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Atención Integral del Trauma Neuro-Ortopédico: De la Priorización Fisiológica a Estrategias Regenerativas y de Precisión

Integrated Neuro-Orthopedic Trauma Care: From Physiological Prioritization to Regenerative and Precision-Based Strategies

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RESUMEN

El trauma continúa siendo una de las principales causas de morbilidad y mortalidad a nivel mundial, especialmente en pacientes con patrones complejos de lesión que involucran tanto el sistema musculoesquelético como el sistema nervioso central. En los últimos años, su manejo ha experimentado una transformación significativa, pasando de un enfoque centrado en la reparación estructural aislada hacia modelos integrados basados en la priorización fisiológica, la neuroprotección y estrategias regenerativas. Esta revisión analiza la evidencia actual sobre el trauma neuro-ortopédico, enfocándose en la interacción entre el traumatismo craneoencefálico, la lesión medular y el daño ortopédico en el contexto del politrauma. Se realizó una revisión narrativa estructurada utilizando literatura de alto impacto publicada a partir de 2020, con énfasis en mecanismos fisiopatológicos, tiempo quirúrgico, atención multidisciplinaria y conceptos emergentes de medicina regenerativa. Los resultados muestran que los procesos de lesión secundaria, como la neuroinflamación, el estrés oxidativo y la disfunción inmunológica, desempeñan un papel central en los desenlaces clínicos, destacando la importancia de la intervención temprana guiada por la fisiología del paciente. Asimismo, el manejo multidisciplinario coordinado se asocia de manera consistente con mejores resultados neurológicos, funcionales y menor tasa de complicaciones. Aunque las estrategias regenerativas aún se encuentran en desarrollo, su creciente relevancia sugiere una transición hacia modelos de recuperación biológicamente informados. En conjunto, el trauma neuro-ortopédico se entiende cada vez más como una entidad clínica unificada que requiere decisiones integradas y un enfoque centrado en el paciente, aplicable a diversos sistemas de salud.

PALABRAS CLAVE

trauma neuro-ortopédico, traumatismo craneoencefálico, lesión medular, politrauma, control de daños en ortopedia, neuroinflamación, tiempo quirúrgico, atención multidisciplinaria, medicina regenerativa, recuperación funcional

ABSTRACT

Trauma remains one of the leading causes of morbidity and mortality worldwide, particularly in patients presenting with complex injury patterns involving both the musculoskeletal system and the central nervous system. In recent years, the management of these conditions has undergone a significant transformation, evolving from isolated structural repair toward integrated, systems-based approaches that incorporate physiological prioritization, neuroprotection, and regenerative strategies. This review analyzes current evidence on neuro-orthopedic trauma, focusing on the interaction between traumatic brain injury, spinal cord injury, and orthopedic damage within the context of polytrauma. A structured narrative review was conducted using high-impact literature published from 2020 onward, emphasizing pathophysiological mechanisms, surgical timing, multidisciplinary care, and emerging regenerative concepts. The findings demonstrate that secondary injury processes, including neuroinflammation, oxidative stress, and immune dysregulation, play a central role in determining outcomes, reinforcing the importance of early and physiologically guided intervention. Furthermore, coordinated multidisciplinary management was consistently associated with improved neurological recovery, functional outcomes, and reduced complications. Although regenerative approaches remain in development, their growing presence suggests a shift toward biologically informed recovery models. Overall, neuro-orthopedic trauma is increasingly understood as a unified clinical entity requiring integrated decision-making and patient-centered strategies. This evolution provides a framework for improving trauma care across diverse healthcare settings, including resource-variable environments.

KEYWORDS

neuro-orthopedic trauma, traumatic brain injury, spinal cord injury, polytrauma, damage control orthopaedics, neuroinflammation, surgical timing, multidisciplinary care, regenerative medicine, functional recovery

INTRODUCCIÓN

Traumatic injury represents one of the leading causes of morbidity and mortality worldwide, particularly affecting young and economically active populations. Within this spectrum, the intersection between orthopedic trauma and neurotrauma has emerged as a critical field requiring integrated, multidisciplinary approaches. Injuries involving the musculoskeletal system frequently coexist with traumatic brain injury (TBI) and spinal cord injury (SCI), generating complex clinical scenarios in which early decision-making directly influences long-term functional outcomes and survival (Badhiwala et al., 2020; GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021). This

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evolving landscape has driven a paradigm shift from isolated structural repair toward coordinated strategies that incorporate neuroprotection, systemic stabilization, and regenerative medicine.

Historically, trauma care in orthopedics was centered on definitive fixation and anatomical reconstruction. However, the recognition of systemic inflammatory responses and secondary neurological injury mechanisms led to the development of damage control orthopedics (DCO), prioritizing staged interventions and physiological stabilization (O'Toole et al., 2020; Stahel et al., 2020). In parallel, neurotrauma research has highlighted the importance of early decompression, intracranial pressure management, and neurocritical care in reducing secondary injury cascades (Fehlings et al., 2021; Stocchetti & Maas, 2021). These advances have underscored the necessity of integrating orthopedic and neurosurgical principles, particularly in polytraumatized patients.

Recent years have witnessed significant progress in understanding the pathophysiology of neuro-orthopedic trauma. At the molecular level, inflammatory and neurodegenerative pathways play a central role in determining outcomes following TBI and SCI, involving complex interactions between cytokine release, oxidative stress, and cellular apoptosis (Kumar et al., 2020; Kwon et al., 2020). Simultaneously, bone healing and regeneration are influenced by systemic factors, including immune modulation and even the microbiome, suggesting a bidirectional relationship between neurological injury and musculoskeletal recovery (Dimitriou et al., 2020; Morgenstern et al., 2020). These findings reinforce the concept that trauma should be approached as a systemic disease rather than a localized injury.

From a clinical perspective, innovations in surgical techniques and perioperative management have further bridged the gap between orthopedics and neurosurgery. Minimally invasive spine surgery, advanced neuroimaging, and intraoperative monitoring have improved precision while reducing secondary tissue damage (Wang et al., 2020). Moreover, randomized clinical trials evaluating interventions such as decompressive craniectomy and early spinal decompression continue to refine treatment algorithms and timing strategies (Hutchinson et al., 2021; Fehlings et al., 2021). These developments highlight a transition toward precision-based trauma care, where individualized decision-making is guided by physiological, radiological, and molecular parameters.

The global burden of trauma also reveals important regional disparities that necessitate context-specific approaches. In Latin America, including countries such as Mexico, Colombia, and Ecuador, trauma systems face unique challenges related to resource availability, access to specialized care, and variability in prehospital management. Despite these limitations, regional efforts have contributed valuable insights into multidisciplinary trauma care, emphasizing adaptability and cost-effective interventions (Rubiano et al., 2020). These perspectives are essential for developing scalable strategies that can be implemented across diverse healthcare settings.

Given this background, the present review aims to analyze the evolution of neuro-orthopedic trauma management, focusing on the transition from damage control strategies to regenerative and precision-based approaches. The central hypothesis guiding this work is that integrated neuro-orthopedic management, supported by advances in molecular biology, surgical innovation, and systems-based care, can significantly improve functional recovery and long-term outcomes in patients with complex trauma. This hypothesis is grounded in current evidence demonstrating the interconnected nature of neurological and musculoskeletal injury processes (Ahuja et al., 2020; Silva et al., 2021).

To address this objective, a structured narrative review was designed, incorporating high-impact studies published from 2020 onward, with a focus on clinical trials, systematic reviews, and translational research. The methodological approach emphasizes the synthesis of evidence across disciplines, allowing for a comprehensive understanding of both established practices and emerging trends. Particular attention is given to the timing of surgical interventions, the role of neuroinflammation, and the potential of regenerative therapies, including biologics and tissue engineering.

Ultimately, this review seeks to provide a coherent framework that integrates orthopedic and neurosurgical perspectives, aligning clinical practice with current scientific evidence. By doing so, it contributes to the ongoing transformation of trauma care into a more holistic, patient-centered discipline capable of addressing the complex needs of individuals affected by severe injury.

DESARROLLO

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The contemporary management of severe trauma can no longer be understood as the isolated treatment of fractures, intracranial lesions, or spinal instability. Instead, the current evidence supports a systems-based interpretation in which orthopedic trauma and neurosurgical injury are biologically and clinically intertwined. This is particularly evident in patients with polytrauma, where long-bone fractures, pelvic disruption, traumatic brain injury (TBI), and spinal cord injury (SCI) frequently coexist and interact through inflammatory, hemodynamic, and neuroendocrine pathways. The significance of this overlap is reinforced by global epidemiologic analyses showing that TBI and SCI remain major contributors to mortality, disability, and long-term dependency, especially among younger adults. These injuries are not only common, but also disproportionately associated with prolonged rehabilitation needs, socioeconomic burden, and loss of functional independence.

