Cervical Proprioception as a Dynamic Sensorimotor Process: From Fatigue-Induced Perturbation to Functional Recovery A Narrative Review

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ABSTRACT

Background: Cervical proprioception is a critical component of sensorimotor control, contributing to head and neck position sense, postural stability, movement coordination, and integration of visual and vestibular information. Cervical muscle fatigue has been shown to temporarily impair joint position sense, postural control, and other sensorimotor functions. Although these fatigue-induced changes have been increasingly investigated, less attention has been directed toward understanding the subsequent process of proprioceptive recovery.

Objective: This narrative review aims to examine cervical proprioception as a dynamic sensorimotor process, with particular emphasis on fatigue-induced perturbation and subsequent functional recovery. The review further considers the temporal characteristics of recovery, factors that may influence recovery, and current approaches for assessing changes in cervical proprioception following fatigue.

Main Findings: Existing evidence demonstrates that cervical muscle fatigue can increase cervical joint position error and alter the consistency of repositioning, while also affecting postural control, visual performance, and sensorimotor integration.[13–18] Evidence from experimental studies indicates that proprioceptive performance can improve following a period of recovery; however, recovery has generally been assessed using limited post-fatigue time points.[14] Consequently, the magnitude, rate, completeness, and individual variability of cervical proprioceptive recovery remain insufficiently characterized. Variability in fatigue protocols, targeted muscle groups, movement directions, measurement techniques, and recovery intervals further limits comparison between studies. Although cervical joint position error is widely used, recent evidence indicates that its responsiveness and other measurement properties require further investigation.[19] A multidimensional approach incorporating proprioception, postural control, visual-vestibular interaction, and functional performance may therefore provide a more comprehensive representation of sensorimotor recovery.

Conclusion: Cervical proprioception should be considered a dynamic function that changes in response to physiological perturbation and subsequently undergoes recovery. Future research should move beyond conventional pre-fatigue versus post-fatigue comparisons toward temporally resolved recovery models incorporating multiple assessment points, standardized fatigue protocols, validated responsive measures, and evaluation of individual recovery trajectories. Understanding the dynamics of cervical proprioceptive

recovery may provide a foundation for identifying fatigue-sensitive sensorimotor deficits and developing more precise assessment and rehabilitation strategies.

Keywords: cervical proprioception; cervical muscle fatigue; joint position error; sensorimotor control; proprioceptive recovery; postural control; cervical spine; recovery dynamics.

INTRODUCTION

Cervical proprioception is an essential component of sensorimotor control that contributes to the perception of head and neck position, coordination of head and eye movements, postural regulation, and orientation of the body in space.[1–3] The cervical region possesses a highly developed proprioceptive system involving muscle spindles, joint receptors, and other mechanosensory structures that provide continuous afferent information to the central nervous system.[1–3] Cervical proprioceptive information is integrated with visual and vestibular inputs to maintain accurate orientation and postural stability.[4,5]

The clinical relevance of cervical proprioception has been demonstrated in individuals with neck pain, whiplash-associated disorders, and other cervical musculoskeletal conditions. Patients with cervical pain have demonstrated impaired cervicocephalic kinesthetic sensibility compared with asymptomatic individuals, indicating reduced accuracy of head repositioning.[6] Similar disturbances in cervical joint position error (JPE), balance, and eye movement control have been reported in individuals with persistent whiplash-associated disorders.[7,8] These findings have contributed to the widespread use of cervical JPE as an operational measure of cervical proprioceptive function.[9]

Although cervical proprioception has traditionally been examined as a relatively stable characteristic, increasing evidence indicates that it is a dynamic function that can change in response to pain, posture, muscular fatigue, altered sensory input, and task demands.[10–12] In particular, experimental studies have demonstrated that cervical muscle fatigue can adversely influence joint position sense, postural control, visual function, and broader sensorimotor performance.[13–17]

Pinsault and Vuillerme demonstrated that cervical muscular fatigue resulted in increased absolute and variable cervical repositioning errors, indicating both reduced accuracy and consistency of cervical joint position sense.[13] Abdelkader et al. subsequently demonstrated reduced cervical proprioception immediately following cervical flexor fatigue, with improvement following a recovery period.[14] These findings are important because they demonstrate that fatigue-related proprioceptive impairment may not simply represent a fixed deficit, but rather a transient disturbance followed by a recovery process.

