Incorporating Virtual Reality Graphics with Brain Imaging for Assessment of Sport-Related Concussions

Semyon Slobounov, Wayne Sebastianelli & Karl M. Newell

***Abstract*—there is a growing concern that traditional neuropsychological (NS) testing tools are not sensitive to detecting residual brain dysfunctions in subjects suffering from mild traumatic brain injuries (mTBI). Moreover, most mTBI patients are asymptomatic based on anatomical brain imaging (CT, MRI), neurological examinations and patients' subjective reports within 10 days post-injury. Our ongoing research has documented that residual balance and visual-kinesthetic dysfunctions along with its underlying alterations of neural substrates may be detected in "asymptomatic subjects" by means of Virtual Reality (VR) graphics incorporated with brain imaging (EEG) techniques.**

I. INTRODUCTION

Concussion in sport, otherwise known as mild traumatic brain injury (MTBI) has been referred to as both the most common and the most puzzling type of traumatic brain injury [1]. It is seen during recreational activities, transportation accidents, and other situations in which the brain accelerates (or decelerates) differentially in relation to the skull. The phenomenon of concussion is puzzling in that there exists no consistent set of theoretical studies which clearly articulates its pathophysiology. Furthermore, most of the initial symptoms including balance [2] and cognitive deficits [3] usually resolve within 7-10 days post-injury. In addition, there is little evidence to suggest that current structural imaging techniques [e.g., magnetic resonance imaging (MRI)] can identify structural changes in the brain following concussion [4]. However, a variety of functional deficits observed using brain imaging studies have been noted in concussion [5,6,7].

There is no single concussion alike in terms of initial symptoms at the site of injury and therefore in symptoms resolution as an injury evolves over time. Therefore, it is our approach to examine multiple modalities (balance, neurocognitive functions and associated neural substrates) in order to properly classify the concussive episode. Accordingly, in the present report, we present a set of behavioral and brain imaging data indicating that residual functional abnormalities may be observed in "asymptomatic, based upon traditional assessment tools" subjects who have recently suffered from a single episode of sport-related concussion. Theoretically, this will help to clarify the nature of alteration of the cortical network following concussion. Clinically, this will help to improve the accuracy of concussion classification and to define more appropriate return-to-play criteria. We designed an EEG study using a virtual reality (VR) graphics aimed to examine the brain activation patterns preceding the loss of postural stability induced by a "Moving Room" experimental paradigm. It should be noted, that VR environment allows one to develop tasks in which the individual can control and manipulate movement along with the sense of *self-motion* while retaining the body fixation requirements of the fMRI environment [8]. Specifically, we developed visual perturbation balance tasks enabling (a) the subjects to experience the *sense of presence* [9] and (b) to track the changing brain activation patterns via EEG in both normal controls (NV) and concussed individuals during exposure to these VR-driven postural task conditions.

2. *Moving Room* Experiment

A. *Rationale:* Balance abnormalities specifically evident during visual-kinesthetic tasks are the most common symptom in TBI patients suffering from sport-related concussions [2]. It should be noted that balance symptom resolution varies among TBI patients and may last up to more than one year post-injury. Our previous research has shown the presence of balance abnormalities and sensori-motor disintegration, induced by VR visual field motion up to 30 days post-injury [10]. Recent studies by Cavanaugh et al [11] have also shown that advanced methods may detect changes in postural control in subjects with "normal" postural stability and neuropsychological (NS) measures based upon conventional balance and neuropsychological testing. The VR moving room appeared to be one with the advanced tools that allow detection of residual postural abnormalities as evidenced by impaired visual-kinesthetic integration. Alterations of neural correlates associated with loss of balance due to stimulated rotations of visual field have not been examined, yet.

B. *Subjects:* Fifteen neurologically normal student-athletes with no history of mTBI (mean age 21.3 +/- 1.5 years) and 14 student-athletes (mean age 20.8 +/- 1.7 years) who had recently suffered a sports-related mTBI (collegiate rugby, ice hockey, lacrosse, etc) were recruited for this study. The sample was 65% male and 35 % female. Academic grade average score for all subjects under study was 3.2 +/- 0.5. All injured subjects suffered from grade 1

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mTBI (Cantu Data Driven Revised Concussion Grading Guideline, [1]). The initial diagnosis of mTBI was made on the field by certified athletic trainers (AT) and as a part of the routine protocol of the Sport Concussion Program at Pennsylvania State University. Testing took place on day 15 (+/-2 days) post-injury and within 24 hours of clinical symptoms resolution and medical clearance for sport participation by their supervising physician.