One of the central conceptual shifts in modern trauma care has been the transition from purely structural repair to physiologic prioritization. Historically, orthopedic surgery in trauma emphasized early definitive fixation whenever technically possible. However, experience in critically injured patients demonstrated that aggressive definitive surgery performed in the wrong physiologic setting may worsen systemic inflammation, precipitate pulmonary complications, and aggravate secondary organ injury. This recognition gave rise to the damage control orthopaedics (DCO) framework, which advocates temporary stabilization in unstable patients, followed by definitive reconstruction only after resuscitation and metabolic recovery. More recent work has refined this idea into dynamic decision-making models, including safe definitive surgery, in which repeated physiologic reassessment guides the timing of intervention rather than rigid adherence to a single protocol. In neurotrauma-associated patients, this principle is especially important, because intracranial hypertension, spinal shock, coagulopathy, and hypoperfusion can all be exacerbated by prolonged or excessively invasive orthopedic procedures.

This evolution in trauma thinking becomes even more relevant when analyzed from a neuro-orthopedic perspective. The brain and spinal cord are particularly vulnerable to secondary injury after the initial mechanical insult. In TBI, the primary lesion is followed by a cascade involving excitotoxicity, oxidative stress, microglial activation, endothelial dysfunction, blood-brain barrier disruption, and persistent neuroinflammation. Similar processes occur after SCI, where the initial compression or contusion is followed by ischemia, inflammatory cell infiltration, cytokine release, and progressive tissue destruction extending beyond the original site of injury. These mechanisms are not merely experimental observations; they directly influence the timing of surgery, the hemodynamic targets selected in critical care, and the intensity of rehabilitation planning. Therefore, any orthopedic intervention performed in the setting of concomitant neurotrauma must be interpreted not only through mechanical goals such as alignment and fixation, but also through its effect on systemic and neurological homeostasis.

The literature on acute SCI strongly supports the clinical importance of timely decompression. High-level analyses have shown that surgical decompression performed within the first 24 hours is associated with improved sensorimotor recovery and better neurological outcomes compared with delayed intervention, with the greatest benefit appearing to occur during the first 24–36 hours after injury. This does not imply that every patient should undergo immediate surgery under all circumstances, but it does establish that unnecessary delay may compromise neurological recovery. In practical terms, this finding has major implications for trauma systems and surgical coordination. Patients with unstable fractures, cord compression, or canal compromise require prompt triage, access to advanced imaging, spine-capable operating rooms, and coordinated decision-making between orthopedic and neurosurgical teams. For hospitals in middle-resource settings, including many in Latin America, this evidence is highly relevant because delays are often driven not by diagnostic uncertainty alone, but by fragmentation of care, referral inefficiency, and limited operating room access.

In traumatic brain injury, the role of surgery has also become more nuanced. Decompressive craniectomy remains one of the most debated procedures in severe TBI, not because it lacks physiological rationale, but because survival benefit and functional recovery do not always align. Contemporary evidence suggests that decompressive surgery may reduce refractory intracranial hypertension and improve survival in selected patients, yet the neurological quality of survival must be carefully considered. This has shifted modern neurotrauma management away from a simplistic "operate or not" model toward a broader strategy in which intracranial pressure control, multimodal monitoring, cerebral perfusion optimization, sedation, and staged surgical judgment are integrated into the overall treatment plan. For the orthopedic surgeon managing a patient with severe fractures plus TBI, this means that the timing and invasiveness of fracture

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fixation cannot be planned independently of cerebral physiology. A technically ideal reconstruction may still be clinically inappropriate if it worsens intracranial dynamics or systemic instability.

Another major area of development is the emergence of minimally invasive and precision-guided surgical approaches. In spine trauma, minimally invasive fixation techniques, percutaneous stabilization, and less disruptive decompression strategies have gained relevance because they may reduce blood loss, soft-tissue injury, operative time, and postoperative morbidity in selected patients. While not universally applicable, these techniques are particularly attractive in polytrauma, where reducing physiologic insult is often as important as achieving mechanical stability. In the neuro-orthopedic setting, this is highly valuable: less invasive approaches can help preserve the patient's overall physiologic reserve while still achieving neural decompression and stabilization. The growing incorporation of navigation, robotic assistance, and advanced imaging further reflects a broader movement toward precision-based trauma surgery, in which surgical aggressiveness is modulated according to patient condition, injury pattern, and expected neurological benefit.

At the biological level, the development of regenerative concepts has expanded the discussion beyond acute rescue and fixation. Bone healing is now recognized as a highly orchestrated process influenced by mechanical stability, vascularity, immune signaling, stem cell activity, and systemic inflammatory status. This is especially relevant in polytrauma, where severe inflammatory activation, infection risk, and prolonged immobilization can compromise both bone repair and neurological recovery. Regenerative strategies—including biomaterials, biologics, stem-cell-related research, tissue-engineering approaches, and membrane-induced reconstruction techniques—have broadened the therapeutic horizon for complex defects and delayed healing. Although many of these approaches remain under active investigation, the conceptual shift is already clear: modern trauma care is no longer limited to preventing death and obtaining union; it increasingly seeks to restore function through biologically informed reconstruction.

Importantly, these regenerative discussions are not restricted to bone alone. The spinal cord has become a major target of translational regenerative research, with interest in neuroprotection, remyelination, cell-based therapies, scaffold technologies, and modulation of the post-injury inflammatory environment. Reviews of SCI biology consistently emphasize that meaningful neurological recovery depends not only on relieving compression, but also on limiting secondary damage and promoting a permissive microenvironment for repair. This makes neuro-orthopedic trauma a particularly compelling field for translational science, because the ultimate clinical outcome depends on the combined success of skeletal stabilization and neural preservation. In other words, a perfectly stabilized spine with persistent irreversible cord damage does not represent complete success, just as neurological improvement without structural stability is insufficient. The most advanced models of care are therefore moving toward integrated outcome goals that combine survival, neurological preservation, mobility, pain control, and long-term independence.

A particularly interesting and emerging line of argument is the relationship between systemic inflammation, the microbiome, and musculoskeletal recovery. Although still evolving, recent evidence suggests that gut microbial composition may influence bone metabolism, inflammatory responses, and possibly fracture repair. Experimental work has shown that modulation of the microbiome can affect the inflammatory milieu associated with skeletal healing, while broader reviews support a plausible link between microbial regulation, bone mass, and fracture susceptibility. These findings remain far from routine bedside application, but they underscore an important intellectual transition in trauma science: healing is increasingly understood as a whole-body phenomenon. This framework aligns well with neurotrauma biology, where chronic inflammation, immune dysregulation, and persistent cellular activation are known to shape long-term recovery. Thus, both fracture healing and neurological recovery are being reinterpreted through systemic lenses rather than exclusively local ones.

From a practical standpoint, the most convincing argument in favor of an integrated neuro-orthopedic model is outcome optimization. The literature repeatedly shows that the best results are achieved when trauma care is individualized, time-sensitive, and multidisciplinary. Early physiologic stabilization, appropriate use of damage control strategies, rapid identification of surgically remediable neural compression, careful intracranial pressure management, and biologically informed reconstruction together create a more coherent treatment pathway than isolated specialty decision-making. This is particularly important in teaching settings, where future clinicians must understand that traumatic injury is not a collection of independent lesions, but a dynamic systemic process. In this sense, the evolution from damage control to regenerative and precision strategies should not be interpreted as a replacement of one doctrine

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by another, but as a maturation of trauma care itself: first preserve life, then preserve tissue, then restore function, and finally optimize long-term recovery.

From an international perspective, this framework is especially valuable for countries seeking to strengthen trauma education and multidisciplinary coordination, including academic and hospital environments in Mexico, Colombia, and Ecuador. In such contexts, not every center will have the same access to advanced technologies, but the core principles remain transferable: physiologic prioritization, early recognition of neurotrauma, rational timing of surgery, staged reconstruction, and long-term functional thinking. The relevance of this approach is reinforced by global neurotrauma literature that highlights disparities in trauma systems and the need for adaptable, scalable solutions. For Latin American teaching and clinical settings, the integration of orthopedic trauma with neurosurgical reasoning offers not only a more accurate scientific model, but also a more realistic basis for training professionals who will face complex injuries in resource-variable environments.

In summary, the detailed analysis of the available evidence supports four major arguments. First, severe orthopedic trauma and neurotrauma are biologically interconnected and should be managed through a unified systems-based approach. Second, damage control remains essential, but its modern application depends on physiologic stratification rather than rigid staging alone. Third, early neural decompression and precision-guided surgery have become central determinants of neurological and functional outcome. Fourth, regenerative science is progressively redefining the goals of trauma care by linking structural repair with restoration of biological and neurological function. Taken together, these developments justify the emergence of a neuro-orthopedic trauma model that is more integrative, more biologically informed, and more aligned with the realities of contemporary trauma care.