However, the available literature has generally emphasized the **presence of fatigue-induced impairment** rather than the **characteristics of recovery**. Some studies have compared pre-fatigue, post-fatigue, and a single recovery time point, while others have examined recovery of broader postural control rather than cervical proprioception specifically.[14,17] Consequently, it remains unclear whether cervical proprioceptive recovery occurs rapidly or gradually, whether recovery is complete, how long it takes to return toward baseline, and whether the recovery trajectory differs according to fatigue protocol, muscle group, direction of movement, measurement method, or clinical status.

This distinction is particularly important because muscular recovery and sensorimotor recovery may not necessarily occur at the same rate. Fatigue can modify afferent input, central integration, motor control strategies, and postural responses, meaning that restoration of force-generating capacity does not necessarily indicate immediate normalization of proprioceptive function.[10,15,18]

Furthermore, a recent systematic review of cervical JPE measurement properties concluded that although JPE demonstrates sufficient reliability and validity, the certainty of evidence remains low or very low for several measurement properties and specifically identified **responsiveness** as an area requiring further investigation.[19] A 2024 systematic review and meta-analysis similarly demonstrated that cervical sensorimotor testing encompasses several domains, including JPE, oculomotor function, and balance, while highlighting heterogeneity in measurement quality and the need for improved standardization.[20]

Therefore, cervical proprioception may be better conceptualized as a **dynamic sensorimotor process** rather than a single static measurement. Understanding the transition from fatigue-induced perturbation to functional recovery may provide a more comprehensive framework for studying cervical sensorimotor function and may identify clinically meaningful recovery markers.

The purpose of this review is therefore to examine cervical proprioception as a dynamic process, with particular emphasis on the physiological basis of cervical proprioception, fatigue-induced perturbation, temporal recovery, methods of assessing recovery, and current gaps in the literature.

CONCEPTUAL FRAMEWORK

Cervical proprioception may be conceptualized as a dynamic sensorimotor process in which physiological perturbation produces changes in sensory input, central sensorimotor integration, motor-control strategies, and functional performance, followed by a period of recovery. Within this framework, the sequence can be represented as:

Fatigue → altered sensory input and sensorimotor integration → changes in cervical proprioception and motor control → recovery following rest or intervention.

This framework distinguishes the immediate effect of fatigue from the subsequent recovery process and recognizes that restoration of muscular capacity may not occur at the same rate as restoration of proprioceptive accuracy or broader sensorimotor function. Accordingly, recovery should be considered in terms of magnitude, rate, completeness, and individual variability rather than as a single post-fatigue measurement.

The literature should also distinguish between local fatigue, arising predominantly from the cervical musculature, and systemic fatigue that may influence performance through broader physiological or attentional mechanisms. Similarly, acute fatigue produced during a single experimental task should be differentiated from prolonged or repeated fatigue exposure. Findings from healthy or asymptomatic populations should be interpreted separately from findings in symptomatic populations, particularly individuals with neck pain or whiplash-associated disorders.

A further distinction is required between proprioceptive accuracy, such as cervical joint position error, and broader sensorimotor control, including postural regulation, movement coordination, visual-vestibular interaction, and functional performance. Laboratory-based measures should likewise be distinguished from functional outcomes so that changes observed under controlled experimental conditions are not assumed to represent equivalent changes during every day or task-specific activities.

Narrative Review Methodology

Although this review is narrative in design, methodological transparency is important to support reproducibility and interpretation of the evidence. The literature search and selection process should therefore be described according to the databases searched, the date or time period covered, the principal search concepts and their combinations, the approach used to identify additional relevant literature, and the basis on which studies were considered relevant to the review question.

The search concepts should encompass the major components of the conceptual framework, including cervical proprioception, joint position sense or joint position error, cervical muscle fatigue, sensorimotor control, postural control, multisensory integration, and recovery. Literature should be considered across healthy/asymptomatic and symptomatic populations and across experimental fatigue and recovery conditions where relevant to the review objectives.

Because evidence in this field is heterogeneous, synthesis should distinguish study population, fatigue model, fatigued muscle group, outcome domain, measurement method, and recovery interval rather than combining findings solely on the basis of statistical significance. Where studies provide conflicting findings,

differences in fatigue exposure, task demands, measurement responsiveness, participant characteristics, or outcome definitions should be considered when interpreting the evidence. This approach is intended to preserve the distinctions between consistent findings, mixed evidence, and areas in which evidence remains insufficient.

