

Review

Restoring Symmetry After Sport-Related Concussion: A Viewpoint on Biofeedback-Guided Rehabilitation

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Abstract

Sport-related concussion (SRC) rehabilitation has advanced toward active, multidomain management, yet recovery may still be judged largely through symptom resolution and broad clinical indicators that may not fully capture persistent functional deficits. Emerging evidence suggests subtle disturbances in postural control, gait, and sensorimotor coordination may persist beyond apparent clinical recovery, raising the possibility that unresolved asymmetries represent an underrecognized dimension of dysfunction. This Viewpoint proposes symmetry restoration as a potential rehabilitative construct in SRC management and explores how biofeedback-guided approaches may provide a conceptual framework for identifying, monitoring, and retraining symmetry-related deficits. Drawing from concussion research, motor control theory, rehabilitation science, and biofeedback applications, this article discusses postural and movement asymmetries as possible markers of incomplete recovery, examines visual, wearable, neuromuscular, and auditory biofeedback strategies as potential mechanisms for symmetry-informed rehabilitation, and outlines clinical implications and future research priorities. Rather than proposing symmetry as a stand-alone determinant of recovery, this Viewpoint advances the conceptual proposition that symmetry-oriented approach may complement existing multidomain models by serving as an additional layer of functional assessment alongside symptom reporting, neurocognitive evaluation, vestibular and oculomotor examination, exertional testing, and routine clinical assessment. Within this framework, symmetry-related measures are envisioned not as independent clearance criteria, but as potentially informative indicators of residual sensorimotor function that may help guide rehabilitation progression and contribute to more functionally informed return-to-sport decision making through adjunctive measures such as center-of-pressure behavior, center-of-mass displacement, gait symmetry, stance and swing time asymmetry, limb-loading patterns, interlimb coordination, and muscle activation symmetry.

Keywords: sport-related concussion; symmetry; biofeedback; rehabilitation; sensorimotor control; postural control; gait; return to sport; precision rehabilitation; motor control



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1. Introduction

Sport-related concussion (SRC) management has evolved substantially over the past two decades, moving away from passive rest paradigms toward active, multidomain models of rehabilitation that address symptom burden, vestibular and oculomotor dysfunction, exertional intolerance, cervical contributions, and neuromuscular impairments [1]. This shift has improved recognition that concussion is a heterogeneous injury requiring

individualized and progressive management [1]. At the same time, contemporary return-to-sport (RTS) decision making often remains anchored to symptom resolution, neurocognitive performance, and standard clinical examinations, measures that may not fully capture persistent functional deficits relevant to recovery [2]. Emerging evidence further suggests that recovery of symptoms may precede normalization of some objective functional measures, raising the possibility that conventional recovery markers may underestimate persistent deficits [3,4]. This potential divergence between apparent clinical recovery and lingering functional disturbance provides part of the rationale for considering symmetry as an underrecognized dimension of post-concussion rehabilitation.

Emerging evidence suggests that subtle impairments in sensorimotor control may persist even after athletes appear clinically recovered [2,3,5]. Alterations in postural stability, gait characteristics, dual-task motor performance, dynamic balance, and movement coordination have all been reported following concussion, raising concerns that recovery may not always represent complete restoration of function [2–5]. Importantly, these disturbances are multidimensional and should not be interpreted solely as mechanical asymmetry. Dual-task deficits, for example, may reflect divided attentional demands, cognitive-motor interference, slowed information processing, or neurocognitive fatigue, in addition to altered sensorimotor control [2–5]. Within this broader framework, symmetry-related deficits are proposed as one possible manifestation of residual dysfunction, including potential asymmetries in force production, movement control, postural regulation, or coordinated neuromuscular performance [4,6].

Despite growing attention to objective measures in concussion assessment, symmetry itself has received relatively limited attention as an explicit rehabilitation target in post-concussion care [4,6]. This represents a notable gap, particularly given that symmetry has long been regarded as a meaningful construct in broader rehabilitation sciences, motor control theory, biomechanics, and sports medicine [6–8]. In other areas of rehabilitation, restoration of symmetry is frequently viewed as an indicator of functional recovery and a target for intervention [8,9]. Applying a similar conceptual framework to concussion rehabilitation may offer a novel perspective for understanding lingering deficits and guiding treatment progression.

Biofeedback may provide one mechanism through which this concept can be operationalized [10]. By supplying augmented visual, auditory, proprioceptive, or performance-based feedback related to movement execution and motor output, biofeedback interventions may support identification, monitoring, and retraining of persistent asymmetries that exceed expected task-related variability and are otherwise difficult to detect or address through conventional rehabilitation approaches alone [10]. Moreover, the integration of biofeedback with symmetry-oriented approach aligns closely with emerging interests in precision rehabilitation, objective monitoring, and individualized recovery strategies [11].

Within the context of the present Special Issue focused on biofeedback applications and symmetry in rehabilitation, sports, and ergonomics, this topic warrants consideration. The intersection of concussion rehabilitation, symmetry restoration, and biofeedback represents a potentially underexplored area with implications for both clinical practice and future investigation. Therefore, the purpose of this Viewpoint is to propose symmetry restoration as an underrecognized target in SRC rehabilitation and to discuss how biofeedback-guided approaches may offer a conceptual framework for advancing assessment, intervention, and RTS decision making.

For the purposes of this Viewpoint, “symmetry” refers to the relative balance or coordination of motor output, postural regulation, loading behavior, gait characteristics, or sensorimotor control across limbs, body segments, or task demands. “Asymmetry” refers to observable or measurable deviations in these domains that may exceed expected

task-related or biological variability. “Symmetry restoration” is therefore not defined as achieving perfect bilateral equivalence, but rather as the process of identifying and reducing potentially meaningful asymmetrical control strategies when they appear to reflect residual dysfunction, compensation, or impaired functional readiness. At present, concussion-specific thresholds for clinically meaningful asymmetry remain insufficiently established; therefore, these constructs are presented as a conceptual framework requiring future empirical validation rather than as prescriptive clinical criteria.

2. Persistent Asymmetry as an Underrecognized Deficit

2.1. Postural Control Asymmetries Following Concussion

Although balance impairment is widely recognized after SRC, postural disturbance may involve more than generalized instability and may instead reflect asymmetrical control strategies that persist beyond apparent clinical recovery [1,2,5]. This distinction is important because standard bedside or field-based balance assessments often suggest recovery within approximately 3 to 5 days in many athletes, whereas instrumented approaches have identified lingering postural-control abnormalities for up to 30 days, and some dual-task gait studies have reported deficits persisting for as long as 2 months after injury [2,3,5].

From a mechanistic standpoint, postural control depends on the continuous integration of visual, vestibular, and somatosensory input to regulate body position and movement in space [12]. When concussion disrupts this integration, the result may manifest as generalized instability, altered sensory weighting, or, in some individuals, asymmetrical control strategies characterized by uneven loading or asymmetrical sway behavior [5,12]. Importantly, existing evidence does not uniformly establish asymmetry as the predominant expression of persistent post-concussion balance deficits. Rather, the symmetry framework proposed here interprets asymmetrical postural behavior as one potential manifestation of disrupted sensorimotor integration that warrants further empirical investigation [5,6,12]. This interpretation is consistent with broader motor-control frameworks suggesting that post-concussion impairment may remain present even when routine clinical testing appears reassuring [5,6].

