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Sub-AOMSI Cervical Translation as a Clinically Meaningful Injury Phenotype Post-Motor Vehicle Collision: A Dynamic Radiographic and Clinical Correlation Study

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Abstract

Background: Persistent neurological symptoms, such as dermatomal paresthesia, following motor vehicle collisions (MVCs) often present a diagnostic challenge, particularly when static imaging modalities like Magnetic Resonance Imaging (MRI) fail to reveal direct nerve root compression or significant structural pathology. A diagnostic gap exists for patients with symptoms suggestive of cervical instability but whose radiographic findings fall below the established thresholds for overt injuries like Alteration of Motion Segment Integrity (AOMSI). These sub-threshold, or sub-AOMSI, translational instabilities may represent a distinct and clinically meaningful injury phenotype rooted in subtle ligamentous laxity.

Objective: This study aimed to investigate the correlation between sub-AOMSI translational instability, identified through dynamic videofluoroscopic radiography, and the presentation of persistent neurological symptoms in a cohort of post-MVC patients with initially unremarkable static imaging. The primary hypothesis was that focal, sub-AOMSI kinematic deviations are significantly associated with specific clinical findings, thereby establishing this as a valid injury phenotype.

Methods: A retrospective analysis was conducted on a cohort of patients who presented with persistent cervical spine symptoms following an MVC. Inclusion criteria required patients to have undergone both static MRI and dynamic videofluoroscopic evaluation of the cervical spine. Dynamic radiographic data were analyzed to quantify intervertebral translation and rotation at each cervical segment. These kinematic findings were then correlated with clinical data, including patient-reported outcome measures, physical examination findings for segmental tenderness, and the presence and distribution of dermatomal paresthesia.

Results: The analysis revealed a significant positive correlation between sub-AOMSI translational instability at specific cervical motion segments and the presence of corresponding dermatomal paresthesia and segmental tenderness. A substantial portion of the symptomatic cohort demonstrated focal translations exceeding normative biomechanical ranges but remaining below the classic AOMSI criteria. These dynamic instabilities were frequently

observed at levels where static MRI findings were reported as normal or showed only minor degenerative changes. The kinematic patterns identified were inconsistent with normal physiological motion and were strongly linked to the localization of patients' primary neurological complaints.

Conclusion: Sub-AOMSI cervical translation represents a clinically meaningful injury phenotype capable of explaining persistent neurological symptoms in post-MVC patients, even in the absence of significant findings on static MRI. Dynamic videofluoroscopic radiography serves as a critical diagnostic tool for identifying this form of functional instability, which arises from underlying facet capsular ligament laxity. Recognition of this phenotype bridges a critical diagnostic gap, providing an objective biomechanical basis for patient symptoms and guiding more targeted and effective therapeutic interventions.

1. Introduction

Motor vehicle collisions (MVCs) are a primary cause of cervical spine injuries, frequently leading to a constellation of chronic and debilitating symptoms known as whiplash-associated disorders (WAD). Among the most challenging clinical presentations are persistent neurological symptoms, such as radiating pain, numbness, and paresthesia, which significantly impair a patient's quality of life. The conventional diagnostic pathway for these individuals typically involves static imaging, with Magnetic Resonance Imaging (MRI) considered the gold standard for evaluating soft tissue and neural structures. However, a significant subset of symptomatic patients exhibits unremarkable or non-specific findings on static MRI, creating a diagnostic conundrum for clinicians and immense frustration for patients whose subjective complaints lack a clear objective correlate 1. This discrepancy often leads to prolonged disability, delayed or ineffective treatment, and a substantial socioeconomic burden.

The core of this diagnostic challenge lies in the inherent limitations of static imaging. While MRI excels at visualizing anatomical structures in a fixed, non-loaded position, it is fundamentally incapable of assessing the functional integrity of the cervical spine under physiological motion. Injuries sustained during the rapid acceleration-deceleration mechanics of an MVC often involve damage to the ligamentous structures responsible for maintaining segmental stability, particularly the facet capsular ligaments. This damage can result in excessive or aberrant intervertebral motion—a condition of functional instability—that only manifests during movement. Consequently, a patient may harbor clinically significant ligamentous laxity that remains occult on a static MRI scan, which cannot capture the dynamic pathology responsible for their symptoms 2.

Current guidelines for diagnosing cervical spine instability, such as the criteria for Alteration of Motion Segment Integrity (AOMSI), provide specific quantitative thresholds for excessive translation or angulation. These criteria, however, are designed to identify gross instability, often associated with severe trauma like fractures or dislocations, and represent the upper echelon of injury severity. This creates a significant diagnostic gap: a vast gray area exists for patients whose degree of instability falls below these high AOMSI thresholds but exceeds the boundaries of normal physiological motion. These "sub-AOMSI" instabilities, characterized by more subtle but biomechanically significant increases in segmental translation, may be insufficient to cause catastrophic failure but are more than capable of producing persistent mechanical and neurological symptoms.

This sub-threshold instability is hypothesized to be a primary generator of persistent neurological complaints through several mechanisms. Excessive shear forces and aberrant motion at a specific vertebral segment can lead to repetitive irritation of the adjacent nerve roots or dorsal root ganglia, even without direct and constant compression visible on a static image. Furthermore, the facet capsular ligaments are richly innervated with mechanoreceptors and nociceptors. Injury and subsequent laxity in these ligaments can become a direct source of localized and referred pain, as well as altered proprioceptive signaling that contributes to sensorimotor dysfunction. Therefore, identifying and quantifying this sub-AOMSI instability is crucial for understanding the pathophysiology of persistent post-traumatic symptoms.

To bridge this diagnostic gap, functional imaging techniques that assess the spine in motion are required. Dynamic videofluoroscopic radiography, which captures real-time images of the cervical spine through its full range of flexion and extension, provides a means to directly visualize and quantify intervertebral kinematics. By measuring segmental translation and rotation, this modality can detect subtle instances of aberrant motion indicative of underlying ligamentous laxity that would otherwise be missed.

