motor control and emotional processing (Burt et al., 2020; Pan et al., 2018). Thus, our results reinforce the interconnection between pain perception, motor control and communication, indicating that facial expressions result from the neural modulation of pain, while subjective reports may be more influenced by individual and psychological factors.

This thesis has contributed to filling gaps in the literature on the steadiness of force during acute low back pain induced experimentally during submaximal efforts. The findings indicated that pain causes a dynamic and lateralised neuromuscular reorganisation, reflected in distinct activation patterns between the muscles ipsilateral and contralateral to the pain site. This adaptation associated with changes in cortical activity, especially an increase in alpha and beta waves in the prefrontal cortex, which influence both emotional regulation and motor control in the face of nociceptive stimuli. In addition, the results suggest that motor control is impacted not only by the perception of pain, but also by the need to modulate the emotional response associated with it. This neural interaction may, in part, explain discrepancies between facial expressions. Therefore, these results highlight the complexity of the mechanisms underlying pain and their implications for understanding and treating musculoskeletal pain.

In clinical terms, the research highlights the need for more integrated and personalised therapeutic strategies. By simultaneously addressing psychological and neuromuscular factors, as well as facial expressions arising from pain, the results suggest that the treatment of low back pain should go beyond simple pharmacological or physical intervention, also incorporating interventions aimed at the psychological control of pain, to mitigate negative emotional responses that can aggravate the condition. The accuracy of the computer models developed proposes a more individualised therapeutic management, considering the specific characteristics of each patient, which potentially increases the effectiveness of the interventions.

Thus, the contribution of this study lies not only in the use of advanced technologies for pain analysis, but in the creation of an integrated and comprehensive model that unites psychological, neuromuscular and biomechanical factors, providing a more complete and personalised view of the treatment of acute low back pain, with a view to reducing new recurrences. By integrating these multiple layers of data, the study opens new possibilities for understanding pain and formulating more effective therapeutic strategies, with the potential to transform the clinical management of this very prevalent condition. Therefore, healthcare professionals should consider prescribing exercise programmes of appropriate intensity for individuals with acute low back pain, not only to improve physical health, but also to address psychological factors that can influence the experience of pain.

## Reference

- Althobaiti, S., & Falla, D. (2023). Reliability and criterion validity of handheld dynamometry for measuring trunk muscle strength in people with and without chronic non-specific low back pain. *Musculoskelet Sci Pract*, *66*, 102799. <https://doi.org/10.1016/j.msksp.2023.102799>
- Althobaiti, S., Rushton, A., Aldahas, A., Falla, D., & Heneghan, N. R. (2022). Practicable performance-based outcome measures of trunk muscle strength and their measurement properties: A systematic review and narrative synthesis. *PLOS ONE*, *17*(6), e0270101. <https://doi.org/10.1371/journal.pone.0270101>
- Alzahrani, H., Mackey, M., Stamatakis, E., Zadro, J., & Shirley, D. (2019). The association between physical activity and low back pain: a systematic review and meta-analysis of observational studies. *Scientific Reports*, *9*. <https://doi.org/10.1038/s41598-019-44664-8>
- Andrews, N., Strong, J., & Meredith, P. (2012). Activity pacing, avoidance, endurance, and associations with patient functioning in chronic pain: a systematic review and meta-analysis. *Archives of physical medicine and rehabilitation*, *93*(11), 2109-2121. <https://doi.org/10.1016/j.apmr.2012.05.029>

- Arvanitidis, M., Falla, D., Sanderson, A., & Martinez-Valdes, E. (2025). Does pain influence control of muscle force? A systematic review and meta-analysis. *Eur J Pain*, 29(2), e4716. <https://doi.org/10.1002/ejp.4716>
- Burt, J. B., Helmer, M., Shinn, M., Anticevic, A., & Murray, J. D. (2020). Generative modeling of brain maps with spatial autocorrelation. *Neuroimage*, 220, 117038. <https://doi.org/10.1016/j.neuroimage.2020.117038>
- Carvalho, R., & Almeida, G. (2019). Aspectos sensoriais e cognitivos do controle postural. *Revista Neurociências*, 17, 156-160. <https://doi.org/10.34024/rnc.2009.v17.8576>
- Cholewicki, J., & McGill, S. M. (1996). Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech (Bristol)*, 11(1), 1-15. [https://doi.org/10.1016/0268-0033\(95\)00035-6](https://doi.org/10.1016/0268-0033(95)00035-6)
- Chowdhury, N. S., Bi, C., Furman, A. J., Chiang, A. K. I., Skippen, P., Si, E., Millard, S. K., Margerison, S. M., Spies, D., Keaser, M. L., Da Silva, J. T., Chen, S., Schabrun, S. M., & Seminowicz, D. A. (2025). Predicting Individual Pain Sensitivity Using a Novel Cortical Biomarker Signature. *JAMA Neurology*, 82(3), 237-246. <https://doi.org/10.1001/jamaneurol.2024.4857>
- Chowdhury, N. S., Chang, W.-J., Millard, S. K., Skippen, P., Bilaska, K., Seminowicz, D. A., & Schabrun, S. M. (2022). The Effect of Acute and Sustained Pain on Corticomotor Excitability: A Systematic Review and Meta-Analysis of Group and Individual Level Data. *The Journal of Pain*, 23(10), 1680-1696. <https://doi.org/10.1016/j.jpain.2022.04.012>
- Christe, G., Crombez, G., Opsommer, E., Jolles, B., & Favre, J. (2020). Relationship between psychological factors and spinal motor behaviour in low back pain: a systematic review and meta-analysis. *PAIN*, 162(3), 672-686. <https://doi.org/10.1097/j.pain.0000000000002065>
- De Blaiser, C., De Ridder, R., Willems, T., Danneels, L., & Roosen, P. (2018). Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population. *Phys Ther Sport*, 34, 180-186. <https://doi.org/10.1016/j.ptsp.2018.10.005>

- Dieën, J., Reeves, N., Kawchuk, G., Kawchuk, G., Dillen, L., & Hodges, P. (2019a). Analysis of Motor Control in Patients With Low Back Pain: A Key to Personalized Care? *The Journal of orthopaedic and sports physical therapy*, 49 6, 380-388. <https://doi.org/10.2519/jospt.2019.7916>
- Dieën, J., Reeves, N., Kawchuk, G., Kawchuk, G., Dillen, L., & Hodges, P. (2019b). Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. *The Journal of orthopaedic and sports physical therapy*, 49 6, 370-379. <https://doi.org/10.2519/jospt.2019.7917>
- Ecsy, K., Brown, C. A., & Jones, A. K. P. (2018). Cortical nociceptive processes are reduced by visual alpha-band entrainment in the human brain. *European Journal of Pain*, 22(3), 538-550. <https://doi.org/https://doi.org/10.1002/ejp.1136>
- Franciotti, R., Ciancetta, L., Della Penna, S., Belardinelli, P., Pizzella, V., & Romani, G. L. (2009). Modulation of alpha oscillations in insular cortex reflects the threat of painful stimuli. *Neuroimage*, 46(4), 1082-1090. <https://doi.org/10.1016/j.neuroimage.2009.03.034>
- Gordon, R., & Bloxham, S. (2016). A Systematic Review of the Effects of Exercise and Physical Activity on Non-Specific Chronic Low Back Pain. *Healthcare*, 4. <https://doi.org/10.3390/healthcare4020022>
- Gross, J., Schnitzler, A., Timmermann, L., & Ploner, M. (2007). Gamma Oscillations in Human Primary Somatosensory Cortex Reflect Pain Perception. *PLOS Biology*, 5(5), e133. <https://doi.org/10.1371/journal.pbio.0050133>
- Gruther, W., Wick, F., Paul, B., Leitner, C., Posch, M., Matzner, M., Crevenna, R., & Ebenbichler, G. (2009). Diagnostic accuracy and reliability of muscle strength and endurance measurements in patients with chronic low back pain. *Journal of rehabilitation medicine*, 41 8, 613-619. <https://doi.org/10.2340/16501977-0391>
- Han, S. S., Han, Y. H., Tong, W. X., Wang, G. X., Ke, Y. Z., Meng, S. Q., Guo, Q., Cui, Z. L., Zhang, J. Y., Ye, Y. P., Zhang, Y., Li, Y. X., & Li, B. (2022). Chinese college students COVID-19 phobia and negative moods: Moderating effects of physical exercise behavior. *Front Public Health*, 10, 1046326. <https://doi.org/10.3389/fpubh.2022.1046326>

- Hauck, M., Lorenz, J., & Engel, A. K. (2007). Attention to Painful Stimulation Enhances  $\gamma$ -Band Activity and Synchronization in Human Sensorimotor Cortex. *The Journal of Neuroscience*, 27(35), 9270-9277. <https://doi.org/10.1523/jneurosci.2283-07.2007>
- Heming, E. A., Cross, K. P., Takei, T., Cook, D. J., & Scott, S. H. (2019). Independent representations of ipsilateral and contralateral limbs in primary motor cortex. *Elife*, 8. <https://doi.org/10.7554/eLife.48190>
- Heneweer, H., Vanhees, L., & Picavet, S. J. H. (2009). Physical activity and low back pain: A U-shaped relation? *PAIN*, 143(1), 21-25. <https://doi.org/10.1016/j.pain.2008.12.033>
- Huijnen, I., Verbunt, J., Peters, M., Delespaul, P., Kindermans, H., Roelofs, J., Goossens, M., & Seelen, H. (2010). Do depression and pain intensity interfere with physical activity in daily life in patients with Chronic Low Back Pain? *PAIN*, 150, 161-166. <https://doi.org/10.1016/j.pain.2010.04.021>
- Izquierdo-Alventosa, R., Inglés, M., Cortés-Amador, S., Gimeno-Mallench, L., Chirivella-Garrido, J., Kropotov, J., & Serra-Añó, P. (2020). Low-Intensity Physical Exercise Improves Pain Catastrophizing and Other Psychological and Physical Aspects in Women with Fibromyalgia: A Randomized Controlled Trial. *International Journal of Environmental Research and Public Health*, 17. <https://doi.org/10.3390/ijerph17103634>
- Kato, S., Murakami, H., Demura, S., Yoshioka, K., Shinmura, K., Yokogawa, N., Igarashi, T., Yonezawa, N., Shimizu, T., & Tsuchiya, H. (2019). Abdominal trunk muscle weakness and its association with chronic low back pain and risk of falling in older women. *BMC Musculoskeletal Disorders*, 20. <https://doi.org/10.1186/s12891-019-2655-4>
- Lee, J., & Park, S. (2017). The relationship between physical capacity and fear avoidance beliefs in patients with chronic low back pain. *Journal of Physical Therapy Science*, 29, 1712-1714. <https://doi.org/10.1589/jpts.29.1712>
- Lee, J.-H., Hoshino, Y., Nakamura, K., Kariya, Y., Saita, K., & Ito, K. (1999). Trunk muscle weakness as a risk factor for low back pain. A 5-year prospective study. *Spine*, 24 1, 54-57.

