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Sensorimotor Mechanisms of Core Stabilization in the Prevention of Recurrence of Non-Specific Low Back Pain: A Narrative Review

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Abstract

Introduction. Non-specific low back pain (LBP) is characterized by a recurrent clinical course, suggesting persistent functional disturbances rather than isolated episodes of tissue injury. Alterations in neuromuscular control, postural coordination, and anticipatory trunk muscle activation have been documented in individuals with LBP. Importantly, "core stability" remains inconsistently defined and should be interpreted as a systems-based construct involving biomechanical and sensorimotor regulation of trunk function rather than isolated muscle activity alone. This narrative review aimed to synthesize current evidence regarding biomechanical and sensorimotor mechanisms associated with trunk control–oriented exercise interventions and their potential role in preventing recurrence of non-specific LBP in adults.
State of knowledge. Current evidence suggests that non-specific LBP is associated with disturbances in feedforward motor control, dysfunction of deep trunk musculature, altered movement coordination, and sensorimotor impairments. Current biomechanical models propose that spinal stability emerges from interactions between passive, active, and neural subsystems. Trunk-focused exercise interventions appear to influence anticipatory activation, intermuscular coordination, and sensorimotor integration, although these effects are more appropriately interpreted as system-level adaptations rather than isolated strengthening effects. Direct evidence linking these mechanisms to reduced recurrence remains limited.
Summary. Trunk control–oriented interventions may contribute to recurrence prevention in non-specific LBP primarily through restoration of sensorimotor control and movement coordination rather than increased muscle strength alone. A systems-based interpretation of these interventions may aid in understanding their clinical effects and developing individualized rehabilitation strategies.

Keywords: core stabilization; low back pain; motor control; recurrence; sensorimotor control; trunk control

1. Introduction

Non-specific low back pain (LBP) is a leading cause of disability worldwide and is characterized by a recurrent clinical course. A substantial proportion of individuals experience repeated episodes over time, suggesting that underlying functional disturbances may persist beyond the resolution of symptoms [1].

Core stability is not a physiological entity but an interpretative construct, variably defined across the literature, encompassing anatomical, biomechanical, and neuromuscular models of trunk function within an integrated system linking the spine, pelvis, diaphragm, and hips [6–8]. This conceptual ambiguity has contributed to heterogeneity in both research and clinical application.

For clarity, the term “core stabilization” is used when referring to terminology present in the literature, whereas “trunk control” is preferred when discussing underlying mechanisms.

Traditional structural explanations of LBP have limited explanatory value, as imaging findings correlate poorly with clinical presentation. This has shifted attention toward functional mechanisms, particularly alterations in neuromuscular control and movement coordination. This shift is also reflected in recent clinical guidelines, which emphasize non-specific exercise approaches and a biopsychosocial framework rather than targeting isolated anatomical structures [2,20].

Experimental studies have demonstrated that individuals with LBP exhibit delayed activation of trunk musculature during limb movement tasks, indicating impaired anticipatory postural control [4]. In addition, persistent dysfunction of the multifidus following symptom resolution has been reported [10], suggesting incomplete recovery of neuromuscular function even in the absence of pain. From a biomechanical perspective, spinal stability is commonly conceptualized as an emergent property resulting from the interaction between passive structures, active muscular components, and neural control systems [8]. Within this framework, coordinated muscle activation contributes to the regulation of spinal stiffness and control of intersegmental motion [7,16].

These findings have contributed to the development of exercise-based interventions targeting trunk function. However, the conceptual foundations of this approach have been critically evaluated. Muscle activation is task-dependent, selective isolation of individual muscles in functional contexts is limited, and the relationship between specific muscle dysfunction and LBP is not clearly causal [6]. Furthermore, systematic reviews indicate that such interventions are not consistently superior to other forms of exercise in reducing pain or disability, suggesting that their specificity remains uncertain [18,19]. Taken together, these observations indicate that the relationship between neuromuscular control, spinal biomechanics, and recurrence of LBP is complex and not fully understood. While alterations in these domains have been documented, their causal role in recurrence and their responsiveness to targeted interventions remain uncertain.

