Head Kinematics and Physiological Effects of Repeated Soccer Heading

C. M. Huber[1,2], D. A. Patton[2], K. R. Rownd[2], C. L. Master[2,3], and K. B. Arbogast[2,4]
[1] University of Pennsylvania, Department of Bioengineering; [2] Children's Hospital of Philadelphia, Center for Injury Research and Prevention; [3] Children's Hospital of Philadelphia, Sports Medicine and Performance Center; [4] University of Pennsylvania, Perelman School of Medicine, Department of Pediatrics

ABSTRACT

Repeated soccer heading has caused immediate but transient decreases in neurocognitive performance, postural control, and ocular reflexes; however, previous studies focused on adults and lack high-quality head kinematic data. The current study quantified the head kinematics of adolescents during frontal and oblique soccer headers using an instrumented mouthguard and assessed changes in physiological function following a series of soccer headers compared to kicking control participants. Participants completed a suite of neurofunction assessments including the Post-Concussion Symptom Inventory (PCSI), visio-vestibular exam (VVE), and pupillary light reflex (PLR) at three timepoints: immediately prior to (pre), immediately after (0-hr post), and 16-72 hours after (24-hr post) completing 10 soccer headers or kicks. Data were collected for 19 participants (17 male) randomized into control (n=8), frontal heading (n=6), and oblique heading (n=5) groups. Frontal soccer headers resulted in higher mean peak linear acceleration (17.4±0.5 g) compared to oblique headers (12.1±0.4 g, $p<0.001$), and oblique headers resulted in higher peak angular velocity (frontal: 5.6±0.2 rad/s, oblique: 10.1±0.4 rad/s, $p<0.001$) and angular acceleration (frontal: 1147±45 rad/s^2, oblique: 1410±65 rad/s^2, $p<0.001$). There were no differences between controls and heading participants pre-intervention in PCSI, VVE, or PLR ($p>0.127$) or change from baseline for either timepoint ($p>0.071$). However, compared to pre-intervention, control participants had fewer total errors + sway in VVE tandem gait at 0-hr post (pre: 1.0±0.4, 0-hr: 0.3±0.2, $p=0.020$), and one of nine PLR metrics (peak dilation velocity) decreased for heading participants one day after heading (pre: 2.1±0.1 mm/s; 24-hr post: 1.9±0.1 mm/s, $p=0.001$). Overall, there was no effect of soccer heading on subjective symptoms and semi-objective VVE, and a single objective PLR metric changed in heading participants. Therefore, based on these results, repeated headers did not leave a clear signature on acute brain function.

INTRODUCTION

An estimated 1.6-3.8 million sports- and recreation-related concussions occur each year (CDC, 2007). Adolescents are particularly vulnerable to head injury and suffer longer recovery periods than adults (Iverson, 2007; Nelson et al., 2016). Furthermore, there is growing concern for the effects of repeated head loading that do not manifest into symptoms and possible effects on neurological outcomes (Mainwaring et al., 2018). Concussion occurs from rotational loading of the head giving rise to diffuse stresses and strains in the brain tissue causing axonal stretching, microstructural damage, and synaptic disconnection (Meaney & Smith, 2011), leading to autonomic and physiological dysfunction (Halstead et al., 2018; Purkayastha et al., 2019). It is unknown whether biomechanical forces from lower severity head kinematics such as those that occur from typical soccer heading cause temporary physiological deficits as well.

Concussion is traditionally diagnosed based on subject-reported symptoms; however, objective quantitative assessments such as pupillary light reflex (PLR) have been useful in the diagnosis of concussion and are indicative of the neural dysfunction that follows injury (Master et al., 2020; Thiagarajan & Ciuffreda, 2015). These sensitive measures can detect neurological changes after clinical symptoms have resolved and provide an objective, quantitative assessment of physiologic dysfunction. While objective measures have been used to discriminate injured from non-injured athletes (Capó-Aponte et al., 2018; Thiagarajan & Ciuffreda, 2015), there is a lack of research quantifying neurophysiological deficits due to repetitive head loading in the absence of diagnosed injury.

Heading the ball in soccer is an integral part of the game, providing a naturalistic setting to study the immediate effects of repetitive head loading. Previous soccer heading studies have evaluated neurophysiological changes pre- and post-repetitive heading. These studies have found conflicting results for the effect on neurocognitive performance immediately following a bout of heading (Di Virgilio et al., 2016; Elbin et al., 2015; Rieder & Jansen, 2011; Wallace et al., 2018) but found changes in measures of vestibular balance, ocular function, and neurochemical biomarkers (Caccese et al., 2021; Kawata et al., 2016; Wallace et al., 2018). Despite evidence that proper heading technique with the forehead reduces head kinematics (Caccese & Kaminski, 2016; Harriss et al., 2019), no controlled study has analyzed the physiological outcomes associated with different primary loading directions. Most previous studies focused on collegiate and adult soccer players; this study will expand upon the work by Caccese et al. (Caccese et al., 2021) in adolescents by introducing novel loading directions and a suite of subjective and objective measures for a broad assessment of neural dysfunction.

Specifically, the objective of this study was to quantify the head kinematics of adolescents during frontal and oblique soccer headers using an instrumented mouthguard and assess changes in neurophysiological function following a series of soccer headers compared to kicking control participants.

METHODS

Study Design and Heading Intervention

Participants were randomly assigned to kicking control, frontal heading, or oblique heading groups as part of a randomized controlled trial approved by the Children's Hospital of Philadelphia Institutional Review Board (IRB 20-017267). Participants completed a suite of neurofunction assessments at three timepoints: immediately prior to (pre), immediately after (0-hr post), and 16-

72 hours after (24-hr post) completing 10 soccer headers or kicks. Between the heading/kicking intervention and 24-hr follow up, participants were asked not to perform any soccer headers and minimize participation in physical contact activities.

The 10 soccer headers/kicks were completed with 1 minute rest periods between headers/kicks to simulate a practice drill, which aligns with previous soccer heading studies (Bevilacqua et al., 2019; Caccese et al., 2021). Soccer headers were performed with a size 5 soccer ball (450 g) inflated to 12 psi projected at approximately 11.2 m/s (25 mph) from a distance of 10 m using a ball launcher (JUGS Sports, Tualatin, OR). The speed replicated a typical overhead throw-in (Van Den Tillaar & Marques, 2009), which is a frequent event leading to a header and a common practice situation. Participants in the frontal heading group headed the ball forward directly toward the ball launch direction, and oblique heading participants directed the ball at a target 90° to the right of the launch location.

