

Pain Neuroscience Education in Anterior Cruciate Ligament Reconstruction Rehabilitation: A Review of Psychological and Return-to-Sport Outcomes in Recreational Athletes

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ABSTRACT

Psychological factors such as fear of reinjury, kinesiophobia, and pain catastrophizing are increasingly recognised as key barriers to successful return to sport following anterior cruciate ligament reconstruction (ACLR). Pain neuroscience education (PNE) has emerged as a biopsychosocial intervention targeting maladaptive pain-related beliefs, yet its role in ACLR rehabilitation remains under-explored. The objective of this study is to map the research landscape of PNE within ACLR rehabilitation among recreational athletes. Specifically, we aimed to characterise the intellectual structure of the field by identifying publication trends, dominant themes, and evidence gaps related to psychological and return-to-sport outcomes. A combined thematic review, bibliometric analysis, and knowledge-mapping approach was adopted using studies retrieved from major scientific databases. Publication trends, citation patterns, and keyword co-occurrence networks were analysed to evaluate the current state of the literature. Research output in this domain has increased over the past decade. Knowledge mapping revealed that dominant themes emphasise psychological readiness, rehabilitation, and return to sport. Thematically, the literature predominantly associates PNE with improvements in psychological outcomes, whereas reported effects on physical performance remain inconsistent. Conclusion on bibliometric and thematic mapping highlights a growing academic interest in PNE as a promising adjunct to multimodal ACLR rehabilitation. However, the current literature base reveals that direct, ACL-specific empirical evidence remains limited, indicating a clear need for future targeted clinical trials.

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1. INTRODUCTION

Anterior cruciate ligament (ACL) injury is a common and debilitating condition among physically active individuals and recreational athletes, frequently necessitating ACL reconstruction (ACLR) to restore knee stability and facilitate return to sport. Despite advances in surgical techniques and rehabilitation protocols, recovery following ACLR remains challenging. A substantial proportion of individuals report persistent pain, functional limitations, psychological distress, and difficulty returning to their pre-injury level of sport participation. These ongoing challenges indicate that optimal recovery after ACLR extends beyond biomechanical restoration alone and underscore the need for rehabilitation approaches that address both physical and psychological determinants of outcome.

Psychological factors are increasingly recognized as critical contributors to rehabilitation success after ACL reconstruction. Fear of reinjury, kinesiophobia, pain catastrophizing, anxiety, and reduced confidence have been consistently associated with delayed recovery, impaired functional performance, and unsuccessful return-to-sport outcomes (Burland et al., 2018; Cronström et al., 2023; Zarzycki et al., 2021). Evidence suggests that psychological readiness may be a stronger predictor of return to sport than physical impairments alone, particularly among recreational athletes who may have limited access to comprehensive, psychologically informed rehabilitation programs (Burland et al., 2018; Zarzycki et al., 2021). Consequently, there is a growing interest in interventions that explicitly target pain-related beliefs and maladaptive cognitive and emotional responses during ACLR rehabilitation.

Pain neuroscience education (PNE) is an educational intervention aimed at improving patients' understanding of pain by addressing the neurophysiological and psychological mechanisms underpinning the pain experience. The primary objective of PNE is to reconceptualize pain, reduce perceived threat, and modify maladaptive beliefs and behaviors that may hinder recovery (Dams et al., 2023; Kararti et al., 2024; Tayfur et al., 2025). Across a range of musculoskeletal and post-surgical populations, PNE has been shown to reduce pain catastrophizing, kinesiophobia, anxiety, and emotional distress, while promoting more adaptive coping strategies and greater engagement in rehabilitation (Dams et al., 2023; Kararti et al., 2024; Ponce-Fuentes et al., 2023; Tayfur et al., 2025). These psychosocial effects closely align with the psychological challenges commonly observed following ACL reconstruction.