- Liu, J., Sheng, Y., & Liu, H. (2019). Corticomuscular Coherence and Its Applications: A Review [Review]. *Frontiers in Human Neuroscience*, 13. <https://doi.org/10.3389/fnhum.2019.00100>
- Macedo, L., Maher, C., Latimer, J., & McAuley, J. (2009). Motor Control Exercise for Persistent, Nonspecific Low Back Pain: A Systematic Review. *Physical Therapy*, 89, 25-29. <https://doi.org/10.2522/ptj.20080103>
- Marshall, P. W. M., Schabrun, S., & Knox, M. F. (2017). Physical activity and the mediating effect of fear, depression, anxiety, and catastrophizing on pain related disability in people with chronic low back pain. *PLOS ONE*, 12(7), e0180788. <https://doi.org/10.1371/journal.pone.0180788>
- Michaela, P., Alan, P. B., Melinda, C., Tim, C., Rhiannon, P., Nigel, S., & Alexandra, P. (2020). Physical activity and exercise in youth mental health promotion: a scoping review. *BMJ Open Sport & Exercise Medicine*, 6(1), e000677. <https://doi.org/10.1136/bmjsem-2019-000677>
- Moon, E. C., Chambers, C. T., Larochette, A. C., Hayton, K., Craig, K. D., & McGrath, P. J. (2008). Sex differences in parent and child pain ratings during an experimental child pain task. *Pain Res Manag*, 13(3), 225-230. <https://doi.org/10.1155/2008/457861>
- Neufuss, J., Hesse, B., Thorpe, S. K., Vereecke, E. E., D'Aout, K., Fischer, M. S., & Schilling, N. (2014). Fibre type composition in the lumbar perivertebral muscles of primates: implications for the evolution of orthogrady in hominoids. *J Anat*, 224(2), 113-131. <https://doi.org/10.1111/joa.12130>
- Pan, J., Zhan, L., Hu, C., Yang, J., Wang, C., Gu, L., Zhong, S., Huang, Y., Wu, Q., Xie, X., Chen, Q., Zhou, H., Huang, M., & Wu, X. (2018). Emotion Regulation and Complex Brain Networks: Association Between Expressive Suppression and Efficiency in the Fronto-Parietal Network and Default-Mode Network [Original Research]. *Frontiers in Human Neuroscience*, 12. <https://doi.org/10.3389/fnhum.2018.00070>
- Paolucci, T., Attanasi, C., Cecchini, W., Marazzi, A., Capobianco, S., & Santilli, V. (2018). Chronic low back pain and postural rehabilitation exercise: a literature review. *Journal of Pain Research*, 12, 95-107. <https://doi.org/10.2147/JPR.S171729>

- Parolini, F., Goethel, M., Becker, K., Fernandes, C., Fernandes, R. J., Ervilha, U. F., Santos, R., & Vilas-Boas, J. P. (2023). Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness and Pain as Defined by the International Association for the Study of Pain. *Biomedicines*, 11(7). <https://doi.org/10.3390/biomedicines11072042>
- Picard, M. E., Kunz, M., Chen, J. I., Coll, M. P., Vachon-Preseu, E., Wager, T. D., & Rainville, P. (2024). A distributed brain response predicting the facial expression of acute nociceptive pain. *Elife*, 12. <https://doi.org/10.7554/eLife.87962>
- Poortvliet, P. C., Tucker, K. J., Finnigan, S., Scott, D., & Hodges, P. W. (2019). Experimental Pain Decreases Corticomuscular Coherence in a Force- But Not a Position-Control Task. *J Pain*, 20(2), 192-200. <https://doi.org/10.1016/j.jpain.2018.08.012>
- Poortvliet, P. C., Tucker, K. J., Finnigan, S., Scott, D., Sowman, P., & Hodges, P. W. (2015). Cortical activity differs between position- and force-control knee extension tasks. *Experimental Brain Research*, 233(12), 3447-3457. <https://doi.org/10.1007/s00221-015-4404-8>
- Prkachin, K. M. (1992). The consistency of facial expressions of pain: a comparison across modalities. *PAIN*, 51(3). [https://journals.lww.com/pain/fulltext/1992/12000/the\\_consistency\\_of\\_facial\\_expressions\\_of\\_pain\\_a.6.aspx](https://journals.lww.com/pain/fulltext/1992/12000/the_consistency_of_facial_expressions_of_pain_a.6.aspx)
- Rohel, A., Desmons, M., Léonard, G., Desgagnés, A., da Silva, R., Simoneau, M., Mercier, C., & Massé-Alarie, H. (2022). The influence of experimental low back pain on neural networks involved in the control of lumbar erector spinae muscles. *Journal of Neurophysiology*, 127(6), 1593-1605. <https://doi.org/10.1152/jn.00030.2022>
- Salamat, S., Talebian, S., Maroufi, N., Kalbassi, G., Salamat, D., & O'Sullivan, K. (2023). People With Low Back Pain Exhibit Higher Trunk Muscle Activity and Impaired Postural Control During Static and Dynamic Functional Tasks: A Cross-Sectional Study. *Journal of applied biomechanics*, 1-8. <https://doi.org/10.1123/jab.2023-0033>
- Schabrun, S. M., Christensen, S. W., Mrachacz-Kersting, N., & Graven-Nielsen, T. (2016). Motor Cortex Reorganization and Impaired Function in the

- Transition to Sustained Muscle Pain. *Cereb Cortex*, 26(5), 1878-1890.  
<https://doi.org/10.1093/cercor/bhu319>
- Schneider, P., Lautenbacher, S., & Kunz, M. (2024). Sex differences in facial expressions of pain: results from a combined sample. *PAIN*, 165(8), 1784-1792. <https://doi.org/10.1097/j.pain.0000000000003180>
- Shiri, R., & Falah-Hassani, K. (2017). Does leisure time physical activity protect against low back pain? Systematic review and meta-analysis of 36 prospective cohort studies. *British Journal of Sports Medicine*, 51, 1410-1418. <https://doi.org/10.1136/bjsports-2016-097352>
- Suzuki, N., & Endo, S. (1983). A Quantitative Study of Trunk Muscle Strength and Fatigability in the Low- Back-Pain Syndrome. *Spine*, 8, 69-74.  
<https://doi.org/10.1097/00007632-198301000-00012>
- Tan, L. L., Oswald, M. J., Heintz, C., Retana Romero, O. A., Kaushalya, S. K., Monyer, H., & Kuner, R. (2019). Gamma oscillations in somatosensory cortex recruit prefrontal and descending serotonergic pathways in aversion and nociception. *Nature Communications*, 10(1), 983.  
<https://doi.org/10.1038/s41467-019-08873-z>
- Tsao, H., Galea, M. P., & Hodges, P. W. (2008). Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain*, 131(8), 2161-2171. <https://doi.org/10.1093/brain/awn154>
- Tucker, K. J., & Hodges, P. W. (2010). Changes in motor unit recruitment strategy during pain alters force direction. *European Journal of Pain*, 14(9), 932-938. <https://doi.org/https://doi.org/10.1016/j.ejpain.2010.03.006>
- Valentin, G., & Maribo, T. (2014). Hand-held dynamometry fixated with a tripod is reliable for assessment of back extensor strength in women with osteoporosis. *Osteoporos Int*, 25(8), 2143-2149.  
<https://doi.org/10.1007/s00198-014-2743-0>
- Van Dillen, L., Lanier, V., Steger-May, K., Wallendorf, M., Norton, B., Civello, J., Czuppon, S., Francois, S., Roles, K., & Lang, C. (2020). Effect of Motor Skill Training in Functional Activities vs Strength and Flexibility Exercise on Function in People With Chronic Low Back Pain. *JAMA Neurology*, 78, 1-11. <https://doi.org/10.1001/jamaneurol.2020.4821>

- Verbrugghe, J., Agten, A., Stevens, S., Hansen, D., Demoulin, C., Eijnde, B., Vandenameele, F., & Timmermans, A. (2019). Exercise Intensity Matters in Chronic Nonspecific Low Back Pain Rehabilitation. *Medicine & Science in Sports & Exercise*. <https://doi.org/10.1249/MSS.0000000000002078>
- Viseux, F. J. F., Simoneau, M., & Billot, M. (2022). A Comprehensive Review of Pain Interference on Postural Control: From Experimental to Chronic Pain. *Medicina*, 58(6), 812. <https://www.mdpi.com/1648-9144/58/6/812>
- Wang, X., Luo, Z., Zhang, M., Zhao, W., Xie, S., Wong, S. F., Hu, H., & Li, L. (2023). The interaction between changes of muscle activation and cortical network dynamics during isometric elbow contraction: a sEMG and fNIRS study. *Front Bioeng Biotechnol*, 11, 1176054. <https://doi.org/10.3389/fbioe.2023.1176054>
- Yang, S., Wu, W., Zhang, C., Wang, D., Chen, C., Tang, Y., Li, K., Xu, J., & Luo, F. (2020). Reliability and validity of three isometric back extensor strength assessments with different test postures. *J Int Med Res*, 48(2), 300060519885268. <https://doi.org/10.1177/0300060519885268>
- Zhang, C., Li, Y., Zhang, Z., Fu, R., Yin, Y., Wang, H., Li, N., Feng, C., Yu, Q., Jiang, G., & Wang, C. (2024). Motor Control Exercise Modulates the Neural Plasticity of the Default Mode Network in Patients with Chronic Low Back Pain. *Pain Physician*, 27(1), E55-e64.
- Zheng, X., Reneman, M., Preuper, R., Otten, E., & Lamoth, C. (2023). Relationship between physical activity and central sensitization in chronic low back pain: Insights from machine learning. *Computer methods and programs in biomedicine*, 232, 107432. <https://doi.org/10.2139/ssrn.4218539>
- Zurcher, U., Kaufman, M., Vyhnaek, B., & Sung, P. (2007). Entropy measures of back muscles EMG for subjects with and without pain. *Bulletin of the American Physical Society*. <https://consensus.app/papers/entropy-measures-of-back-muscles-emg-for-subjects-with-and-zurcher-kaufman/226a6d0bfe565a39aebdd127b2c4321c/>

### Conclusions

This thesis proposed an integrated approach to the study of acute low back pain, combining mathematical modeling, neurophysiological analysis, and behavioral biomarkers. The starting point was the computational modeling of the relationships between physiological and psychological variables, using artificial neural network to identify complex patterns in the pain experience. This strategy enabled a quantitative analysis aligned with the definition of the International Association for the Study of Pain (IASP), contributing to the understanding of the interactions between emotional, biomechanical, and neuromuscular factors in pain modulation.