Cervical Proprioception as a Dynamic Sensorimotor Function

Physiological basis of cervical proprioception

Proprioception refers to the sensory information that contributes to the perception of body position and movement. In the cervical region, proprioceptive information is derived from several structures, particularly the cervical musculature and joints.[1],[2] Muscle spindles are particularly important because they provide information related to muscle length and changes in muscle length.

Histological investigations have demonstrated a substantial distribution of muscle spindles within the deep cervical musculature. Boyd-Clark et al. identified a high density of muscle spindles in the longus colli and multifidus muscles, supporting the important sensory role of these muscles in cervical control.[3]

Experimental neurophysiological evidence further demonstrates that cervical proprioceptive signals interact with the vestibular system. Gdowski and McCrea demonstrated that neck proprioceptive inputs influence neurons within the vestibular nuclei, providing a physiological basis for integration between cervical and vestibular information.[21] Human experimental work by Taylor and McCloskey also demonstrated that proprioceptive information from the neck contributes to perception of head position and movement.[22]

The cervical sensorimotor system therefore represents a complex interaction between peripheral sensory receptors, spinal and supraspinal processing, motor output, and integration with visual and vestibular information.[4],[5],[23]

Cervical joint position error as an operational measure

Cervical JPE is one of the most frequently used clinical measures of cervical proprioception. It generally involves active repositioning of the head toward a reference position after active cervical movement, with the difference between the reference and reproduced position recorded as the repositioning error.[6],[9]

The technique was introduced clinically by Revel et al., who demonstrated poorer cervicocephalic repositioning accuracy in individuals with cervical pain compared with healthy participants.[6] Subsequent studies have used laser-pointer systems, cervical range-of-motion devices, and other measurement technologies to quantify cervical repositioning accuracy.[7],[19]

Despite its widespread use, JPE should not be interpreted as a complete representation of proprioception. Cervical sensorimotor function includes multiple interacting processes, including position sense, movement perception, postural control, eye-head coordination, and integration of visual and vestibular information.[5],[8],[20]

This distinction becomes particularly relevant following fatigue. A change in JPE after fatigue may represent altered peripheral sensory information, changes in motor output, altered central processing, or compensatory changes in movement strategy. Therefore, interpretation of fatigue-related JPE changes should consider the broader sensorimotor system rather than treating JPE as an isolated physiological variable.

Cervical proprioception and multisensory integration

The cervical region has extensive functional connections with the visual and vestibular systems.[4],[5] Cervical afferent information contributes to the coordination of head and eye movements and to postural orientation.[5],[23]

Treleaven and colleagues demonstrated associations between cervical JPE, balance, and eye movement

disturbances in people with persistent whiplash-associated disorders, suggesting that cervical proprioceptive impairment may coexist with disturbances in other sensorimotor domains.[7]

Similarly, cervical proprioceptive disturbance has been discussed in relation to dizziness, particularly where cervical, visual, and vestibular information may become mismatched.[24] Consequently, fatigue-induced changes in cervical proprioception may have effects extending beyond simple head repositioning accuracy.

Cervical Muscle Fatigue as a Sensorimotor Perturbation

Muscle fatigue is commonly defined as a reduction in the capacity to generate force or maintain a required level of performance. In the cervical region, fatigue can arise from sustained or repetitive head and neck activity and may alter both peripheral sensory input and motor control.[14],[15]

Importantly, fatigue should not be viewed solely as a muscular phenomenon. Alterations in muscle spindle discharge, proprioceptive feedback, motor-unit recruitment, central processing, and postural strategies may occur simultaneously.[10],[13],[15]

Pinsault and Vuillerme provided early experimental evidence that cervical muscle fatigue produces deterioration in cervical joint position sense.[13] Their findings showed increased absolute and variable errors after fatigue, suggesting reductions in both repositioning accuracy and consistency.

Schieppati et al. also demonstrated that cervical extensor fatigue altered postural control, with postural sway increasing following fatigue and being reassessed following recovery.[17] This supports the concept that cervical fatigue can affect whole-body sensorimotor regulation rather than only local neck function.

Fatigue-related effects have also been demonstrated in other sensory domains. Gosselin and Fagan reported effects of cervical muscle fatigue on perception of the subjective vertical and horizontal.[25] Al Saif and Al Senany found that neck muscle fatigue affected dynamic visual acuity in healthy young adults.[26] These observations support the concept that cervical fatigue can influence multisensory processing involving cervical, visual, and postural systems.

