Jordán-López *et al.*
Journal of NeuroEngineering and Rehabilitation (2025) 22:138
https://doi.org/10.1186/s12984-025-01664-2

Journal of NeuroEngineering and Rehabilitation

RESEARCH

Open Access

Modifying lumbar flexion pain thresholds in patients with chronic low back pain through visual-proprioceptive manipulation with virtual reality: a cross-sectional study

Jaime Jordán-López[1], María D. Arguisuelas[2], Julio Doménech[3], M. Lourdes Peñalver-Barrios[4], Marta Miragall[5,6], Rocío Herrero[5,7], Rosa M. Baños[5,6,8], Juan J. Amer-Cuenca[2*] and Juan F. Lisón[1,5]

Abstract

Study design Cross-sectional study.

Background Movement-evoked pain may serve as a protective response influenced by visual-proprioceptive cues signaling potentially threatening movements. This study aimed to assess the impact of manipulating visual-proprioceptive feedback using virtual reality (VR) during lumbar flexion on movement-evoked pain thresholds. Additionally, we explored whether individuals with elevated pain, kinesiophobia, and catastrophizing were more susceptible to visual-proprioceptive manipulation.

Methods Fifty participants with non-specific chronic low back pain (cLBP) were included. We assessed lumbar flexion-evoked pain thresholds alongside pain levels, pain interference, kinesiophobia, and catastrophizing. Participants performed lumbar flexion movements in three conditions: (1) without VR (control, F), (2) with a virtual illusion shortening the perceived arm length by 20% (understated condition, F−), and (3) with a virtual illusion elongating arm length by 20% (overstated condition, F +). Range of motion (ROM) was measured using an electro-goniometer. One-way ANOVA with Bonferroni post-hoc tests examined differences among conditions, and three two-sample t-tests explored whether individuals with higher pain, kinesiophobia, and catastrophizing were more affected by visual-proprioceptive manipulation.

Results Understating the flexion task (F−) led to a 5% increase in movement compared to the control ($P = 0.04$; 95% CI [0.6%, 10.7%]) and a 7% increase compared to the overstated condition (F +) ($P < 0.001$; 95% CI [2.6%, 11.6%]). Additionally, individuals with higher pain levels and pain interference, exhibited a more pronounced response to the understated condition (F−).

Conclusions Manipulating visual-proprioceptive feedback through VR significantly influenced pain thresholds during lumbar flexion in cLBP patients. The understated condition (F−) extended pain-free movement, delaying pain onset. Furthermore, pain intensity and interference modulated susceptibility to visual feedback manipulation. These findings enhance our understanding of how visual-proprioceptive feedback influences pain perception

*Correspondence:
Juan J. Amer-Cuenca
juanjoamer@uchceu.es
Full list of author information is available at the end of the article

and movement patterns in cLBP. They suggest new avenues for pain assessment, therapeutic interventions, and clinical strategies, particularly for individuals with high pain levels, interference, kinesiophobia, and catastrophizing.

Trial registration This study was retrospectively registered in the ClinicalTrials.gov with identifier NCT06750887

Keywords Chronic low back pain, Virtual reality, Movement evoked-pain, Illusions, Visual-proprioceptive cues, Modulation, Multisensory processing

Introduction

One of the leading causes of disability worldwide, surpassing conditions including heart disease, severe depression, and diabetes, is low back pain (LBP) [1]. LBP is a prevalent musculoskeletal disorder that affects around 90% of individuals at least once in their lifetimes [2]. Cases categorized as non-specific LBP lack a clearly identifiable origin and represent the majority of instances encountered in primary care [3]. The non-specific nature of this condition stems from the intricate nature of LBP. Multifactorial elements contribute to both the pain experience and the resulting disability. These factors encompass biophysical characteristics, psychological aspects such as kinesiophobia and catastrophizing, and social determinants, as well as lifestyle factors, occupational elements, and comorbidities [3, 4].

Biomechanical and postural abnormalities have been consistently correlated with non-specific LBP [2]. Indeed, literature reviews highlight the association between increased exposure to forward lumbar flexion and frequent lifting and the occurrence of LBP. Studies suggest that a workplace environment characterized by elevated forward lumbar flexion, lifting frequencies surpassing 25 lifts per day, and regular lifting of loads exceeding 25 kg is linked to an augmented risk of LBP [5, 6]. Moreover, individuals with LBP exhibit significantly reduced low back flexion compared to their healthy counterparts [7]. Finally, a meta-analysis investigated the coefficient of variance among patients with and without LBP during lumbar flexion, extension, rotation, and inclination movements and concluded that lumbar flexion was the most affected movement in the presence of LBP [8].

The central nervous system plays a pivotal role in influencing the systems that underlie pain processing in cases of chronic LBP (cLBP) and there is a profound interconnection between them [9]. How we feel during movement is shaped by a combination of internal (interoceptive) and external (exteroceptive) sensory information [10]. Interoceptive information encompasses proprioceptive and nociceptive signals originating from the muscles, joints, skin, and arteries. On the other hand, exteroceptive information involves sensory cues about the movement environment, including visual input [10]. Proprioception abnormalities and a lack of feedback response from the back muscles are frequently associated with cLBP, which impairs the sense individuals have of the position of their own body and movement. Thus, proprioceptive signals pertaining to the lumbar region are less accurate [2, 11, 12].

Individuals with non-specific cLBP often exhibit a protective response known as movement-evoked pain [13]. This response can be influenced by visual-proprioceptive cues, which encompass both interoceptive and exteroceptive sensory information. This suggests that patients may perceive their back movement as potentially threatening, thereby eliciting pre-emptive pain [14]. This type of response, while possibly triggered by nociceptive input, is increasingly understood as having a strong nociplastic component, reflecting altered central pain processing and sensorimotor integration, rather than ongoing tissue damage [15, 16]. To explore the impact of visual-proprioceptive cues on movement-evoked pain, virtual reality (VR) offers a useful platform for modulating pain thresholds during motion by manipulating visual feedback. Evidence for this has been published in the work of Harvie et al. (2015) [14], conducted in patients with non-specific cervical pain. These authors showed that manipulation of visual input in a VR environment could either increase or decrease the amount of pain-free movement experienced by users. They noted that when VR overstated the extent of the real neck rotation performed, pain manifested at a rotation 7% lower than that observed in situations with real or precise visual feedback. Conversely, when VR understated the actual rotation performed, pain occurred at a 6% higher rotation than instances with real or precise visual feedback [14].