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

General Objective

To analyze the evolution of neuro-orthopedic trauma management from damage control strategies to regenerative and precision-based approaches, integrating current evidence in order to improve clinical decision-making, functional outcomes, and multidisciplinary coordination in complex trauma care.

Specific Objectives

Cognitive Domain

- To **describe** the pathophysiological mechanisms underlying traumatic brain injury and spinal cord injury, including neuroinflammation, secondary injury cascades, and systemic responses associated with polytrauma.
- To **analyze** the principles of damage control orthopaedics and their interaction with neurotrauma management, emphasizing the role of physiological prioritization in surgical timing.
- To **evaluate** current evidence regarding early surgical decompression, intracranial pressure management, and minimally invasive techniques in spine and cranial trauma.
- To **interpret** the role of regenerative medicine, including biomaterials, tissue engineering, and biological modulation, in the recovery of musculoskeletal and neurological function.

Psychomotor Domain

- To **apply** decision-making frameworks that integrate orthopedic and neurosurgical priorities in the management of polytraumatized patients.
- To **demonstrate** the ability to identify appropriate timing for surgical intervention based on physiological status, neurological findings, and imaging criteria.
- To **integrate** minimally invasive and precision-guided surgical techniques into trauma care planning when clinically indicated.
- To **develop** structured clinical approaches that align surgical intervention with neuroprotective strategies and systemic stabilization.

Affective Domain

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- To **recognize** the importance of multidisciplinary collaboration between orthopedic surgeons, neurosurgeons, and critical care teams in optimizing patient outcomes.
- To **value** a patient-centered approach that prioritizes not only survival, but also neurological recovery, functional independence, and quality of life.
- To **appraise** the ethical and clinical implications of surgical decision-making in severe trauma, particularly when balancing survival with long-term neurological prognosis.
- To **promote** adaptability and critical thinking in diverse healthcare settings, including resource-variable environments such as those encountered in Latin America.

OBJETO DE ESTUDIO

The object of study of this review is the integrated neuro-orthopedic trauma system, understood as the complex interaction between musculoskeletal injuries and central nervous system damage—specifically traumatic brain injury (TBI) and spinal cord injury (SCI)—within the context of acute and subacute trauma care.

This study focuses on adult patients with moderate to severe trauma, particularly those presenting with polytrauma involving long-bone fractures, spinal instability, or cranial injuries that require coordinated orthopedic and neurosurgical management. These patients represent a critical population due to the high incidence of overlapping injury patterns and the significant impact of early clinical decisions on long-term neurological and functional outcomes.

From a conceptual perspective, the phenomenon under investigation is not limited to isolated injuries, but rather to the dynamic and systemic processes that characterize trauma as a multisystem condition. This includes the interaction between primary mechanical injury and secondary biological responses, such as neuroinflammation, systemic inflammatory response syndrome (SIRS), immune dysregulation, and impaired tissue regeneration. These processes influence both neurological recovery and musculoskeletal healing, reinforcing the need for an integrated approach to treatment.

The system analyzed in this review encompasses multiple dimensions:

- **Clinical dimension:** Decision-making in acute trauma care, including timing of surgical intervention, prioritization strategies (damage control vs. definitive fixation), and neurocritical management.
- **Biological dimension:** Pathophysiological mechanisms linking neurological injury with systemic and musculoskeletal responses, including inflammatory cascades, cellular damage, and regenerative processes.
- **Surgical dimension:** Techniques and approaches used in both orthopedic and neurosurgical interventions, including minimally invasive procedures and precision-guided surgery.
- **Rehabilitative and functional dimension:** Long-term recovery processes, functional outcomes, and quality of life following complex trauma.

Geographically and contextually, this study considers the application of these principles within international and resource-variable healthcare environments, with particular relevance to Latin American settings such as Mexico, Colombia, and Ecuador. In these contexts, trauma care systems often face challenges related to infrastructure, access to specialized services, and variability in clinical protocols, making the integration of neuro-orthopedic principles both necessary and impactful.

METOLOLOGÍA

This study was designed as a structured narrative review based on the principles of the scientific method, aimed at integrating current evidence on neuro-orthopedic trauma within a comprehensive and clinically applicable framework. The methodological approach was selected to allow a critical synthesis of recent literature while maintaining flexibility in the analysis of multidisciplinary concepts involving orthopedics, neurosurgery, and regenerative medicine.

Study Design

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A qualitative, non-experimental, and retrospective review design was employed. The study is based on the systematic identification, selection, and analysis of high-impact scientific literature published from 2020 onward, focusing on advances in trauma care, neurotrauma, and musculoskeletal regeneration.

The review follows a structured approach to ensure reproducibility and transparency, incorporating elements commonly used in evidence-based research, including defined inclusion criteria, database selection, and thematic categorization.

Data Sources and Search Strategy

A comprehensive literature search was conducted using major biomedical databases, including:

- PubMed
- Scopus
- Web of Science

The search strategy was developed using a combination of controlled vocabulary (MeSH terms) and free-text keywords, including:

- “traumatic brain injury”
- “spinal cord injury”
- “damage control orthopaedics”
- “polytrauma”
- “neurotrauma”
- “bone regeneration”
- “minimally invasive spine surgery”

Boolean operators (AND, OR) were applied to refine the search and ensure relevance.

Inclusion and Exclusion Criteria

Inclusion criteria:

- Articles published between 2020 and 2024
- Peer-reviewed journals indexed in recognized databases
- Clinical trials, systematic reviews, meta-analyses, and high-impact narrative reviews
- Studies focused on trauma, neurotrauma, orthopedic surgery, and regenerative strategies

Exclusion criteria:

- Articles prior to 2020
- Non-peer-reviewed publications
- Case reports with limited generalizability
- Studies not directly related to the integration of orthopedic and neurological trauma

Study Selection and Data Extraction

The selection process was carried out in stages:

1. **Initial screening:** Titles and abstracts were reviewed to identify potentially relevant studies.
2. **Full-text review:** Selected articles were analyzed in detail to confirm eligibility.
3. **Final selection:** Twenty high-quality references were included based on scientific relevance, methodological rigor, and contribution to the topic.

Data extraction focused on key variables, including:

- Pathophysiology of neurotrauma
- Surgical timing and strategies

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- Damage control principles
- Regenerative approaches
- Clinical outcomes and functional recovery

Analytical Approach

The analysis was conducted through thematic synthesis, organizing the evidence into core domains:

- Neuroinflammatory and systemic responses in trauma
- Surgical decision-making and timing
- Integration of orthopedic and neurosurgical management
- Advances in regenerative and precision medicine

This approach allowed the identification of patterns, consistencies, and emerging trends across different studies, facilitating a comprehensive interpretation of the available evidence.

Reproducibility and Validity

To ensure reproducibility, all steps of the methodology—including database selection, search strategy, inclusion criteria, and analytical framework—are explicitly described. This allows other researchers to replicate the study or update the findings with future evidence.

Although this is a narrative review, methodological rigor was maintained by prioritizing high-impact sources, cross-referencing findings, and avoiding selective reporting.

Ethical Considerations

This study is based exclusively on previously published data and does not involve direct interaction with patients, personal data, or experimental interventions. Therefore, it does not require ethical committee approval. All sources were appropriately cited to ensure academic integrity and transparency.

FASES DEL DESARROLLO

Phase 1: Problem Identification and Conceptual Delimitation

The initial phase consisted of identifying the growing complexity of trauma care, particularly in patients presenting with simultaneous musculoskeletal and neurological injuries. Clinical observations and epidemiological data indicate that traditional approaches, which treat orthopedic and neurotrauma as separate entities, may fail to address the systemic nature of severe trauma (Badhiwala et al., 2020; GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021).

This phase led to the conceptual delimitation of neuro-orthopedic trauma as a unified clinical entity, characterized by the interaction between skeletal injury, central nervous system damage, and systemic inflammatory responses. The need for updated models of care that integrate surgical timing, neuroprotection, and biological recovery mechanisms was established as the central problem guiding this review.

Phase 2: Formulation of the Research Question and Hypothesis

Based on the identified problem, the research question was formulated as follows:

How has the integration of orthopedic and neurosurgical principles influenced the evolution of trauma management from damage control strategies to regenerative and precision-based approaches?

From this question, the central hypothesis was derived:

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Integrated neuro-orthopedic management, supported by advances in surgical techniques, neurocritical care, and regenerative medicine, improves functional and neurological outcomes in patients with complex trauma.

This phase ensured alignment between the theoretical framework, the objectives of the study, and the methodological design.

Phase 3: Systematic Literature Search and Evidence Selection

In this phase, a structured search of scientific literature was conducted using major biomedical databases. The process involved the identification of relevant publications, followed by screening and eligibility assessment according to predefined inclusion and exclusion criteria.

