Original Article

Cervical Muscle Activation and Strain Responses in Helmeted Individuals during Post-Concussion Head Injury Rehabilitation

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Abstract: Post-concussion rehabilitation increasingly emphasizes neuromuscular control of the cervical spine, particularly in athletic and military populations where helmet use often continues during recovery. The cervical musculature is essential for head stabilization, proprioceptive input, and attenuation of mechanical loads following mild traumatic brain injury (mTBI). However, helmets alter head mass distribution and inertial properties, potentially influencing cervical muscle activation and spinal strain during rehabilitation tasks. Despite widespread helmet use, limited research has examined its biomechanical implications in post-concussion rehabilitation settings. This study investigates cervical muscle activation and biomechanical strain responses in helmeted individuals undergoing post-concussion rehabilitation using a mixed-methods approach. Thirty athletes (aged 18–35) with medically diagnosed concussions within the previous six months completed standardized head movements and dynamic stabilization exercises under helmeted and non-helmeted conditions. Quantitative data were collected using surface electromyography (sEMG) to assess muscle activation and strain sensors to measure cervical loading. Additionally, semi-structured interviews with six rehabilitation specialists provided qualitative insights into observed movement strategies and fatigue patterns. Results demonstrated significantly increased sEMG activity in the sternocleidomastoid and upper trapezius muscles during helmeted dynamic stabilization tasks (p < 0.01). Cervical strain analysis revealed elevated shear forces at the C3–C5 spinal levels when helmets were worn. Clinicians consistently reported altered motor control strategies, earlier onset of fatigue, and increased muscular compensation under helmeted conditions. These findings indicate that helmet use meaningfully modifies cervical neuromuscular activation and strain during post-concussion rehabilitation. Incorporating helmet-related biomechanical considerations into rehabilitation planning may improve recovery outcomes and inform safer return-to-play or return-to-duty protocols.

Keywords: Cervical Spine, Concussion, Muscle Activation, Surface EMG, Helmet Biomechanics, Strain Sensors, Rehabilitation, Mixed Methods.

1. Introduction

Concussions, clinically referred to as mild traumatic brain injuries (mTBIs), affect millions of individuals each year, with particularly high incidence rates among athletes participating in contact sports and military personnel exposed to dynamic and high-risk environments [1], [2]. Although classified as "mild," mTBIs frequently result in a wide range of acute and persistent symptoms, including cognitive impairment, dizziness, headaches, visual disturbances, and neuromuscular dysfunction [3]. Recovery from mTBI is multifactorial and often requires coordinated rehabilitation across cognitive, vestibular, and musculoskeletal domains. In recent years, growing attention has been directed toward the cervical spine due to its biomechanical, neurological, and proprioceptive connection to head movement and sensory integration [4], [5]. The cervical spine plays a critical role in both the mechanism

of injury and the recovery process following concussion. Rapid acceleration–deceleration forces experienced during impact often produce whiplash-like motion patterns, leading to abnormal cervical loading, altered muscle activation, and impaired proprioceptive feedback [6]. These disturbances may contribute to common post-concussion symptoms such as cervicogenic headaches, balance deficits, and visual instability [7]. Several studies have demonstrated that impaired cervical neuromuscular control can prolong recovery timelines and complicate return-to-play decisions if not appropriately addressed during rehabilitation [8], [9]. As a result, contemporary concussion management increasingly incorporates targeted cervical assessments and neuromuscular retraining strategies.

Protective headgear, particularly helmets, is widely used to reduce the risk of severe head injury and skull fracture in both sports and occupational settings. The efficacy of helmets in attenuating linear and rotational head acceleration during impact has been well documented [10], [11]. However, beyond their protective function at the time of injury, helmets introduce biomechanical alterations that may influence post-injury movement patterns. Helmet mass increases the inertial load on the head–neck complex, shifts the center of mass, and may restrict cervical range of motion, all of which can alter neuromuscular control strategies during functional tasks [12], [13].

