Neural Control of Posture in Individuals with Persisting Postconcussion Symptoms

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ABSTRACT

HELMICH, I., A. BERGER, and H. LAUSBERG. Neural Control of Posture in Individuals with Persisting Postconcussion Symptoms. *Med. Sci. Sports Exerc.*, Vol. 48, No. 12, pp. 2362–2369, 2016. **Introduction**: Postural instability has been shown to characterize individuals who suffered from long-term symptoms after mild traumatic brain injury. However, recordings of neural processes during postural control are difficult to realize with standard neuroimaging techniques. Thus, we used functional nearinfrared spectroscopy to investigate brain oxygenation of individuals with persistent postconcussion symptoms (pPCS) during postural control in altered environments. **Methods**: We compared brain oxygenation and postural sway during balance control in three groups: individuals suffering from pPCS, individuals with a history of mild traumatic brain injury but without pPCS, and healthy controls. Individuals were investigated during postural control tasks with six different conditions: i) eyes opened, ii) eyes closed, and iii) blurred visual input, each while standing a) on a stable and b) an unstable surface. **Results**: In all groups, during the eyes closed/unstable surface condition as compared with the other conditions, the postural sway increased as well as the brain oxygenation in frontal brain cortices. In the most difficult balance condition, as compared with the other two groups, subjects with pPCS applied more force over time to keep balance as measured by the force plate system with a significantly greater activation in frontopolar/orbitofrontal areas of the right hemisphere. **Conclusions**: As subjects with pPCS applied more force over time to control balance, we propose that with regard to cognitive processes, the increase of cerebral activation in these individuals indicates an increase of attention-demanding processes during postural control in altered environments. **Key Words:** PERSISTENT POSTCONCUSSION SYMPTOMS, FUNCTIONAL NEARINFRARED SPECTROSCOPY, BALANCE, POSTURAL CONTROL, FRONTAL CORTEX

According to the Centers for Disease Control sports-related mild traumatic brain injuries (mTBI), a term which is often used interchangeably with the term "concussion," occur in the United States approximately 1.6 to 3.0 million times per year (2). Postconcussive symptomatology concerns a variety of symptoms, e.g., headache, dizziness, and cognitive difficulties that usually resolve over a period of several days. However, a subgroup of patients experience continuous postconcussive symptoms and neuropsychological deficits that can persist for months or even years (3,4,19,37,39). Several investigations have shown behavioral and neuronal alterations as a long-term effect of mTBI (4,38,39). For example, Wrightson et al. (39) found in preschool children with mild head injury a significant deficit in interpreting visual puzzles, which remained impaired up to 6 months after the incident. When compared with healthy controls, patients with mild traumatic injuries showed smaller increases in regional cerebral blood flow in the prefrontal cortex during a spatial working memory task until 35 months after the incident (4). Because the latter authors did not find differences between concussed and control subjects during resting state activity, Chen et al. (4) concluded that a cognitively challenging task might be necessary to uncover cerebral changes associated with mild head trauma.

A characteristic postconcussive symptom is the loss of balance control (12,13). Guskiewicz et al. (13) found in a study involving 1003 individuals with sport-related concussions that balance problems were present in 30% of them. The degree of balance impairment in the concussed subjects increased with increasing task demands (12). Because it has been argued that cognitive challenges might be necessary to uncover cerebral changes associated with mild head trauma (4), computerized dynamic posturography of patients who had suffered from postconcussive symptoms for at least more than 2 yr revealed that postural balance deficits are most evident when individuals are challenged by the

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combined manipulation of visual, vestibular, and somatosensory systems (21).

However, the role of the brain during postural control processes with increasing task complexity is difficult to investigate with standard neuroimaging techniques, such as Functional Magnetic Resonance Imaging (fMRI) or positron emission tomography (PET). Thus far, one study has investigated the pattern of neural activity that accompanies balance control by using a mobile gantry PET system (28). Depriving the participant of visual input (eyes closed) during postural control particularly activated the prefrontal cortex (Brodmann area 8/9) (28). By using electroencephalography, Wiese et al. (37) showed that TBI patients displayed alterations of the movement-related potentials of self-initiated right index finger abductions in the prefrontal cortex up to 52-wk postinjury. The authors supposed that TBI patients need increased attentional resources during movement preparation (37).