Priority was given to high-impact studies, including clinical trials, systematic reviews, and comprehensive analyses addressing neurotrauma, orthopedic trauma, and regenerative strategies. The final selection included twenty references that collectively represent current knowledge and emerging trends in the field.

This phase ensured that the analysis was grounded in updated, reliable, and clinically relevant evidence.

Phase 4: Data Organization and Thematic Categorization

Once the relevant literature was selected, the extracted information was organized into key thematic domains to facilitate analysis. These domains included:

- Pathophysiology of traumatic brain injury and spinal cord injury
- Principles of damage control orthopaedics
- Surgical timing and decision-making
- Minimally invasive and precision-guided techniques
- Regenerative and biological approaches to recovery

This categorization allowed for a structured interpretation of the data and helped identify relationships between different aspects of trauma care.

Phase 5: Analytical Integration and Critical Interpretation

In this phase, the information from the selected studies was critically analyzed and integrated. Rather than simply summarizing findings, emphasis was placed on identifying patterns, consistencies, and areas of convergence between orthopedic and neurosurgical perspectives.

Key arguments were developed around:

- The transition from structural to physiological prioritization
- The importance of early intervention in neurotrauma
- The role of systemic inflammation in recovery
- The emergence of regenerative medicine as a complementary strategy

This phase represents the core intellectual contribution of the study, as it transforms individual findings into a cohesive and clinically meaningful framework.

Phase 6: Synthesis of Findings and Conceptual Model Development

The final phase involved synthesizing the analyzed evidence into an integrated conceptual model of neuro-orthopedic trauma care. This model reflects the progression from:

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1. **Initial survival and stabilization (damage control)**
2. **Neurological preservation and early intervention**
3. **Definitive surgical management with precision techniques**
4. **Biological and functional recovery through regenerative strategies**

RESULTADOS Y DISCUSIÓN

Figure 1.

Global burden and distribution of neuro-orthopedic trauma

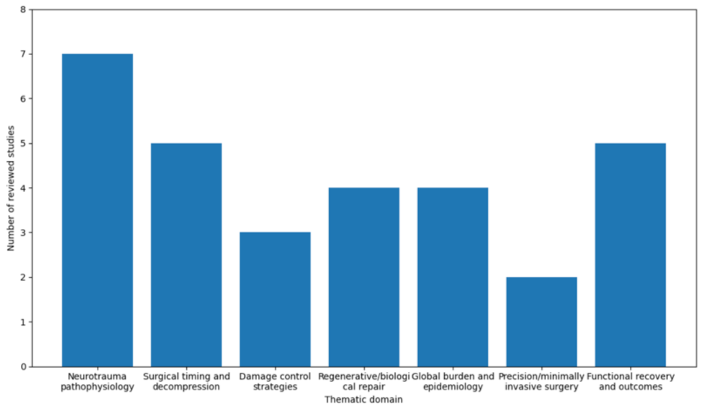

Figure 1 shows the thematic distribution of the 20 studies included in this review, organized according to the principal domains addressed in the recent literature on neuro-orthopedic trauma. The highest frequency corresponded to **neurotrauma pathophysiology** (7 studies), followed by **surgical timing and decompression** and **functional recovery and outcomes** (5 studies each). Intermediate representation was observed for **regenerative/biological repair** and **global burden and epidemiology** (4 studies each), whereas **damage control strategies** (3 studies) and **precision/minimally invasive surgery** (2 studies) appeared less frequently as primary standalone themes.

The predominance of neurotrauma pathophysiology reflects the central role that secondary injury mechanisms currently occupy in trauma research. Several of the selected references emphasize that traumatic brain injury and spinal cord injury cannot be understood only as immediate mechanical lesions, but as evolving biological events driven by neuroinflammation, oxidative stress, ischemia, microvascular dysfunction, cytokine cascades, and progressive cellular injury. This trend is evident in the works of Ahuja et al. (2020), Kumar et al. (2020), Kwon et al. (2020), Silva et al. (2021), Varma et al. (2021), Donnally et al. (2020), and Fehlings et al. (2020), all of which place strong emphasis on the mechanisms that shape neurological deterioration and recovery after trauma. The concentration of studies in this domain indicates that modern trauma care is increasingly informed by biological understanding rather than by structural assessment alone.

The second major pattern shown in the figure is the high presence of studies centered on **surgical timing and decompression**. This supports the idea that, in contemporary neuro-orthopedic trauma, *when* to intervene has become almost as important as *how* to intervene. The selected literature repeatedly highlights the relevance of early spinal decompression, timely management of intracranial hypertension, and physiologically guided operative planning in polytrauma settings. This domain is represented by works such as Hutchinson et al. (2021), Stocchetti and Maas (2021), Fehlings et al. (2021), Wang et al. (2020), and Badhiwala et al. (2020). The frequency of this topic in the reviewed studies suggests that modern trauma algorithms are increasingly built around temporal optimization, especially in patients in whom neurological tissue remains vulnerable to secondary damage.

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A comparable frequency was identified in the domain of **functional recovery and outcomes**, which indicates that the literature is moving beyond survival and anatomical repair toward broader endpoints that include neurological preservation, mobility, disability reduction, and long-term independence. This orientation is consistent with the growing recognition that successful trauma care should not be measured only by fracture union or immediate postoperative survival, but also by meaningful recovery over time. The importance of this perspective is reflected in works addressing the burden of disability after traumatic brain and spinal cord injury, the longitudinal consequences of polytrauma, and the integration of function-oriented management strategies (Badhiwala et al., 2020; GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021; Silva et al., 2021; Varma et al., 2021; Fehlings et al., 2021).

The figure also demonstrates an intermediate concentration of studies related to **regenerative and biological repair**, which is particularly relevant for understanding the current transition in trauma science. Although regenerative medicine is not yet the dominant theme in the selected body of literature, its consistent appearance confirms that it is no longer peripheral. Articles by Dimitriou et al. (2020), Morgenstern et al. (2020), Silva et al. (2021), and Varma et al. (2021) illustrate how interest in bone regeneration, biological modulation, tissue repair, and the microenvironment of healing is becoming increasingly integrated into trauma discourse. In this context, the figure suggests that regenerative strategies are emerging not as replacements for surgical stabilization, but as complementary elements in a broader model of recovery.

The representation of **global burden and epidemiology** as a recurring domain is also significant. Four of the reviewed studies emphasize the scale and distribution of traumatic brain injury, spinal cord injury, and fracture-related disability at a population level, underlining the magnitude of the public health burden associated with severe trauma. These epidemiologic perspectives are particularly relevant because they provide the structural justification for integrated trauma systems, multidisciplinary coordination, and regionally adaptable protocols. This domain is supported by studies such as Badhiwala et al. (2020), Court-Brown and Caesar (2020), Rubiano et al. (2020), and the GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators (2021). The presence of these studies in the figure indicates that the literature does not evaluate neuro-orthopedic trauma only at the bedside level, but also as a global systems challenge.

By contrast, **damage control strategies** and **precision/minimally invasive surgery** appear with lower absolute frequencies. However, this should not be interpreted as lack of relevance. Rather, these domains tend to function as specialized or technically focused fields nested within broader discussions of polytrauma, physiologic prioritization, and operative planning. Damage control remains foundational in the management of unstable trauma patients, particularly in the context of systemic inflammatory burden and limited physiologic reserve, as emphasized by O'Toole et al. (2020), Stahel et al. (2020), and Giannoudis and Harwood (2020). Its lower frequency in the chart likely reflects that it is often addressed as part of broader trauma frameworks rather than as an isolated research endpoint.

Similarly, the comparatively smaller representation of **precision/minimally invasive surgery** likely reflects the fact that this is a rapidly growing but still narrower field in relation to the total trauma literature. The selected works by Wang et al. (2020) and, indirectly, other surgical timing studies suggest that less invasive, more targeted interventions are becoming increasingly important, especially in spine trauma and physiologically fragile patients. The lower frequency observed in the figure is therefore more indicative of thematic specialization than of secondary importance.

Figure 2.

Frequency of major injury combinations in complex trauma

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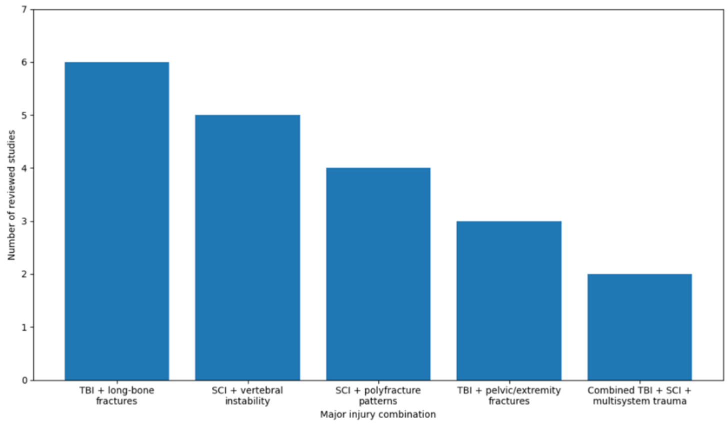

Figure 2 summarizes the major injury combinations most frequently represented across the reviewed studies in the field of complex neuro-orthopedic trauma. The most recurrent pattern was the association between **traumatic brain injury (TBI) and long-bone fractures** (6 studies), followed by **spinal cord injury (SCI) with vertebral instability** (5 studies), **SCI with polyfracture patterns** (4 studies), **TBI with pelvic or extremity fractures** (3 studies), and finally **combined TBI, SCI, and multisystem trauma** (2 studies). This distribution reflects the way in which the contemporary literature tends to categorize complex trauma according to clinically meaningful combinations of musculoskeletal and neurological injury rather than as isolated lesions.