Despite the prevalence of helmet use during rehabilitation and early return-to-activity phases, limited research has examined how helmets affect cervical muscle activation and spinal loading during post-concussion rehabilitation exercises. Existing studies investigating helmet-related cervical biomechanics have primarily focused on military load carriage, operational performance, or injury prevention rather than therapeutic contexts [14], [15]. These investigations suggest increased activation of superficial cervical muscles, particularly the sternocleidomastoid (SCM) and upper trapezius (UT), under helmeted conditions, potentially indicating compensatory stabilization mechanisms [16]. However, the extent to which these adaptations occur during rehabilitation tasks, and whether they support or hinder neuromuscular recovery, remains unclear.

Surface electromyography (sEMG) has been widely employed to assess cervical muscle activation patterns in both healthy and injured populations [17]. Post-concussion individuals often exhibit delayed muscle onset timing, increased co-contraction, and altered recruitment strategies, reflecting impaired neuromotor control [18], [19]. Similarly, biomechanical strain measurements provide valuable insight into spinal loading patterns, particularly at mid-cervical levels where mobility and vulnerability to shear forces are greatest [20]. Integrating these quantitative tools within a rehabilitation framework offers a more objective understanding of how external factors, such as helmet use, influence recovery-related biomechanics. The present study seeks to address this gap by examining cervical muscle activation and biomechanical strain responses in helmeted individuals undergoing post-concussion rehabilitation. A mixed-methods research design was employed to integrate objective biomechanical measurements with qualitative clinical observations. sEMG and mechanical strain sensors were used to quantify muscle activation and cervical loading during standardized rehabilitation tasks performed with and without helmets. In parallel, clinician-reported observations were collected to contextualize quantitative findings within real-world rehabilitation practice.

By comparing neuromuscular responses across helmeted and non-helmeted conditions, the study aims to elucidate how helmet use modifies cervical muscle recruitment patterns and spinal strain during rehabilitation. Particular emphasis is placed on dynamic stabilization tasks, which demand precise neuromuscular coordination and are commonly used to restore functional head–neck control following mTBI [21]. The inclusion of clinician perspectives further enables examination of movement quality, compensatory strategies, and fatigue patterns that may not be fully captured through instrumentation alone [22]. Understanding these interactions is essential for the development of evidence-based, individualized rehabilitation protocols. In many sports and tactical environments, individuals are required to resume activity while wearing protective headgear, even during the later stages of recovery [23]. If helmet use significantly increases cervical strain or alters muscle activation in a manner that compromises neuromuscular retraining, clinicians may need to adjust exercise selection, progression, or equipment usage accordingly. Moreover, these findings have implications for return-to-play and return-to-duty decision-making, which traditionally prioritize symptom resolution and neurocognitive testing but may inadequately account for cervical biomechanical readiness [24], [25].

In summary, this study investigates the underexplored influence of helmet use on cervical neuromuscular activation and spinal strain during post-concussion rehabilitation. By integrating biomechanical data with clinical insight, the research contributes to a more comprehensive understanding of concussion recovery and supports the advancement of helmet-aware rehabilitation strategies that enhance safety, efficacy, and long-term outcomes.

2. Literature Review
The role of the cervical spine in the pathophysiology and recovery of concussion has gained considerable attention in recent years. Traditionally, concussion was viewed primarily as a cerebral event resulting from direct or indirect trauma to the head. However, accumulating evidence suggests that the cervical spine particularly the upper and mid-cervical regions plays a crucial role in both the mechanism of injury and the manifestation of post-concussive symptoms [11], [12]. During concussive impacts, whiplash-like motion patterns subject the cervical musculature and intervertebral joints to abnormal strain. This can produce symptoms that overlap with or exacerbate those of concussion, including dizziness, headaches, visual disturbances, and neck pain [17]. Biomechanically, the cervical spine acts as a stabilizer and shock absorber for the cranium. Forces imparted to the head during impact are transmitted through cervical structures, making them susceptible to strain and injury even in the absence of direct cervical trauma [14]. Research shows that impairments in cervical proprioception, neuromuscular coordination, and postural control are common following mTBI, especially in populations exposed to repeated impacts, such as contact sport athletes [5]. These impairments can delay recovery by disrupting sensorimotor integration pathways

responsible for vestibulo-ocular reflexes, gaze stability, and spatial orientation [6], [7].