As a novel brain imaging technique, functional nearinfrared spectroscopy (fNIRS) allows for the investigation of neural processes providing continuous readings of cerebral oxygenation with a high temporal resolution (33). The particular advantage of fNIRS in comparison to conventional brain imaging methods, such as fMRI, for example, is that it allows recordings during the execution of movement tasks in a natural context (16), in particular during balance control (10,25). Examination of brain activity during motor tasks is specifically relevant for assessing the return-to-play state of athletes with mTBI. fNIRS signals closely correspond to fMRI signals (33) and have been shown, likewise, to reliably detect alterations in brain activity signals from mTBI patients (17,36). In fact, test–retest reliability of NIRS measures in subjects with traumatic brain injury showed that NIRS is a reliable noninvasive technique for evaluating cerebral oxygenation and blood volume changes during motor function/performance (reported intraclass correlation coefficients for the cerebral oxygenation in subjects without and with traumatic brain injuries: 0.83/0.70) (1). However, thus far, there has been no research undertaken on brain processes during balance control in individuals with persistent postconcussion symptoms (pPCS). Because the frontal cortex is frequently involved in concussion, and thus is likely to be affected in the long-term cognitive and behavioral impairments in pPCS (3,4,37,38), in the present study, we investigated the contribution of the frontal cortex in the control of posture. Because it has been assumed that mTBI patients rely on increased attentional resources during movement execution (37), we hypothesize that individuals suffering from a pPCS will show increased brain activity during balance control with increasing task demands as compared with healthy control subjects.

METHODS

Subjects. Thirty-five subjects (female = 18, male = 17) were recruited via billboard notices ("looking for participants with sports-related concussions that participate in a experimental brain-imaging study") at the German Sports-University Cologne, Germany. After written informed consent was obtained for each participant, the individuals with a history of a concussion underwent a clinical neurological and psychiatric–psychosomatic examination by a specialist (medical doctor of neurology, psychiatry, and psychosomatic medicine) to identify individuals with and without postconcussive symptoms according to the International Classification of Diseases (10F 07.2) and to exclude participants with primarily somatoform and dissociative disorders (International Classification of Diseases 10F 45 and F 44). Based on the medical examination, five individuals were excluded from the study as their complaints were related to somatoform and dissociative disorders. Thus, 30 of the 35 subjects were included in this study; 20 of them (mean age, 27.2 ± 10.4; 10 women, 10 men) sustained an mTBI in sports, such as ice hockey, American football, soccer, horseback riding, basketball, etc.; 10 of them matched in age (mean age, 26.7 ± 7.9; six women, four men) and without a history of a concussion served as controls. The medical examination resulted in three groups of investigation: i) a concussed group with persisting postconcussive symptoms, i.e., a sustaining pPCS (ConcS) (*n* = 7); ii) a concussed group with no postconcussive symptoms, i.e., no sustaining pPCS (ConcM) (*n* = 13); and iii) a healthy control group without any history of mTBI (Ctrl) (*n* = 10; detailed information about participants are summarized in Tables 1 and 2). None of the concussed subjects was actually being medically treated. The local ethics committee of the German Sports University Cologne approved the study.

Additional symptom and neuropsychological assessment. In addition to the clinical examination, symptoms were registered according to the Concussion Symptom Inventory (30). Given the presumed association between mTBI and depressive symptoms, in addition, the Beck depression inventory (BDI) was administered. Furthermore, we used the Sport Concussion Assessment Tool 2 (SCAT2) (24), which incorporates a symptom evaluation scale, the Glasgow Coma Scale, the Standardized Assessment of Concussion (SAC), a modified version of the Balance Error Scoring System (BESS), and a modified version of the Maddocks

TABLE 1. Results of the diagnostic tests for the three examination groups.