The investigation progressed to explore the impact of physical activity on the functionality and motor control of individuals with low back pain. The findings demonstrated that different exercise intensities influence force steadiness and pain perception, highlighting the role of physical activity in neuromuscular modulation and rehabilitation. It was shown that pain alters motor recruitment and compromises the ability to control force, reinforcing the need for therapeutic strategies that consider both the effects of pain on biomechanics and its interaction with the central nervous system.

Furthermore, the analysis of neuromuscular reorganization in the presence of low back pain revealed asymmetric muscle activation patterns and changes in cortical activity, with an increase in alpha and beta oscillations in the prefrontal cortex. These findings suggest that acute pain induces not only peripheral adaptations but also modifications in central modulation, emphasizing the interdependence between motor control and nociceptive processing.

Another relevant methodological advancement was the use of advanced imaging techniques for the objective quantification of facial expressions associated with pain. The implementation of Haar Cascade and Local Binary Pattern Histogram

(LBPH) algorithms enabled the identification of specific facial patterns, offering a complementary method to subjective reports and strengthening the validity of pain assessment.

In summary, this thesis significantly contributes to the understanding of the underlying mechanisms of acute low back pain by integrating computational, biomechanical, and neurophysiological approaches. The results presented provide support for the development of more precise and individualized therapeutic strategies, promoting advancements in the assessment and rehabilitation of musculoskeletal pain. Additionally, the findings of this research open new perspectives for future investigations that delve deeper into the neural and motor processes involved in pain, enabling more effective and evidence-based interventions.

## Chapter 10

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### Recommendations for future research

This thesis has provided a comprehensive and integrated understanding of the multiple factors that influence low back pain, ranging from psychological and behavioral aspects to neurophysiological mechanisms. To advance this field, future studies should consider multidisciplinary approaches that integrate the following directions:

- Development of a comprehensive computational model capable of integrating multiple variables biopsychosocial for a more precise analysis of low back pain. The creation of advanced mathematical models will enable the identification of nonlinear interactions among these factors, contributing to a more refined understanding of the underlying mechanisms of pain and its influence on motor control and functionality.
- Furthermore, the application of artificial intelligence could facilitate the development of predictive systems that anticipate individual pain response patterns. This would enable the customization of therapeutic approaches, making them more effective and tailored to the specific needs of each patient.
- Another important area to be explored in future studies is the validation of interventions based on physical activity modulation, considering different intensities and training protocols. Investigating how these interventions affect motor stability and neuromuscular reorganization in the context of acute low back pain could provide more accurate guidelines for exercise prescription.

Finally, longitudinal studies are recommended to analyze the evolution of neuromuscular and neurophysiological adaptations over time, considering the transition from acute to chronic pain. Understanding these processes could significantly contribute to the formulation of more effective preventive and

therapeutic strategies, improving the clinical management of musculoskeletal pain.

**VISUALIZING LOW BACK PAIN: ANALYSIS OF FACIAL EXPRESSIONS  
FOR OBJECTIVE MEASUREMENT THROUGH IMAGE PROCESSING.**

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**KEYWORDS:** Artificial intelligence, Induced acute low back pain, Strength, Facial expression.

## **1 INTRODUCTION**

Detailed coding of facial activity provides a mechanism for understanding the biological, behavioral, cognitive and social processes of pain that self-report measures do not address (Höfling & Alpers, 2023). Facial activity appears to be the most consistent expression of pain, mediated by specific neurological circuits (Craig, 1992). Studies have shown that facial expressions of pain are consistent and universal across different cultures, reflecting automatic responses to nociceptive stimuli (Liu et al., 2024; Prkachin, 2009). Thus, the proposed objective was to develop software to objectively measure experimentally induced acute low back pain during a submaximal strength test, using facial activity coding to capture biological and behavioral processes that complement traditional self-reporting methods.

## **2 MATERIALS AND METHODS**

### **2.1 SOFTWARE CODE**

Software code has been developed to detect changes in facial expression in the context of experimentally induced acute low back pain. face detection in each frame is carried out using the haar cascade algorithm (Viola & Jones, 2001). in the facial region, histograms are assembled and concatenated using local binary pattern histograms (LBPH) (Ahonen et al., 2004). the system is trained with a reference video containing neutral facial expressions and evaluates a second video in which the expressions are analyzed frame by frame. The program measures and displays the difference between each frame of the second video and the 'average' face of the training frames, calculating average module differences between the histograms of the current frame and the average training histogram.

### **2.2 EXPERIMENTALLY INDUCED ACUTE LOW BACK PAIN**

The study included 15 healthy volunteers ( $30.6 \pm 6.4$  years;  $72.4 \pm 10.69$  kg;  $171.53 \pm 6.45$  cm) who received injections of hypertonic saline solution (6.0%) to induce low back pain. They were assessed in two conditions: without pain and

during acute low back pain, during a spinal extension task in the prone position, with a dynamometer measuring submaximal force positioned on the midline of the scapulae. Facial expressions were captured by a GoPro camera and the videos were analyzed using the OpenCV library in the Python programming language. The force data was processed using MATLAB® software. Significant differences between conditions were assessed using descriptive statistics and the Wilcoxon test.

## 2. RESULTS

Table 1 presents the main results, highlighting the significant differences between the pain and no-pain conditions, and providing a detailed analysis of the behavior of facial expressions and muscle strength in response to experimentally induced acute low back pain. The software demonstrated a robust ability to capture facial variations in both conditions (figure 1), evidencing its effectiveness in consistently identifying facial changes associated with the pain state and its enhanced sensitivity to detect facial responses in the context of pain.

Table 1: Descriptive data from software measurements during pain and in the absence of pain.

	During Pain	No Pain	<i>p</i>
<b>Facial expression</b>	10.04 (4.14)	5.47 (2.59)	<0.001
<b>CV%</b>	41.21	47.34	
<b>SEM %</b>	2.53	1.58	
<b>Force</b>	1.96 (0.29)	2.02 (0.31)	<0.001

Legend: values are expressed as mean (standard deviation), coefficient of variation (CV) expressed as percentages, Standard Error of the Mean (SEM), *p* value of the difference in facial expression between those with pain and



Figure 1: difference in facial expression without and during induced acute low back pain Legend: a) no pain, b) during pain.

#### 4. DISCUSSION AND CONCLUSION

Low back pain can trigger neuromuscular responses that are manifested in specific changes in facial expressions, such as frowning, squinting or lips Liu et al., 2024). These results are consistent with force inhibition and the theory that low back pain can cause visible and measurable changes in the facial expressions of those affected (Courbalay et al., 2016). Objectively analyzing these changes using the software developed not only confirms the presence of pain, but also quantifies these changes in a measurable and reproducible way, offering a more accurate and reliable approach compared to subjective assessments (Courbalay et al., 2016; Liu et al., 2024). The software proved to be effective in recognizing facial changes associated with low back pain across various conditions, providing an objective analysis of these signals. The use of this technology can improve diagnosis and treatment by providing a more personalized and accurate approach, especially when verbal reporting of pain may not be reliable or possible.

#### REFERENCES

- Ahonen, T., Hadid, A., & Pietikäinen, M. (2004). *Face Recognition with Local Binary Patterns* (Vol. 3021). [https://doi.org/10.1007/978-3-540-24670-1\\_36](https://doi.org/10.1007/978-3-540-24670-1_36)
- Courbalay, A., Deroche, T., Descarreaux, M., Prigent, E., O'Shaughnessy, J., & Amorim, M. A. (2016). Facial Expression Overrides Lumbopelvic Kinematics for Clinical Judgements about Low Back Pain Intensity. *Pain Research and Management*, 2016(1), 7134825. <https://doi.org/https://doi.org/10.1155/2016/7134825>
- Craig, K. D. (1992). The facial expression of pain Better than a thousand words? *APS Journal*, 1(3), 153-162. [https://doi.org/https://doi.org/10.1016/1058-9139\(92\)90001-S](https://doi.org/https://doi.org/10.1016/1058-9139(92)90001-S)
- Höfling, T., & Alpers, G. (2023). Automatic facial coding predicts self-report of emotion, advertisement and brand effects elicited by video commercials. *Frontiers in Neuroscience*, 17. <https://doi.org/10.3389/fnins.2023.1125983>
- Liu, H., Xu, H., Qiu, J., Wu, S., & Liu, M. (2024). Hierarchical global and local transformer for pain estimation with facial expression videos. *Pattern*

*Analysis and Applications*, 27. <https://doi.org/10.1007/s10044-024-01302->

[y](#)

Prkachin, K. M. (2009). Assessing pain by facial expression: facial expression as nexus. *Pain Res Manag*, 14(1), 53-58.

<https://doi.org/10.1155/2009/542964>

Viola, P., & Jones, M. (2001, 8-14 Dec. 2001). Rapid object detection using a boosted cascade of simple features. Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. CVPR 2001,



## Appendix II (Book Chapter)

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Meira, J., Cássio, M. M., Carlos, B. M. (2024). Artes, ciências e humanidades da atividade física. In F. C. S. P., M. V. S., K. M. B., F. M. B., J. P. V.B., M. F. G., e U. F. E. EACH (Ed), 2.3 Análise multidimensional da dor: interações psicológicas, respostas neuromusculares e dinâmicas de produção de força (p.193-213). São Paulo.

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## INTRODUÇÃO

A dor é um fenômeno complexo que integra componentes sensoriais, cognitivos e afetivos, afetando profundamente a qualidade de vida dos indivíduos (de ridder; adhia; vanneste, 2021; wiech; tracey, 2009). Esta visão é sustentada pela definição revisada da associação internacional para o estudo da dor (iasp), que conceitua a dor como “uma experiência sensorial e emocional desagradável associada a, ou semelhante a uma lesão tecidual real ou potencial”(raja; carr; cohen; finnerup *et al.*, 2020). A relevância desta definição foi testada por meio de um modelo matemático que incorporou dados sobre a funcionalidade dos indivíduos com dor lombar, e verificou-se que os eventos psicológicos e a dor estão diretamente associados, demonstrando que os aspectos mentais podem intensificar a dor e afetar a funcionalidade do indivíduo (parolini; goethel; becker; fernandes *et al.*, 2023).

