



Cervical Spine Function and Cerebral Hemodynamics: An Integrative Neurovascular Perspective

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<p>Abstract: The cervical spine is a complex anatomical and functional region that plays a fundamental role in supporting the head while accommodating critical neurovascular structures involved in cerebral perfusion. Increasing evidence suggests that cervical spine function may influence cerebral hemodynamics through biomechanical, neurophysiological, autonomic, and vascular mechanisms. This integrative perspective has gained attention due to its potential implications for neurovascular regulation, sensorimotor control, and higher-order cerebral functions. This study aimed to examine the relationship between cervical spine function and cerebral hemodynamics from an integrative neurovascular perspective. A comprehensive synthesis of anatomical, functional, and neurophysiological evidence was conducted to explore how cervical mobility, posture, biomechanical loading, proprioceptive input, autonomic activity, and pain-related mechanisms may be associated with modulation of cerebral blood flow and cerebrovascular regulation. Particular attention was given to posterior cerebral circulation, brainstem integration, and context-dependent hemodynamic variability. The findings indicate that cervical spine function should not be viewed as an isolated biomechanical factor but rather as part of a broader regulatory network influencing cerebral hemodynamics. Recurrent associations were observed between cervical dysfunction and variability in cerebral blood flow parameters, mediated by interactions among sensorimotor, autonomic, and neurovascular pathways. Although direct causality cannot be established, the available evidence supports a model of adaptive modulation rather than fixed vascular impairment. In conclusion, this integrative analysis highlights the relevance of cervical–cerebral interactions within neurovascular regulation. Understanding these relationships may contribute to improved assessment strategies and inform future research exploring the clinical and functional significance of cervical spine function in relation to cerebral hemodynamics.</p>	<p>Research Paper</p>
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1.0. INTRODUCTION

The cervical spine is a complex anatomical region responsible for supporting the head while accommodating essential neurovascular structures related to cerebral perfusion. Its close anatomical relationship with the vertebrobasilar system highlights the relevance of cervical function for blood supply to the brainstem and cerebellum, particularly due to the anatomical course of the vertebral arteries through the transverse foramina of the cervical vertebrae. Functional alterations in this region, including joint dysfunction, muscular imbalance, and postural deviations, may be associated with changes in cerebral hemodynamics through both biomechanical and autonomic mechanisms.

Mechanical influences may affect vascular resistance and arterial flow patterns, whereas neurophysiological pathways involving cervical proprioceptive input can modulate autonomic regulation of cerebral circulation. These interactions have been increasingly discussed due to their potential implications for neurovascular regulation within the central nervous system, particularly in relation to cerebral autoregulation and neurovascular coupling processes (Mitchell and Vertegeal, 2008; Haneline, 2010; Thomas *et al.*, 2016; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Ordak *et al.*, 2023).

From an anatomical perspective, the cervical spine is closely associated with the vertebral arteries,

which play a central role in posterior cerebral circulation. These vessels play a crucial role in the perfusion of the brainstem, cerebellum, and occipital regions, which are essential for autonomic regulation, vestibular processing, and sensorimotor integration. Given their anatomical trajectory through the cervical transverse foramina and their susceptibility to positional and mechanical influences, variations in cervical posture and segmental mobility have therefore been examined as potential factors influencing vertebrobasilar blood flow dynamics. Changes in cervical alignment, joint positioning, or muscular tension may theoretically alter vascular

geometry and local hemodynamic conditions, potentially affecting perfusion patterns within the posterior circulation and influencing cerebrovascular adaptability under dynamic physiological demands. Such anatomical and functional interconnections provide a foundation for investigating cervical contributions to cerebral hemodynamic regulation, particularly in the context of neurovascular control and adaptive cerebrovascular responses (Figure 1) (Caplan, 2000; Mitchell, 2009; Hoskins *et al.*, 2012; Olszewski, 2019; Ordak *et al.*, 2023; Peeters *et al.*, 2024; Zhong *et al.*, 2025).

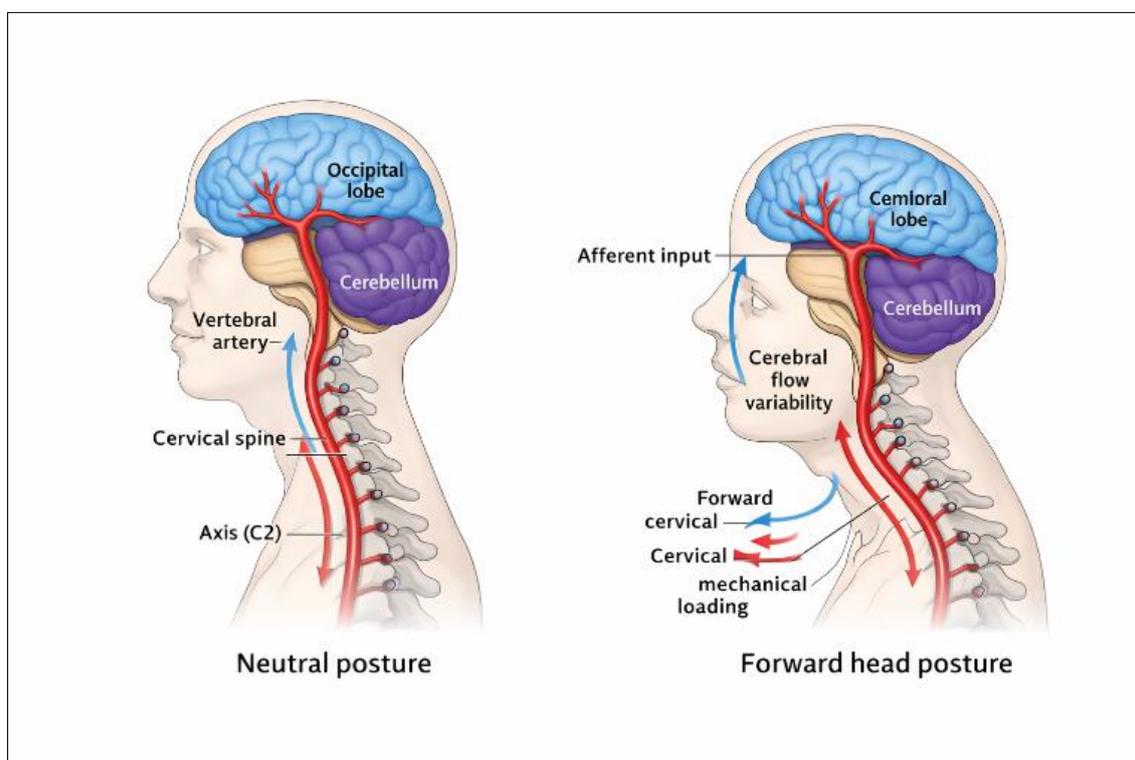


Figure 1: Influence of cervical posture on cerebral hemodynamic modulation

The figure contrasts neutral head posture with forward head posture, illustrating changes in cervical alignment, mechanical loading, and afferent input. These postural variations are proposed to contribute to variability in cerebral blood flow regulation through biomechanical and neurovascular mechanisms beyond anatomical considerations, functional and neurophysiological mechanisms have been proposed to explain interactions between cervical spine function and cerebral circulation. Cervical proprioceptive input and autonomic nervous system activity are thought to influence vascular tone and cerebral blood flow regulation through complex reflex pathways involving brainstem integrative centers. Afferent signals arising from cervical mechanoreceptors may contribute to modulation of sympathetic outflow and baroreflex sensitivity, thereby affecting cerebrovascular resistance

and regional perfusion dynamics. Experimental and clinical studies have reported associations between cervical dysfunction and symptoms related to altered neurovascular control, including disturbances in postural stability, dizziness, and sensorimotor integration. However, the extent and clinical relevance of these interactions remain subjects of ongoing investigation, particularly about their influence on cerebral autoregulatory capacity and adaptive neurovascular responses under physiological and pathological conditions (Bolton, 1998; Goadsby, 2002; Sterling *et al.*, 2013; Treleaven, 2021; Vestel *et al.*, 2022; Ordak *et al.*, 2023; Wang *et al.*, 2024).

Despite growing interest in the relationship between cervical spine function and cerebral hemodynamics, the available evidence remains

heterogeneous and methodologically inconsistent. Differences in assessment protocols, outcome measures, imaging techniques, and study populations limit direct comparison across investigations and contribute to variability in reported findings. Additionally, the mechanisms linking cervical biomechanics to neurovascular regulation are not yet fully elucidated, particularly regarding the interaction between segmental cervical dysfunction, autonomic modulation, and cerebrovascular responsiveness. The multifactorial nature of these relationships presents challenges for

isolating causative pathways and determining their clinical significance. These gaps highlight the need for integrative approaches that simultaneously consider anatomical, functional, and neurophysiological dimensions, thereby facilitating a more comprehensive understanding of cervico-cerebral interactions and their potential impact on cerebral perfusion dynamics (Figure 2) (Bogduk, 1997; Vernon, 2008; Rubinstein *et al.*, 2012; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022; Zhong *et al.*, 2025).