Group (Female/Male)	ConcS (4/3)	ConcM (7/6)	Ctrl (6/4)
Age	29 ± 15	26 ± 7	27 ± 8
Months after concussion	21 ± 21	28 ± 16	—
BDI	5 ± 4	4 ± 2	3 ± 2
PCS	17* ± 4	8* ± 6	2 ± 3
SSS[a]	50* ± 17	19* ± 18	3 ± 3
BESS[a]	11* ± 8	7 ± 3	4 ± 3
SAC	26* ± 2	27 ± 2	28 ± 1
SCAT2	67* ± 8	82* ± 9	92 ± 3

Months after concussion (mean ± SD).

*Significant differences compared to the Ctrl group.

[a] Number of symptoms/errors are summated to form the score.

PCS, sum of postconcussive symptoms (of 22; mean ± SD) evaluated by the symptom evaluation scale implemented in the SCAT2; SSS, sum of symptom severity score (maximum possible 132) implemented in the SCAT2.

TABLE 2. Results of the diagnostic tests for the seven concussed participants with severe symptomatology.

ID	Age	NoC	LoC	MaC	PCS	SSS	SCAT2
1	21	1	yes	24	18	59	63
2	40	2	yes	54	20	47	71
3	22	>2	yes	2	22	61	73
4	20	1	yes	30	13	24	76
5	30	1	no	1	19	74	72
6	58	1	no	36	19	52	55
7	14	2	yes	1	10	35	62

NoC, number of experienced concussions; LoC, loss of consciousness; MaC, months after experienced concussion.

questions. The results of the neuropsychological assessment of the three groups are summarized in Table 1. The results of the group with a sustaining pPCS are provided separately for each participant in Table 2.

Balance test. Balance tasks were carried out according to Shumway-Cook and Horak (32), which examine combinations of three visual manipulations and two support-surface conditions during balance control. Visual conditions include, first, a condition without visual impairment (sighted condition); second, the elimination of visual input (eyes closed condition); and third, a visual-conflict situation for producing inaccurate input (blurred vision condition; Fig. 1). The three "visual" conditions were performed either on a firm (/stable) surface or on an unstable surface. The unstable surface was created using a piece of 6-cm-thick foam pad ("AIREX Balance-Pad").

Each balance condition comprised two randomized blocks, each of which included five trials (10 s per trial), resulting in a total of 10 trials per condition. The subjects were instructed to stand still on both feet without losing balance. During all balance tasks, the participants wore a harness for safety.

During balance tasks, a force plate system ("Soehnle Balance-X-Sensor Pro," test frequency 160 Hz) was used to register center of mass displacement by measuring ground reaction forces. This system provides three parameters of information about the ability to keep balance control of each subject. First, it registers the deviations from the center of pressure (CoP) by the length of the path per second [millimeters per second] (path length [PL]). The second parameter surface of pressure [cm^2] provides information about the area used for balancing. The third parameter, effort of balance (EoB) [watts], represents the efficiency/effort to keep balance control by the recording of force [newtons] over time [seconds]. The smaller the values of PL, SuP, and EoB the better the postural control.

fNIRS acquisition and analysis. Cerebral oxygenation changes were recorded during balance tasks using a near-infrared optical tomographic imaging device (DYNOT Imaging System, NIRx; wavelengths, 760, 830 nm; sampling rate, 6.88 Hz; Fig. 1). Methodology and underlying physiology are explained in detail elsewhere (27). A total of 20 optodes (four emittors, 16 detectors) were placed according to the 10-20 system in four 1 × 4 grids on the skull above the frontal cortex of each hemisphere resulting in 16 channels of measurement. Coordinates of optode positions were collected for spatial registration of NIRS channels into the standard brain from the Montreal Neurological Institute (MNI space) using a three-dimensional digitizing system (Zebris 3D Measuring Systems, Zebris Medical GmbH). Channel positions covered identical regions above both hemispheres including the frontopolar area, orbitofrontal area, dorsolateral prefrontal cortex (DLPFC), inferior prefrontal gyrus, pars triangularis (Broca area), pars opercularis (Broca area), and frontal eye fields.