To provide a structured interpretation of this complexity, this review adopts a stepwise approach. First, commonly used exercise-based interventions are classified according to their underlying mechanisms, rather than their clinical labels. Second, key domains of sensorimotor function relevant to trunk control are synthesized within a unified mechanistic framework. Finally, the heterogeneity of non-specific low back pain is addressed through subgrouping, with emphasis on identifying individuals in whom these mechanisms are most likely to be clinically relevant.

Therefore, the aim of this narrative review is to synthesize current evidence on the biomechanical and sensorimotor mechanisms associated with exercise-based approaches targeting trunk control, and to examine their potential relevance for the prevention of recurrence of non-specific LBP in adults. To address these issues, this narrative review was conducted using literature identified through PubMed, Scopus, and Web of Science, with emphasis placed on studies investigating neuromuscular control, spinal biomechanics, and sensorimotor mechanisms associated with non-specific low back pain.

2. Mechanistic Framework

The present review adopts a mechanistic framework in which recurrence of non-specific LBP is interpreted as a consequence of persistent disturbances in sensorimotor control and movement coordination rather than isolated structural pathology.

Within this framework:

• neuromuscular control deficits, including delayed feedforward activation, may impair anticipatory stabilization [4]

• persistent dysfunction of local stabilizing muscles may reflect incomplete recovery of motor control [10]
• altered coordination patterns may lead to inefficient load distribution across spinal segments [7,16]
• spinal stability emerges from the interaction of passive, active, and neural subsystems [8]
• sensorimotor integration deficits may contribute to suboptimal movement variability and control

Interventions targeting coordination and control are therefore conceptualized not as methods of selectively strengthening specific muscles, but as approaches aiming to modify system-level coordination, improve feedforward–feedback regulation, and optimize movement strategies [6]. Within this model, recurrence may be interpreted as a failure of the system to maintain adaptable control under repeated or variable loading conditions. The proposed link between these mechanisms and recurrence prevention remains indirect and should be interpreted as mechanistically plausible rather than definitively established.

2.1. Subtypes of Interventions

Overview

Exercise-based approaches commonly grouped under the term “core stabilization” represent a heterogeneous set of interventions that differ substantially in their underlying mechanisms. Rather than constituting a uniform therapeutic entity, these approaches can be more meaningfully classified according to their primary effects on neuromuscular coordination, stiffness regulation, and sensorimotor integration. This mechanistic classification distinguishes between interventions that primarily increase stability through stiffness and those that aim to restore adaptable, task-specific motor control.

2.1.1. Isolated Activation Approaches

These interventions focus on selective activation of deep trunk muscles, particularly the transversus abdominis and multifidus, typically under low-load and controlled conditions. This approach is grounded in early findings of delayed activation and persistent dysfunction of these muscles in individuals with LBP [4,10]. However, the assumption that individual muscles can be selectively trained in functional contexts remains limited, and observed effects are more plausibly interpreted as changes in general motor coordination rather than restoration of isolated muscle function [6].

2.1.2. Co-Contraction and Stiffness-Oriented Approaches

These approaches emphasize simultaneous activation of multiple trunk muscles to increase spinal stiffness, often through bracing strategies or static holds. Biomechanical models indicate that co-contraction contributes to spinal stiffness and control of intersegmental motion [7,16]. However, increased stiffness is not inherently beneficial. Persistent or excessive co-contraction may increase compressive loading and reduce movement efficiency, suggesting that such strategies may reflect protective rather than optimal motor behavior [17].

2.1.3. Variability and Exploratory Movement Approaches

These interventions emphasize movement variability, adaptability, and exploration of multiple motor solutions rather than rigid stabilization. Altered movement variability has been observed in individuals with LBP, often reflecting either overly rigid or poorly controlled motor behavior [11,17]. Promoting variability may facilitate more adaptable motor strategies and reduce reliance on stiffness-based control.