This issue becomes particularly relevant when considering the limits of conventional clinical testing. Gross performance scores may normalize while more subtle features of postural regulation remain altered [5,12]. Quantitative investigations have shown that instrumented measures can reveal persistent abnormalities in center-of-pressure (COP) or center-of-mass (COM) behavior that are not always evident in lower-technology assessments [5,12]. For example, prior work has noted that high-technology balance methods detect deficits that may persist to 30 days, whereas lower-technology approaches may fail to capture those same lingering abnormalities [5].

The same concern applies to dynamic postural control. In a longitudinal study of adolescents with concussion, Howell and colleagues reported that after return to activity, participants demonstrated significant increases in total medial–lateral COM displacement ($p = 0.009$; $\eta p = 0.175$) and peak medial–lateral COM velocity ($p = 0.048$; $\eta p = 0.104$) during dual-task walking, even though no comparable changes were detected for cognition or single-task gait [13]. These findings are notable because they suggest that the apparent return of symptoms or routine performance does not necessarily indicate restoration of higher-order postural control during more demanding conditions [2,13].

At present, however, the degree to which such instrumented abnormalities should be interpreted as clinically meaningful remains uncertain. Concussion-specific thresholds defining normal versus pathological postural or symmetry-related performance have not been firmly established, and measurable deviations should therefore be interpreted alongside symptom presentation, functional performance, and other components of multidomain

assessment rather than as independent markers of incomplete recovery [1,11]. Future work establishing normative values, minimal clinically important differences, and context-specific thresholds will be essential for translating these measures into routine practice.

Framed through a symmetry lens, these findings raise the possibility that some post-concussion balance deficits may involve more than simple reductions in stability alone and, in certain individuals, may include asymmetrical strategies of postural regulation [5,12,13]. Rather, they may include altered strategies of stabilization, asymmetrical control of mass over the base of support, and compensatory postural behaviors that become most visible under complex or dual-task demands [12,13]. This perspective is especially relevant in athletic populations, where sport participation requires rapid sensory integration, reactive control, and efficient movement adaptation [12]. Even small unresolved asymmetries in postural regulation could plausibly influence cutting, landing, perturbation response, and other high-demand tasks, particularly when the athlete has otherwise been cleared to participate [4,7].

Although direct causal pathways remain under investigation, this interpretation aligns with broader evidence that athletes returning after concussion experience elevated rates of subsequent musculoskeletal injury [4,7]. A meta-analysis reported that athletes with prior concussion demonstrated 2.11-fold greater odds of later musculoskeletal injury and a 1.67-fold higher injury incidence rate than controls, suggesting that conventional RTS markers may not fully capture persistent functional vulnerability [7]. Importantly, these findings do not establish a direct relationship between measurable asymmetry and subsequent injury outcomes. Current evidence indicates that impaired reaction time, altered dual-task processing, neurocognitive fatigue, attentional demands, and disrupted sensorimotor integration likely represent major contributors to post-concussion injury susceptibility [2–4,7]. Within this broader framework, unresolved asymmetry is proposed only as one hypothetical and potentially interacting mechanism among multiple factors influencing functional recovery and subsequent injury risk [4,7].

Accordingly, postural symmetry is not proposed here as a singular determinant of recovery, nor as a replacement for existing multidomain assessment models [1]. Rather, it is better understood as a potentially underrecognized rehabilitative construct that may complement current concussion management [8]. Viewing postural control through a symmetry framework may help clinicians identify residual dysfunction that remains hidden beneath symptom improvement and may also provide a more targeted rationale for rehabilitation strategies designed to restore efficient and adaptable movement [6,8].

While postural regulation represents one manifestation of persistent sensorimotor dysfunction, similar principles may extend to dynamic movement behaviors that place greater demands on coordination, attention, and neuromuscular control. Examining gait and functional movement patterns therefore provides an important bridge between isolated balance impairments and the broader demands associated with athletic participation and return to sport.

2.2. Movement and Sensorimotor Asymmetry as Markers of Incomplete Recovery

Beyond postural control, concussion-related dysfunction may also be reflected in asymmetrical movement behavior during dynamic and cognitively demanding tasks [2–5]. Although SRC is often managed through symptom reports, neurocognitive testing, and gross clinical examination, growing evidence suggests that subtle disturbances in locomotor control, sensorimotor integration, and coordinated movement may persist beyond apparent recovery [2–5,12]. Framed through a symmetry lens, these disturbances may represent more than generalized motor deficits and instead reflect asymmetrical patterns of function indicative of incomplete restoration [6,12].

Gait has been one of the clearest models through which these deficits have been examined [2,3]. Investigations using instrumented gait analysis have identified alterations in stride characteristics, gait variability, and movement coordination following concussion, particularly under dual-task conditions that more closely reflect real-world demands [2,3,13]. Importantly, several studies suggest that these deficits may persist despite symptom resolution [2,3,13]. In a systematic review, Fino and colleagues reported that gait-related impairments can remain detectable after athletes are otherwise considered clinically recovered, particularly when attentional demands are increased [3]. Similarly, dual-task gait paradigms have demonstrated persistent decrements in walking speed, increased mediolateral sway, and altered coordination that may not be evident during routine single-task assessments [2,13]. These findings support the possibility that functional recovery may lag behind traditional recovery markers [2,3,13]. Representative quantitative findings supporting the possibility that functional recovery may persist beyond symptom resolution, including evidence from postural control, gait, and injury-risk studies, are summarized in Table 1, while Figure 1 provides a conceptual illustration of how these findings collectively support the proposed divergence between apparent clinical recovery and persistent functional deficits following SRC. Collectively, these findings suggest that postural, gait, and sensorimotor disturbances should not be viewed as isolated phenomena, but rather as interconnected expressions of functional recovery after SRC. This broader perspective provides the conceptual foundation for considering whether movement quality and symmetry-related constructs may hold value as potential rehabilitation targets.

Table 1. Representative Quantitative Findings Supporting Persistent Functional Deficits After Sport-Related Concussion.

Study Domain	Representative Quantitative Finding	Potential Relevance to Symmetry
Clinical balance recovery	Clinical balance measures often normalize within 3–5 days	Conventional measures may normalize before functional recovery
Instrumented postural control	Deficits reported up to 30 days post injury	Residual asymmetrical control may persist
Dual-task gait performance	Alterations reported up to 2 months post injury	Functional movement recovery may lag
Subsequent musculoskeletal injury risk	OR 2.11; IRR 1.67 following concussion	May reflect unresolved sensorimotor dysfunction

From a symmetry perspective, such findings are noteworthy because gait efficiency depends heavily on temporal and spatial coordination between limbs and across sensorimotor systems [6,12]. Potential symmetry-related variables of interest may include step length asymmetry, stance and swing time differences, mediolateral center-of-mass displacement, cadence variability, interlimb coordination, and loading symmetry during dynamic tasks [3,12,13]. Although clinically meaningful thresholds for these measures have not yet been established in post-concussion populations, disturbances in these domains may represent candidate markers of residual dysfunction worthy of future investigation. Rather than interpreting these findings solely as generalized instability or slowed performance, a symmetry-informed framework suggests they may reflect incomplete reintegration of motor control processes after injury [6,12].

