



Head impact magnitudes that occur from purposeful soccer heading depend on the game scenario and head impact location

Alexandra Harriss^a, Andrew M. Johnson^{a,b}, David M. Walton^{b,c}, James P. Dickey^{d,*}

^a Health and Rehabilitation Sciences, The University of Western Ontario, London, Ontario, Canada

^b School of Health Studies, The University of Western Ontario, London, Ontario, Canada

^c School of Physical Therapy, The University of Western Ontario, London, Ontario, Canada

^d School of Kinesiology, The University of Western Ontario, London, Ontario, Canada

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ABSTRACT

Purpose: This study quantified the linear and angular kinematics that result from purposeful heading during youth soccer games, and the influence of game scenario and head impact location on these magnitudes.

Method: This observational study recruited thirty-six female soccer players (13.4 ± 0.9 years old) from three elite youth soccer teams (U13, U14, U15) and followed for an entire soccer season. Players wore wireless sensors during each game to quantify head impact magnitudes. A total of 60 regular season games (20 games per team) were video recorded, and purposeful heading events were categorized by game scenario (e.g. throw in), and head impact location (e.g. front of head).

Results: Game scenario had a statistically significant effect on the linear head acceleration, and rotational head velocity, that resulted from purposeful headers. Rotational velocity from purposeful headers varied significantly between head impact locations, with impacts to the top of the head (improper technique) resulting in larger peak rotational velocities than impacts to the front of the head (proper technique); this was also the case for the linear acceleration for punts.

Conclusion: Our findings suggest that the magnitude for both linear and angular head impact kinematics depend on the game scenario and head impact location. Headers performed with the top of the head (improper technique) result in larger rotational velocities compared to the front of the head (proper technique). Accordingly, youth players should be educated on how to execute proper heading technique to reduce head impact accelerations.

1. Introduction

The potential for long-term neurological impairment resulting from repetitive head impacts is a concern for athletes participating in contact and collision sports such as ice hockey, rugby, and American football (Breedlove et al., 2012; Poole et al., 2015). Emerging evidence also shows neurocognitive effects associated with purposeful soccer heading (Lipton et al., 2013; Moore et al., 2016; Mussack et al., 2003; Zhang et al., 2013). Observational research has determined that under-14 youth female soccer players can perform up to nine purposeful headers during a single soccer game, and can accumulate more than 50 purposeful headers during a soccer season (Harriss et al., 2018b). While the cumulative linear and rotational head impact accelerations experienced by collegiate players (Caccese et al., 2018c) are greater than that of high-school players (McCuen et al., 2015), the developing brains of

younger players (Paus, 2010) may be more vulnerable to neurological impairments, even at lower head impact accelerations and cumulative loads.

In 2016 the United States Soccer Federation announced the Recognize to Recover program to limit the number of purposeful headers that youth players perform (USAClubSoccer, 2016; Yang and Baugh, 2016). This initiative bans heading for players younger than ten years old, and limits the number of headers that players aged 11–13 can perform during practices. These thresholds for safe headers were defined through expert consensus rather than empirical evidence, raising questions as to their appropriateness for preventing neurocognitive problems. Other leagues have used data-driven models to reduce the incidence of impacts during sport (Black et al., 2016; Ruestow et al., 2015). For example, the number of head impacts that collegiate American football players experience during practices is limited by

* Corresponding author. The University of Western Ontario, School of Kinesiology, 1151 Richmond Street, 3M Centre, Room 3159A, London, Ontario, N6A 3K7 Canada.

E-mail address: jdickey@uwo.ca (J.P. Dickey).

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imposing practices with no equipment, and enforcing that no tackling occurs during these practices (Reynolds et al., 2016). We cannot create empirically-derived guidelines for this vulnerable population without such data for youth soccer.

Several studies have quantified the magnitude of head impact accelerations during soccer games (Caccese et al., 2016; Lynall et al., 2016; Press and Rowson, 2017) though few have fully characterized these head impacts as far as their context is concerned. For example, one study evaluating female collegiate soccer players revealed that purposeful headers occurring from common maneuvers such as “shots” and “clears” result in larger linear head accelerations compared to “passes” (Lamond et al., 2018); however, it did not report rotational head accelerations that may be a better predictor of neurological consequences of repetitive head impacts (Rowson et al., 2012). Most such work has been conducted on adult collegiate players (Caccese et al., 2016, 2018c; Lynall et al., 2016; McCuen et al., 2015; Naunheim et al., 2003; Press and Rowson, 2017; Shewchenko et al., 2005), and youth players have been relatively understudied (Chrisman et al., 2016; Hanlon and Bir, 2012).

