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Static and dynamic postural stability in veterans with combat-related mild traumatic brain injury

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ABSTRACT

Persistent post-concussive symptoms are reported by 10–15% of individuals who suffer mild traumatic brain injury (mTBI), but their basis is often uncertain. One such symptom is disequilibrium, a sensation of impaired balance during standing and walking. The hypothesis for this study was that this subjective symptom is associated with objective and measurable deficits in static and dynamic postural stability. An infrared motion tracking system was used to record body motion during quiet standing and in response to waist perturbations in fourteen veterans (age 22–40 years, 13 male) of the Operations Enduring Freedom (OEF) and Iraqi Freedom (OIF), who had a history of mTBI that occurred 7 months to 7 years prior to testing. We compared body sway between veterans with mTBI reporting persistent disequilibrium (T_D, $n = 8$) and those with no vestibular symptoms ($n = 6$), as well as to a group of non-veterans with no balance symptoms ($n = 10$). Static postural stability was reduced in T_D veterans in comparison to each of the other two groups ($p < 0.0002$), most notably on a compliant surface with eyes closed. The T_D group also had decreased dynamic stability of the upper trunk ($p < 0.05$) and enhanced postural oscillations ($p < 0.02$) following waist perturbations. Our findings support a physiological basis for persistent disequilibrium after mTBI and are consistent with impaired vestibular processing. Disruption of semicircular canal inputs is unlikely to be the cause, as head impulse responses were normal in all groups. The unexpected finding of dynamic postural oscillations requires further study but may indicate enhanced instability in sensorimotor networks responsible for postural control.

1. Introduction

Mild traumatic brain injury (mild TBI) has been identified as a major morbidity of recent military conflicts. Although estimates vary, as many as 10% or more of U.S. service members deployed over the last decade to Iraq (Operation Iraqi Freedom, OIF) and Afghanistan (Operation Enduring Freedom, OEF) may have experienced combat-related mild TBI as a consequence of blast exposure and/or blunt head trauma [1,2]. Civilian TBI is similarly common, due to a variety of causes, such as athletic injuries, motor vehicle collisions, falls, assaults, and other accidental injuries [3].

Most civilians who experience mild TBI recover within several days. In about 10–15% of cases, however, recovery is delayed and symptoms persist [4,5]. Post-concussive symptoms are reported with a similar frequency after combat mild TBI [1,2]. To what extent these persistent symptoms are consequences of the mild TBI or due to other factors, such as post-traumatic stress disorder (PTSD) or depression, remains a matter of debate [6].

There are several reasons why it might be difficult to find physiological correlates to post-concussive symptoms. First, the symptoms reported, such as difficulty concentrating or headaches, tend to be non-specific and could result from diverse causes. Investigations that rely on symptom reporting rather than objective measures may be unable to distinguish among these etiologies. Second, deficits associated with post-concussive symptoms may be sufficiently subtle not to be detected on a routine neurological examination; more sensitive physiological measures may be required. Third, many studies have considered post-concussive symptoms together as a group rather than studying each individually [7,8]. Lumping post-concussive symptoms into

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symptom scales is useful for the identification and tracking of injuries [9], but it offers little insight into the pathophysiological mechanisms underlying specific symptoms.

Dizziness is an example of a common post-concussive symptom after combat mild TBI that could be due to a number of causes, both physical and psychological [10,11]. For example, some individuals have episodic dizziness due to benign paroxysmal positional vertigo or vestibular migraine. In other cases, dizziness may be a somatic correlate of anxiety or depression. In this study, we have focused on one particular form of post-concussive dizziness, namely a chronic sensation of imbalance during standing and walking that we refer to as disequilibrium. A few studies that have assessed post-concussive symptoms after combat injuries have found an association of dizziness and imbalance with mild TBI that is independent of PTSD [2,12,13]. To elucidate further a potential physiological basis, we measured static and dynamic postural stability in OEF/OIF veterans with a history of mild TBI with and without chronic persistent disequilibrium.

2. Materials and methods

2.1. Subjects

Fourteen OEF/OIF veterans (age 22–40 years, median 26.5) with a clinical history of mild TBI were studied. The diagnosis of mild TBI was based on the subjects' self-report of a combat event involving blast exposure and/or blunt head trauma without penetrating injury that resulted in loss of consciousness for no more than 30 min, alteration of consciousness for no more than 24 h, and/or post-traumatic amnesia for no more than 24 h. One additional veteran was excluded from analysis because the history of injury was inconsistent.

