Brain Tissue Strain During Adolescent Soccer Heading Using the Cloud-Based Brain Simulation Research Platform Finite Element Head Model

Colin M. Huber, Declan A. Patton, Kristy B. Arbogast, Reuben H. Kraft

Abstract The current study aimed to quantify the strain of the brain associated with soccer headers in adolescent athletes using a cloud-based finite element (FE) human head model. Eleven male and female participants aged 13–18 years completed 10 frontal or oblique soccer headers. Linear acceleration and angular velocity of the head were captured using the Prevent Biometrics boil-and-bite Impact Monitoring Mouthguard (IMM). Head kinematics time series were applied to the Brain Simulation Research Platform (BSRP) FE head model. Frontal headers resulted in significantly ($p<0.001$) higher mean peak linear acceleration (17.5±0.5 *g*) but significantly ($p<0.001$) lower mean peak angular acceleration (1142±45 rad/s^2) than oblique headers (12.3±0.4 *g*, 1431±66 rad/s^2). Frontal headers had similar peak MPS95 values compared to oblique headers (4.8±1.1% vs. 4.5±1.2%, $p=0.128$). Using equivalent loading conditions, frontal and oblique headers did not differ in peak MPS95 despite oblique headers having significantly higher angular kinematics, which is associated with brain tissue strains. Comparisons with previous results from a validated FE head model suggest that the BSRP FE head model has potential for simulating on-field head impact sensor data, especially considering the reduced computational time, but estimations of strain and model comparisons with more severe on-field sporting impacts are needed.

Keywords Cloud-based computing, finite element model simulation, head impact biomechanics, repetitive head loading, traumatic brain injury.

I. INTRODUCTION

Adolescents are especially vulnerable to head injury due to high participation in contact sports and experiencing longer recovery periods than adults following concussion [1]. There is growing concern for the neurological effects of repeated head impacts, and prior studies have shown immediate but transient deficits after repeated soccer heading [2]. Many studies have employed head kinematic sensors on athletes to measure head impact magnitude and direction in live sport and to capture concussion events [3]. However, kinematics data alone are limited and tissue-level metrics, such as strain, improve our understanding.

In vivo animal axonal stretch models have found that strains of at least 10% are required to cause electrophysiological functional deficits from a single stretch event [4]; however, *in vitro* repeated stretch events (x2) with strains as low as 0.5% have resulted in increased growth cone collapses [5]. Finite element (FE) modeling employs accurate anatomy and tissue properties to estimate brain tissue strains, providing a tool to evaluate tissue-level injury risk in humans without the invasive techniques only possible in controlled cadaveric or animal studies. For example, studies have applied head impact kinematics from multiple sports and activities, including soccer heading [6,7], roller coasters [8], and American football [9] to FE models in order to understand non-injurious strains in sport. Furthermore, previous studies have applied FE head models to compare non-injurious head acceleration events and concussion cases using tissue metrics such as maximum principal strain (MPS), showing that whole-brain 95th percentile MPS of 23% is representative of a 50% injury risk in American football cases in adult males [10]. Injury risk is also dependent on the direction of head loading, with many concussion cases occurring when primary contact was to the side of the head [11]. Additionally, in post-mortem human subjects (PMHS), axial rotations (transverse plane) created brain displacements 25% larger than coronal or sagittal rotations with equivalent head kinematics [12].

Current validated FE models of the brain vary by orders of magnitude in the number of elements to represent the head and brain from 15,000 to 2,000,000 [13]. Such models are designed to balance instabilities at extreme mesh densities, accurately capturing brain biomechanics, and computational requirements [14], with the

R. H. Kraft (e-mail: rhk12@psu.edu; tel: +1 814-867-4570) is a Professor at the Pennsylvania State University in University Park, PA, USA. C. M. Huber completed the research as a PhD candidate at the University of Pennsylvania and Center for Injury Research and Prevention (CIRP), Children's Hospital of Philadelphia (CHOP) in Philadelphia, PA, USA. D. A. Patton is a Senior Scientist at CIRP at CHOP, PA, USA. K. B. Arbogast is the Scientific Director of CIRP at CHOP and Professor at the University of Pennsylvania, PA, USA.

computational requirements and time increasing with mesh density. Current FE models are typically simulated using proprietary software (e.g., LS-DYNA) on individual head impacts, typically running overnight to accommodate long simulations times and maximize computational capacity. The commercial codes pose three challenges: restricted user access to the source code, general design for a wide range of problems, and paid subscription is required, limiting widespread use of computational brain biomechanics. However, with the growth and ease-of-use of cloud computing, there may be an opportunity to take advantage of open-source, freely available finite element codes for widescale brain computing.