Participants

Participants were active male and female soccer players aged 13-18 with at least 1 year of soccer heading experience. Participants were excluded if they: (1) sustained a concussion or spinal injury within the past 6 months or still had active symptoms from a previous injury, (2) were unable to exercise due to a lower-extremity orthopedic injury or significant vestibular or visual dysfunction, (3) were taking medications that can affect autonomic function, (4) played the goalkeeper position exclusively, (5) had fixed orthodontia on upper teeth and were unable to complete the instrumented mouthguard fitting, or (6) did not understand English and were unable to complete the informed consent process. Demographic information (i.e., age, sex, height, and weight) was collected for all participants.

Head Kinematic Data Collection and Processing

Head kinematic data was collected using the Prevent Biometrics, Inc. (Edina, MN) boil-and-bite Impact Monitoring Mouthguard (IMM), which comprises a triaxial linear accelerometer and gyroscope measuring linear acceleration and angular velocity, respectively, at 3200 Hz (Prevent Biometrics, 2020). The IMM has shown good coupling to the skull and performance in validation testing for accurate measurement of head kinematics (Bartsch et al., 2014; Liu et al., 2020). Sensor-recorded events were triggered when any linear acceleration axis exceeded 5 g. Data were automatically uploaded to the Prevent Biometrics cloud-based portal, filtered at 200 Hz, and transformed to the head center of gravity based on the NOCSAE 50th percentile male headform (Bartsch et al., 2020; Liu et al., 2020).

Sensor-recorded events were timestamped with 1 second resolution, and time-synchronized video was used to verify sensor-recorded soccer headers and remove false-positive recordings. Sensor data for individual headers were excluded if more than 1 event was recorded within 2 seconds because it was not possible to identify which event was associated with the header. The IMM includes a proximity sensor to detect if the mouthguard was coupled to the upper dentition during an acceleration event; sensor-recorded events were additionally removed as false-positives if poor coupling was detected based on the proximity sensor data. Prevent Biometrics has developed a patented algorithm to identify and remove false positives (Bartsch et al., 2019);

however, the algorithm was not used for this study to ensure all sensor-recorded events were available for review.

Neurophysiological Measurements

Participants completed the Post-Concussion Symptom Inventory (PCSI), visio-vestibular exam (VVE), and pupillary light reflex (PLR) as part of a larger suite of neurofunction assessments. All assessments were conducted by research staff who received standardized training from a sports medicine specialist, including observed practice sessions. Research staff conducted assessments in an athletic training room and were not blinded to participant group because the information was needed for heading/kicking study procedures.

For PCSI, participants self-reported current symptom severity on the 21-item PCSI on a Likert scale of 0-6 (0=none, 6=most severe) for total score range of 0-126 (Sady et al., 2014). PCSI total symptom score was used in the analysis.

The VVE evaluates vestibular function, visual function, and gait via 9 subtests, as described previously (Roby et al., 2021) and applied in various settings (Arbogast et al., 2017; Corwin et al., 2019; Corwin, Arbogast, et al., 2020). The assessment includes the following subtests administered in order: smooth pursuit, horizontal and vertical saccades, horizontal and vertical gaze stability (angular vestibular-ocular reflex [VOR]), near point of convergence (NPC), right and left monocular accommodation, and complex tandem gait. Descriptions and definitions of abnormal performance for each subtest can be found in Table 1.

Table 1. Visio-Vestibular Exam

Subtest	Description	Definition of Abnormal Performance
Smooth Pursuit	The ability to track in a horizontal plane for 5 repetitions	Symptom provocation or jerky or jumpy eye movements
Horizontal and Vertical Saccades	Participant's eyes moving rapidly between two fixed objects	Symptom provocation with 20 or fewer repetitions
Horizontal and Vertical Gaze Stability (VOR)	Participant's eyes are fixed and his or her head moves in the horizontal or vertical plane	Symptom provocation with 20 or fewer repetitions
Near Point of Convergence (NPC)	Binocular break (double vision) using a standard Astron accommodative rule with a single column 20/30 card	Break distance >6 cm
Right and Left Monocular Accommodation	Clear to blur distance with one eye open using a standard Astron accommodative rule	Distance based on age using Hofstetter's formula (13 years old, >10.2 cm; 18 years old, >11.7 cm)
Complex Tandem Gait	Errors (steps off a straight line) + the presence of sway when walking in tandem for 5 steps forward and backward, eyes open and closed	

PLR was assessed by measuring monocular pupil diameter at 30 frames per second for 5 seconds in response to a brief white light stimulus (154 ms duration; 180 mW) using a PLR-3000 (NeurOptics, Irvine, CA) handheld infrared, automated, monocular pupillometer as previously described (Master et al., 2020). At least 3 trials were completed for each eye to produce 3 artifact-free measurements per eye. Artifacts were blinks or eye movements which prevented the device from continuously measuring pupil diameter. Measurements were taken by alternating eyes with at least 1 minute rest for light adaptation. Eight metrics were quantified by the device software, and a ninth, peak dilation velocity, was calculated from the time series (Master et al., 2020; Truong, 2016) (

Table 2). For each participant, the mean of each metric was calculated for both eyes combined. Trials were removed from analysis if artifacts were identified by the PLR-3000, visual inspection of the time series, or outlier pupil constriction and dilation velocity calculated from the time series.

Table 2. Pupillary Light Reflex Metrics

Subtest	**Units**	**Description**
Maximum Pupil Diameter	mm	Steady-state pupil size before the light stimulus
Minimum Pupil Diameter	mm	Pupil size after maximum constriction in response to the light stimulus
Percentage Pupil Constriction	%	$\frac{\text{Maximum Diameter - Minimum Diameter}}{\text{Maximum Diameter}}$
Latency	ms	Time to maximum constriction in response to the light stimulus
Peak and Average Constriction velocity	mm/s	Maximum and mean velocity during pupil constriction
Peak and Average Dilation velocity	mm/s	Maximum and mean velocity during pupil dilation
T75	s	Time for pupil redilation from minimum diameter to 75% maximum diameter

Statistical Analysis

Peak head kinematics were pooled for all headers by group and compared between frontal and oblique heading groups using linear regression. Heading groups were combined for comparison of physiologic metrics to kicking control participants. Demographics were compared using Fisher's exact tests for sex or two-sample t-tests for age, height, and weight. The proportion of abnormal assessments in VVE were evaluated for pre-post change and between control and heading groups using Fisher's exact tests. Quantitative physiologic changes from pre-intervention were assessed within group by paired t-tests and compared between control and heading groups using linear regression. Bonferroni corrections for multiple comparisons within an assessment were applied (kinematics: $p<0.017$, PCSI and VVE: $p<0.025$, PLR: $p<0.003$). All summary data is presented at mean ± standard error of the mean (SEM).