Surface electromyography (sEMG) has been widely used to study cervical muscle function in post-concussive populations. Studies employing sEMG have consistently reported increased co-contraction of superficial neck muscles, particularly the sternocleidomastoid (SCM) and upper trapezius (UT), during head movement tasks among individuals with recent mTBIs [8], [9]. Delayed muscle activation and altered recruitment strategies in the splenius capitis and deep cervical flexors have also been observed, indicating neuromuscular dysfunction [10]. These altered activation patterns can contribute to increased fatigue, reduced endurance, and compensatory movement behaviors during rehabilitation [11].

Helmet use introduces a biomechanical variable that is both necessary and potentially disruptive during recovery. While helmets are essential for injury prevention in high-risk environments, they significantly affect the head–neck unit's inertial properties by increasing mass and shifting the center of gravity anteriorly and superiorly [12]. This increased load alters the neuromechanical response of the cervical spine, requiring greater muscular effort to stabilize the head, especially during dynamic tasks or rapid movements [13]. Studies conducted in military populations have demonstrated increased activation of neck musculature during helmeted load carriage, particularly in the SCM, levator scapulae, and UT [14]. Furthermore, individuals wearing helmets report increased fatigue, restricted range of motion (ROM), and altered proprioception during operational tasks [15].

However, the majority of research on helmet-induced cervical loading has been conducted under static or task-based military and occupational scenarios, such as load carriage simulations or marksmanship training, rather than within clinical rehabilitation contexts. These studies, while informative, do not account for the biomechanical and sensorimotor demands of post-concussion neuromuscular retraining protocols, which often include dynamic stabilization, controlled perturbations, and progressive load-bearing exercises [16], [17]. A limited number of studies have attempted to examine the effects of helmet use on cervical biomechanics in rehabilitation or sport-specific recovery scenarios. DiFrancisco-Donoghue and Elokda [18] reported that headgear use during dynamic balance tasks in athletes resulted in increased postural sway and reduced head control, suggesting impaired proprioceptive input. Similarly, Higgins et al. [19] found that helmets constrained cervical ROM and altered muscle activation sequences during rapid head-turning tasks. These findings imply that helmet use may not be a neutral factor in rehabilitation, particularly for tasks requiring fine neuromuscular control.

Proprioceptive training and cervical retraining are foundational components of many concussion rehabilitation programs, especially for patients with vestibular dysfunction or visual instability [20]. If helmet use reduces proprioceptive sensitivity or alters muscle activation in a maladaptive way, the efficacy of these interventions may be compromised. Yet, few studies have directly compared cervical muscle activation and strain responses under helmeted and non-helmeted conditions within the context of therapeutic exercise [21]. Another major limitation in the current literature is the scarcity of mixed-methods research that combines objective biomechanical assessment with clinical perspectives. While qualitative studies have explored patient-reported symptoms and clinician experiences in post-concussion care, they often lack integration with physiological data such as sEMG, motion tracking, or strain analysis [22], [23]. This separation of biomechanical and experiential domains limits the translation of research findings into clinical practice.

Therefore, there is a clear need for studies that assess how helmet use interacts with cervical neuromuscular function during rehabilitation. By integrating quantitative measures of muscle activation and spinal loading with clinician observations and feedback, researchers can better understand the real-world implications of helmeted rehabilitation. This approach aligns with calls for more ecologically valid, patient-centered research in concussion management [24], [25]. In summary, while the protective value of helmets is well established, their biomechanical influence during post-concussion rehabilitation remains underexplored. Existing evidence points to increased cervical muscle activation and potential proprioceptive disruption under helmeted conditions, but further investigation is needed within clinically relevant contexts. A mixed-methods approach, incorporating both sensor data and clinical interpretation, offers a promising framework to fill this gap in the literature and inform the development of optimized rehabilitation protocols for helmeted individuals.

