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Review

Postural control deficits identify lingering post-concussion neurological deficits

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Abstract

Concussion, or mild traumatic brain injury, incidence rates have reached epidemic levels and impaired postural control is a cardinal symptom. The purpose of this review is to provide an overview of the linear and non-linear assessments of post-concussion postural control. The current acute evaluation for concussion utilizes the subjective balance error scoring system (BESS) to assess postural control. While the sensitivity of the overall test battery is high, the sensitivity of the BESS is unacceptably low and, with repeat administration, is unable to accurately identify recovery. Sophisticated measures of postural control, utilizing traditional linear assessments, have identified impairments in postural control well beyond BESS recovery. Both assessments of quiet stance and gait have identified lingering impairments for at least 1 month post-concussion. Recently, the application of non-linear metrics to concussion recovery have begun to receive limited attention with the most commonly utilized metric being approximate entropy (ApEn). ApEn, most commonly in the medial-lateral plane, has successfully identified impaired postural control in the acute post-concussion timeframe even when linear assessments of instrumented measures are equivalent to healthy pre-injury values; unfortunately these studies have not gone beyond the acute phase of recovery. One study has identified lingering deficits in postural control, utilizing Shannon and Renyi entropy metrics, which persist at least through clinical recovery and return to participation. Finally, limited evidence from two studies suggest that individuals with a previous history of a single concussion, even months or years prior, may display altered ApEn metrics. Overall, non-linear metrics provide a fertile area for future study to further the understanding of postural control impairments acutely post-concussion and address the current challenge of sensitive identification of recovery.

Keywords: Balance; Concussion; Mild traumatic brain injury; Postural control; Variability

1. Concussion overview

The National Institute of Health has deemed concussion, a mild traumatic brain injury (mTBI), a major public health disorder.[1] Concussions have reached epidemic levels both epidemiologically and in the popular media.[2,3] Indeed, the discussion of concussion permeates major sporting events from the Super Bowl to the World Cup to the Olympic Games.[4,5] There are estimated 1.6–3.8 million concussions which occur annually in the US; however, between 50% and 80% of concussions may go underreported either through intentional non-disclosure or lack of injury recognition.[6–8] However, sports and recreation related concussions comprise only a small minority (4%–11%) of all head injuries in children in the United States.[9] Beyond sports and recreation, TBI has been referred to as the signature injury of the current military engagements in Iraq and Afghanistan with up to 23% of active deployment military personal suffering an mTBI.[10] The costs associated with all TBI exceed US$60 billion annually in direct and indirect costs with mTBI comprising 75%–90% of all TBIs with an annual economic burden of ~US$22 billion alone.[11,12]

While many neurological pathologies are associated with specific supraspinal structures or pathways, the pathophysiology of concussion is less well understood.[13] Frequently described as a functional injury, recent advances in imaging have identified microstructural anatomical damage post-concussion.[13] The acute pathophysiology, often termed the neurometabolic cascade, is associated with elevated glutamate, potassium, and calcium levels resulting in an energy crisis due to impaired mitochondrial dysfunction.[13] This process does not

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affect a specific structure or pathway, rather it is termed a "spreading depression" in which diffuse areas of the brain are affected.[13] Although some recent human studies have suggested prolonged recovery, animal studies indicate that reduced cerebral blood flow and glucose metabolism persist for up to 7–10 days post-concussion which correlates well with symptom resolution.[13–16] Thus, it is not surprising that the 4th International Consensus Statement on Concussion in Sports suggests that 80%–90% of concussions recover, based on standard clinical markers, within this same 7- to 10-day window.[2] Herein, clinical recovery refers to achieving baseline (pre-morbid) values on the assessment battery utilized by the clinicians which typically includes assessment of concussion related symptoms, cognition, balance, and computerized neuropsychological tests.[2]

The consequences of concussion include elevated risks acutely, the potential for recurrent concussions, and later life neuropathological consequences. Specifically, in the acute post-concussion period there is a risk of the rare, but potentially fatal and debated, second impact syndrome which is believed to occur when a subsequent head impact occurs prior to resolution of the neurometabolic cascade.[17,18] Furthermore, there is an elevated risk of recurrent concussion which will likely present worse and have prolonged recovery as well as the recent suggestion of increased risk of non-concussion sports injuries.[19–21] The well-publicized long-term complications of repeated concussions include elevated risk of clinically diagnosed depression, mild cognitive impairment, earlier onset of Alzheimer's disease and the much discussed, albeit debated, chronic traumatic encephalopathy.[22–24] Finally, there is even emerging evidence for elevated rate of future traumatic death amongst individuals in the general population who suffered mTBI.[25]