Therefore, this significant finding implies a possible association between visual-proprioceptive cues and movement-evoked pain. Additionally, Kragting et al. (2023) [13] investigated the repercussions of manipulating visual feedback within a VR setting on cervical pain-free ROM in patients with and without kinesiophobia. Similarly, their results indicated that the visual sense of the extent of rotation could affect cervical pain-free ROM and that people with a higher level of kinesiophobia seemed to be especially susceptible to this effect. Importantly, both the aforementioned studies [13, 14] explored cervical pain, yet they did not focus on the most prevalent back pain condition according to the National Institutes of Health: LBP [17]. To the best of our knowledge,

no publications in the academic literature have yet examined how VR-induced illusory motions might alter visual-proprioceptive information or modulate lumbar flexion pain thresholds in people with cLBP. Therefore, the main goal of this current study was to determine if manipulating visual-proprioceptive feedback using VR during lumbar flexion influences the point at which patients start to feel pain, also known as the movement-evoked pain threshold.

Our initial hypothesis posited that the use of VR could unveil a delay in pain onset when visual-proprioceptive information understates real-world lumbar flexion. Thus, our second hypothesis was that individuals who experienced higher levels of pain, greater interference of pain with daily functioning, elevated kinesiophobia, increased disability, and heightened catastrophizing would exhibit a heightened susceptibility to the effects of manipulating visual-proprioceptive feedback.

Materials and methods

Study design

This was a double-blind, within-subject cross-sectional study employing a randomised order of conditions and repeated measures in individuals with cLBP. Following the foundational tenets outlined in the Helsinki Declaration, ethical clearance for this study was obtained from the Ethics Committee at the CEU Cardenal Herrera University in Valencia, Spain and the Arnau de Vilanova Hospital in Valencia, Spain (CEEI21/203 and CEIm:30/2021, respectively). Before joining the study, each participant received a detailed information letter and provided their written consent. The collected data were handled confidentially, adhering to the prevailing regulations on personal data protection. The STROBE reporting guidelines for cross-sectional observational studies was followed. This study was retrospectively registered in the ClinicalTrials.gov with identifier NCT06750887.

Participants

Fifty participants with cLBP were recruited by the Orthopedic Surgery Service and the Physical Medicine and Rehabilitation Service at the Arnau de Vilanova Hospital (Valencia, Spain) between November 2022 and October 2023. Initial screening was conducted by orthopaedic surgeons and physical medicine and rehabilitation physicians in these services. This study included participants of both sexes who were aged between 18 and 65 years and diagnosed with non-specific cLBP according to the European COST B13 guidelines [18]. In addition, only participants who reported pain specifically during active lumbar flexion were included. Finally, eligible participants were required to have reported an average pain score equal to or greater than 3 on the Numerical Rating Scale (NRS; 0: no pain; 10: worst pain imaginable) [19] in the 6 months prior. CLBP is defined as persistent pain lasting for more than 6 months according to the IMMPACT (Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials, 2010) recommendations. This criterion was applied to minimize the likelihood of pain reduction resulting from the natural evolution of the pathology [20]. Patients with infections, spinal tumors, systemic diseases, fractures, cauda equina syndrome, fibromyalgia, lower extremity musculoskeletal injuries, or previous spinal surgery were excluded.

Experimental procedure

Participants provided their informed consent and completed a digital questionnaire (Qualtrics, Provo, UT) 7 days before undergoing the VR procedure. The questionnaire gathered personal information and data related to lumbar pain including age, sex, pain intensity and duration, the impact of pain on daily life, disability, kinesiophobia, and catastrophizing. Subsequently, the participants visited the physiotherapy department at the Arnau de Vilanova Hospital. A researcher conducted anthropometric measurements of the patients immediately before the VR procedure.

Participants used a VR headset (HTC Vive Pro, China) and wore trackers on their hands, waists, and feet throughout the VR experiment (see Fig. 1). This configuration was designed to establish a precisely calibrated avatar within the virtual environment so as to faithfully replicate the actual movements of the patients and thereby create an authentic and immersive encounter from a first-person perspective. Inside the VR, the participants looked at themselves in a mirror to improve their sense of embodiment. Of note, before performing the VR tasks, the patients underwent a tutorial to familiarize themselves with the core aspects of the VR environment. Finally, integrated speakers delivered pre-recorded audio files giving standardized instructions for performing the assigned tasks.

Participants were directed to execute lumbar flexions in a virtual gymnasium, without bending their knees, until the point of pain onset. The verbal instructions given during the assessment were as follows: *"Now I'm going to ask you to stand upright, with your feet slightly apart, about hip-width. It is very important that you DO NOT BEND your knees during the entire task. The task will consist of bending your body forward, trying to touch the footprints you see in front of your feet, but always WITHOUT PAIN. That is, you should bend forward as long as you feel no pain. The moment you start to feel back pain, you must stop for 1 s, and then return to the initial standing position with your back straight. You will rest for 1 s and then repeat the movement two more times."* The goal was for

Fig. 1 The virtual reality set up and virtual environment

Fig. 2 Lumbar flexion (handprints): the left image shows the view of the researcher and right image shows the view of the participant within the virtual reality space

them to reach virtual handprints strategically placed in front of their feet. As the participants descended towards the floor and the handprints, the latter expanded in size and transitioned to a deeper shade of blue (see Fig. 2). This flexion task was repeated 3 times under 3 different conditions in a randomized order, meaning that the patients performed a total of 9 lumbar flexions.