This paper presents a retrospective analysis aimed at establishing sub-AOMSI cervical translation as a clinically meaningful and distinct injury phenotype in post-MVC patients. We sought to correlate specific dynamic radiographic findings of sub-threshold instability with clinical symptoms, particularly dermatomal paresthesia and segmental tenderness. Our central hypothesis is that a significant association exists between focal, sub-AOMSI translational instability and the presence of corresponding neurological symptoms, independent of findings on static MRI. By providing objective, biomechanical evidence for this injury pattern, this study aims to validate the clinical complaints of a frequently overlooked patient population, refine diagnostic paradigms for post-traumatic cervical spine injury, and ultimately inform the development of more targeted and effective treatment strategies. This research underscores the necessity of moving beyond a purely static, anatomical assessment of cervical spine injury toward a more comprehensive, functional understanding of post-traumatic instability.

2. Literature Review and Theoretical Framework

A comprehensive understanding of post-traumatic cervical spine pathology requires a critical evaluation of existing diagnostic paradigms, their inherent limitations, and the biomechanical principles that underpin clinical symptomology. For decades, the assessment of cervical spine stability following motor vehicle collisions has been anchored in radiographic and advanced imaging standards designed to identify gross structural failure. However, a growing body of clinical evidence suggests that a significant cohort of patients with persistent, debilitating symptoms falls into a diagnostic gray area, where conventional imaging fails to reveal an overt pathological correlate. This chapter will review the current standards for cervical injury assessment, elucidate the diagnostic gap that exists for motion-based injuries below established instability thresholds, and explore the biomechanical and neurophysiological rationale for why sub-threshold, or sub-AOMSI, instability represents a clinically meaningful injury phenotype.

2.1 Current Standards for Cervical Spine Injury Assessment

The contemporary approach to evaluating cervical spine injuries following trauma, such as a motor vehicle collision, is multifaceted, integrating clinical examination with a hierarchical application of imaging modalities. The primary objective is to identify fractures, dislocations, and significant ligamentous instability that could compromise spinal cord or nerve root integrity. Clinical decision rules, such as the Canadian C-Spine Rule and the National Emergency X-ray Utilization Study (NEXUS) criteria, serve as initial screening tools to determine the necessity of radiographic imaging, effectively reducing unnecessary radiation exposure in low-risk patients.

When imaging is indicated, the standard protocol often begins with plain radiography (anteroposterior, lateral, and open-mouth odontoid views). These images are effective for detecting significant fractures, malalignment, and gross instability. However, their sensitivity for subtle ligamentous injuries is limited. Consequently, computed tomography (CT) has become the gold standard for bony injury assessment due to its superior spatial resolution and ability to create multiplanar reconstructions, offering an unparalleled view of complex fracture patterns, particularly in the upper cervical spine.

In cases where ligamentous injury or neurological deficit is suspected, Magnetic Resonance Imaging (MRI) is the modality of choice. MRI provides exceptional soft-tissue contrast, enabling the direct visualization of ligaments, the spinal cord, nerve roots, and intervertebral discs. It is invaluable for detecting spinal cord edema or hemorrhage, traumatic disc herniations, and ligamentous disruptions, such as tears of the transverse atlantoaxial ligament or the anterior longitudinal ligament. Several classification systems, including the AO Spine Upper Cervical Injury Classification, have been developed to systematize the description of these injuries and guide treatment. These systems heavily rely on identifying patterns of bony and significant ligamentous disruption, often defined by specific measurement thresholds for instability.

A key concept in stability assessment is Alteration of Motion Segment Integrity (AOMSI), a term used to describe pathological increases in intervertebral motion resulting from ligamentous or osseous injury. Diagnostic criteria for AOMSI are often based on specific measurements derived from flexion-extension radiographs or inferred from static imaging findings. For instance, in the subaxial cervical spine, translational motion exceeding 3.5 mm or angulation greater than 11 degrees beyond that of adjacent segments is widely considered indicative of clinical instability. For the upper cervical spine, specific criteria such as the basion-dental interval (BDI) and atlantodental interval (ADI) are used to assess atlanto-occipital and atlantoaxial stability, respectively. Injuries that meet or exceed these thresholds are generally well-recognized and have established treatment algorithms, often involving surgical stabilization.

These standards and thresholds form the bedrock of modern cervical spine trauma care. They are highly effective at identifying catastrophic or surgically relevant injuries, thereby preventing devastating neurological consequences. However, this framework is predicated on the detection of overt structural failure. Its utility diminishes when faced with injuries that do not produce gross malalignment or easily visualized ligamentous tears on static imaging, yet result in chronic pain and neurological symptoms. This creates a critical diagnostic challenge for a substantial subset of post-traumatic patients whose symptoms persist despite "normal" or "unremarkable" findings on standard imaging studies.

2.2 The Diagnostic Gap: AOMSI Thresholds vs. Sub-Threshold Instability

While the established AOMSI criteria are essential for identifying severe, often surgically-managed instabilities, they create a diagnostic dichotomy: a motion segment is either stable or unstable. This binary classification system inadvertently establishes a significant diagnostic gap for patients whose injuries fall below these high thresholds but still result in pathological kinematics and persistent clinical symptoms. This "sub-threshold" or "sub-AOMSI" instability represents a form of functional impairment where ligamentous laxity is sufficient to cause abnormal motion and symptom generation but insufficient to meet the criteria for gross instability.

The limitations of a rigid, threshold-based system are twofold. First, the normative values upon which these thresholds are based are derived from population averages, which may not account for individual variations in baseline flexibility, anatomy, or age-related changes. An amount of translation that is normal for one individual could be pathological for another, particularly if it represents a significant change from their pre-injury state. Second, the thresholds are designed to detect injuries that pose an immediate risk of catastrophic neurological injury. They are not calibrated to identify more subtle forms of ligamentous damage that lead to chronic pain, cervicogenic headaches, dizziness, or radicular symptoms through mechanisms other than gross compression.

Patients with sub-AOMSI instability often present with a frustrating clinical picture. They report chronic neck pain, headaches, and often, perplexing neurological symptoms like intermittent paresthesia or radicular pain that follows a dermatomal pattern, yet their standard CT and static MRI scans are frequently reported as negative for any acute traumatic abnormality. This discrepancy between subjective complaints and objective imaging findings can lead to delayed diagnosis, inappropriate treatment, and patient-physician friction. Clinicians may be left to attribute the symptoms to non-specific "whiplash," myofascial pain, or even psychological factors, while the underlying biomechanical pathology remains unaddressed.

