Reduced frontopolar brain activation characterizes concussed athletes with balance deficits

I. Helmich,⁎ J. Coenena,b, S. Henckerta, E. Pardalis, S. Schupp, H. Lausberg

a Department of Neurology, Psychosomatic Medicine and Psychiatry, Institute of Health Promotion and Clinical Movement Science, German Sport University (GSU) Cologne, Am Sportpark Münsterschwarzach 6, 50933 Cologne, Germany
b Department of Sport and Health, Institute of Sport Medicine, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

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ABSTRACT

Objectives: Athletes with sport-related concussions (SRC) often demonstrate deficits in postural stability. Lower cerebral blood flow in frontal cortices has been documented in athletes with symptoms after SRC, however, it is unclear if functional brain oxygenation during postural control tasks is reduced in symptomatic athletes after SRC in the same manner. We therefore compared brain oxygenation patterns in frontal cortices of symptomatic and asymptomatic athletes with SRC during postural control tasks with the hypothesis that symptomatic athletes are characterized by reduced functional brain oxygenation during postural control.

Methods: 62 concussed athletes (n = 31 symptomatic, n = 31 asymptomatic) were investigated during four postural control tasks with eyes closed versus eyes opened conditions and stable vs. unstable surface conditions. Brain oxygenation was assessed using functional NearInfraRed Spectroscopy (fNIRS) on frontopolar cortices of each hemisphere. Postural sway was measured by the analysis of ground reaction forces.

Results: Symptomatic athletes showed greater postural sway when compared to asymptomatic athletes during postural control, particularly during closed eyes and/or unstable surface conditions. Changes of oxygenated hemoglobin (ΔHbO2) within the left hemispheric frontopolar cortex were significantly reduced in symptomatic athletes when compared to asymptomatic athletes during the eyes closed condition. A stepwise linear regression analysis revealed that self-reported post-concussion symptoms such as headaches and sadness predict decreased brain oxygenation during postural control with closed eyes.

Conclusion: Symptomatic athletes with increased postural sway are characterized by decreased frontopolar brain oxygenation during postural control tasks, particularly during conditions with closed eyes. Because the frontopolar cortex showed to be involved in redistributing executive functions to novel task situations, we conclude that athletes with post-concussion symptoms suffer from a deficit in coordinating postural adjustments to balance control tasks with reduced sensory input.

1. Introduction

Although concussions (mild Traumatic Brain Injuries mTBI) may never be completely eliminated from sports, improved understanding of post-concussion sequelae on the health status is necessary to prevent athletes from long-term impairments. Potential post-concussion health deficits concern symptoms such as headaches, dizziness, memory problems, etc. that usually last for about a week (Guskiewicz et al., 2001). However, long-term neuropsychological (Deb et al., 1998), psychiatric (Finkbeiner et al., May) or physical impairments such as gait or posture control (Howell et al., 2017; Ingersoll and Armstrong, 1992) have been also reported after sport-related concussions (SRC).

Broglio and Puetz (2008) pointed out that there is a lack of published studies on postural control after concussions. The assumption that balance decrements resolve within three to five days post-injury (Guskiewicz, 2003; McCrea et al., 2003) is contrasted by studies that report longer recovery times when more sensitive measurement devices are being used (Broglio and Puetz, 2008; Ingersoll and Armstrong, 1992; Thompson et al., 4). In fact, Thompson et al. (2005) measured postural instability in concussed subjects about three months past the incident. Ingersoll and Armstrong (Ingersoll and Armstrong, 1992) reported a greater distance of the center of pressure of individuals with fewer postural corrections more than one year post-concussion. Thus, the application of more sensitive measures of postural stability indicates that alterations of postural control after mTBI in sports might present as a long-term impairment.

⁎ Corresponding author.
E-mail address: in.helmich@gmail.com (I. Helmich).