Adicionalmente, há evidências substanciais que vinculam a dor lombar à fraqueza e à diminuição da resistência dos músculos paravertebrais que podem ser exacerbadas por aspectos psicológicos que afetam a funcionalidade e a percepção da dor (van dieën; reeves; kawchuk; van dillen *et al.*, 2019). A redução da força muscular é potencialmente um precursor crítico para o desenvolvimento de limitações funcionais, destacando a importância do controle dos músculos do torso na manutenção da estabilidade e da saúde da coluna vertebral (alaranta; luoto; heliövaara; hurri, 1995; nava; tozim; morcelli; navega, 2018). O declínio na função motora, pode resultar em uma redução da autonomia, especialmente em idosos, pois a força é considerada a valência física mais importante e está intimamente envolvida com a capacidade funcional (brill; macera; davis; blair *et al.*, 2000; van dieën; reeves; kawchuk; van dillen *et al.*, 2019). Estudos demonstram que os níveis de força muscular estão correlacionados com índices de limitações funcionais e problemas de saúde gerais ao longo da vida (abdelaty; shendy; lotfy; hassan, 2024; brill; macera; davis; blair *et al.*, 2000; ruiz; sui; lobelo; lee *et al.*, 2009). A interdependência entre força muscular e funcionalidade

realça a necessidade de uma compreensão abrangente que vá além dos aspectos fisiológicos, explorando também os mecanismos subjacentes à interação entre dor e controle motor (abdelaty; shendy; lotfy; hassan, 2024). O estudo da dor experimentalmente induzida emerge como uma abordagem fundamental neste contexto, pois permite a investigação detalhada de como a dor afeta o desempenho motor e a funcionalidade (bank; peper; marinus; beek *et al.*, 2013).

Nesse sentido, no que tange à interação entre a dor experimental e o controle motor, a literatura tem buscado compreender essas associações através do controle do movimento (ervilha; farina; arendt-nielsen; graven-nielsen, 2005; smith; pearce; miles, 2006). Entender essas alterações é importante na tentativa de desenvolver intervenções eficazes que possam melhorar a qualidade de vida e o desempenho dos indivíduos. Dessa forma, estudos (ervilha; farina; arendt-nielsen; graven-nielsen, 2005; graven-nielsen; lund; arendt-nielsen; danneskiold-samsøe *et al.*, 2002; farina; cescon; negro; enoka, 2008) têm investigado essa relação focando em contrações isométricas voluntárias máximas (cvm) entretanto, para contrações explosivas, a literatura ainda é escassa, mesmo com o crescente interesse em estudar a força explosiva em diferentes condições (d'emanuele; maffiuletti; tarperi; rainoldi *et al.*, 2021; maffiuletti; aagaard; blazevich; folland *et al.*, 2016). Para os autores citados, a taxa de desenvolvimento de força (tdf) – derivado a partir da curva torque vs. Tempo analisada durante contrações explosivas, apresenta-se com uma variável mais sensível comparada à cvm, sendo capaz de detectar alterações em diferentes contextos (e.g. Treinamentos de força, reabilitação, dano muscular, dor).

A capacidade de gerar força explosiva é resultado da interação coordenada entre os sistemas nervoso central e periférico. No sistema nervoso central, a produção de força explosiva está relacionada à velocidade do comando neural e à frequência e intensidade dos disparos das unidades motoras (aagaard; simonsen; andersen; magnusson *et al.*, 2002; farina; arendt-nielsen; graven-nielsen, 2005; folland; buckthorpe; hannah, 2014; maffiuletti; aagaard; blazevich;

folland *et al.*, 2016). No sistema nervoso periférico, é influenciada pela intensidade e rapidez da contração muscular, assim como pela transmissão eficiente da força para o sistema esquelético, sendo depende de características contráteis intrínsecas, como o tipo de fibras musculares, e características morfológicas, como o comprimento dos fascículos e a área de secção transversal (aagaard; simonsen; andersen; magnusson *et al.*, 2002; farina; arendt-nielsen; graven-nielsen, 2005; folland; buckthorpe; hannah, 2014; maffiuletti; aagaard; blazevich; folland *et al.*, 2016). Na condição de dor, ambos os sistemas (i.e. Central e periférico) podem estar comprometidos. No sistema nervoso central as alterações podem ocorrer através da redução da velocidade do comando neural, como na frequência e intensidade dos disparos das unidades motoras (farina; arendt-nielsen; graven-nielsen, 2005; graven-nielsen; lund; arendt-nielsen; danneskiold-samsøe *et al.*, 2002; salomoni; tucker; hug; mcphée *et al.*, 2016; henriksen; rosager; aaboe; graven-nielsen *et al.*, 2011). No sistema nervoso periférico, a dor pode afetar a intensidade e velocidade da contração muscular e a eficiência na transmissão da força para o sistema esquelético (folland; buckthorpe; hannah 2014; graven-nielsen; lund; arendt-nielsen; danneskiold-samsøe *et al.*, 2002; salomoni; tucker; hug; mcphée *et al.*, 2016; henriksen; rosager; aaboe; graven-nielsen *et al.*, 2011). Portanto, compreender as adaptações da dor na força explosiva pode contribuir para entender os mecanismos e as interações sensório-motoras, que podem ser direcionadas para a melhora do desempenho em modalidades esportivas e de práticas preventivas.

A dor pode causar vários níveis de mudança na ativação muscular; no entanto, não há uma explicação definitiva sobre como a dor altera a estratégia de recrutamento da unidade motora (um). Foi demonstrado que a dor muscular interfere na produção de força ao alterar a descarga do motoneurônio em um nível central (Moseley; Brhyn; Ilowiecki; Solstad *et al.*, 2003). Isso pode ser causado pelo fato de que estímulos nocivos podem interferir com entradas excitatórias ou inibitórias no acionamento do motoneurônio (Jankowski; Rau; Ekmann; Anderson *et al.*, 2013). Através da eletromiografia de superfície (emg)

é possível adquirir informações relevantes sobre as manifestações mioelétricas periféricas e centrais da dor e os comprometimentos neuromusculares decorrentes (Hodges; Coppieters; Macdonald; Cholewicki, 2013; Sohn; Graven-Nielsen; Arendt-nielsen; Svensson, 2000). Embora a amplitude do emg e a produção de força durante as contrações voluntárias isométricas máximas sejam diminuídas durante condições de dor muscular (Ervilha; Arendt-Nielsen; Duarte; Graven-Nielsen, 2004).

Entretanto, alguns estudos demonstraram que a dor não interfere na capacidade de realizar uma tarefa de produção de força (Ervilha; Arendt-Nielsen; Duarte; Graven-Nielsen, 2004; Tucker; Hodges, 2009), mesmo quando o comando motor é alterado. O que indica que o sistema motor deve ter mecanismos para compensar as alterações causadas pela dor na atividade elétrica do músculo (Tucker; Hodges, 2009; Martinez-Valdes; Negro; Farina; Falla, 2020).

Atualmente, a literatura científica apresenta duas hipóteses para explicar as estratégias de ativação da unidade motora em resposta à dor, enquanto sustenta uma produção de força constante. A primeira hipótese é que o sistema nervoso central aumentará a entrada sináptica recebida por unidades motoras de alto limiar de recrutamento, para compensar a inibição de unidades motoras de baixo limiar de recrutamento (Martinez-valdes; Negro; Arvanitidis; Farina, 2021). A segunda hipótese é que a dor implica uma redistribuição de atividade entre unidades motoras, com preferência por unidades motoras de maior limiar de recrutamento (Hodges; Butler; Tucker, 2021; Cleary; Coombes; Hodges; Tucker, 2022; Becker; Goethel; Fonseca; Vilas-Boas, 2022). A compreensão dos mecanismos subjacentes às alterações do sistema motor durante a experiência dolorosa representa um pilar fundamental para o desenvolvimento de estratégias terapêuticas mais eficazes e personalizadas, com implicações significativas para a saúde e o bem-estar dos indivíduos.

## **Inteligência artificial na análise multidimensional da dor lombar**

Considerando que a dor é uma experiência sensorial e emocional desagradável associada a um dano tecidual real/potencial, deve haver variáveis emocionais quantificáveis que permitam transcrevê-la em um modelo matemático (okafor; levin; boadi; cook *et al.*, 2023). Neste sentido desenvolvemos uma representação matemática baseada em um modelo multivariado para elucidar a relação entre dor lombar e aspectos biopsicossociais e identificamos subpopulações que apresentam desvios do padrão emergido. Levantamos a hipótese de que é possível testar o conceito de dor da iasp por meio de uma representação matemática (evidenciando sua coerência) e que existe uma forte relação entre a saúde mental e a forma como o sujeito lida com a experiência da dor e suas consequências funcionais.

### **Métodos**

A amostra foi composta por 1.021 adultos jovens (73% do sexo feminino), com idade entre 18 e 35 anos ( $24,68 \pm 1,5$  anos, altura  $167,9 \pm 0,1$  m e peso  $65,8 \pm 3,5$  kg). Os critérios de exclusão foram  $< 18$  anos ou  $> 35$  anos ou não ter completado a pesquisa. A investigação envolveu abordagens metodológicas que usamos para analisar as interações complexas dos fenômenos de dor lombar e tentar entender os padrões e relações subjacentes, com o auxílio da modelagem matemática e os algoritmos da inteligência artificial. Os participantes forneceram informações sobre a massa, idade, sexo, altura, informações sociodemográficas, preenchimentos dos questionários índice de incapacidade de Oswestry (ODI)(Davidson; keating, 2002), escalas de estresse de ansiedade e depressão (DASS-21) (Marijanović; Kraljević; Buhovac; Cerić *et al.*, 2021), catastrofização da dor no dia (d-pcs) (Darnall; Sturgeon; Cook; Taub *et al.*, 2017), existência de diagnóstico médico de transtorno psiquiátrico e frequência de episódios de dor lombar em seis semanas.