2.1.4. Perturbation-Based Training

Perturbation-based approaches introduce controlled external disturbances to challenge postural control and enhance both anticipatory and reactive responses. These interventions target integration of sensory input and motor output, potentially improving robustness of motor responses under unpredictable conditions.

2.1.5. Task-Specific Integration

These approaches embed trunk control within functional, goal-directed movements rather than training it in isolation. From a systems perspective, trunk control emerges as part of whole-body coordination. Task-specific approaches aim to improve transfer to real-world activities by promoting efficient load distribution and intersegmental coordination.

Synthesis

Across these categories, a central distinction emerges:

• stiffness-oriented strategies (co-contraction–dominant)

• control-oriented strategies (variability, perturbation, task integration)

While both may influence neuromuscular function, interventions emphasizing adaptability and coordination are more consistent with motor control models. These distinctions are clinically relevant, as different intervention strategies may differentially target mechanisms potentially associated with recurrence, including impaired anticipatory control, maladaptive stiffness regulation, or reduced movement adaptability.

2.2. Mechanisms of Action

Overview

Building on the proposed framework, exercise-based interventions targeting trunk function appear to act through three interacting mechanisms rather than through isolated strengthening of specific muscles. These mechanisms can be conceptualized across three primary domains: temporal control, mechanical regulation, and sensorimotor integration. Importantly, these domains are interdependent and context-specific, and their relevance likely varies across individuals.

2.2.1. Temporal Control: Feedforward–Feedback Regulation

Alterations in anticipatory postural adjustments represent one of the most consistently described findings in individuals with recurrent LBP, including delayed activation of trunk musculature during limb movement tasks [4]. Interventions emphasizing coordination and timing may influence these processes by modifying the temporal organization of muscle activation. However, it remains unclear whether observed changes represent restoration of a pre-existing deficit or the development of alternative motor strategies [9]. Accordingly, adaptations in feedforward control should be interpreted as task-specific and not necessarily indicative of normalization, which may increase vulnerability to recurrence during dynamic or unpredictable task demands.

2.2.2. Mechanical Regulation: Modulation of Stiffness

Coordinated activation of trunk musculature contributes to regulation of spinal stiffness and intersegmental motion [7,16]. Within this framework, stiffness represents a controllable parameter rather than a fixed property. Interventions may increase or decrease stiffness depending on context. While increased co-contraction may provide short-term stabilization, excessive stiffness may reduce movement efficiency and increase mechanical loading [17].

Thus, the relevant mechanism is not enhancement of stiffness per se, but its adaptive modulation, potentially contributing to recurrence through inefficient load management under repeated or sustained loading conditions.

2.2.3. Sensorimotor Integration and Movement Variability

Alterations in sensorimotor processing, including changes in proprioceptive function and postural control, have been documented in individuals with NSLBP [3,12,14,15]. These findings suggest that dysfunction may arise not only from altered muscle activation but also from impaired integration of sensory input and motor output, including deficits in proprioceptive processing and anticipatory postural control. Movement variability provides a functional expression of this integration. Reduced variability may reflect rigid, protective strategies, whereas excessive variability may indicate impaired control [11,17]. Interventions incorporating variability, perturbation, and task-specific challenges may promote refinement of internal models and improve the system's ability to adjust motor output to changing task demands. However, the concept of "optimal variability" remains difficult to quantify and apply in clinical settings, and both insufficient and excessive variability have been associated with suboptimal motor control, potentially increasing susceptibility to recurrent episodes when environmental or task demands change.