Within ACL reconstruction rehabilitation, PNE has increasingly been integrated alongside traditional physiotherapy, strength training, and neuromuscular rehabilitation programs. This integration reflects a broader shift toward biopsychosocially informed rehabilitation models that aim to address psychological barriers such as pain catastrophizing, fear of movement, anxiety, and depressive symptoms—issues that may persist despite adequate tissue healing (Calabrò et al., 2025; Onate et al., 2019; Tatiya et al., 2021). Emerging evidence suggests that combining PNE with physical interventions can enhance rehabilitation outcomes by addressing both psychological and physical components of recovery. For example, case-based evidence indicates that integrating PNE with eccentric training after ACL repair may improve quadriceps strength, range of motion, and overall functional performance (Tatiya et al., 2021). However, the extent to which these benefits translate into consistent improvements in pain intensity, functional capacity, and return-to-sport outcomes remains unclear.

Evaluation of PNE within post-surgical and orthopedic rehabilitation contexts has demonstrated more consistent effects on psychological outcomes than on physical measures. Randomized controlled trials in orthopedic populations have reported significant reductions in kinesiophobia and improvements in mental

health-related quality of life following PNE, whereas effects on pain intensity and physical function have been more variable (Kararti et al., 2024; Ponce-Fuentes et al., 2023; Tayfur et al., 2025). This pattern suggests that PNE may exert its primary influence through psychological pathways that indirectly support physical recovery and readiness to return to sport. In ACLR populations, this is particularly relevant given the established role of psychological readiness, confidence, and fear of reinjury in determining successful return-to-sport outcomes (Burland et al., 2018; Cronström et al., 2023; Zarzycki et al., 2021).

When evaluating the current literature, it is crucial to carefully distinguish evidence derived specifically from ACL rehabilitation studies from evidence extrapolated from broader musculoskeletal or post-surgical populations. Extensive research in general chronic pain and broader orthopedic cohorts has robustly demonstrated the efficacy of PNE in reducing kinesiophobia and pain catastrophizing. While direct, ACL-specific empirical studies remain in their infancy, extrapolating these broader findings to the ACLR context is highly clinically relevant. The psychosocial barriers observed in generalized orthopedic recovery closely mirror the fear of reinjury, movement-related anxiety, and reduced confidence that frequently hinder return-to-sport following ACLR. Therefore, mapping how these established broader PNE principles are being conceptualized and adapted for ACL-specific populations provides a necessary foundation for identifying current research gaps.

Several dominant themes emerge from the existing literature on PNE in ACL rehabilitation. First, the psychological impact of PNE is consistently highlighted. Evidence supports its role in reducing pain catastrophizing, anxiety, and kinesiophobia factors known to delay rehabilitation progress and return to sport (Calabrò et al., 2025; Kararti et al., 2024; Tatiya et al., 2021). Second, integrating PNE with physical therapy (including strength, neuromuscular, and neurocognitive training) reflects an emerging consensus that combined approaches may offer greater benefits than single modality interventions (Calabrò et al., 2025; Onate et al., 2019). Third, return-to-sport readiness has gained increasing attention, with psychological constructs such as fear of reinjury, confidence, and self-efficacy now recognized as critical determinants of successful return to sport following ACL reconstruction (Burland et al., 2018; Cronström et al., 2023).

Despite these promising developments, several important evidence gaps remain. The long-term effects of PNE following ACL reconstruction are poorly understood, as most available studies focus on short to medium term outcomes (Kararti et al., 2024; Ponce-Fuentes et al., 2023; Tayfur et al., 2025). In addition, there is a lack of standardized PNE protocols and considerable heterogeneity in outcome measures, which limits comparability across studies and weakens the strength of conclusions that can be drawn (Adenis et al., 2024; Pico et al., 2025). Furthermore, limited attention has been given to individualized or patient-tailored PNE approaches, despite growing recognition that personalized interventions may be more effective in addressing diverse psychological profiles and rehabilitation needs (Dams et al., 2023; Mills et al., 2021).

Emerging trends in ACL rehabilitation further contextualize the potential role of PNE. Growing interest in neurocognitive and visual-motor training reflects advances in understanding neuroplastic changes following ACL injury and reconstruction, with the aim of improving neuromuscular control and reducing reinjury risk (Grooms et al., 2015; Vélez-Gutiérrez et al., 2025). Concurrently, holistic and biopsychosocial rehabilitation models that integrate PNE, physical therapy, and psychological support are becoming increasingly prominent in contemporary practice (Calabrò et al., 2025; Sharp & Pollard, 2024). Technological innovations, including neuromodulatory techniques and motor cortex stimulation, are also

being explored as adjuncts to enhance motor learning, neuroplasticity, and functional recovery after ACL injury (Vicente-Mampel et al., 2025).