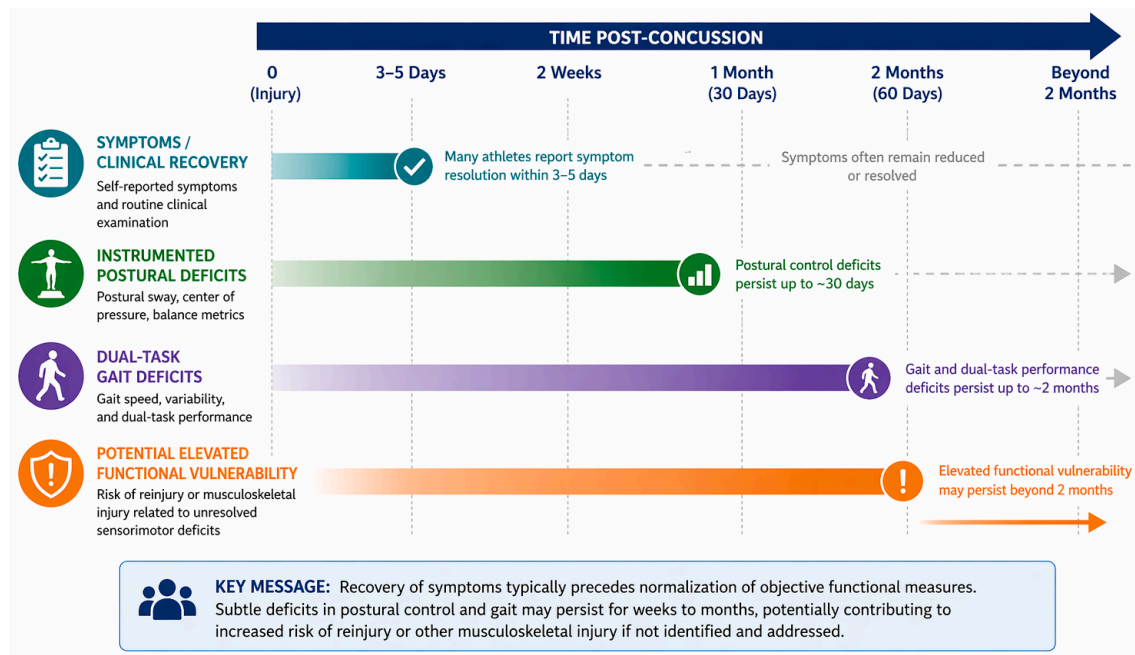


Figure 1. Conceptual Timeline Illustrating the Potential Divergence Between Symptom Resolution and Persistence of Subtle Functional Deficits Following Sport-Related Concussion. Conceptual illustration of the proposed divergence between symptom resolution and persistence of subtle functional deficits following sport-related concussion (SRC). The timeline depicts representative recovery intervals reported across the literature and is intended to illustrate the conceptual progression of recovery rather than discrete physiological phases, universal recovery timelines, or normative clinical expectations. The figure synthesizes the broader conceptual framework informed by the representative quantitative findings summarized in Table 1.

This perspective may be even more relevant during higher-demand movement tasks. Athletic participation rarely depends on steady-state walking alone, but instead requires rapid acceleration, deceleration, cutting, pivoting, single-leg landing, multidirectional change-of-direction maneuvers, perturbation response, and dynamic postural adjustments performed under cognitive and environmental stress [6,12]. Although this area remains emerging, altered movement strategies after concussion have been reported during dynamic tasks involving jump landing, gait initiation, reactive movement control, and dual-task locomotion, raising the possibility that subtle asymmetries in limb loading, interlimb coordination, or movement timing may persist after apparent recovery [14]. These deficits may become particularly relevant during sport-specific activities requiring rapid decision making, visual tracking, and simultaneous cognitive processing, where residual sensorimotor impairments may be more readily exposed than during routine clinical assessments.

These considerations may have implications for RTS readiness. Conventional clinical recovery often assumes that symptom resolution corresponds with restoration of functional capacity; however, if asymmetrical sensorimotor strategies persist, this assumption may be incomplete [1,4]. This concern is supported indirectly by evidence linking concussion history to elevated subsequent musculoskeletal injury risk, including reports suggesting approximately twofold greater odds of lower extremity injury after RTS [7]. While the mechanisms underlying this association remain multifactorial and no causal relationship with symmetry-related deficits has been established, unresolved movement asymmetry may represent one plausible contributing factor worthy of future investigation alongside impaired reaction time, altered dual-task processing, neurocognitive fatigue, and other neuromuscular or sensorimotor mechanisms [2–4,7].

Importantly, the argument advanced here is not that symmetry should be treated as a singular surrogate for recovery or that all movement deviations after concussion represent pathological asymmetry [8]. Rather, the contention is that symmetry may provide an underutilized lens through which residual dysfunction can be interpreted and potentially measured [6,8]. In this sense, movement and sensorimotor asymmetry may serve less as isolated abnormalities and more as markers of incomplete recovery that warrant greater attention within rehabilitation models [6,8].

Within a symmetry-informed framework, these deficits may also represent modifiable targets rather than merely observational findings [8]. This possibility provides the rationale for considering whether interventions specifically designed to detect and retrain asymmetrical movement behavior, including biofeedback-guided approaches, may offer added value in concussion rehabilitation [8,10].

Collectively, these findings suggest that postural, gait, and sensorimotor disturbances should not be viewed as independent phenomena, but rather as interconnected expressions of functional recovery following SRC. This broader perspective provides the conceptual foundation for considering whether movement quality and symmetry-related constructs may hold value as potential rehabilitation targets.

2.3. Symmetry as a Potential Rehabilitation Target

In many areas of rehabilitation science, restoration of symmetry is not viewed merely as an observational outcome but as a meaningful target of intervention [8,9]. Symmetry has long been used as a marker of movement efficiency, neuromuscular recovery, and functional readiness in populations recovering from orthopedic injury, neurological insult, and other movement disorders [6,8,9]. In these contexts, persistent asymmetry is often interpreted as evidence of incomplete recovery and, in some cases, a modifiable risk factor warranting therapeutic attention [8,9]. Despite these broader applications, symmetry has received comparatively limited emphasis as an explicit rehabilitative construct within SRC management [1,4].

This relative absence is notable because contemporary concussion rehabilitation has increasingly embraced active, targeted intervention approaches aimed at addressing specific impairments rather than relying solely on symptom resolution [1]. Vestibular rehabilitation, exertional therapy, cervical interventions, and multimodal treatment paradigms all reflect this evolution [1]. Yet even within these advances, rehabilitation often focuses on symptom reduction or generalized functional improvement without explicitly framing restoration of symmetrical sensorimotor performance as a therapeutic objective [1,8]. This may represent a conceptual gap in current rehabilitation models [8].

Viewing symmetry as a rehabilitation target does not imply that recovery should be reduced to symmetrical performance alone, nor that perfect bilateral or movement symmetry is always attainable or even necessary [8]. Importantly, not all asymmetrical behavior should be considered pathological. In some cases, compensatory movement strategies may represent adaptive responses that protect function, accommodate transient deficits, or facilitate ongoing sensorimotor recovery [6,12]. The framework proposed here therefore does not advocate forcing mechanical symmetry or eliminating normal variability, but rather encourages distinguishing potentially maladaptive asymmetries that persist beyond expected recovery from compensatory behaviors that remain functionally beneficial. Within this framework, “sufficient” symmetry is conceptualized functionally rather than numerically and refers to movement behavior that falls within expected biological variability, does not contribute to symptom provocation or performance limitations, and supports progression toward activity demands and return to sport. In this sense, symmetry

is understood less as an absolute endpoint and more as a contextual construct that may help distinguish adaptive recovery from persistent compensation [6,8].