This diagnostic gap is perpetuated by a reliance on static imaging to assess a dynamic problem. An injury characterized by excessive motion under physiological loads cannot be fully appreciated on an image taken with the patient lying supine and motionless. The very nature of ligamentous laxity is that its consequences—abnormal translation and rotation—are most evident during movement. Therefore, a diagnostic paradigm heavily weighted toward static imaging is inherently ill-equipped to identify this injury phenotype. The existence of this gap highlights the need for a more nuanced approach to cervical spine assessment, one that moves beyond a simple stable/unstable classification and incorporates functional, motion-based analysis to identify clinically significant kinematic abnormalities, even when they do not meet the traditional high-threshold criteria for AOMSI.

2.3 Role and Limitations of Static MRI in Motion-Based Injuries

Magnetic Resonance Imaging (MRI) has revolutionized the diagnosis of spinal pathology, offering unparalleled visualization of soft tissues. Its role in the acute trauma setting is undisputed for identifying spinal cord injury, ligamentous rupture, epidural hematomas, and traumatic disc herniations.

Advanced MRI techniques can further enhance the diagnosis of conditions like degenerative cervical myelopathy by providing detailed views of the spinal cord and surrounding structures 3. In the context of chronic post-traumatic symptoms, MRI is primarily used to rule out compressive lesions, such as a disc bulge or foraminal stenosis, that could explain a patient's neurological complaints.

However, the utility of conventional, static MRI in diagnosing motion-based instability is fundamentally limited. The primary limitation is its static nature. A standard cervical MRI is acquired with the patient in a supine, non-weight-bearing, and neutral position. This imaging environment unloads the cervical spine, potentially masking abnormalities in alignment and motion that only become apparent under physiological weight-bearing or during active movement. A ligament that has been stretched or partially torn—resulting in laxity—may allow for excessive vertebral translation during flexion or extension, but the vertebrae may return to a near-normal alignment when the patient is at rest. Consequently, the static MRI can appear "normal" because it fails to capture this pathological dynamic event. Even when certain injuries are suspected, imaging may be non-diagnostic due to motion degradation or other technical factors 2.

Furthermore, MRI findings such as disc bulges, desiccation, or mild degenerative changes are highly prevalent in the asymptomatic population. The presence of these findings on an MRI in a symptomatic post-traumatic patient does not inherently establish causality. Without a functional or biomechanical correlate, it can be difficult to determine whether a pre-existing degenerative finding has been rendered symptomatic by the trauma or if it is merely an incidental finding unrelated to the patient's primary pain generator. This ambiguity can confound the clinical picture and lead to treatments misdirected at static abnormalities rather than the underlying functional instability.

While positional or kinematic MRI exists, where images are taken in flexion and extension, its adoption is not widespread, and it faces challenges related to patient positioning, claustrophobia, and image quality. Crucially, even these techniques capture only static end-range positions rather than the quality of motion throughout the entire arc. They may not reveal the aberrant "jerks" or sudden translations that can occur mid-range, which are often indicative of segmental instability.

The evaluation of upper cervical spine injuries further highlights these limitations. While MRI is critical for assessing the integrity of key structures like the transverse atlantoaxial ligament, some injuries without obvious vertebral body translation may still require additional imaging techniques for a definitive diagnosis 1. The inherent complexity of the craniocervical junction makes it susceptible to subtle ligamentous injuries that manifest as abnormal kinematics rather than overt structural disruption visible on a static scan. In summary, while MRI is an indispensable tool for identifying direct neural compression and gross ligamentous tears, its reliance on static, non-weight-bearing imaging creates a significant blind spot for diagnosing functional instability resulting from ligamentous laxity. This limitation underscores the need for complementary diagnostic tools that can assess the cervical spine in motion to bridge the gap between patient symptoms and imaging findings.

2.4 Biomechanical Basis for Sub-AOMSI Injury: Facet Capsular Laxity and Neural Mechanisms

The clinical manifestations of sub-AOMSI instability, particularly persistent neck pain and referred neurological symptoms, are directly rooted in the biomechanics of the cervical spine and the neurophysiology of its innervated structures. The primary pathological substrate for this condition is believed to be laxity of the ligamentous structures that guide and restrain intervertebral motion, most notably the facet joint capsules.

The cervical facet (zygapophyseal) joints are true synovial joints that are critical for guiding segmental motion and providing posterior column stability. Each joint is enclosed by a fibrous capsule that is richly innervated with mechanoreceptors and nociceptors (pain receptors). These nerve endings provide proprioceptive information about the position and movement of the head and neck, and they also serve as a source of nociceptive signals when the capsule is injured or pathologically stressed. During a whiplash-type injury, the complex acceleration-deceleration forces can strain these facet capsules beyond their physiological limits, causing microscopic fiber tearing and subsequent laxity without resulting in a complete rupture.

This acquired capsular laxity disrupts the normal, smooth kinematics of the motion segment. Instead of controlled movement, the segment may exhibit excessive translation or aberrant patterns of motion under physiological loads. This increased shear motion places abnormal stress on the articular cartilage of the facet joints, potentially leading to synovitis, inflammation, and chronic localized pain—a condition known as facet syndrome.

More significantly, this abnormal motion provides a plausible mechanism for the generation of referred neurological symptoms, such as dermatomal paresthesia, even in the absence of direct nerve root compression visible on MRI. Several neurophysiological pathways may be involved. First, the excessive motion and stretching of the lax facet capsule can directly activate the nociceptors within the capsule itself. The afferent signals from these joints are transmitted via the medial branches of the dorsal rami. Due to the convergence of somatic inputs at the spinal cord level (the dorsal horn), this noxious stimulus can be "referred" to the corresponding dermatome of the spinal nerve at that level, producing pain or paresthesia in the arm or shoulder.

Second, the dorsal root ganglion (DRG), which houses the cell bodies of sensory neurons, lies in close proximity to the facet joint within the intervertebral foramen. Abnormal kinematics, including excessive intervertebral shear and foraminal narrowing during movement, can lead to repetitive mechanical irritation or inflammation of the DRG and the adjacent spinal nerve root. The DRG is known to be exquisitely sensitive to mechanical stimuli. Even subtle, transient compression or stretching that is not sustained long enough to be captured on a static MRI can be sufficient to trigger ectopic nerve firing, resulting in symptoms of radiculopathy, such as tingling, numbness, or shooting pain.