To systematically understand how this intervention is documented in the literature, the primary objective of this study is to map the research landscape of PNE within ACLR rehabilitation among recreational athletes. Utilizing a combined thematic review, bibliometric analysis, and knowledge-mapping approach, this article aims to characterise the intellectual structure of the field. Specifically, it seeks to identify publication trends, dominant themes, evidence gaps, and emerging trends related to psychological and return-to-sport outcomes.

2. METHODS

This study utilized a combined thematic review, bibliometric analysis, and knowledge-mapping approach to systematically map and synthesize the scientific literature examining the use of pain neuroscience education (PNE) in individuals undergoing anterior cruciate ligament reconstruction (ACLR), with a particular focus on recreational athletes. This combined methodological approach was grounded in established knowledge-mapping frameworks that enable the identification of research trends, thematic structures, and intellectual relationships within health sciences literature (Azizan, 2025). To guide the conceptual scope of the mapping, the research question was structured using the PICO framework, as follows:

- **Population:** Recreational or non-elite athletes following ACL reconstruction.
- **Intervention:** PNE and related educational constructs (e.g., pain neurophysiology education, pain science education, pain reconceptualization).
- **Comparison:** Usual care or exercise-based rehabilitation without structured pain education.
- **Outcomes:** Pain-related, psychological, functional, and return-to-sport indicators.

Comprehensive research was conducted across major electronic databases commonly used for health and sports science research, including Scopus, Web of Science, and PubMed. In line with bibliometric mapping methodologies, search strategies employed both controlled vocabulary and free-text terms to maximize conceptual coverage, rather than restricting inclusion based on study design or level of evidence (Azizan, 2025a). Database-specific subject headings (e.g., MeSH terms) were combined with free-text keywords and Boolean operators to ensure sensitive retrieval of relevant literature. No restrictions were placed on study design or publication type, to capture the full evolution of research in this domain. The final search query was:

("ACL injuries" OR "anterior cruciate ligament injury*")
 AND ("pain*" OR "physical suffering*" OR "ache*")
 AND ("outcome*" OR "psychological*")*

All retrieved records were exported in a compatible format and screened for relevance based on title and abstract before inclusion in the review dataset. Duplicate records were removed prior to analysis.

Various bibliometric indicators, including annual publication trends, citation counts, co-authorship networks, and keyword co-occurrence, were then analyzed using dedicated software. Keyword clustering was guided by the predefined PICO domains to identify dominant research themes, conceptual relationships, and emerging topics, particularly those related to fear-avoidance, pain catastrophizing, self-efficacy, and return-to-sport readiness. Findings were visualized using network maps to illustrate the intellectual structure and thematic evolution of PNE research within ACL rehabilitation. The combination of co-word analysis, citation analysis, and thematic mapping provided a robust overview of the field's development, thereby informing future intervention development and research directions.

3. RESULT AND DISCUSSION

The results present a bibliometric and thematic synthesis of literature examining pain neuroscience education, neurophysiological constructs, and psychological factors within ACL rehabilitation. Publication trends and citation patterns are first analyzed to characterize the temporal development of this research area, followed by thematic mapping to contextualize the positioning of PNE within the broader ACL rehabilitation landscape.

Temporal Trends in PNE and Neurophysiology in ACL Rehabilitation

As shown in Figure 1, the annual number of publications (TP) remained very low from 1990 to the late 1990s, with only sporadic single publications and negligible citation impact. Early outputs during this phase (1990–1998) were infrequent and inconsistently cited, suggesting that PNE and related neuropsychological perspectives had not yet gained traction within ACL rehabilitation research. A notable early citation peak occurred in 1999 (total citations, TC = 598) despite only two publications that year. This was followed by a pronounced surge in 2003–2004, where total citations peaked sharply in 2004 (TC = 1500) with only two publications. These early citation spikes indicate the publication of seminal or highly influential works that shaped subsequent discourse, despite the low overall publication volume. Between 2005 and 2012, publication output increased modestly and irregularly, accompanied by fluctuating citation counts. This pattern reflects an exploratory phase during which foundational concepts were being tested and disseminated but had not yet achieved sustained research momentum.

