Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability

Semyon Slobounov a,*, Cheng Cao a, Wayne Sebastianelli b, Elena Slobounov c, Karl Newell a

a Department of Kinesiology, The Pennsylvania State University, 19 Recreation Building, University Park, PA 16802, USA
b Athletic Medicine Clinic, The Pennsylvania State University, USA
c Information Technology Services, The Pennsylvania State University, USA

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Abstract

Objective: Traumatic brain injury (TBI), including mild traumatic brain injury (MTBI), commonly known as a “concussion”, is still one of the most puzzling neurological disorders and least understood injuries facing sport medicine and the scientific community [Cantu R. Concussion assessment Ongoing controversy. In: Slobounov S, Sebastianelli W, editors. Foundations of sport-related brain injuries. New York: Springer Press; 2006. p. 87–111.]. It was our primary objective to assess the dynamic properties of postural control in subjects prior to and after sport-related MTBI using the traditional center of pressure (COP) and virtual time-to-contact (VTC) measures.

Methods: We assessed 12 student-athletes prior to and 30 days after they suffered sport-related MTBI on a number of standing still and dynamic postural tasks. All subjects were clinically asymptomatic at day 30 of testing and were cleared for full sport participation based upon neurological and neuropsychological assessments, as well as clinical symptoms resolution.

Results: The findings showed: (1) no significant differences for any of the standard COP-based measures of postural control (i.e., 90% ellipse COP area, COP velocity and Stability Index) as a function of testing day (prior to and 30 days post-injury, \( p > .05 \)); (2) no differences in terms of VTC shape, distribution and nominal values before and after concussion during standing still postural tasks regardless of vision conditions, \( p > .05 \); and (3) there were significant alterations in VTC in terms of absolute values, range of VTC at the deflection points and mode at the day 30 post-injury.

Conclusions: The deficits in VTC control are indicative of residual postural abnormality in subjects suffering from mild traumatic brain injuries and provide further evidence that VTC is used to regulate dynamic postural movement.

Significance: The results show that residual postural abnormalities in concussed individuals may be undetected using conventional research methods and the implications of this for clinical practice are discussed.

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Keywords: VTC; Mild traumatic brain injury (MTBI); Postural control

1. Introduction

Despite dramatic advances in the field of sport medicine, mild traumatic brain injury (MTBI), known as “concussion” is still one of the most puzzling neurological disorders and least understood injuries. The problem with concussion is that with the exception of the unconscious individual or someone who is severely dazed, it is often very difficult to identify who has sustained a concussion and who has not (Cantu, 2006). Although blunt trauma involved with MTBI appeared to be a relatively simple type of brain injury, the potpourri of symptoms varies from subject to subject and often hint at the true complexity of the injury (Barth et al., 2001; Guskiewicz, 2003; Lowell et al., 2003; Cantu, 2006). The consequence is that attempts to classify concussion as a traumatic event with predictable findings upon initial examination may be erroneous.
Several previous studies have identified a negative effect of MTBI on postural stability (Lishman, 1988; Ingelsoll and Armstrong, 1992; Wober et al., 1993). Generally, balance problems in MTBI subjects have been attributed to a disruption of various CNS functions responsible for postural stability (Guskiewicz, 2003; Slobounov et al., 2006c; Thompson et al., 2005). A growing body of experimental studies has demonstrated postural stability deficits, as measured by the Balance Error Scoring System (BESS, a clinical test that uses modified Romberg stances on different surfaces) on post-injury day 1 (Guskiewicz et al., 1997; Guskiewicz, 2001a, 2003; Guskiewicz and Mihalik, 2006; Rieman and Guskiewicz, 2002; Valovich et al., 2003; Peterson et al., 2003). It was suggested that the recovery of balance occurred between day 1 and day 3 post-injury for most of the MTBI subjects (Peterson et al., 2003). However, Cavanaugh et al. (2005a,b, 2006) have shown that the Approximate Entropy (ApEn) method may detect postural abnormalities long after cerebral concussion in asymptomatic subjects as assessed by traditional clinical tools. This is consistent with other recent studies demonstrating long-lasting residual balance abnormalities in MTBI subjects, that is most evident during dynamic postural tasks (Slobounov et al., 2006a,b,c).