RESULTS

Data were collected for 19 participants (17 male) randomized into control kicking (n=8), frontal heading (n=6), and oblique heading (n=5) groups (Table 3). There were no differences in demographics and anthropometrics between control and heading groups ($p>0.180$). On average, the participants returned for their follow-up assessment 24.0±1.6 hours after the intervention.

Table 3: Demographics and Anthropometrics

	Overall	**Control**	**Heading**	**p-value**
n, sex (F)	17 (2 F)	7 (1 F)	10 (1 F)	>0.999
Age, Mean (SEM)	15.7 (0.4)	16.1 (0.8)	15.3 (0.5)	0.381
Height (m), Mean (SEM)	1.72 (0.02)	1.73 (0.02)	1.70 (0.03)	0.488
Weight (kg), Mean (SEM)	59.9 (2.4)	63.7 (4.5)	57.1 (2.4)	0.180

Head Impact Kinematics

Of the 110 headers (60 frontal, 50 oblique) completed by participants, 107 (60 frontal, 47 oblique) were recorded by the IMM sensor. Data was removed for an additional 3 oblique headers because it was not possible to identify a single recording associated with the header (i.e., multiple sensor event recordings). Additionally, data was removed for 2 frontal headers because the IMM proximity sensor indicated poor coupling during the impact. The remaining 102 direct head impact events with evaluable sensor data were included for analysis (58 frontal, 44 oblique). Frontal soccer headers resulted in higher mean peak linear acceleration (17.4±0.5 *g*) compared to oblique headers (12.1±0.4 *g*, $p<0.001$), and oblique headers resulted in higher peak angular velocity (frontal: 5.6±0.2 rad/s, oblique: 10.1±0.4 rad/s, $p<0.001$) and angular acceleration (frontal: 1147±45 rad/s^2, oblique: 1410±65rad/s^2, $p<0.001$, Figure 1).

Neurophysiological and Clinical Measurements

Frontal and oblique heading groups were combined for physiological analysis due to small sample size. Control and heading participants did not differ in pre-intervention PCSI total symptom scores (Figure 2, control=0.9±0.7; heading=3.1±1.0, p=0.127), and overall PCSI values were extremely small given the full-scale range (0-126) of the assessment. There were no changes in either group after the kicking/heading intervention ($p>0.064$), and there were no differences between control and heading subjects at any of the three timepoints ($p>0.059$). When reported, the most common symptoms were balance problems, headache, dizziness, and sleep more than usual.