On-site advanced computing can be expensive to maintain and requires substantial resources that are often only available to universities and researchers; however, increased offerings of high-performance computing instances in the cloud provide an alternative to run many simulations simultaneously. Cloud-based FE model platforms, such as the Brain Simulation Research Platform (BSRP) [15], allow a high-throughput of thousands of impact simulations simultaneously in less than an hour and for minimal cost. The BSRP is fully open source, maximizing transparency and has no software cost. Recently developed machine learning-based models have been used to rapidly predict strains based on prior FE model estimations with improving performance [16,17]; however, cloud-based models similarly calculate strains quickly while maintaining the underlying engineering principles of FE models.

The primary objective of the current study was to quantify the strain of the brain associated with frontal and oblique soccer headers in adolescent athletes using a cloud-based FE human head model, with a secondary objective to compare those brain strains to data generated by a FE human head model run on computing clusters.

II. METHODS

As part of a larger randomised controlled trial on the effects of soccer heading (NCT04810130) approved by the Children's Hospital of Philadelphia Institutional Review Board (IRB 20-017267) [18], 11 male and female participants (10 M, 1 F) aged 13–18 years completed 10 soccer headers. Specifically, participants completed 10 frontal (i.e. ball headed directly back to launch point) or oblique (i.e. ball redirected at a right-angle) headers performed with a size 5 soccer ball inflated to 0.83 bar projected using a ball launcher (JUGS Sports, Tualatin, OR) at 11.2 m/s over a distance of 10 m. Ball speeds prior to heading were confirmed via video analysis filmed from an orthogonal angle using Kinovea. Head kinematics were recorded with custom-fit boil-and-bite instrumented mouthguards, and kinematic traces were applied to a cloud-based FE model of the head and brain to estimate maximum principal strain.

Head Kinematics – Instrumented Mouthguard

Head kinematics were captured using the Prevent Biometrics, Inc. (Edina, MN) Impact Monitoring Mouthguard (IMM), which has shown good coupling to the skull and performance in validation testing with <10% average error [19–21]. A pre-made boil-and-bite IMM was individually fit to each participant. The IMM sensor comprised a triaxial linear accelerometer (ADXL372, Analog Devices, Boston, MA) and triaxial gyroscope (BMG250, Bosch, Gerlingen, Germany) measuring linear acceleration (± 200 *g* in each axis) and angular velocity (± 35 rad/s in each axis) at 3200 Hz for 50 ms (pre-trigger, 10 ms; post-trigger, 40 ms) when linear acceleration measured in any axis exceeded 5 *g* [22]. Data were filtered at 200 Hz with a 4th order Butterworth filter and transformed to the head centre of gravity of a 50th percentile male headform. The proprietary filtering algorithm from Prevent Biometrics was turned off, and instead, all sensor-recorded events were verified via rigorous video verification using time-stamped sensor and video data from three camera views (Sony HD Camcorder CX405, Sony Corporation, Tokyo, Japan) [18].

Cloud-Based Finite Element Head Model

Head kinematic time series were applied to the Brain Simulation Research Platform (BSRP) 50th percentile male FE coarse (17,030 elements) head model (Fig. 1), described fully in a prior publication [15]. The BSRP is a cloud-based model hosted at https://www.brainsimresearch.io and accesses parallel high-performance computing via Amazon Web Services to rapidly run hundreds of simulations simultaneously [15]. It uses AWS Cognito for robust access and security management, enabling connectivity via desktop, mobile, and API interfaces. The user interface, built with React.js, requires only a web browser to operate. The brain is modeled using an Ogden hyper-elastic model combined with a linear viscoelastic component, and the BSRP also has fully customized and automated post-processing specific for brain strain injury metrics. The BSRP was originally developed at The

Pennsylvania State University and has been validated using to cadaveric data and compared to other contemporary models [15]. As an open-source model, the in-depth verification and validation can also be found online (https://brainsimresearch.io/validation). The BSRP is capable of quasi-individual FE head models based on headshot images; however, the 50th percentile male version was used to match the kinematic transformation and consistency.

