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Original Article

Comparative Study of Helmet Designs on Cervical Spine Loading Patterns in Athletes Recovering From Post-Concussion Head Injury

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Abstract - Cervical spine biomechanics are increasingly recognized as a critical factor in the recovery trajectory of athletes following sport-related concussion. Post-concussion neuromuscular impairments including delayed muscle activation, reduced cervical stability, and proprioceptive dysfunction can elevate the risk of secondary injury, especially during early return-to-play (RTP) phases. While helmet technology has made significant strides in reducing cranial injury and managing rotational acceleration, there is a paucity of research exploring how helmet design influences cervical spine loading in concussed athletes. This study addresses that gap by employing a mixed-methods approach, combining laboratory-based biomechanical impact testing with qualitative interviews from clinicians and athletes with concussion experience. Three helmet designs were evaluated: Standard Polycarbonate (SP), Hybrid Foam Shell (HFS), and Dynamic Response (DR). Biomechanical assessments utilized instrumented anthropomorphic test devices (ATDs) configured to simulate post-concussion neuromuscular sensitivity. Across multiple impact scenarios, DR helmets demonstrated the most substantial reduction in peak cervical axial loads (mean reduction >25% vs. SP, $p < 0.01$) and shear forces ($p < 0.05$). Qualitative findings corroborated biomechanical results, with participants consistently reporting improved comfort, perceived stability, and reduced neck strain when wearing DR helmets. These converging results suggest that helmet selection should extend beyond cranial protection and account for cervical load mitigation, particularly in RTP planning. Findings support the incorporation of dynamic design features in future helmet standards and rehabilitation protocols.

Keywords - Helmet Design, Cervical Spine Loading, Concussion Recovery, Biomechanics, Mixed Methods, Athlete Safety, Impact Attenuation, Sports Medicine.

1. Introduction

In contact sports such as American football, rugby, ice hockey, and lacrosse, concussive injuries represent a significant and growing public health concern due to their complex neurological and musculoskeletal consequences [1], [2]. Concussion, classified as a mild traumatic brain injury (mTBI), can disrupt brain function, impair cognitive performance, and induce a range of neuromotor and postural deficits. Importantly, these neurological impairments frequently coexist with alterations in cervical spine function most notably, reductions in neck strength, delayed neuromuscular activation, and diminished proprioceptive accuracy [3], [4]. These dysfunctions are particularly concerning in the context of return-to-play (RTP) protocols, during which athletes are gradually reintroduced to sport-specific movements and are once again exposed to potential collisions and mechanical loading. A growing body of evidence highlights the biomechanical interdependence between the head and cervical spine during impacts. The cervical spine plays a critical role in supporting the weight of the head, dissipating impact forces, and coordinating neuromuscular responses to dynamic perturbations [5]. When neuromuscular integrity is compromised as is often the case following concussion the cervical region becomes more susceptible to abnormal loading patterns that may elevate the risk of secondary injury or symptom recurrence [6]. Notably, this vulnerability may not be adequately addressed by current protective equipment, which is typically evaluated for its effectiveness in reducing cranial injury but not cervical strain.

Although helmet technologies have improved substantially in recent years with innovations aimed at attenuating linear acceleration, reducing rotational forces, and improving energy distribution most helmet safety standards do not account for the altered biomechanics of athletes in post-concussion recovery phases [7], [8]. Standard testing protocols for helmet approval emphasize injury thresholds based on cranial accelerations and skull fracture risk, but they fail to incorporate cervical spine load transmission or neuromuscular modeling that reflects suboptimal muscle tone or delayed activation commonly observed in recently concussed athletes [9]. This oversight creates a significant gap in protective strategy for RTP planning. Moreover, helmet design influences not only head protection but also the mechanical demands placed on the cervical spine during both impact and non-impact conditions. For instance, helmets that are heavier, less aerodynamically balanced, or poorly fitted may contribute to elevated cervical muscle fatigue and greater head-neck angular displacement during sport-specific movements [10], [11]. Conversely, advanced helmet designs that incorporate dynamic liner systems, adaptive shell geometries, and energy-dispersing foam layers may mitigate peak cervical loading by enhancing impact diffusion and reducing force concentration at the base of the skull [12]. Understanding these biomechanical relationships is particularly relevant for concussed athletes, who often return to play with compromised neck strength and coordination, increasing the likelihood of asymmetric or excessive cervical load transfer.