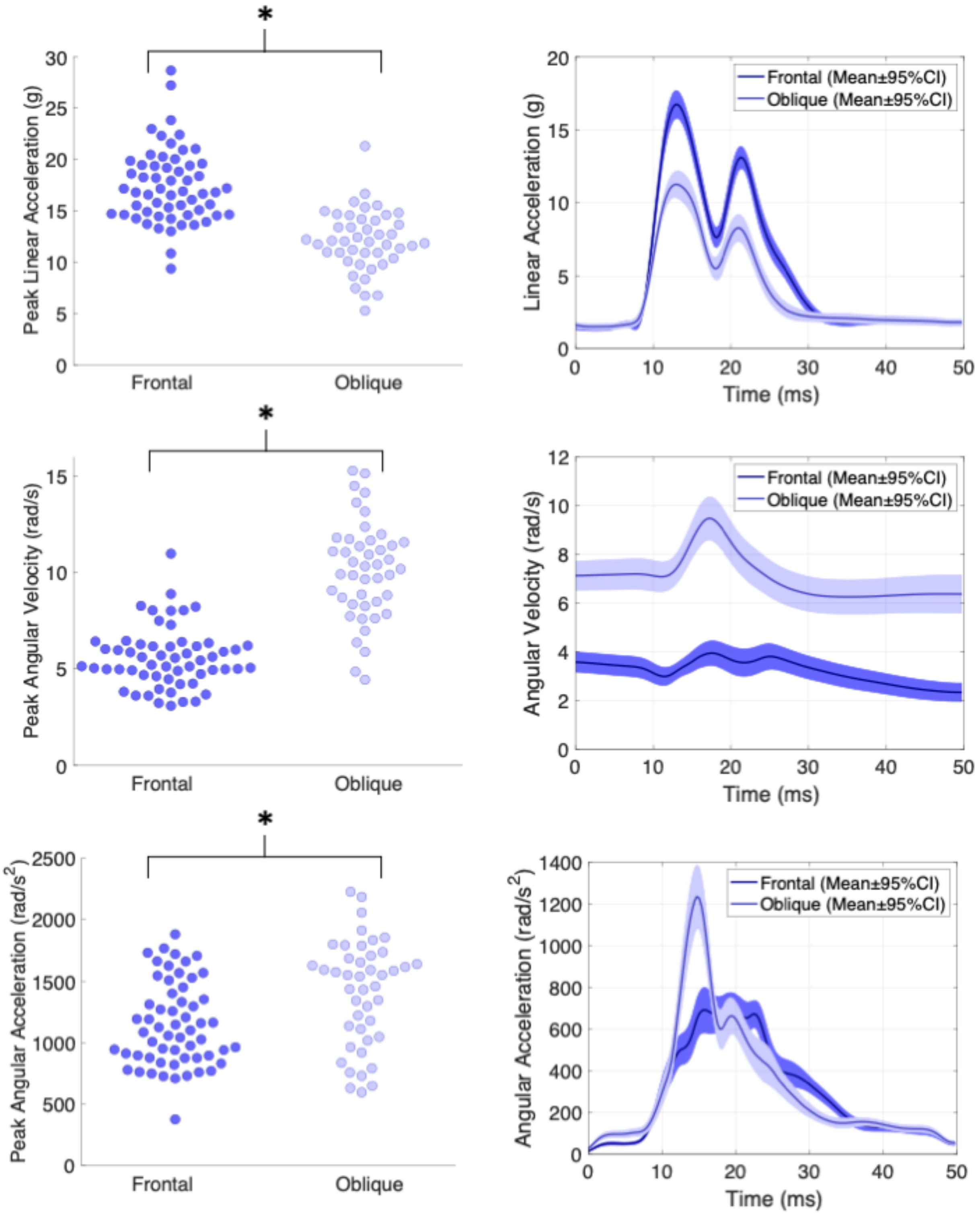

Figure 1: (Left) Peak resultant kinematics for each header (58 frontal, 44 oblique) are represented in beehive plots. *Difference between frontal and oblique heading groups ($p<0.017$). (Right) Average resultant frontal and oblique kinematic time series plotted with 95th percentile confidence intervals (CI) of the mean.

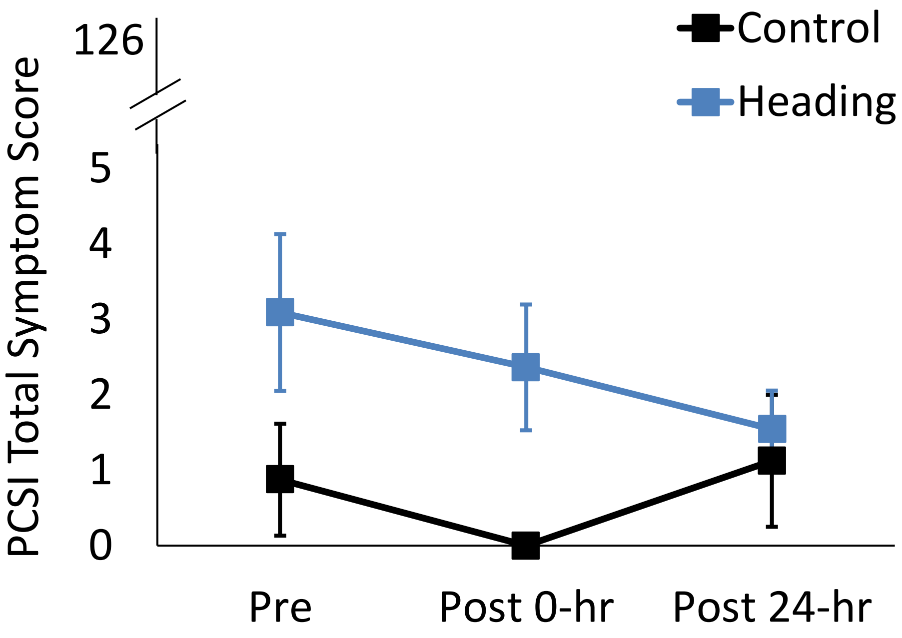

Figure 2: Post concussion symptom inventory (PCSI) total symptom score for control (n=8) and heading (n=11) participants presented as mean ± standard error of the mean (SEM). Control and heading participants did not differ in pre-intervention PCSI total symptom scores (p=0.127). There were no changes in PCSI relative to pre-intervention for control or heading participants at the 0-hr post (p=0.277, p=0.267, respectively) or 24-hr post (p=0.170, p=0.064, respectively) timepoints, and there were no differences between control and heading participants in total symptom score change from pre-intervention at the 0-hr post (p=0.880) or 24-hr post (p=0.059) timepoints.

Visio-Vestibular Exam (VVE)

The 9 VVE components were analyzed individually. The proportion of abnormal smooth pursuit, saccades, VOR, accommodation, and NPC assessments were calculated (Table 4). A single control participant was unable to track a fast-moving object in smooth pursuit at the 0-hr post timepoint. All participants at all timepoints were able to complete the maximum 20 repetitions for saccades and VOR. At pre-intervention, 37% and 32% of participants met the for abnormal monocular accommodation and NPC, respectively, which remained unchanged at post-intervention timepoints. There were no changes from pre-intervention in proportion of abnormal assessments for control or heading participants at either post-intervention timepoint (p>0.362), and there were no differences between control and heading subjects at any timepoint (p>0.319).

For NPC, control and heading participants did not differ in pre-intervention break distance (Figure 3, p=0.754). There were no changes after the kicking/heading intervention (p>0.069), and there were no differences between control and heading subjects (p>0.275).

Table 4: Abnormal Visio-Vestibular Exams

	Abnormal (%)					
	Control			**Heading**		
	Pre	**0-hr Post**	**24-hr Post**	**Pre**	**0-hr Post**	**24-hr Post**
Smooth Pursuit	0%	13%	0%	0%	0%	0%
Horizontal Saccades	0%	0%	0%	9%	0%	0%
Vertical Saccades	0%	0%	0%	0%	0%	0%
Horizontal VOR	0%	0%	0%	0%	0%	0%
Vertical VOR	0%	0%	0%	0%	0%	0%
NPC	50%	50%	50%	18%	45%	27%
Left Accommodation	25%	25%	38%	45%	45%	45%
Right Accommodation	25%	25%	13%	36%	36%	18%