Slobounov et al. (1997) developed an approach and method to determine the virtual time to contact (VTC) to the stability boundary in a 3 or even n dimensional space, and applied this method to the estimate of postural stability in human standing posture. Fig. 1 shows a schematic for the calculation of VTC (see also the algorithm for calculation of VTC in Appendix). In a series of studies in our laboratory, VTC has been shown to be a more sensitive measure of declines in postural stability with advancing age than traditional center of pressure (COP) based measures (Slobounov et al., 1998; Haibach et al., 2007). Van Wegen and colleagues using a variation of this virtual time to contact measure have shown similar age-related properties of time-to-contact in the control of postural stability (Van Wegen et al., 2001, 2002). Hertel et al. (2006) have shown the robustness of the virtual time to contact measure in human single leg postural standing. More recently, Hertel and Olmsted-Kramer (2007) revealed changes of time-to-boundary measures (TTB) in subjects suffering from chronic ankle instability (CAI), and suggested that TTB measures may detect postural control deficits related to CAI that are not detected by traditional measures (i.e., COP range and velocity etc.).

In this study we use VTC to assess dynamic properties of postural control in subjects prior to and after sport-related MTBI. It was expected that abnormal signs of postural control in MTBI subjects will be revealed via the enhanced sensitivity of the VTC measures that will not be detectable using conventional COP-based measures. It was anticipated that this study will provide additional evidence that VTC is being used to regulate dynamic postural movement and can be used as a preclinical biomarker to reveal residual postural abnormality in subjects suffering from MTBI.

Fig. 1. Schematic of VTC computation with respect to two-dimensional physical stability boundary. Clearly, it is temporal-spatial properties of the instantaneous COP values and combination of position, velocity and acceleration vectors rather than just position of the COP within the stability boundary are important fully appreciate VTC as an informational variable in control of posture. As can be seen, the virtual trajectory (VT) has a parabolic shape if the direction of the initial velocity and acceleration vectors is not collinear. However, the VT is linear if the initial velocity and initial acceleration have the same direction or if either of them is equal to zero.

2. Methods

2.1. Subjects

A total of 160 subjects were initially recruited for this sport-related concussion study. All subjects were Pennsylvanisia State University athletes at risk for traumatic brain injury (collegiate rugby players), aged between 18 and 25 years, male \( n = 84 \), mean age \( = 20.95 \) years) and female \( n = 76 \), mean age \( = 21.42 \) years). None of these subjects had a concussion history at the time of pre-injury testing. Thirty-eight of these subjects suffered from grade 1 MTBI (Cantu Data Driven Revised Concussion Grading Guidelines, 2006) within 6 months after baseline testing and were tested on day 30 post-injury. The results from 12 randomly selected subjects prior to and on day 30 post injury are presented in this report. It should be noted that we have achieved statistical power and highly significant differences \( p < 0.001 \) using results from 12 subjects before and after concussion, however, the data from all 38 subjects are available for future relevant reports. It was expected that no balance symptoms will be present at day 30 post injury as assessed by conventional postural research methods (Guskiewicz et al., 2001b). It should be noted that all 12 subjects were clinically asymptomatic at day 30 of testing and were cleared for full sport participation based upon
neurological and neuropsychological (NS) assessments, as well as clinical symptoms resolution. A detailed description of inclusion criteria for MTBI can be found in (Slobounov et al., 2002). Consent forms approved by the Institutional Review Board of the Pennsylvania State University were obtained from each subject prior to each testing session.

2.2. Apparatus and procedures

An Advanced Mechanical Technology, Inc. (AMTI) force platform and CAS software package were used to collect and process the center of pressure (COP) data. Three force components (Fx, Fy and Fz) along with three respective moment components (Mx, My and Mz) were simultaneously measured from the force platform. The signals were amplified through a six-channel AMTI model SGA6-4 amplifier. A maximum gain of 4000 was used, with a low-pass filter of 10.5 Hz. The bridge excitation was set to 10 V. All six channels were factory calibrated. The data were collected with a sample frequency of 90 Hz.