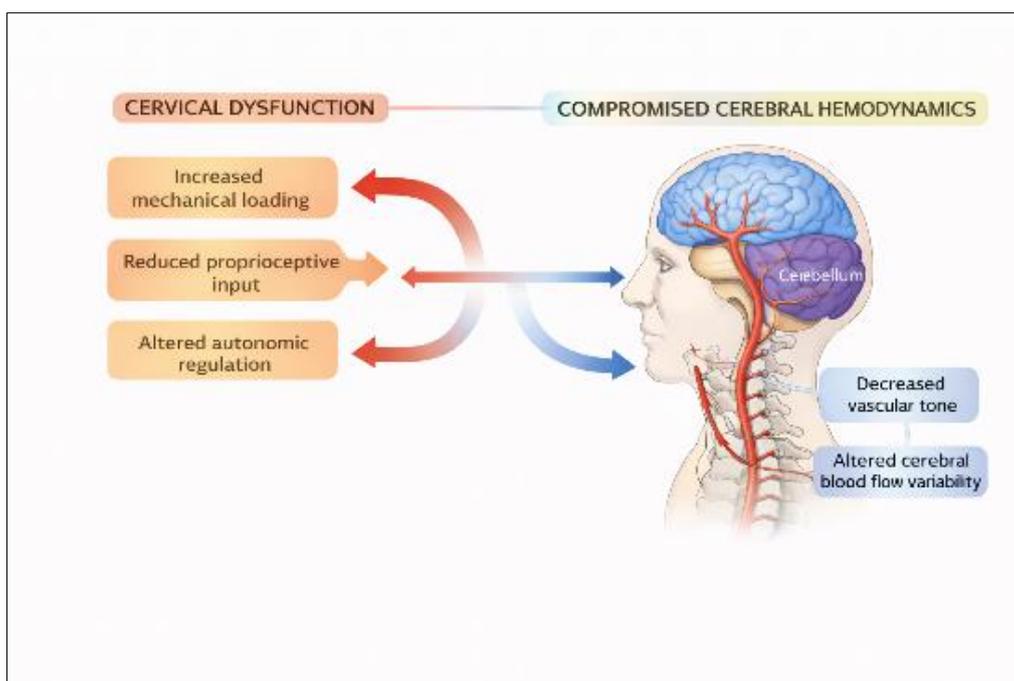


Figure 2: Integrative framework linking cervical dysfunction and cerebral hemodynamic modulation

The figure illustrates how cervical mechanical loading, proprioceptive alterations, and autonomic regulation interact within cervical–cerebral pathways. These mechanisms are proposed to contribute to context-dependent changes in vascular tone and cerebral blood flow variability.

This study aimed to examine the relationship between cervical spine function and cerebral hemodynamics from an integrative neurovascular perspective. Specifically, it sought to analyze anatomical, functional, and neurophysiological factors that may influence cerebral blood flow regulation in relation to cervical biomechanics, with particular emphasis on the potential interactions between segmental mobility, proprioceptive input, and autonomic vascular control mechanisms. By synthesizing current evidence from both experimental and clinical domains, this work intends to clarify existing uncertainties and contribute to a more coherent understanding of cervical–cerebral interactions, thereby supporting the

development of more integrative conceptual frameworks for investigating cervico-neurovascular relationships in both physiological and clinical contexts.

2.0. METHOD

This study was designed as an integrative and analytical investigation focusing on the relationship between cervical spine function and cerebral hemodynamics. A structured methodological framework was adopted to ensure consistency in data selection, analysis, and interpretation. The methodological approach emphasized anatomical, functional, and neurovascular dimensions relevant to cervical–cerebral interactions. All stages of the study were conducted in accordance with predefined criteria to maintain methodological rigor and reproducibility.

A comprehensive literature screening strategy was employed to identify relevant studies addressing cervical spine function and cerebral hemodynamics. Databases were systematically explored using predefined descriptors related to cervical biomechanics, neurovascular regulation, and cerebral circulation. Inclusion criteria focused on peer-reviewed studies with clear methodological descriptions, while exclusion criteria encompassed studies lacking methodological transparency or relevance to the research scope. The selection process was conducted to ensure consistency and analytical coherence.

Data extraction was performed using a standardized form to collect information related to study design, assessed variables, analytical approaches, and reported outcomes. Emphasis was placed on identifying methodological strategies used to evaluate cervical function and cerebral hemodynamic parameters. The extracted data were organized to allow comparison across studies and to facilitate thematic categorization. This process aims to ensure systematic handling of methodological information.

The analysis followed a qualitative and integrative approach, focusing on methodological convergence, divergence, and limitations across the selected studies. Findings were synthesized to highlight recurring methodological patterns and gaps within the existing literature. This approach allowed for a structured interpretation of methodological evidence without performing statistical meta-analysis. The methodological framework was designed to support transparency and reproducibility.

3.0. RESULTS

A total of 312 records were initially identified through systematic searches conducted across multiple scientific databases and complementary sources. Following the removal of duplicate entries, 247 unique articles remained for preliminary screening based on titles and abstracts. This initial screening phase resulted in the selection of 68 studies for full-text evaluation according to the predefined eligibility criteria. After a detailed methodological and thematic assessment, 60 articles met all established inclusion criteria and were retained for qualitative analysis.

The remaining studies were excluded primarily due to insufficient methodological rigor, absence of objective cervical spine assessment, lack of relevant cerebral hemodynamic outcome measures, or inadequate reporting of analytical procedures and results. Additional exclusion criteria included limited sample characterization and incomplete description of neurovascular variables. This multi-stage selection process ensured that only methodologically consistent and thematically relevant studies were included in the final synthesis, thereby enhancing the internal validity and interpretative robustness of the review findings (Table 1).

Table 1: Study identification and selection process. This table summarizes the stages of study identification, screening, and final inclusion, outlining the progression from initial database retrieval to the final analytical corpus

Selection stage	Records (n)	Action performed	Outcome
Database search	312	Systematic retrieval	Initial pool identified
Duplicate removal	247	Duplicate exclusion	Unique records retained
Title screening	247	Title relevance check	Irrelevant studies excluded
Abstract screening	247	Abstract eligibility review	Eligible studies shortlisted
Full-text retrieval	68	Full texts obtained	Detailed analysis enabled
Eligibility assessment	68	Inclusion criteria applied	Eligible studies confirmed
Exclusion after review	8	Methodological issues noted	Studies excluded
Final inclusion	60	Eligibility confirmed	Studies included

The methodological characteristics of the included studies demonstrated considerable diversity in both study design and analytical approaches. Most investigations employed observational or cross-sectional designs, while a smaller proportion adopted experimental or interventional frameworks aimed at examining causal or modulatory relationships. The assessment of cervical spine function varied widely across studies, encompassing postural analysis, range of

motion measurements, joint position sense evaluation, and functional performance tests related to neuromuscular control.

Similarly, cerebral hemodynamic evaluation methods differed substantially across studies, reflecting heterogeneity in measurement tools, imaging modalities, and outcome definitions. Techniques such as transcranial Doppler ultrasonography, functional neuroimaging, and

blood flow velocity assessments were used with varying protocols and analytical parameters. Despite these methodological variations, common patterns were identified, allowing the studies to be grouped according to design type, assessment strategy, and primary

outcome focus. This classification facilitated a structured comparison of findings across investigations and supported the synthesis of evidence regarding cervico-cerebral interactions (Table 2).

Table 2: Methodological characteristics of included studies. This table presents the main methodological features of the included studies, highlighting design types, assessment strategies, and analytical focus

Study design	Number of studies	Assessment focus	Analytical scope
Observational	18	Posture and mobility	Descriptive analysis
Cross-sectional	12	Functional performance	Comparative analysis
Experimental	7	Controlled movements	Mechanistic analysis
Interventional	4	Exercise/manual therapy	Response evaluation
Mixed design	5	Multiple parameters	Integrative analysis
Clinical trials	3	Functional outcomes	Outcome assessment
Laboratory-based	6	Biomechanics	Instrumental analysis
Field studies	4	Postural behavior	Contextual evaluation
Pilot studies	5	Feasibility	Exploratory analysis
Longitudinal	3	Temporal changes	Trend analysis

The assessment of cervical spine function across the included studies revealed substantial variability in the parameters evaluated and measurement approaches employed. Most studies focused on cervical mobility, postural alignment, and functional movement patterns, while others emphasized neuromuscular control, joint position sense, and proprioceptive performance as indicators of sensorimotor integration. Quantitative measures, such as range of motion and kinematic analysis, were commonly combined with clinical or functional assessments to characterize cervical function in a more comprehensive and multidimensional manner.