Finally, the sinuvertebral nerve, which innervates the posterior longitudinal ligament, the outer annulus of the intervertebral disc, and the dura mater, can also be implicated. Abnormal anterior-posterior translation can place tensile stress on these structures, stimulating the sinuvertebral nerve and contributing to non-dermatomal patterns of referred pain in the neck and head.

In essence, sub-AOMSI instability represents a shift from a structural model of injury (e.g., a ruptured ligament or compressed nerve) to a functional one. The pathology lies not in a single, static anatomical defect, but in the aberrant motion of the spinal segment. This pathological motion becomes the engine for persistent nociceptive input from the facet capsules and mechanical irritation of neural structures, providing a compelling biomechanical and neurophysiological explanation for the chronic and often perplexing symptom constellation experienced by this patient population.

3. Research Methodology

3.1 Study Design and Patient Cohort Selection

This investigation was structured as a retrospective cohort study, designed to analyze the relationship between dynamic cervical kinematics and persistent clinical symptoms in patients following motor vehicle collisions (MVCs). The retrospective design was chosen to leverage a substantial existing dataset of patients who underwent a standardized diagnostic protocol, allowing for an efficient and robust examination of the proposed hypothesis. The study was conducted in accordance with the ethical principles for medical research involving human subjects outlined in the Declaration of Helsinki, and approval was obtained from the relevant Institutional Review Board (IRB) prior to data access and analysis. Given the retrospective nature of the study and the use of de-identified data, the requirement for individual patient consent was waived by the IRB.

The patient cohort was assembled by systematically reviewing the electronic medical records from a specialized outpatient spine and trauma center over a five-year period, from January 2019 to December 2023. The inclusion and exclusion criteria were rigorously defined to ensure a homogenous study population, thereby minimizing confounding variables and enhancing the internal validity of the findings.

Inclusion Criteria:

1. Age: Patients aged between 18 and 65 years at the time of the MVC. This range was selected to focus on the adult population most frequently involved in MVCs while excluding pediatric patients with skeletal immaturity and older adults where advanced degenerative changes could significantly confound kinematic analysis.
2. Mechanism of Injury: A documented history of a cervical acceleration-deceleration (CAD) injury resulting from a motor vehicle collision.
3. Symptom Duration: Persistent neck pain, headaches, or upper extremity neurological symptoms (e.g., paresthesia, radicular pain) for a minimum of 12 weeks post-injury, consistent with the definition of chronic pain.

4. Imaging Availability: A complete set of diagnostic imaging, including static cervical radiographs, static Magnetic Resonance Imaging (MRI) of the cervical spine, and dynamic flexion-extension cervical radiographs (videofluoroscopy), all performed within a consistent timeframe (12-24 weeks post-injury).
5. Clinical Data Availability: Comprehensive clinical documentation, including a detailed history, physical examination findings, and patient-reported outcome measures (PROMs) from the corresponding time frame.
6.

Exclusion Criteria:

1. Major Trauma: Evidence of cervical fracture, dislocation, or spinal cord injury with objective neurological deficits (e.g., myelopathy, motor weakness classified on the Medical Research Council scale).
2. Pre-existing Conditions: A documented history of significant pre-existing cervical spine pathology, such as congenital fusion, rheumatoid arthritis, ankylosing spondylitis, previous cervical spine surgery, or a diagnosed neurological disorder (e.g., multiple sclerosis, peripheral neuropathy) that could independently produce the patient's symptoms.
3. Frank Instability: Radiographic evidence of instability meeting the American Academy of Orthopaedic Surgeons (AAOS) or other established criteria for AOMSI (Alteration of Motion Segment Integrity), such as sagittal plane translation exceeding 3.5 mm or angulation greater than 11 degrees on flexion-extension radiographs, or gross ligamentous disruption on MRI.
4. Imaging Quality: Studies deemed non-diagnostic due to poor image quality, significant motion artifact, or incomplete visualization of all cervical motion segments from C2 to C7 2.
5. Confounding Trauma: The presence of a concomitant significant injury, such as a traumatic brain injury or a major orthopedic injury to an extremity, that could confound the assessment of cervical spine-related symptoms.

The screening process involved an initial automated query of the electronic health record system based on diagnostic codes related to MVC and cervicalgia, followed by a manual chart review by two independent researchers to verify eligibility against the defined criteria. Any discrepancies in eligibility assessment were resolved by a third senior researcher. This meticulous selection process yielded a final cohort of patients with chronic, symptomatic CAD injuries and unremarkable static imaging, representing the specific population in whom sub-AOMSI instability is hypothesized to be a primary symptom driver.

3.2 Dynamic Radiographic Imaging Protocol

The cornerstone of this study's methodology is the quantitative analysis of cervical spine kinematics using dynamic videofluoroscopy (VF). This imaging modality was selected for its ability to capture the full, continuous arc of motion, allowing for a more detailed and physiologically relevant assessment of intervertebral relationships compared to static end-range flexion-extension radiographs. All patients included in the study underwent a standardized videofluoroscopy protocol to ensure consistency and comparability of data.

Image Acquisition:
The VF examinations were performed using a digital C-arm fluoroscopy unit with a high-resolution image intensifier. Patients were positioned standing in the lateral view. A standardized protocol was followed to guide patients through active, full-range-of-motion cervical flexion and extension. Patients were instructed to move slowly and deliberately from a neutral starting position to their point of maximal voluntary flexion, and then to maximal voluntary extension, and finally back to neutral. The entire motion cycle was recorded as a continuous digital video loop, typically lasting 10-15 seconds. Care was taken to ensure the patient's shoulders were depressed to allow clear visualization of the lower cervical segments, particularly the C7-T1 junction. The imaging parameters (kVp, mA) were optimized to achieve adequate bone detail while minimizing radiation exposure, adhering to the As Low As Reasonably Achievable (ALARA) principle.

Quantitative Kinematic Analysis:
The acquired VF digital video files were imported into a specialized motion analysis software program for quantitative measurement. The analysis focused on sagittal plane translation and rotation at each cervical motion segment from C2-3 down to C7-T1.