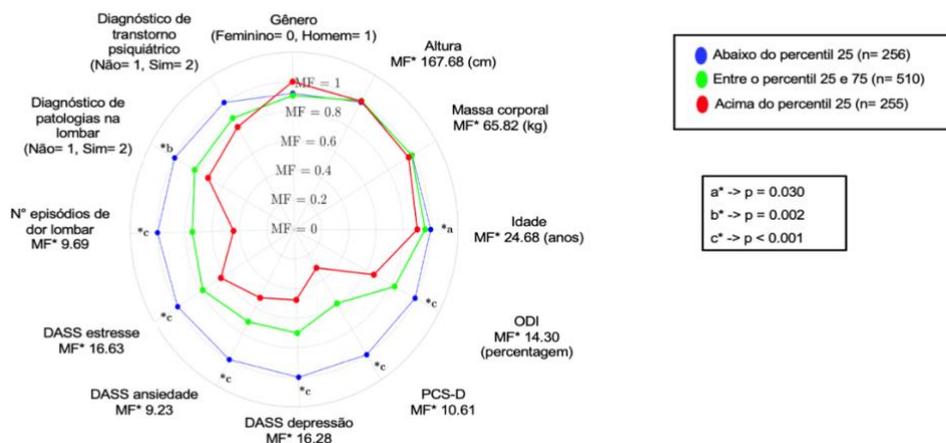
Uma estrutura de rede neural artificial com duas camadas ocultas foi treinada, incluindo transferência hiperbólica tangente e um sigmóide logístico com 20 neurônios cada e totalmente conectados. A camada de entrada foi composta por variáveis relacionadas às dimensões socioantropométricas (idade, sexo, massa

corporal, estatura e índice de massa corporal) e dados do ODI (Davidson; Keating, 2002), das escalas DASS (Marijanović; Kraljević; Buhovac; Cerić *et al.*, 2021) e do D-PCS (Darnall; Dudgeon; Dook; Taub *et al.*). A camada de saída continha as mesmas informações, mas com a ordem aleatória dos sujeitos. O espaço de saída consistiu em uma classificação binária "1" ou "2", indicando "sem alteração" e "mudança" no perfil funcional geral. O algoritmo de aprendizado utilizado foi a regularização bayesiana, e o conjunto de dados foi dividido aleatoriamente em 80% de amostras para treinamento e 20% para teste. Para maiores informações acessar o artigo (Parolini; Goethel; Becker; Fernandes *et al.*, 2023).

### **Resultados e discussão**

O modelo capturou algumas diferenças interessantes entre os grupos apresentados na figura 1, mostrando uma relação entre as variáveis de número de eventos de dor lombar no período de 6 semanas ( $p = 0,001$ ), diagnóstico médico de patologias na coluna lombar ( $p = 0,002$ ), ODI ( $p = 0,001$ ), idade ( $p = 0,030$ ), dados antropométricos e correlacionados com as variáveis psicológicas, estresse ( $p = 0,001$ ), ansiedade ( $p = 0,001$ ), depressão ( $p = 0,001$ ) e catastrofização nas últimas 24 horas em episódios de lombalgia ( $p = 0,001$ ). Os resultados são expressos como o fator de multiplicação (mf) de cada condição que é multiplicado pelo valor constante (como média) de cada variável (Parolini; Goethel; Becker; Fernandes *et al.*, 2023).

**Figura 1** - comparação de diferentes variáveis entre os três subgrupos, sendo os nomes das variáveis seguidos do valor a ser multiplicado pelo fator de multiplicação. Legenda: estresse (dass stress), ansiedade (dass ansiedade), depressão (dass depressão) escalas curtas, catastrofização da dor diariamente (pcs-d) e formam o índice de incapacidade de Oswestry (odi) (Parolini; Goethel; Becker; Fernandes *et al.*, 2023).



O estudo demonstrou uma robustez significativa na análise final, identificando subpopulações que apresentaram desvios notáveis em relação ao padrão esperado, particularmente no contexto da dor lombar e dos aspectos biopsicossociais, destacando as relações emergentes entre as variáveis nos perfis dos grupos analisados. O modelo matemático permitiu a investigação das relações lineares e não lineares entre as variáveis que compõem o fenômeno em estudo (Hooten, 2016). Os resultados revelaram interdependências significativas entre essas variáveis. Notavelmente, entre os participantes no percentil inferior (25º percentil), verificou-se uma associação estreita entre o diagnóstico de patologia lombar e variáveis como níveis de estresse, ansiedade e depressão, catastrofização diária da dor, bem como a frequência de eventos de dor lombar, resultando em uma leve incapacidade funcional individual (Baron; Binder; Wasner, 2010). Essa incapacidade funcional parece interferir na execução das atividades diárias dos indivíduos, contribuindo para o seu isolamento social e exercendo um impacto significativo no bem-estar geral (Crombez; Eccleston; Van Damme; Vlaeyen *et al.*, 2012).

Observou-se, por exemplo, que o grupo de participantes mais velhos também apresentou uma maior prevalência de diagnósticos de problemas lombares e episódios de lombalgia aguda no período de seis semanas, além de pontuações mais elevadas em escalas de depressão, ansiedade, estresse, catastrofização da dor diária e no questionário ODI (Davidson; Keating, 2002). Contudo, os dados

não proporcionaram uma explicação clara sobre o mecanismo subjacente, ou seja, se o episódio de dor lombar contribui para piores condições psicológicas ou se o comprometimento psicológico leva à percepção e intensificação da dor, influenciando a busca por diagnóstico médico (Parolini; Goethel; Becker; Fernandes *et al.*, 2023; Stegemann; Liu; Retana Romero; Oswald *et al.*, 2023).

A modelagem matemática utilizada em nosso estudo tem o potencial de avançar a prestação de cuidados em todas as áreas da saúde (Malhotra; Ramakrishnan; Anand; Vig *et al.*, 2016). Usando algoritmos eficazes de inteligência artificial para triagem, padrões incomuns na frequência, intensidade ou duração da dor lombar ao longo do tempo podem ser identificados, sendo úteis para detectar episódios de dor aguda intensa ou mudanças significativas no padrão de dor (Malhotra; Ramakrishnan; Anand; Vig *et al.*, 2016). Essa abordagem pode ser aplicada para identificar atividades, posturas ou movimentos específicos que levam a um aumento significativo da dor.

Diante do exposto, concluímos que é possível validar e confirmar a definição de dor pela IASP por meio de modelagem matemática. As subpopulações identificadas apresentaram uma relação direta entre dor e transtornos mentais, sendo que ambas as condições resultaram em maiores incapacidades (Parolini; Goethel; Becker; Fernandes *et al.*, 2023). Além disso, é imperativo analisar a força da musculatura lombar utilizando técnicas avançadas como a eletromiografia fornecendo dados sobre a ativação e coordenação neuromuscular, assim como a eletroencefalografia, que por sua vez, permiti avaliarmos a atividade elétrica cerebral, proporcionando insights sobre os processos neurais relacionados à percepção e modulação da dor. Esta análise se faz necessária, pois os dados deste estudo não proporcionaram uma explicação clara sobre o mecanismo subjacente de dor lombar. A dor experimentalmente induzida apresenta-se como uma metodologia eficaz para investigar os mecanismos de dor central e periférica. Esta abordagem permitirá uma análise minuciosa das respostas neuromusculares à dor e conseqüentemente a dor lombar, fornecendo uma maior compreensão sobre os

mecanismos subjacentes e orientando o desenvolvimento de intervenções terapêuticas mais eficazes e personalizadas.

### **Dor experimental no controle motor da produção de força**

Estudos envolvendo a dor experimental induzida têm sido utilizados como alternativa a estudos clínicos. Dentre as vantagens dos estudos experimentais, destaca-se a possibilidade de se fazer análises pareadas, assim com a possibilidade de se avaliar o mesmo indivíduo nas condições sem e com dor aguda (Hodges; Tucker, 2011; Graven-nielsen; Lund; Arendt-Nielsen; Danneskiold-Samsøe *et al.*, 2002). Também é possível estudar o efeito da dor num músculo específico, posto que a infusão de substância algogênica é realizada num músculo alvo ou em mais de um músculo, se for de interesse para o estudo. Quanto à intensidade da dor, os estudos experimentais permitem que esta seja parcialmente controlada, uma vez que a quantidade de substância infundida e a intensidade da dor guardam correlação (Gracely, 1999; ervilha; Arendt-nielsen; Duarte; Graven-nielsen, 2004). A influência da dor muscular na produção de força pode ser estudada tanto por meio de contrações voluntárias quanto induzidas por estimulação elétrica transcutânea. Frente a isso, tem sido utilizada a estimulação elétrica para se verificar a influência na capacidade de produção de força pelas propriedades contráteis sem qualquer dependência de fatores neurais (Tillin; Pain; Folland, 2011; Graven-nielsen; Lund; Arendt-nielsen; Danneskiold-samsøe *et al.*, 2002). Deste modo, se na presença de dor muscular induzida experimentalmente houver diminuição da força produzida por estimulação elétrica, pode-se concluir que a dor compromete o mecanismo neuromuscular periférico da produção de força e não exclusivamente os mecanismos centrais.

Assim, para compreender as adaptações do sistema neuromuscular em resposta à dor, foi realizado um estudo para explorar os efeitos neurais e periféricos associados à produção de força na condição de dor induzida experimentalmente.

## **Método**

Nove participantes visitaram o laboratório duas vezes, com intervalo de sete dias entre as visitas. Um delineamento cruzado randomizado foi realizado com participantes recebendo injeção intramuscular de solução salina hipertônica ou infusões isotônicas (indutor de dor e placebo, respectivamente) em cada visita. Foram avaliadas as respostas basais e imediatas à infusão intramuscular de solução hipertônica ou isotônica.

Todos os testes de força foram realizados no membro inferior direito (dominante) utilizando um dinamômetro isocinético (biodex medical systems 4, shirley, ny, eua). Participantes realizaram, com o membro inferior esquerdo (não dominante), uma familiarização, em seguida um aquecimento de 10 contrações isocinéticas concêntricas submáximas. O protocolo consistiu em realizar extensões isométricas de joelho na seguinte ordem: (i) duas contrações voluntárias máximas; (ii) seis contrações isométricas explosivas; e (iii) seis contrações isométricas induzidas por estimulação elétrica (pulsos simples e octetos). Após 15 minutos de repouso passivo, uma infusão de 2,2 ml de solução salina hipertônica ou isotônica (6,0 e 0,9%, respectivamente) foi infundida na porção média do vasto lateral barriga. Imediatamente após o protocolo experimental descrito anteriormente foi repetido. A atividade muscular do vasto lateral, vasto medial e reto femoral foi registrada usando eletromiografia de superfície (emg) durante todo o protocolo. Os valores de emg e de torque foram adquiridos em uma frequência de amostragem de 1000 hz. Os dados são apresentados como média e desvio padrão. Medidas repetidas manova foi aplicada para testar os efeitos entre condições experimentais (infusões hipertônicas e isotônicas) versus momentos (pré-protocolo e durante às infusões intramusculares). Para mais detalhes do protocolo, análise de dados e estatísticos ver Sousa; Goethel; Becker; Diefenthaler *et al*, 2024.