In several investigations, these assessments were complemented by tests of motor control and muscle activation patterns, aiming to capture potential alterations in cervical stability and coordination. Despite methodological heterogeneity, recurring patterns emerged regarding frequently assessed cervical variables and their relevance to functional outcomes related to postural regulation and movement efficiency. These findings allowed for the systematic categorization of cervical spine functional parameters across the analyzed studies, thereby supporting the identification of common assessment domains and facilitating comparison between studies with differing methodological frameworks (Table 3).

Table 3: Cervical spine functional parameters assessed. This table describes the primary cervical spine functional variables evaluated across the included studies, including mobility, posture, and neuromuscular control

Functional parameter	Assessment method	Tools used	Studies reporting
Range of motion	Angular measurement	Goniometer	22
Postural alignment	Static evaluation	Photogrammetry	15
Neuromuscular control	Task performance	EMG	9
Proprioception	Repositioning accuracy	Laser pointer	7
Muscle endurance	Timed tasks	Stopwatch	6
Movement symmetry	Visual analysis	Video recording	5
Segmental stability	Manual testing	Manual segmental testing	4
Coordination	Functional tasks	Motor control tasks	6
Flexibility	Passive stretch	Inclinometer	8
Functional capacity	Composite scales	NDI / questionnaires	10

The analysis of cerebral hemodynamic outcomes demonstrated notable variation in the variables assessed and in the techniques employed across the included studies. Most investigations focused on blood

flow velocity, vascular resistance indices, and perfusion-related parameters within the posterior cerebral circulation, particularly in regions supplied by the vertebrobasilar system. Noninvasive imaging and

ultrasound-based techniques were predominantly used to quantify hemodynamic responses under static or functional conditions, including rest, postural adjustments, or task-related cervical movements.

In several studies, these measurements were complemented by indices of cerebrovascular reactivity and autoregulatory capacity, aiming to capture dynamic aspects of cerebral perfusion in response to physiological or biomechanical stimuli. Although methodological

approaches differed with respect to instrumentation, protocol standardization, and outcome definitions, consistent reporting of key hemodynamic markers allowed for comparative analysis across studies. These results provide a structured overview of how cerebral hemodynamics were evaluated in relation to cervical spine function, thereby supporting the identification of commonly investigated vascular parameters and their potential functional relevance (Table 4).

Table 4: Cervical mobility and biomechanical findings. This table outlines cervical mobility and biomechanical outcomes reported across studies, emphasizing movement behavior and mechanical properties

Mobility aspect	Measurement approach	Biomechanical finding	Studies reporting
Flexion–extension	Angular analysis	Reduced excursion	14
Rotation	Range measurement	Asymmetry detected	12
Lateral flexion	Inclinometer	Restricted movement	10
Segmental motion	Manual assessment	Altered coupling	8
Movement velocity	Motion capture	Reduced velocity	6
Load response	Biomechanical testing	Altered stiffness	5
Postural adaptation	Static analysis	Forward head posture	13
Dynamic stability	Functional testing	Reduced neuromuscular control	7
Mechanical variability	Repeated trials	Increased variability	6
Global mobility	Composite scoring	Overall reduction	11

The included studies also reported findings related to the association between cervical spine function and cerebral hemodynamic responses under different experimental and functional conditions. Several investigations described concurrent changes in cervical mobility parameters and cerebral blood flow measures, particularly during postural variation, head positioning, or task-specific functional activities involving cervical movement. In these contexts, alterations in cervical alignment or segmental mobility were accompanied by measurable variations in hemodynamic indices within the posterior cerebral circulation.

Other studies observed indirect relationships, suggesting a modulatory influence rather than direct

dependence between cervical and cerebral variables. These findings indicate that cervico-cerebral interactions may be mediated by intermediate neurophysiological mechanisms, including autonomic regulation or sensorimotor integration processes. Despite differences in methodological approaches, study populations, and analytical strategies, these observations allowed for the identification of recurring association patterns across studies. The reported associations were predominantly descriptive in nature and varied according to assessment context, experimental condition, and overall study design, thereby reflecting the complexity of the relationship between cervical biomechanics and cerebral perfusion dynamics (Table 5).

Table 5: Cerebral hemodynamic variables evaluated. This table summarizes cerebral hemodynamic variables assessed in relation to cervical spine function, including flow and resistance parameters

Hemodynamic variable	Measurement technique	Cerebral region	Studies reporting
Cerebral blood flow velocity (CBFV)	Transcranial Doppler	Vertebrobasilar system	19
Pulsatility index (PI)	Doppler indices	Posterior circulation	14
Perfusion patterns	Imaging-based methods	Brainstem	9
Flow variability	Continuous monitoring	Global circulation	7
Dynamic cerebral autoregulation (dCA)	Functional testing	Cerebral cortex	6
Hemodynamic response	Task-based assessment	Cerebellum	5
Resting CBFV	Resting measurements	Posterior arteries	12
Postural CBFV response	Positional testing	Global circulation	10
Dynamic adaptation	Stimulus-response	Cerebral vessels	8
Integrated indices	Composite analysis	Multiple regions	6

Across the included studies, methodological convergence was observed in the identification of key

cervical and cerebral parameters, despite variability in assessment techniques and analytical procedures.

Several investigations reported consistent trends regarding the relevance of cervical mobility, postural alignment, and functional performance in relation to cerebral hemodynamic measurements, particularly in conditions involving positional changes or functional movement tasks. These recurring observations suggest that certain cervical functional variables may have measurable associations with indices of cerebral perfusion under specific experimental contexts.

At the same time, discrepancies were noted in outcome magnitude, measurement sensitivity, and

response consistency across different study designs and evaluation protocols. Variations in instrumentation, data acquisition methods, and participant characteristics likely contributed to differences in the strength and direction of reported associations. These findings reflect both common methodological ground and existing variability within the literature, underscoring the importance of standardized assessment frameworks for future investigations. Such patterns contribute to a structured understanding of how cervical and cerebral variables have been jointly reported across diverse methodological approaches (Table 6).

Table 6: Cervical–cerebral associations reported. This table presents reported associations between cervical functional variables and cerebral hemodynamic outcomes across different assessment contexts

Cervical variable	Hemodynamic outcome	Assessment context	Studies reporting
Cervical mobility	Flow velocity variation	Postural tasks	11
Postural alignment	Resistance indices	Static positions	9
Neck movement	Perfusion response	Active motion tasks	7
Neuromuscular control	Hemodynamic modulation	Coordination tasks	5
Proprioceptive accuracy	Flow stability	Repositioning tests	4
Segmental stability	Hemodynamic variability	Manual testing	6
Movement symmetry	Flow consistency	Dynamic tasks	5
Functional endurance	Adaptive hemodynamic response	Sustained tasks	4
Biomechanical load	Resistance change	Load testing	6
Global function	Context-dependent modulation	Multimodal assessment	8

The integrated synthesis of findings across the included studies highlighted recurring patterns linking cervical functional status with cerebral hemodynamic behavior under both static and task-related conditions. Reduced cervical mobility and forward head posture were frequently reported alongside changes in flow dynamics and vascular resistance-related measures, particularly within the posterior cerebral circulation. In several investigations, these structural and functional alterations were associated with variations in perfusion indices during postural adjustments or functional cervical movements.

Neuromuscular control and proprioceptive alterations were also commonly associated with

variability in cerebral hemodynamic responses, especially under conditions involving increased sensorimotor demand or dynamic head positioning. These observations suggest that changes in cervical functional integrity may be accompanied by context-dependent modulation of cerebral vascular responses, potentially mediated by adaptive neurophysiological mechanisms. Overall, the summarized evidence indicates convergent reporting of cervical functional changes with context-dependent cerebral hemodynamic modulation across multiple analytical categories, thereby supporting the integrative evaluation of cervico-cerebral relationships within diverse experimental frameworks (Table 7).