The three conditions were: (1) lumbar flexion performed without the use of VR [control condition, (F)]; (2) lumbar flexion performed with a VR illusion induced by shortening the perceived length of the arms of the participants by 20% relative to the real length, thereby creating a feeling that they were moving less compared to the control condition [understated visual feedback (F −)]; (3) lumbar flexion performed with a virtual illusion induced by elongating the perceived real length of their arms by 20%, in so creating a feeling that they were moving more compared to control condition [overstated visual feedback (F +)].

We utilized the outcomes of a preliminary study to identify the virtual deception ratios that participants were most likely to perceive as 'non-manipulated', thereby minimizing the likelihood they would detect the deception (see Appendix A1 for more information on the pilot study). Thus, the following numbers were selected for each of the two VR conditions: 0.8 (− 20% of the real arm length) for F − and 1.2 (+ 20% of the real arm length) for F +.

To ensure that participants were unaware of the changes in the two illusory VR conditions, a two-minute rest period was allowed between the 3 repeats of each condition. In addition, we measured task difficulty throughout this rest interval to see how conscious the patients were of changes in gain between the 2 scenarios. The VR procedure was administered by the same experienced researcher in all cases. Furthermore, both the patients and the researcher were unaware of the order in which each condition was treated. Finally, to assess whether the participants had remained unaware of the gain alterations, at the end of the experiment they were asked if they had observed any variations between the different flexions. The entire experimental process is shown in a video in Appendix B1.

Outcome measures

1. Maximum pain-free lumbar ROM wasdefined as the range of flexion from the starting position to the point at which the participant first perceived a noticeable increase in their typical symptoms. In most cases, participants reported only mild discomfort at rest, and the pain-free threshold was identified as the transition point from discomfort to active pain during movement. It was measured using a 3-Space Fastrack motion electro-goniometer linked to a Windows 10 computer (Microsoft Corporation, Red-

mond, WA, USA). This analysis system has demonstrated excellent reliability and has been validated for the measurement of lumbar mobility in patients with LBP [21, 22]. To track lumbar spine movement, two motion sensors were affixed to the spinous processes of T12 and S1 [22]. The same researcher installed all of the sensors and used manual palpation to identify the bone landmarks. The 3-Space Fastrack quantified the total ROM in degrees for each repetition. The average ROM for each gain condition (F + and F −) was subsequently computed from three repetitions (absolute data). To account for individual variations in overall lumbar ROM, data from F − and F + were converted to a percentage (relative data) of the mean flexion range from the control condition.

2. The Brief Pain Inventory (BPI) is a pain assessment tool designed to measure pain intensity and interference with daily functioning in patients with LBP. Previous studies have demonstrated both the high reliability (Cronbach's alpha = 0.95) and validity of the BPI across cultures and languages [23, 24]. Patients were asked to rate how their pain had interfered with 7 life domains (general activity, mood, walking ability, normal work, relationships with others, sleep, and enjoyment of life) in the week prior. Moreover, they also indicated the level of pain they experienced using a Likert-style scale with values ranging from 0 (no pain) to 10 (worst imaginable pain). Higher scores indicated higher pain intensity or interference.
3. To assess kinesiophobia, we employed the reliable and validated version of the Tampa Scale for Kinesiophobia (TSK) [25]. This scale comprises 17 distinct statements, each rated on a 4-point scale (1 = totally disagree to 4 = totally agree). The total score ranges from 17 to 68, with a score exceeding 37 being regarded as indicative of kinesiophobia [26]. Its application in cLBP studies is well-established, given the substantial association between kinesiophobia and the onset of cLBP [27].
4. To evaluate catastrophizing in LBP, we employed the validated version of the Pain Catastrophizing Scale (PCS). This scale, known for its internal consistency, test–retest reliability, and sensitivity to change, comprises 13 items rated on a 5-point scale from 0 (never) to 4 (always). It assesses three components of catastrophizing: rumination, magnification, and helplessness [28]. The total score ranges from 0 to 52, with a score of 30 or more being indicative of high catastrophizing [29].
5. To evaluate the awareness of the participants regarding the gain changes in the two illusory VR conditions, we performed a comparative analysis of the perceived task difficulty of the patients under the F − and F + conditions, measured on a scale from 0 to 10, where 0 represented 'very easy' and 10 denoted 'extremely difficult.'
6. Motion sickness, a common side effect of VR and a potential impediment to its implementation, was explored by conducting a direct interview at the conclusion of the experiments.

Statistical analyses

An external researcher, who was not involved in the procedures and who was blinded to the intervention, determined the requisite sample size using G*Power 3 software [30]. A priori analysis for effect and sample size was executed at an α level of 0.05 with a desired power of 95%. The effect size, estimated using the ηp^2 parameter derived from related studies on analogous dependent variables (visual-proprioceptive feedback during cervical rotation while using VR) [14], projected that a minimum sample size of 36 participants would be necessary. To allow for potential losses of 30%, we set the final desired sample size at 47 participants.

To evaluate our main hypothesis, which postulates that visual feedback manipulation (by either overstating or understating real lumbar flexion) might impact movement-evoked pain, we studied pain-free ROM in each of the three conditions. Shapiro–Wilk tests were used to assess compliance with the assumption of normality for each dependent variable and indicated that the data was parametric for all the variables being investigated. Therefore, we performed a one-way ANOVA followed by adjusted Bonferroni post-hoc tests for the three experimental conditions (F −, F and F +) to examine within-group differences (setting the significance level to $p < 0.05$). Effect sizes were estimated using ηp^2 and were interpreted according to Cohen's guidelines for small, moderate, and large effect sizes ($\eta p^2 = 0.01$, 0.06, or 0.14, respectively) [31].