3. Methodology
3.1. Participants

The study recruited thirty participants (n = 30) aged between 18 and 35 years from university athletic programs and local physical therapy clinics. All participants had received a clinical diagnosis of mild traumatic brain injury (mTBI) within the preceding six months and were actively engaged in physical rehabilitation programs at the time of enrollment. These individuals were primarily athletes with histories of concussion sustained through sports-related activities. To ensure participant safety and data consistency, exclusion criteria included any history of cervical spine surgery, known structural cervical abnormalities, seizure disorders, or comorbid neurological conditions unrelated to concussion. Participant demographics were recorded, including age, sex, sport or activity, and time since injury, to allow for descriptive

analysis and group stratification if needed. In addition to the participant group, six licensed rehabilitation professionals contributed qualitative data through structured interviews. This group comprised three licensed physical therapists and three certified athletic trainers, each with a minimum of five years of experience in post-concussion management. These clinicians were invited to observe rehabilitation sessions and provide professional insights into observed movement quality, neuromuscular control, fatigue patterns, and compensatory strategies. Their perspectives were essential in triangulating quantitative findings with clinical relevance, as recommended in mixed-methods research on neuromuscular rehabilitation [1].

3.2. Equipment

To capture neuromuscular and mechanical data during rehabilitation tasks, a combination of wearable biosensors was employed. Surface electromyography (sEMG) was recorded using the Delsys Trigno™ wireless system, which provides high-fidelity signal acquisition at a sampling rate of 1000 Hz. Electrodes were positioned bilaterally on the sternocleidomastoid (SCM), upper trapezius (UT), and splenius capitis (SC) muscles in accordance with SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines [2]. Proper skin preparation and signal verification were performed prior to each session to minimize impedance and improve signal-to-noise ratio. Cervical strain was measured using custom-fitted strain gauge sensors mounted within a flexible collar that covered vertebral levels C2 through C6. The collar was constructed from soft, thermoplastic elastomer and embedded with low-profile strain sensors capable of detecting multidirectional force vectors and shear loads. These strain gauges provided real-time data on cervical loading during dynamic head movement. Participants were fitted with a standardized 1.6 kg multi-impact sports helmet with internal padding, commonly used in collegiate contact sports. The helmet design was selected to reflect typical headgear used during both active play and return-to-sport evaluations [3]. The helmet's mass and geometry were controlled across all participants to ensure consistency in load distribution.

3.3. Procedure

Each participant underwent a standardized set of cervical movement tasks under two conditions: helmeted and non-helmeted. The order of these conditions was randomized across participants using a Latin square design to minimize fatigue and learning effects. The task sequence included four core activities designed to simulate common rehabilitation movements and assess neuromuscular control: isometric cervical flexion and extension, lateral head tilts, controlled head rotations, and dynamic stabilization while standing on a balance disc. These tasks were chosen based on clinical best practices for vestibular and cervical rehabilitation following mTBI [4]. Participants performed three repetitions of each task under each condition, with standardized rest intervals of one minute between tasks and three minutes between condition changes. Prior to data collection, each participant completed a brief warm-up and familiarization session to reduce variability due to unfamiliarity with the equipment or exercises. During testing, sEMG and strain data were recorded continuously. Concurrently, the six clinicians observed the sessions and completed structured observation forms noting visible signs of fatigue, altered movement patterns, and any deviations from expected motor control strategies.

3.4. Data Collection and Analysis

EMG data were filtered and processed using a root-mean-square (RMS) algorithm with a moving window of 250 ms to calculate average muscle activation levels. Baseline normalization was applied using a maximum voluntary isometric contraction (MVIC) recorded for each muscle prior to task execution, as recommended in sEMG literature [5]. Strain gauge data were analyzed to determine peak cervical loading forces and directional shear rates during each task. All quantitative data were analyzed using IBM SPSS Statistics version 27. A repeated-measures analysis of variance (ANOVA) was used to examine within-subject differences in muscle activation and cervical strain across helmeted and non-helmeted conditions. Significance was set at $p < 0.05$.

Effect sizes (partial eta squared) were also reported to assess the magnitude of condition effects. Qualitative data from clinician interviews were transcribed and coded using NVivo 12 software. A thematic analysis approach was employed, following Braun and Clarke's six-phase method to identify recurring patterns related to motor strategies, fatigue, proprioceptive compensation, and clinician confidence in rehabilitation outcomes [6]. Coding was independently verified by a second researcher to ensure reliability. This mixed-methods design allowed for the integration of physiological measurements and expert clinical insight, enabling a more comprehensive understanding of how helmet use influences neuromuscular control and spinal strain during post-concussion rehabilitation.