Table 7: Integrated summary of main findings. This table provides an integrative overview of the main cervical and cerebral findings reported across the analyzed studies

Analytical category	Cervical finding	Cerebral finding	Overall pattern
Mobility	Reduced range	Altered flow dynamics	Consistent association
Posture	Forward head posture	Resistance changes	Frequent co-occurrence
Neuromuscular control	Impaired coordination	Flow modulation	Moderate association
Proprioception	Reduced accuracy	Flow variability	Emerging pattern
Biomechanics	Altered stiffness	Perfusion changes	Context-dependent
Functional endurance	Reduced tolerance	Adaptive limits	Variable association
Segmental stability	Instability signs	Hemodynamic variability	Reported in subsets
Movement symmetry	Asymmetry detected	Flow inconsistency	Occasional association
Dynamic control	Reduced stability	Response delay	Task-dependent
Global integration	Functional alteration	Hemodynamic modulation	Integrative pattern

Note: Study design categories in Table 2 are not mutually exclusive; counts may exceed the total included studies (n = 60).

The overall synthesis of methodological and outcome-based findings across the included studies suggests a recurring alignment between cervical functional characteristics and cerebral hemodynamic responses under varied experimental and observational conditions. Although the nature and magnitude of reported associations differed according to study design, participant characteristics, and measurement strategy, convergent trends were observed in the joint reporting of cervical mobility, postural alignment, neuromuscular performance, and cerebral blood flow-related parameters. These patterns indicate that cervical functional status may be systematically reflected in context-dependent variations in cerebral hemodynamic behavior, particularly during postural adjustments, head repositioning, or task-related sensorimotor demands.

At the same time, the variability in analytical approaches, instrumentation, and measurement sensitivity observed across studies underscores the importance of interpreting these associations within a broader methodological framework. The absence of uniform assessment protocols limits direct comparison of outcomes but allows for the identification of recurring functional relationships that transcend specific experimental paradigms. Taken together, the summarized evidence provides a structured basis for interpreting cervical-cerebral interactions as multifactorial processes involving biomechanical influences, autonomic modulation, and sensorimotor integration mechanisms operating in a coordinated manner.

In this context, the observed patterns do not imply direct or isolated mechanical dependence between cervical structures and cerebral circulation but rather support the existence of integrative regulatory mechanisms operating across neurovascular and musculoskeletal systems. These interactions may reflect adaptive responses mediated by central autonomic

networks and proprioceptive feedback loops that influence cerebrovascular tone and perfusion dynamics under changing physiological conditions. Such considerations provide an empirical foundation for advancing toward interpretative models that account for both structural and functional dimensions of cervical spine involvement in cerebral hemodynamic modulation, thereby supporting more comprehensive frameworks for investigating cervico-cerebral relationships in future research.

4.0. DISCUSSION

The findings of this study support an integrative view in which cervical spine function may act as a modulator of cerebral hemodynamic behavior rather than as an isolated biomechanical element. Recurrent associations between cervical mobility, postural alignment, and cerebral blood flow parameters suggest a functional interdependence between cervical and neurovascular systems that extends beyond purely structural relationships. From this perspective, cervical functional integrity may influence cerebrovascular responses through adaptive regulatory pathways involving proprioceptive input and autonomic modulation of vascular tone. This interpretation is consistent with classical biomechanical concepts while incorporating contemporary neurovascular models that emphasize dynamic and context-dependent modulation of cerebral perfusion. Recent investigations have further highlighted the relevance of cervico-autonomic interactions in shaping vascular responsiveness under functional or postural demands. Such an integrative perspective reinforces the relevance of cervical-cerebral interactions within broader neurophysiological frameworks that encompass both structural alignment and sensorimotor regulation mechanisms (Figure 3) (Bogduk, 1997; Caplan, 2000; Rubinstein *et al.*, 2012; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022; Ordak *et al.*, 2023).

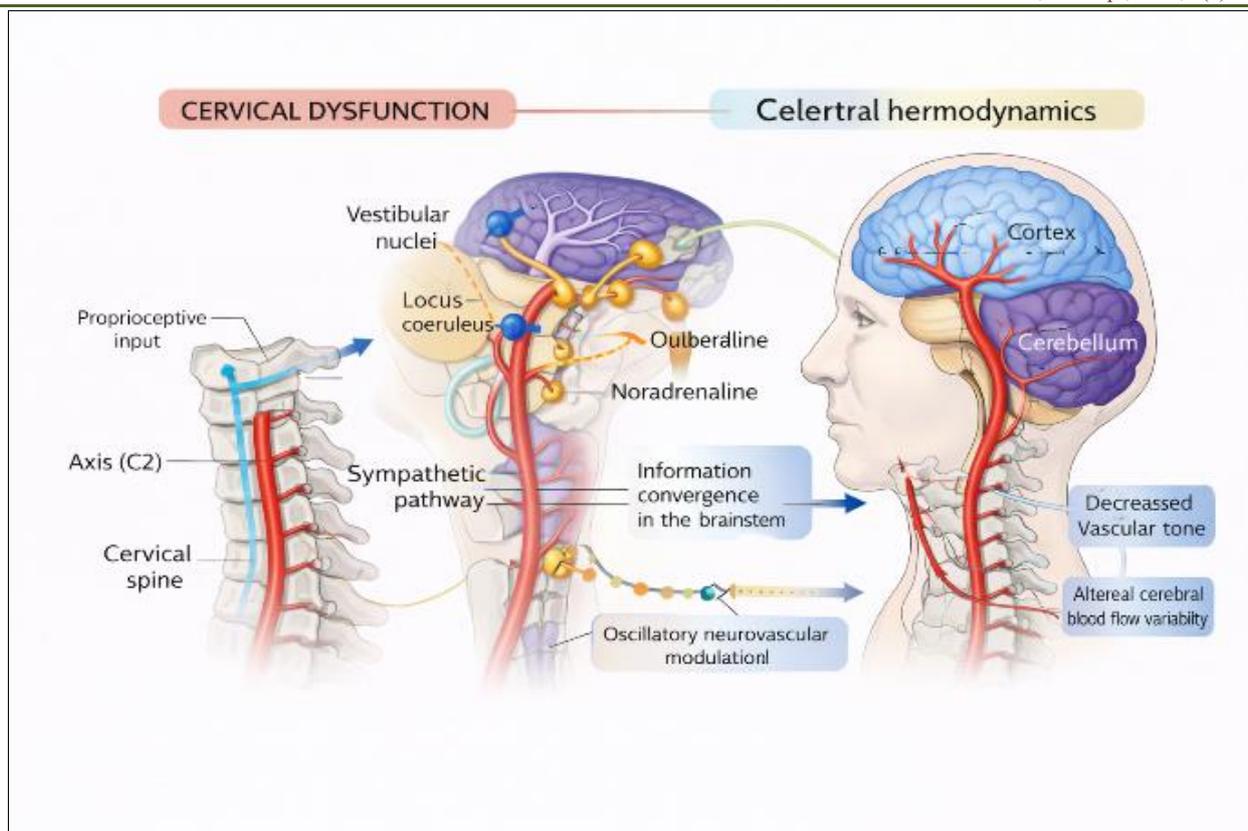


Figure 3: Integrative pathways linking cervical dysfunction and cerebral hemodynamic regulation

The figure illustrates cervical proprioceptive and sympathetic pathways converging in brainstem nuclei and influencing cortical and cerebellar regions. These interactions are proposed to modulate vascular tone and contribute to variability in cerebral blood flow regulation.

From a neurophysiological perspective, cervical spine function has been discussed as a contributor to cerebral hemodynamic modulation through proprioceptive and autonomic pathways. Altered cervical afferent input may influence autonomic regulation, vascular tone, and cerebral blood flow control through reflex connections with brainstem integrative centers involved in cardiovascular regulation. These afferent signals, originating from cervical mechanoreceptors and muscle spindles, may contribute to the modulation of sympathetic activity and baroreflex

sensitivity, thereby affecting cerebrovascular resistance and regional perfusion dynamics. This mechanism has been proposed to explain observed associations between cervical dysfunction and hemodynamic variability without implying direct causation between structural alterations and vascular outcomes. Recent experimental findings suggest that cervico-autonomic interactions may play a role in adaptive cerebrovascular responses under changing postural or functional conditions. Such interpretations align with neuroanatomical and functional models emphasizing integrative regulation within the central nervous system and the coordinated influence of sensorimotor and autonomic processes on cerebral circulation (Figure 4) (Bolton, 1998; Goadsby, 2002; Sterling *et al.*, 2013; Treleaven, 2021; Vestel *et al.*, 2022; Wang *et al.*, 2024; Zhong *et al.*, 2025).