From 2013 onwards, a clear growth trajectory is observed, characterized by a steady increase in annual publications and a more stable citation pattern. Publication output accelerated markedly after 2015, peaking in recent years (TP = 14 in both 2024 and 2025), which indicates expanding scholarly interest and consolidation of this research domain. Citation trends in this later period were comparatively lower on a per-year basis but more evenly distributed across publications, suggesting a transition from reliance on a few highly cited landmark papers to a broader, more diversified body of literature. Notably, years with high publication volume (2016, 2017, 2020, and 2024–2025) did not correspond to extreme citation peaks, likely reflecting citation lag effects and the emergence of newer studies that have not yet accrued citations. Overall, the data reveal a maturation of the field, marked by a shift from isolated, high-impact contributions toward sustained research productivity and incremental knowledge accumulation in PNE within ACL rehabilitation.

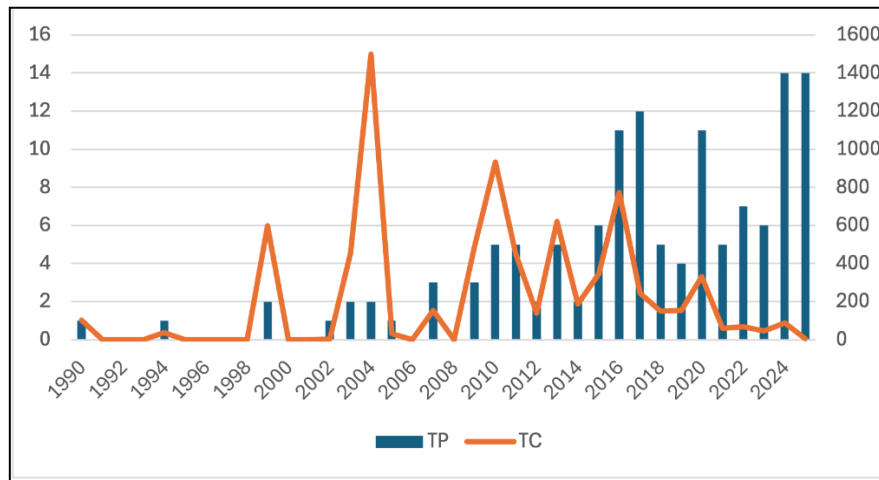


Figure 1: The annual distribution of total publications (TP) and total citations (TC) for PNE, neurophysiology within ACL

Figures 2.1 to 2.4 present the network visualisation of keyword co-occurrence across the analysed literature, illustrating the thematic structure of research related to anterior cruciate ligament rehabilitation. The clustering reflects recurrent conceptual groupings based on the frequency and strength of keyword associations, enabling identification of dominant research domains and their interrelationships. Four principal clusters were identified, corresponding to surgical and structural outcomes, psychological factors and return-to-sport processes, injury characterisation and risk profiling, and pain epidemiology with degenerative sequelae.

Surgical Outcomes and Long-Term Structural Sequelae

The red cluster is centered on keywords such as anterior cruciate ligament reconstruction, outcomes, follow-up, graft, patellar tendon, quality of life, and osteoarthritis. This indicates a dominant focus on surgical management and long-term structural and patient-reported outcomes following ACL injury. The strong co-occurrence of outcome- and follow-up-related terms reflects sustained research attention on graft selection, surgical techniques, knee stability, and long-term degenerative changes, including post-traumatic knee osteoarthritis. Crucially for the application of PNE, this thematic emphasis aligns with literature demonstrating that despite successful structural reconstruction, individuals frequently experience persistent functional limitations and reduced quality of life that biomechanical models alone cannot fully explain (Calabrò et al., 2025; Vélez-Gutiérrez et al., 2025).