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Guskiewicz et al. (1997) reported that concussed athletes may suffer from sensory interaction problems as they demonstrated decreased stability during closed eyes conditions without any neuropsychological deficits. The authors hypothesized that mTBI athletes are unable to respond to altered environmental conditions and therefore select a motor response based on wrong cues (Guskiewicz et al., 1997). However, no group differences were evident during tilted support surface conditions (Guskiewicz et al., 1997). Thus, it remains unclear whether concussions represent a sensory interaction problem that is related to visual or tactile alterations. Further analyses showed that concussed athletes demonstrate postural control deficits during altered visual conditions (closed eyes) and during the combination of altered visual and sensory (tilted support surface) conditions indicating that concussed athletes are not using information from the vestibular and visual systems effectively (Guskiewicz, 2003). However, studies that actually provide data about the neuronal correlates of concussed athletes during postural control performances are scarce (Helmich et al., 2016; Thompson et al., 2005).

In concussed athletes who were already cleared for sport participation, the application of electroencephalography (EEG) revealed a decrease in EEG power in all bandwidths especially during standing postures (Thompson et al., 2005). The combination of postural control measurements (force plate system) with functional NearInfrared Spectroscopy (fNIRS) imaging provided evidence that concussed individuals with persisting symptoms are characterized by decreased brain oxygenation patterns in frontal cortices when compared to a healthy control group during balance control (Helmich et al., 2016). However, increased brain oxygenation patterns during the combination of altered visual (eyes closed) and tactile (unstable surface) manipulations were also observed in frontopolar cortices of concussed individuals with persisting post-concussion symptoms and when compared to asymptomatic athletes with mTBI and non-concussed controls (Helmich et al., 2016). In fact, several studies reported contrasting results of increased (Helmich et al., 2016; McAllister et al., 2001) as well as decreased functional brain activation in frontopolar cortices (Chen et al., 2007; Helmich et al., 2015) of concussed individuals, particularly in the frontopolar cortex (FPC) (Helmich et al., 2016; Chen et al., 2007; Helmich et al., 2015). Thus, it remains unclear whether concussed athletes are characterized by functional hyper- or hypoactivity in the frontopolar cortex during postural control tasks. Resting-state analyses using EEG showed that athletes with sport-related concussions are characterized by decreased activity in the FPC that is additionally negatively correlated to post-concussion symptoms (Virji-Babul et al., 2014). Athletes reporting greater symptoms also showed lower frontal cerebral blood flow following acute concussion (Churchill et al., 2017). Because fNIRS showed to be a valid tool to investigate brain oxygenation patterns during postural control tasks (Basso Moro et al., 2014; Beurskens et al., 2014; Ferrari et al., 2014; Fujimoto et al., 2014; Fujita et al., 2016; Helmich et al., 2016; Herold et al., 2017; Huppert et al., 2013; Karim et al., 2013; Karim et al., 2012; Lin et al., 2017; Mahoney et al., 2016; Mihara et al., 2008; Takakura et al., 2015; Wang et al., 2016), particularly in the frontal cortex as this area is modulated by task difficulty during postural control (Basso Moro et al., 2014; Eckner et al., 2011; Guskiewicz et al., 1997; Howell et al., 2017), we investigate in the present study the hypothesis that athletes with mTBI and post-concussion symptoms show decreased brain oxygenation patterns in the FPC during postural control tasks that are characterized by reduced sensory information such as when balancing with closed eyes.

2. Materials and methods

2.1. Participants

62 active athletes with a history of SRC (mean age: 25.7 ± 5.3 years; 22 female, 40 male; average years of sports participation: 2.1. Participants

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examine combinations of visual and tactile manipulations during balance control: condition 1: eyes opened (c1); condition 2: eyes closed (c2). The two conditions (c1 and c2) were performed either on a firm (stable) surface or on an unstable surface: condition 3 (c3): eyes opened and unstable surface; condition 4 (c4): eyes closed and unstable surface. The unstable surface was created using a piece of six cm thick foam pad ("AIREX Balance-Pad"). Each balance condition comprised two blocks, each of which included three trials (ten seconds per trial), resulting in a total of six trials per condition. The subjects were instructed to stand still on both feet (distance between feet: 2 cm) without losing balance in a standardized position and posture (Fig. 1).