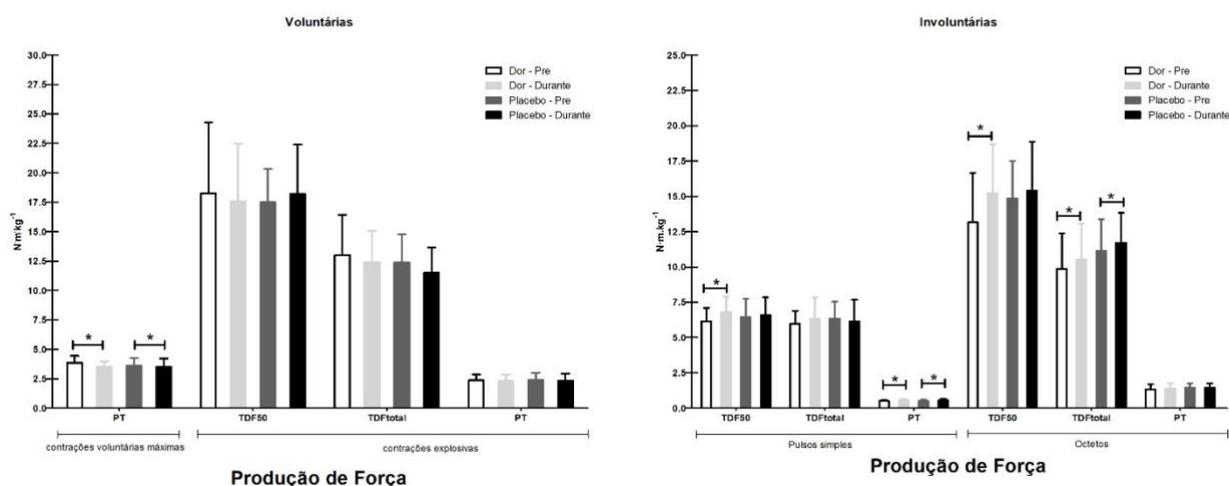
## **Resultado e discussão**

A figura 2 mostra as variáveis de produção de força nas condições de dor e placebo. Não foi encontrada interação (condições\*momento –  $f = 132,87$ ,  $p = 0,68$ ,  $d = 1,00$ ) para qualquer variável obtida durante contrações voluntárias máximas, explosivas e induzidas por estimulação elétrica. No entanto, quando analisadas separadamente, o pt para as contrações voluntárias máximas, foi reduzido tanto na dor quanto no placebo condições ( $p = 0,009$ ;  $p = 0,031$ , respectivamente). O declínio na produção de força voluntária observado durante condições de dor é um resultado complexo influenciada por vários mecanismos neurofisiológicos interligados. Para Henriksen *et al.* (2011), Salomoni *et al.* (2016) e Farina *et al.* (2005), a diminuição simultânea do impulso descendente do córtex, caracterizada por uma excitabilidade reduzida dos motoneurônios, contribui significativamente para esse fenômeno. A dor muscular experimental agrava esse desafio, diminuindo a capacidade do sistema nervoso de processar informações proprioceptivas, interrompendo assim a coordenação necessária para manter constante produção de força (Farina; Arendt-nielsen; Graven-nielsen, 2005). Para a contração explosiva, houve redução na tdf (tdftotal) durante a condição placebo ( $p = 0,032$ ).

Para o pulso simples, houve um aumento na tdf50 na condição de dor ( $p < 0,01$ ), e um aumento no pt tanto para dor quanto para placebo condições ( $p < 0,01$ ;  $p = 0,037$ ). Para os octetos, houve aumento do tdf50 na condição de dor ( $p = 0,029$ ), e no tdftotal em ambas as condições (dor -  $p = 0,018$ ; placebo -  $p = 0,02$ ). Sabe-se que quando um músculo é estimulado, seja voluntária ou involuntariamente, ocorre a liberação de íons de cálcio ( $Ca^{2+}$ ) do retículo sarcoplasmático para o sarcoplasma. A estimulação elétrica causa uma liberação consistente e suficiente de cálcio no sarcoplasma, independente da presença ou não de dor, assegurando que o mecanismo de contração das pontes cruzadas seja eficiente. No entanto, a dor pode estar associada à disfunção do retículo sarcoplasmático, resultando em uma regulação anormal dos íons de cálcio, o que pode levar a uma liberação inadequada de cálcio, e assim podendo afetar a contração muscular (Maffiuletti; Roig; Karatzanos; Nanas, 2013). Dessa forma, na condição de dor, pode haver um aumento da

sensibilidade dos nociceptores e outras vias periféricas, em adição, a estimulação elétrica pode se beneficiar dessa sensibilização, resultando em uma resposta contrátil mais forte devido à maior sensibilidade do retículo sarcoplasmático à liberação de cálcio, promovendo uma liberação mais eficiente de cálcio e resultando em uma resposta contrátil aumentada (Jafri, 2014). Esses resultados também podem ser influenciados por um estímulo secundário que direciona recursos de atenção para tarefas motoras resultando em melhor desempenho (Dancey; Murphy; Andrew; Yelder, 2016), bem como pelo tipo de estímulo e grupo muscular que pode modular a excitabilidade do motor primário córtex (Boudreau; Romaniello; Wang; Svensson, *et al* 2007).

**Figura 2** – média e desvio padrão das contrações voluntárias e involuntárias dos extensores do joelho nos momentos pré e durante as condições de dor induzida experimentalmente e placebo.



Nota: pico de torque (pt); taxa total de desenvolvimento de força (tdf);  
\*significativamente diferente do momento pré (p < 0,05).

Em suma, este estudo demonstrou que tanto a dor como as condições placebo têm um impacto significativo na produção de força. As contrações voluntárias máximas foram afetadas em ambas as condições, registrando uma redução na dor e para o placebo, enquanto a taxa de desenvolvimento de torque foi reduzida na condição placebo. Estes resultados apoiam a conclusão de que os

efeitos têm origem no sistema nervoso central. Além disso, houve um aumento observado na produção de força durante contrações involuntárias, devido a uma liberação mais eficiente de cálcio, resultando em uma resposta contrátil mais forte.

## **Dor e controle motor**

A teoria mais recente para explicar a adaptação motora à dor, é a de que a dor musculoesquelética infere mudanças importantes no controle motor em múltiplos níveis do sistema motor, levando à uma redistribuição da atividade dentro e entre os músculos, resultando em comportamento mecânico e distribuição de cargas alterados, além de aumento na rigidez articular. Estas adaptações fornecem benefícios potenciais imediatos para o sistema, porém, possivelmente carrega consigo consequências de longo prazo devido às mudanças no controle motor associadas à dor (hodges; tucker, 2011). Neste sentido o objetivo deste estudo foi investigar as alterações no pool de ativação da unidade motora, e a amplitude do potencial de ação da unidade motora (muapamp) durante a dor.

## **Método**

Quatorze participantes do sexo masculino foram recrutados. Cada participante visitou o laboratório duas vezes, com sete dias de intervalo entre as visitas. Um desenho cruzado randomizado foi utilizado, com os participantes recebendo um único bolus de 2 ml de solução salina hipertônica (6,0%), projetada para induzir dor, ou uma solução salina isotônica (0,9%), projetada para atuar como placebo. As soluções foram injetadas no ventre do músculo vasto lateral em cada visita. A intensidade da dor foi relatada pelo participante a cada minuto da injeção usando uma escala visual analógica ancorada com “sem dor” em zero e “pior dor imaginável” em 10.

Em cada sessão, os voluntários realizaram: (i) duas repetições, com 60 s de intervalo, de contrações isométricas voluntárias máximas de extensão do joelho,

com a articulação do joelho em um ângulo de 60° (0° = extensão total); (ii) 5 extensões de joelho de esforço máximo (concêntricas/excêntricas) na mesma velocidade e amplitude de movimento da etapa 1, com forte incentivo verbal do pesquisador; (iii) um período de descanso de 3 min; (iv) a injeção da solução hipertônica ou isotônica; e (v) a repetição das etapas (i) e (ii) imediatamente após a injeção salina. A seleção do tipo de injeção salina na primeira sessão foi aleatória.

#### *Registro e decomposição de emg*

O sinal foi adquirido usando o sistema de decomposição do sinal eletromiográfico, esta tecnologia é capaz de detectar os padrões individuais de unidades motoras do trem de potencial de ação. A decomposição do sinal eletromiográfico foi realizada através do algoritmo criado por De Luca & Nawab De Luca *et al.* (2006) e aprimorado por De Luca *et al.* (2015) por meio do software neuromap system. Para cada unidade motora detectada, seu limiar de recrutamento (força no início da atividade da unidade motora, apresentado em percentual do torque da contração voluntária isométrica máxima), taxa de disparo e amplitude do potencial de ação da unidade motora, foram considerados para análise.

#### *Análise de dados*

Usando um algoritmo com base no k-means no software matlab foi possível agrupar as unidades motoras (arthur; vassilvitskii, 2007) em clusters com base em três variáveis: limiar de recrutamento, taxa de disparo e amplitude do potencial de ação da unidade motora. Em uma analogia ao tipo de fibra, predefinimos o número de clusters para dois: g1 e g2. A normalidade da distribuição dos dados foi verificada com o teste de shapiro-wilk. Os resultados são apresentados por média e desvio padrão. Uma manova de medidas repetidas foi aplicada para testar os efeitos entre épocas (pré e pós), condições (hipertônica e isotônica) e grupos unidades motoras g1 e g2. Quando os efeitos

principais foram encontrados, múltiplas comparações usando correção de bonferroni foram conduzidas. Então, cada contração voluntária isométrica máxima e pico de torque em fases concêntricas e excêntricas foram comparados usando o teste t de student pareado. Os critérios d de cohen foram usados para calcular o poder das análises (>0,2: pequeno; >0,50: moderado; >0,80: grande) (cohen; 1988). Todos os testes foram realizados usando o spss statistics versão 27.

## Resultados

Todas as unidades motoras foram detectadas durante as cinco contrações isocinéticas. Um total de 365 e 481 unidades motoras puderam ser rastreadas em condições isotônicas e hipertônicas, respectivamente, de todos os participantes durante as épocas de pré-injeção e pós-injeção. Conforme ilustrado na tabela 1, o número de unidades motoras recrutadas no g1 durante a dor aumentou expressivamente, em relação à sua época de pré-injeção; esse fenômeno não pode ser visto em outros grupos ou épocas.