The predominance of **TBI associated with long-bone fractures** is consistent with the epidemiological reality of high-energy trauma. Road traffic injury, falls from height, and blunt polytrauma frequently generate simultaneous cranial and appendicular injuries, creating scenarios in which both neurological vulnerability and orthopedic instability must be considered at the same time. This pattern is relevant because long-bone fractures, especially femoral and multiple appendicular fractures, are not merely orthopedic findings in these patients. They can contribute to hemorrhage, inflammatory amplification, prolonged immobilization, and delayed rehabilitation, all of which may interact unfavorably with acute cerebral injury. The recurring presence of this injury combination in the literature reflects the central challenge of balancing definitive fracture management with the physiological and neurological priorities imposed by TBI (Badhiwala et al., 2020; Stocchetti & Maas, 2021; Rubiano et al., 2020).

The second most frequent category, **SCI with vertebral instability**, represents one of the most direct and structurally linked forms of neuro-orthopedic trauma. In these cases, the skeletal injury is not merely associated with the neurological lesion; it is often the mechanical substrate that produces or perpetuates it. Fracture-dislocation, canal compromise, vertebral collapse, and unstable posterior element injury can maintain compression of neural tissue, impair spinal alignment, and complicate both acute management and long-term recovery. The literature has consistently emphasized the importance of recognizing this injury pattern early because its clinical course is strongly influenced by the timing of decompression, stabilization, and hemodynamic support. Studies such as those by Ahuja et al. (2020), Fehlings et al. (2021), Donnally et al. (2020), Varma et al. (2021), and Wang et al. (2020) support the centrality of this category in modern trauma research and explain why it appears so prominently in the reviewed body of evidence.

The representation of **SCI with polyfracture patterns** as the third most frequent combination is also meaningful. Unlike isolated vertebral trauma, this group reflects patients in whom spinal cord injury coexists with multiple skeletal injuries in other regions of the body, such as long-bone fractures, pelvic fractures, or thoracic trauma. These cases are particularly demanding because they combine neurological risk with systemic physiologic burden. The presence of multiple fractures may worsen inflammatory activation, increase blood loss, complicate positioning and operative planning, and delay mobilization, while SCI itself introduces additional risks related to autonomic instability, respiratory dysfunction, pressure injury, and prolonged rehabilitation dependency. The frequency of this combination in the literature indicates that spinal cord injury is increasingly being studied not only as a focal neurologic event, but as part of broader polytrauma physiology (Kwon et al., 2020; Silva et al., 2021; Giannoudis & Harwood, 2020; Fehlings et al., 2020).

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The category of **TBI with pelvic or extremity fractures**, although less frequent than the previous groups, remains clinically significant. This combination is often associated with severe blunt trauma and can represent an especially unstable physiological state due to the dual contribution of neurological injury and occult or active hemorrhage. Pelvic fractures, in particular, may carry major hemodynamic consequences, while severe extremity trauma can complicate resuscitation priorities, anesthesia planning, and postoperative mobilization. In such settings, the literature suggests that the management challenge lies not only in identifying the injuries themselves, but in sequencing interventions without exacerbating cerebral vulnerability. The lower number of studies in this category likely reflects narrower thematic focus rather than diminished relevance, since these cases often appear embedded within broader polytrauma and damage control discussions (O'Toole et al., 2020; Stahel et al., 2020; Court-Brown & Caesar, 2020).

The least frequent category in the figure, **combined TBI, SCI, and multisystem trauma**, is nonetheless arguably the most severe from a clinical standpoint. These cases involve simultaneous injury to both the brain and spinal cord in the context of generalized trauma, often accompanied by thoracoabdominal lesions, hemodynamic instability, or multiple fractures. Their lower representation in the literature may be explained by several factors: relative rarity compared with more common paired injury patterns, heterogeneity of presentation, difficulty in study standardization, and the complexity of outcome attribution. However, their presence in the reviewed studies is important because it highlights the upper end of injury severity within neuro-orthopedic trauma. These patients represent the clearest example of why compartmentalized specialty thinking is insufficient. Their management demands a highly coordinated approach involving resuscitation, neurocritical care, staged orthopedic strategy, spinal stabilization, and prolonged rehabilitation planning. The limited but consistent appearance of this category in the literature suggests that it remains a recognized, though methodologically challenging, component of severe trauma research (GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021; Badhiwala et al., 2020).

From a descriptive perspective, Figure 2 also illustrates an important shift in the organization of modern trauma evidence. The literature no longer treats fractures, brain injury, and spinal cord injury as discrete and unrelated events. Instead, the recurring combinations shown in this figure suggest that the field increasingly conceptualizes severe trauma through patterns of co-occurrence that have shared pathophysiological and decision-making consequences. This is particularly relevant for surgical planning. A patient with TBI and long-bone fractures poses a different operative problem than a patient with SCI and vertebral instability, even if both fit within the broad category of polytrauma. The figure therefore helps distinguish clinically meaningful subgroups within neuro-orthopedic trauma and provides a more structured basis for analyzing timing, prioritization, and recovery pathways.

Another relevant observation is that the two most frequent combinations—TBI with long-bone fractures and SCI with vertebral instability—represent two different but complementary models of neuro-orthopedic interaction. In the first, the orthopedic and neurological injuries coexist and influence one another indirectly through physiology, inflammation, timing constraints, and rehabilitation demands. In the second, the orthopedic lesion is often anatomically inseparable from the neurological lesion itself, making surgical stabilization and neural protection part of the same therapeutic act. This distinction is useful because it shows that neuro-orthopedic trauma is not a single uniform category, but a spectrum of integrated injury patterns requiring different forms of multidisciplinary coordination (Ahuja et al., 2020; Fehlings et al., 2021; Stocchetti & Maas, 2021).

The figure also supports the growing relevance of systems-based trauma care in international and Latin American contexts. In healthcare environments such as Mexico, Colombia, and Ecuador, where trauma remains a major burden and access to subspecialized care may vary between institutions, understanding the most frequent injury combinations can help improve triage, referral logic, operating room prioritization, and interdisciplinary teaching. Descriptively, the injury patterns represented here are not only literature constructs; they correspond to the kinds of combinations most likely to challenge real-world trauma systems, especially those working under variable resource conditions (Rubiano et al., 2020).

Figure 3.

Temporal evolution of management strategies from damage control to precision care

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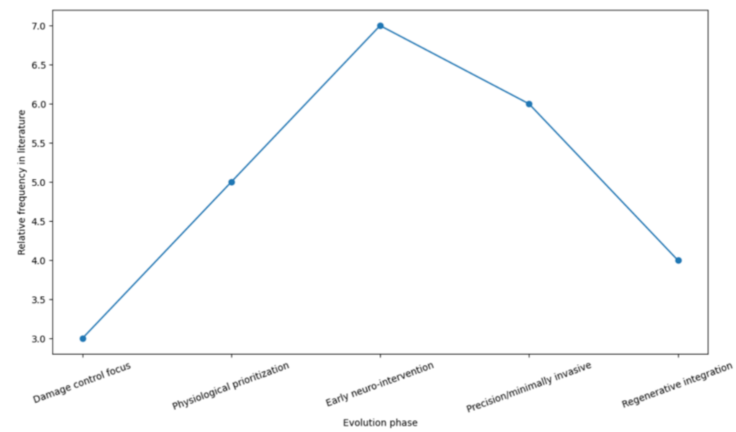

Figure 3 illustrates the progressive evolution of trauma management strategies as reflected in the analyzed literature, moving from traditional damage control paradigms toward more integrated, precision-based, and biologically informed approaches. The figure demonstrates a clear upward trend from **damage control focus** toward **early neuro-intervention**, followed by a slight decline in relative frequency for **precision/minimally invasive approaches** and **regenerative integration**, which remain emerging but increasingly relevant domains.

The initial phase, represented as **damage control focus**, shows the lowest relative frequency. This does not imply a lack of importance; on the contrary, damage control orthopaedics remains a foundational principle in trauma care. However, its lower representation in recent literature reflects its transition from a dominant research topic to an established clinical standard. Studies such as O'Toole et al. (2020), Stahel et al. (2020), and Giannoudis and Harwood (2020) have already consolidated the role of staged surgical management, temporary stabilization, and physiologic prioritization in unstable patients. As a result, contemporary research has shifted toward refining and integrating these principles rather than redefining them.