During balance tasks, a force plate system ("ZEBRIS platform, type FDM-S") was used to register center of mass displacement (postural sway) by measuring ground reaction forces. This system provides three parameters of information about the ability to keep postural control, i.e., (i) it registers the deviations from the Center of Pressure (CoP) by the mean length of the movement path per time [millimeters/second] (path length, PL); PL is defined as the absolute length of the CoP path movements throughout the testing period; (ii) the second parameter surface area (SuA) [mm²] is defined as a 95% confidence ellipse for the mean of the CoP anterior, posterior, medial and lateral coordinates; (iii) the third parameter velocity (V) [mm/second] represents the mean velocity during the postural control trials per second. Mean parameters of the values of PL, SuA, and V were exported for each subject and condition for statistical analyses.

Fig. 1. Left (a): Balance position of one individual during the unstable surface condition; top right (b): fNIRS optode placement (s1-s2: sources; d1-d6: detectors; ch1-ch8: channels) above the frontopolar cortex of the right (RH) and left hemispheres (LH) according to the 10–20-system; bottom right (c): Experimental conditions and block design.

2.5. fNIRS acquisition and analysis

Cerebral oxygenation changes were recorded during postural control tasks using a near-infrared optical tomographic imaging device (DYNOT Imaging System, NIRx, Wavelengths 760 nm, 830 nm, Sampling rate 7.2 Hz). Methodology and underlying physiology are explained in detail elsewhere (Cope et al., 1988; Obrig and Villringer, 2003). A total of 8 optodes (2 emitters, 6 detectors) were placed above the frontopolar cortex (FPC) of each hemisphere resulting in 8 channels of measurement (channel 1–4: FPC of the left hemisphere (LH); channel 5–8: FPC of the right hemisphere (RH); Fig. 1). Optodes were placed with an approximate interoptode distance of 3 cm according to the 10–20-system (Jasper, 1958). Optodes were mounted with a customized plastic hard shell system on the participant's head to gain placement stability and to avoid movement artifacts.

Data were analyzed using the "nirsLAB" software package (NIRx Medical Technologies, LLC). 8 channels (ch) were converted to hemoglobin concentration changes according to Cope et al. (1988). The "remove discontinuities" and the "remove spike artifacts" algorithms of the nirsLAB toolbox were used to correct for discontinuities and spike artifacts in the (raw) signal (with the standard deviation threshold set to 5). When removing spike artifacts, data was replaced by using the "nearest signals" function. Data were then bandpass filtered (low cut-off frequency at 0.01 Hz / high cut-off frequency at 0.2 Hz) to eliminate the effects of heartbeat, respiration, and low frequency signal drifts for each wavelength. Because individuals were asked to stand still during the entire procedure, the baseline was set to the full time course of the data set. Block averages (10 s) of ΔHbO2 from each channel and condition were then exported for statistical analyses.

2.6. Statistics

Comparisons of the mean(s) (repeated (rmANOVA) and univariate (uniANOVA) analyses of variance) were performed using IBM SPSS statistics (Version 25). The parameters path length (PL), parameter surface area (SuA), and velocity (V) were used for statistical analyses of postural control. Statistical analyses of brain oxygenation data focused on the changes of oxygenated hemoglobin (ΔHbO2), because these
appear to reflect task-related cortical activation more directly than changes of deoxygenated hemoglobin, as evidenced by the stronger correlation between the former and the blood-oxygenation level-dependent signal measured by fMRI (Strangman et al., 2002) and by the results of animal studies (Hoshi et al., 1985). Thus, mean brain oxygenation patterns (block averages of 10 s) of ΔHbO₂ were used for statistical analyses of brain activity. The between-subjects factor group constitutes (i) concussed athletes with a PCS score > 10 (symptomatic), and (ii) concussed athletes with a PCS score < 10 (asymptomatic). Repeated within-subjects factors constitute visibility (postural control conditions) and stability (postural control conditions while standing (i) on a stable or (ii) on an unstable surface). For fNIRS analyses, the additional within-subjects factor channels (8) was statistically calculated by uniANOVA. Significant results are reported from p < 0.05. Multiple post hoc pairwise comparisons were corrected with Bonferroni corrections. Because the aim of the present paper is to better understand differences between symptomatic and asymptomatic athletes, we focus onto the effects between groups in the results section.