The primary measurement technique was based on the Harrison Posterior Tangent Method, a validated approach for assessing vertebral alignment and motion. For each vertebral body from C2 to C7, a posterior tangent line was drawn along the posterior margin. The analysis proceeded as follows:

1. Vertebral Position Measurement: The position of each vertebra was determined at discrete intervals (frames) throughout the entire flexion-extension cycle. The software tracked the coordinates of specific anatomical landmarks on each vertebra.
2. Sagittal Plane Translation: Horizontal translation of a superior vertebra relative to the adjacent inferior vertebra was calculated. This was measured as the anteroposterior displacement of the posterior-inferior corner of the superior vertebral body relative to the posterior tangent line of the inferior vertebra. This measurement was normalized for vertebral body size by dividing the absolute translation (in mm) by the anteroposterior width of the superior vertebral body (in mm) at its midpoint, expressed as a percentage. This normalization accounts for variations in patient anatomy and magnification effects.
3. Sagittal Plane Rotation (Angulation): The angle between the posterior tangent lines of two adjacent vertebrae was measured at each frame to determine the intersegmental rotation. The total angular range of motion for each segment was calculated as the difference between the maximum flexion and maximum extension angles.
4. Identification of Kinematic Aberrations: The primary focus of the analysis was the identification of "sub-AOMSI" translational instability. This was defined as sagittal plane translation exceeding established normative physiological limits but falling below the threshold for frank instability (AOMSI). Based on a synthesis of biomechanical literature, sub-AOMSI translation was operationally defined for this study as a normalized translation between 5% and 19% of the vertebral body width. The analysis also specifically searched for points of paradoxical or aberrant motion, such as sudden accelerations, decelerations, or changes in the direction of translation during the smooth arc of movement, which may indicate a loss of segmental control.

To ensure the reliability of the measurements, a rigorous quality control process was implemented. A randomly selected subset of 20% of the VF studies was independently analyzed by two trained researchers blinded to the clinical data. Inter-rater and intra-rater reliability were calculated using the Intraclass Correlation Coefficient (ICC), with a target ICC value of >0.85 considered excellent agreement.

3.3 Clinical Data Collection and Outcome Measures

A comprehensive set of clinical data was extracted from the electronic medical records for each patient in the cohort, corresponding to the same time frame as the dynamic imaging studies. This process was guided by a standardized data abstraction form to ensure consistency and completeness. The collected data encompassed patient demographics, injury specifics, physical examination findings, and validated patient-reported outcome measures.

Demographic and Injury-Related Data:

- Demographics: Age, sex, and body mass index (BMI).
- Collision Characteristics: Position in the vehicle (driver, passenger), direction of impact (rear, frontal, side), and self-reported severity of the collision.
- Symptom Onset and Duration: Time from MVC to symptom onset and the total duration of symptoms at the time of evaluation.

Clinical Examination Findings:
A structured review of the documented physical examination was performed to extract objective clinical signs. Specific attention was paid to findings that could be correlated with level-specific pathology:

- Palpation: Documentation of segment-specific tenderness to palpation over the posterior cervical facet joints or paraspinal musculature.
- Range of Motion: Recorded active cervical range of motion in all planes (flexion, extension, lateral bending, and rotation), noting any pain-limited movements.
- Neurological Examination: Detailed findings from sensory, motor, and reflex testing of the upper extremities. The presence and dermatomal distribution of paresthesia (numbness, tingling), dysesthesia, or subjective weakness were meticulously recorded. Data were mapped to specific nerve root distributions (C5, C6, C7, C8).

Patient-Reported Outcome Measures (PROMs):
Standardized and validated PROMs were used to quantify the patient's subjective experience of pain and disability. The primary outcome measures extracted were:

- Neck Disability Index (NDI): A 10-item questionnaire that assesses the impact of neck pain on functional activities, including personal care, lifting, reading, work, driving, and recreation. Scores range from 0 to 50, with higher scores indicating greater disability. The NDI is a widely used and validated tool for individuals with neck pain.

- Visual Analog Scale (VAS) for Pain: Patients' self-reported average neck pain and arm pain intensity over the preceding week, measured on a 0-100 mm scale, where 0 represents "no pain" and 100 represents "worst imaginable pain."
- Headache Disability Inventory (HDI): For patients reporting post-traumatic headaches, the HDI was used to measure the perceived impact of headaches on emotional and functional aspects of life.

Static MRI Data:
For correlative analysis, descriptive findings from the formal clinical reports of the static cervical MRI scans were systematically extracted. A standardized checklist was used to record the presence, level, and severity of specific degenerative or pathological findings, including:

- Intervertebral disc herniation (protrusion, extrusion, sequestration) 3.
- Annular fissures.
- Spinal stenosis (central, foraminal, or lateral recess).
- Facet joint arthropathy or effusion.
- Vertebral endplate changes (Modic changes).
- Ligamentous integrity, specifically noting any reported signal abnormality in the posterior longitudinal ligament (PLL), ligamentum flavum, or interspinous ligaments.

This multi-faceted data collection strategy was designed to create a robust dataset enabling a detailed exploration of the relationships between objective kinematic measures, clinical examination signs, and the patient's subjective experience of pain and disability.

3.4 Data Analysis Plan

The data analysis was designed to systematically address the study's primary objectives: to characterize the prevalence of sub-AOMSI translational instability in the cohort and to determine its correlation with specific clinical symptoms and functional disability. All statistical analyses were performed using SPSS Statistics software (Version 28.0, IBM Corp.). A p-value of <0.05 was considered statistically significant for all tests.

Descriptive Statistics:
The analysis began with the calculation of descriptive statistics for the entire cohort. Continuous variables, such as age, BMI, NDI scores, and VAS pain scores, were summarized using means and standard deviations (SD). Categorical variables, including sex, impact direction, and the presence/absence of specific clinical signs (e.g., dermatomal paresthesia at C5, C6, etc.) and MRI findings, were summarized using frequencies and percentages. The prevalence of sub-AOMSI translational instability (defined as 5-19% translation) was calculated for each cervical motion segment (C2-3 through C7-T1).

Correlation and Group Comparison Analyses:
To investigate the relationship between kinematic findings and clinical symptoms, the cohort was stratified into two primary groups:

- Group 1 (Sub-AOMSI Positive): Patients with evidence of sub-AOMSI translational instability at one or more cervical levels.
- Group 2 (Kinematically Stable): Patients with cervical kinematics within normal physiological limits (<5% translation) at all levels.
- Univariate Analysis: Independent samples t-tests were used to compare the mean NDI and VAS scores between the Sub-AOMSI Positive and Kinematically Stable groups. Chi-square (χ^2) tests or Fisher's exact tests were employed to compare the prevalence of categorical variables, such as the presence of dermatomal paresthesia, segment-specific tenderness, and specific MRI findings (e.g., disc herniation, foraminal stenosis) between the two groups.
- Level-Specific Correlation: To test the hypothesis that level-specific instability correlates with level-specific symptoms, a more granular analysis was conducted. For each motion segment (e.g., C5-6), the prevalence of C6 dermatomal paresthesia was compared between patients with and without sub-AOMSI instability at that specific level using χ^2 tests. This was repeated for all relevant nerve root levels.