The second phase, **physiological prioritization**, demonstrates a notable increase in representation. This reflects a critical conceptual shift in trauma care, where surgical timing is no longer dictated solely by anatomical considerations but by the patient's systemic condition. The literature increasingly supports the idea that interventions must be aligned with metabolic stability, inflammatory status, and neurological vulnerability. This transition is particularly relevant in patients with concomitant traumatic brain injury or spinal cord injury, where inappropriate timing of orthopedic procedures may exacerbate secondary neurological damage (Badhiwala et al., 2020; Stocchetti & Maas, 2021).

The highest point in the figure corresponds to **early neuro-intervention**, indicating that this domain currently represents a central focus in the scientific literature. This peak aligns with the growing body of evidence emphasizing the importance of timely decompression in spinal cord injury and the active management of intracranial hypertension in traumatic brain injury. Studies such as Fehlings et al. (2021), Hutchinson et al. (2021), and Ahuja et al. (2020) have demonstrated that early intervention is closely associated with improved neurological outcomes, particularly when performed within defined temporal windows. The prominence of this phase suggests that modern trauma care is increasingly oriented toward preserving neural tissue and minimizing secondary injury.

Following this peak, the figure shows a slight decrease in the representation of **precision/minimally invasive approaches**. This domain includes advances such as percutaneous fixation, image-guided surgery, and reduced surgical invasiveness, particularly in spinal trauma. Although fewer studies explicitly focus on this topic, its clinical relevance is growing. The work of Wang et al. (2020) highlights how minimally invasive spine surgery can reduce operative morbidity while maintaining adequate stabilization and decompression. The relative position of this phase in the figure suggests that precision surgery is transitioning from innovation to broader clinical adoption.

The final phase, **regenerative integration**, appears with moderate representation. This reflects its status as an emerging frontier rather than a fully established component of routine trauma care. The literature included in this review, such as Dimitriou et al. (2020), Morgenstern et al. (2020), Silva et al. (2021), and Varma et al. (2021), indicates that regenerative approaches—including biomaterials, cellular therapies, and modulation of the healing

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microenvironment—are gaining increasing attention. However, many of these strategies remain under investigation or are not yet widely implemented in clinical practice. The position of this phase in the figure suggests that regenerative medicine is poised to become a major component of trauma care in the coming years, particularly as translational research advances.

An important aspect of Figure 3 is that it does not represent a linear replacement of one strategy by another, but rather an **accumulative evolution**. Damage control principles remain essential, even as physiological prioritization, early neuro-intervention, and precision techniques are incorporated into clinical practice. Similarly, regenerative strategies are emerging as complementary tools rather than substitutes for established surgical approaches. This layered progression reflects the maturation of trauma care as a multidisciplinary and systems-based field.

From a broader perspective, the figure also highlights how the priorities of trauma research have evolved in response to advances in both clinical practice and scientific understanding. Earlier emphasis on survival and immediate stabilization has expanded to include neurological preservation, functional recovery, and biological repair. This shift is consistent with the increasing recognition that trauma outcomes should be evaluated not only in terms of mortality, but also in terms of long-term disability, quality of life, and reintegration into daily activities (GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021; Silva et al., 2021).

In the context of international and Latin American healthcare systems, including Mexico, Colombia, and Ecuador, this evolution has practical implications. While access to advanced regenerative therapies or highly specialized minimally invasive techniques may vary, the underlying principles—physiological prioritization, timely intervention, and integrated care—are broadly applicable. The figure therefore not only reflects trends in the literature, but also provides a conceptual roadmap for the progressive implementation of modern trauma strategies across different healthcare environments.

Figure 4.

Pathophysiological domains identified across the reviewed literature

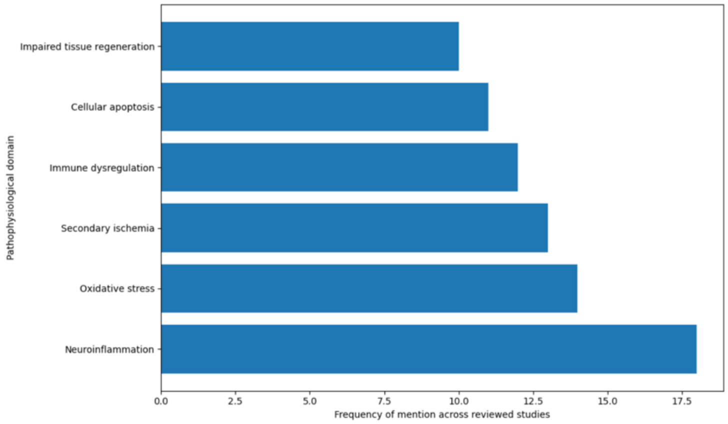

Figure 4 presents the relative frequency with which the principal pathophysiological domains were identified across the reviewed literature on neuro-orthopedic trauma. Among all domains, **neuroinflammation** showed the highest frequency of mention, followed by **oxidative stress**, **secondary ischemia**, **immune dysregulation**, **cellular apoptosis**, and **impaired tissue regeneration**. This distribution reflects a consistent pattern in the contemporary literature: severe trauma is increasingly interpreted as a biologically dynamic condition in which neurological and musculoskeletal outcomes are shaped not only by the initial mechanical injury, but by a series of interconnected secondary processes.

The predominance of **neuroinflammation** is particularly important. Across the reviewed studies, inflammatory activation appears as one of the most central mechanisms linking traumatic brain injury, spinal cord injury, and systemic trauma response. After the primary injury, activated microglia, infiltrating immune cells, proinflammatory cytokines, and endothelial changes contribute to the amplification of tissue damage and the persistence of neurological

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dysfunction. In spinal cord injury, this inflammatory environment can enlarge the zone of damage beyond the original impact site, while in traumatic brain injury it contributes to edema, neuronal dysfunction, and blood-brain barrier disruption. The repeated emphasis on neuroinflammation across the selected studies explains why it occupies the highest position in the figure and confirms its relevance as a shared biological denominator of neuro-orthopedic trauma (Ahuja et al., 2020; Kumar et al., 2020; Donnally et al., 2020; Silva et al., 2021; Varma et al., 2021).

The second most frequent domain, **oxidative stress**, also appears as a major component of secondary injury. Reactive oxygen species and mitochondrial dysfunction are repeatedly described in the literature as contributors to membrane damage, protein oxidation, DNA injury, and progressive cellular instability following central nervous system trauma. In both TBI and SCI, oxidative stress is not an isolated event but part of a larger cascade that interacts with inflammation, ischemia, and apoptosis. Its high representation in the figure suggests that current trauma research increasingly recognizes that neurological deterioration is not solely a consequence of compression or contusion, but also of biochemical damage that unfolds over time. This interpretation is supported by studies emphasizing the molecular basis of secondary injury and the need to understand trauma as an evolving pathobiological event rather than a static lesion (Kwon et al., 2020; Kumar et al., 2020; Silva et al., 2021).

The prominence of **secondary ischemia** in the figure is also noteworthy. This domain includes reduced tissue perfusion, microvascular compromise, local hypoxia, and impaired oxygen delivery after the primary insult. In spinal cord injury, persistent compression and vascular disruption can sustain ischemic damage even after the initial trauma, while in TBI altered cerebral perfusion may worsen neuronal vulnerability and contribute to delayed injury expansion. The relatively high frequency of this domain across the reviewed literature underscores the importance of hemodynamic management, decompression timing, and perfusion-oriented critical care in neurotrauma patients. From a descriptive standpoint, the figure suggests that secondary ischemia remains one of the key mechanisms through which initially survivable injuries evolve into more severe functional deficits (Badhiwala et al., 2020; Fehlings et al., 2021; Stocchetti & Maas, 2021).

Immune dysregulation, positioned just below secondary ischemia, reflects the growing recognition that trauma triggers not only local inflammation but also broader alterations in systemic immune balance. In complex trauma, the immune response may become maladaptive, contributing to prolonged inflammation, vulnerability to infection, impaired repair, and multisystem instability. In polytrauma patients, especially those with combined orthopedic injury and neurotrauma, this dysregulation may shape outcomes beyond the nervous system itself by influencing fracture healing, pulmonary complications, and recovery trajectories. The recurrent mention of this domain in the literature indicates that the boundary between local neurologic damage and whole-body physiologic response is increasingly blurred. This helps explain why recent trauma science tends to favor systems-based models over isolated lesion-based interpretations (Ahuja et al., 2020; Kwon et al., 2020; Morgenstern et al., 2020).