C. *Apparatus and Procedures:* The HeadRehab, LLC VR system that includes: (a) VisMini portable stereo 3D projection system; (b) Draper Inc. 6 X 8 portable Cinefold surface screen; and (c) AMTI force plate for assessment of postural responses to Visual Field Motion was used in this study. The VR system was also synchronized with the whole body motion tracking 64 channels NeuroScan EEG systems. Specifically, EEG data were acquired using Ag/AGCl electrode mounted in a 64 channel Electro-Cap (NeuroScan, Inc, Eaton, OH). The ground electrode was located 10% anterior to FZ, with linked earlobes serving as references, and impedances were kept below 5 kΩ. The EEG signals were amplified using a programmable DC coupled broadband SynAmps amplifier (NeuroScan, Inc., El Paso, TX). The EEG data were sampled at 250 Hz and then segmented in 500-ms epochs. Data were digitized and stored offline. The field sequential stereo images were separated into right and left eye images using liquid crystal shutter glasses. An additional sensor was located on the subject's head to interact with the visual field motion. The visual field motion consists of a realistic looking "moving room" (see Fig.1).

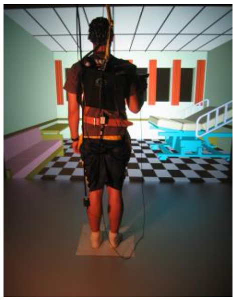

Fig.1. AMTI force platform and 6 degrees of freedoms ultra-sound IS-900 micro motion tracking technology from "*InterSense Inc*" was used to control the head and body kinematics and postural responses to visual manipulations of VR scenes.

Preprogrammed manipulations of the VR moving room included the following: (1) viewing stationary VR room; (2) VR room forward-backward oscillatory translation within 18 cm displacement at .2 Hz; (3) VR room "Roll" around heading *y*-axis between 10-30 degrees at .2 Hz; (4) VR room "Pitch" around interaural *x*-axis between 10-30 degrees at .2 Hz; (5) VR room "Yaw" around vertical *z*-axis between 10-30 degrees at .2Hz; (6) VR room translation along x-axis within 18 cm displacement at .2 Hz. The subjects were instructed to acquire the Romberg stance and stand as still as possible on the force platform while viewing the computer generated "moving room" visual scenes for 30 s trial duration. The area of the center of pressure (COP) was calculated from obtained original dataset sampled at 100 Hz. A specially developed MATLAB program was used to estimate the subject response data obtained from AMTI force plate. Coherence values between quantities of moving room and subject responses were assessed using a specially developed m-code in MATLAB 6.5 (see below). The auto-spectra for each signal were calculated by using Welsh's averaged periodogram method. Coherence was calculated based on the cross-spectra f_{xy} and auto-spectra f_{xx}, f_{yy} with the spectra estimated from segments of data and the coherence R_{xy} estimated from the combined spectra:

$$R_{xy}(\lambda)|2=|f_{xy}(\lambda)|^2/(f_{xx}(\lambda)f_{yy}(\lambda));$$

The significance of coherence was also calculated. That is the confidence limit for zero coherence at the α %, and L, is the number of disjoint segments: sig $(\alpha) = 1-(1-\alpha)^{1/(L-1)}$. In addition, continuous wavelet transform (CWT) was performed to track the dynamics of coupling between subject body motion and visual scenes oscillation over the entire trial duration (30 s). The CWT is able to resolve both time and scale (frequency) events better than the short Fourier transform (STFT). In mathematics and signal processing, the continuous wavelet transform (CWT) of a function *f* is defined by: Where τ represents translation, s represents scale which is related to frequency and ψ is the mother wavelet. $\overline{z}$ is the complex conjugate of z. The mother wavelet is a complex Morlet wavelet, as it has both good time and frequency accuracy.