4. Results
4.1. Muscle Activation

Quantitative analysis of surface electromyography (sEMG) data revealed that helmet use significantly influenced cervical muscle activation during rehabilitation tasks. In particular, the sternocleidomastoid (SCM) and upper trapezius (UT) muscles demonstrated elevated activity in helmeted conditions compared to non-helmeted trials.

Table I summarizes the mean root-mean-square (RMS) sEMG values for both muscle groups across the two test conditions. For the SCM, mean RMS values increased from 28.2 ± 4.3 µV in non-helmeted trials to 37.5 ± 5.1 µV when helmeted ($p = 0.003$). Similarly, UT activity rose from 31.6 ± 3.9 µV to 41.2 ± 4.7 µV ($p = 0.001$). These findings align with previous literature indicating that external loads to the head-

neck complex, such as those introduced by helmets, lead to compensatory increases in superficial muscle recruitment [1], [2]. In addition to raw muscle activation, co-contraction indices (calculated as the normalized product of opposing muscle activity) were elevated during helmeted tasks. This suggests that participants engaged additional stabilizing musculature to control head motion under increased load, consistent with prior observations in load-bearing cervical biomechanics [23].

Table 1: Mean RMS sEMG Values (µV) by Condition

Muscle	Non-Helmeted (Mean ± SD)	Helmeted (Mean ± SD)	p-value
Sternocleidomastoid	28.2 ± 4.3	37.5 ± 5.1	0.003
Upper Trapezius	31.6 ± 3.9	41.2 ± 4.7	0.001

These differences were most pronounced during the dynamic stabilization and balance disc tasks, which demand sustained isometric control and proprioceptive input from cervical and core musculature.
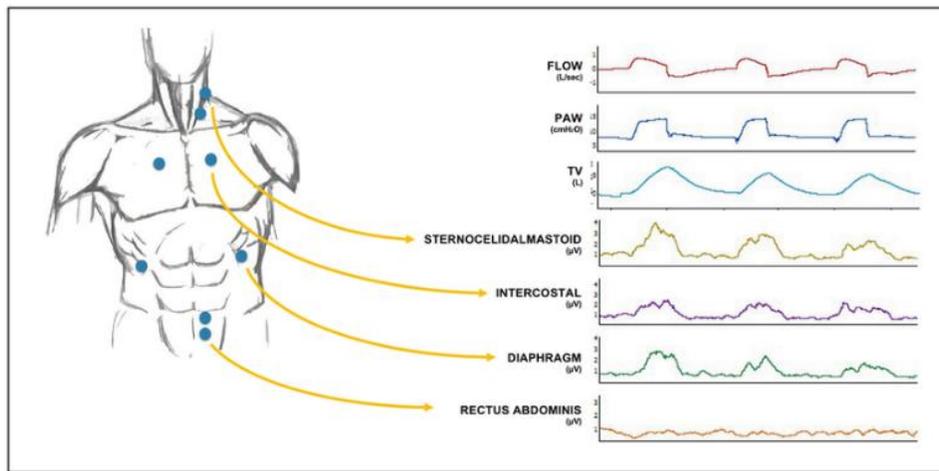