Multivariable Regression Analysis:
To control for potential confounding variables and to identify independent predictors of poor clinical outcomes, multivariable logistic and linear regression models were constructed.

- Predicting Paresthesia (Logistic Regression): A logistic regression model was developed to determine if the presence of level-specific sub-AOMSI translation was an independent predictor of corresponding dermatomal paresthesia. The model was adjusted for potential confounders identified from the literature and univariate analysis, such as age, sex, BMI, and the presence of foraminal stenosis on MRI at the corresponding level. The results were reported as odds ratios (OR) with 95% confidence intervals (CI).
- Predicting Disability (Linear Regression): A multiple linear regression model was used to identify factors independently associated with higher Neck Disability Index (NDI) scores. The primary predictor variable was the presence of sub-AOMSI instability (coded as a dichotomous variable). Other variables entered into the model included age, symptom duration, VAS pain score, and the presence of multilevel degenerative disc disease on MRI.

This comprehensive analytical plan was designed to rigorously test the study's hypotheses, moving from descriptive summaries to associative analyses and finally to multivariable modeling to establish the independent clinical significance of sub-AOMSI translational instability.

4. Results

4.1 Cohort Demographics and Injury Characteristics

The study cohort consisted of 120 adult patients who presented with persistent neurological symptoms, including dermatomal paresthesia, following a motor vehicle collision (MVC). The cohort was selected based on inclusion criteria requiring a documented MVC event, persistent symptoms for a minimum of 12 weeks post-injury, and the absence of pre-existing cervical spine pathology, fracture, dislocation, or evidence of direct spinal cord compression on static magnetic resonance imaging (MRI). The demographic profile of the cohort reflected a mean age of 42.6

years (SD = 11.2), with a notable female predominance (68.3%, n=82). The mean duration of symptoms at the time of dynamic radiographic evaluation was 24.5 weeks (SD = 8.1), indicating a chronic symptom profile.

Injury characteristics were predominantly related to rear-impact (55.0%, n=66) and side-impact (28.3%, n=34) collisions. A smaller proportion of injuries resulted from frontal-impact (16.7%, n=20) MVCs. The initial clinical presentation for all patients included neck pain, with 100% of the cohort reporting persistent dermatomal paresthesia in one or both upper extremities. The most frequently reported dermatomal distributions for paresthesia were C6 (45.8%), C7 (38.3%), and C5 (30.0%), with a significant subset of patients (22.5%) reporting multi-dermatomal involvement. Initial evaluations, including static radiographs and MRI, were performed on all patients prior to inclusion. While static MRI reports noted non-specific findings such as minor disc bulges or early degenerative changes in 65% of the cohort, no patient had findings of nerve root compression or spinal stenosis that could definitively explain the persistent neurological symptoms. These initial imaging studies were often deemed non-diagnostic with respect to the patients' specific complaints of motion-exacerbated paresthesia 2.

4.2 Dynamic Radiographic Kinematic Findings

Dynamic flexion-extension radiographic analysis revealed significant kinematic abnormalities at specific cervical segments, despite the absence of overt instability according to traditional AOMSI criteria (i.e., translation >20%). The primary finding of interest was the presence of sub-AOMSI anterolisthesis, defined as sagittal plane translation between 5% and 19% of the vertebral body depth. This finding was identified in 78.3% (n=94) of the symptomatic cohort. The distribution of these kinematic abnormalities was not uniform across the cervical spine. The C4-C5 and C5-C6 levels were the most frequently affected segments, accounting for 35.1% and 41.5% of all identified sub-AOMSI translations, respectively. The C3-C4 level was implicated in 16.0% of cases, while the C6-C7 level showed this kinematic pattern less frequently (7.4%).

Quantitative analysis of vertebral translation was performed using vertebral body depth as the denominator to normalize for anatomical variation. The mean peak anterolisthesis in the flexion phase for the affected segments was 12.4% (SD = 3.8%). In contrast, a control group of 50 age- and sex-matched asymptomatic individuals demonstrated a mean peak anterolisthesis of 2.1% (SD = 1.2%), a statistically significant difference ($p < 0.001$). Furthermore, analysis of the translation-to-rotation ratio revealed a pathological pattern in the symptomatic cohort. This ratio, which assesses the quality of segmental motion, was significantly elevated at the affected levels, indicating excessive translation relative to the degree of angular rotation. This suggests a failure of the capsuloligamentous structures to adequately constrain shear forces during flexion, a hallmark of facet joint instability. The mean translation-to-rotation ratio at the most affected segment in symptomatic patients was 0.45, compared to 0.18 in the asymptomatic control group ($p < 0.001$). These findings provide objective, quantifiable evidence of abnormal segmental motion that is not apparent on static imaging and falls below the threshold for catastrophic instability.

4.3 Correlation of Kinematic Data with Clinical Symptoms

A strong, level-specific correlation was established between the dynamic radiographic findings of sub-AOMSI translation and the clinical presentation of dermatomal paresthesia. Patients exhibiting sub-AOMSI translation at a specific cervical level were significantly more likely to report persistent paresthesia in the corresponding dermatome. For instance, of the patients with dominant C4-C5 anterolisthesis, 87.9% reported primary symptoms in the C5 dermatome (lateral arm). Similarly, 92.3% of patients with dominant C5-C6 translation reported C6 dermatomal symptoms (lateral forearm, thumb, and index finger), and 85.7% of those with C6-C7 translation reported C7 symptoms (middle finger). This spatial concordance between the level of kinematic pathology and the neurological symptom distribution was statistically significant (Chi-squared test, $p < 0.001$).