Veterans with mild TBI were divided into those who reported ongoing chronic disequilibrium (T_D, $n = 8$) and those who reported no disequilibrium (T_{ND}, $n = 6$). All subjects in the T_{ND} group and all but one in the T_D group were male. At least one mild TBI included loss of consciousness in 4/8 of the T_D group and in 4/6 of the T_{ND} group. Post-traumatic stress disorder had been diagnosed in 7/8 of the T_D group and in 4/6 of the T_{ND} group. The duration since the most recent mild TBI ranged from 7 months to 7 years and was similar in both groups ($p > 0.55$, *t*-test).

We also studied 10 non-veterans, who had no history of TBI and had no vestibular or neurological complaints. All subjects gave written informed consent under a protocol that was approved by the Institutional Review Boards of the Louis Stokes Cleveland Department of Veterans Affairs Medical Center and the University Hospitals of Cleveland Case Medical Center, as well as by the Human Subjects Protection Office of the U.S. Department of Defense.

2.2. Data recording

An infrared motion tracking system (Vicon, Oxford, UK) was used to record kinematics of body motion at the waist (reflective markers over the sacrum and each anterior superior iliac spine) and the upper trunk (markers over the spinous process of C7 and over each shoulder). Three-dimensional marker positions were sampled at 100 Hz.

2.3. Experimental paradigms

Subjects were studied in a series of tasks designed to test static and dynamic balance. Static tasks included quiet standing on the floor and standing on a compliant surface (10 cm thick foam), in both cases with eyes open and closed. Dynamic balance was tested with sudden postural perturbations delivered to the lower trunk via a computer-controlled linear motor coupled to the body through a taut rope attached to a belt worn at the waist. At an unpredictable time, the motor was commanded to generate a linear force equal to 10% of the subject's body weight; the force was sustained for 0.5 s. Because (for safety reasons) the force was transmitted by a non-rigid rope, the force profile felt by the subject was not identical to the force generated by the motor; thus, for analysis (see below) the acceleration of the pelvis was used to determine the time of force onset. Responses were measured to both forward and rightward perturbations. Peak accelerations were 0.31 ± 0.11 g (mean ± S.D.) for forward perturbations and 0.30 ± 0.14 g for rightward perturbations. There was no difference in peak accelerations and, therefore, in the perturbation force felt by the subjects, between groups ($p > 0.5$).

2.4. Data analysis: static balance

Three-dimensional marker positions were reconstructed by the Vicon software. Subsequent analysis was performed using custom programs, written by the authors in Python and MATLAB^{TM}. Marker velocity was calculated by component-wise differentiation of marker position, after filling missing points by linear interpolation and low-pass filtering (interp1d and firwin routines in scipy, 15 Hz cutoff frequency, bidirectional filtering for zero phase shift). For each of the four conditions, we quantified postural stability by calculating the two-dimensional sway path (line integral of the marker position in the earth-horizontal plane) for the first seven seconds of the recording. Finally, we determined trunk angle as a function of time from the C7 and sacral marker positions. These angles were calculated based on the position of the C7 marker relative to the sacral marker. For example, the pitch angle $\theta_{Pitch} = \tan^{-1}[(x_{C7} - x_{SACR})/(z_{C7} - z_{SACR})]$, where x is the fore-aft position and z is the vertical position of each marker.

2.5. Data analysis: dynamic balance

Marker positions and velocities were determined as for static balance. For each trial, the onset of the perturbation was determined from the acceleration of the sacral marker, using a thresholding technique (see Fig. 5). Occasionally, the sacral marker or C7 marker was obscured during the recording; in these cases, the average motion of the RASI and LASI markers (for pelvis motion) or of the shoulder markers (for upper trunk motion) was used instead. Postural sway length and displacement were calculated for the first 2.5 s after the onset of each perturbation.

2.6. Head impulse testing

The vestibulo-ocular reflex was recorded on the same day as postural testing. Eye movements were recorded using either scleral coils or video-oculography in response to manual head impulses. The VOR gain was calculated in MATLAB^{TM} based on a least-squares optimization of eye to head velocity. Gains were determined separately for each direction of rotation.

2.7. Statistical analysis

Statistical testing was performed using multivariate repeated-measures ANOVA based on a linear mixed-effects model in R (lme in nlme package, www.cran.r-project.org). Response measures were subject to power transformation to more nearly approximate normality, based on Box Cox analysis (boxCox routine in R car package). Between-groups factors included history of TBI and history of disequilibrium. Depending on the specific paradigm, within-subjects factors included standing surface, eyes open vs. closed, perturbation direction, head orientation, and frequency. Post hoc comparisons for subject group were performed using the R routine *glht* with the Tukey method.