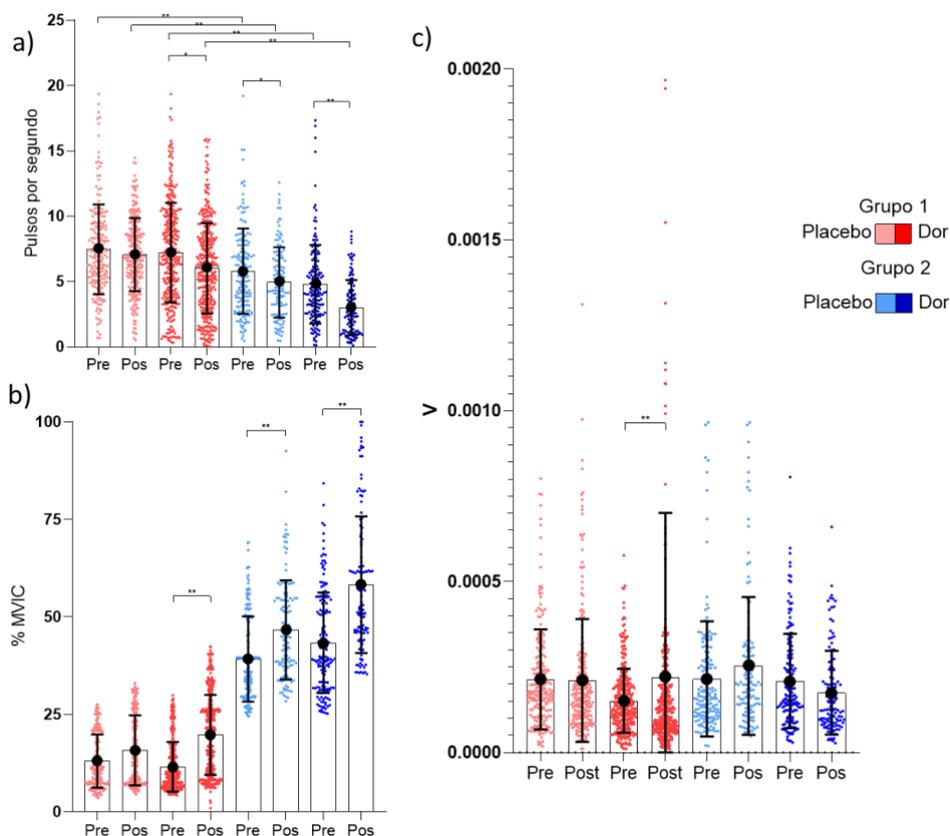
**Tabela 1** - número de unidades motoras reconhecidas durante cinco contrações isocinéticas, separadas por grupos e épocas em cada protocolo de injeção. A tabela mostra o total de unidades motoras da amostra de cada época acima do limite de precisão de 80%.

	G1		G2		Total MUs
	Pre	Post	Pre	Post	
Hypertonic	148	180	89	64	481
Isotonic	98	115	87	65	365

No g1, o teste manova bidirecional mostrou uma diminuição significativa da fr entre as épocas com a injeção hipertônica ( $p < 0,016$ ), enquanto nenhuma diferença foi observada com a solução isotônica ( $p < 0,409$ ) (figura 3a). O limiar de recrutamento diminuiu entre as épocas com injeção hipertônica ( $p < 0,001$ ) e nenhuma diferença ocorreu durante a injeção de placebo ( $p = 0,06$ ) (figura 3b).

A amplitude do potencial de ação da unidade motora aumentou entre as épocas durante a injeção hipertônica ( $p < 0,001$ ) e não houve nenhuma diferença entre as épocas durante a injeção de placebo ( $p = 0,32$ ). As diferenças encontradas nessa variável são devidas ao agrupamento de unidades motoras de amplitudes maiores que diminuíram seu limiar de recrutamento (veja a figura 3).

No g2, o fr diminuiu durante as injeções hipertônicas ( $p < 0,001$ ) e placebo ( $p = 0,008$ ) (figura 3a). O limiar de recrutamento do g2 aumentou durante a injeção hipertônica ( $p < 0,001$ ) e isotônica ( $p < 0,001$ ) (figura 3b). A amplitude do potencial de ação da unidade motora não mudou durante nenhuma das injeções. A figura 3c mostra um grande aumento na amplitude das unidades motoras do g1.



**Figura 3** - média e desvio padrão das variáveis da unidade motora identificadas em dezenove indivíduos durante cinco contrações isocinéticas e estratificadas em época, tipo de solução e grupos unidades motoras. (a) taxa média de disparo

(b) limiar de recrutamento (c) amplitude do potencial de ação da unidade motora. Os dados foram obtidos durante a linha de base (pré) e durante (pós) dor induzida experimentalmente ou placebo. A significância estatística foi testada usando manova entre momentos na mesma condição (\*  $p < 0,01$ , \*\*  $p < 0,001$ ).

Nossos dados são apoiados por dois estudos recentes (Hodges; Butler; Tucker, 2021) que investigaram o curso temporal dos motoneurônios após a hiperpolarização em uma única atividade da unidade motora. Seus dados mostraram um curso temporal encurtado e alongado após a hiperpolarização (Hodges; Butler; Tucker, 2021), o que indica um efeito não uniforme da nocicepção na excitabilidade do motoneurônio. Em outro estudo, os investigadores mostraram que a dor experimental aguda altera a taxa de descarga da unidade motora do quadríceps quando a dor é induzida no tibial anterior, o que não contribui mecanicamente com a produção de força do quadríceps ou bíceps femorais (músculo antagonista). A taxa de descarga diminuiu no vasto lateral e vasto medial durante a dor, independentemente do músculo dolorido, enquanto a força permaneceu a mesma, o que indica uma redistribuição da atividade da unidade motora, com algumas unidades recrutadas no controle ou na dor, mas não em ambos (Cleary; Coombes; Hodges; Tucker, 2022).

Nosso estudo fornece evidências de que o sistema motor realiza um recrutamento seletivo de unidades motoras durante a dor muscular para manter a produção de torque isocinético. Para isso, unidades motoras com limiar de recrutamento e amplitude do potencial de ação da unidade motora mais altos são recrutados, mesmo que a taxa de disparo diminua. Isso não suporta a hipótese de uma redistribuição de atividade em umas únicas unidades motoras, explicando toda a resposta a estímulos dolorosos.

## **CONCLUSÃO**

Neste capítulo discorremos e ilustramos a complexidade inerente às interações entre dor, controle motor e respostas neuromusculares, enfatizando a necessidade de uma abordagem multidimensional para compreender esses fenômenos. Sabemos que a dor não apenas altera a capacidade de produzir força, mas também afeta diferencialmente a taxa de desenvolvimento de força e a eficiência da contração muscular, além da sua íntima relação com a saúde mental. Destacamos também que as alterações observadas são mediadas por mecanismos centrais e periféricos, envolvendo alterações no recrutamento de unidades motoras. Estes resultados realçam a importância de considerar a dor como um modulador essencial do controle motor. A integração destes resultados sugere uma abordagem holística da gestão da dor, que abranja não só a vertente fisiológica, mas também a vertente psicológica e social, garantindo assim esforços máximos na melhoria da qualidade de vida dos indivíduos acometidos por este fenômeno multidimensional.

## REFERÊNCIAS

AAGAARD, P.; SIMONSEN, E. B.; ANDERSEN, J. L.; MAGNUSSON, P. et al. Increased rate of force development and neural drive of human skeletal muscle following resistance training. **J Appl Physiol** (1985), 93, n. 4, p. 1318-1326, Out 2002.

ABDELATY, E. M.; SHENDY, S.; LOTFY, O.; HASSAN, K. A. The difference in multifidus muscle morphology and motor control in non-specific low back pain with clinical lumbar instability and healthy subjects: A case-control study. **Physiother Res Int**, 29, n. 1, p. e2047, Jan 2024.

ALARANTA, H.; LUOTO, S.; HELIÖVAARA, M.; HURRI, H. Static back endurance and the risk of low-back pain. **Clin Biomech** (Bristol, Avon), 10, n. 6, p. 323-324, Set 1995.

ARTHUR, D.; VASSILVITSKII, S. k-means++: the advantages of careful seeding.

ACM-SIAM Symposium on Discrete Algorithms. **ACM-SIGART** , 2007.

BANK, P. J.; PEPPER, C. E.; MARINUS, J.; BEEK, P. J. et al. Motor consequences of experimentally induced limb pain: a systematic review. **Eur J Pain**, 17, n. 2, p. 145-157, Feb 2013.

BARON, R.; BINDER, A.; WASNER, G. Neuropathic pain: diagnosis, pathophysiological mechanisms, and treatment. *The Lancet Neurology*, 9, n. 8, p. 807-819, 2010.

BECKER, K.; GOETHEL, M.; FONSECA, P.; VILAS-BOAS, J. P. *et al.* The Strategy of the Brain to Maintain the Force Production in Painful Contractions—A Motor Units Pool Reorganization. **Cells**, v. 11, n. 20, 2022. MDPI.

BOUDREAU, S.; ROMANIELLO, A.; WANG, K.; SVENSSON, P. et al. The effects of intra-oral pain on motor cortex neuroplasticity associated with short-term novel tongue-protrusion training in humans. *Pain*, 132, n. 1-2, p. 169-178, Nov 2007.

BRILL, P. A.; MACERA, C. A.; DAVIS, D. R.; BLAIR, S. N. et al. Muscular strength and physical function. *Med Sci Sports Exerc*, 32, n. 2, p. 412-416, Feb 2000.

COHEN, J. **Statistical Power Analysis for the Behavioral Sciences; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 1988; Volume 2.**

CLEARY, J.; COOMBES, B. K.; HODGES, P.; TUCKER, K. Motor Unit Recruitment is Altered When Acute Experimental Pain is Induced at a Site Distant to the Contracting Muscle. **Neuroscience**, v. 496, p. 141–151, 2022.

CROMBEZ, G.; ECCLESTON, C.; VAN DAMME, S.; VLAEYEN, J. W. et al. Fear-avoidance model of chronic pain: the next generation. **Clin j Pain**, 28, n. 6, p. 475-483, 2012.

DANCEY, E.; MURPHY, B.; ANDREW, D.; YIELDER, P. Interactive effect of acute pain and motor learning acquisition on sensorimotor integration and motor learning outcomes. **J Neurophysiol**, 116, n. 5, p. 2210-2220, Ago 2016.

DARNALL, B. D.; STURGEON, J. A.; COOK, K. F.; TAUB, C. J. et al. Development and Validation of a Daily Pain Catastrophizing Scale. **J Pain**, 18, n. 9, p. 1139-1149, Set 2017.

DAVIDSON, M.; KEATING, J. L. A comparison of five low back disability questionnaires: reliability and responsiveness. **Phys Ther**, 82, n. 1, p. 8-24, Jan 2002.