Synthesis

Across these domains, a consistent pattern emerges:

• interventions act at the level of system-wide motor control

• effects involve coordination, timing, and adaptability, rather than isolated muscle strength

These mechanisms may be particularly relevant in the context of recurrence, as persistent alterations in coordination, stiffness regulation, or sensorimotor integration may not produce symptoms under all conditions but can increase susceptibility to recurrent episodes when system demands exceed adaptive capacity. The relationship between these adaptations and the prevention of recurrence remains indirect. Current evidence supports mechanistic plausibility but does not establish causal pathways.

3. Clinical Implications

Importantly, the relevance of these findings is most apparent in the context of recurrence rather than isolated episodes of pain, which remain the primary focus of most clinical trials and systematic reviews. The findings of this review have several implications for clinical reasoning, particularly in the interpretation and application of trunk-focused interventions in NSLBP.

First, commonly used terms such as “core stabilization” encompass heterogeneous interventions with differing mechanisms. As a result, clinical effects observed in studies cannot be attributed to a single physiological process but likely reflect multiple interacting pathways related to coordination, stiffness regulation, and sensorimotor integration.

Second, neuromuscular alterations are not uniformly present across all individuals with NSLBP [21]. Evidence indicates that such impairments characterize specific subgroups, particularly those with recurrent or persistent symptoms. These subgroups can be identified using clinical movement control tests that assess the ability to regulate lumbopelvic motion during functional tasks [13,21]. This has direct implications for treatment selection, as the lack of consistent superiority of trunk-focused interventions over other exercise approaches may reflect mismatch between intervention mechanisms and patient characteristics, rather than absence of therapeutic effect.

Third, different motor control strategies may coexist within the NSLBP population, including both reduced activation and increased co-contraction patterns. These may represent context-dependent adaptations rather than uniform dysfunction, further complicating the identification of a single therapeutic target.

Fourth, although exercise-based interventions can modify neuromuscular coordination and aspects of sensorimotor processing, the interpretation of these changes remains uncertain. Observed adaptations may reflect restoration, compensation, or task-specific learning, and their relationship to clinically meaningful outcomes, particularly recurrence, remains insufficiently established.

Finally, these considerations support a shift toward a mechanistic and subgroup-oriented approach. Rather than applying uniform intervention strategies, future research and clinical practice should focus on:

• identifying clinically relevant subgroups
• linking specific impairments to targeted interventions
• evaluating long-term outcomes, including recurrence

At present, the proposed mechanisms provide a coherent explanatory framework but do not justify definitive conclusions regarding the prevention of recurrence.

4. Discussion

The present review integrates evidence from neuromuscular, biomechanical, and sensorimotor domains to examine the potential role of trunk-focused exercise interventions in the prevention of recurrence of non-specific low back pain (NSLBP). The findings indicate that while alterations in motor control are consistently described in subsets of individuals with NSLBP, their causal role in recurrence and their responsiveness to targeted interventions remain incompletely established.

Experimental studies have demonstrated delayed anticipatory activation of trunk musculature and persistent dysfunction of deep stabilizing muscles following symptom resolution. These observations have been interpreted as evidence of impaired feedforward control and incomplete neuromuscular recovery, particularly in individuals with recurrent symptoms. However, such findings are not uniformly present across all NSLBP populations [21], and their specificity remains uncertain.

A critical unresolved issue is whether these alterations represent predisposing factors for recurrence or context-dependent adaptations that emerge following repeated episodes. This distinction has important implications: if such changes precede recurrence, they may constitute therapeutic targets; if they reflect adaptive or protective strategies, attempts to normalize them may be unnecessary or even counterproductive.

The mechanistic framework adopted in this review suggests that recurrence may not be attributable to a single deficit, but rather to a reduced capacity of the whole system to maintain adaptable control under varying or repeated loading conditions. Within this perspective, alterations in coordination, timing, and stiffness regulation may not produce symptoms under stable conditions but may increase susceptibility to recurrence when task demands exceed the system's adaptive capacity.