In both (prior to and after concussion) experimental sessions subjects were required to produce two static postural tasks: (a) standing still with eyes open (EO); (b) standing still with eyes closed (EC); and (c) a dynamic task – anterior–posterior (A–P) oscillatory postural movement predominantly at the ankle joint (all for a trial duration of 30 s). In the dynamic task condition subjects were instructed to sway forward and backward as far as they could to the limits of their respective stability boundary at a comfortable speed without moving their feet. The rational is that the comfortable oscillatory speed (amplitude/frequency) is highly stable and produces the lowest variability of outcome because it is organized by the intrinsic dynamics of the individual’s system (Kugler and Turvey, 1987). Subjects were requested to perform 3 trials per condition. Before each condition the participant was asked to obtain their maximum “functional stability boundary” by leaning forward, backward, laterally and diagonally pivoting at the ankle joint, and proceeding in the circular direction leaning as far as possible without having to initiate a step (Slobounov et al., 1998). If a step was initiated, the trial was aborted. The force platform was covered by a detailed paper grid allowing the maintenance of the same position of the subjects’ feet between experimental sessions and within task conditions.

2.3. Data analysis

We measured the size of each subject’s feet and the platform calibration markers in order to estimate the shape and location of the stability boundary during the execution of the required stances (Barin, 1992). The traditional COP-based measures of postural performances included the center of pressure (COP) area and standard deviation (SD) and COP Velocity. In addition a Stability Index (i.e., ratio of maximum excursion of COP along X–Y axes (i.e., functional boundary) over physical stability boundary (i.e., size and position of a subject’s feet on the force plate) was computed (see Slobounov et al., 1998 for details for computation of the Stability Index). The center of pressure at each instantaneous time defined by sample rate reflecting the degree of postural motion was calculated as:

\[ \text{COP}_x = \frac{-My + Fx}{Fz} \]  
\[ \text{COP}_y = \frac{-Mx + Fy}{Fz} \]

There is a high correlation between several of the standard force platform measures (Goldie et al., 1989; Slobounov and Newell, 1994), so the area of COP and velocity of COP were used as traditional measures to characterize the degree of postural motion exhibited by the participant. In addition, two-dimensional stability boundary measures and time-series of COP instantaneous position vector along with velocity and acceleration vectors were used to compute the VTC similar to our previous reports (Slobounov et al., 1997, 1998; Haibach et al., 2007; see also Fig. 1 and Appendix for details).

2.4. Statistical analysis

There were a number of dependent variables under study, including COP-based traditional measures (i.e., 90% ellipse COP areas, COP velocity and Stability Index) and VTC measures (mean, minimal values and mode). A one-way within-subject repeated measures ANOVA was used to analyze the COP-based variables with testing day (2, prior and post-concussive injury) and vision condition (2) as factors. Two-tailed t-test and ANOVA when appropriate were used to test for significant differences between experimental sessions (2, prior to and after MTBI) for VTC measures. The significance level was set at \( p < 0.01 \). The Minitab.Inc. software package was used to perform the statistical analysis.

3. Results

3.1. COP-based traditional measures of postural control

The results of balance testing using traditional COP-based measures prior to and after concussion episodes are shown in Table 1.

There were no significant differences for any of the standard COP-based measures of postural control as a function

<table>
<thead>
<tr>
<th>Experimental Session</th>
<th>COP area (cm²)</th>
<th>Velocity (cm/s)</th>
<th>Stability Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-injury/EO</td>
<td>0.554 ± 0.24</td>
<td>1.580</td>
<td>0.71 ± 0.09</td>
</tr>
<tr>
<td>Post-injury/EO</td>
<td>0.598 ± 0.32</td>
<td>1.699</td>
<td>0.69 ± 0.10</td>
</tr>
<tr>
<td>Pre-injury/EC</td>
<td>0.940 ± 0.34</td>
<td>2.312</td>
<td>0.63 ± 0.11</td>
</tr>
<tr>
<td>Post-injury/EC</td>
<td>0.926 ± 0.28</td>
<td>2.598</td>
<td>0.61 ± 0.13</td>
</tr>
</tbody>
</table>

COP area for both vision conditions and velocity are reported during static quite stance. Stability Index was computed for dynamic task as a ratio Functional boundary/physical boundary.
of testing day (prior to and 30 days post-injury, \( p > .01 \)).