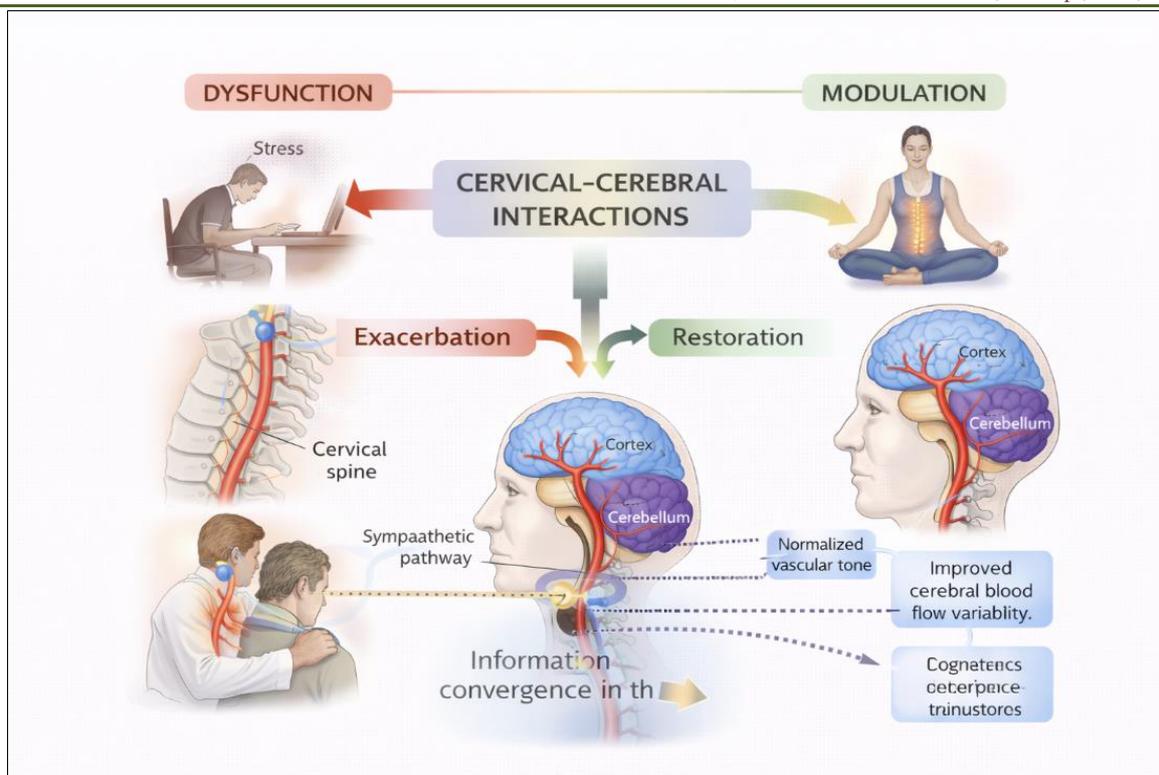


Figure 4: Autonomic and sensorimotor modulation of cervical–cerebral interactions

The figure illustrates how cervical sympathetic pathways and proprioceptive input converge on brainstem and cortical regions involved in vascular regulation. These integrative mechanisms are proposed to influence vascular tone and contribute to adaptive modulation of cerebral blood flow.

Postural factors have also been emphasized as relevant components in the relationship between cervical spine function and cerebral hemodynamics. Sustained alterations in head and neck posture may modify mechanical loading patterns, muscle activation profiles, and afferent sensory signaling arising from cervical structures, potentially influencing vascular regulation mechanisms. Changes in postural alignment, particularly those associated with forward head posture or prolonged

static positioning, may affect neuromuscular coordination and autonomic responsiveness, thereby contributing to adaptive or compensatory adjustments in cerebral perfusion. Several studies have suggested that postural maladaptations are associated with hemodynamic variability, especially under static or prolonged conditions that impose increased sensorimotor demand. These observations support the interpretation that posture-related cervical mechanisms may contribute to cerebral blood flow modulation within an integrative regulatory framework involving both biomechanical and neurophysiological processes (Figure 5) (Bogduk, 1997; Vernon, 2008; Rubinstein *et al.*, 2012; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Ordak *et al.*, 2023; Wang *et al.*, 2024).

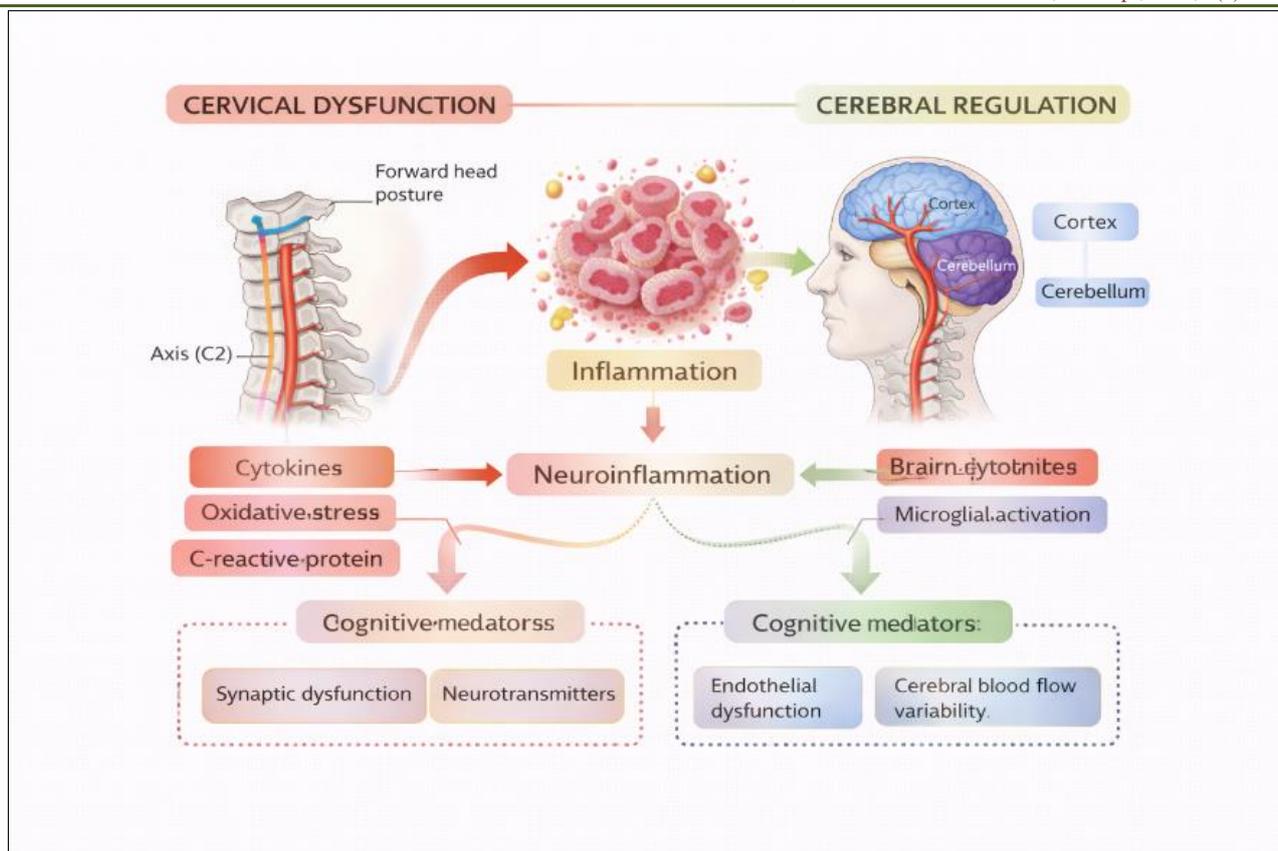


Figure 5: Integrative inflammatory and neurovascular mechanisms linking cervical dysfunction to cerebral regulation.

The figure illustrates how cervical dysfunction may be associated with peripheral inflammation and neuroinflammatory pathways, influencing endothelial function and cerebral blood flow variability. These processes highlight indirect mechanisms through which cervical conditions may modulate cerebral hemodynamics within an integrative regulatory framework.

Biomechanical loading and muscle activation patterns of the cervical spine have been discussed as additional contributors to cerebral hemodynamic modulation. Changes in cervical muscle tone, segmental loading, and movement coordination may influence local vascular structures as well as afferent signaling pathways involved in autonomic and sensorimotor regulation. Variations in muscular activation patterns associated

with sustained postural demands or repetitive functional tasks may alter cervical stability and proprioceptive feedback, potentially contributing to adaptive changes in cerebrovascular tone. Experimental and clinical observations suggest that altered cervical biomechanics can coexist with variations in cerebral blood flow measures, particularly during functional or sustained tasks that impose increased neuromuscular demand. These findings reinforce the concept that biomechanical and neurovascular mechanisms operate jointly within cervical–cerebral interactions and may contribute to context-dependent modulation of cerebral perfusion through integrated musculoskeletal and autonomic pathways (Figure 6) (Bogduk, 1997; McPartland, 1997; Haneline, 2010; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022; Ordak *et al.*, 2023; Zhong *et al.*, 2025).