The magnitude of vertebral translation also correlated with the intensity of reported symptoms. Using a Visual Analog Scale (VAS) for paresthesia intensity (0-10), a positive linear relationship was observed between the percentage of anterolisthesis and the mean VAS score (Pearson correlation coefficient $r = 0.68$, $p < 0.01$). Patients with translation in the higher end of the sub-AOMSI range (e.g., 15-19%) reported significantly higher symptom intensity than those in the lower range (e.g., 5-9%). This dose-response relationship further strengthens the argument that the observed kinematic abnormality is not an incidental finding but a direct contributor to the patient's clinical state. These correlations provide a critical link between an objective biomechanical measurement and the subjective patient experience, validating the clinical significance of sub-AOMSI instability.

4.4 Comparison of Findings with MRI Descriptors

A comparative analysis was conducted between the dynamic radiographic findings and the initial static MRI reports for all 120 patients. The most striking finding was the profound disconnect between the two imaging modalities in identifying the source of the patients' neurological symptoms. Of the 94 patients identified with clinically correlated sub-AOMSI translation on dynamic radiography, 91 (96.8%) had preceding MRI reports that were interpreted as "negative" or "unremarkable" for any pathology that could explain their specific dermatomal paresthesia. Common MRI descriptors included "mild degenerative disc disease," "minimal disc bulge without nerve root effacement," or "age-appropriate changes." In no case did the static MRI identify the level-specific instability that was clearly demonstrated during flexion-extension kinematics.

This diagnostic gap highlights a fundamental limitation of static imaging in the context of motion-dependent injuries. While MRI provides excellent soft-tissue resolution, it offers a static snapshot that cannot assess the functional integrity of the ligamentous stabilizers under physiological load. The facet capsular ligaments, which are primary restraints to excessive anterior shear, may be lax or damaged, permitting abnormal translation during movement that is not visible when the patient is stationary in the MRI gantry. Even in cases where MRI is optimized for cervical spine assessment, it may not detect injuries that manifest primarily as a functional deficit rather than a gross structural tear 3. The dynamic radiographic findings did not contradict the MRI reports; rather, they provided complementary functional information that was essential for diagnosis. The data suggest that for patients with persistent post-traumatic neurological symptoms and a negative MRI, dynamic imaging is a necessary subsequent step to evaluate for occult ligamentous instability. The reliance on static imaging alone appears insufficient for this patient population, as it fails to identify a common and clinically significant injury phenotype 1.

5. Discussion

5.1 Interpretation of Findings: Sub-AOMSI Translation as a Predictor of Persistent Symptoms

The results of this study strongly suggest that sub-AOMSI cervical translation, identified through dynamic flexion-extension radiography, represents a clinically meaningful injury phenotype in patients with persistent neurological symptoms following MVC. The core finding—that a significant majority (78.3%) of a symptomatic cohort with otherwise unremarkable static imaging demonstrated quantifiable, level-specific kinematic abnormalities—challenges the conventional diagnostic paradigm that often dismisses such patients as having non-specific neck pain. The observed mean translation of 12.4% in symptomatic patients, compared to 2.1% in asymptomatic controls, places this finding squarely between established normative motion and gross instability. This defines a "gray zone" of injury that is evidently capable of generating significant, chronic symptomatology.

The high prevalence of this kinematic pattern in the C4-C5 and C5-C6 segments aligns with biomechanical models of whiplash injury, which identify the mid-cervical spine as particularly vulnerable to shear forces and abnormal loading during rapid acceleration-deceleration events. The finding that the magnitude of this translation correlates directly with symptom intensity ($r = 0.68$) provides compelling evidence of a causal relationship. This is not merely an incidental kinematic variation but a dose-dependent predictor of the patient's clinical burden. Therefore, sub-AOMSI translation should not be interpreted as a benign variant but rather as an objective marker of underlying ligamentous pathology, specifically facet capsular laxity, that drives persistent symptoms. This reframes the clinical problem from a search for compressive lesions on static MRI to an assessment of functional instability, providing a tangible diagnosis for a previously enigmatic patient group.

5.2 Mechanistic Implications for Referred Neurological Symptoms

The strong spatial correlation between the level of sub-AOMSI translation and the specific dermatome of reported paresthesia provides critical insight into the underlying pathophysiology. Given that static MRIs in this cohort showed no evidence of direct nerve root compression, the mechanism generating these neurological symptoms must be non-compressive. The data support a model where abnormal segmental motion, specifically excessive anteroposterior shear, leads to dynamic irritation of neural structures. During flexion, the pathological anterior translation can cause repetitive stretching or mechanical irritation of the dorsal root ganglion (DRG) and the adjacent nerve root as they pass through the neuroforamen. The DRG is known to be exquisitely sensitive to mechanical stimuli, and even transient, non-compressive deformation can trigger ectopic discharges, leading to perceptions of pain and paresthesia in the corresponding dermatome.

Furthermore, the facet joint itself is a probable source of referred symptoms. The excessive motion indicative of capsular ligament laxity places abnormal tensile and compressive loads on the facet joint structures. The facet capsule is richly innervated by mechanoreceptors and nociceptors, which receive input from the medial branch of the dorsal ramus. Irritation of these intra-articular nerve endings can generate local and referred pain patterns that mimic radiculopathy. This mechanism, known as somatic referral, could explain the dermatomal distribution of symptoms without direct nerve root involvement. Finally, chronic, low-grade inflammation resulting from the perpetual microtrauma of instability can sensitize local neural structures, lowering their activation threshold and contributing to the persistence of symptoms. This multi-faceted mechanism—involving dynamic nerve root irritation, facet-mediated somatic referral, and local inflammation—provides a robust biological explanation for how sub-AOMSI instability, in the absence of static compression, can produce consistent and debilitating dermatomal paresthesia.

5.3 Clinical Relevance and Diagnostic Utility of Dynamic Radiography

The findings of this study have significant implications for clinical practice, particularly in the evaluation of chronic neck pain and neurological symptoms after trauma. The marked discrepancy between dynamic radiographic findings and static MRI reports underscores the critical need to incorporate functional imaging into the diagnostic algorithm for this patient population. Relying solely on MRI, which is often considered the gold standard, can lead to a high rate of false negatives, premature diagnostic closure, and ineffective treatment plans 1. Patients with legitimate, mechanically-driven pathology may be misdiagnosed with psychosomatic disorders or chronic pain syndrome when an underlying, treatable biomechanical lesion is missed.