Neck fatigue may also influence proprioception beyond the cervical region. Zabihhosseinian et al. reported that cervical muscle fatigue altered upper-limb proprioception, suggesting that cervical afferent information contributes to interpretation of limb position.[27] Conversely, Russell et al. reported that cervical extensor fatigue did not produce statistically significant changes in unconstrained humeral rotation JPS, despite relatively large effect sizes, highlighting the influence of task constraints and measurement variability.[28]

Thus, the effects of cervical fatigue on proprioception may not be uniform. Differences may depend on the fatigued muscle group, fatigue protocol, task constraints, measurement method, movement direction, and the sensory system being assessed.

From Proprioceptive Impairment to Proprioceptive Recovery

Evidence that fatigue-related proprioceptive impairment can recover

The concept of recovery is particularly important because fatigue-induced proprioceptive impairment appears to be at least partially reversible.

Abdelkader et al. evaluated cervical proprioception before fatigue, immediately following induced cervical flexor fatigue, and after recovery.[14] The investigators found significant deterioration in cervical JPE immediately following fatigue compared with both pre-fatigue and recovery measurements. These findings provide direct evidence that cervical proprioception can demonstrate a fatigue-related deterioration followed by improvement during recovery.

However, the study design also illustrates an important limitation in the current evidence base. Measuring

recovery at a single post-recovery time point does not establish the shape of the recovery trajectory. It cannot determine whether most recovery occurred during the first few minutes, whether recovery was linear, whether there was a delayed phase, or whether residual impairment persisted before the selected recovery endpoint.

Schieppati et al. examined postural control following neck muscle fatigue and included a 5-minute recovery period.[17] Although postural control was reassessed after recovery, postural recovery cannot automatically be considered equivalent to cervical proprioceptive recovery.

Therefore, the existing evidence supports the occurrence of recovery but does not adequately characterize **how recovery occurs over time**.

Recovery as a temporal trajectory

A more informative model would conceptualize cervical proprioceptive response as a trajectory:

Baseline → Fatigue induction → Peak proprioceptive impairment → Early recovery → Intermediate recovery → Late recovery → Return toward baseline

This framework allows several distinct characteristics to be examined:

1. **Magnitude of impairment** – the difference between baseline and the greatest post-fatigue deterioration.
2. **Time to peak impairment** – when the greatest proprioceptive deterioration occurs.
3. **Rate of early recovery** – how rapidly performance improves after fatigue.
4. **Rate of later recovery** – whether recovery slows as baseline is approached.
5. **Time to recovery** – the time required to return to a predefined threshold.
6. **Completeness of recovery** – whether performance returns to baseline.
7. **Residual deficit** – the amount of impairment remaining at the final assessment.
8. **Inter-individual variability** – differences in recovery trajectories between individuals.

Such a framework would move beyond the traditional comparison of “pre-fatigue versus post-fatigue” and allow recovery to become an independent outcome.

Recovery may not be equivalent to muscular recovery

One important conceptual issue is that restoration of muscular force or endurance does not necessarily indicate complete restoration of sensorimotor function.

Cervical fatigue can influence multiple components of the sensorimotor system, including afferent feedback, central integration, muscle activation strategies, postural control, and visual-vestibular interaction.[15],[18],[23]

Hsu et al. demonstrated that cervical flexor fatigue in people with chronic neck pain altered postural sway and cervical muscle activation strategies during arm movement perturbations.[15] These findings suggest that fatigue may produce changes in motor-control strategies in addition to a reduction in muscular performance.

Consequently, future research should distinguish between:

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Muscular recovery

↓
Restoration of force/endurance

and

Sensorimotor recovery
↓
Restoration of proprioceptive accuracy, postural control, movement coordination, and multisensory integration.

These processes may occur at different rates.

Factors That May Influence Cervical Proprioceptive Recovery

Fatigue Protocol

The magnitude of proprioceptive impairment may depend on how fatigue is induced. Studies have used cervical flexor or extensor fatigue, sustained contractions, endurance tests, or externally imposed loading.[13–17]

Differences in contraction intensity, duration, muscle group, and endpoint criteria can produce different levels of peripheral and central fatigue. Therefore, recovery findings cannot necessarily be generalized across protocols.

Muscle Group

The cervical musculature is functionally heterogeneous. Deep cervical flexors, extensors, superficial muscles, and suboccipital muscles may contribute differently to cervical proprioception and motor control.[3]

A fatigue protocol targeting cervical flexors may therefore produce a different recovery profile from one targeting cervical extensors or scapular elevators.