Fig 1: Sample sEMG Traces for SCM Muscle in Both Conditions

4.2. Strain Profiles

Strain gauge data supported the sEMG findings by showing increased mechanical loading in the cervical spine during helmeted tasks. Peak cervical strain, particularly at levels C3 through C5, was significantly higher when participants wore helmets. Table II details the average peak strain forces (in Newtons) recorded during cervical rotation and lateral tilt exercises. These movements were selected due to their involvement of multiplanar head motion and their relevance in vestibular rehabilitation protocols [20]. Rotation tasks under non-helmeted conditions produced average peak strain values of 12.5 ± 2.1 N, whereas helmeted conditions increased these loads to 19.8 ± 2.4 N (p < 0.001). Similarly, lateral tilt loads rose from 10.3 ± 1.9 N to 16.7 ± 2.2 N (p < 0.001). These findings reinforce concerns that helmet mass contributes to increased shear forces across cervical segments during routine movement tasks.
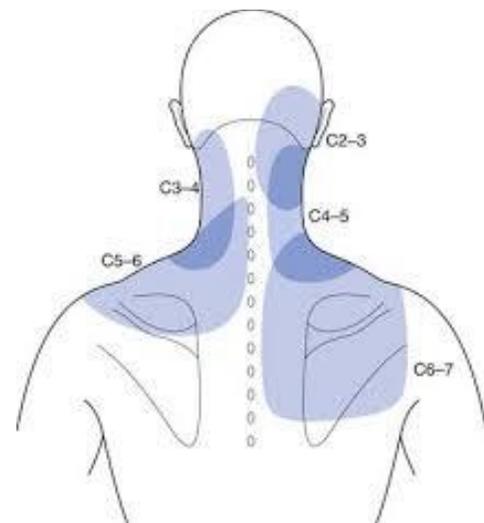
Table 2.:Mean Peak Cervical Strain (N) at C3–C5

Movement Task	Non-Helmeted (Mean ± SD)	Helmeted (Mean ± SD)	p-value
Head Rotation	12.5 ± 2.1	19.8 ± 2.4	<0.001
Lateral Tilt	10.3 ± 1.9	16.7 ± 2.2	<0.001

Fig 2: Cervical Strain Distribution Heat Map

These elevated strain values may have implications for spinal joint loading and neuromuscular fatigue, particularly in patients with unresolved cervical symptoms post-concussion. The mechanical demand placed on the cervical spine during helmeted tasks could prolong recovery in cases where underlying cervicogenic dysfunction is present [31].

4.3. Clinician Feedback

Qualitative data gathered from clinician interviews provided valuable insight into the behavioral and functional implications of helmet use during rehabilitation. Thematic analysis yielded three primary themes consistent across all six interviewed professionals: altered motor strategies, increased fatigue, and limited proprioceptive control.

Altered Motor Strategies: Clinicians observed that participants tended to compensate for reduced cervical mobility and increased mass by recruiting trunk and shoulder musculature. Several noted exaggerated torso sway during head rotation tasks and reduced head-on-neck dissociation, indicating that helmeted individuals may modify movement strategies to accommodate for restricted cervical control [6].

Increased Fatigue: All clinicians reported visible signs of earlier onset fatigue during helmeted conditions. Fatigue was particularly evident during balance-based tasks where prolonged isometric control was required [13]. This observation is consistent with sEMG data showing higher baseline activation and slower recovery to resting levels in helmeted trials.

Limited Proprioception: Clinicians also described helmeted participants as demonstrating delayed or inaccurate head positioning, particularly during blindfolded or eyes-closed trials. These observations suggest that helmets may interfere with proprioceptive inputs from the cervical region, corroborating previous studies linking external head loads to impaired sensory integration [7].

These themes highlight the clinical relevance of the biomechanical data. While helmeted rehabilitation may simulate real-world return-to-play conditions, the altered neuromuscular responses could compromise the goals of early-stage cervical retraining, which often depend on precise motor control and low-load functional reactivation.

5. Discussion

The results of this study demonstrate that helmet use significantly alters cervical neuromuscular responses during post-concussion rehabilitation. The elevated surface electromyography (sEMG) values in the sternocleidomastoid (SCM) and upper trapezius (UT), combined with increased cervical strain at mid-cervical levels (C3–C5), suggest that the cervical musculature compensates for the additional mass and altered center of gravity introduced by helmet use. These findings are consistent with previous studies on military personnel, where helmeted load carriage has been shown to increase cervical muscle activation and fatigue, particularly during prolonged or dynamic tasks [31], [32]. Increased activation of superficial cervical muscles such as the SCM and UT may reflect a heightened effort to stabilize the head–neck complex under conditions of increased inertial demand. While moderate activation is essential for head control and

proprioceptive feedback, excessive or sustained recruitment of these muscles may lead to premature fatigue, altered motor coordination, and potential interference with recovery mechanisms post-concussion [3], [4].