Injury Characteristics, Measurement, and Clinical Risk Profiling

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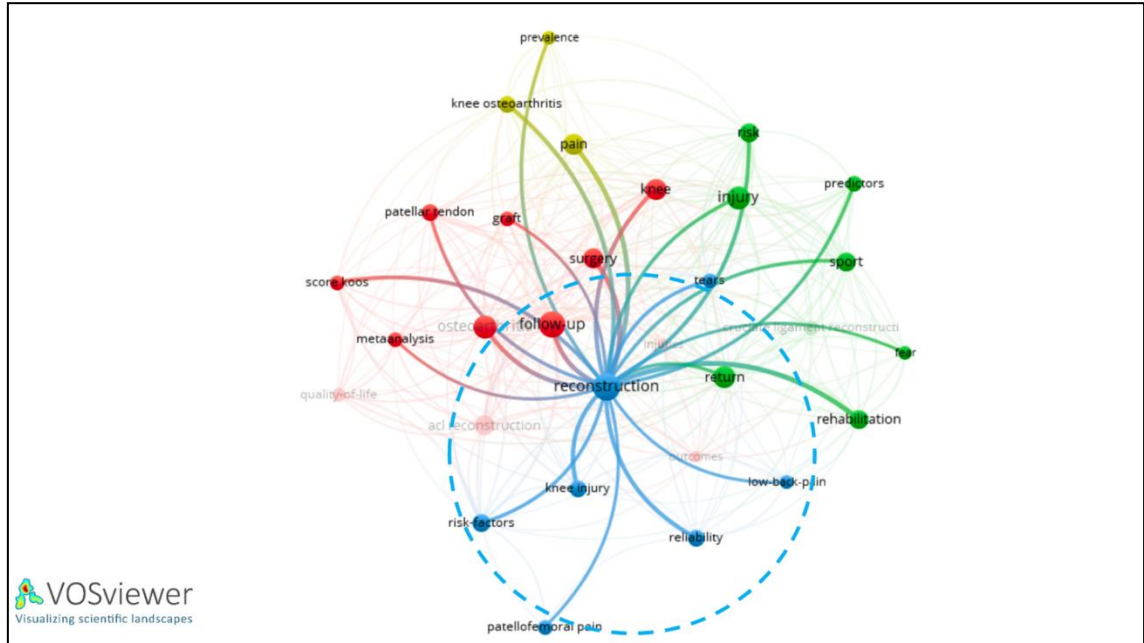


Figure 2.3: ACL injuries characteristic, measurement and risk profiling

Pain, Epidemiology, and Degenerative Outcomes

The yellow cluster is defined by keywords such as pain, prevalence, knee, and knee osteoarthritis, reflecting an epidemiological and symptom-focused theme. This cluster highlights population-level investigations examining pain prevalence, symptom burden, and degenerative joint changes following ACL injury and reconstruction. The close association between pain-related and osteoarthritis-related terms underscores the recognition that pain persistence and degenerative changes are common even years after injury, often demonstrating a weak relationship with structural findings alone. This disconnect between tissue damage and symptom severity provides the core rationale for integrating PNE into ACL rehabilitation, emphasizing the need to reconceptualize persistent knee pain through a neurophysiological lens rather than a purely structural one (Pico et al., 2025; Tayfur et al., 2025).