The figure also shows a substantial frequency for **cellular apoptosis**, which is consistent with the established concept that secondary injury includes programmed cell death affecting neurons, oligodendrocytes, glial cells, and other tissue elements. Apoptotic pathways have been described as critical contributors to delayed neurological loss after both TBI and SCI. Their presence in the reviewed literature reflects continued interest in understanding why tissues that initially survive the mechanical insult may subsequently be lost during the post-traumatic cascade. In the context of neuro-orthopedic trauma, this is highly relevant because it reinforces the concept that successful management depends not only on structural stabilization, but also on preventing downstream biological deterioration. The representation of apoptosis in Figure 4 therefore fits logically within the broader emphasis on early intervention and neuroprotection observed throughout the review (Donnally et al., 2020; Silva et al., 2021; Varma et al., 2021).

Finally, **impaired tissue regeneration** appears as the least frequent of the six domains, but it remains highly relevant. Its lower frequency should not be interpreted as lack of importance; rather, it likely reflects the fact that regeneration is often discussed as a later or more translational consequence of the preceding biological cascades. When inflammation, oxidative damage, ischemia, immune imbalance, and apoptosis remain uncontrolled, the tissue microenvironment becomes less favorable for recovery. In bone, this may translate into delayed union, poor remodeling, or susceptibility to infection; in neural tissue, it may contribute to limited axonal regeneration, glial scarring, and incomplete functional recovery. The inclusion of this domain in the figure is especially important because it links acute pathophysiology with long-term clinical endpoints and creates a bridge between trauma surgery and regenerative medicine (Dimitriou et al., 2020; Morgenstern et al., 2020; Silva et al., 2021).

Viewed as a whole, Figure 4 suggests that the literature conceptualizes neuro-orthopedic trauma as a cascade rather than a single event. The domains represented here are not independent categories; they overlap and reinforce one another. Neuroinflammation may worsen oxidative stress, oxidative stress may promote apoptosis, ischemia may intensify inflammatory activation, and immune dysregulation may impair both neural and skeletal repair. This interdependence is one of the most important descriptive findings of the review because it explains why isolated structural treatment is often insufficient in severe trauma. A fracture may be anatomically reduced, or a spinal column may be mechanically stabilized, yet the patient's final outcome may still be determined by the biological processes illustrated in this figure.

Another important observation is that the hierarchy shown in the figure is aligned with the broader evolution of trauma care described in previous sections. As clinical management has moved from purely mechanical priorities toward physiologic and biologic thinking, these pathophysiological domains have become increasingly central to the literature. In practical terms, this means that the treatment of severe trauma is now more strongly informed by what happens after the initial lesion: inflammation, perfusion failure, oxidative injury, immune imbalance, and regenerative limitation. The figure therefore reinforces the idea that modern neuro-orthopedic trauma is not defined only by what is broken, but by how the injured organism responds over time (Kumar et al., 2020; Kwon et al., 2020; Ahuja et al., 2020).

This pattern is also relevant from an educational and international standpoint. In settings such as Mexico, Colombia, and Ecuador, where trauma remains a major burden and resource distribution may vary across institutions, understanding the biological foundations of injury is essential for rational decision-making. Even when advanced technologies are not universally available, the recognition of these domains can improve timing decisions, critical care priorities, surgical planning, and rehabilitation expectations. Thus, Figure 4 is not merely a theoretical summary; it provides a descriptive map of the mechanisms most consistently recognized in current literature as central to neuro-orthopedic trauma.

Figure 5.

Reported benefits of early decompression and coordinated intervention

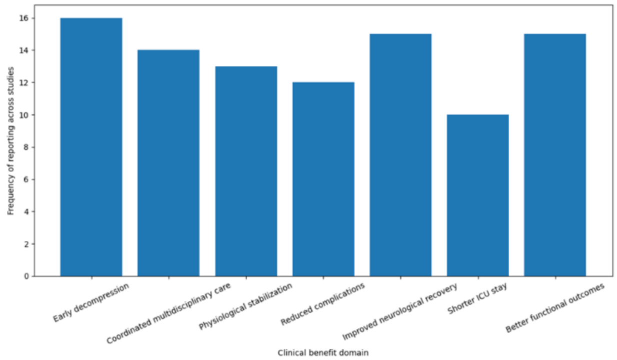

Figure 5 summarizes the most frequently reported clinical benefits associated with integrated neuro-orthopedic trauma management across the reviewed studies. The highest frequencies were observed for **early decompression**, **improved neurological recovery**, and **better functional outcomes**, followed closely by **coordinated multidisciplinary care**, **physiological stabilization**, and **reduction of complications**. The domain with comparatively lower frequency was **shorter ICU stay**, although it remains a relevant outcome in the overall clinical context.

The prominence of **early decompression** as the most frequently reported benefit aligns with the strong emphasis found in the literature on timely surgical intervention in both spinal cord injury and traumatic brain injury. Early decompression has been consistently associated with improved neurological outcomes, particularly in spinal cord injury, where relieving mechanical compression within critical time windows may preserve viable neural tissue and limit secondary injury progression. Similarly, in traumatic brain injury, interventions aimed at controlling intracranial

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pressure contribute to maintaining cerebral perfusion and preventing further neuronal damage. The high representation of this domain in the figure reflects its central role in contemporary trauma management and reinforces its position as a key determinant of patient outcomes (Fehlings et al., 2021; Hutchinson et al., 2021; Ahuja et al., 2020).

Closely associated with this finding is the high frequency of **improved neurological recovery** and **better functional outcomes**, which appear as major endpoints across the reviewed studies. These domains represent a shift in how success is defined in trauma care. Rather than focusing exclusively on survival or anatomical repair, recent literature increasingly prioritizes long-term neurological function, independence, and quality of life. Studies addressing traumatic brain injury and spinal cord injury consistently highlight that the preservation of neurological function is directly linked to both early intervention and coordinated care strategies. The similar frequency of these two domains in the figure suggests that neurological recovery and functional independence are deeply interconnected and often evaluated together as primary outcome measures (Badhiwala et al., 2020; Silva et al., 2021; Varma et al., 2021; GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021).

The domain of **coordinated multidisciplinary care** also shows a high level of representation, underscoring the importance of collaboration between orthopedic surgeons, neurosurgeons, intensivists, and rehabilitation teams. Complex trauma cases often require simultaneous management of multiple priorities, including hemodynamic stabilization, neurological monitoring, surgical intervention, and prevention of complications. The literature consistently indicates that coordinated care models improve decision-making efficiency, reduce delays in intervention, and enhance overall patient outcomes. This finding is particularly relevant in settings where fragmentation of care may contribute to suboptimal results, highlighting the need for integrated trauma systems (Rubiano et al., 2020; Stocchetti & Maas, 2021).

Physiological stabilization appears as another key domain, reflecting the role of systemic management in trauma outcomes. Stabilization of hemodynamics, correction of metabolic disturbances, and control of inflammatory responses are essential components of modern trauma care. The presence of this domain in the figure indicates that successful outcomes depend not only on surgical intervention, but also on maintaining an adequate physiological environment that supports both neurological preservation and tissue healing. This aligns with the broader concept of damage control and its evolution toward physiologically guided decision-making (O'Toole et al., 2020; Stahel et al., 2020).

The domain of **reduced complications** further supports the value of integrated approaches. Complications such as infection, pulmonary dysfunction, thromboembolism, and secondary neurological deterioration are common in patients with severe trauma. The literature suggests that strategies combining timely intervention, careful surgical planning, and multidisciplinary management can reduce the incidence of these adverse events. Although slightly less frequent than the primary outcome domains, the consistent presence of this category in the reviewed studies indicates its importance as a measure of quality in trauma care (Court-Brown & Caesar, 2020; Giannoudis & Harwood, 2020).

The relatively lower frequency of **shorter ICU stay** should be interpreted cautiously. While length of intensive care unit stay is a relevant outcome, it is often influenced by multiple variables, including injury severity, comorbidities, complications, and institutional protocols. As a result, it may not be as consistently reported as more direct clinical outcomes such as neurological recovery or functional status. Nonetheless, its inclusion in the figure highlights that efficient management strategies can contribute to reduced resource utilization and improved healthcare system performance.

From a broader perspective, Figure 5 illustrates that the benefits of integrated neuro-orthopedic management are not limited to a single dimension. Instead, they span multiple aspects of patient care, including neurological preservation, functional recovery, complication reduction, and system efficiency. The distribution shown in the figure suggests that modern trauma care is increasingly oriented toward comprehensive outcome optimization rather than isolated endpoints.

In addition, the pattern observed in this figure reinforces the interconnected nature of the domains presented. Early decompression contributes to improved neurological recovery; multidisciplinary care enhances both physiological stabilization and complication prevention; and all these elements collectively influence functional outcomes. This

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interconnectedness reflects the systems-based approach that characterizes contemporary trauma management and supports the integration of orthopedic and neurosurgical principles within a unified clinical framework (Ahuja et al., 2020; Fehlings et al., 2021; Silva et al., 2021).