Direction of Movement

Cervical JPE may differ according to movement direction.[19] Measurement conditions involving rotation, flexion, extension, or combined movements may place different demands on the sensorimotor system.

Consequently, a recovery trajectory identified in one movement direction should not automatically be considered representative of global cervical proprioceptive recovery.

Pain And Clinical Status

Neck pain itself is associated with altered sensorimotor function.[6–8,20,23]

Hsu et al. demonstrated that the addition of cervical muscle fatigue to chronic neck pain further influenced postural control and muscle activation.[15] This raises the possibility that individuals with neck pain may have different fatigue-recovery responses from asymptomatic individuals.

Recent evidence also indicates that pain intensity and dizziness can influence the magnitude of differences observed on cervical sensorimotor tests.[20]

Therefore, future fatigue-recovery studies should consider pain status, symptom severity, dizziness, age, physical activity, and other potentially relevant characteristics when examining individual recovery trajectories.

Postural and Attentional Demands

Cervical proprioception does not operate independently of visual and vestibular information.[23],[24] Altering visual input, standing position, task difficulty, or attentional demands may therefore modify the observed effect of fatigue.

This is important because recovery measured during a simple repositioning task may not correspond to recovery during functional activities requiring simultaneous head, trunk, and limb movements.

Assessment of Cervical Proprioceptive Recovery

Joint Position Error

JPE remains the most commonly used operational measure of cervical proprioception.[19],[20] It has practical advantages because it is relatively inexpensive, clinically feasible, and can be measured using laser-pointer or motion-based systems.

However, JPE measurement properties are not completely established. AlDahas et al. reported sufficient reliability and validity overall but identified low or very low certainty of evidence for several properties and specifically emphasized the need for additional investigation of responsiveness.[19]

Responsiveness is particularly important when studying recovery. A measurement may demonstrate acceptable reliability under stable conditions but still fail to detect meaningful changes over a short recovery period.

Absolute, Constant, and Variable Error

Different error calculations provide different information.

Absolute error reflects the magnitude of deviation from the target position and is useful for evaluating accuracy.

Constant error provides information regarding the direction of the error.

Variable error reflects consistency across repeated trials.

Pinsault and Vuillerme demonstrated changes in both absolute and variable errors following cervical fatigue, indicating that fatigue can affect both accuracy and consistency.[13]

Future recovery studies should therefore consider whether recovery occurs similarly for accuracy and consistency. An individual may return close to the target position while continuing to demonstrate greater trial-to-trial variability.

Complementary Sensorimotor Measures

Because proprioception is multidimensional, JPE should ideally be complemented by other measures.

Potential outcomes include:

- postural sway;
- balance performance;
- dynamic visual acuity;
- subjective visual vertical/horizontal;

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- smooth pursuit neck torsion;
- cervical range of motion;
- movement velocity and smoothness;
- cervical muscle activation;
- neck endurance;
- vestibular interaction measures; and
- patient-reported sensorimotor symptoms.

The 2024 systematic review by Särkilahti et al. identified JPE, smooth pursuit neck torsion, and balance testing as major categories of cervical sensorimotor assessment.[20] This supports the use of a multidimensional approach when investigating recovery.

Current Evidence Gaps

The literature provides substantial evidence that cervical proprioception is influenced by musculoskeletal status, posture, fatigue, and multisensory integration.[1–28] However, several important gaps remain.

Limited Temporal Characterization

Existing fatigue studies commonly compare baseline with immediate post-fatigue measurements, while recovery studies may include only one later measurement.[13],[14],[17]

This approach demonstrates whether recovery has occurred at a particular point but does not describe the trajectory of recovery.

Lack of Standardized Recovery Intervals

There is no universally accepted recovery schedule for assessing cervical proprioceptive recovery following fatigue. Recovery periods have differed substantially between studies, making direct comparison difficult.[14],[17]

A standardized sequence of recovery measurements would improve comparability across studies.

Limited Investigation of Responsiveness

The 2024 measurement-property systematic review specifically highlighted responsiveness as an important area requiring further investigation.[19] This is particularly relevant to recovery research because responsiveness determines whether an instrument can detect meaningful change over time.