Data were analyzed using the Matlab-based Homer2 software package (18). Sixteen channels were converted to hemoglobin concentration changes according to Cope et al. (5). The raw intensity data were normalized to provide a relative (percent) change by dividing by the mean of the data. Because fNIRS data can be affected by movement artifacts, each individual channel for each participant was visually inspected, and movement artifacts were corrected using the artifact correction algorithm developed by Scholkmann et al. (31). High-frequency components, mainly caused by the heartbeat, were attenuated by a low-pass filter at 0.1 Hz. To correct drifts and slow fluctuations, an additional high-pass

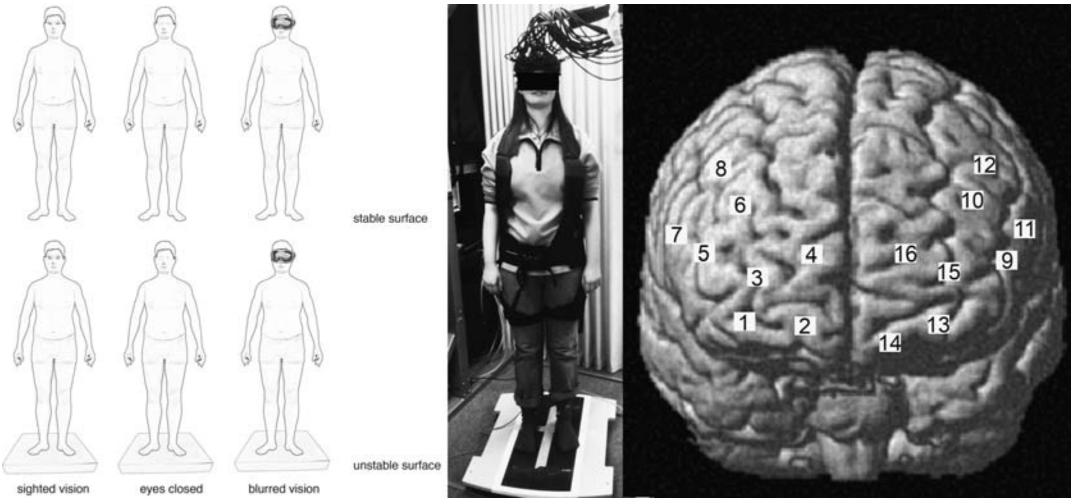

FIGURE 1—Experimental conditions and setup; fNIRS channel positions within the Montreal Neurological Institute coordinate system.

filter at 0.001 Hz was applied. Block averages of oxygenated hemoglobin [HbO_2] and deoxygenated hemoglobin [HHb] of each condition were obtained for statistical analysis. However, because changes of HbO_2 appear to reflect task-related cortical activation more directly than decreases in HHb, as evidenced by the stronger correlation between the former and the blood oxygenation level-dependent signal measured by fMRI (34), we focused in the discussion of this article on changes of HbO_2.

Statistical analyses. Statistical analyses were performed using SPSS (IBM SPSS statistics, version 22). Group characteristics and neuropsychological outcomes were analyzed using analyses of variance and/or *t*-tests (when comparing between the concussed groups only). The outcomes of fNIRS and force place measurements were calculated using ANOVA with repeated measurements for each fNIRS channel/for each parameter of the force plate system (PL, SuP, EoB), with the within subjects parameters vision (sighted, eyes closed, or blurred vision) and surface (stable versus unstable surface) and the between-subjects factor groups (ConcS, ConcM, Ctrl). Due to multiple comparisons of fNIRS channels we set the significance level at $P < 0.01$. For the *post hoc* pairwise comparisons within fNIRS channels, P values were Bonferroni corrected.

RESULTS

Postconcussive Symptoms and Neuropsychological Findings

All participants had a score of 15 on the Glasgow Coma Scale, a score of five for the modified Maddocks questions, and a BDI score ≤ 10 (no differences between groups were observed, $F(2,27) = 1.675$, $P = 0.21$). All brain injuries were therefore and in combination with the medical examination classified as "mild." No significant differences between groups were found regarding the participants age ($F(2,27) = 0.255$, $P = 0.77$) nor did the two concussed groups differ regarding the number of months past the concussion ($t(18) = -0.822$, $P = 0.42$).