DE LUCA, C. J.; ADAM, A.; WOTIZ, R.; GILMORE, L. D. *et al*; Decomposition of Surface EMG Signals. **J. of Neurophysiology**, v. 96, n. 3, p. 1646–1657, 2006. American Physiological Society.

DE LUCA, C. J.; CHANG, S. S.; ROY, S. H.; KLINE, J. C. *et al*. Decomposition of surface EMG signals from cyclic dynamic contractions. **J. of Neurophysiology**, v. 113, n. 6, p. 1941–1951, 2015.

DE RIDDER, D.; ADHIA, D.; VANNESTE, S. The anatomy of pain and suffering in the brain and its clinical implications. **Neurosci Biobehav Rev**, 130, p. 125-146, Nov 2021.

D'EMANUELE, S.; MAFFIULETTI, N. A.; TAPERI, C.; RAINOLDI, A. et al. Rate of Force Development as an Indicator of Neuromuscular Fatigue: A Scoping Review. **Front Hum Neurosci**, 9, n. 15, p. 701916, Jul 2021.

ERVILHA, U. F.; ARENDT-NIELSEN, L.; DUARTE, M.; GRAVEN-NIELSEN, T. Effect of load level and muscle pain intensity on the motor control of elbow-flexion movements. **Eur J Appl Physiol**, 92, n. ½, p. 168-175, Mar. 2004a.

ERVILHA, ULYSSES F.; ARENDT-NIELSEN, L.; DUARTE, M.; GRAVEN-NIELSEN, T. The effect of muscle pain on elbow flexion and coactivation tasks. **Exp Brain Res**, v. 156, n. 2, p. 174–182, 2004b.

ERVILHA, U. F.; FARINA, D.; ARENDT-NIELSEN, L.; GRAVEN-NIELSEN, T. Experimental muscle pain changes motor control strategies in dynamic contractions. **Exp Brain Res**, 164, n. 2, p. 215-224, Jun 2005.

FARINA, D.; ARENDT-NIELSEN, L.; GRAVEN-NIELSEN, T. Experimental muscle pain decreases voluntary EMG activity but does not affect the muscle potential evoked by transcutaneous electrical stimulation. **Clin Neurophysiol**, 116, n. 7, p. 1558-1565, Jul 2005.

FARINA, D.; CESCO, C.; NEGRO, F.; ENOKA, R. M. Amplitude cancellation of motor-unit action potentials in the surface electromyogram can be estimated with spike-triggered averaging. **J Neurophysiol**, 100, n. 1, p. 431–440, Jul 2008.

FOLLAND, J. P.; BUCKTHORPE, M. W.; HANNAH, R. Human capacity for explosive force production: Neural and contractile determinants. **Scand J Med Sci Sports**, 24, n. 6, p. 894–906, Dez 2014.

GRACEY, R. H. Pain measurement. *Acta Anaesthesiol Scand*, 43, n. 9, p. 897-908, Out 1999.

GRAVEN-NIELSEN, T.; LUND, H.; ARENDT-NIELSEN, L.; DANNESKIOLD-SAMSØE, B. et al. Inhibition of maximal voluntary contraction force by experimental muscle pain: A centrally mediated mechanism. *Muscle Nerve*, 26, n. 5, p. 708-712, Nov 2002.

HENRIKSEN, M., ROSAGER, S.; AABOE, J.; GRAVEN-NIELSEN T. *et al.* Experimental knee pain reduces muscle strength. **J Pain**, 12, n. 4, p. 460-467, Dez 2011.

HODGES, P. W.; TUCKER, K. Moving differently in pain: A new theory to explain the adaptation to pain. **Pain**, mar. 2011.

HODGES, P. W.; COPPIETERS, M. W.; MACDONALD, D.; CHOLEWICKI, J. New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. **Eur J. of Pain**, v. 17, n. 8, p. 1138–1146, 2013. John Wiley & Sons, Ltd.

HODGES, P. W.; BUTLER, J.; TUCKER, K.; et al. Non-uniform Effects of Nociceptive Stimulation to Motoneurons during Experimental Muscle Pain. **Neuroscience**, v. 463, p. 45–56, 2021.

HOOTEN, W. M. Chronic Pain and Mental Health Disorders: Shared Neural Mechanisms, Epidemiology, and Treatment. **Mayo Clin Proc**, 91, n. 7, p. 955-970, Jun 2016.

JAFRI, M. S. Mechanisms of Myofascial Pain. **Int Sch Res Notices**, 14, p. 523924, Ago 2024

MAFFIULETTI, N. A.; ROIG, M.; KARATZANOS, E.; NANAS, S. Neuromuscular electrical stimulation for preventing skeletal-muscle weakness and wasting in critically ill patients: a systematic review. **BMC Med**, 23, n. 11, p. 137, Mai 2013

JANKOWSKI, M. P.; RAU, K. K.; EKMANN, K. M.; ANDERSON, C. E. *et al.* Comprehensive phenotyping of group III and IV muscle afferents in mouse. **J Neurophysiol**, v. 109, n. 9, p. 2374–2381, 2013. American Physiological Society.

MAFFIULETTI, N. A.; AAGAARD, P.; BLAZEVIČH, A. J.; *et al.* Rate of force development: physiological and methodological considerations. **Eur J Appl Physiol**, 116, n. 6, p. 1091-1116, Mar 2016.

MALHOTRA, P.; RAMAKRISHNAN, A.; ANAND, G.; VIG, L. *et al.* LSTM-based encoder-decoder for multi-sensor anomaly detection. **arXiv preprint arXiv:1607.00148**, 2016.

MARIJANOVIĆ, I.; KRALJEVIĆ, M.; BUHOVAC, T.; CERIĆ, T. *et al.* Use of the Depression, Anxiety and Stress Scale (DASS-21) questionnaire to assess levels of depression, anxiety, and stress in healthcare and administrative staff in 5 oncology institutions in Bosnia and Herzegovina during the 2020 COVID-19 pandemic. *Med Sci Monit*, 19, n. 27, p. e930812, Abr 2021.

MARTINEZ-VALDES, E.; NEGRO, F.; FARINA, D.; FALLA, D. Divergent response of low- versus high-threshold motor units to experimental muscle pain. **J. of Phys**, v. 598, n. 11, p. 2093–2108, 2020.

MARTINEZ-VALDES, E.; NEGRO, F.; ARVANITIDIS, M.; FARINA, D. *et al.* Pain-induced changes in motor unit discharge depend on recruitment threshold and contraction speed. **J. of App Phys**, v. 131, n. 4, p. 1260–1271, 2021.

MOSELEY, G. L.; BRHYN, L.; ILOWIECKI, M.; SOLSTAD, K. *et al.* The threat of predictable and unpredictable pain: Differential effects on central nervous system processing? **A. J. of Physio**, v. 49, n. 4, p. 263–267, 2003.

NAVA, G. T. D. A.; TOZIM, B. M.; MORCELLI, M. H.; NAVEGA, M. T. Influence of pain in strength, resistance and recruitment of trunk muscles. **BrJP**, 1, 2018.

OKAFOR, C.; LEVIN, J. M.; BOADI, P.; COOK, C. *et al.* Pain associated psychological distress is more strongly associated with shoulder pain and function than tear severity in patients undergoing rotator cuff repair. **JSES Int**, 7, n. 4, p. 544-549, Jul 2023.

PAROLINI, F.; GOETHEL, M.; BECKER, K.; FERNANDES, C. *et al.* Breaking Barriers: Artificial Intelligence Interpreting the Interplay between Mental Illness

and Pain as Defined by the International Association for the Study of Pain. **Biomedicines**, 11, n. 7, p. 2042, 2023.

RAJA, S. N.; CARR, D. B.; COHEN, M.; FINNERUP, N. B. *et al.* The revised International Association for the Study of Pain definition of pain: concepts, challenges, and compromises. **Pain**, 161, n. 9, p. 1976-1982, Sep 1 2020.

RUIZ, J. R.; SUI, X.; LOBELO, F.; LEE, D. C. *et al.* Muscular strength and adiposity as predictors of adulthood cancer mortality in men. **Cancer Epidemiol Biomarkers Prev**, 18, n. 5, p. 1468-1476, May 2009.

SALOMONI, S.; TUCKER, K.; HUG, F.; MCPHEE, M. *et al.* Reduced Maximal Force during Acute Anterior Knee Pain Is Associated with Deficits in Voluntary Muscle Activation. **PLoS ONE**, 11, n. 8, p. e0161487, Ago 2016.

STEGEMANN, A.; LIU, S.; RETANA ROMERO, O. A.; OSWALD, M. J. *et al.* Prefrontal engrams of long-term fear memory perpetuate pain perception. **Nat Neurosci.**, 26, n. 5, p. 820-829, 2023.

SMITH R.; PEARCE, S.L.; MILES, T. S. Experimental muscle pain does not affect fine motor control of the human hand. **Exp Brain Res**, 174, n. 3, p. 397-402, Out 2006.

SOHN, M. K.; GRAVEN-NIELSEN, T.; ARENDT-NIELSEN, L.; SVENSSON, P. Inhibition of motor unit firing during experimental muscle pain in humans. **Muscle & Nerve**, v. 23, n. 8, p. 1219–1226, 2000. John Wiley & Sons, Ltd.

SOUSA, M. V.; GOETHEL, M.; BECKER, K. M.; DIEFENTHAELER, F. *et al.* Effect of experimentally induced muscle pain on neuromuscular control of force production. **Hum Mov Sci**, 95, p. 103219, Jun 2024

TILLIN, N. A.; PAIN, M. T. G.; FOLLAND, J. P. Short-term training for explosive strength causes neural and mechanical adaptations. **Int J Clin Exp Physiol**, 97, n. 5, p. 630–641, Mai 2012

TUCKER, K.; BUTLER, J.; GRAVEN-NIELSEN, T.; RIEK, S. *et al.* Motor Unit Recruitment Strategies Are Altered during Deep-Tissue Pain. **J. of Neuroscience**, v. 29, n. 35, p. 10820, 2009.

TUCKER, K. J.; HODGES, P. W. Motoneurone recruitment is altered with pain induced in non-muscular tissue. **Pain**, v. 141, n. 1, 2009.

VAN DIEËN, J. H.; REEVES, N. P.; KAWCHUK, G.; VAN DILLEN, L. R. *et al.* Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. **J Orthop Sports Phys Ther**, 49, n. 6, p. 370-379, Jun 2019.

WIECH, K.; TRACEY, I. The influence of negative emotions on pain: behavioral effects and neural mechanisms. **Neuroimage**, 47, n. 3, p. 987-994, Sep 2009.