$$\gamma(\tau,s)=\int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{|s|}}\overline{\psi\left(\frac{t-\tau}{s}\right)}dt$$

EEG data were processed offline with EEGLAB 5.03 software [12] using Matlab open source toolbox (Mathworks, Natick, USA). Epochs were baseline normalized and then visually screened for unique, nonstereotypic artifacts such as eye blinks, eye movements, heartbeats, and muscle activity, which were eliminated. To compute power spectra during cognitive testing, Fast Fourier Transform power calculations were performed within each epoch and then averaged across them for each frequency band (*theta*, *alpha*, and *beta*). To ensure homogeneous data processing, relative power for each frequency band was used instead of absolute power. Only theta band results are reported in this paper.

D. Results: Representative examples of subjects' responses to visual field motion are shown in Fig 2. Clear lack of coherent *ego-motion* was noticed in mTBI subjects.

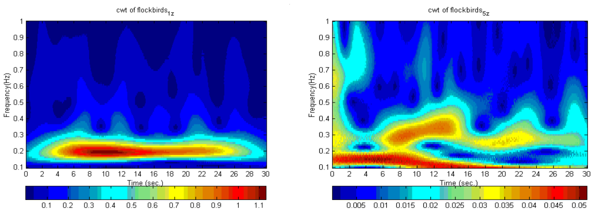

Fig.2. Time-frequency decomposition of the coherence values between motion of the VR room at .2 Hz and postural compensatory adjustments achieved by wavelet transforms. The plots are representing 2D color maps of evolution of coherence over the trial duration (30s) while subjects were viewing VR motion (Roll condition) at .2 Hz. Note a highly synchronized

whole body motion produced by normal controls (Left) and lack of synchrony observed in mTBI patients (Right).

Although, visual field motion induced ego-motion, as evidenced by highly coherent postural responses ($r > .08$, $p < .01$), 85% of the normal volunteers in this study preserved postural stability for all of the programmed manipulations of the VR moving room. In contrast, 75% of TBI subjects experienced destabilizing effect of visual field motion, loss of balance as evidenced by making compensatory steps and significant increased center of pressure area (mean COPx and COPy, $p<.01$, see also Fig. 3) and incoherent postural responses ($r< .05$, $p< .01$) to VR scenes. The most destabilizing conditions were: VR room “roll” around y-axis between 10-30 degrees; and VR room pitch” around x-axis within 10-30 degrees. It should be noted that all subjects under study experienced *vection* in addition to ego-motion, as evidenced by subjective reports after the completion of each experimental condition. Specifically, the subjects reported *vection* strength was on average 8 on an 11 point scale with 0 representing “no *vection*” was perceived and 10 representing “vection so strong that the perceived self-motion could not be differentiated from real physical motion” [13]

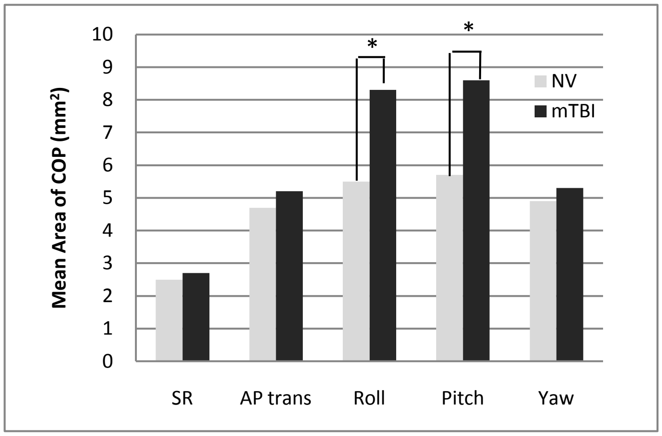

Fig. 3. Mean COP area during viewing the stationary VR room and those associated with viewing “moving room” conditions. Note, only successful trials (no lose of balance) both for normal volunteers (NV) and mTBI subjects are included in this analysis. Clearly, significant increase of mean area of the COP was evident in mTBI subjects compare to NV, especially during “Roll” and “Pitch” conditions. SR – stationary room; AP – trans – moving room translation in Anterior-Posterior directions; * - differences are significant ($p<.01$).