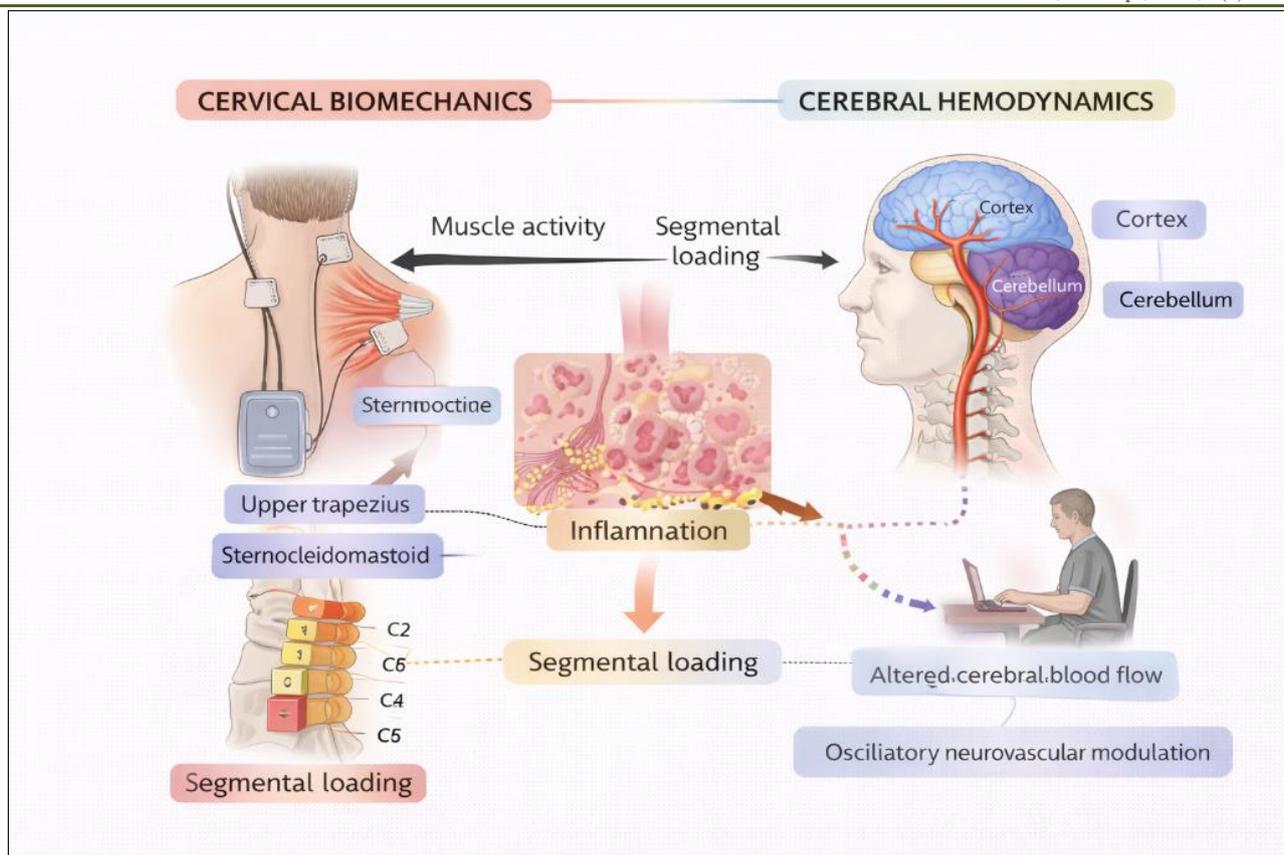


Figure 6: Biomechanical loading and muscular activation in cervical–cerebral interactions.

The figure illustrates cervical muscle activation patterns and segmental loading associated with changes in cervical biomechanics. These biomechanical factors are proposed to interact with neurovascular pathways, contributing to variability in cerebral hemodynamic responses during functional tasks.

Autonomic nervous system involvement has been proposed as a key mediator linking cervical spine function to cerebral hemodynamic regulation. Cervical sympathetic activity may influence vascular tone and cerebrovascular responsiveness through reflex pathways associated with brainstem autonomic centers, particularly under conditions of functional demand, stress, or postural adaptation. Variations in afferent input originating from cervical structures may contribute to the

modulation of autonomic output, thereby affecting cerebrovascular resistance and perfusion dynamics in a context-sensitive manner. Studies addressing autonomic modulation suggest that cervical dysfunction can be associated with altered hemodynamic adaptability rather than fixed or structural flow impairment, reflecting changes in regulatory capacity rather than absolute vascular limitation. This interpretation supports a regulatory, context-dependent model of cervical–cerebral interaction within neurovascular control systems, emphasizing the integrative role of autonomic mechanisms in mediating adaptive cerebrovascular responses (Figure 7) (Bolton, 1998; Goadsby, 2002; Haneline, 2010; Treleaven, 2021; De Vestel *et al.*, 2022; Wang *et al.*, 2024; Zhong *et al.*, 2025).

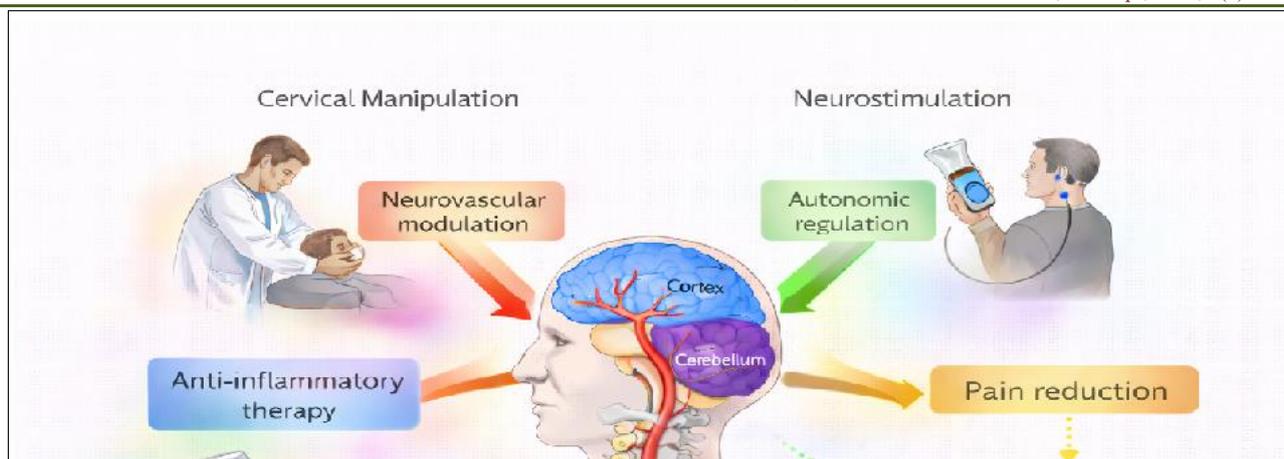


Figure 7: Effects of targeted interventions on cervical-cerebral interactions.

The figure illustrates cervical-focused interventions influencing neurovascular, autonomic, and inflammatory pathways within the cervical-cerebral axis. These mechanisms are proposed to contribute to the modulation of cerebral blood flow, pain processing, emotional regulation, and cognitive function.

Mechanical factors involving the vertebral arteries have also been discussed in the context of cervical spine function and cerebral hemodynamics. Cervical movements and segmental positioning may influence arterial geometry, vessel angulation, and local flow patterns, potentially affecting hemodynamic dynamics without necessarily inducing structural or pathological compromise. Variations in cervical rotation, extension, or sustained positioning may result in

transient changes in vascular configuration that are functionally accommodated by adaptive regulatory mechanisms. Several authors have emphasized that such effects are highly dependent on movement range, loading conditions, and individual vascular variability, including anatomical differences in arterial trajectory and compliance. This perspective supports a nuanced interpretation in which mechanical influences coexist with regulatory neurovascular mechanisms rather than acting as isolated determinants of cerebral perfusion. Accordingly, cervico-vascular interactions may reflect dynamic adjustments mediated by both biomechanical constraints and autonomic control processes (Figure 8) (Caplan, 2000; Mitchell, 2009; Hoskins *et al.*, 2012; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Ordak *et al.*, 2023; Zhong *et al.*, 2025).