The classification of interventions highlights that approaches commonly grouped under "core stabilization" differ substantially in their underlying principles. Strategies emphasizing isolated activation, co-contraction, variability, or task-specific integration may produce distinct adaptations in motor control. These differences are rarely accounted for in clinical trials, which often treat such interventions as a homogeneous category.

The identification of clinically relevant subgroups further complicates interpretation. Evidence suggests that neuromuscular impairments, including altered feedforward control, cortical reorganization, and changes in movement coordination, are not universally present but characterize specific patient populations. At the same time, alternative motor strategies involving increased co-contraction and reduced movement variability have been observed, suggesting that opposing mechanisms may coexist within the NSLBP population.

This heterogeneity provides a plausible explanation for inconsistent findings in intervention studies. When interventions targeting specific mechanisms are applied to heterogeneous populations, their effects may be diluted, leading to an apparent lack of superiority over other exercise approaches. From this perspective, the question is not whether trunk-focused interventions are effective in general, but whether they are appropriately matched to underlying patient-specific mechanisms.

Despite increasing evidence describing alterations in motor control, feedforward activation, and movement coordination in subsets of individuals with recurrent NSLBP, direct evidence linking these mechanisms to recurrence prevention remains limited. Most studies rely on surrogate outcomes, including electromyographic measures, biomechanical modeling, or short-term clinical improvements, while longitudinal studies evaluating recurrence as a primary outcome remain scarce.

Rather than supporting muscle-specific models, the current literature increasingly favors a systems-based interpretation in which coordination, adaptability, variability, and context-dependent motor strategies are considered central features of trunk function. However, the clinical significance of these mechanisms and their role in recurrence prevention remain insufficiently established and require further longitudinal and mechanistically informed research.

5. Conclusions

Non-specific low back pain is a heterogeneous condition in which alterations in neuromuscular control and sensorimotor function are present in specific subgroups rather than universally.

Core stability should be understood not as a discrete physiological entity, but as an interpretative construct encompassing multiple interacting systems involved in trunk control.

Exercise-based interventions targeting trunk function appear to influence neuromuscular coordination, timing, and sensorimotor integration; however, these effects are more appropriately interpreted at the level of system-wide motor control rather than isolated muscle activation.

The relationship between these mechanistic adaptations and the prevention of recurrence of low back pain remains indirect and insufficiently supported by longitudinal evidence.

A mechanistic and subgroup-oriented framework may provide a more appropriate basis for future research, with emphasis on linking specific impairments to targeted interventions and clinically meaningful outcomes.

Disclosure:

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

AI

During the preparation of this work, the authors used OpenAI ChatGPT for the purpose of basic data analysis and to identify linguistic patterns associated with specific logical fallacies. It is important to emphasize that the AI tool was used strictly as an assistive instrument under human supervision. Human experts in clinical medicine and formal logic determined the final interpretation of results, classification of errors, and conclusions, and take full responsibility for the substantive content of the publication.

References

1. da Silva T, Mills K, Brown BT, Herbert RD, Maher CG, Hancock MJ. Risk of Recurrence of Low Back Pain: A Systematic Review. Journal of Orthopaedic & Sports Physical Therapy 2017;47:305–13. https://doi.org/10.2519/jospt.2017.7415.

2. Foster NE, Anema JR, Cherkin D, Chou R, Cohen SP, Gross DP, et al. Prevention and treatment of low back pain: evidence, challenges, and promising directions. The Lancet 2018;391:2368–83. https://doi.org/10.1016/s0140-6736(18)30489-6.

3. Brumagne S, Janssens L, Janssens E, Goddyn L. Altered postural control in anticipation of postural instability in persons with recurrent low back pain. Gait & Posture 2008;28:657–62. https://doi.org/10.1016/j.gaitpost.2008.04.015.

4. Hodges PW, Richardson CA. Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. J Spinal Disord. 1998 Feb;11(1):46-56.