When our main hypothesis was fulfilled (i.e., the onset of movement pain was delayed in the F − condition) and the data was normally distributed, we applied two-sample *t*-tests to investigate whether the effect of visual feedback manipulation in F − varied between individuals with different levels of pain, as well as to assess whether it interfered with daily functioning, kinesiophobia, and catastrophizing. Thus, we compared patients categorized as 'VR responders,' whose %ROM was above the mean, with those designated as 'VR non-responders,' whose %ROM fell below the mean, in the F − condition for the dependent variable of pain and its interference.

Additionally, we also compared participants classified as exhibiting kinesiophobia based on their TSK scores (TSK > 37), with those classified as without kinesiophobia

(TSK ≤37) and those classified as high catastrophizing (PCS ≥30) and low catastrophizing (PCS <30). The effect sizes were gauged using the Cohen *d* measure, with interpretations categorized as small, moderate, and large effect sizes having sores of $d = 0.2$, 0.5, or 0.8, respectively [31].

Finally, because of the parametric nature of the data, a two-sample *t*-test was used to assess the task difficulty perceived by patients under the F− and F+ conditions. The statistical analysis was carried out using SPSS software (version 27.0 for Mac OS; IBM Corp., Armonk, NY, USA), applying a 95% confidence interval (CI) and a significance level of $p < 0.05$ for all the analyses. The study data are presented as means and standard deviations (*SD*).

Results

Fifty patients with cLBP willingly took part in this study. An overview of the participant characteristics is provided in Table 1.

The one-way ANOVA test, followed by adjusted Bonferroni post-hoc tests, revealed significant differences ($p < 0.001$) among the three experimental conditions (F −, F+, and F) with a moderate effect size ($\eta p^2 = 0.11$). Pairwise comparisons using Bonferroni post-hoc analysis indicated significant differences between F− (105%; ±2.1) and both F (100%; ±0) and F+ (98%; ±2.3). Specifically, when visual feedback understated true lumbar flexion (F −condition), pain-free range of motion increased by 5% compared to the control condition (p =0.04, 95% CI [0.6%, 10.7%]), and by 7% compared to the overstated condition (F +) (p <0.001, 95% CI [2.6%, 11.6%]). No significant difference was found between the control and overstated conditions ($p = 1.00$; 95% CI [− 4.1%, 7.6%]).

Table 1 The global characteristics of the participants in this study

N (women/men)	50 (28/22)
Age (years)	52 (± 13)
Height (cm)	169 (± 9)
Weight (kg)	75 (± 15)
Employment status (working/not working)	13/37
Duration of pain (in months)	11 (± 5)
BMI (kg/m^2)	25.9 (± 4.1)
Pain (BPI_Intensity)	5.2 (± 1.8)
Pain interference (BPI_Interference)	4.6 (± 2.3)
Kinesiophobia (TSK)	31.2 (± 6.1)
Catastrophizing (PCS)	34.9 (± 10.6)

The values are presented as the means ± standard deviations. *N* number, *BMI* body mass index, *BPI_Intensity* Brief Pain Inventory_Intensity, *BPI_Interference* Brief Pain Inventory_Interference, *TSK* Tampa Scale for Kinesiophobia, *PCS* Pain Catastrophizing Scale

Therefore, the overall effect of visual-proprioceptive manipulation in this study was a 7% difference in pain-free lumbar flexion between the understated and overstated conditions (Fig. 3).

Afterwards, we conducted a two-sample *t*-test to assess potential variations in pain intensity and its interference between individuals categorized as 'VR responder's and 'VR non-responder's and to assess potential variations between patients with and without kinesiophobia and catastrophizing tendencies in the F− condition during which patient movement was increased. Significant differences were noted both in pain intensity and pain interference scores, both with a moderate effect size. Participants with higher levels of pain and increased pain interference in their daily lives ('VR responder's) exhibited a more favorable response to the F− condition compared to the 'VR non-responder's (Table 2). However, no significant differences were observed in pain-free ROM responses to the F− condition between participants with and without high levels of kinesiophobia or catastrophizing (Table 3).

The repeated measures *t*-test comparing the perceived difficulty levels of the task in each condition (F −vs. F+) showed no significant differences between the two conditions ($p = 0.55$). Moreover, none of the participants reported having been aware of any changes in the gain between conditions or having experienced any nausea or dizziness at any time during the experiment.

Discussion

To the best of our knowledge, no studies have yet been published in the academic literature to describe how VR-induced illusory motions might alter visual-proprioceptive information and modulate lumbar flexion pain thresholds in people with cLBP. Thus, we investigated how altering visual-proprioceptive feedback during lumbar flexion influenced the threshold of movement-evoked pain. We hypothesised that pain would begin with less movement when the visual feedback overstated true flexion (i.e., reduced pain-free range of motion), and

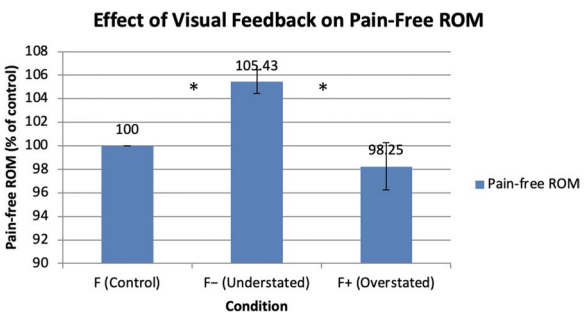

Fig. 3 Effect of visual feedback on pain-free range of motion

Table 2 Differences between 'VR responder's (%ROM above the mean) and 'VR non-responder's (%ROM below mean) in the F − condition in terms of pain

	'VR responder's N = 21	**'VR non-responder's N = 25**	***p***	**Mean difference (95% CI)**	**Cohen's *d***
	Mean (± *SD*)	**Mean (± *SD*)**			
Pain intensity (BPI_Intensity)	5.9 (± 1.9)	4.8 (± 1.6)	0.05*	− 1 [− 2.1; 0.02]	0.6
Pain interference (BPI_Interference)	5.5 (± 2.4)	4.1 (± 2.1)	0.04*	− 1.4 [−2.7;0.1]	0.6

Values are expressed as the mean ± standard deviation (SD). *N* number, *BPI_Intensity* Brief Pain Inventory_Intensity, *BPI_Interference* Brief Pain Inventory_Interference.