Significant differences between groups were found for the number of symptoms, i.e., the PCS score ($F(2,27) = 20.336$, $P < 0.001$), the number of balancing errors on the modified BESS ($F(2,27) = 5.077$, $P < 0.05$), the SAC ($F(2,27) = 4.008$, $P < 0.05$), and the total SCAT2 score ($F(2,24) = 34.585$, $P < 0.001$). *Post hoc* comparisons showed an increased quantity of postconcussive symptoms for individuals with a pPCS as compared with individuals with a history of a mTBI but no pPCS ($P < 0.01$) and the healthy control group ($P < 0.001$). Individuals with a pPCS showed significantly higher modified BESS scores, lower SAC scores, and lower total SCAT2 scores when compared with both other groups. Individuals with the history of a mTBI but no pPCS also differed from the healthy control group by lower SCAT2 scores ($P < 0.01$).

Balance Performance

Effects of surface and balance condition independent of group differences. The balance factors PL, SuP, and EoB revealed significant effects for the within subject factors *surface* (PL, $F(1,29) = 33.511$, $P < 0.001$; SuP, $F(1,29) = 77.508$, $P < 0.001$; EoB, $F(1,29) = 33.294$, $P < 0.001$), vision (PL, $F(2,58) = 71.980$, $P < 0.001$; SuP, $F(2,58) = 51.218$, $P < 0.001$; EoB, $F(2,58) = 25.907$, $P < 0.001$), and the interaction of vision and surface (PL, $F(2,58) = 50.700$, $P < 0.001$; SuP, $F(2,58) = 39.745$, $P < 0.001$; EoB, $F(2,58) = 24.962$, $P < 0.001$). *Post hoc* comparisons revealed significantly longer mean PL, higher mean values of SuP, and higher means of EoB during the balance condition with closed eyes, the unstable surface conditions, and during the combination of the unstable surface with the eyes closed as compared with the conditions with eyes opened and/or blurred vision and the stable surface conditions.

Between-group effects. The balance factor EoB showed significant effects between groups, i.e., group ($F(2,29) = 5.434$, $P < 0.05$), surface–group ($F(2,29) = 3.963$, $P < 0.05$), vision–group ($F(4,58) = 3.773$, $P < 0.01$), and surface–vision–group ($F(4,58) = 3.359$, $P < 0.05$; see Table 3 for detailed information). *Post hoc* comparisons revealed that the mean EoB is significantly higher for individuals with a pPCS compared with both other groups' overall conditions ($P < 0.05$), during the balance condition on the unstable surface ($P < 0.05$), during the eyes closed condition ($P < 0.05$), and during the combination of eyes closed and unstable surface condition ($P < 0.05$; Fig. 2).

Brain Oxygenation (fNIRS)

Effects of surface and vision independent of group. The factor surface reached significance for ΔHbO_2

TABLE 3. Significant group effects of balance performance and brain oxygenation.

Balance Performance

Effect	*Post Hoc* Comparison	Parameter
Group ($F(2,29) = 5.434$, $P < 0.05$)	ConS > ConM, Ctrl ($P < 0.05$)	EoB
Surface–group ($F(2,29) = 3.963$, $P < 0.05$)	ConS > ConM, Ctrl ($P < 0.05$) during unstable surface condition	EoB
Vision–group ($F(4,58) = 3.773$, $P < 0.01$)	ConS > ConM, Ctrl ($P < 0.05$) during eyes closed	EoB

Brain Oxygenation

Effect	*Post Hoc* Comparison	Channel	Chromophore	Localization
Vision–group ($F(4, 54) = 4.136$, $P < 0.01$)	ConS < Ctrl ($P < 0.05$) during blurred vision condition	10	ΔHbO_2	BA 9/45, LH
Vision–group ($F(4, 54) = 6.237$, $P < 0.001$)	ConS: eyes closed < blurred vision ($P < 0.05$)	11	ΔHHb	BA 45/44, LH
Surface–vision–group ($F(4, 54) = 3.937$, $P < 0.01$)	ConS > ConM ($P < 0.05$), ConS > Ctrl ($P < 0.05$) during unstable surface and with closed eyes	2	ΔHbO_2	BA 10/11, RH