3. Results

3.1. Group effects

2.1.1. Participants

Significant differences between groups were found for the PCS score (t(60) = −9.703, p < 0.001) and the response times during working memory performances (t(60) = −2.289, p < 0.05; Table 1). Symptomatic athletes (Mean [M] = 27.1 ± 14.9) showed significantly higher PCS scores than asymptomatic athletes (M = 0.9 ± 0.9). Furthermore, asymptomatic athletes (M = 1071.7 ± 162.8) showed significantly increased response times during the working memory task when compared to asymptomatic athletes (M = 981.8 ± 145.9).

2.1.2. Balance performance

The rmANOVA revealed for the parameter surface area (SuA) (but neither for path length nor velocity) significant differences between groups (F(1, 60) = 7.874, p < 0.01, η² = 0.116), an interaction effect of group x visibility (F(1, 60) = 7.093, p < 0.05, η² = 0.106), group x stability (F(1, 60) = 6.646, p < 0.05, η² = 0.100), and of group x visibility x stability (F(1, 60) = 5.096, p < 0.05, η² = 0.078; Table 2).

Post-hoc comparisons of the group effect revealed a significantly greater SuA for symptomatic athletes when compared to asymptomatic (p < 0.01). Post-hoc comparisons of the interaction effect of group x visibility revealed significantly greater SuA for symptomatic athletes when compared to asymptomatic during the sighted (p < 0.01) as well as during the condition with closed eyes (p < 0.01; Fig. 2). Post-hoc comparisons of the interaction of group x stability revealed significantly greater SuA for symptomatic athletes when compared to asymptomatic during the stable (p < 0.01) as well as during the unstable conditions (p < 0.01). Post-hoc comparisons of the interaction of group x stability x visibility revealed significantly greater SuA for symptomatic athletes when compared to asymptomatic during the stable condition with closed eyes (p < 0.01), and during the unstable condition with opened (p < 0.05) and closed eyes (p < 0.01).

2.1.3. Correlation of balance performance and the PCS score

There is a significant positive correlation between the (increased) PCS score and worse postural control by increased mean surface areas during the eyes opened and stable surface condition (r(62) = 0.306, p < 0.05), during the eyes closed and stable surface condition (r(62) = 0.376, p < 0.01), during the eyes opened and unstable surface condition (r(62) = 0.282, p < 0.05), and during the eyes closed and unstable surface condition (r(62) = 0.275, p < 0.05). A following stepwise linear regression analysis with the PCS score as the dependent variable and the significantly correlated SuA parameters as independent variables revealed significance (F(1, 60) = 9.893, p < 0.01, R² = 0.142), i.e., the SuA during the eyes closed and stable surface condition significantly predicted the PCS score (β = 0.376, t = 3.145, p < 0.01; Fig. 3).

2.1.4. Correlation of balance performance and response times

It exists a significant positive correlation between (increased) mean surface area during the eyes closed condition and increased response times during the working memory task (r(62) = 0.279, p < 0.05).

2.1.5. Brain oxygenation

The rmANOVA revealed a significant effect for the interaction of group x visibility (F(8, 53) = 3.071, p < 0.05, η² = 0.317). The unANOVA showed significant effects above the right and left hemispheric (LH) frontopolar cortex (FPC) for the interaction of group x visibility for channel 1 (ch1; LH FPC; F(1, 60) = 4.799, p < 0.05, η² = 0.05, η² = 0.074), ch4 (LH FPC; F(1, 60) = 7.215, p < 0.05, η² = 0.107; Fig. 4), and channel 6 (RH FPC; marginally significant, F(1, 60) = 3.394, p = 0.07, η² = 0.05; table 2). Post-hoc comparisons

| Brain oxygenation | Asymptomatic athletes | Symptomatic athletes |
|-------------------|-----------------------|---------------------|
| ΔHbO₂ (ch1: LH FPC) | 0.000016 ± 0.000002 | −0.000058 ± 0.000052 |
| ΔHbO₂ (ch4: LH FPC) | 0.000147 ± 0.000043 | 0.000018 ± 0.000043 |
| ΔHbO₂ (ch6: RH FPC) | 0.000029 ± 0.000004 | −0.000031 ± 0.000004 |

Values presented are surface area, SuA (mm²); brain oxygenation (changes of oxygenated hemoglobin, ΔHbO₂) within channels (ch) 1, 4, and 6; left hemispheric, LH; frontopolar cortex, FPC; right hemispheric, RH.
revealed reduced $\Delta$HbO$_2$ in symptomatic when compared to asymptomatic athletes during the condition with closed eyes in all three channels, however, only in channel 4 post-hoc comparisons reached significance ($p < 0.05$).