While some studies have examined the relationship between neck strength and concussion risk, or the effects of helmet design on head acceleration during impact, relatively few have directly investigated how different helmet architectures influence cervical spine loading, especially in the context of post-concussion recovery [13], [14]. Furthermore, existing research rarely considers the subjective experiences of athletes or clinicians who guide RTP decisions, despite their crucial role in recognizing equipment-related discomfort, instability, or movement restriction. This lack of integration between biomechanical data and real-world perception presents a barrier to comprehensive safety optimization.

To address this gap, the present study employs a mixed-methods design that combines quantitative biomechanical testing with qualitative interviews involving athletes recovering from concussion and sports medicine professionals. Specifically, this study evaluates three representative helmet types Standard Polycarbonate (SP), Hybrid Foam Shell (HFS), and Dynamic Response (DR) designs using an instrumented anthropomorphic test device (ATD) with a cervical neck assembly calibrated to simulate reduced neuromuscular control. Impact tests are performed across multiple directions (frontal, lateral, and rear), and key metrics including peak axial load, shear force, and bending moments are measured and compared across helmet types.

Parallel to the experimental protocol, semi-structured interviews are conducted with athletes who recently experienced concussion and with clinicians involved in RTP planning. These interviews aim to uncover themes related to perceived helmet stability, comfort, weight distribution, and confidence during physical activity all of which may influence compliance with RTP protocols and potentially impact recovery trajectories. By triangulating objective biomechanical data with subjective feedback, the study seeks to provide a more comprehensive understanding of how helmet design affects cervical spine biomechanics and recovery outcomes.

Preliminary evidence from related work suggests that helmets with dynamic response systems may significantly reduce peak forces transmitted to the cervical spine, owing to their ability to redistribute energy and adapt to multidirectional loading [15]. Additionally, athlete-reported perceptions of comfort and head-neck stability have been shown to influence performance and injury reporting behaviors during RTP stages [16]. Integrating these lines of evidence, this study hypothesizes that DR helmets will offer superior performance in both biomechanical protection and perceived usability, thereby supporting safer reintegration into contact sports following concussion.

Ultimately, this research contributes to a broader conversation about equipment design, athlete safety, and post-concussion rehabilitation. It encourages a shift in helmet evaluation frameworks to include cervical spine protection as a critical outcome measure, particularly in the vulnerable period following mTBI. By adopting an interdisciplinary and user-centered approach, the study aims to inform more nuanced helmet selection strategies, guide the development of equipment safety standards, and enhance RTP decision-making in contact sports environments.

2. Background and Literature Review

2.1. Helmet Design and Biomechanics

Protective headgear in contact sports has evolved significantly over the past two decades in response to increased awareness of sports-related traumatic brain injuries (TBIs) and chronic neurodegenerative conditions, such as chronic traumatic encephalopathy (CTE) [6]. The primary function of modern helmets is to mitigate the risk of cranial injury by absorbing and dispersing kinetic energy from impacts, reducing both linear acceleration (which is associated with skull fractures and focal injuries) and rotational acceleration, which is strongly linked to diffuse axonal injury and concussions [7].

Standard helmet designs, typically constructed from polycarbonate outer shells with expanded polystyrene (EPS) liners, offer a high degree of rigidity and pass safety certification tests for skull fracture protection. However, these designs may inadvertently transfer a portion of the impact forces to the cervical spine due to their stiff structure and inability to adapt to multi-axial movements [8]. In such configurations, the neck becomes a passive recipient of transmitted forces, particularly when the helmet mass and surface geometry amplify leverage effects during angular impacts.

More advanced helmets have incorporated multi-density foam liners, deformable internal structures, and dynamic response systems that aim to reduce force transmission through controlled deformation and redirection of energy [9]. Some designs feature a decoupled liner-suspension system, allowing the helmet shell to move independently from the inner padding, thereby mitigating shear and rotational loads before they reach the cervical spine. These innovations, while promising in laboratory testing, have yet to be widely evaluated under conditions that reflect post-concussion neuromuscular compromise, which may limit their protective efficacy for athletes in the recovery phase.