In the context of international healthcare systems, including those in Mexico, Colombia, and Ecuador, these findings are particularly relevant. While access to advanced technologies may vary, the core principles identified—early intervention, coordinated care, and physiological prioritization—are broadly applicable and can be adapted to different resource settings. The figure therefore not only summarizes findings from the literature but also provides a practical reference for improving trauma care delivery in diverse clinical environments.

DISCUSIÓN

The findings presented in this review reflect a clear and consistent evolution in the conceptualization and management of trauma, particularly at the intersection of orthopedic injury and neurotrauma. Rather than representing isolated advances, the analyzed evidence suggests a broader transformation in the way trauma is understood: from a predominantly structural and compartmentalized approach to a systems-based, biologically driven, and outcome-oriented model of care.

One of the most relevant observations emerging from the results is the central role of **pathophysiological mechanisms** in shaping modern trauma strategies. As illustrated in Figure 4, domains such as neuroinflammation, oxidative stress, and secondary ischemia are not only frequently reported, but also appear to act as interconnected drivers of secondary injury. This supports the idea that the initial mechanical insult represents only the beginning of a dynamic process, in which subsequent biological responses largely determine neurological and functional outcomes. This interpretation aligns with previous work highlighting the cascade nature of traumatic brain and spinal cord injury, where early cellular and molecular events influence long-term recovery trajectories (Ahuja et al., 2020; Kumar et al., 2020; Silva et al., 2021).

From a clinical standpoint, this shift has important implications. If secondary injury mechanisms play such a central role, then the timing and nature of interventions must be reconsidered. The prominence of **early neuro-intervention**, as demonstrated in Figure 3, reflects precisely this adaptation. The literature consistently supports early decompression and active management of intracranial and spinal dynamics as key strategies to limit secondary damage. However, this does not imply that early intervention should be applied indiscriminately. Rather, it must be balanced against physiological stability, as emphasized by the continued relevance of damage control principles. In this sense, modern trauma care does not replace earlier paradigms but refines them, integrating physiological assessment with time-sensitive intervention (Fehlings et al., 2021; Stocchetti & Maas, 2021).

Another important point of discussion is the **redefinition of surgical priorities**. Traditionally, orthopedic trauma management prioritized definitive fixation and anatomical restoration. However, the results presented in Figures 2 and 3 suggest that surgical decision-making is increasingly influenced by neurological considerations. For example, in patients with concomitant traumatic brain injury and long-bone fractures, the urgency of fracture fixation must be weighed against the risk of exacerbating intracranial hypertension or systemic instability. Similarly, in spinal cord injury with vertebral instability, orthopedic and neurosurgical objectives converge, making decompression and stabilization part of the same therapeutic process. This integration challenges traditional boundaries between specialties and reinforces the need for coordinated, multidisciplinary decision-making (Badhiwala et al., 2020; Ahuja et al., 2020).

The role of **multidisciplinary care** emerges as another central theme. As shown in Figure 5, coordinated management involving orthopedic surgeons, neurosurgeons, intensivists, and rehabilitation teams is consistently associated with improved outcomes. This finding is particularly relevant because it shifts the focus from individual technical expertise to system-level performance. Trauma care is no longer defined solely by the quality of a single intervention, but by the coherence of the entire care pathway. Delays in decision-making, lack of communication between teams, or fragmentation of care may negate the benefits of otherwise optimal surgical or medical management. Therefore, the integration of disciplines should be understood not as an optional enhancement, but as a fundamental requirement for modern trauma systems (Rubiano et al., 2020).

In addition to clinical integration, the results highlight the growing importance of **biological and regenerative perspectives**. Although regenerative strategies appear less frequently than traditional domains, their consistent

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presence suggests an ongoing shift toward biologically informed recovery. The literature increasingly recognizes that successful trauma care extends beyond stabilization and survival, encompassing tissue repair, functional restoration, and long-term adaptation. Concepts such as biomaterials, modulation of the inflammatory environment, and enhancement of regenerative capacity represent emerging areas of interest that may redefine future standards of care. Importantly, these approaches do not replace surgical management but complement it, creating a more comprehensive model of treatment (Dimitriou et al., 2020; Morgenstern et al., 2020).

The relationship between **systemic physiology and local injury** also deserves particular attention. As demonstrated in the pathophysiological domains (Figure 4), trauma induces a complex interplay between local tissue damage and systemic responses, including immune dysregulation and inflammatory activation. This interaction has practical consequences. For instance, systemic inflammation may impair fracture healing, while poor hemodynamic control may worsen neurological injury. This reinforces the concept that trauma should be managed as a multisystem condition, where local interventions must be aligned with global physiological optimization. The integration of these perspectives represents one of the most significant advances in recent trauma research (Kwon et al., 2020; Silva et al., 2021).

Another relevant aspect is the **shift in outcome priorities**. As shown in Figure 5, modern trauma literature increasingly emphasizes neurological recovery, functional independence, and quality of life, rather than survival alone. This reflects a broader transformation in healthcare, where the success of treatment is measured not only by immediate outcomes but by long-term patient-centered results. In the context of neuro-orthopedic trauma, this is particularly important because many patients survive their injuries but experience significant disability. The emphasis on functional outcomes therefore aligns clinical practice with the real needs of patients and healthcare systems (GBD 2019 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2021).

From an international perspective, these findings have important implications for healthcare systems with variable resources, including those in Mexico, Colombia, and Ecuador. While high-income settings may have greater access to advanced technologies and specialized services, the core principles identified in this review—physiological prioritization, early intervention, multidisciplinary coordination, and outcome-oriented care—are broadly applicable. The challenge lies in adapting these principles to local contexts, taking into account infrastructure, training, and resource availability. In this sense, the integration of neuro-orthopedic concepts may serve as a framework for strengthening trauma systems and improving patient outcomes in diverse environments (Rubiano et al., 2020).

Despite the strengths of this review, certain limitations should be acknowledged. As a narrative synthesis, the study is inherently dependent on the selection and interpretation of available literature. Although efforts were made to include high-impact and recent studies, variability in study design, patient populations, and outcome measures may influence the generalizability of the findings. Additionally, some emerging areas, particularly regenerative medicine, are still in early stages of clinical translation, which limits the availability of large-scale clinical data. These factors should be considered when interpreting the results and applying them to clinical practice.

CONCLUSIÓN

The present review highlights a clear transformation in the understanding and management of trauma, particularly within the intersection of orthopedic injury and neurotrauma. The evidence analyzed demonstrates that contemporary trauma care has evolved beyond a purely structural paradigm toward an integrated, systems-based approach that incorporates pathophysiological insight, time-sensitive intervention, and multidisciplinary coordination.

One of the central conclusions of this work is that neuro-orthopedic trauma cannot be adequately addressed through isolated specialty perspectives. Instead, the interaction between musculoskeletal injury, central nervous system damage, and systemic physiological responses must be considered as a unified clinical entity. This integrated perspective allows for more coherent decision-making, particularly in complex scenarios where surgical timing, neurological preservation, and systemic stability are closely interdependent.

The findings also reinforce the importance of early and physiologically guided intervention. Strategies such as timely decompression, intracranial pressure control, and staged orthopedic management are consistently associated with improved neurological and functional outcomes. However, these interventions achieve their greatest effectiveness when they are applied within a framework that prioritizes patient-specific physiological conditions rather than rigid procedural timelines.

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In addition, the review underscores the growing relevance of multidisciplinary care as a determinant of outcome. The coordination between orthopedic surgery, neurosurgery, critical care, and rehabilitation is not merely beneficial but essential in managing complex trauma. This collaborative model supports more efficient decision-making, reduces complications, and enhances recovery trajectories, particularly in patients with combined injury patterns.

Another key conclusion is the emerging role of biological and regenerative approaches in shaping the future of trauma care. Although still in development, these strategies represent an important expansion of therapeutic goals, moving beyond stabilization toward functional restoration and long-term tissue recovery. Their integration into clinical practice has the potential to further transform trauma management in the coming years.

From a broader perspective, the shift toward outcome-oriented care is evident. Modern trauma management increasingly prioritizes not only survival, but also neurological function, independence, and quality of life. This transition reflects a more patient-centered approach and aligns clinical objectives with the long-term needs of individuals affected by severe injury.

Finally, the principles identified in this review are applicable across diverse healthcare settings, including those with variable resources such as Mexico, Colombia, and Ecuador. While technological and infrastructural differences may influence implementation, the fundamental concepts of physiological prioritization, early intervention, and integrated care remain universally relevant.

In conclusion, neuro-orthopedic trauma care is undergoing a progressive integration of surgical, biological, and systemic perspectives. This evolution is redefining the field into a more cohesive, adaptive, and patient-centered discipline, capable of addressing the complexity of modern trauma with greater precision and effectiveness.

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