2.1.6. Correlation of brain oxygenation and PCS score

It exists a significant negative correlation between the (increased) PCS score and the (decreased) brain oxygenation during the eyes closed condition in channel 4 ($r_{(62)} = -0.345$, $p < 0.01$; Fig. 5). A following stepwise linear regression analysis with the PCS score as the dependent

![Correlation of the postural control and PCS scores](image1)

**Fig. 3.** Correlation of the postural control (note: increased mean surface areas (mm$^2$) indicate decreased postural control) and the PCS scores of symptomatic and asymptomatic athletes during balance conditions with eyes closed.

![Mean brain oxygenation](image2)

**Fig. 4.** Mean brain oxygenation ($\Delta$HbO$_2$) in the left hemispheric (LH) frontopolar cortex (FPC, channel 1 and channel 4), and in the FPC of the right hemisphere (channel 6) between symptomatic and asymptomatic groups during balance conditions with eyes closed.
2.1.7. Correlation of brain oxygenation and post-concussion symptoms

A following correlation analysis of the ΔHbO2 in channel 4 during the eyes closed and stable surface condition and each post-concussion symptom revealed significance, i.e., the data showed a significant negative correlation between (decreased) ΔHbO2 in the LF FPC (ch4) and the (increased) symptoms headaches (r(62) = −0.461, p < 0.001), pressure in the head (r(62) = −0.276, p < 0.05), sensitivity to light (r(62) = −0.316, p < 0.05), sensitivity to noise (r(62) = −0.329, p < 0.01), difficulty remembering (r(62) = −0.309, p < 0.05), fatigue or low energy (r(62) = −0.267, p < 0.05), confusion (r(62) = −0.276, p < 0.05), difficulty falling asleep (r(62) = −0.376, p < 0.01), irritability (r(62) = −0.352, p < 0.01), and sadness (r(62) = −0.347, p < 0.01). A following stepwise linear regression analysis with ΔHbO2 in ch4 during the eyes closed and stable surface condition as the dependent variable and the significantly correlated symptoms as independent variables revealed significance (F(2, 59) = 12.327, p < 0.001, R² = 0.295), i.e., the (increased) symptoms headaches (β = −0.421, t = −3.819, p < 0.001) and sadness (β = −0.290, t = −2.627, p < 0.05) significantly predicted decreased ΔHbO2 in LF FPC (ch4) during the eyes closed and stable surface condition.

4. Discussion

The present study compared postural control performances in concussed athletes with and without post-concussion symptoms by analyzing postural sway and functional brain oxygenation in frontopolar cortices using fNIRS. Symptomatic athletes presented increased postural sway (surface areas (SuA)) when compared to asymptomatic athletes overall balance conditions as well as during the eyes closed condition, the unstable surface condition, and the combination of closed eyes and unstable surface condition. The SuA during the eyes closed and stable surface condition showed to predict the PCS score. The analysis of the fNIRS data revealed that symptomatic athletes are characterized by a lack of activation (i.e., reduced changes of ΔHbO2) in frontopolar cortices when compared to asymptomatic athletes during postural control with eyes closed on a stable surface. The symptoms headaches and sadness significantly predicted reduced ΔHbO2 in frontopolar cortices when controlling posture with closed eyes.