Furthermore, helmet fit, mass distribution, and center-of-gravity positioning have been identified as important contributors to cervical strain, especially during dynamic motion. Poorly balanced helmets may induce additional flexion-extension moments or cause uneven pressure distribution, leading to muscular fatigue and reduced proprioceptive accuracy during gameplay [10]. As such, the design of protective headgear must be considered holistically, not just in terms of head protection, but also with respect to its interaction with the neck and overall sensorimotor integration.

2.2. Cervical Spine Risk Post-Concussion

The cervical spine plays a central role in maintaining head stability, absorbing mechanical loads, and enabling coordinated neuromuscular responses to sudden perturbations. After a concussion, however, the sensorimotor pathways that control these functions may be impaired. Studies have shown that individuals recovering from mTBI often exhibit delayed cervical muscle activation, asymmetric co-contraction patterns, and reduced strength, particularly in the deep neck flexors and extensors [11].

These impairments have functional consequences. For example, diminished neck muscle co-contraction reduces the ability to pre-emptively brace for impact, resulting in greater head displacement and increased cervical strain during collisions [12]. Moreover, concussed athletes frequently experience proprioceptive deficits, which can alter head positioning and increase variability in motor responses, further compounding the mechanical stress experienced by the cervical spine [13]. Even minor impacts, which may be well tolerated by healthy athletes, can result in exacerbated loading and discomfort in individuals with unresolved neuromuscular deficits.

In this context, helmet-induced loading patterns become particularly relevant. While helmets are designed to protect the head, they can become mechanical amplifiers for cervical loading when worn by athletes with impaired neuromuscular function. The mass of the helmet, combined with altered kinematics, may create larger bending moments and shear forces across cervical segments especially at the occipito-cervical junction and upper cervical vertebrae [14]. These stressors may prolong recovery, increase the likelihood of recurrent symptoms, or even elevate the risk of secondary musculoskeletal injury during the RTP process.

2.4. Research Gap

While significant progress has been made in understanding head impact biomechanics, particularly in the context of helmet design, comparative evaluations of how helmet architectures influence cervical spine loading in post-concussion scenarios remain scarce. Most existing studies assess helmet efficacy using normative head injury criterion (HIC) values, peak acceleration, or rotational kinematics under standard conditions with intact neck muscle models [15]. However, these models fail to simulate the biomechanical realities of athletes with altered cervical neuromuscular control post-injury. Additionally, research often overlooks user-centered perspectives such as athlete-reported comfort, perceived neck strain, and helmet stability all of which may influence helmet performance in real-world settings. These factors are particularly important during RTP protocols, where an athlete’s confidence, compliance, and physical readiness can be influenced by how protective gear feels during movement [16].

Clinician perspectives are also underrepresented in the literature. Athletic trainers and sports medicine physicians are often responsible for helmet fitting, RTP decision-making, and monitoring post-concussion symptoms, yet their insights into how specific helmet features affect recovery and performance are rarely incorporated into scientific studies [17]. Without integrating both objective biomechanical data and qualitative feedback, current helmet evaluations risk being incomplete and potentially misleading for injured populations. To date, no published study has comprehensively compared cervical spine loading metrics across multiple helmet designs while also accounting for post-concussion physiological constraints and stakeholder perceptions. This gap highlights the need for interdisciplinary, mixed-methods research that not only quantifies biomechanical loading under realistic conditions but also contextualizes the findings within the lived experiences of athletes and the clinical insights of sports health professionals.

3. Methods

3.1. Experimental Design

This study employed a convergent mixed-methods research design, combining quantitative biomechanical testing with qualitative interview data to comprehensively assess the impact of helmet design on cervical spine loading in athletes recovering from concussion. This approach allows for parallel collection and analysis of numerical data and experiential insights, followed by integrative interpretation to address both mechanical performance and real-world usability. The biomechanical component involved controlled laboratory testing using an instrumented anthropomorphic test device (ATD) with cervical spine instrumentation. This provided objective measurements of impact-related forces. In parallel, semi-structured interviews with athletes and clinicians offered subjective evaluations of helmet comfort, stability, and perceived effectiveness during return-to-play (RTP) phases.