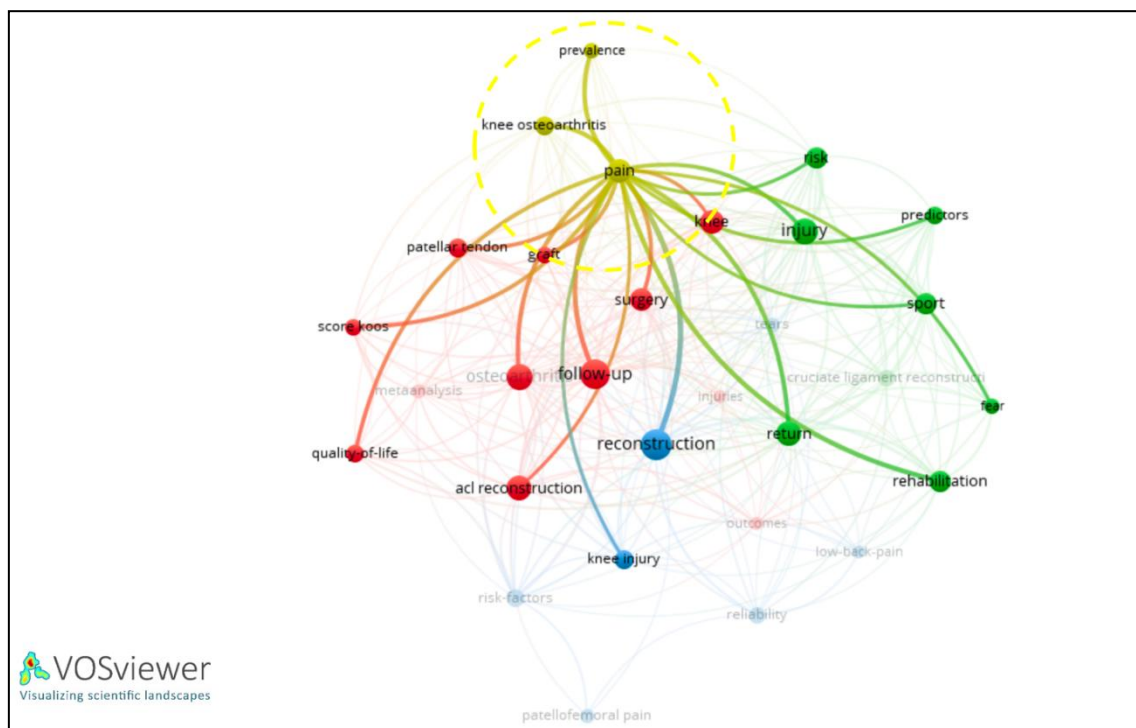


Figure 2.4: Epidemiology and Degenerative outcomes

3.2 Discussion

This review aimed to examine how pain neuroscience education (PNE) has been conceptualized, integrated, and evaluated within ACLR rehabilitation research, with a specific focus on psychological and return-to-sport (RTS) outcomes among recreational athletes. The findings demonstrate a clear paradigmatic shift in ACL rehabilitation research from a predominantly biomechanical, tissue-focused model toward a more integrative biopsychosocial framework. Both the review data and the keyword co-occurrence analyses revealed an increasing emphasis on psychological readiness, fear of reinjury, and confidence as central constructs, reinforcing the contemporary understanding that successful RTS following ACLR extends beyond physical recovery alone (Burland et al., 2018; Cronström et al., 2023; Zarzycki et al., 2021).

Across the identified thematic clusters, PNE emerged as conceptually aligned with the evolving demands of ACL rehabilitation, particularly in addressing maladaptive pain beliefs and threat-related cognitions. Psychological barriers such as kinesiophobia, pain catastrophizing, and reinjury anxiety are consistently reported as major impediments to RTS, even in individuals who demonstrate adequate strength and functional performance (Burland et al., 2018; Zarzycki et al., 2021). In this context, the thematic mapping indicates that PNE provides a theoretically grounded mechanism to reframe pain experiences, reduce perceived threat, and facilitate behavioral engagement in rehabilitation. While our bibliometric analysis highlights a scarcity of direct ACL-specific trials, evidence from the broader orthopedic and post-surgical populations captured within this network supports this role, with multiple randomized controlled trials demonstrating improvements in psychological outcomes following PNE interventions (Dams et al., 2023; Kararti et al., 2024; Ponce-Fuentes et al., 2023; Tayfur et al., 2025).

Comparisons across thematic clusters also highlight a notable discrepancy in how psychological and physical outcomes are represented in the intervention literature. Within the subset of studies evaluating clinical effects, PNE is consistently associated with favorable psychological variables, whereas its direct impact on pain intensity, muscle strength, and functional performance appears less consistent (Kararti et al., 2024; Ponce-Fuentes et al., 2023; Tayfur et al., 2025). This contrast, reflected in our knowledge mapping, suggests that PNE may operate primarily through cognitive and neurophysiological pathways, influencing rehabilitation engagement and movement behavior rather than inducing immediate structural or biomechanical adaptations. In ACLR populations, where fear of reinjury and lack of confidence frequently persist despite physical readiness, these indirect effects may be particularly relevant for RTS outcomes (Cronström et al., 2023).

The rehabilitation-focused (green) cluster further underscores the importance of integrating PNE within multimodal intervention strategies. The synthesis of this thematic domain suggests that PNE is most effective when combined with progressive exercise, neuromuscular training, or eccentric strengthening, rather than delivered as a standalone educational component (Tatiya et al., 2021). This aligns with emerging neurocognitive and neuroplasticity-informed approaches to ACL rehabilitation identified in the literature, which emphasize the interaction between cognition, perception, and motor control (Grooms et al., 2015; Vélez-Gutiérrez et al., 2025).