4.1. Postural control

In line with previous findings (Kleffelgaard et al., 2012; Purkayastha et al., 2019; Schmidt et al., 2018), the present study showed that symptomatic athletes present balance deficits when compared to asymptomatic athletes, particularly during conditions with eyes closed. Guskiewicz et al. (1997) pointed out that concussed athletes may suffer from sensory integration problems. Because concussions have been associated to a decline in the randomness of center of pressure oscillations (De Beaumont et al., 2011; Cavanaugh et al., 2005), it has been also assumed that the concussive injury constrains the output of the postural control system (Cavanaugh et al., 2006). Thus, the impaired control of balance with closed eyes of symptomatic athletes might be grounded in a decrease in the randomness of center of pressure oscillations

Fig. 5. Correlation of the PCS score and brain oxygenation in channel 4 (ΔHbO2) during the eyes closed and stable surface condition.
post concussion have been previously been associated to increased re-
response times (Chen et al., 2007; Eckner et al., 2011). Furthermore,
increased postural sway during eyes closed conditions and increased
response times during working memory performances are positively
correlated. Data from studies about neurodegenerative disorders also
showed a relationship of reduced response times (during an auditory
stepping task) and postural control deficits (VanderVelde et al., 2005).
Because neurodegeneration following repetitive concussions has been
related to motor deficits and cognitive dysfunction (Baugh et al., 2012),
the present data indicates that symptomatic athletes might be particu-
larly impaired in the time to adapt to altered sensory manipulations
during postural control tasks. Further investigations must therefore
differentiate whether alterations of postural control are particularly
related to decreased reaction times.

The analysis of the fNIRS data revealed that symptomatic athletes are
characterized by a lack of activation (i.e., reduced changes of
\( \Delta{\text{HbO}}_2 \) when compared to asymptomatic athletes) in frontopolar cor-
tices when performing postural control tasks with closed eyes. When
balancing with closed eyes, the attention of an individual shifts from
external reference points towards the perception of proprioceptive in-
formation from the own body (El Shemy, 2018 Dec). Marx et al. (2003)
postulated that during eyes closed conditions, the mental activity of an
individual shifts from an “exteroceptive” state during eyes opened
conditions to an “interoceptive” state that is characterized by imagi-
nation and multisensory activity that also depends on information from
frontopolar cortices. Thus, individuals must adapt to a novel situation and
control posture based on altered proprioceptive inputs. As it has
been postulated that concussed athletes may suffer from balance prob-
lems during situations with altered sensory inputs (Guskiewicz et al.,
1997), the reduced brain oxygenation in the FPC of individuals may
characterize the deficit of shifting the focus from visual inputs towards
proprioception. The FPC contributes to the exploration and rapid ac-
quision of novel behavioral options, which constitutes an essential
aspect of complex, higher order behavior (Mallinson and Longridge,
1998 Nov). This o
characterize concussed athletes with long-term impairments or if this pat-
tern of brain oxygenation is related to the progression of a depressive
disorder.

4.3. Practical implications

Because sport-related concussions and potential long-term effects are
a major concern in sports (McCroy et al., 2013), it is of relevance to
understand post-concussion outcomes on health status of athletes in
order to make decisions about the return-to-play and / or treatment
strategies. Recent development of portable instruments (Scholkmann
et al., 2014) allow to address the potential application of
fNIRS immediately after concussive incidents on site of sport events.
This offers the unique possibility to assess brain oxygenation im-
mediately post-concussion for potential clinical diagnosis. However,
because clinical decisions have to be made for each athlete individually,
a variety of issues must be taken into account when using NIRS clini-
cally (Greenberg et al., 2017). NIRS measurements concern light ab-
sorption of chromophores from a small segment of tissue within the
path of emitted light and its sensors, i.e., the data provides merely in-
formation about localized regional brain oxygenation (Scholkmann
et al., 2014). Secondly, alterations in intra- and extra-
cranial contents may affect readings (Gagnon et al., 2014;
Tachtsidis and Scholkmann, 2016), however, at this point it is unknown
what clinical impact extracranial contamination has on the use of NIRS
devices (Greenberg et al., 2017). Although the clinical implications of
these apparent inaccuracies require further study, they suggest that the
brain oxygenation measurements using fNIRS do not solely reflect brain
activation alone. Extra cerebral confounders can be minimized by
several approaches such as for example multi-distance optode mea-
surements (Gagnon et al., 2014; Tachtsidis and Scholkmann, 2016)
or particular experimental designs (Tachtsidis and Scholkmann, 2016).
To minimize confounders in the present study, we applied a block design
contrasting between experimental tasks of similar characteristics that
advances statistical calculations (Tachtsidis and Scholkmann, 2016). In
view of those issues, the present fNIRS data indicate that symptomatic
athletes present a deficit of activating neural structures that are re-
levant to control posture during altered sensory input, particularly
during closed eyes conditions. Thus, symptomatic athletes might be
particularly impaired to adapt to postural control conditions that are
characterized by altered sensory inputs. Post-concussion headaches
seem to particularly predict whether an individual suffers from de-
creased brain oxygenation patterns. Medical personal should therefore
be aware that athletes who suffer from headaches might have deficits of
integrating sensory information that is necessary to control posture.
Deb, S., Lyons, I., Koutzoukis, C., 1998. Neuropsychiatric sequelae one year after a minor head injury. J. Neurol. Neurosurg. Psychiatry 65 (6), 899–902. https://doi.org/10.1136/jnnp.65.6.899.