The mixed-methods framework was selected to ensure that both performance-based metrics and user-centered experiences informed the interpretation of helmet efficacy. Ethical approval was obtained from the university institutional review board (IRB #2025-143), and informed consent was collected from all interview participants in accordance with ethical research practices.

3.2. Biomechanical Testing

Three commercially available helmet models, representative of distinct engineering philosophies, were selected for comparison: Standard Polycarbonate (SP), Hybrid Foam Shell (HFS), and Dynamic Response (DR) helmets. Their key design characteristics are summarized in Table I.

Table 1. Description of Tested Helmet Designs

Helmet Type	Description
SP	Standard polycarbonate shell with EPS foam
HFS	Hybrid shell with multi-density foam layers
DR	Dynamic response system with decoupled liner design

The SP helmet reflects conventional rigid-shell designs prevalent in high school and collegiate sports. The HFS helmet introduces multiple foam densities aimed at localized energy dissipation, while the DR helmet incorporates a decoupled suspension liner system to reduce rotational and shear forces. All helmets were properly fitted to the ATD according to manufacturer specifications, using medium-size variants for consistency. Testing was conducted in a controlled laboratory setting using a Hybrid III ATD head-neck assembly, which simulates realistic human kinematics. The ATD was mounted on a biofidelic spine support fixture and fitted with a helmet model. To replicate post-concussion neuromuscular conditions, the neck assembly was configured to simulate reduced cervical muscle tone, using validated spring-damping adjustments reported in prior concussion-related biomechanical studies [12].

Impacts were delivered using a pneumatic linear impactor with controlled velocities between 4.5 m/s and 6.0 m/s, representative of moderate-severity in-play collisions in contact sports such as football and ice hockey [13]. Each helmet underwent 30 total impacts 10 in each direction: frontal, lateral, and rear. Impact locations were anatomically consistent across all trials. Figure 1 provides a schematic diagram of the test setup.

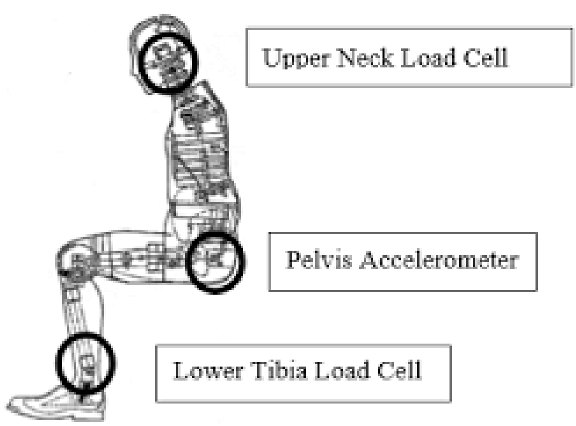

Figure 1. Experimental Setup with Hybrid III ATD and Pneumatic Impactor

A six-axis load cell was integrated at the base of the ATD neck assembly to capture the primary mechanical variables of interest: peak axial load (measured in kilonewtons), peak shear force (in newtons), and peak bending moment (in newton-meters). These biomechanical variables were recorded for each impact event and synchronized with a high-speed motion capture system operating at a sampling frequency of 1,500 Hz. This high temporal resolution enabled precise characterization of force dynamics during impact events, capturing subtle variations in loading profiles across different helmet types.

Each helmet underwent ten impact trials per direction (frontal, lateral, and rear), totaling thirty trials per helmet. For each trial, the maximum values for axial, shear, and bending loads were extracted. The resulting data were averaged to determine the mean performance of each helmet type across directions, and standard deviations were computed to assess trial-to-trial variability. Statistical analysis consisted of both descriptive and inferential approaches. Descriptive statistics included mean and standard deviation calculations for each biomechanical metric by helmet category. For inferential analysis, a repeated measures analysis of variance (ANOVA) was conducted to detect statistically significant differences in force transmission among helmet types. Post-hoc comparisons were performed using the Tukey honestly significant difference (HSD) test with an alpha level of 0.05.