Statistical Analysis

The peak resultant linear acceleration, angular velocity, and angular acceleration were extracted for each header. The 95th percentile maximum principal strain (MPS95) was calculated for all brain elements at each timepoint, and the peak MPS95 was extracted. A two-sample t-test was used to compare frontal and oblique header kinematics and MPS95. A paired t-test was used to compare MPS95 within header direction to previous simulations using the Kungliga Tekniska högskolan (KTH) FE head model [6].

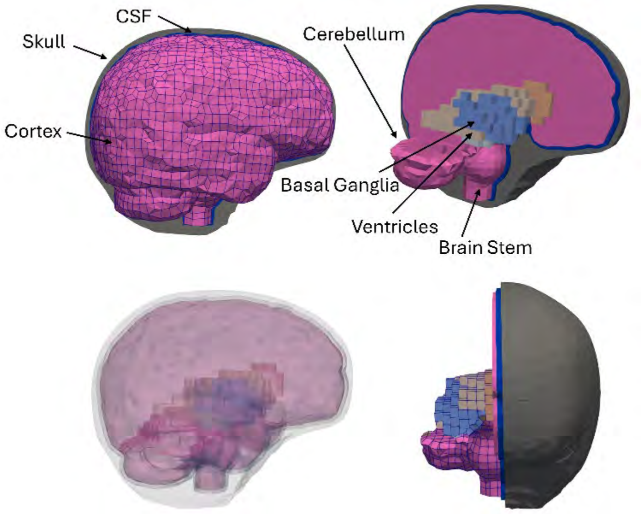

Fig. 1. The Brain Simulation Research Platform finite element coarse mesh finite element head model comprises 17,030 elements. The model can be freely downloaded from https://github.com/PSUCompBio/brain-meshing/tree/master/coarse_7-23-2020.

III. RESULTS

The head kinematics data from 99 soccer headers (57 frontal, 42 oblique) were verified by video review. Frontal headers resulted in significantly ($p < 0.001$) higher mean peak resultant linear acceleration (17.5 ± 0.5 *g*, Fig. 2) but significantly ($p < 0.001$) lower mean peak resultant angular acceleration (1142 ± 45 rad/s^2, Fig. 3) than oblique headers (12.3 ± 0.4 *g*, 1431 ± 66 rad/s^2). Oblique headers resulted in higher peak angular acceleration in the coronal and transverse planes while frontal headers resulted in higher angular acceleration the sagittal plane.

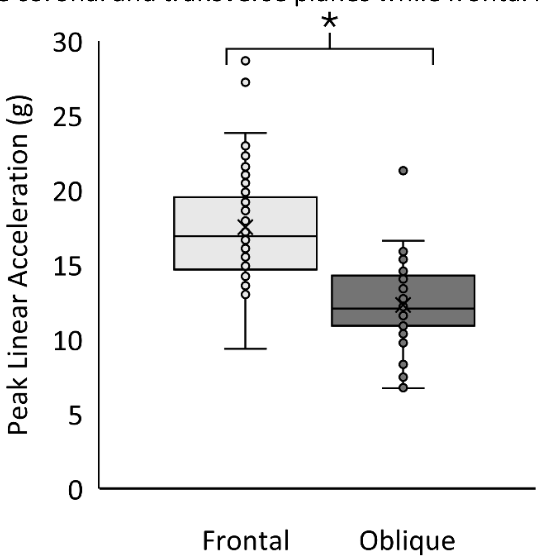

Fig. 2. Frontal headers had higher peak resultant linear acceleration than oblique (*p < 0.001).

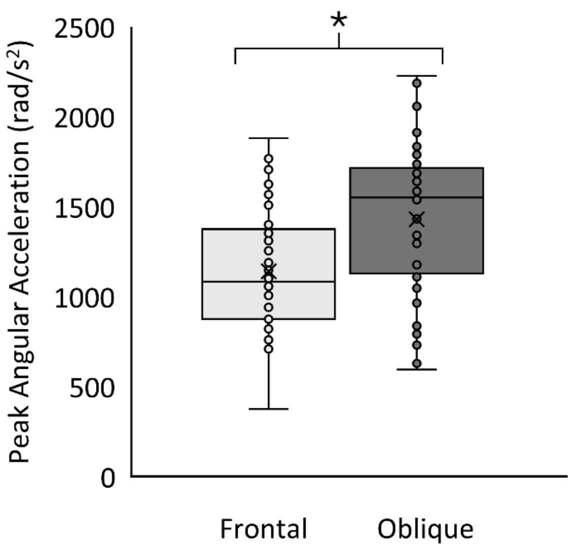

Fig. 3. Oblique headers had higher peak resultant angular acceleration than frontal headers (*p < 0.001).