This perspective may be particularly relevant in athletic populations, where efficient movement often depends on coordinated and adaptable control across multiple systems [6,12]. Small residual asymmetries that appear inconsequential during routine clinical tasks may become more meaningful during high-demand sport activity, where rapid decision making, perturbation response, and movement precision are essential [12,14]. From this standpoint, incorporating symmetry-oriented thinking into rehabilitation may offer a way to better align treatment progression with functional performance demands [8].

Importantly, other areas of rehabilitation suggest that targeting symmetry may be clinically meaningful [8,9]. In post-operative lower extremity rehabilitation, for example, limb symmetry indices have often been used to inform readiness for activity progression and RTS, with asymmetry commonly viewed as a marker of incomplete recovery [8,9]. However, important pathophysiological differences distinguish concussion from orthopedic injury. Whereas musculoskeletal conditions frequently involve localized structural damage and unilateral impairments, and severe neurological conditions may reflect focal ischemic or structural injury, SRC is characterized by a transient neurometabolic cascade with complex sensorimotor, neuromuscular, and cognitive-motor consequences [1,12]. Accordingly, the comparison presented here should be interpreted as a conceptual analogy rather than a direct translational model. The broader principle that asymmetry may serve as an indicator of incomplete functional recovery may retain relevance, but concussion-specific metrics, thresholds, and applications require independent empirical validation [8]. Borrowing these conceptual principles does not imply direct transferability of orthopedic or neurological rehabilitation models to SRC, but rather provides a framework for generating concussion-specific hypotheses and more functionally informed recovery strategies that require independent empirical validation [1,8].

This framework also aligns with increasing interest in precision rehabilitation, in which interventions are guided by measurable deficits rather than generalized treatment algorithms [11]. If asymmetry can be identified as a persistent feature of post-concussion dysfunction in some athletes, then symmetry restoration may represent a logical and potentially trainable rehabilitation target [8]. This possibility is particularly relevant when considered alongside emerging technologies capable of providing objective monitoring and feedback during rehabilitation [10,11].

Accordingly, the value of emphasizing symmetry is not to replace existing multidomain concussion care models, but to complement them by introducing a potentially underutilized construct through which residual dysfunction may be identified and addressed [1,8]. This proposition forms the rationale for the next question central to this Viewpoint: whether biofeedback may provide a practical mechanism for operationalizing symmetry-oriented approach [10]. Representative symmetry-related disturbances potentially relevant to concussion rehabilitation, their possible clinical implications, and candidate biofeedback targets are summarized in Table 2.

Table 2. Representative Symmetry-Related Deficits and Potential Clinical Relevance Following Sport-Related Concussion.

Domain	Potential Asymmetry	Clinical Relevance	Candidate Biofeedback Strategy
Postural Control	COP shifts, uneven loading	Dynamic stability	Force platform or visual feedback training
Gait	Temporal/spatial asymmetry	Movement efficiency	Wearable sensor-guided gait retraining
Neuromuscular	Limb loading or muscle activation asymmetry	Injury risk	EMG or movement biofeedback
Sensorimotor	Coordination asymmetry	Functional recovery	Multimodal biofeedback for motor control

3. Biofeedback as a Tool for Symmetry Restoration

3.1. Visual and Performance-Based Biofeedback

If symmetry is considered a potentially meaningful rehabilitation target following SRC, a related question becomes how that target might be identified, monitored, and trained. Biofeedback may offer one mechanism through which this can occur [10]. Broadly, biofeedback interventions provide augmented external information regarding movement performance, force production, postural behavior, or physiological output, allowing individuals to recognize and modify motor strategies in ways that may be difficult to achieve through intrinsic feedback alone [6,10]. Within a movement-based rehabilitation framework, this may be particularly relevant for addressing subtle sensorimotor asymmetries that are not readily perceived by the athlete or clinician [10].

If persistent asymmetries and compensatory movement behaviors represent meaningful dimensions of post-concussion recovery, the next challenge involves determining how these patterns may be identified, monitored, and, when appropriate, selectively modified. Biofeedback technologies provide one possible framework through which these multidimensional processes may be operationalized and empirically investigated.

Visual biofeedback represents one of the most established approaches through which symmetry-oriented retraining may be operationalized [10,15]. In broader rehabilitation contexts, visual feedback has been used to improve postural control, modify limb-loading asymmetries, refine movement mechanics, and promote motor relearning through real-time performance information [10,15]. Force platform displays, COP visualizations, mirror feedback, and task-specific motion feedback have all been used to provide immediate information regarding movement deviations and symmetry-related performance variables [15]. Although much of this work originates outside concussion rehabilitation specifically, the underlying principles may have important conceptual relevance [6,10].

Within post-concussion care, such approaches may offer a way to make otherwise subtle asymmetries observable and trainable [10,15]. For example, an athlete demonstrating asymmetrical weight distribution during static or dynamic balance tasks may benefit from real-time feedback designed to promote more symmetrical postural regulation [15,16]. Similarly, visual or performance-based feedback during gait, landing, or reactive movement tasks may help identify compensatory strategies that persist despite symptom resolution and facilitate more targeted retraining [14–16]. In this sense, biofeedback may not simply serve as a measurement adjunct, but as an active intervention capable of supporting motor recalibration [10,15].

Importantly, the presence of asymmetry alone should not be interpreted as evidence of dysfunction requiring intervention. Human movement is inherently variable, and task-specific differences in loading, coordination, or movement strategy may reflect normal biological variability rather than pathology [6,8,12]. Within the framework proposed here, symmetry-oriented biofeedback is intended to target asymmetries only when they appear to exceed expected variability and are accompanied by persistent symptoms, functional limitations, impaired performance, or other indicators of incomplete recovery. Establishing clinically meaningful thresholds that distinguish adaptive variability from maladaptive asymmetry remains an important area for future investigation [8,11].

This possibility is consistent with broader motor learning theory, which suggests that augmented external feedback can facilitate error detection, reinforce corrective strategies, and accelerate adaptation, particularly when intrinsic awareness of deficits may be limited [6,10]. This may be especially relevant after concussion, where subtle disturbances in movement coordination or sensory integration may not be consciously perceived despite their functional relevance [12,14]. By enhancing awareness of asymmetrical performance and guiding corrective responses, visual biofeedback may provide a mechanism

for transforming symmetry from an observational construct into a trainable rehabilitation target [6,10,15].

Emerging quantitative evidence from rehabilitation research supports this premise. Visual biofeedback interventions have been associated with improvements in postural sway measures, gait symmetry, and movement control across neurological and musculoskeletal populations, while force-based feedback paradigms have demonstrated favorable effects on reducing asymmetrical loading strategies during dynamic tasks [15,16]. However, these findings should be interpreted cautiously when considering SRC populations. Unlike many orthopedic conditions, concussion may involve impairments in sensory integration, attention, and cognitive-motor processing that could influence how individuals perceive and respond to augmented feedback [12]. Accordingly, the literature cited here provides conceptual support rather than direct evidence for symmetry-oriented concussion rehabilitation, and concussion-specific validation studies remain necessary [10,15].