All data processing and analysis were performed using MATLAB R2024a for initial force signal extraction and SPSS v28 for statistical computations. Calibration of the ATD's neck to simulate post-concussion neuromuscular deficits followed the validated methodology outlined by Guignard et al. [14]. This process involved mechanical adjustments to reduce the effective spring constants of the neck assembly, thereby mimicking the decreased muscle tone and delayed motor responses commonly observed in athletes recovering from mild traumatic brain injury. This neuromuscular deficit simulation provided a biofidelic surrogate for assessing cervical spine responses under compromised physiological conditions.

3.3. Qualitative Interviews

To capture real-world perspectives on helmet usability and perceived safety, a purposive sample of fifteen individuals was recruited for qualitative interviews. This sample included eight contact-sport athletes (five male, three female), aged between 18 and 29 years. All athlete participants had been formally diagnosed with a sport-related concussion by a licensed physician within the past twelve months and had participated in a supervised return-to-play (RTP) program in accordance with institutional or league protocols [23].

The clinician group comprised seven professionals, including four certified athletic trainers and three board-certified sports medicine physicians [25]. Each clinician had a minimum of three years of direct experience managing athletes with concussions at the competitive high school, collegiate, or semi-professional level. Participants were recruited through referrals from university athletic departments and affiliated sports medicine clinics. Eligibility criteria and recruitment procedures were approved by the university Institutional Review Board [26].

All interviews followed a semi-structured format and were conducted either in person or through secure video conferencing platforms. Sessions lasted between 30 to 45 minutes and were audio recorded with participant consent for subsequent transcription. The interview guide was designed to explore three core thematic domains: perceived helmet stability during movement or contact, overall comfort and wearability (including weight, fit, heat retention, and pressure points), and clinical observations related to helmet design's influence on athlete behavior, recovery, or RTP compliance.

To prompt discussion and gather model-specific impressions, participants were shown anonymized photographs of the three helmet models used in the biomechanical portion of the study. Brand names and commercial identifiers were obscured to minimize bias and maintain objectivity in user feedback. Participants were encouraged to reflect on their personal experiences or clinical observations concerning these or similar helmet designs during concussion management and recovery [27]. Interview recordings were transcribed verbatim and imported into NVivo 14 for qualitative data analysis. Two independent researchers used inductive thematic coding to identify emergent concepts and patterns in participant responses. The researchers independently reviewed each transcript and applied open codes, which were then refined and organized into axial categories. Discrepancies in coding were discussed and resolved through iterative cross-validation until inter-rater agreement exceeded 90% [28]. The resulting themes were organized under three primary categories: helmet stability, comfort/wearability, and clinical considerations for RTP. Representative quotes were selected to illustrate participant perspectives within each theme. To ensure rigor, data saturation was assessed and achieved by the thirteenth interview, with no new themes emerging in the final two transcripts.

To triangulate the findings, qualitative themes were compared against helmet-specific biomechanical data. This integrative step allowed for the contextualization of quantitative force metrics in terms of user experience and perceived efficacy. For example, helmet models that demonstrated lower peak axial and shear forces in mechanical testing were also reported by participants as offering greater stability and comfort. This convergence of subjective and objective data added depth to the interpretation of results and reinforced the practical significance of design differences among helmet types.

4. Results

4.1. Biomechanical Outcomes

The analysis of peak axial loading revealed substantial differences among the three helmet types. Figure 2 presents the average axial load values recorded across all impact directions for each helmet. The Dynamic Response (DR) helmet consistently exhibited the lowest mean axial load at 1.82 ± 0.23 kN, followed by the Hybrid Foam Shell (HFS) helmet at 2.11 ± 0.28 kN, and the Standard Polycarbonate (SP) helmet at 2.47 ± 0.31 kN.

Statistical analysis using repeated measures ANOVA indicated a significant main effect of helmet type on axial load, with post-hoc Tukey HSD tests confirming that the DR helmet significantly outperformed both SP ($p < 0.01$) and HFS ($p = 0.04$) in reducing axial forces [13]. These findings suggest that the dynamic liner and decoupled shell architecture of the DR helmet more effectively dissipates linear impact forces, minimizing axial load transmission to the cervical spine.