Similar to previous reports (e.g., Slobounov and Newell, 1994), COP-based measures (COP area & COP velocity; Stability Index) systematically changed as a function of vision condition, \( F(1,44) = 10.45, p = 0.002 \). Specifically, COP area and COP velocity significantly increased during standing still with eyes closed (\( p's < .01 \)). Also, the stability index significantly decreased during the dynamic postural task in the eyes closed condition (\( F(1,44) = 11.23, p < .001 \)).

3.2. VTC measures-static tasks

Prototypical examples of the VTC time series 3D plots during standing still for eyes open and eyes closed are shown in Fig. 2. Visually, no obvious differences in terms of VTC shape, distribution and nominal values were observed before and after concussion for eyes open and eyes closed conditions.

The respective VTC measures for the static task and vision conditions before and after concussion are shown in Fig. 3. Statistically, there were no significant differences for VTC measures before and after concussion for the eyes open condition for the mean, mean minimal values and mode (two tailed t-test \( p \)-value for minimal VTC is 0.12; \( p \)-value for mean VTC is 0.114, \( p \)-value for mode VTC is 0.222). However, there was a trend for significant differences between testing days for eyes closed condition considering VTC mean minimal values (\( p = 0.08 \)) and mode (\( p = 0.05 \)).

3.3. VTC measures-dynamic tasks

VTC time series with respect to COP displacement, COP velocity and COP acceleration along y-axis during dynamic

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Fig. 2. 2D VTC time-series plots during standing still with (A) eyes open prior to concussion; (B) eyes closed prior to concussion; (C) eyes open 30 day after concussion; and (D) eyes closed 30 days after concussion.
postural task – A–P oscillations is shown in Fig. 4A. The VTC 3D distribution/plots as a prototypical example consistently observed in all 12 subjects prior to and after concussion are also shown in Fig. 4B and 5C.

Overall, VTC was sensitive to the location of the COP with respect to the 2D stability boundary. As can be seen from Fig. 4B and C, there is a relatively flat and constant area along the central position of the COP trajectory during A–P sway. However, the magnitude and range of VTC nominal values increased at the deflection point, when the COP “spatially approached” the stability boundary at both ends of the sway segment. There is a systematic sequential U-shaped pattern for the VTC throughout the trial duration. A striking feature of the time series is that the minimal VTC for each segment tends to a common level at around 250 ± 25 ms prior to concussion and around 450 ± .45 ms post-concussion. Both visually and statistically, there were significant alterations in VTC in terms of absolute values, range of VTC at the deflection points and mode in all 12 subjects under study at day 30th post-injury. Statistically, both mean minimal values and mode significantly increased after concussion (p < .001) in the absence of any signs of balance deficiency based upon traditional COP measures (see also Fig. 5).

To further examine the changes in VTC associated with dynamic tasks (i.e., Anterior–Posterior sway) after concussion, the following analysis of the VTC distribution was conducted. The VTC time-series along the y-axis separately for anterior (starting from initial maximum posterior and ending at maximum anterior COP position) and backward (starting from initial maximum anterior and ending at maximum posterior COP) sway were evenly partitioned into n segments and spatially ordered from 1 to 10. This spatial segmentation, in addition to traditionally reported mean and standard deviation values for entire trial duration, allows the examination of the dynamic of VTC changes within the trial duration for both directions of sway. The mean VTC and coefficients of variation (i.e., SD/mean) in each segment were calculated separately for both directions of sway within subject and then averaged across all 12 subjects prior to and after concussion. Our preliminary empirical analysis revealed that n = 10 is adequate number to obtain considerable spatial resolution and guaranteed sufficient data points (n > = 10) fitted into each segment. The spatial distribution of VTC and its variability in subjects prior to and after concussion are shown in Fig. 6. Fig. 6 is complementary to Fig. 4B and C and further quantifies the observation that: (a) VTC progressively increased when subjects “spatially approached” the stability boundary at both ends of the sway; and (b) both mean and variability of VTC increased at different segments of the sway in subjects following concussion episode.