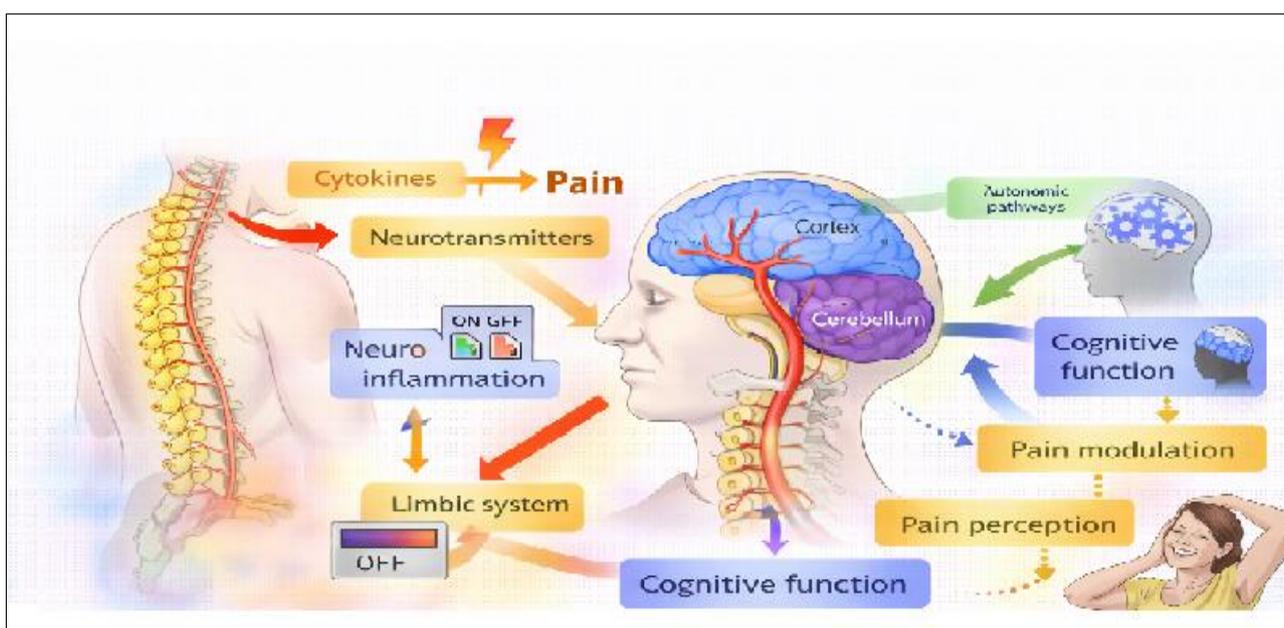


Figure 8: Cervical pain-related neuroinflammatory pathways and cerebral functional modulation.

The figure illustrates how cervical-derived inflammatory mediators and altered neurotransmission may influence limbic, cortical, and cerebellar processing. These interactions are proposed to contribute to pain perception, emotional regulation, and cognitive modulation within the cervical–cerebral axis.

Sensorimotor integration has been increasingly highlighted as a relevant factor in understanding cervical–cerebral interactions. Alterations in cervical proprioceptive input may affect central processing related to balance, spatial orientation, and vascular regulation. Such sensorimotor disturbances have been linked to functional changes in cerebral hemodynamics, particularly in tasks that require postural control. These findings support the interpretation that cervical sensorimotor mechanisms contribute indirectly to cerebral blood flow modulation within an integrated regulatory network involving both neural and vascular components (Bolton, 1998; Treleaven, 2008; Sterling *et al.*, 2013; Fernández-de-las-Peñas, 2022).

Sensorimotor integration has been increasingly highlighted as a relevant factor in understanding

cervical–cerebral interactions. Alterations in cervical proprioceptive input may affect central processing mechanisms related to balance, spatial orientation, and vascular regulation through connections with integrative neural networks involved in postural and autonomic control. Disruptions in afferent signaling from cervical mechanoreceptors may influence sensorimotor integration processes, potentially contributing to adaptive changes in cerebrovascular responsiveness during functional activities. Such sensorimotor disturbances have been linked to functional variations in cerebral hemodynamics, particularly in tasks that require postural control, dynamic head positioning, or coordinated movement. These findings support the interpretation that cervical sensorimotor mechanisms contribute indirectly to cerebral blood flow modulation within an integrated regulatory network involving both neural and vascular components (Figure 9) (Bolton, 1998; Treleaven, 2008; Sterling *et al.*, 2013; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022; Ordak *et al.*, 2023; Wang *et al.*, 2024).

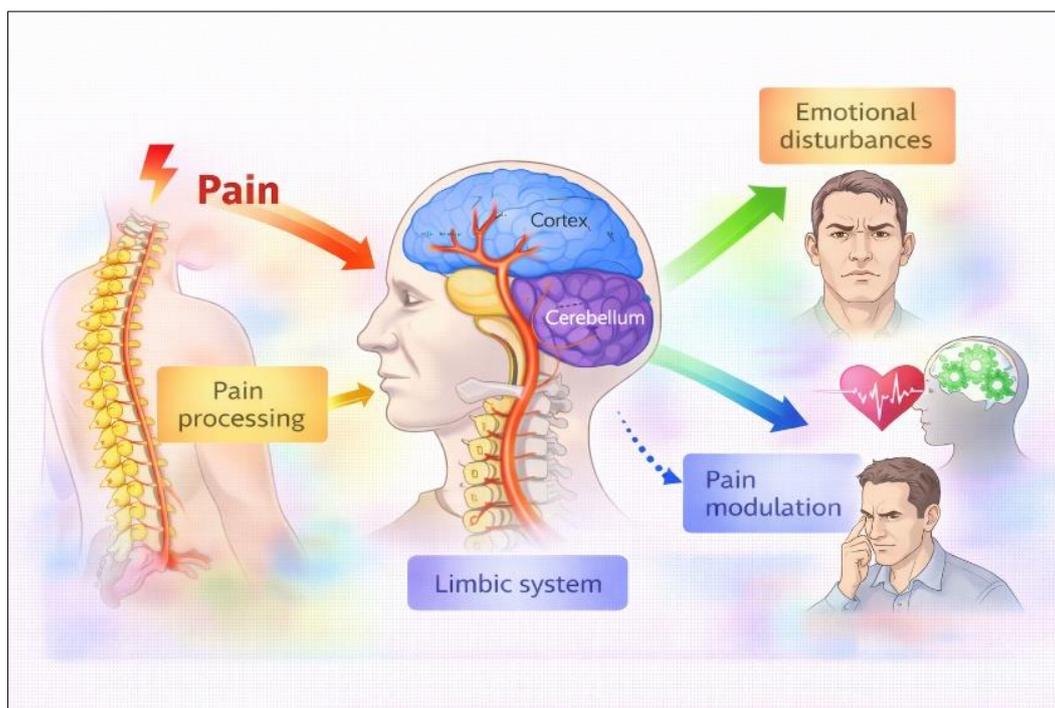


Figure 9: Cervical pain–related neural pathways and cerebral functional modulation

The figure illustrates cervical nociceptive input influencing limbic, cortical, and cerebellar regions involved in pain processing, autonomic regulation, and emotional responses. These interactions highlight integrative mechanisms linking cervical dysfunction to cognitive and affective modulation.

Pain-related mechanisms have also been discussed as modulators of cervical–cerebral

interactions, particularly through processes involving central sensitization and altered neural processing within supraspinal regulatory networks. Persistent cervical discomfort may influence autonomic balance, muscle activation patterns, and afferent input arising from cervical tissues, indirectly affecting cerebral hemodynamic regulation through adaptive neurophysiological responses. In this context, nociceptive signaling may interact with autonomic

pathways that contribute to the modulation of vascular tone and cerebrovascular responsiveness under functional or stress-related conditions. Several investigations suggest that pain-associated cervical dysfunction is linked to variability in cerebral blood flow responses rather than fixed vascular alterations, indicating context-dependent modulation rather than structural impairment. These observations support an

integrative model in which nociceptive and neurovascular mechanisms interact within central regulatory systems, contributing to dynamic adjustments in cerebral perfusion through coordinated neural and vascular processes (Figure 10) (Bogduk, 1997; Goadsby, 2002; Sterling *et al.*, 2013; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Wang *et al.*, 2024; Zhong *et al.*, 2025).