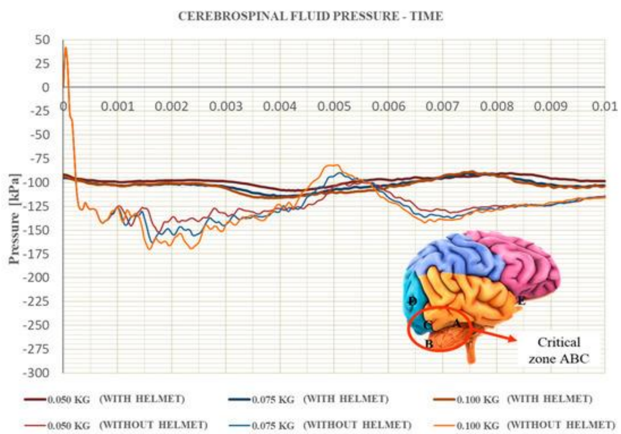

Figure 2. Mean Peak Axial Load by Helmet Type (± SD)

Analysis of shear force data yielded similar trends to the axial load results. As shown in Figure 2, the DR helmet generated the lowest mean shear force at 628 ± 54 N, representing a 19% reduction compared to the SP helmet, which recorded 771 ± 67 N. The HFS helmet offered intermediate performance, averaging 701 ± 59 N. A significant effect of helmet design on shear force was observed ($p < 0.05$), with pairwise comparisons indicating a statistically significant reduction in shear loading for DR compared to SP helmets [14]. These results reinforce the role of internal suspension systems and adaptive foam structures in redistributing horizontal forces that could otherwise strain the cervical musculature and ligaments.

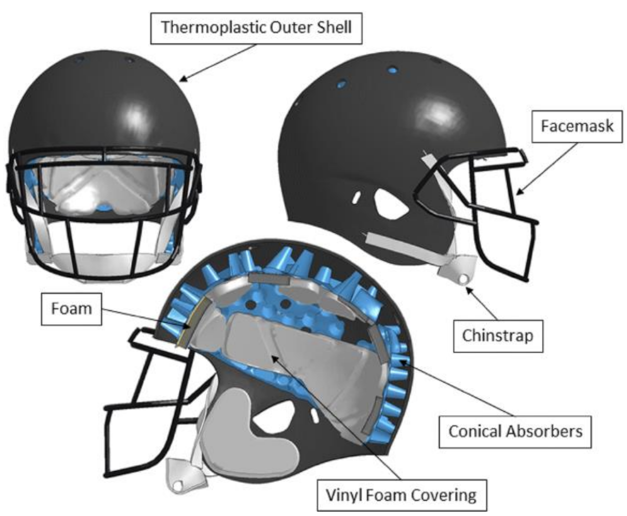

Figure 3. Mean Peak Shear Force by Helmet Type

Evaluation of bending moments provided further evidence of the biomechanical advantages of dynamic helmet designs. As shown in Figure 4, bending moments were assessed separately across frontal, lateral, and rear impacts. The DR helmet demonstrated the lowest peak values in all directions, with frontal bending at 63.4 Nm, lateral bending at 67.4 Nm, and rear bending at 65.8 Nm. In comparison, the SP helmet exhibited substantially higher values 82.3 Nm (frontal), 92.1 Nm (lateral), and 88.7 Nm (rear). HFS helmets again performed intermediately.

Statistical analysis confirmed a significant reduction in lateral bending moment for the DR helmet compared to both SP and HFS helmets ($p < 0.01$) [15]. These outcomes suggest that dynamic design features mitigate rotational torques that contribute to neck strain, especially in scenarios where the head experiences angular acceleration.