Fig. 6 shows that although the shape of VTC distribution along the y-axis was similar before and after concussion (i.e., systematically increased at the deflection point when direction of sway changed to opposite, i.e., a subject approach stability boundary), the VTC mean values were significantly higher after concussion for both forward, F(1,250) = 7.92, p < .001, and backward, F(1,250) = 7.98, p < .001 sway. Moreover, these significant differences were observed at each segment under analysis for forward, F(9,250) = 11.57, p < .001, and backward, F(9,250) = 10.27, p < .001 sway. Finally, VTC variability, as evidenced by COV values, was significantly higher in concussed subjects considering both forward, F(1,250) = 7.96, p < .001; and backward, F(1,250) = 35.28, p < .001 sway directions. This pattern of findings was present for each segment of the trajectory under analysis, p < .001.

4. Discussion

There is still an ongoing debate in the literature as to whether concussion causes a short-term functional disturbance in the brain or induces long-lasting residual disability that may be overlooked. Recent empirical findings suggest that the notion of transient and rapid symptoms resolution is misleading since symptoms resolution is frequently not indicative of injury resolution (Slobounov and Sebastianelli, 2006d). The alteration of postural control measures was observed during the challenging dynamic postural tasks within 30 days post-injury in concussed...
individuals with apparent "normal" balance as assessed by conventional clinical tools (Slobounov et al., 2006a). This residual deficit was most prominent when concussed individuals were exposed to more demanding conflicting visual scene information induced by virtual reality graphics (Slobounov et al., 2006b,c).

Previous research has shown not only erroneous motor responses but also prolonged reaction time (RT) especially during choice RT but not RT tests between normal control and concussed individuals (Hugenholtz et al., 1988). Similarly, abnormalities in isometric force production in concussed individuals have been documented, but only when the complexity of the motor task was systematically increased (Slobounov et al., 2002). Cavanaugh et al. (2005a,b, 2006) have shown that methods from non-linear dynamics (i.e., Approximate Entropy, ApEn) may detect changes in postural control in concussed athletes with "normal" postural stability as revealed by conventional balance testing measures. It appears that both ApEn and VTC measures can detect postural abnormalities that are not observed using traditional balance testing. However, it should be also noted that the center of pressure oscillations in Cavanaugh et al. (2005,2006) studies were more...
regular (i.e., less variable) unlike the variability of VTC (i.e., more variable) observed in our subjects after concussion.

Whether the regularity/variability paradox considering VTC and ApEn measures is a function of postural task constraints (static versus dynamic) or stability boundary/injury dependent phenomenon is an empirical question requiring careful examination. A number of recent studies have shown long-term motor deficits (i.e., oculomotor and visuomotor functions) in absence of neuropsychological abnormalities in subjects suffering concussion at least 12 months post-injury (Heitger et al., 2004, 2006). That the concussed subjects were able to accomplish dynamic postural tasks in the presence of signs of altered measures of postural control may be explained by the enormous brain plasticity to control movement in spite of deficiency (Hallett, 2001).

The major finding from our study is in agreement with the aforementioned line of research, indicating that residual postural abnormalities in concussed individuals may be undetected using conventional research methods. Indeed, VTC measures were altered in the absence of signs of postural instability based on traditional measures of postural control. Most importantly, VTC changes were more prominent when postural stances were challenged by introducing dynamic stability tasks that utilize more of the functional cognitive reserve (Kahneman, 1973). Both minimal/mean and mode values of VTC increased along with enhanced VTC variability in subjects suffering from concussion. This implies that concussed subjects may conserve an enlarged “temporal safety margin” (Carello et al., 1985) in the regulation of posture. Collectively, the data from our study show that the residual deficits of concussion are most sharply revealed when the postural system is challenged by more demanding tasks.

There are a growing number of reports suggesting that the VTC method of estimating the postural stability is more sensitive than standard measures of postural control. In our laboratory, the alteration of VTC measures in elderly population has been documented (Slobounov et al., 1998), especially when the base of support was challenged (Haibach et al., 2007). Similarly, Hertel et al. (2006) have shown the robustness of the virtual time to contact measure for assessment of postural stability in human single leg standing. Interestingly, VTC measures may detect postural control deficits in subjects suffering from chronic ankle instability (CAI), that traditional measures (i.e., COP range and velocity etc.) do not (Hertel and Olmsted-Kramer, 2007). Moreover, Van Wegen et al. (2001, 2002) have shown age-related changes in time-to-contact...
measures, suggesting that VTC may serve as a controlled property in regulation of upright posture. The novel finding from our current report is that VTC measures may detect residual postural abnormalities in concussed individuals.