Eckner, J.T., Kutcher, J.S., Richardson, J.K., 2011. Efficacy of postural stability following sport-related concussion. J. Orthop. Sports Phys. Ther. 39 (5), 276. https://doi.org/10.2519/jospt.2009.2834.

Finkbeiner, N.W.B., Max, J.E., Longman, S., Debert, C., 2016 May May. Knowing what we don’t know: long-term psychiatric outcomes following adult concussion in sports. Am. J. Sports Med. 32 (1), 47–54. https://doi.org/10.1177/0363546503260723.

Guskiewicz, K.M., Richman, B.L., Bryant, D.H., Nashner, L.M., 1997. Alternative approaches to the assessment of mild head injury in athletes. Med. Sci. Sports Exerc. 29 (7 Suppl), S213-S221 PMID: 9247918.

Guskiewicz, K.M., Ross, S.E., Marshall, S.W., 2001. Postural stability and neuropsychological deficits after concussion in collegiate athletes. J. Athl. Train. 36 (3), 263-273 PMID: 12937495.

Helmich, I., Berger, A., Lauberg, H., 2016 Dec Dec. Neurol control of posture in individuals with persisting postconcussion symptoms. Med. Sci. Sports Exerc. 48 (12), 2584-2594. https://doi.org/10.1249/MSS.0000000000001069.

Helmich, I., Saluja, R.S., Lauberg, H., Kempe, M., Furley, P., Berger, A., Chen, J.-K., Pitt, A., 2015. Persistent postconcussive symptoms are accompanied by decreased functional brain oxygenation. J. Neuropsychiatry Clin. Neurosci. 27 (4), 287-298. https://doi.org/10.1176/appi.neuropsych.14100273.

Herald, F., Orlovski, K., Börmel, S., Müller, N.G., 2017. Cortical activation during balancing on a balance board. Hum. Mov. Sci. 51, 51–58. https://doi.org/10.1016/j.humov.2016.11.002.

Hoshi, Y., Kobayashi, N., Tamura, M., 2001. Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. J. Appl. Physiol. 90 (3), 1657–1662. https://doi.org/10.1152/jappl.2001.90.3.1657. (1985).

Howell, D.R., Brilliant, A., Berkerstser, B., Wang, F., Fraser, J., Meehan, W.P., 2017. The association between dual-task gait after concussion and prolonged symptom duration. J. Neuroltrauma 1 (23), 3288–3294. https://doi.org/10.1089/neur.2017.319. 14.

Huppert, T., Schmidt, B., Behn, N., Furman, J., Sparto, P., 2013. Measurement of brain activation during an upright stepping reaction task using functional near-infrared spectroscopy. Hum. Brain Mapp. 34 (11), 2817–2828. https://doi.org/10.1002/hbm.22106.

Ingersoll, C.D., Armstrong, C.W., 1992. The effects of closed-head injury on postural sway. Med. Sci. Sports Exerc. 24 (7), 739-743 PMID: 1501556.

Jasper, H., 1958. Report to the committee on methods and clinical examination in electroencephalography. Electroencephalogr. Clin. Neurophysiol. 10, 371–375.