Importantly, the value of visual and performance-based biofeedback may extend beyond impairment correction alone [10,15]. These approaches may also provide objective, scalable means of monitoring progress during rehabilitation, potentially offering clinicians additional information regarding whether observed improvements reflect compensation or true restoration of more symmetrical control strategies [6,10,15]. This aligns with broader interest in precision rehabilitation models emphasizing measurable and individualized treatment progression [11].

At the same time, biofeedback should not be viewed as a stand-alone solution or a substitute for established multidomain rehabilitation approaches [1,10]. Rather, its proposed value lies in its potential integration within those models as a mechanism for enhancing detection and retraining of residual asymmetries that may otherwise remain under-addressed [1,10,15]. Within this framework, visual and performance-based biofeedback represent one potential foundation upon which symmetry-informed concussion rehabilitation may be built [10,15].

3.2. Wearable and Sensor-Based Feedback Approaches

Beyond traditional visual and performance-based feedback methods, advances in wearable and sensor-based technologies have expanded the ways in which symmetry-related deficits may be identified, monitored, and potentially addressed during rehabilitation [10,15,17]. These technologies may be particularly relevant to concussion care because many residual deficits hypothesized to involve asymmetrical sensorimotor control can be subtle, context dependent, and difficult to detect through routine clinical observation alone [12,14,17]. Wearable and sensor-driven approaches may offer a means of making these disturbances more objectively measurable while also creating new opportunities for feedback-guided intervention [15,17].

In recent years, inertial measurement units (IMUs), wearable accelerometers, pressure-sensing systems, motion capture interfaces, and electromyographic (EMG) technologies have increasingly been used to quantify movement characteristics relevant to symmetry, including limb loading, spatiotemporal gait parameters, postural sway behavior, joint kinematics, and muscle activation patterns [17]. In broader rehabilitation science, such technologies have been applied to monitor asymmetrical movement behavior in both laboratory and field settings and, in some cases, to provide real-time feedback intended to support motor retraining [15,17].

Despite their promise, these technologies also present important methodological challenges. The ability to detect subtle asymmetries during dynamic athletic activity depends on factors including sensor placement, sampling frequency, signal quality, motion artifact, and the signal-to-noise characteristics of the measurement system. Equally important is the

current lack of standardized analytical approaches for quantifying clinically meaningful asymmetry following sport-related concussion. Although numerous symmetry metrics have been described across biomechanics and rehabilitation research, concussion-specific thresholds, normative reference values, minimal clinically important differences, and standardized processing pipelines have not yet been established. Consequently, future work should prioritize methodological standardization alongside technological development to improve the reliability, interpretability, and clinical translation of symmetry-related measurements. Moreover, ecological validity remains an important consideration, as movement behavior observed in controlled laboratory settings may differ substantially from performance during sport-specific environments or competition. Consequently, the application of IMU- and EMG-based approaches to concussion rehabilitation requires further methodological validation to determine the technical requirements necessary for reliable detection and interpretation of clinically meaningful asymmetries in real-world settings [15,17].

Within a symmetry-informed concussion rehabilitation framework, these technologies may offer several conceptual advantages. First, they may improve detection of subtle asymmetries that are not readily observable during conventional examination, although the sensitivity and reliability of these measurements remain dependent on appropriate technical implementation and environmental context [15,17]. For example, wearable sensors may identify persistent side-to-side differences in gait timing, movement variability, or dynamic stability that would otherwise remain undetected [3,13,17]. Similarly, pressure-based systems or force-sensing platforms may help characterize asymmetrical loading strategies during functional tasks such as landing, cutting, or perturbation response [14,15,17].

Second, wearable technologies may provide a mechanism for integrating feedback directly into rehabilitation [10,15,17]. Rather than serving solely as assessment tools, sensors may support active retraining by providing real-time or near-real-time feedback regarding movement deviations, loading asymmetries, or coordination errors during task performance [15,17]. This expands the role of biofeedback beyond traditional clinic-based paradigms and may be particularly attractive in sports medicine settings where portable and scalable rehabilitation tools are increasingly valued [11,15,17].

Third, these technologies align with growing interest in ecologically valid monitoring of movement outside laboratory environments [11,17]. Because many post-concussion deficits may emerge most clearly under complex or real-world demands, wearable approaches may offer opportunities to assess symmetry-related behavior during sport-specific drills, functional training, or other contexts that better reflect RTS demands [14,17]. However, the feasibility and tolerability of implementing biofeedback-guided wearable systems within real-world athletic settings remain insufficiently studied. Factors such as athlete adherence, comfort, usability, training interruptions, and integration into existing rehabilitation workflows warrant further investigation before widespread clinical adoption can be recommended. Consequently, the advantages described here should be interpreted as conceptual possibilities requiring empirical validation rather than established practice [17].

Emerging evidence supports the broader promise of these approaches. Wearable sensor systems have demonstrated utility in detecting gait abnormalities, monitoring postural control, and characterizing movement quality across diverse neurological and orthopedic populations [15–17]. Similarly, EMG biofeedback has shown potential for improving neuromuscular coordination and motor control in rehabilitation settings where altered activation strategies contribute to dysfunction [10,15,17]. Nevertheless, the extent to which these findings generalize to concussed populations remains uncertain, particularly given the potential effects of SRC on sensorimotor integration and cognitive-motor processing. Consequently, these broader findings should be viewed as providing a conceptual and

technological rationale for future exploration rather than direct evidence supporting clinical implementation in concussion rehabilitation [15,17].

Importantly, wearable and sensor-based approaches may also support a shift toward precision rehabilitation models in which intervention is guided by objective, individualized markers of dysfunction [11,17]. If asymmetrical sensorimotor behavior can be quantified longitudinally and linked to rehabilitation progression, these tools may help move concussion care toward more responsive and data-informed models of recovery monitoring [11,17].

At the same time, several considerations warrant caution. Increased measurement sensitivity does not necessarily guarantee clinical relevance, and not all detectable asymmetries will represent meaningful targets for intervention [8,17]. Preliminary interpretation should consider whether identified abnormalities persist beyond expected recovery timelines, are associated with symptoms or functional limitations, influence rehabilitation progression, or relate to sport-specific performance demands. Questions regarding threshold values, normative variability, ecological validity, and integration into routine practice remain unresolved [11,17]. Future research should prioritize the development of normative datasets, minimal clinically important differences, longitudinal recovery trajectories, and associations with patient-centered outcomes to determine which symmetry-related abnormalities warrant clinical attention [11,17]. Nonetheless, from a conceptual standpoint, wearable and sensor-driven technologies may offer a promising bridge between the theoretical construct of symmetry restoration and its practical implementation within rehabilitation [15,17].

Viewed alongside more traditional visual biofeedback methods, these approaches expand the range of tools through which movement-based rehabilitation might be operationalized [10,15,17]. This, in turn, raises the broader question of how biofeedback may function not merely as a collection of technologies, but as a framework for guiding rehabilitation progression, a concept considered in the next section [10].

3.3. Biofeedback-Guided Movement Retraining

Taken together, visual biofeedback approaches and emerging wearable or sensor-based technologies suggest that biofeedback may be viewed not merely as a collection of tools, but as a broader framework through which movement-based rehabilitation can be conceptualized and operationalized [10,15,17]. This distinction is important. The argument advanced in this Viewpoint is not simply that biofeedback technologies may be useful adjuncts in concussion rehabilitation, but that they may provide a mechanism for translating the construct of symmetry restoration into a measurable, trainable, and clinically actionable component of care [8,10,11].