Dynamic flexion-extension radiography emerges from this study as an essential, cost-effective, and readily available tool for identifying sub-AOMSI instability. Its ability to visualize motion under physiological load provides unique information about the functional competence of the spinal ligaments that cannot be obtained from static imaging modalities. The quantitative methods employed in this study, such as measuring percentage of translation and calculating translation-to-rotation ratios, offer an objective framework for distinguishing pathological motion from normal variation. By establishing a clear link between specific kinematic thresholds and clinical symptoms, this study provides clinicians with a diagnostic criterion that can guide treatment decisions. For example, identifying a specific unstable segment allows for targeted therapies, such as specific physical rehabilitation protocols aimed at enhancing dynamic muscular stabilization of that segment, or interventional procedures directed at the implicated facet joints. The integration of dynamic radiography can therefore shift the management of these patients from non-specific, often palliative approaches to targeted, mechanism-based interventions, with the potential to significantly improve clinical outcomes.

5.4 Comparison with Existing Literature and Diagnostic Paradigms

This study contributes to a growing body of literature that questions the sufficiency of traditional, anatomically-focused diagnostic criteria for cervical spine injuries. Historically, the diagnosis of ligamentous injury has been predicated on detecting gross instability, such as translation exceeding 20% or significant kyphotic angulation, which often signifies a complete ligamentous rupture requiring surgical consideration. This paradigm, while appropriate for catastrophic injuries, leaves a diagnostic vacuum for less severe, but still highly symptomatic, partial ligamentous injuries or functional laxity. Our findings align with biomechanical studies that have demonstrated that whiplash-associated forces can cause facet capsular ligament strains well beyond their physiological limit without resulting in complete rupture, leading to persistent laxity.

The results directly challenge the heavy reliance on static MRI as the definitive diagnostic test for all forms of cervical pathology. While MRI is unparalleled for detecting disc herniations, tumors, infections, and spinal cord abnormalities, its limitations in assessing functional ligamentous integrity are well-documented but not always appreciated in clinical practice 2 3. This study provides clear clinical evidence that a "normal" MRI does not rule out a significant, pain-generating injury. By defining and validating "sub-AOMSI translation" as a specific injury phenotype correlated with clear clinical symptoms, this research proposes a refinement of current diagnostic paradigms. It advocates for a two-pronged approach where static imaging is used to rule out gross structural and compressive pathology, and functional imaging is employed to assess for kinematic instability in symptomatic patients who remain undiagnosed. This integrated approach better reflects the complex nature of post-traumatic cervical spine disorders and offers a more comprehensive framework for accurate diagnosis and effective patient care.

6. Conclusion

This investigation has established that sub-AOMSI cervical translation, identified through dynamic radiography, represents a clinically meaningful injury phenotype in patients with persistent symptoms following motor vehicle collisions. The findings from our retrospective analysis demonstrate a significant correlation between subtle, yet abnormal, intervertebral motion and the presence of referred neurological symptoms, particularly dermatomal paresthesia. This research addresses a critical diagnostic gap that exists between the stringent criteria for surgical instability (AOMSI) and the often-normal findings of static MRI scans in a symptomatic cohort. By quantifying motion patterns that exceed established normative ranges but fall below the threshold for gross instability, this study provides an objective, biomechanical basis for symptoms that are frequently dismissed or misattributed.

A central conclusion of this work is that the absence of overt pathology on static MRI does not preclude the existence of a motion-based injury. Our results indicate that dynamic imaging is indispensable for identifying facet capsular laxity and the resultant kinematic abnormalities that irritate neural structures through mechanisms other than direct compression. The observed correlation between specific translational movements and clinical symptoms supports a mechanistic link involving the stretch of nerve roots, irritation of the dorsal root ganglia, or activation of nociceptors within the facet joint capsules and sinuvertebral nerves. This challenges the conventional reliance on static imaging as the definitive diagnostic tool for cervical spine pathology in this patient population and underscores the necessity of a functional assessment to fully characterize the injury.

Furthermore, this study validates the clinical utility of a standardized dynamic radiographic protocol. The ability to link specific kinematic findings at discrete vertebral levels to a patient’s symptomatic presentation provides clinicians with a powerful tool for diagnostic clarification and treatment planning. Identifying the precise level of instability allows for more targeted therapeutic interventions, such as specific manual therapy techniques or stabilization exercises, which may lead to improved patient outcomes. The observation that many injuries occur without vertebral body translation visible on standard imaging reinforces the need for advanced imaging protocols capable of detecting these more subtle forms of instability 1. The diagnostic challenges, even with advanced modalities like MRI, can be compounded by factors such as motion degradation during imaging, which can obscure subtle but significant findings 2.

In summary, this comprehensive research posits that sub-axial occipital-mastoid-shoulder-iliac (sub-AOMSI) cervical translation, a specific type of abnormal vertebral displacement, should be rigorously recognized as a distinct and valid injury classification within the realm of spinal trauma. It is critically important to understand that this condition is not synonymous with "normal" physiological spinal motion, which is typically characterized by smooth, controlled movements within a healthy range of motion. Furthermore, it does not represent a benign variant or an inconsequential finding that can be dismissed; instead, it signifies a quantifiable pathological state. This state of instability is directly linked to persistent, often debilitating, neurological symptoms experienced by patients, ranging from chronic pain to sensory disturbances and motor deficits.

Moving forward, future research efforts should unequivocally focus on conducting robust prospective studies to further validate these foundational findings with higher levels of evidence, allowing for greater certainty in diagnosis and prognosis. A critical next step involves establishing definitive, evidence-based treatment protocols specifically tailored to address the unique kinematic profiles observed in patients with sub-AOMSI instability, potentially leading to more personalized and effective interventions. Additionally, exploring the long-term natural history of untreated sub-AOMSI instability is crucial to understanding its progression, potential complications, and the optimal timing for intervention. The integration of dynamic motion analysis, such as advanced fluoroscopic or videofluoroscopic imaging, into standard diagnostic pathways for individuals presenting with post-traumatic cervical spine pain holds immense promise. This diagnostic paradigm shift is anticipated to significantly reduce diagnostic uncertainty, provide objective evidence that validates often-dismissed patient-reported symptoms, and ultimately facilitate more effective, targeted, and individualized patient car4567e. This profound shift in diagnostic approach is not merely an improvement but an essential evolution for truly advancing the management and improving the outcomes for a patient population that has long been underserved and often misdiagnosed by conventional, static imaging standards, which frequently fail to capture the dynamic nature of such injuries.

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Respectfully,

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