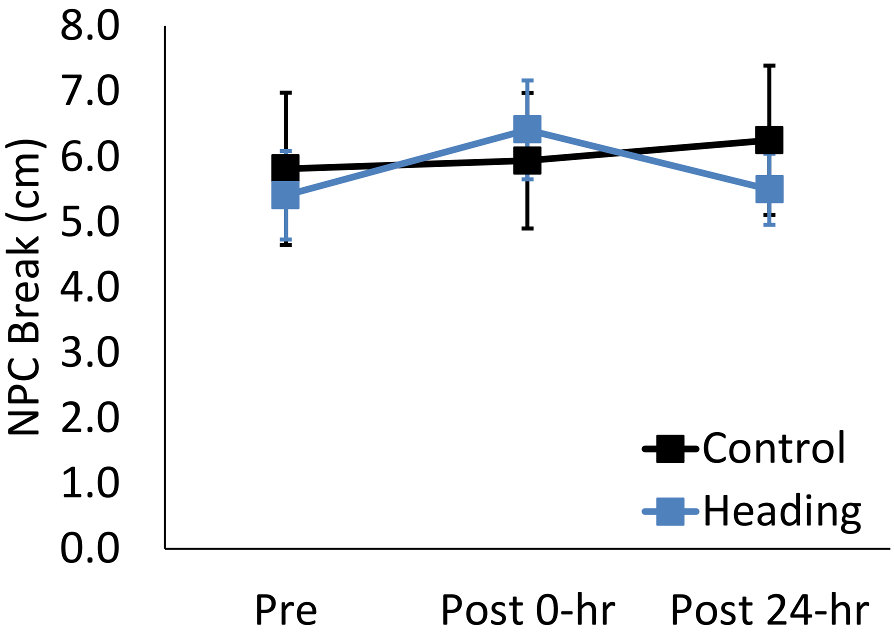

Figure 3: Near point of convergence (NPC) break distance for control (n=8) and heading (n=11) participants displayed as mean ± SEM. Control and heading participants did not differ in pre-intervention break distance (p=0.754). There were no changes in NPC break relative to pre-intervention for control or heading participants at the 0-hr post (p=0.844, p=0.069, respectively) or 24-hr post (p=0.422, p=0.841, respectively) timepoints, and there were no differences between control and heading participants in change from pre-intervention of NPC break at the 0-hr post (p=0.275) or 24-hr post (p=0.616) timepoints.

For complex tandem gait, control and heading participants did not differ in pre-intervention total errors + sway (Figure 4, p=0.688). Control participants improved their performance at the 0-hr post timepoint compared to pre-intervention (p=0.020). Heading participant scores did not significantly change after heading, and there were no differences between control and heading subjects (p>0.288).

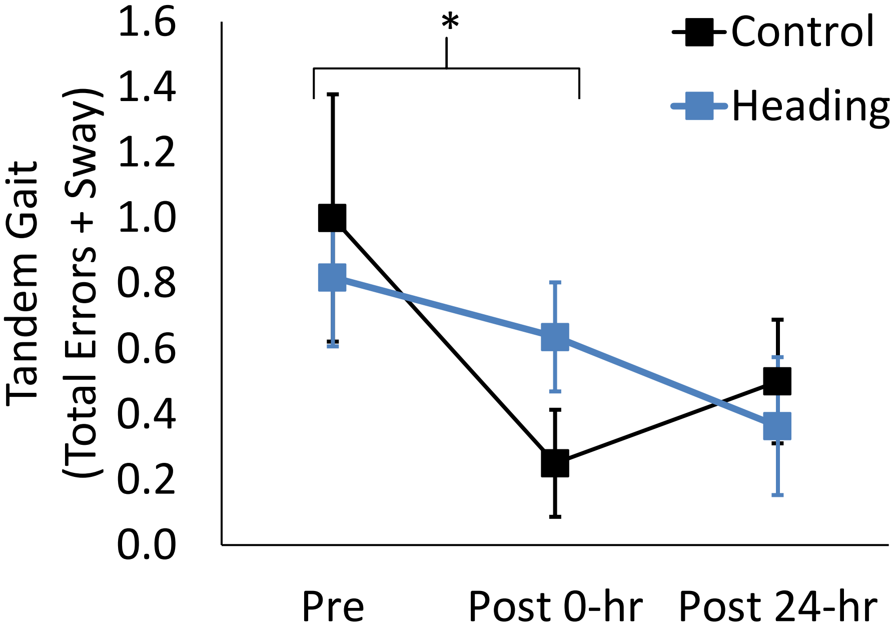

Figure 4: Tandem gait total errors + sway scores for control (n=8) and heading (n=11) participants displayed as mean ± SEM. Control and heading participants did not differ pre-intervention (p=0.688). Compared to pre-intervention, control participants had lower scores at the 0-hr post timepoint (*p=0.020) but not at the 24-hr post timepoint (p=0.316). Heading participants did not change from pre-intervention at the 0-hr (p=0.659) or 24-hr post (p=0.138) timepoints, and there were no differences between control and heading participants in change from pre-intervention at the 0-hr post (p=0.288) or 24-hr post (p=0.930) timepoints.

For PLR, 394 trials were recorded (6.9 trials per participant per timepoint), and 80 (20%) of trials were removed due to artifacts. There were no differences between controls and heading participants for any of the components of PLR (Table 5) pre-intervention (p>0.188) or change from pre-intervention for either timepoint (p>0.071). However, compared to pre-intervention, heading participants had lower PLR peak dilation velocity one day after heading (p=0.001).

Table 5: Pupillary light reflex summary metrics presented as mean ± SEM.

	Control			Heading		
	Pre	**0-hr Post**	**24-hr Post**	**Pre**	**0-hr Post**	**24-hr Post**
Pupil Diameter (mm)						
Maximum	5.5 ± 0.2	5.0 ± 0.2	5.2 ± 0.3	5.6 ± 0.2	5.6 ± 0.2	5.4 ± 0.2
Minimum	3.2 ± 0.1	2.9 ± 0.1	3.0 ± 0.2	3.2 ± 0.1	3.2 ± 0.1	3.2 ± 0.1
% Constriction	42.4 ± 1.1	41.9 ± 1.0	41.6 ± 0.9	42.4 ± 0.9	42.9 ± 0.9	40.3 ± 1.4
Latency (ms)	209.8 ± 6.8	200.9 ± 5.4	203.8 ± 7.1	201.8 ± 4.4	202.3 ± 2.9	206.9 ± 4.8
Constriction Velocity (mm/s)						
Average	-3.4 ± 0.1	-3.3 ± 0.1	-3.4 ± 0.2	-3.5 ± 0.1	-3.7 ± 0.2	-3.3 ± 0.2
Peak	-5.6 ± 0.2	-5.5 ± 0.3	-5.5 ± 0.3	-5.6 ± 0.2	-5.9 ± 0.3	-5.4 ± 0.3
Dilation Velocity (mm/s)						
Average	1.4 ± 0.1	1.3 ± 0.1	1.2 ± 0.1	1.4 ± 0.1	1.5 ± 0.1	1.3 ± 0.1
Peak	2.0 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	2.1 ± 0.1	2.1 ± 0.1	**1.9 ± 0.1***
T75 (s)	2.5 ± 0.3	2.5 ± 0.1	2.6 ± 0.1	2.2 ± 0.1	2.4 ± 0.1	2.1 ± 0.1