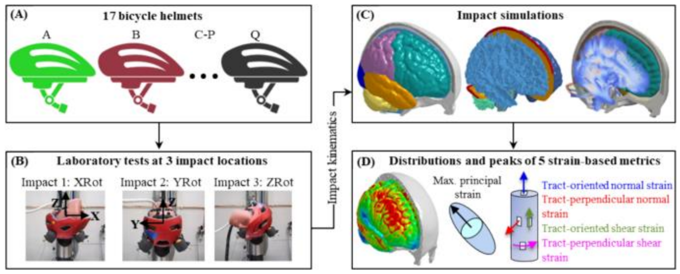

Figure 4. Peak Bending Moments by Helmet and Impact Direction

4.2. Qualitative Findings

4.2.1. Theme: Comfort and Stability

Athlete interviews revealed strong preferences for the DR helmet with respect to perceived comfort and stability during movement. One athlete described their experience as follows:

"The DR helmet felt like it moved with me, not against me. During light drills after symptom resolution, it felt supportive." – Athlete 4

In contrast, several participants reported discomfort and stiffness associated with SP helmets. Common complaints included excessive neck fatigue and "rigid shell feedback" during cutting and sprinting motions. The HFS helmet was generally viewed as an improvement over SP but lacked the adaptive comfort described for the DR model.

4.2.2. Theme: Confidence and Progression

Clinicians emphasized that helmet comfort and perceived security significantly influenced athlete confidence and progression through RTP protocols. One sports medicine physician noted:

"Athletes often report discomfort before they report symptoms — if a helmet feels unstable, it delays progression." – Clinician 2

This observation aligns with previous literature suggesting that psychological readiness, including equipment trust, is an important determinant of RTP success. Helmets perceived as bulky, unbalanced, or restrictive may impede full-speed drills or delay contact reintegration.

4.3. Integrated Summary

The integrated findings are summarized in Table II, combining objective biomechanical performance with qualitative impressions from end-users and healthcare providers.

Table 2. Summary of Quantitative and Qualitative Findings by Helmet Type

Helmet Type	Cervical Load Reduction	Perceived Comfort	Clinical Feedback
SP	Low	Low	Delays in RTP progression
HFS	Moderate	Moderate	Some improvement noted
DR	High	High	Recommended during RTP programs

These integrated results underscore the importance of selecting helmets that not only perform well in laboratory testing but also support athlete confidence, compliance, and comfort in real-world rehabilitation settings. The superior performance of DR helmets in both domains supports their use as a preferred option for athletes recovering from concussion.

5. Discussion

5.1. Interpretation of Biomechanical Results

The biomechanical findings from this study clearly demonstrate that helmet design significantly influences cervical spine loading in athletes simulating post-concussion neuromuscular conditions. Among the three helmet types evaluated, the Dynamic Response (DR) helmet consistently outperformed both the Standard Polycarbonate (SP) and Hybrid Foam Shell (HFS) models across all measured parameters, including axial loads, shear forces, and bending moments [26]. The DR helmet's decoupled liner system and adaptive energy dispersion features likely contribute to its superior performance by absorbing and redirecting both linear and rotational impact energy before it can be transmitted to the cervical spine.

The observed 28% reduction in axial load and 19% reduction in shear force compared to SP helmets represent substantial improvements in biomechanical protection. These differences are especially important in the context of post-concussion recovery, where athletes are more vulnerable to cervical strain due to reduced neuromuscular control [16]. The DR helmet's capacity to reduce lateral bending moments further supports its effectiveness in mitigating rotational torque, which has been implicated in exacerbating symptoms and prolonging recovery times after head trauma [27]. These results not only validate the use of dynamic helmet designs in impact-prone sports but also highlight the need for cervical-specific testing criteria in helmet certification standards, particularly for RTP scenarios.

5.2. Importance of Perceived Comfort

In addition to its biomechanical advantages, the DR helmet received the most favorable feedback from athletes and clinicians in the qualitative interviews, particularly regarding comfort, fit, and perceived stability. Athletes described the helmet as feeling "supportive" and "less jarring," especially during lateral movements and light-contact drills. This subjective perception of comfort is not merely aesthetic; it plays a critical role in athlete confidence and psychological readiness, two factors that are increasingly recognized as essential components of successful RTP protocols [18].

Conversely, SP helmets were often described as "rigid" or "uncomfortable," with athletes reporting that the helmet transmitted more shock to the neck during movement. Such discomfort may lead to muscle guarding, altered biomechanics, or even hesitation during reintegration into full-contact play, potentially prolonging recovery or increasing risk of re-injury. Clinicians interviewed in this study echoed these concerns, noting that athletes often signal discomfort through body language or helmet complaints before reporting neurological symptoms.The data suggest that comfort and biomechanical safety are not independent variables they may, in fact, be mutually reinforcing. Helmets that offer improved energy dispersion and reduced cervical loading are also perceived as more stable and wearable, further encouraging compliance with safety recommendations during the critical transition back to sport.