*p ≤ 0.05

Table 3 Differences between patients with and without kinesiophobia and with high and low catastrophizing in the F − condition (% ROM)

	With kinesiophobia (TSK > 37) N = 21	**Without kinesiophobia (TSK ≤ 37) N = 25**	***p***	**Mean difference (95% CI)**	**Cohen's *d***
	Mean (± *SD*)	**Mean (± *SD*)**			
F − (% ROM)	111 (± 12.1)	104 (± 15.3)	0.22	− 6.8 [− 17.8; 4.2]	0.5
	With catastrophizing (PCS ≥ 30) N = 21	**Without catastrophizing (PCS < 30) N = 25**	***p***	**Mean difference (95% CI)**	**Cohen's *d***
	Mean (± *SD*)	**Mean (± *SD*)**			
F − (% ROM)	112 (± 16)	104 (± 14.4)	0.15	− 8 [− 19; 3.1]	0.5

Values are expressed as the mean ± standard deviation (SD). *N* number, *TSK* Tampa Scale for Kinesiophobia, *PCS* Pain Catastrophizing Scale, *F* − understated condition, *% ROM* percentage range of movement (flexion).

*p ≤ 0.05

that pain would be delayed when visual feedback understated actual flexion (i.e., increased pain-free range of motion). Our hypothesis was supported. In the F − condition, patients were able to bend further before feeling pain, on average, 5% more than in the control condition and 7% more the F + condition. This suggests that what people *see* about their movement can significantly change when they *feel* pain, even if the actual physical movement remains the same. Furthermore, elevated pain levels and its interference in their daily lives influenced the susceptibility of patients with cLBP to the effect of visual feedback manipulation.

These findings align with the results documented by Harvie et al. (2015) [14], who found similar effects using cervical rotation. Together, these studies suggest that visual-proprioceptive mismatches may affect pain thresholds, supporting models of pain as a perceptual construct influenced by sensory integration and threat-related cues.

Although the percentage changes in pain-free ROM between conditions were relatively small (approximately 5–7%), these differences were statistically significant and were achieved through purely perceptual manipulations. This highlights the sensitivity of pain thresholds to non-nociceptive factors such as visual feedback and encourages future investigation into whether such effects could be amplified or sustained over time when applied as part of a structured clinical intervention protocol.

Our results are consistent with the theory that pain represents the experience of the brain of a perceived danger to bodily tissues, an idea also backed by previous research [32, 33]. This is also consistent with studies demonstrating an association between pain intensity and stimuli that imply a threat to tissues [14, 34]. Therefore, a sensory modality like vision can impact the perception, behavioral responses, or neural processing of a stimulus presented by another sensory modality such as pain. Indeed, neuroimaging studies have shown increased connectivity between visual and sensorimotor areas in individuals with cLBP, suggesting cross-modal interactions [35]. Additionally, experimental findings indicate that visual cues associated with tissue threat, such as red light, can amplify pain perception and expectations independently of nociceptive input [36].

Our results suggest that the observed effects vary according to patient symptomatology, specifically pain intensity, its interference with daily functioning, kinesiophobia, and catastrophizing. Patients with higher baseline pain and greater interference in daily life were more

responsive to visual feedback manipulation. During the tasks in the F− condition, participants exhibited greater lumbar flexion and delayed pain onset. This may reflect a learned association between movement and pain, modifiable via visual cues [13, 14]. While the underlying mechanisms require further investigation, existing evidence suggests that individuals with lower pain and minimal interference may more easily disassociate movement from pain. In contrast, those experiencing higher pain levels and disruption to daily life may reinforce maladaptive protective responses. This is consistent with prior research showing that high pain expectations influence perceptual and autonomic responses [39]. These findings support the notion that pain experience, functional interference, and pain–movement associations interact in complex ways, and highlight the need for future studies to explore whether patients with greater symptom burden are more susceptible to the effects of visual feedback manipulation.

Of note, Kragting et al. [13] investigated the effect of visual feedback manipulation in 75 patients with non-specific neck pain, including 37 individuals with kinesiophobia (TSK > 37)—the same cut-off used in our study. Using a 0.7 gain (understated condition) for cervical rotation, they found that patients with fear of movement exhibited a significantly greater pain-free range than those without. These results align with our findings and can be interpreted within the framework of associative learning, whereby individuals with kinesiophobia may struggle to disassociate non-nociceptive visual cues from pain experiences. In our sample, a similar trend was observed, with the 9 patients scoring above 37 on the TSK showing a 7% increase in lumbar flexion under the F− condition compared to those without kinesiophobia. However, this difference did not reach statistical significance, likely due to the smaller subgroup size. In summary, although both studies investigated the impact of visual feedback on movement-evoked pain and demonstrated similar outcomes in the understated condition, they differed in terms of gain conditions and the movements studied. Coupled with the limited number of patients with kinesiophobia included in our study, the latter may have contributed to the disparities in the results from patients that fear movement.

Focusing on catastrophizing, it was notable that patients exhibiting catastrophizing tendencies showed an average 8% increase in lumbar flexion under the F− condition compared to participants without such tendencies. However, these differences were not significant. Nevertheless, it is important to note that this observation was based on a small subset in our study consisting of only 9 out of 50 patients whose PCS score surpassed a threshold of 30, which could also represent a potential limitation of our work. Therefore, more studies with a balanced representation of participants in each group are warranted to investigate these trends further to elucidate the potential impact of kinesiophobia and catastrophizing on movement-evoked pain through VR, thereby ensuring more robust and generalizable findings.