*Significant change from pre-intervention accounting for multiple comparisons (p=0.001). All other p-values >0.005. Abbreviations: T75=time for pupil diameter recovery to 75% maximum diameter

DISCUSSION

The current study examined a sample of adolescents participating in a series of repetitive soccer headers – quantifying biomechanics in two impact directions – coupled with a comprehensive suite of clinical and neurophysiological assessments immediately after heading and approximately one day later. From a biomechanics perspective, frontal heading participants had similar average peak resultant linear acceleration to a collegiate study using the GForceTracker (a head kinematic sensor secured with pre-wrap and tape) with the same ball launch conditions (14.5 *g*) (Kawata et al., 2016) and lower peak resultant linear and angular accelerations than those measured by a Triax SIM-G (a head kinematic sensor embedded in a neoprene headband) in high school (33.5 *g*, 2745 rad/s^2) (Caccese et al., 2018) and collegiate (31.8 *g*, 3560 rad/s^2) athletes (Wirsching et al., 2019). Instrumented mouthguards have better coupling than headband-mounted sensors (Wu et al., 2016), and therefore, the kinematics presented in this study are expected to be more representative of soccer heading than previous studies. For additional context, peak kinematics were substantially below 50% injury risk levels observed in Australian football and rugby (65.1 *g*, 22.2 rad/s, 3958 rad/s^2) (McIntosh et al., 2014).

Oblique heading participants redirecting the ball 90° to the side in this study had lower peak resultant linear acceleration than frontal heading participants but 80% and 21% higher peak resultant angular velocity and acceleration, respectively. Therefore, for equal loading conditions (i.e., contact surface and ball velocity), distinct impact locations and directions influenced the global kinematics of the head and likely the biomechanical forces on the brain. This study quantitatively supports the use of the forehead to drive the ball forward as an effective soccer heading technique to minimize angular head kinematics (Caccese & Kaminski, 2016). Angular accelerations generate shear strains and stresses causing diffuse tissue damage as the primary mechanism of injury for concussion (Meaney & Smith, 2011) and are more strongly associated with injury compared with linear accelerations. Therefore, emphasizing proper heading technique can reduce the severity of angular kinematics in repetitive loading.

Average PCSI total symptom scores for heading participants at all timepoints were very low (overall average = 1.6) compared to average symptom scores (36.5) following a concussion in adolescents (Ledoux et al., 2019). Further, symptoms in this study stayed the same after the kicking/heading intervention, and therefore, heading did not affect symptoms experienced by the athletes. Two previous studies found heading participants reported higher symptoms following a bout of 18-20 headers compared to controls who reported no change in symptoms (Schmitt et al., 2004; Wallace et al., 2018); A higher number of repeated head impacts may cause a higher symptom burden compared to the current study.

There were no changes in the proportion of abnormal assessments of smooth pursuit, saccades, VOR, or accommodation for control or heading subjects across timepoints, and there were no differences between control and heading subjects. The proportion of abnormal assessments of smooth pursuit, saccades, VOR were similar to a previous study in uninjured adolescents (<11%) (Corwin et al., 2021). The proportion of abnormal accommodation and NPC tests were higher than levels previously measure in uninjured adolescents (5%) (Corwin et al., 2021); however, the proportion remained unchanged or decreased after heading. The large proportion may be due to a small sample size, but there was no effect of heading on accommodation. For NPC, there were no changes in break distance for controls or heading participants across timepoints. Pre-intervention NPC break values were higher than normative values in adults (2.5 cm) (Scheiman et al., 2003) but lower than a previous soccer heading study (7.8-8.2 cm) (Kawata et al., 2016). With the same heading paradigm as the current study, Kawata et al. reported an increase in NPC break distance in young adults from 8.2 cm to 10.5 cm at 0-hr post-heading and further increased 24-h post-heading to 11.5 cm. For tandem gait, pre-heading total errors + sway scores were similar to levels of previously observed adolescent uninjured controls (2 [0, 3.5] errors + sway) and below the cutoff for distinguishing concussed and uninjured youth (5 errors + sway) (Corwin, McDonald, et al., 2020). Control participants in this study significantly improved in balance performance at the 0-hr post-kicking timepoint, which is likely a practice effect of completing the task in quick succession. There was no effect of heading on balance performance or differences between control and heading participants. Previous soccer heading studies have found mixed effects of heading on various assessments of balance and postural stability with some finding significant decreases in performance (Haran et al., 2013; Hwang et al., 2016) and numerous finding no effect (Broglio et al., 2004; Caccese et al., 2021; Di Virgilio et al., 2016; Mangus et al., 2004; Schmitt et al., 2004). Based on the current study results, repeated soccer heading did not affect overall performance in any of the 9 VVE tasks – representing a comprehensive clinical evaluation of neural dysfunction.

One of 9 pupillary light reflex metrics, peak dilation velocity, changed at the 24-hr timepoint for heading participants compared to baseline. PLR has previously been shown to discriminate between concussed athletes and uninjured controls in 8 of the 9 metrics (Master et al., 2020). In the current study, peak dilation velocity decreased after heading; however, concussed athletes were found to have higher peak dilation velocity compared to uninjured controls (Master et al., 2020). Overall, there was no clear effect of heading on PLR metrics and no differences from control participants.

Limitations of the current study include the participant sample and a single heading paradigm. The study sample was adolescent, predominately male athletes, which limits the generalizability of the study. Continued data collection will aim to include more female athletes and add sample size to differentiate between frontal and oblique heading groups in analyses of the neurophysiologic metrics. The heading paradigm was limited to 10 headers launched at 25 mph (11.2 m/s), which approximated that of a throw-in typically experienced in practice or a game. Previous studies with a larger number of headers at higher speeds found a significant increase in symptoms; therefore, a more severe header paradigm may cause neural dysfunction.

CONCLUSIONS

Header impact direction influenced both linear and angular kinematics with frontal headers resulting in higher peak linear acceleration and oblique headers in higher peak angular velocity. The neurophysiological effects of soccer heading were evaluated via multiple subjective and objective clinical assessments. There was no effect of soccer heading on subjective symptoms and semi-objective VVE, and only one of nine objective PLR metrics showed changes over time amongst heading participants. Therefore, based on these results, a bout of repeated headers did not leave a clear signature on acute brain function. These data provide high-quality soccer heading kinematic data comparing multiple impact directions, and future studies should investigate potential sex differences in physiological deficits.