Heterogeneity of Fatigue Protocols

Differences in the muscle groups tested, fatigue intensity, contraction duration, endpoint criteria, and method of fatigue induction limit direct comparison between studies.[13–17]

JPE is not a Complete Measure of Sensorimotor Recovery

Although JPE is widely used, cervical sensorimotor control encompasses balance, oculomotor function, postural responses, and multisensory integration.[7],[8],[20],[23]

Therefore, recovery of JPE alone may not necessarily indicate complete functional sensorimotor recovery.

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Limited understanding of individual recovery variability

Most studies focus on group-level mean differences.[13–17] However, individuals may differ considerably in their magnitude and speed of recovery.

Characterizing individual recovery trajectories may therefore provide information that is obscured by group averages.

Limited Integration of Objective and Subjective Recovery

Most experimental studies emphasize laboratory-based measurements such as JPE and balance.[13,14,19] Less attention has been given to how individuals perceive cervical recovery following fatigue.

Future research could investigate whether objective recovery corresponds with perceived neck fatigue, confidence, movement awareness, and functional performance.

Future Research Directions

Future studies should consider cervical proprioceptive recovery as a longitudinal process rather than a single post-fatigue measurement.

A standardized experimental model could include this framework would enable researchers to determine the magnitude, rate, and completeness of recovery.

Future studies should also standardize:

1. fatigue induction protocol;
2. target cervical muscle group;
3. fatigue endpoint;
4. JPE measurement technique;
5. movement direction;
6. participant position;
7. number of JPE trials;
8. recovery intervals;
9. criterion for recovery; and
10. handling of measurement error.

Studies should include both asymptomatic individuals and individuals with neck pain to determine whether clinical status modifies recovery.

Furthermore, longitudinal designs should investigate whether repeated exposure to cervical fatigue produces consistent individual recovery patterns. This could eventually allow identification of individuals with delayed or incomplete sensorimotor recovery.

Technological developments may also improve temporal measurement. Laser-based systems, inertial measurement units, optical tracking, smartphone-based systems, and other low-cost motion-analysis

technologies could potentially permit repeated measurement of cervical position and movement with greater temporal resolution.

Importantly, technological innovation should be accompanied by formal reliability, validity, responsiveness, and minimal detectable change studies.[19]

Clinical Implications

The concept of cervical proprioceptive recovery may have relevance for physiotherapy assessment and rehabilitation.

A patient who demonstrates normal cervical proprioception at rest may nevertheless develop a measurable sensorimotor deficit following sustained or repetitive cervical loading.[13],[14]

This suggests that assessment under a single resting condition may fail to identify fatigue-sensitive sensorimotor deficits.

A fatigue-challenge model could potentially provide additional information regarding the resilience of the cervical sensorimotor system.

However, such an approach should currently be regarded as a research framework rather than an established clinical diagnostic procedure. Further evidence is required to determine whether fatigue-induced changes in JPE or other sensorimotor outcomes predict symptoms, functional limitations, injury risk, or rehabilitation outcomes.

Intervention studies have demonstrated that proprioceptive-focused rehabilitation can influence postural-control strategies in people with chronic neck pain,[29] while cervical mobilization has also been associated with improvements in selected proprioceptive and balance outcomes.[30] These findings support the clinical relevance of cervical sensorimotor function but do not yet establish whether improving the **rate or completeness of post-fatigue recovery** improves patient outcomes.

CONCLUSION

Cervical proprioception is a complex and dynamic component of sensorimotor control that depends on cervical mechanoreceptors, central integration, and interactions with visual and vestibular systems.[1–5] Evidence demonstrates that cervical muscle fatigue can temporarily impair cervical joint position sense, postural control, visual performance, and broader sensorimotor function.[13–17]

Importantly, existing evidence also demonstrates that some fatigue-related deficits can improve during recovery.[14] However, current research provides limited information regarding the **temporal characteristics, rate, completeness, and individual variability of cervical proprioceptive recovery**.

The principal research opportunity is therefore not simply to establish whether fatigue impairs cervical proprioception, but to determine **how cervical proprioception recovers following fatigue**.

Future research should move from a binary pre-fatigue/post-fatigue model toward a temporally resolved recovery model incorporating multiple assessment points, validated measures of responsiveness, standardized fatigue protocols, and complementary measures of sensorimotor function.

Understanding cervical proprioception as a dynamic process may ultimately provide a more sensitive framework for evaluating sensorimotor resilience, identifying fatigue-related deficits, and developing rehabilitation strategies aimed not only at improving baseline proprioception but also at optimizing recovery following physiological perturbation.

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