Importantly, no differences in task difficulty were observed between conditions (F − and F +). Participants were unaware of gain manipulations. Moreover, even though motion sickness is a frequent negative effect of VR [40], its potential as a barrier to the implementation of VR was not observed in our procedure with 50 patients with cLBP. This absence of symptoms may be attributed to the specific patient population (LBP) or the innovative design of our virtual environment.

This study has certain limitations. First, a potential selection bias may have arisen, as patients were recruited from Orthopaedic Surgery and Physical Medicine and Rehabilitation consultations, possibly skewing the sample toward less severe or treatment-resistant cases. As a result, the heterogeneity of the study population may limit the generalisability of the findings, particularly to individuals with more acute, subacute, or highly disabling chronic LBP. Furthermore, this study was constrained by the fact we considered a relatively small sample size of patients with elevated levels of kinesiophobia and catastrophizing. Another limitation relates to the clinical heterogeneity inherent to non-specific cLBP. Despite applying strict inclusion criteria and selecting only patients who reported pain during lumbar flexion, underlying pain mechanisms likely varied (e.g., discogenic vs. motor control-related origins). As discogenic pain is common in the general population [41], its presence cannot be entirely ruled out. This variability may affect the generalisability of our results and should be addressed in future studies aiming to stratify patients by pain mechanisms. Nonetheless, all participants underwent all three experimental conditions, allowing for within-subject comparisons and reducing inter-individual variability. Finally, although participants were selected based on an average NPRS score ≥ 3 in the past 6 months, this criterion may be affected by recall bias. However, all participants also reported pain during active lumbar flexion at the time of evaluation, ensuring clinical relevance of the sample.

The implications of our findings extend beyond lumbar pain, contributing to a broader understanding of pain perception. They emphasise the complex interaction between nociceptive and non-nociceptive factors, challenging traditional models centred solely on tissue damage. This study highlights the critical role of visual-proprioceptive cues in shaping movement-evoked pain, underscoring the importance of sensory

information processing. Accordingly, our methodology not only advances knowledge of pain mechanisms but also informs innovative strategies for pain assessment and intervention.

Although our study specifically focused on the manipulation of visual-proprioceptive feedback, VR may also exert analgesic effects through mechanisms such as attentional distraction, increased engagement, and reduced threat perception during movement. Previous research has shown that VR can reduce pain intensity during range of motion exercises, particularly in clinical populations such as patient's with burns [42]. It is therefore possible that VR distraction contributed to an overall reduction in pain across conditions in our study, without differentially affecting the F− and F+ conditions. Furthermore, future studies may benefit from assessing patient's sense of presence within the virtual environment, their enjoyment of the tasks, and the subjective experience of pain under different VR scenarios, to better understand the broader potential of VR analgesia.

In addition, the use of VR to manipulate visual-proprioceptive feedback offers a promising avenue for assessing pain responses to non-nociceptive sensory cues. This approach may allow clinicians to evaluate how sensory integration processes contribute to pain perception, particularly in movement-evoked contexts. For instance, VR environments could be designed to gradually expose patients with fear-avoidance behaviour to trunk flexion tasks in which visual feedback is subtly altered to reduce perceived threat. Such an approach could enable patients to engage in movements they would otherwise avoid, thereby offering a controlled and personalised method to assess pain-related beliefs and behavioural responses.

In conclusion, VR manipulation of visual-proprioceptive information can serve as a modulator of pain thresholds during lumbar flexion in individuals with cLBP. Specifically, under the F− condition, patients with cLBP exhibited an increase in movement before they encountered pain, thereby delaying pain onset. Moreover, our results highlight the considerable influence of pain intensity and its impact on the quality of life in determining the susceptibility of individuals with cLBP to the effects of visual feedback manipulation (F −). Greater pain levels and increased pain interference were associated with heightened susceptibility to visual feedback manipulation. These findings contribute to our understanding of the complex relationship between visual-propioceptive feedback, pain perception, and movement patterns in cLBP. From a clinical perspective, this approach may support graded exposure strategies in patients with fear-avoidance behaviours, allowing them to perform trunk flexion movements in VR scenarios where visual feedback is adjusted to reduce perceived threat. Over time, such exposure could help to reconsolidate maladaptive pain memories and facilitate safer, pain-free movement, an essential aim in modern pain rehabilitation. Future research should explore the application of F− conditions not only to expand pain-free range of motion, but also to reshape learned associations between movement and pain.

Abbreviations

cLBP	Chronic low back pain
VR	Virtual reality
ROM	Range of movement
N	Number
BMI	Body mass index
BPI_Intensity	Brief pain inventory_intensity
BPI_Interference	Brief pain inventory_interference
TSK	Tampa Scale for Kinesiophobia
PCS	Pain Catastrophizing Scale
F	Control condition
F−	Understated condition
F +	Overstated condition

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-025-01664-2.

Supplementary material 1

Supplementary material 2

Supplementary material 3

Supplementary material 4

Acknowledgements
The authors wish to extend their sincere gratitude to all the individuals who contributed to the successful completion of this study. We deeply appreciate the invaluable contributions of the participants, without whom this research would not have been possible. Our acknowledgment also goes to the Arnau de Vilanova Hospital for providing the necessary infrastructure and a conducive environment for conducting this study. This work was made possible through a grant from the Ministerio de Ciencia e Innovación (Plan Estatal de Investigación Científica y Técnica y de Innovación [PID2020-115609RB-C22]).

Author contributions
JJL, JD, RMB, JJAC and JFL conceived this research. MM, RH, RMB, MDA, LMPB and JFL were responsible for the methodology. JJL, JJAM and JFL prepared and edited the article. All authors reviewed the article and approved the submitted version.

Funding
This work was supported by grant from the Ministerio de Ciencia e innovación (Plan Estatal de Investigación Científica y Técnica y de Innovación [PID2020-115609RB-C22]).

Data availability
The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. Interested researchers can contact us via email to request access to the data, which will be provided in accordance with ethical and legal guidelines.