The kinematics data for all video-verified soccer headers were simulated using the BSRP, and the mean coarse mesh model simulation time was 9.7 ± 0.3 minutes. Figure 4 displays mean MPS95 ± 95% confidence interval for the full simulation. Frontal headers had similar peak MPS95 values compared to oblique headers (Fig. 5, 4.8 ± 1.1% vs. 4.5 ± 1.2%, p = 0.128).

The MPS95 values of the oblique headers in the current study were not significantly different from the MPS95 values of the same soccer heading dataset previously simulated using the KTH FE model (4.5 ± 1.2% vs. 4.2 ± 1.3%, p = 0.390), an FE model run on computing clusters rather than the cloud [6]. However, peak MPS95 for frontal headers in the current study were significantly greater than those from the KTH FE model (4.8 ± 1.1% vs. 4.0 ± 0.9%, p<0.001).

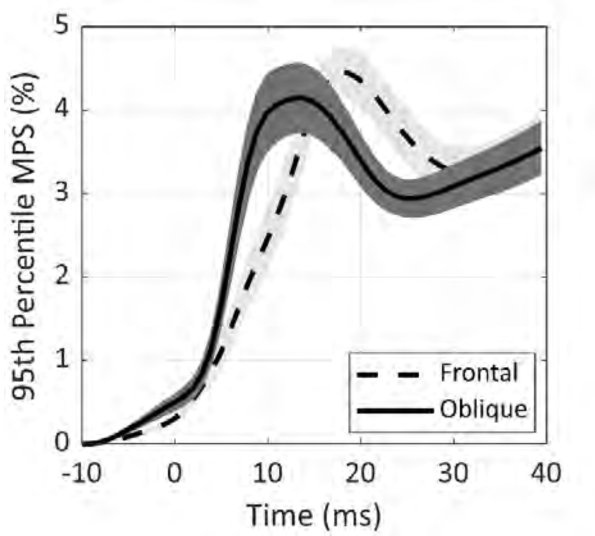

Fig. 4. 95th percentile MPS time series calculated by the BSRP presented as mean ± 95% confidence interval by header direction.

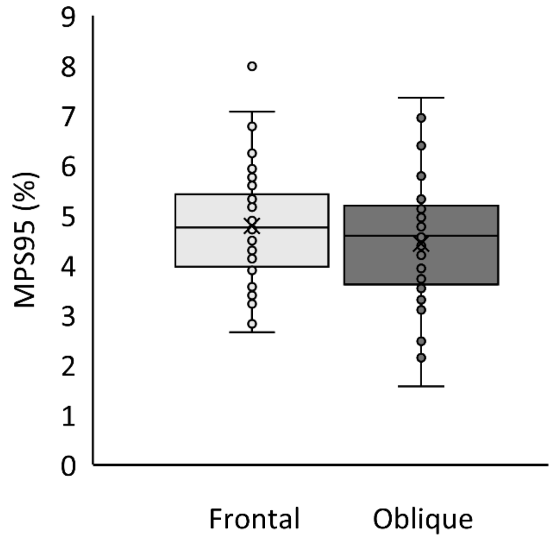

Fig. 5. Peak MPS95 calculated by the BSRP was not significantly different between frontal and oblique headers (p = 0.128).

IV. DISCUSSION

There is growing concern for the effects of repeated head loading, and soccer heading has led to transient neurophysiological deficits. The current study aimed to understand brain biomechanics in adolescent soccer heading in two distinct directions, using a cloud-based FE model that demonstrates improved computational efficiency compared to FE models run using proprietary solvers. For the same soccer ball launch speeds, frontal and oblique headers did not differ in peak MPS95. Oblique headers predominately loaded the head in the transverse axis, which has been shown previously to be associated with higher strains [12]. Oblique headers resulted in higher variability of peak MPS95, as expected, due to the additional skill required to execute an oblique header; therefore, while oblique headers on average may not result in higher average strains, the highest intensity oblique impacts may result in higher peak strains than those resulting from the highest intensity frontal impacts.