Within such a framework, biofeedback may serve at least three interconnected functions: detection, retraining, and progression monitoring [10,15,17]. First, biofeedback may assist in detecting residual asymmetries that may otherwise remain underrecognized through conventional clinical examination [15,17]. Whether through force-based visual displays, wearable sensor outputs, or other performance feedback systems, these approaches may help identify subtle disturbances in postural regulation, movement coordination, or sensorimotor control that may be relevant to rehabilitation planning [12,15,17].

Second, biofeedback may provide a means of selectively retraining asymmetries when they appear maladaptive or functionally limiting [10,15,17]. Through augmented external feedback, athletes may receive information that supports error recognition, corrective adaptation, and refinement of movement strategies during rehabilitation tasks [6,10]. However, not all compensatory behaviors should necessarily be eliminated, as some may represent adaptive responses that support safety, function, or ongoing neuromotor recovery [6,12].

From a motor learning perspective, biofeedback should therefore be applied judiciously, with the goal of facilitating efficient movement patterns rather than enforcing rigid mechanical symmetry. In this way, biofeedback may help clinicians distinguish between persistent dysfunction and protective compensation while supporting individualized restoration of function [8,10].

Third, biofeedback may contribute to rehabilitation progression by providing objective indicators of change over time [11,15,17]. Rather than relying exclusively on symptom improvement or generalized task completion, symmetry-related performance metrics may offer additional information regarding whether observed gains reflect compensation or evolving restoration of more efficient motor control [6,8]. This possibility aligns with broader interest in rehabilitation models that emphasize objective progression criteria and individualized treatment dosing [11].

Conceptually, this framework may be understood as a progression in which SRC may contribute to residual asymmetrical sensorimotor behavior, biofeedback-guided intervention is used to identify and retrain those disturbances, and symmetry restoration serves as one component supporting improved functional recovery and RTS readiness [8,10,11]. While theoretical at present, this model offers a potential organizing structure through which future empirical work may be designed and evaluated.

Importantly, the proposed framework does not assume that symmetry restoration is universally necessary or sufficient for recovery, nor that biofeedback should be considered superior to established rehabilitation approaches [1,8]. Rather, it suggests that biofeedback may enhance existing multidomain models by providing an additional mechanism for targeting a potentially underrecognized dimension of dysfunction [1,10,17]. This integrative perspective may be particularly valuable in concussion rehabilitation, where complex and individualized recovery trajectories often require more than symptom-guided intervention alone [1,11].

This framework may also have implications for future research. If these movement-based rehabilitation approaches are to be advanced meaningfully, studies will be needed to determine which symmetry-related variables are most clinically relevant, how asymmetries should be quantified, whether biofeedback can meaningfully modify these patterns, and whether such changes relate to functional outcomes or safer RTS decisions [8,10,11]. Representative approaches may include randomized trials comparing symmetry-oriented biofeedback interventions with established rehabilitation methods, prospective cohort studies examining recovery trajectories, and predictive investigations evaluating whether symmetry-related measures contribute additional explanatory value beyond traditional clinical indicators. In this regard, the present Viewpoint is intended less as a definitive model than as a conceptual proposition meant to stimulate empirical investigation.

Within the context of this Special Issue, this perspective also aligns with growing emphasis on symmetry as both a scientific construct and a practical rehabilitation consideration [6,8,10]. By integrating principles of motor control, biofeedback, and concussion rehabilitation, biofeedback-guided movement retraining may offer a framework worthy of further exploration [6,10,11].

Conceptually, the proposed framework may be understood as a progression in which SRC contributes to residual sensorimotor asymmetry, biofeedback-guided rehabilitation is used to identify and retrain those disturbances, and symmetry restoration serves as one component supporting improved functional recovery and RTS readiness [8,10,11]. This conceptual relationship is illustrated in Figure 2.

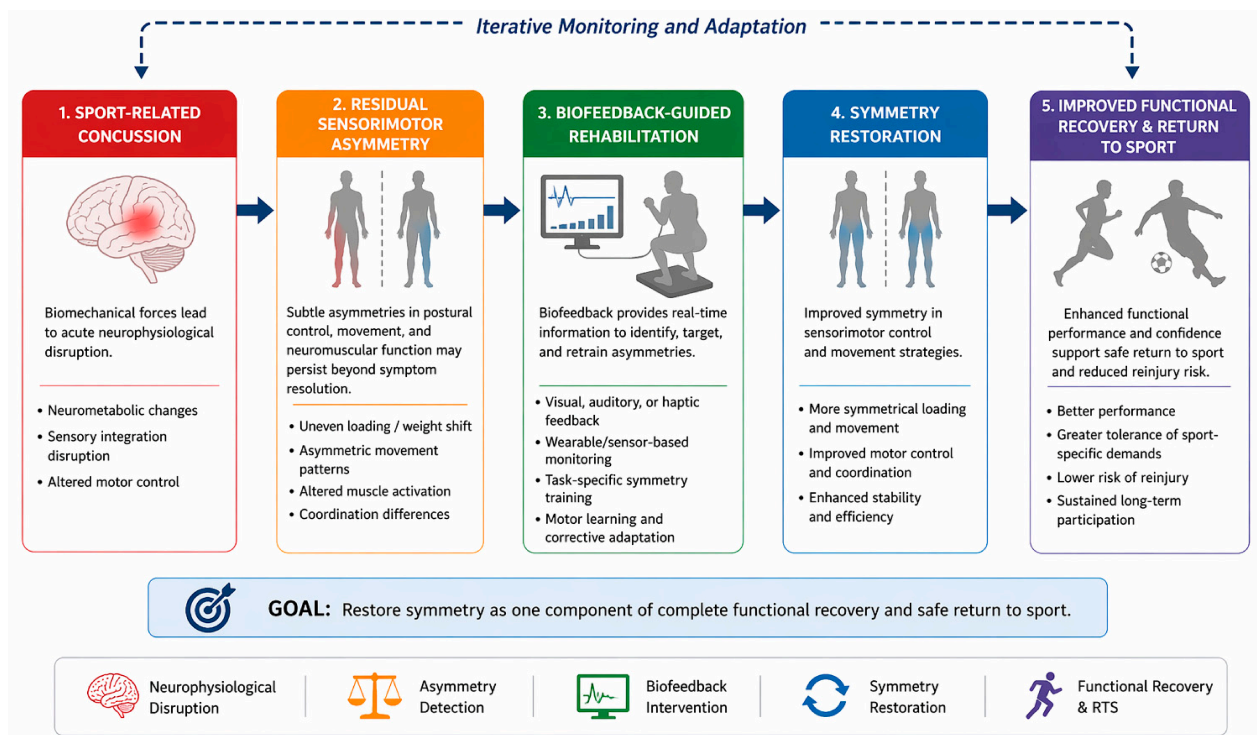


Figure 2. Proposed Conceptual Model of Symmetry-Informed Rehabilitation Following Sport-Related Concussion. High-level conceptual model illustrating the proposed theoretical progression from SRC-associated sensorimotor disturbances to biofeedback-guided intervention, symmetry restoration, and improved functional recovery and RTS readiness. The figure is intended to summarize the overarching framework advanced in this Viewpoint rather than depict specific rehabilitation domains or technologies.