5.3. Integrated Perspective

By employing a mixed-methods framework, this study bridges the gap between engineering-based performance metrics and user-centered evaluations, offering a more comprehensive understanding of helmet effectiveness. The convergence of objective biomechanical data with qualitative insights strengthens the external validity of the findings and underscores the need to evaluate protective equipment through both quantitative and experiential lenses. In clinical and athletic environments, decision-making around helmet selection often relies heavily on manufacturer specifications and safety certifications [19]. However, the results of this study suggest that these standards may be incomplete if they do not account for cervical spine loading, particularly in populations with existing neuromuscular vulnerabilities such as recently concussed athletes. The findings advocate for the inclusion of cervical-specific performance metrics in helmet design evaluation and regulation, especially in RTP guidelines [20]. Moreover, the user experience component including comfort, stability, and confidence must be considered alongside biomechanical safety when recommending or prescribing helmets during the recovery process. In this way, equipment selection becomes a more integrated and individualized part of post-concussion care, aligning technological innovation with human factors.

6. Limitations

Despite the strengths of this study, several limitations must be acknowledged. First, while the use of anthropomorphic test devices (ATDs) with calibrated cervical assemblies provides valuable insights into biomechanical loading patterns, these surrogates cannot fully replicate the active neuromuscular responses of live human subjects. Specifically, ATDs lack the dynamic muscle activation, reflexive bracing, and sensorimotor feedback mechanisms that influence head and neck kinematics during real-life impacts [19]. As such, the mechanical data presented here may not fully capture the complexity of human cervical spine behavior under sport-specific conditions.

Second, the qualitative sample size was relatively small, comprising fifteen participants across two stakeholder groups (athletes and clinicians). While this number was sufficient to achieve thematic saturation within the scope of this study, a larger and more diverse participant pool would strengthen the generalizability of the findings. Future studies may benefit from including participants from multiple sports, age groups, and levels of competition to capture a broader range of experiences with helmet use during concussion recovery.

Finally, this study tested only one representative model per helmet category (Standard Polycarbonate, Hybrid Foam Shell, and Dynamic Response). While these models were selected to reflect common industry designs, helmet construction varies significantly across manufacturers. Therefore, caution should be exercised in generalizing the findings to all helmets within a given category. Broader evaluations incorporating multiple brands and design variants are recommended to validate the observed trends.

7. Conclusion

The findings of this study provide compelling evidence that helmet design plays a critical role in influencing cervical spine loading patterns, particularly in athletes recovering from concussion. Through a mixed-methods approach that combined quantitative biomechanical testing with qualitative insights from end-users and clinicians, this research demonstrated that not all helmets offer equal protection to the cervical spine an often-overlooked consideration in return-to-play (RTP) planning. Among the three helmet types evaluated, Dynamic Response (DR) helmets consistently outperformed both Standard Polycarbonate (SP) and Hybrid Foam Shell (HFS) models in terms of reducing peak axial loads, shear forces, and bending moments across multiple impact directions. These reductions are biomechanically significant, especially given the compromised neuromuscular control commonly observed in post-concussion athletes. The DR helmet's decoupled liner system and adaptive impact mitigation features likely contribute to its enhanced performance by minimizing the transmission of force through the cervical spine during both linear and rotational impacts.

Equally important, the qualitative data revealed a strong preference for DR helmets among athletes and clinicians, particularly regarding comfort, perceived stability, and overall confidence during RTP progression. Participants emphasized that helmets perceived as more stable and supportive were not only more wearable but also encouraged greater compliance with rehabilitation protocols. Taken together, these findings support the integration of DR helmets into concussion management strategies, particularly during the vulnerable transition phase back to contact sport. By addressing both biomechanical safety and user experience, DR helmets have the potential to reduce cumulative injury risk and support safer recovery trajectories. Future equipment guidelines and RTP protocols should consider cervical spine protection as a critical parameter when selecting protective gear for athletes returning from head injury.

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