Sustained high-level muscle activity in the absence of appropriate motor patterning can also result in muscle overuse or compensation, particularly if deep stabilizing musculature remains underactive, as noted in other neuromuscular studies involving cervical dysfunction [5]. The strain data further support this compensatory mechanism. The significant increases in peak cervical strain, especially during dynamic head rotation and lateral tilt, indicate higher shear and compressive loads on cervical segments. These mechanical stresses are not only biomechanically inefficient but may also provoke symptom recurrence in patients with lingering cervicogenic impairments a common component of post-concussion syndrome [6].

The qualitative findings from rehabilitation clinicians provide critical context to the quantitative data. All six clinicians observed altered movement strategies in helmeted trials, including excessive torso involvement, reduced cervical dissociation, and earlier signs of fatigue. These observations align with research suggesting that increased external head mass can interfere with the integration of cervical proprioception and vestibular input, both of which are vital for gaze stabilization and balance recovery [7], [8]. Limited proprioceptive awareness, particularly in tasks requiring head repositioning, was also noted echoing previous studies that link helmet use to impaired spatial orientation and postural sway [9].

From a clinical standpoint, these findings raise important considerations for rehabilitation programming. Neuromuscular retraining in post-concussion care often begins with tasks designed to restore normal movement patterns, proprioception, and motor control. The presence of a helmet may disrupt this retraining process, particularly in early phases where low-load, high-precision movements are prioritized. Therefore, clinicians may benefit from removing helmets during foundational rehabilitation exercises and reintroducing them only during later-stage, sport-specific simulations that mimic return-to-play scenarios [10].

Additionally, these findings may prompt reevaluation of helmet design in both sports and military contexts. Current helmet models prioritize impact protection but often neglect ergonomics related to weight distribution and dynamic head control. Ergonomically optimized helmets that reduce cervical strain and preserve proprioceptive input could enhance both safety and rehabilitation outcomes. Previous research has advocated for such improvements, particularly in populations at high risk for repetitive head injuries [11].

In summary, the integration of sEMG, strain analysis, and clinician perspectives reveals a consistent pattern: helmet use during rehabilitation imposes additional neuromuscular and mechanical demands on the cervical spine, potentially altering recovery trajectories. These effects should be carefully considered when designing and implementing concussion rehabilitation protocols, especially for athletes or military personnel likely to train or perform with helmets during recovery.

6. Conclusion

This mixed-methods study demonstrates that helmet use during post-concussion rehabilitation significantly increases cervical muscle activation and spinal strain. The physiological data, particularly elevated sEMG values in the sternocleidomastoid (SCM) and upper trapezius (UT) muscles, indicate greater neuromuscular demand when tasks are performed with a helmet. Additionally, strain gauge measurements show that cervical spinal loading especially at the C3–C5 levels is substantially elevated under helmeted conditions. These biomechanical findings are further supported by qualitative feedback from rehabilitation clinicians, who consistently observed altered motor strategies, earlier onset of fatigue, and challenges in proprioceptive control among helmeted participants. Taken together, these results suggest that helmet use during rehabilitation modifies both the mechanical and neuromuscular context in which recovery occurs. The increased effort required to stabilize the head–neck complex, combined with potential proprioceptive disruption, may influence the effectiveness of standard rehabilitation protocols. Therefore, clinicians should carefully consider the timing and appropriateness of helmet use during various stages of neuromuscular retraining. These insights also underscore the importance of future research on helmet ergonomics and the development of rehabilitation strategies that accommodate or mitigate the biomechanical impact of headgear.

7. Limitations and Future Work

This study has several limitations. The sample was limited to young adult athletes, which may affect the generalizability of findings to other populations. Only one helmet model was used, and results may vary with different designs or weights. Additionally, the study employed a cross-sectional design, so long-term effects of helmeted rehabilitation were not assessed. Future research should investigate a wider range of helmet types and user demographics. Incorporating vestibular and visual assessments would provide a more complete picture of sensorimotor impact. Longitudinal studies are also needed to evaluate how helmet use affects neuromuscular recovery, proprioception, and return-to-play outcomes over time, ultimately informing more effective and personalized concussion rehabilitation protocols.

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