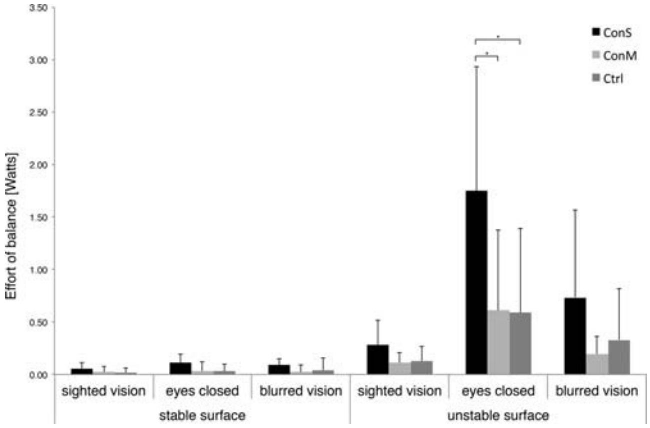

FIGURE 2—Significant group effects for the balance parameter "effort of balance" (force over time).

in channel 10 ($F(1, 27) = 11.920$, $P < 0.01$; DLPFC Brodmann area [BA 9]/pars triangularis [BA 45], left hemisphere [LH]) displaying greater ΔHbO_2 during the unstable compared to the stable surface condition (channel 10, $P < 0.01$). The surface–vision interaction reached significance for ΔHbO_2 in channel 2 ($F(2, 54) = 6.203$, $P < 0.01$; frontopolar area (BA 10)/orbitofrontal area (BA 11), RH). *Post hoc* comparisons showed significantly greater ΔHbO_2 during closed eyes and unstable conditions compared with the stable surface ($P < 0.05$) as well as standing on the unstable surface with eyes closed compared to the blurred vision ($P < 0.05$). The same interaction effect (surface–vision) reached significance for ΔHHb in channel 2 ($F(2, 54) = 5.193$, $P < 0.01$) and in channel 12 ($F(2, 54) = 6.032$, $P < 0.01$; DLPFC (BA 9/46)/pars triangularis (BA 45)/pars opercularis (BA 44), LH). *Post hoc* comparisons showed, for channel 2, significantly decreased ΔHHb during closed eyes and unstable surface compared to the stable surface (channel 2, $P < 0.05$), and, for channel 12, significantly decreased ΔHHb changes on the unstable surface with blurred vision as compared with closed eyes condition (channel 12, $P < 0.05$).

Between-group effects. Significant interaction effects of vision–group were observed in channel 10 for ΔHbO_2 ($F(4, 54) = 4.136$, $P < 0.01$). *Post hoc* comparisons showed significant decreased ΔHbO_2 for individuals with a pPCS when compared with the healthy control group during blurred vision ($P < 0.05$; see Figure, Supplemental Digital Content, Interaction effect of vision–group, http://links.lww.com/MSS/A721). The vision–group interaction also showed significant differences for ΔHHb in channel 11 covering the pars triangularis (BA 45) and the pars opercularis (BA 44) ($F(4, 54) = 6.237$, $P < 0.001$), showing that the eyes closed condition led to significantly decreased ΔHHb when compared with blurred vision in individuals with a pPCS ($P < 0.05$). The interaction effect of surface–vision–group in channel 2 ($F(4, 54) = 3.937$, $P < 0.01$; see Table 3 for detailed information) showed for individuals with pPCS significantly increased ΔHbO_2 during unstable surface and with closed eyes compared with concussed individuals without a pPCS ($P < 0.05$) and the healthy control group ($P < 0.05$; Fig. 3).

DISCUSSION

The present study compared brain activity (fNIRS) and kinetic parameters (force plate system) during postural control in individuals with pPCS, individuals with a history of mTBI but no symptoms, and a healthy control group without a history of concussion. The present study revealed for all groups that balancing on an unstable surface with eyes closed compared with the vision and stable surface conditions leads to increased postural sway and to altered brain activity in frontal brain cortices. During the inaccurate (/blurred) vision condition, individuals with pPCS show decreased brain oxygenation within the left hemispheric DLPFC when compared with the healthy control group. In the most challenging condition (eyes closed–unstable surface), the group with pPCS as compared with both other groups applied significantly more force over time to keep balance, and they showed an increased brain oxygenation in frontopolar/orbitofrontal areas of the right hemisphere.