A symmetry-oriented approach to rehabilitation may also be considered a multidomain construct involving several interacting domains of function, including postural, gait, neuromuscular, sensorimotor, and functional movement symmetry [4,8,12,14]. Whereas Figure 2 presents the overarching conceptual pathway proposed in this Viewpoint, Figure 3 focuses specifically on the interacting domains through which symmetry-related deficits and biofeedback applications may intersect during rehabilitation [10,17].

Potential biofeedback strategies, including visual, wearable, neuromuscular, and auditory feedback approaches, and their proposed applications for targeting symmetry-related deficits in concussion rehabilitation are outlined in Table 3 [10,15,17].

Table 3. Potential biofeedback applications for symmetry-oriented concussion rehabilitation.

Biofeedback Approach	Example Application	Potential Symmetry Target
Visual feedback	Real-time force plate or COP feedback	Postural symmetry
Wearable sensors	Sensor-guided gait retraining	Temporal-spatial symmetry
EMG biofeedback	Muscle activation retraining	Neuromuscular symmetry
Auditory biofeedback	Rhythmic cueing for cadence and coordination	Temporal symmetry

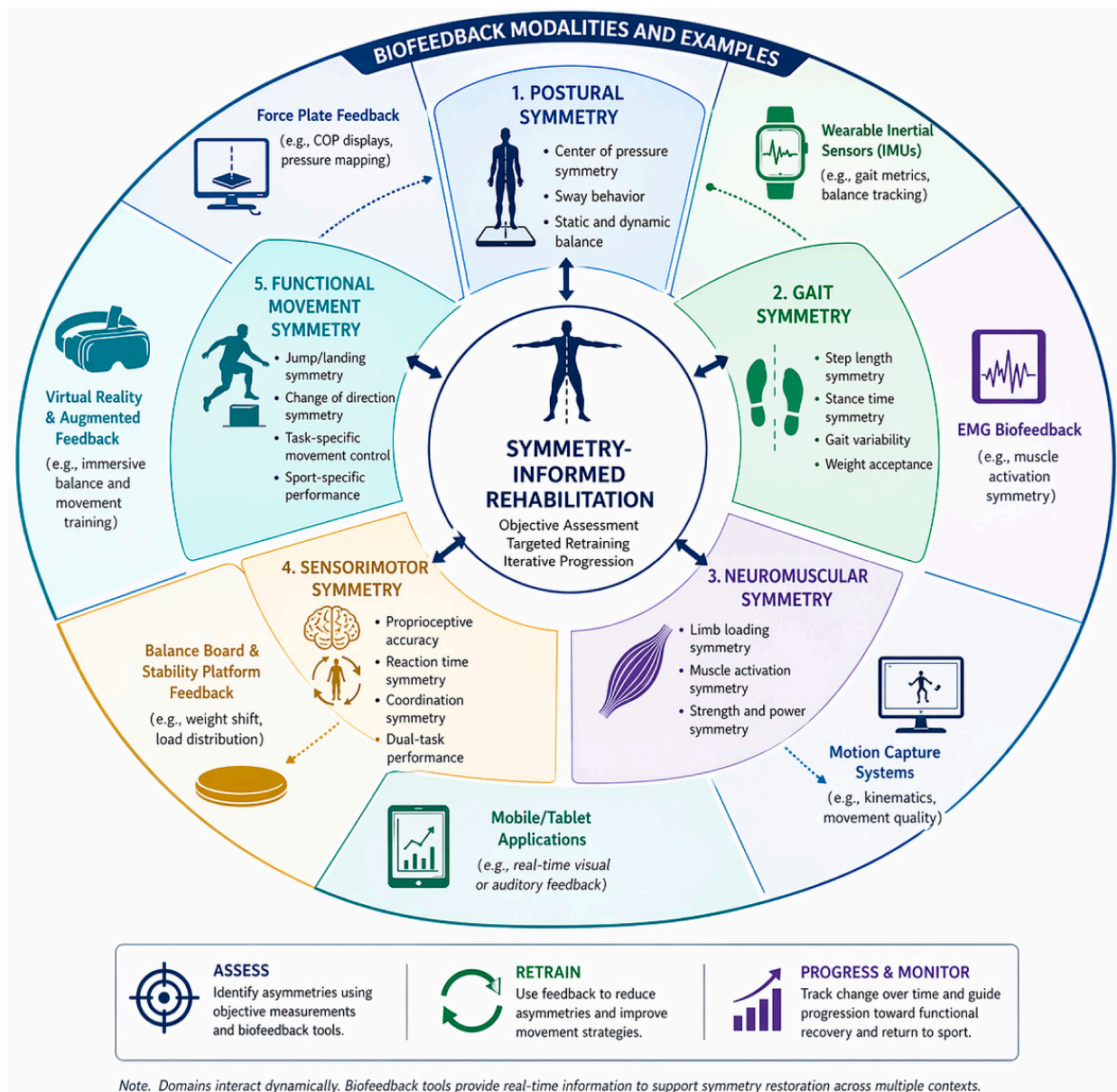


Figure 3. Multidomain Framework Linking Domains of Symmetry and Biofeedback Applications in Concussion Rehabilitation. Multidomain framework illustrating proposed areas of postural, gait, neuromuscular, sensorimotor, and functional movement symmetry relevant to concussion rehabilitation, together with their potential intersections with biofeedback applications. Unlike Figure 2, this model emphasizes the multidimensional nature of the proposed framework rather than its overall conceptual progression.

4. Clinical Implications and Future Directions

The framework proposed in this Viewpoint has potential implications for how SRC rehabilitation may be conceptualized, assessed, and progressed. Although symptom resolution and multidomain clinical assessment remain central to contemporary concussion management [1], the possibility that residual asymmetrical sensorimotor behavior may persist beyond apparent recovery suggests that additional functional dimensions of recovery may warrant consideration [4,7,14]. From this perspective, biofeedback-guided movement retraining may offer a complementary layer of clinical reasoning rather than a replacement for existing care models [1,8].

One potential implication is the expansion of rehabilitation targets beyond symptom reduction alone. Current concussion rehabilitation increasingly emphasizes active

intervention, yet treatment progression is often guided by symptom tolerance, task completion, or broad functional performance markers [1]. Incorporating symmetry-oriented constructs may provide an additional means of identifying residual dysfunction and refining intervention strategies, particularly in athletes progressing toward higher-level activity demands [8,10,17]. In this sense, symmetry may represent not only a possible outcome of rehabilitation, but a framework for informing how rehabilitation is individualized [8,11].

A second implication relates to RTS decision making. Determining readiness for return to participation remains one of the more complex aspects of concussion management, particularly when traditional clinical indicators may suggest recovery while subtle functional deficits persist [1,4]. Although symmetry measures should not be viewed as standalone clearance criteria, they may eventually serve as adjunctive indicators of functional recovery when interpreted alongside symptom burden, neurocognitive performance, vestibular and oculomotor function, exertional tolerance, and routine clinical assessment [1,8,10]. Within this framework, symmetry-related measures may provide additional insight into movement quality, residual sensorimotor compensation, and rehabilitation progression, particularly during higher-demand or sport-specific activities. At present, however, their role should be considered supportive and hypothesis-generating rather than determinative, pending further evidence linking these measures to clinical outcomes, RTS readiness, and subsequent injury risk [7,14].