ACKNOWLEDGEMENTS

The authors thank members of the research team for their contributions to data collection and analysis: Alexis Brzuchalski, Anne Mozel, Kaitlyn Housel, Kristi Metzger, Divya Jain. In addition, the authors thank the athletes and parents from Delaware County Christian School and Falls Fire soccer club for their participation and appreciate the support of Minda Garner and Tiffany Pereira. The current study was funded with internal funds from the Children’s Hospital of Philadelphia.

REFERENCES

ARBOGAST, K.B., CURRY, A.E., METZGER, K.B., KESSLER, R.S., BELL, J.M., HAARBAUER-KRUPA, J., ZONFRILLO, M.R., BREIDING, M.J., MASTER, C.L. (2017). Improving Primary Care Provider Practices in Youth Concussion Management. Clinical Pediatrics, 56(9), 854–865.

BARTSCH, A., MIELE, V., ALBERTS, J.L. (2019). Estimates of High-Risk Single and Cumulative Head Impact Doses in American Football. Biomed Sci Instrum, 55(2), 224–229.

BARTSCH, A., SAMOREZOV, S., BENZEL, E., MIELE, V., BRETT, D. (2014). Validation of an "intelligent Mouthguard" Single Event Head Impact Dosimeter. Stapp Car Crash Journal, 58, 1–27.

BARTSCH, A.J., BENZEL, E.C., SAMOREZOV, S., MIELE, V.J. (2020). Summary of accurate and precise head impacts collected on-ice in hockey players and how these data will be used to improve equipment and rules for safer play. ASTM Special Technical Publication, STP 1625, 45–63.

BEVILACQUA, Z.W., HUIBREGTSE, M.E., KAWATA, K. (2019). In vivo protocol of controlled subconcussive head impacts for the validation of field study data. Journal of Visualized Experiments, 2019(146), 1–6.

BROGLIO, S.P., GUSKIEWICZ, K.M., SELL, T.C., LEPHART, S.M. (2004). No acute charges in postural control after soccer heading. British Journal of Sports Medicine, 38(5), 561–567.

CACCESE, J.B., BUCKLEY, T.A., TIERNEY, R.T., ROSE, W.C., GLUTTING, J.J., KAMINSKI, T.W. (2018). Sex and age differences in head acceleration during purposeful soccer heading. Research in Sports Medicine, 26(1), 64–74.

CACCESE, J.B., BUCKLEY, T.A., TIERNEY, R.T., ROSE, W.C., GLUTTING, J.J., KAMINSKI, T.W. (2021). Postural Control Deficits After Repetitive Soccer Heading. Clinical Journal of Sport Medicine, 31(3), 266–272.

CACCESE, J.B., KAMINSKI, T.W. (2016). Minimizing Head Acceleration in Soccer: A Review of the Literature. Sports Medicine, 46(11), 1591–1604.

CAPÓ-APONTE, J.E., BELTRAN, T.A., WALSH, D. V, COLE, W.R., DUMAYAS, J.Y. (2018). Validation of Visual Objective Biomarkers for Acute Concussion. Military Medicine, 183(suppl_1), 9–17.

CENTERS FOR DISEASE CONTROL AND PREVENTION (CDC). (2007). Nonfatal traumatic brain injuries from sports and recreation activities--United States, 2001-2005. MMWR. Morbidity and Mortality Weekly Report, 56(29), 733–737.

CORWIN, D.J., ARBOGAST, K.B., SWANN, C., HABER, R., GRADY, M.F., MASTER, C.L. (2020). Reliability of the visio-vestibular examination for concussion among providers in a pediatric emergency department. The American Journal of Emergency Medicine, 38(9), 1847–1853.

CORWIN, D.J., MCDONALD, C.C., ARBOGAST, K.B., MOHAMMED, F.N., GRADY, M.F., MASTER, C.L. (2021). Visio-Vestibular Deficits in Healthy Child and Adolescent Athletes. Clinical Journal of Sport Medicine, Online ahe.

CORWIN, D.J., MCDONALD, C.C., ARBOGAST, K.B., MOHAMMED, F.N., METZGER, K.B., PFEIFFER, M.R., PATTON, D.A., HUBER, C.M., MARGULIES, S.S., GRADY, M.F., MASTER, C.L. (2020). Clinical and Device-based Metrics of Gait and Balance in Diagnosing Youth Concussion. Medicine and Science in Sports and Exercise, 52(3), 542–548.

CORWIN, D.J., PROPERT, K.J., ZORC, J.J., ZONFRILLO, M.R., WIEBE, D.J. (2019). Use of the vestibular and oculomotor examination for concussion in a pediatric emergency department. The American Journal of Emergency Medicine, 37(7), 1219–1223.

DI VIRGILIO, T.G., HUNTER, A., WILSON, L., STEWART, W., GOODALL, S., HOWATSON, G., DONALDSON, D.I., IETSWAART, M. (2016). Evidence for Acute Electrophysiological and Cognitive Changes Following Routine Soccer Heading. EBioMedicine, 13, 66–71.

ELBIN, R.J., BEATTY, A., COVASSIN, T., SCHATZ, P., HYDEMAN, A., KONTOS, A.P. (2015). A Preliminary Examination of Neurocognitive Performance and Symptoms Following a Bout of Soccer Heading in Athletes Wearing Protective Soccer Headbands. Research in Sports Medicine, 23(2), 203–214.

HALSTEAD, M.E., WALTER, K.D., MOFFATT, K. (2018). Sport-Related Concussion in Children and Adolescents. Pediatrics, 142(6), e20183074.

HARAN, F.J., TIERNEY, R., WRIGHT, W.G., KESHNER, E., SILTER, M. (2013). Acute changes in postural control after soccer heading. International Journal of Sports Medicine, 34(4), 350–354.

HARRISS, A., JOHNSON, A.M., WALTON, D.M., DICKEY, J.P. (2019). Head impact magnitudes that occur from purposeful soccer heading depend on the game scenario and head impact location. Musculoskeletal Science and Practice, 40, 53–57.

HWANG, S., MA, L., KAWATA, K., TIERNEY, R., JEKA, J.J. (2016). Vestibular Dysfunction after Subconcussive Head Impact. Journal of Neurotrauma, 34(1), 8–15.