Despite growing interest in this area, substantial evidence gaps remain. Notably, there is a scarcity of ACL-specific randomized controlled trials examining PNE, with much of the available evidence extrapolated from other musculoskeletal or post-surgical populations. Additionally, heterogeneity in PNE content, delivery methods, dosage, and outcome measures limits comparability across studies and complicates interpretation of overall effectiveness (Adenis et al., 2024; Pico et al., 2025). The predominance of short-term follow-up in existing studies further restricts our understanding of whether PNE-induced psychological improvements translate into sustained RTS participation, reduced reinjury risk, or long-term functional outcomes following ACLR (Kararti et al., 2024; Tayfur et al., 2025).

From a clinical and research perspective, the findings suggest that PNE should be viewed as a complementary component of ACLR rehabilitation rather than a replacement for physical training. Its primary value lies in targeting fear-avoidance behaviors, pain-related beliefs, and self-efficacy, factors strongly linked to rehabilitation adherence and RTS decision-making in recreational athletes (Burland et al., 2018; Cronström et al., 2023). Future research should prioritize well-designed, ACL-specific trials that integrate standardized PNE protocols within progressive rehabilitation programs and include RTS-relevant psychological and functional endpoints. Such studies would strengthen the evidence base and support the development of more comprehensive, psychologically informed ACL rehabilitation models.

4. CONCLUSION

This review systematically mapped the research landscape concerning the conceptualization, integration, and evaluation of pain neuroscience education (PNE) within ACL reconstruction rehabilitation, with a particular focus on psychological and return-to-sport (RTS) outcomes in recreational athletes. The bibliometric findings indicate that ACL rehabilitation research has progressively shifted from a predominantly biomechanical focus toward a biopsychosocial perspective, recognizing the critical influence of psychological factors on recovery trajectories. Within this evolving framework, PNE has

emerged in the literature as a theoretically congruent intervention that addresses maladaptive pain beliefs, fear of reinjury, and cognitive barriers that may persist despite adequate physical recovery.

Thematic synthesis of the retrieved literature indicates that PNE is predominantly associated with improving psychological outcomes, including reductions in kinesiophobia and pain catastrophizing and enhancements in confidence and mental readiness. Although reported direct effects on physical performance and pain intensity are less robust and more variable, these psychological changes are clinically meaningful in the context of ACLR, where fear and lack of confidence often limit rehabilitation engagement and delay RTS. Consequently, the existing evidence base suggests PNE may exert an indirect yet important influence on functional recovery by facilitating greater participation in progressive loading, sport-specific training, and overall rehabilitation adherence.

Importantly, the knowledge-mapping findings highlight an emerging consensus in the literature that PNE is optimally conceptualized when integrated within multimodal rehabilitation programs rather than delivered as a standalone intervention. The strong thematic co-occurrence of psychological terms with strength training, neuromuscular re-education, and neurocognitively informed rehabilitation approaches appears to better address the complex interplay between physical capacity, perception, and behavior that characterizes post-ACLR recovery. These integrated strategies align with contemporary rehabilitation models that emphasize neuroplasticity, motor learning, and psychological readiness as key components of successful RTS.

Despite the growing interest in PNE, substantial gaps remain in the literature, particularly the lack of ACL-specific randomized controlled trials and standardized PNE protocols. Future research should prioritize long-term, well-designed studies that evaluate both psychological and RTS outcomes in recreational athletes, and examine how PNE can be optimally tailored and timed within rehabilitation pathways. Addressing these gaps will be essential for advancing evidence-based, psychologically informed ACLR rehabilitation and improving long-term sport participation and recovery outcomes.

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6. CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to this narrative review. The authors report no financial, personal, or professional relationships that could be perceived as influencing the content, interpretation, or conclusions of this work. This review was conducted independently and objectively, without funding or involvement from any commercial or non-commercial entities.

7. AUTHORS' CONTRIBUTION

All the authors involved in this study contributed to the research by analysing and interpreting the data, developing the methodology, checking grammar and spelling, reviewing the literature, refining ideas and theories, conducting critical reviews, facilitating discussions and preparing the questionnaire and manuscript. All authors made a substantive contribution to this study.

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