Neural correlates of balance control during altered environments. The present research revealed that, for all three groups, postural sway was generally higher when the sensory input was manipulated. When balancing on an unstable surface and/or with eyes closed, the amplitude of corrective postural actions, which is necessary to maintain balance, increases. This is in line with previous research that have shown increased postural sway during conditions of visual manipulation and altered surface conditions (26,32).

In line with previous findings from a mobile PET (28) and fNIRS systems (10,25), the present results indicate that the prefrontal brain areas contribute particularly to posture control when visual information is missing and/or sensory input is altered by an unstable surface. Our results showed a significant effect of surface independent from the visual manipulation, i.e., changes of oxygenation increased in left hemispheric DLPFC when subjects were standing on an unstable as compared with a stable surface. It has been proposed that the left DLPFC represents a flexible link

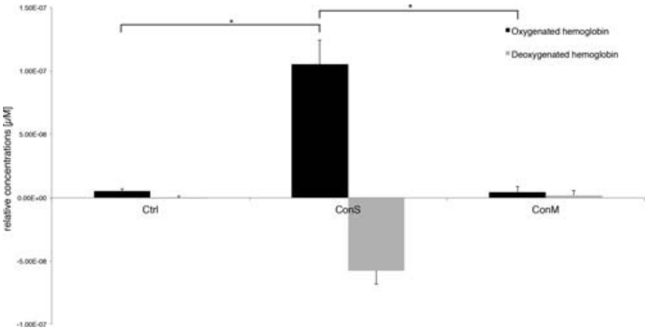

FIGURE 3—Interaction effect of vision–surface–group. Significant increased brain oxygenation of individuals with pPCS during the unstable surface condition with closed eyes in channel 2 covering the frontopolar area ([BA] 10)/orbitofrontal area (BA 11) of the right hemisphere.

among sensory evidence, decision, and action (15). Using fNIRS during balance control, previous research showed that the DLPFC was significantly activated after postural perturbation tasks (25) or tilt board balance tasks (10). The latter authors concluded that attention-demanding tasks are responsible for increased enrollment of prefrontal brain structures during balance tasks (10,25). In the more complex condition, i.e., when standing with eyes closed on an unstable surface, there was an increase in brain oxygenation in the right hemispheric frontopolar/orbitofrontal cortex. The lateralization to the right hemisphere is in line with the previously proposed dependence on right hemispheric visual information during postural control (9,11,22). In fact, patients with right hemispheric brain damage are generally more unstable (22), which is often related to deficits in environmental perception. Duclos et al. (9) reported that patients with right hemispheric brain damage (as compared with patients with left hemispheric brain damage) were the most unstable without vision, and this instability was increased by proprioceptive perturbation. The analysis of the interaction between visual restrictions and somatosensory disturbances on unipedal control equilibrium in individuals with or without classical dance training indicated that right hemispheric visual dominance is particularly useful for postural control in complex equilibrium conditions (11). Furthermore, participants with greater symptoms suffering from a persistent postconcussion syndrome exhibited greater activation in attention-related areas, along with reduced activation left prefrontal brain areas as cognitive load was increased from easy to difficult (7). Thus, the present results indicate that prefrontal brain structures are relevant for attention-demanding balance tasks; however, the control of balance during the most difficult task, i.e., when visual information is missing and standing on a unstable surface, might be a process that is particularly dependent on processes within in frontopolar/orbitofrontal cortices of the right hemisphere.

Postural sway and neural differences between groups. The present combination of brain imaging methods with measures of postural sway revealed that individuals suffering from pPCS showed a significantly decreased brain oxygenation when controlling posture during the inaccurate vision condition within the left hemispheric DLPFC. However, when standing on the unstable surface with closed eyes, the pPCS group was characterized by increased changes of oxygenation compared with the control group in frontopolar/orbitofrontal areas of the right hemisphere. The cerebral activation, as measured with fNIRS, is accompanied by increased postural sway of the pPCS group during postural control in altered environments, which is in line with previous studies that showed the loss of balance control in concussed subjects (12,13,21). Changes to DLPFC function are also well documented in the concussion literature (3,17). The DLPFC has been associated to impaired executive function after mTBI (14,20), which might be of particular relevance when inaccurate visual information has to be integrated for posture control. Because continuous representation of the external world must be reconstructed from a succession of discrete visual fixations (23), information about surrounding features and spatial positions must be retained and integrated by visual working memory (29). Functional brain imaging studies of human prefrontal cortex activity showed that spatial memory is associated with DLPFC activity (6). Because the DLPFC showed characteristic reductions of brain activity during memory tasks after mTBI (3,17), the present results suggest that individuals with persisting symptoms after a concussion might suffer from inaccurate memory functioning of when to process visual information to maintain balance in altered conditions.