IVERSON, G. (2007). Predicting slow recovery from sport-related concussion: The new simple-complex distinction. Clinical Journal of Sport Medicine, 17(1), 31–37.

KAWATA, K., TIERNEY, R., PHILLIPS, J., JEKA, J.J. (2016). Effect of Repetitive Sub-concussive Head Impacts on Ocular Near Point of Convergence. International Journal of Sports Medicine, 37(5), 405–410.

LEDOUX, A.A., TANG, K., YEATES, K.O., PUSIC, M. V., BOUTIS, K., CRAIG, W.R., GRAVEL, J., FREEDMAN, S.B., GAGNON, I., GIOIA, G.A., OSMOND, M.H., ZEMEK, R.L. (2019). Natural Progression of Symptom Change and Recovery from Concussion in a Pediatric Population. JAMA Pediatrics, 173(1).

LIU, Y., DOMEL, A.G., YOUSEFSANI, S.A., KONDIC, J., GRANT, G., ZEINEH, M., CAMARILLO, D.B. (2020). Validation and Comparison of Instrumented Mouthguards for Measuring Head Kinematics and Assessing Brain Deformation in Football Impacts. Annals of Biomedical

Engineering, 48(11), 2580–2598.

MAINWARING, L., FERDINAND PENNOCK, K.M., MYLABATHULA, S., ALAVIE, B.Z. (2018). Subconcussive head impacts in sport: A systematic review of the evidence. International Journal of Psychophysiology, 132(Pt A), 39–54.

MANGUS, B.C., WALLMANN, H.W., LEDFORD, M. (2004). Analysis of postural stability in collegiate soccer players before and after an acute bout of heading multiple soccer balls. Sports Biomechanics, 3(2), 209–220.

MASTER, C.L., PODOLAK, O.E., CIUFFREDA, K.J., METZGER, K.B., JOSHI, N.R., MCDONALD, C.C., MARGULIES, S.S., GRADY, M.F., ARBOGAST, K.B. (2020). Utility of pupillary light reflex metrics as a physiologic biomarker for adolescent sport-related concussion. JAMA Ophthalmology, 138(11), 1135–1141.

MCINTOSH, A.S., PATTON, D.A., FRÉCHÈDE, B., PIERRÉ, P.A., FERRY, E., BARTHELS, T. (2014). The biomechanics of concussion in unhelmeted football players in Australia: A case-control study. BMJ Open, 4(5), 1–9.

MEANEY, D.F., SMITH, D.H. (2011). Biomechanics of concussion. Clinics in Sports Medicine, 30(1), 19–31, vii.

NELSON, L.D., GUSKIEWICZ, K.M., BARR, W.B., HAMMEKE, T.A., RANDOLPH, C., AHN, K.W., WANG, Y., MCCREA, M.A. (2016). Age differences in recovery after sport-related concussion: A comparison of high school and collegiate athletes. Journal of Athletic Training, 51(2), 142–152.

PREVENT BIOMETRICS. (2020). *Impact Monitor Mouthgaurd: Gen 1.3 Instructions for Use*. https://preventbiometrics.com/

PURKAYASTHA, S., STOKES, M., BELL, K.R. (2019). Autonomic nervous system dysfunction in mild traumatic brain injury: a review of related pathophysiology and symptoms. Brain Injury, 1–8.

RIEDER, C., JANSEN, P. (2011). No neuropsychological consequence in male and female soccer players after a short heading training. Archives of Clinical Neuropsychology, 26(7), 583–591.

ROBY, P.R., METZGER, K.B., MCDONALD, C.C., CORWIN, D.J., HUBER, C.M., PATTON, D.A., MARGULIES, S.S., GRADY, M.F., MASTER, C.L., ARBOGAST, K.B. (2021). Pre- And Post-season Visio-vestibular Function In Healthy Adolescent Athletes. The Physician and Sportsmedicine, 1–9.

SADY, M.D., VAUGHAN, C.G., GIOIA, G.A. (2014). Psychometric characteristics of the postconcussion symptom inventory in children and adolescents. Archives of Clinical Neuropsychology, 29(4), 348–363.

SCHEIMAN, M., GALLAWAY, M., FRANTZ, K.A., PETERS, R.J., HATCH, S., CUFF, M., MITCHELL, G.L. (2003). Nearpoint of convergence: Test procedure, target selection, and normative data. Optometry and Vision Science, 80(3), 214–225.

SCHMITT, D.M., HERTEL, J., EVANS, T.A., OLMSTED, L.C., PUTUKIAN, M. (2004). Effect of an acute bout of soccer heading on postural control and self-reported concussion symptoms. International Journal of Sports Medicine, 25(5), 326–331.

THIAGARAJAN, P., CIUFFREDA, K.J. (2015). Pupillary responses to light in chronic non-blast-induced mTBI. Brain Injury, 29(12), 1420–1425.

TRUONG, J.Q. (2016). Mild Traumatic Brain Injury (mTBI) and Photosensitivity: Objective Pupillometric Findings. In *State University of New York, College of Optometry*. http://hdl.handle.net/1951/67743

VAN DEN TILLAAR, R., MARQUES, M.C. (2009). Effect of two different training programs with the same workload on soccer overhead throwing velocity. International Journal of Sports Physiology and Performance, 4(4), 474–484.

WALLACE, C., SMIRL, J.D., ZETTERBERG, H., BLENNOW, K., BRYK, K., BURMA, J., DIERIJCK, J., WRIGHT, A.D., VAN DONKELAAR, P. (2018). Heading in soccer increases serum neurofilament light protein and SCAT3 symptom metrics. BMJ Open Sport and Exercise Medicine, 4(1), 3–7.

WIRSCHING, A., CHEN, Z., BEVILACQUA, Z.W., HUIBREGTSE, M.E., KAWATA, K. (2019). Association of Acute Increase in Plasma Neurofilament Light with Repetitive Subconcussive Head Impacts: A Pilot Randomized Control Trial. Journal of Neurotrauma, 36(4), 548–553.

WU, L.C., NANGIA, V., BUI, K., HAMMOOR, B., KURT, M., HERNANDEZ, F., KUO, C., CAMARILLO, D.B. (2016). In Vivo Evaluation of Wearable Head Impact Sensors. Annals of Biomedical Engineering, 44(4), 1234–1245.