There are currently no well accepted methods to predict or prevent concussions, thus the key to reduce the associated risks are proper acute evaluation and identification of recovery for safe return to participation. Encouragingly, a multifaceted concussion assessment battery is highly sensitive, 0.89–0.96, in the acute concussion evaluation and most athletic trainers are utilizing this type of battery.[26–28] However, the sensitivity of this battery drops to unacceptably low levels (0.14–0.30) within a week likely due to a practice effect from repeat administration of the assessments.[29] Currently, computerized neuropsychological testing is the standard of care to identify post-concussion cognitive recovery; whereas, assessment of postural control remains substantially limited with the balance error scoring system (BESS) is the current clinical recommendation despite extremely low sensitivity (0.07) at 1 week post-injury.[2,27–29] However, recovery of cognitive processing capabilities occurs independent of postural control and therefore neurocognitive testing alone is insufficient to identify recovery.[30–34] Thus, a multifaceted approach, including postural control assessment, is critical in both the acute recognition of concussion as well as the determination of recovery and the safe return to participation.[35] The purpose of this review is to provide an overview of the linear and non-linear assessments of post-concussion postural control.

2. Linear assessment of post-concussion postural control

Postural control requires controlling the body's orientation in space and encompasses both postural stability and postural steadiness.[36] Traditionally, linear dynamic postural control modeling stems from a stimulus-response paradigm, during which output is predicted using linear equations (e.g., position, displacement, velocity, acceleration).[36] Within this model, postural steadiness is measured by variations in the center of pressure (CoP) as a function of time whereas an increase in the area of CoP measures is associated with greater impairment in postural stability.[36] Following a concussive injury, the impairments to the postural control system are thought to result from an impaired interaction between the somatosensory, visual, and vestibular systems.[37,38] However, this approach may be limited by emphasis on the sensory system (e.g., primarily static and single tasks challenges) and resulting limited consideration of the motor and cognitive systems (e.g., dynamic and dual task challenges).[38,39] The Romberg test was one of the first static balance tests to be used in the clinical setting for concussion management which challenges the sensory system by evaluating sway during quiet stance with both the eyes open and closed.[40] However, the Romberg has been criticized as being insensitive due to its subjective nature of the interpretation and it has never been validated for clinical management of sports concussion.[40,41] These limitations, in an effort to objectify balance impairments, lead to the development of the BESS.[40,42] While an improvement over the Romberg test, the BESS also suffers from multiple limitations leading to the implementation of instrumented measures of postural control, primarily using force plates and the sensory organization test (SOT).

The most commonly utilized postural control assessment for sports-related concussion is the BESS.[27,28] The BESS was created as a cost effective and clinically feasible test which assessing balance on multiple surfaces (firm and foam) in multiple stances (double limb, single limb, and tandem).[42] The BESS has demonstrated strong correlations with force plate sway measures in five static balance positions (single-leg firm surface, tandem firm surface, double leg foam surface, single leg foam surface, and tandem foam surface), has with an intertester reliability coefficient correlations (ICC) ranging from 0.78 to 0.96, and produced results similar to those on the SOT.[40,42,43] However, the total BESS score, the score utilized clinically, has low to moderate ICC values (0.57–0.74) that have been identified raising reliability concerns. Following a concussion, BESS scores typically increases by 3–6 errors which is less than the minimal detectable change scores (7.3–9.4 errors) which could explain the test's low initial sensitivity (0.34).[29,44] Further, environmental distractions, fatigue, functional ankle instability, and dehydration may all impair performance whereas improved performance may occur secondary to a learning effect associated with repeat administration.[45–51] These limitations may be underlying the low initial sensitivity which decreases substantially within the first week post-injury (0.07).[29]

To address these considerations, instrumented measures of postural control, primarily the SOT, has been incorporated into research testing paradigms. The SOT disrupts information