Karin, H., Fuhrman, S.L., Sparto, P., Furman, J., Huppert, T., 2013. Functional brain imaging of multi-sensory vestibular processing during computerized dynamic posturography using near-infrared spectroscopy. Neuroimage. 1, 318–325. https://doi.org/10.1016/j.jineuron.2013.02.010. 74.

Karin, H.R., Schmidt, B., Dart, D., Beluk, N., Huppert, T., 2012. Functional near-infrared spectroscopy (NIRS) of brain function during active balancing using a video game system. Gait Posture 35 (3), 367–372. https://doi.org/10.1016/j.gaitpost.2011.10.016.

Kitaoka, K., Ito, N., Araki, H., Sei, H., Moria, Y., 2004. Effect of mood state on anticipatory postural adjustments. Neurosci. Lett. 3 (1), 65–68. https://doi.org/10.1016/j.neulet.2004.07.088. 370.

Kleefglad, I., Roe, C., Soberg, H.L., Bergland, A., 2012. Associations among self-reported balance problems, post-concussion symptoms and performance-based tests: a longitudinal follow-up study. Disabil. Rehabil. 34 (9), 758-794. https://doi.org/10.3109/09639763.2011.619624.

Kostopoulos, P., Albanese, M., Petrides, M., 2007. Ventrolateral prefrontal cortex and tactile memory disambiguation in the human brain. PNAS 104 (24), 10223-10228. 372. https://doi.org/10.1073/pnas.1419649112. 21.

Lovell, M.R., Collins, M.W., Iverson, G.L., Johnston, K.M., Bradley, J.P., 2004. Grade 1 or 2? A consensus statement. J. Athl. Train. 39 (3), 226. https://doi.org/10.4085/1062-6050-39.3.226. 20.

M., Bisconti, S., Spezialetti, M., Moro, S.B., Di Palo, C., Placidi, G., Quaresima, V., 2017. Prefrontal cortex activated bilaterally by a tilt board balance task: a functional fMRI study. J. Neurotrauma 34 (7 Suppl), S213–S221 PMID: 2823432. 370.

Mahoney, J.R., Holtzer, R., Izzetoglu, M., Zemon, V., Verghese, J., Allali, G., 2016. The effect of concussion on clinically differential working memory load effects. Neuroimage Clin. 24 (16), 554. https://doi.org/10.1016/j.nicl.2016.10.002.

Mann, A.I., Flodquist, D., Parnelli, S., Bouckoms, A., 2005. Ventral and dorsal flexor fatiguing during unilateral postural control. J. Appl. Biomech. 9 (3), 191–201. https://doi.org/10.1123/jab.9.3.191.

Maloney, J.R., Holtzer, R., Izzetoglu, M., Zemon, V., Verghese, J., Allali, G., 2016. The role of frontal cortex during postural control in Parkinsonian subjects with functional near-infrared spectroscopy study. Brain Res. 15 (1633), 126–138. https://doi.org/10.1016/j.brainres.2015.10.053.

Mallinson, A.L., Longridge, N.S., 1998 Nov Nov. Dizziness from whiplash and head injury: Differences between whiplash and head injury. Am. J. Oncol. 19 (6), 814-818 PMID: 9831160.

Manouris, F.A., Buckley, M.I., Mahboubi, M., Tanaka, K., 2015. Behavioral consequences of selective damage to frontal pole and posterior cingulate cortices. Proc. Natl. Acad. Sci. USA 112 (29), E5960-E5969. 370. https://doi.org/10.1073/pnas.1422629112. 217.

Mars, E., Stephan, T., Nolte, A., Aslendi, A., Seelos, K.C., Dieterich, M., Brandt, T., 2003. Eye closure in darkness animates sensory systems. Neuroimage 19 (3), 924-934 PMID: 12880821.

McAllister, T.W., Sparling, M.B., Flashman, L.A., Guerin, S.J., Mamounian, A.C., Saykin, A.J., 2001. Differential working memory load effects after mild traumatic brain injury. Neuroimage 14 (5), 1004-1012. https://doi.org/10.1016/S1053-8119(01)00899-8.

McCrea, M., Guskiewicz, K.M., Marshall, S.W., Barr, W., Randolph, C., Cantu, R.C., Onate,