5. Tsao H, Danneels LA, Hodges PW. ISSLS prize winner: Smudging the motor brain in young adults with recurrent low back pain. Spine (Phila Pa 1976) 2011;36:1721–7. https://doi.org/10.1097/brs.0b013e31821c4267.

6. Lederman E. The myth of core stability. Journal of Bodywork and Movement Therapies 2010;14:84–98. https://doi.org/10.1016/j.jbmt.2009.08.001.

7. McGill SM. Low Back Stability: From Formal Description to Issues for Performance and Rehabilitation. Exercise and Sport Sciences Reviews 2001;29:26–31. https://doi.org/10.1097/00003677-200101000-00006.

8. Panjabi MM. The Stabilizing System of the Spine. Part I. Function, Dysfunction, Adaptation, and Enhancement. Journal of Spinal Disorders 1992;5:383–9. https://doi.org/10.1097/00002517-199212000-00001.

9. Hodges PW, Moseley GL, Gabrielsson A, Gandevia SC. Experimental muscle pain changes feedforward postural responses of the trunk muscles. Experimental Brain Research 2003;151:262–71. https://doi.org/10.1007/s00221-003-1457-x.

10. Hides JA, Richardson CA, Jull GA. Multifidus Muscle Recovery Is Not Automatic After Resolution of Acute, First-Episode Low Back Pain. Spine 1996;21:2763–9. https://doi.org/10.1097/00007632-199612010-00011.

11. Hodges PW, Tucker K. Moving differently in pain: A new theory to explain the adaptation to pain. Pain 2011;152:S90–8. https://doi.org/10.1016/j.pain.2010.10.020.

12. 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. https://doi.org/10.1186/1471-2474-15-229.

13. Luomajoki H, Kool J, de Bruin ED, Airaksinen O. Movement control tests of the low back; evaluation of the difference between patients with low back pain and healthy controls. BMC Musculoskelet Disord 2008;9. https://doi.org/10.1186/1471-2474-9-170.

14. Brumagne S, Cordo P, Lysens R, Verschueren S, Swinnen S. The Role of Paraspinal Muscle Spindles in Lumbosacral Position Sense in Individuals With and Without Low Back Pain. Spine 2000;25:989–94. https://doi.org/10.1097/00007632-200004150-00015.

15. Tong MH, Mousavi SJ, Kiers H, Ferreira P, Refshauge K, van Dieën J. Is There a Relationship Between Lumbar Proprioception and Low Back Pain? A Systematic Review With Meta-Analysis. Archives of Physical Medicine and Rehabilitation 2017;98:120-136.e2. https://doi.org/10.1016/j.apmr.2016.05.016.

16. Cholewicki J, McGill S. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clinical Biomechanics 1996;11:1–15. https://doi.org/10.1016/0268-0033(95)00035-6.

17. van Dieën JH, Selen LPJ, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. Journal of Electromyography and Kinesiology 2003;13:333–51. https://doi.org/10.1016/s1050-6411(03)00041-5

18. Hayden JA, Ellis J, Ogilvie R, Malmivaara A, van Tulder MW. Exercise therapy for chronic low back pain. Cochrane Database of Systematic Reviews 2021;2021. https://doi.org/10.1002/14651858.cd009790.pub2.

19. Saragiotto BT, Maher CG, Yamato TP, Costa LO, Menezes Costa LC, Ostelo RW, et al. Motor control exercise for chronic non-specific low-back pain. Cochrane Database of Systematic Reviews 2016;2016. https://doi.org/10.1002/14651858.cd012004.

20. National Institute for Health and Care Excellence (NICE). Low back pain and sciatica in over 16s: assessment and management (NG59). London: NICE; 2016; [cited 2026 May 4]. Available from: https://www.nice.org.uk/guidance/ng59

21. Salvioli S, Pozzi A, Testa M. Movement Control Impairment and Low Back Pain: State of the Art of Diagnostic Framing. Medicina 2019;55:548. https://doi.org/10.3390/medicina55090548.