For both frontal and oblique directions, a single soccer header at speeds equivalent to an overhead throw-in was unlikely to cause injury as strains were below the FE model-calculated 50% concussion risk levels in American football [10] and Australian football and rugby (Table I) [23]. Similarly, in comparison to an *in vivo* rat spinal nerve axonal stretch model, strains in the current study were below the 50% risk of complete conduction block depending on strain rate [24]. The highest MPS95 in the current study was 8%. Therefore, substantially less than 5% of all brain elements reached 10% MPS. Further, MPS may not align with axonal tracts, so axonal strain is likely to be lower than MPS. These combined suggest a very small likelihood of a single header causing functional axonal deficits. However, FE models are currently unable to capture the potential biomechanical effects of repeated head impacts. Repetitive *in vitro* axonal stretch models with strains as low as 0.5% found functional deficits in axons [5]. Repeated soccer headers with strains up to 5% observed in this study may have the potential to lead to functional deficits based on a cumulative load, and future FE models should consider how repeated events may be simulated.

Recent studies have identified the limitation that peak MPS values from FE simulations are not always achieved during the time window of kinematics recorded by a head impact sensor [25,26]. Therefore, it is possible that the peak MPS occurred after the end of the recording and simulation (40 ms post-impact trigger) for a limited number of soccer headers. However, head impact durations in the current study were <20 ms [18], and the peak MPS predominately occurred in the first 25 ms post-trigger (84%).

Compared to prior simulations using the validated KTH FE head model [6,27,28], the BRSP FE model had similar MPS95 for oblique headers and had significantly but not substantially higher MPS95 in frontal headers. Small differences may be due to mesh density and resolution (KTH: ~4,000 brain elements vs. BRSP: 9,964 brain elements) or structural differences leading to sensitivity to rotation direction as only frontal headers (sagittal rotation) resulted in statistically significant differences. The KTH model simulations were run overnight (>10 hours) on LS-DYNA (R12.0.0, Ansys, Canonsburg, PA, USA) using a double precision solver either serially on a single computer (4 cores, 16 GB RAM) or in groups of 10 on private high-performance computing clusters (16 cores). In the current study, all 99 simulations were run in parallel on the cloud-based BRSP with no software costs, and all were completed in approximately a total of 10 minutes. The platform was designed for rapid, high-throughput simulation for easier and rapid access to biomechanical tissue metrics of injury. Based on the rapid simulation time and good agreement with validation datasets and prior FE models, the cloud-based BRSP showed potential for increasing the use of FE head models to better understand head impact biomechanics.

TABLE I
STRAIN-BASED INJURY RISK IN LITERATURE

Study	Species	Injury Type	Injury Measure	FE Head Model	Sport	Strain Measure and Risk Level	Strain Injury Threshold
Fahlstedt *et al.* [10]	Human	Concussion ATD reconstruction	Concussion Diagnosis	KTH	Male American football	95% MPS 50% injury risk	Whole Brain: 23%
Patton *et al.* [23]	Human	Concussion Rigid body reconstructions	Concussion Diagnosis	KTH	Male Australian Football and Rugby	Maximum MPS 50% injury risk	Thalamus: 13% CC: 15% WM: 26%
Oeur *et al.* [29]	Human	Concussion ATD reconstruction	Concussion Diagnosis	UCDBTM	Male and Female Ice Hockey	Maximum MPS range	Whole brain: 19–61%
Singh *et al*. [24]	Rat *in vivo*	Axonal stretch	Axon conduction block	-	-	Axonal Strain 50% injury risk	9–16% for strain rates 0.01 -15 mm/s
Bain and Meaney [4]	Guinea pig *in vivo*	Axonal stretch	Functional VEP deficit	-	-	Axonal Strain 25% injury risk	18%
Yap *et al.* [5]	Rat *in vitro*	Axonal stretch (x2)	Axon growth cone collapse	-	-	Axonal Strain	0.5%

ATD: anthropomorphic test device. CC: corpus callosum. FE: finite element. KTH: Kungliga Tekniska Högskolan Head Model. MPS: maximum principal strain. UCDBTM: University College Dublin Brain Trauma Model. VEP: visual evoked potential. WM: white matter.

V. CONCLUSION

For the same soccer ball launch speeds and using a cloud-based high-throughput FE model, frontal and oblique headers did not differ in peak MPS95 despite oblique headers having significantly higher angular kinematics, which is associated with brain tissue strains. Comparisons with previous results from another validated FE head model suggest that the BSRP FE head model has potential utility for simulating on-field head impact sensor data, especially considering the reduced computational time. MPS95 from oblique headers showed no differences between the BSRP and KTH FE models. Frontal headers showed a significant but relatively small difference between the BSRP and KTH models. Future work should continue to simulate and estimate strain on more severe on-field sporting impacts using the BSRP and other FE models.

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