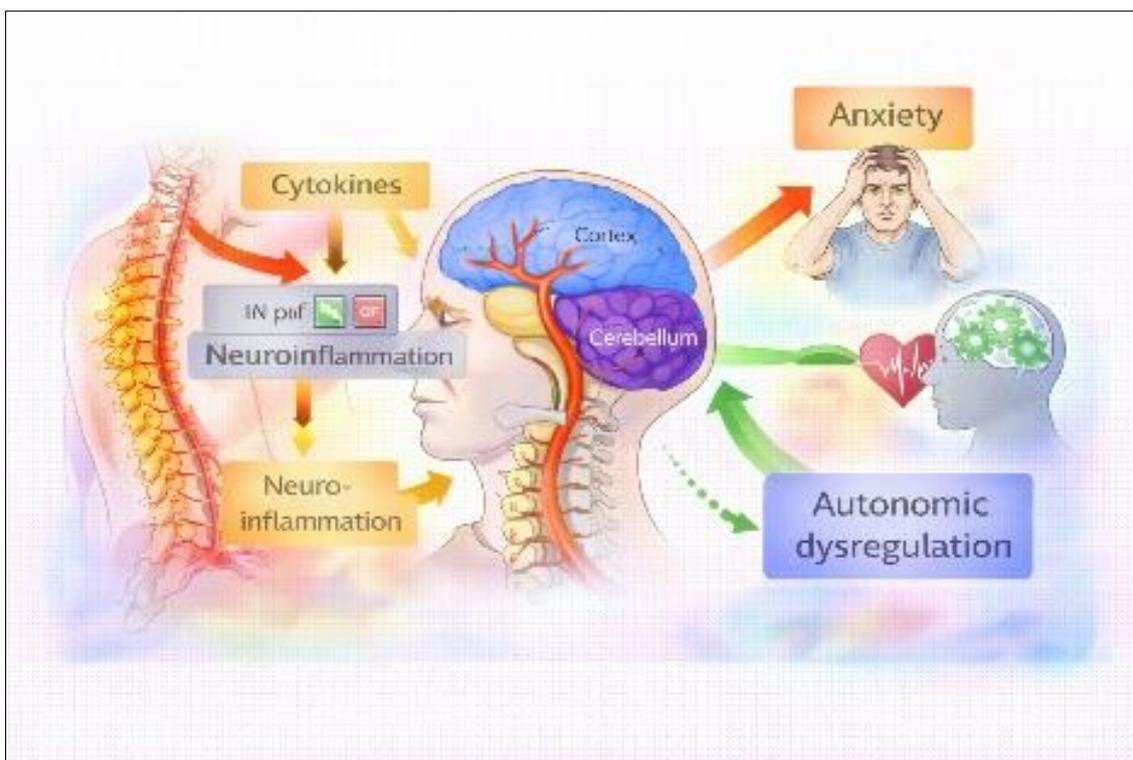


Figure 10: Cervical inflammation, neuroinflammatory pathways, and autonomic dysregulation

The figure illustrates how inflammatory processes originating in the cervical region may propagate through neuroinflammatory and autonomic pathways, influencing cortical and cerebellar function. These mechanisms are proposed to contribute to anxiety-related symptoms and variability in cerebral functional and hemodynamic regulation.

Despite the integrative insights provided by the present analysis, several limitations must be acknowledged. The heterogeneity of study designs, assessment protocols, and outcome measures restricts direct comparability and limits the strength of causal inference regarding the relationship between cervical function and cerebral hemodynamics. Additionally, variability in cervical and hemodynamic measurement techniques, including differences in imaging modalities, data acquisition protocols, and analytical thresholds, may contribute to inconsistent findings across studies. Such methodological diversity highlights the need for greater standardization in the evaluation of both cervical

functional parameters and cerebrovascular responses. Future research should prioritize the adoption of standardized methodologies, longitudinal designs, and multimodal assessment strategies capable of simultaneously capturing biomechanical, autonomic, and sensorimotor variables. These approaches may help clarify the underlying mechanisms of cervical–cerebral interactions and enhance the translational relevance of emerging evidence for both clinical assessment and functional interpretation (Bogduk, 1997; Caplan, 2000; Rubinstein *et al.*, 2012; De Vestel *et al.*, 2022; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022).

Future research in this field should move beyond descriptive associations by integrating standardized cervical assessment protocols with high-resolution cerebrovascular measurements capable of capturing dynamic perfusion responses. Longitudinal and task-based experimental designs may help clarify temporal dynamics and context-dependent modulation of cerebral hemodynamics in relation to cervical functional

status. The incorporation of autonomic biomarkers, advanced neuroimaging techniques, and biomechanical modeling approaches could further elucidate the underlying regulatory mechanisms linking cervical biomechanics to neurovascular responsiveness. Additionally, stratifying study populations according to clinical presentation, functional demand, and

sensorimotor characteristics may enhance translational applicability and clinical relevance by allowing more precise interpretation of cervico-cerebral interactions across different physiological and pathological contexts (Figure 11) (Bogduk, 1997; Caplan, 2000; Hoskins *et al.*, 2012; Fernández-de-las-Peñas, 2022; Vestel *et al.*, 2022; Ordak *et al.*, 2023; Zhong *et al.*, 2025).

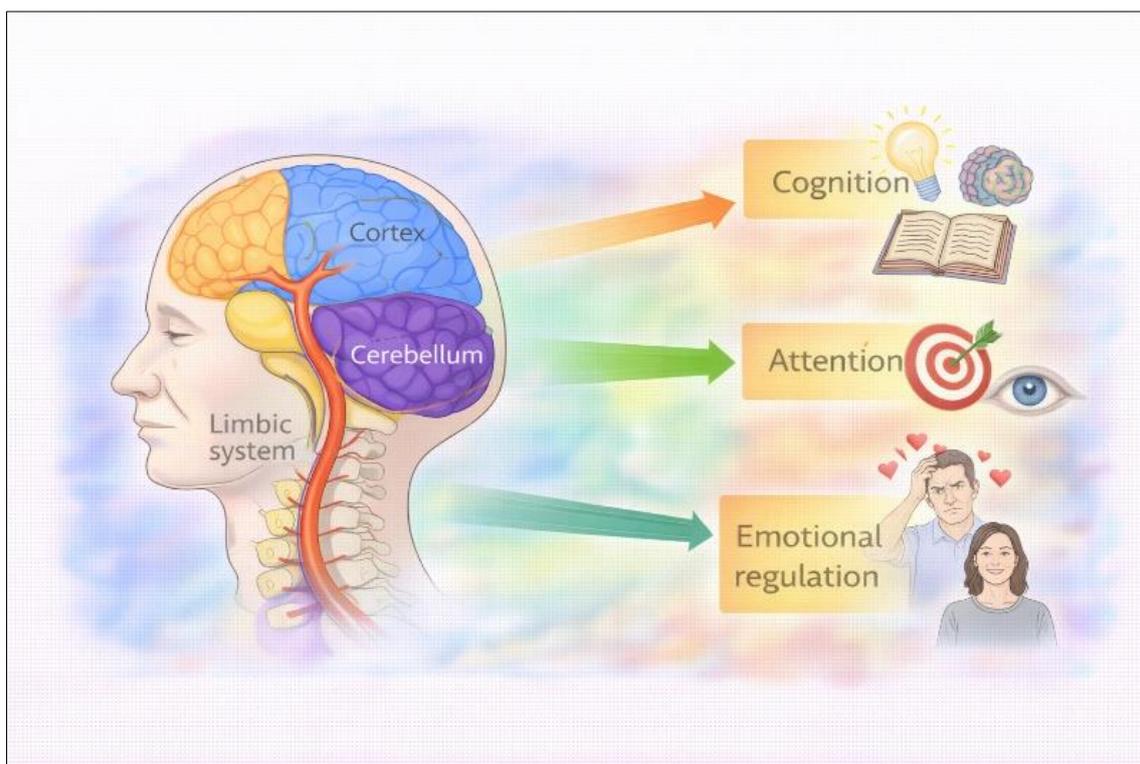


Figure 11: Cognitive and emotional outcomes associated with cervical–cerebral interactions

The figure illustrates cortical and limbic structures involved in cognitive processing, attention, memory, and emotional regulation as downstream functional outcomes. These domains represent higher-order effects proposed to emerge from integrative cervical–cerebral modulation.

5.0. CONCLUSION

This study offers an integrative synthesis of current evidence linking cervical spine function to cerebral hemodynamics by bringing together findings derived from heterogeneous methodological approaches. The results indicate that cervical mobility, posture, and sensorimotor function are recurrently associated with variations in cerebral blood flow regulation. These interactions appear to occur through combined biomechanical, autonomic, and neurovascular mechanisms rather than direct causal pathways, supporting a systems-based interpretation of cervical–cerebral regulation.

By organizing and critically examining the available literature, this work contributes to a clearer conceptual framework for understanding cervical–cerebral interactions. The findings emphasize the relevance of contextual and functional factors in modulating cerebral hemodynamics and caution against reductionist interpretations of cervico-vascular relationships. Overall, this synthesis reinforces the importance of integrative perspectives for future research and clinical investigation of cervical spine function within the broader context of neurovascular regulation.

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