Declarations

Ethics approval and consent to participate
Following the foundational tenets outlined in the Helsinki Declaration, ethical clearance for this study was obtained from the Ethics Committee at the CEU Cardenal Herrera University in Valencia, Spain and the Arnau de Vilanova

Hospital in Valencia, Spain. Before joining the study, each participant received a detailed information letter and provided their written consent.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Biomedical Sciences, School of Health Sciences, Universidad Cardenal Herrera-CEU, CEU Universities, Alfara del Patriarca, Valencia, Spain. [2]Department of Physiotherapy, School of Health Sciences, Universidad Cardenal Herrera-CEU, CEU Universities, Alfara del Patriarca, Valencia, Spain. [3]Department of Orthopedic Surgery and Traumatology, Clínica Universidad de Navarra, Pamplona, Spain. [4]Department of Physical Medicine and Rehabilitation, Hospital Arnau de Vilanova, Valencia, Spain. [5]CIBER of Physiopathology of Obesity and Nutrition (CIBEROBN), Instituto de Salud Carlos III, Madrid, Spain. [6]Department of Personality, Evaluation, and Psychological Treatments, University of Valencia, Valencia, Spain. [7]Department of Psychology and Sociology, Universidad de Zaragoza, Teruel, Spain. [8]Polibienestar Research Institute, University of Valencia, Valencia, Spain.

Received: 22 March 2025 Accepted: 4 June 2025
Published online: 19 June 2025

References

1. Alonso-García M, Sarría-Santamera A. The economic and social burden of low back pain in Spain: a national assessment of the economic and social impact of low back pain in Spain. Spine. 2020;45(16):E1026–32. https://doi.org/10.1097/BRS.0000000000003476.
2. Mazloum V, Sahebozamani M, Barati A, Nakhaee N, Rabiei P. The effects of selective Pilates versus extension-based exercises on rehabilitation of low back pain. J Bodyw Mov Ther. 2018;22(4):999–1003. https://doi.org/10.1016/j.jbmt.2017.09.012.
3. Hartvigsen J, Hancock MJ, Kongsted A, et al. What low back pain is and why we need to pay attention. Lancet Lond Engl. 2018;391(10137):2356–67. https://doi.org/10.1016/S0140-6736(18)30480-X.
4. Karran EL, Grant AR, Moseley GL. Low back pain and the social determinants of health: a systematic review and narrative synthesis. Pain. 2020;161(11):2476–93. https://doi.org/10.1097/j.pain.0000000000001944.
5. Coenen P, Gouttebarge V, van der Burght ASAM, et al. The effect of lifting during work on low back pain: a health impact assessment based on a meta-analysis. Occup Environ Med. 2014;71(12):871–7. https://doi.org/10.1136/oemed-2014-102346.
6. Heneweer H, Staes F, Aufdemkampe G, van Rijn M, Vanhees L. Physical activity and low back pain: a systematic review of recent literature. Eur Spine J. 2011;20(6):826–45. https://doi.org/10.1007/s00586-010-1680-7.
7. Gombatto SP, D'Arpa N, Landerholm S, et al. Differences in kinematics of the lumbar spine and lower extremities between people with and without low back pain during the down phase of a pick up task, an observational study. Musculoskelet Sci Pract. 2017;28:25–31. https://doi.org/10.1016/j.msksp.2016.12.017.
8. Laird RA, Gilbert J, Kent P, Keating JL. Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet Disord. 2014;15:229. https://doi.org/10.1186/1471-2474-15-229.
9. Bingel U, Schoell E, Büchel C. Imaging pain modulation in health and disease. Curr Opin Neurol. 2007;20(4):424–31. https://doi.org/10.1097/WCO.0b013e328259c34d.
10. Mouatt B, Smith AE, Parfitt G, et al. What I see and what I feel: the influence of deceptive visual cues and interoceptive accuracy on affective valence and sense of effort during virtual reality cycling. PeerJ. 2023;11:e16095. https://doi.org/10.7717/peerj.16095.
11. Tsay A, Allen TJ, Proske U, Giummarra MJ. Sensing the body in chronic pain: a review of psychophysical studies implicating altered body representation. Neurosci Biobehav Rev. 2015;52:221–32. https://doi.org/10.1016/j.neubiorev.2015.03.004.
12. Brumagne S, Dolan P, Pickar J. What is the relation between proprioception and low back pain? Spinal Control Rehabil Back Pain State Art Sci. 2013. https://doi.org/10.1016/B978-0-7020-4356-7.00019-7.
13. Kragting M, Voogt L, Coppieters MW, Pool-Goudzwaard AL. Visual feedback manipulation in virtual reality to influence pain-free range of motion. Are people with non-specific neck pain who are fearful of movement more susceptible? PLoS ONE. 2023;18(7):e0287907. https://doi.org/10.1371/journal.pone.0287907.
14. Harvie DS, Broecker M, Smith RT, Meulders A, Madden VJ, Moseley GL. Bogus visual feedback alters onset of movement-evoked pain in people with neck pain. Psychol Sci. 2015;26(4):385–92. https://doi.org/10.1177/0956797614563339.
15. Raja SN, Carr DB, Cohen M, et al. The revised IASP definition of pain: concepts, challenges, and compromises. Pain. 2020;161(9):1976–82. https://doi.org/10.1097/j.pain.0000000000001939.
16. Shraim MA, Sluka KA, Sterling M, et al. Features and methods to discriminate between mechanism-based categories of pain experienced in the musculoskeletal system: a Delphi expert consensus study. Pain. 2022;163(9):1812–28. https://doi.org/10.1097/j.pain.0000000000002577.
17. Nguyen AT, Aris IM, Snyder BD, et al. Musculoskeletal health: an ecological study assessing disease burden and research funding. Lancet Reg Health Am. 2024;29:100661. https://doi.org/10.1016/j.lana.2023.100661.
18. Airaksinen O, Brox JI, Cedraschi C, et al. European guidelines for the management of chronic nonspecific low back pain. Eur Spine J. 2006;15(S2):s192–300. https://doi.org/10.1007/s00586-006-1072-1.
19. Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), mcgill pain questionnaire (MPQ), short-form mcgill pain questionnaire (SF-MPQ), chronic pain grade scale (CPGS), short form-36 bodily pain scale (SF-36 BPS), and measure of intermittent and constant osteoarthritis pain (ICOAP). Arthritis Care Res. 2011;63(Suppl 11):S240-252. https://doi.org/10.1002/acr.20543.
20. Dworkin R, Turk D, Peirce-Sandner S, et al. Research design considerations for confirmatory chronic pain clinical trials: IMMPACT recommendations. Pain. 2010;149:177–93. https://doi.org/10.1016/j.pain.2010.02.018.
21. Ribeiro DC, Sole G, Abbott JH, Milosavljevic S. Validity and reliability of the Spineangel lumbo-pelvic postural monitor. Ergonomics. 2013;56(6):977–91. https://doi.org/10.1080/00140139.2013.781233.
22. Arguisuelas MD, Lisón JF, Doménech-Fernández J, Martínez-Hurtado I, Salvador Coloma P, Sánchez-Zuriaga D. Effects of myofascial release in erector spinae myoelectric activity and lumbar spine kinematics in non-specific chronic low back pain: randomized controlled trial. Clin Biomech Bristol Avon. 2019;63:27–33. https://doi.org/10.1016/j.clinbiomech.2019.02.009.
23. Song CY, Lin SF, Huang CY, Wu HC, Chen CH, Hsieh CL. Validation of the brief pain inventory in patients with low back pain. Spine. 2016;41(15):E937–42. https://doi.org/10.1097/BRS.0000000000001478.
24. de Andrés Ares J, Cruces Prado LM, Canos Verdecho MA, et al. Validation of the short form of the brief pain inventory (BPI-SF) in Spanish patients with non-cancer-related pain. Pain Pract Off J World Inst Pain. 2015. https://doi.org/10.1111/papr.12219.
25. Gómez-Pérez L, López-Martínez AE, Ruiz-Párraga GT. Psychometric properties of the Spanish version of the Tampa Scale for Kinesiophobia (TSK). J Pain. 2011;12(4):425–35. https://doi.org/10.1016/j.jpain.2010.08.004.
26. Vlaeyen JWS, Kole-Snijders AMJ, Boeren RGB, van Eek H. Fear of movement/(re)injury in chronic low back pain and its relation to behavioral performance. Pain. 1995;62(3):363. https://doi.org/10.1016/0304-3959(94)00279-N.
27. Bodes Pardo G, Lluch Girbés E, Roussel NA, Gallego Izquierdo T, Jiménez Penick V, Pecos MD. Pain neurophysiology education and therapeutic exercise for patients with chronic low back pain: a single-blind randomized controlled trial. Arch Phys Med Rehabil. 2018;99(2):338–47. https://doi.org/10.1016/j.apmr.2017.10.016.
28. Lami M, Martínez MP, Miró E, Sánchez AI. Spanish version of "pain catastrophizing scale": psychometric study in healthy women. Behav Psychol Psicol Conduct. 2013;21:137–56.
29. Sullivan MJL. The pain catastrophizing scale: user manual. *McGill Univ*. 2009.
30. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav Res Methods. 2009;41(4):1149–60. https://doi.org/10.3758/BRM.41.4.1149.
31. Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale: L. Erlbaum Associates; 1988.