There was a difference in the direction of change of the nominal values of time to contact and variability (SD) between VTC measures observed in our study and those TtC values reported by Hertel and Olmsted-Kramer (2007), Hertel et al. (2006) and Van Wegen et al. (2001, 2002). It should be noted that a static single-limb task stance was used in Hertel and Olmsted-Kramer versus the dynamic double limb task in our study, in addition to differences in the nature of injury under study here. However, most importantly, both the conceptualization of the time-to-contact approach and computational differences may be the major reason for discrepancies between the studies. In short, the one-dimensional constant velocity Lee’s tau method (originally developed for posture by Riccio, 1993), adopted by Hertel and Olmsted-Kramer (2006) and Van Wegen et al. (2002) is conceptually different than our originally proposed virtual time-to-contact (VTC) method (Slobounov et al., 1997). Specifically, unlike Lee’s tau method, the VTC takes into account the instantaneous position, velocity and acceleration vectors with respect to two-dimensional stability boundary in computation of VTC. It has been noted the use of different methodologies makes interpretation of time-to-contact data and comparisons between studies less than straightforward (Haddad et al., 2006).

Our previous research has provided support for the proposition that VTC, which specifies the spatiotemporal proximity of the center of pressure to the stability boundary, is an informative variable in the regulation of human posture (Slobounov et al., 1997, 1998; Haibach et al., 2007). This study provides additional evidence for this proposition. Specifically, the nominal values of VTC regardless of subjects’ injury status were significantly lower during dynamic postural task compared to static quite stances. This may indicate a reduced “safety margin” (Carello et al., 1985; Hertel et al., 2006; Van Wegen et al., 2002) resulting in less time available to initiate compensatory postural adjustments (Riccio, 1993) to preserve balance. This interpretation is in agreement with more recent conceptualization of anticipatory postural adjustment (APA) reversals that emphasizes the important role of safety margin in generation of postural adjustments (Krishnamoorthy and Latash, 2005). Indeed, the APA phenomenon could be defined as changes in the activity of postural muscles associated with a predictable perturbation that act to provide maximal safety of the postural task component.

It should be noted that the shape and structure of VTC time series distribution during A–P sway before concussion are similar to those after concussion. VTC consistently increased with enhanced variability as a subject approached the stability boundary (see Fig. 4), implying that the same strategy was implemented to preserve balance in the dynamic task regardless of injury status. It should be emphasized that although VTC values were reduced during dynamic postural tasks with respect to those during static postural tasks, these were significantly increased after concussion. This suggests that concussed subjects may be more conservative in terms of preserving larger “safety margin” in order to accomplish the dynamic postural task. All subjects prior to and after concussion episodes were able to accomplish the task and preserve balance. Therefore, direct examination of this suggestion is necessary using an experimental paradigm that actually provokes the loss of balance. That the overall shape of the VTC distribution was preserved after concussion, though its nominal values and variability were increased, provides further evidence that VTC may serve as a low dimensional control variable in the regulation of upright posture (Slobounov et al., 1997).

To conclude, the major findings from this study provide further evidence that VTC is a sensitive measure that may act as a control parameter in the regulation of upright standing posture (Slobounov et al., 1998; Van Wegen et al., 2001, 2002; Haibach et al., 2007) Regardless of subjects’ brain injury status. The current findings reveal that the alteration in the regulation of postural movement in concussed individuals may not be detected using conventional assessment tools. Whether this alteration is relatively transient resulting in the acquisition of more conservative compensatory strategies to preserve balance, or a long-term persistent residual postural abnormality, is yet to be determined.

The clinical implication of our findings is in agreement with Cantu (2006) that the athletes who prematurely return to play based solely on conventional symptom resolution criteria may be highly susceptible to future and possibly more severe brain injuries. Indeed, a combination of various assessment methods and tools should be used by clinicians in order to make an accurate decision in terms of return to play and to identify athletes at risk for re-current concussions (Notebaert and Guskiewicz, 2005). This is ongoing challenge of our multi-disciplinary research group at Penn State University to predict athletes at risk for future concussions based on pre-season assessment and rate of multi-modal symptoms resolution following the first episode of concussion.

Appendix A. Supplementary data


References


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