However, during the most complex balance condition, i.e., when standing on the unstable surface with closed eyes, the pPCS group was characterized by increased changes of oxygenation compared with the control group in frontopolar/orbitofrontal areas of the right hemisphere. The results from the force plate system provided the same picture, i.e., the pPCS group applied more force over time when balancing without visual information and when balancing on the unstable surface. As previously mentioned, the right hemisphere dominates postural control in particular during complex balance conditions (9,11,22). Previous research further showed that participants with greater symptoms suffering from a persistent postconcussion syndrome exhibited greater activation in attention-related areas as cognitive load was increased from easy to difficult (7). Wiese et al. (37) pointed out that there is a deficit in the preparatory motor network but an increased need for attentional resources during movement execution in traumatic brain injury patients. The present findings might therefore point out to inefficient neural processing in persons suffering from pPCS as compared with healthy controls during balance tasks of “high complexity.” With regard to the “neural efficiency hypothesis” of posture control (8), i.e., elite athletes, as compared with nonathletes, showed reduced cortical activity during upright balance tasks, the present results of more applied force over time to control balance and increased brain oxygenation patterns in right hemisphere during the most complex balance condition indicates that individuals with pPCS suffer from inefficient neural control processes when balancing in altered environmental conditions. The fNIRS data therefore suggest that individuals with pPCS rely on the retrieval of additional cognitive resources from right hemispheric frontal brain cortices for the control of posture particularly during the most challenging balance condition.

Limitations. Obviously, the present study also presents some limitations, which have to be considered. First, this study was limited to a relatively small group of individuals with persisting symptoms. Thus, more studies are necessary to not only gain insights into neural correlates of postural but also into the neuronal characteristics of concussed individuals when controlling posture. Thus far, several groups of research addressed neural correlates of balance; however, to overcome methodical restrictions when using MRI (lying in a scanner instead of actual balancing in an upright position), most studies used substitutes for upright standing positions, such as for example observation of balance tasks or imagined stance during fMRI recordings (35). Thus, more studies are necessary to investigate neural correlates of actual balance performances and its characteristics in concussed subjects. Another limitation of this study is the fact that we performed fNIRS measurements only once for each participant. Although difficult to realize, future experiments should integrate multiple assessments across different time points of concussive incidents, i.e., before (baseline)/immediately after a concussion and before return to play, to quantify intraindividual changes in brain activation after concussion. By using such a design, individual differences caused by physical condition, age, training effects in different sports, etc., could be controlled for. Last, a disadvantage of fNIRS in comparison to fMRI presents its spatial resolution and thus, measurements are limited to the cortex (33). We therefore were not able to measure activation in subcortical structures that are also related to postural control, in particular the brainstem and the cerebellum (28). Thus, we cannot conclude that the described factors contributing to balance control are exclusive.

CONCLUSIONS

The present results suggest that individuals that suffer from persisting symptoms after a concussion present a mixed pattern of both hypoactivation and hyperactivation during the control of balance. Whereas unimodal sensory perturbations led to decreased brain oxygenation in left hemispheric dorsolateral prefrontal cortices in individuals with pPCS, more difficult situations when multiple senses were manipulated during balance control, i.e., when standing on an unstable surface with closed eyes, led to increased brain oxygenation patterns in right hemispheric frontopolar brain cortices. Increased brain oxygenation was accompanied by increased applied force over time when controlling posture in the latter subjects. Consequently, we conclude that individuals with pPCS are not principally characterized by a loss of balance control; however, the costs to keep balance are higher on the muscular as well as on the neuronal level.

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