The results from EEG analyses are shown in Fig 4. Consistent with predictions, there were significant changes in *theta* power activation in the normal volunteers at the beginning compared with the end of trial in frontal, $F(2, 18) = 13.78$, $p < .01$, central, $F(2, 18) = 7.30$, $p < .01$, and parietal, $F(1.4, 12.5) = 5.16$, $p < .05$ areas. Effect sizes were greatest in central-frontal areas ($\eta^2 = .61$) and declined across temporal-occipital ($\eta^2 = .45$) and parietal ($\eta^2 = .36$) areas. As shown in Fig 3(top), there was a significant increase of *theta* power during as balance task progressed. Specifically, this *theta* increment was obvious initially at central areas with further diffusion to frontal electrode sites bilaterally. This finding is consistent with our previous EEG report suggesting increase of *theta* power as a function of successful performance of perceptual-motor tasks [14]. Interestingly, no significant *theta* power was present in concussed subjects at either phases of postural task progression (see Fig. 3 bottom)

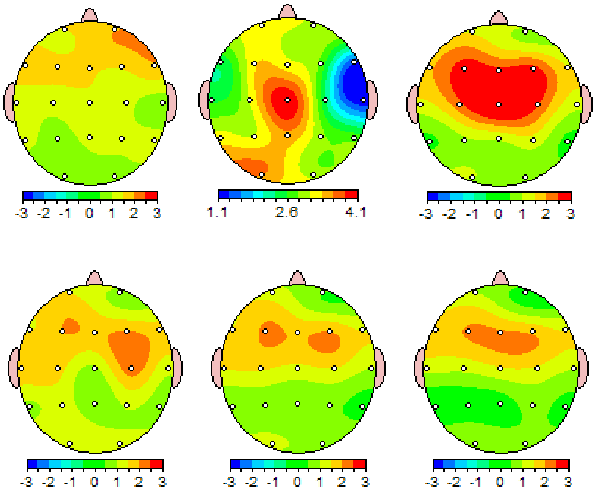

Fig.4. 2D plots of *theta* power as the postural task progressed over 30 seconds of trial duration in NV (top) and concussed individuals (bottom). Note a significant enhancement of *theta* power over frontal-central electrode sites as trial progressed in NV but not in concussed subjects.

E. *Discussion:* We designed this study to examine destabilizing effect of visual field motion induced by virtual reality graphics on postural responses in subjects suffering from mild traumatic brain injury. It should be noted that in contrast to mTBI patients, NV subjects were able to adapt to confusing visual field motion demonstrating intact perceptual-motion integration in control of balance. NV subjects experienced increase of the mean COP most likely due to presence of ago-motion. This finding is consistent with other studies reporting that an immersive dynamic visual field induces a postural reorganization as reflected in the subjects’ head, trunk and ankle responses [15]. Standard balance tests revealed that balance problems are cleared within 10 days post-injury [2]. However, more challenging postural tasks such as responses to visual field motion induced postural dysfunctions beyond 10 days post-injury. In fact, none of the concussed subjects were able to preserve balance while viewing a moving room on day 3 post-injury (data not reported in this paper). This may be attributed to perceptual-motor disintegration induced by conflicting visual field motion in concussed individuals.

EEG findings in this study are complementary to our previous research brain imaging studies (both EEG and fMRI) demonstrating neural underpinning of postural responses to visual field motion, that may be impaired as a result of mild TBI [16,17,18,19]. The absence of prominent enhancement of central-frontal *theta* power in concussed individuals, in conjunction with balance problems may indicate impaired neural substrates responsible for focused attention when more challenging postural stance are required and/or executed.

Conclusion: The major findings from this study suggest `the presence of a residual disturbance of the neuronal network that is involved in execution of postural [12][12] movement and possibly lowering the threshold for brain re/injury. Thus, it is feasible that the VR environment in conjunction with EEG can be used to examine the effects of visual field motion on balance in normal controls and especially in individual suffering from traumatic brain injury. The presence of perceptual-motor disintegration induced by visual field motion and associated alterations of brain functions could potentially be considered within the scope of existing grading scales of concussion.

ACKNOWLEDGMENT

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