32. Butler DS, Moseley GL. Explicando el Dolor. Adelaide: Noigroup Publications; 2010.
33. Vlaeyen JWS, Crombez G. Behavioral conceptualization and treatment of chronic pain. Annu Rev Clin Psychol. 2020;16:187–212. https://doi.org/10.1146/annurev-clinpsy-050718-095744.
34. Moseley GL, Arntz A. The context of a noxious stimulus affects the pain it evokes. Pain. 2007;133(1–3):64–71. https://doi.org/10.1016/j.pain.2007.03.002.
35. Shen W, Tu Y, Gollub RL, et al. Visual network alterations in brain functional connectivity in chronic low back pain: a resting state functional connectivity and machine learning study. NeuroImage Clin. 2019;22:101775. https://doi.org/10.1016/j.nicl.2019.101775.
36. Wiercioch-Kuzianik K, Brączyk J, Bieniek H, Bąbel P. Red induces hyperalgesia and white induces hypoalgesia regardless of pain modality. Sci Rep. 2023;13(1):6360. https://doi.org/10.1038/s41598-023-33313-w.
37. Moseley GL, Vlaeyen JWS. Beyond nociception: the imprecision hypothesis of chronic pain. Pain. 2015;156(1):35–8. https://doi.org/10.1016/j.pain.0000000000000014.
38. Meier ML, Vrana A, Schweinhardt P. Low back pain: the potential contribution of supraspinal motor control and proprioception. Neuroscientist. 2019;25(6):583–96. https://doi.org/10.1177/1073858418809074.
39. Barnes K, McNair NA, Harris JA, Sharpe L, Colagiuri B. In anticipation of pain: expectancy modulates corticospinal excitability, autonomic response, and pain perception. Pain. 2021;162(8):2287–96. https://doi.org/10.1097/j.pain.0000000000002222.
40. Henderson A, Korner-Bitensky N, Levin M. Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. Top Stroke Rehabil. 2007;14(2):52–61. https://doi.org/10.1310/tsr1402-52.
41. Tonosu J, Inanami H, Oka H, et al. Diagnosing discogenic low back pain associated with degenerative disc disease using a medical interview. PLoS ONE. 2016;11(11):e0166031. https://doi.org/10.1371/journal.pone.0166031.
42. Carrougher GJ, Hoffman HG, Nakamura D, et al. The effect of virtual reality on pain and range of motion in adults with burn injuries. J Burn Care Res Off Publ Am Burn Assoc. 2009;30(5):785–91. https://doi.org/10.1097/BCR.0b013e3181b485d3.

Publisher's Note