The framework also carries implications for rehabilitation technology integration. As wearable sensing, real-time movement analytics, and portable biofeedback platforms continue to advance, opportunities may emerge to incorporate more objective and scalable symmetry-informed approaches into routine care [15,17]. Such developments align with broader shifts toward precision rehabilitation and data-informed intervention models, though their application in concussion care remains early and requires careful validation [11,17]. Future investigations should specifically examine feasibility, athlete acceptance, usability, adherence, and ecological validity within authentic training and return-to-sport environments to determine whether these technologies can be effectively integrated into routine concussion management.

Several research priorities emerge from this perspective. First, greater clarity is needed regarding which symmetry-related variables are most clinically meaningful in concussion rehabilitation. Candidate measures may include center-of-pressure excursion, step length and stance-time asymmetry, mediolateral center-of-mass displacement, postural loading patterns, interlimb coordination metrics, muscle activation symmetry, and sport-specific movement characteristics involving cutting, landing, reactive control, and dual-task performance [4,8,14]. Second, future studies should determine whether asymmetries identified after concussion represent modifiable treatment targets rather than merely observational markers of dysfunction [8,10]. This work should include the establishment of normative reference values, minimal clinically important differences, and longitudinal analyses linking symmetry-related measures to symptoms, functional performance, rehabilitation progression, and return-to-sport outcomes. Third, empirical work is needed to evaluate whether biofeedback-guided interventions can meaningfully alter these asymmetries and whether such changes translate into improved symptoms, functional performance, rehabilitation progression, return-to-sport readiness, or reductions in subsequent musculoskeletal injury risk [10,15,17]. Potential study designs may include randomized controlled trials comparing visual center-of-pressure biofeedback with standard vestibular or multimodal rehabilitation approaches, longitudinal cohort studies tracking symmetry-related measures throughout recovery, and prospective investigations examining whether these variables predict clinically meaningful outcomes after return to sport.

Importantly, several challenges warrant acknowledgement. Human movement is inherently variable, and not all asymmetry is pathological or clinically meaningful [8,12]. Distinguishing adaptive variability from maladaptive asymmetry will be essential if this framework is to advance responsibly [6,8]. Likewise, thresholds for clinically relevant asymmetry, normative expectations, and feasibility of implementation remain unresolved [11,17]. These limitations underscore that the framework proposed here is intended as a conceptual proposition requiring empirical refinement rather than a prescriptive clinical model.

Nonetheless, even as a conceptual framework, biofeedback-guided movement retraining may offer a potentially useful extension of current concussion management paradigms [1,8]. By reframing asymmetry as a potentially measurable and trainable dimension of recovery, and biofeedback as one mechanism through which that dimension may be operationalized, this perspective may help stimulate future work at the intersection of motor control, rehabilitation science, and sports medicine [6,10].

Limitations of the Proposed Framework

As a conceptual Viewpoint, several limitations of the proposed framework warrant acknowledgment. First, the ideas advanced herein are intended to synthesize emerging evidence and propose a conceptual model rather than provide empirical validation of symmetry-informed rehabilitation following SRC. Although the framework is grounded in principles from concussion research, motor control theory, and broader rehabilitation science [1,6,10], direct evidence specifically linking symmetry-targeted biofeedback interventions to improved post-concussion outcomes remains limited and requires future investigation [10,15,17].

Second, although asymmetry is proposed as a potentially meaningful dimension of residual dysfunction, human movement is inherently variable, and not all asymmetry should be interpreted as pathological or clinically relevant [8,12]. Distinguishing maladaptive asymmetry from normal biological variability or adaptive compensatory behavior remains an important challenge [6,8]. Accordingly, the concept of “sufficient” symmetry proposed herein should be interpreted as a functional and context-dependent construct rather than a fixed numerical threshold. Relatedly, thresholds for clinically meaningful asymmetry and other instrumented measures in post-concussion populations remain insufficiently established, including normative expectations and minimal clinically important differences, which currently limits translation of this framework into prescriptive clinical decision making [11,17]. Consequently, distinguishing clinically meaningful abnormalities from normal biological variability remains dependent upon multidomain clinical interpretation rather than objective thresholds alone.

Third, much of the rationale for biofeedback-guided symmetry restoration presented in this Viewpoint draws in part from the broader neurological, orthopedic, and motor rehabilitation literature, where symmetry-oriented interventions have been more extensively studied [8–10,15]. Although these parallels offer conceptual support, important differences in underlying pathophysiology limit direct translation to concussion populations. Extrapolation of findings from orthopedic or neurological rehabilitation should therefore be approached cautiously until concussion-specific evidence, metrics, and intervention frameworks are more fully developed. Moreover, because concussion may impair sensory integration and information processing, the mechanisms through which individuals engage with and benefit from biofeedback may differ substantially from those observed in other rehabilitation populations. In addition, the practical feasibility, tolerability, long-term adherence, and technical performance characteristics associated with wearable biofeedback systems in athletic populations remain unclear and represent important considerations for future implementation research. Issues related to sampling requirements, signal quality,

motion artifact, and ecological validity must be addressed before subtle symmetry-related measures can be confidently translated into routine clinical practice.

Fourth, the potential role of symmetry-informed approaches in return-to-sport decision making remains theoretical [1,7]. While persistent asymmetry may plausibly contribute to incomplete functional recovery, this relationship has not been definitively established, nor should symmetry-related metrics presently be viewed as independent clearance criteria [7,8]. Rather, their possible value may lie in complementing, rather than replacing, multidomain assessment models [1].

Finally, the proposed framework emphasizes symmetry as a rehabilitative construct, but it does not imply that symmetry restoration should be considered a universal goal for all athletes recovering from concussion. Recovery trajectories are heterogeneous, and the relevance of symmetry-targeted intervention may vary across individuals, injury presentations, and functional demands [1,8]. Accordingly, this framework should be viewed as a conceptual proposition intended to stimulate discussion and future study rather than a prescriptive clinical model.

5. Conclusions

SRC rehabilitation has advanced considerably, yet recovery may still be conceptualized primarily through symptom resolution and broad clinical indicators that may not fully capture persistent functional deficits. This Viewpoint proposes that residual sensorimotor asymmetries may represent an underrecognized dimension of post-concussion dysfunction and that symmetry restoration may warrant greater consideration as a rehabilitative construct.

Drawing from principles of motor control, rehabilitation science, and biofeedback applications, we further propose that biofeedback-guided approaches may offer one framework for identifying, monitoring, and potentially retraining asymmetrical movement behavior during recovery. While empirical validation is needed, viewing symmetry as a potentially measurable and modifiable target may extend current concussion rehabilitation paradigms beyond symptom management alone.

Importantly, the purpose of this perspective is not to position symmetry as a singular determinant of recovery or biofeedback as a stand-alone solution, but rather to stimulate discussion regarding whether symmetry-informed rehabilitation may represent a meaningful extension of multidomain concussion care. In this context, the intersection of symmetry science and biofeedback may offer promising directions for future research, rehabilitation innovation, and more functionally informed RTS decision making.

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Abbreviations

SRC	Sport-Related Concussion
COP	Center-of-Pressure
COM	Center-of-Mass
EMG	Electromyography
IMU	Inertial Measurement Unit
RTP	Return-to-Play
RTS	Return-to-Sport

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