Purposeful headers account for the majority of impacts sustained by female youth soccer players during scrimmages, and result in large peak linear and rotational accelerations (4.5–62.9 g and 444.8–8869.1 rad/s², respectively) (Dorminy et al., 2015). Other work has quantified youth head impacts during weekend soccer tournaments and report similar impact magnitudes (Chrisman et al., 2016). Youth players have reduced head mass and neck strength, compared to adults, which may lead to larger head accelerations with impact (Collins et al., 2014; Eckner et al., 2014). One group revealed that female high school soccer players showed moderate, consistent negative correlations between neck strength (flexion, extension, left lateral flexion, and right lateral flexion) and resultant linear head acceleration in header drills (Gutierrez et al., 2014). Other work indicates greater head size and neck strength are associated with lower peak linear and rotational accelerations (Caccese et al., 2018a), while sex and age may not influence head impact accelerations (Caccese et al., 2018b). Cellular, structural, and metabolic changes (Kawata et al., 2016), as well as neurocognitive outcome measures such as, verbal learning (Janda et al., 2002) are also critical components to understanding impairment that results from heading. Although the number of headers alone is unlikely to be enough to fully understand the risk of purposeful heading, the game scenario in which the header occurred may also influence the head impact magnitude. For example, “punts” and “goal kicks” result in significantly larger head accelerations than “kicks” (Caccese et al., 2016). Laboratory (Shewchenko et al., 2005), and on-field (Hanlon and Bir, 2012), studies reveal that head impact location influences the magnitude of linear and rotational head accelerations that result from purposeful soccer heading. Accordingly, to fully understand the linear and rotational head accelerations that result from purposeful heading in youth soccer, game scenario and head impact location may provide valuable information for developing informed guidelines in youth soccer.

The purpose of this study was to quantify the linear and angular head kinematics that result from purposeful heading during youth soccer games, and to determine whether the magnitude of these head impacts are influenced by the game scenario and head impact location. Consistent with previous work (Hanlon and Bir, 2012; Shewchenko et al., 2005; Self et al., 2016; Caccese et al., 2016) it is hypothesized that purposeful headers occurring from punts will result in the largest linear head accelerations, and that purposeful headers occurring from corner kicks will result in the largest rotational velocity. Furthermore, we hypothesize that purposeful headers performed with the top of the head will result in larger head accelerations compared to the front or side of the head.

2. Materials and methods

2.1. Participants

This observational study recruited a convenience sample of 36 female soccer players (13.4 (SD 0.9) years old, 1.6 (SD 0.1) m, 50.6 (SD 8.7) kg) from three elite youth soccer teams (U13, U14, U15) participating in the Ontario Player Development League (OPDL). Players competed in one game per week during their soccer season. Players also participated in weekly practices; however, these data were not recorded. Written informed consent from parents and written informed assent from players was obtained prior to participation. This study was approved by the Health Sciences Research Ethics Board at the University of Western Ontario.

2.2. Instrumentation

Head impacts for each game were recorded using wireless sensors (GForce Tracker (GFT2), Artaflex Inc., Markham, Ontario, Canada) at the back of the head that were secured with a headband, similarly to other work (Caccese et al., 2016; Gutierrez et al., 2014). The GForce Tracker sensors contains a tri-axial accelerometer and a tri-axial gyroscope that measure linear acceleration, and rotational velocity, respectively. The sensors triggered when head impacts exceeded a linear acceleration of 7 g, as preliminary data measured prior to the soccer season indicated that purposeful header impacts can be as low as 8 g. The devices recorded 8 ms of data preceding the threshold and 32 ms of the data following the threshold. Linear accelerations were sampled at 3000 Hz, and filtered through an onboard analog low-pass filter with a cutoff frequency of 300 Hz. Rotational velocity was sampled at 800 Hz, and low pass filtered with a cutoff frequency of 100 Hz. All data were time stamped and stored on the sensors’ onboard memory. Although some researchers have incorporated a rigid body kinematic transformation to predict the accelerations at the center of mass of the head (Caccese et al., 2016, 2018b), we report impact measurements based on sensor data, similarly to some other researchers (Diakogeorgiou and Miyashita, 2018; Gutierrez et al., 2014; Muise et al., 2016). Following each game, head impact data were uploaded to a cloud-based server. Peak linear acceleration, and peak rotational velocity for each head impact were extracted for further analysis.

2.3. Study protocol

A total of 60 regular season games (20 games per team) were recorded using a Sony Vixia HD camera that mounted to a telescoping system (EVS25, Endzone Video Systems, Sealy, Texas, United States). Game video was uploaded to a video analysis software program (dba HUDL, Agile Sports Technologies Inc., Lincoln, Nebraska, United States). An appointed researcher matched each purposeful header from the video with the associated peak linear acceleration and peak rotational velocity collected from the sensor. One rater was deemed appropriate for this analysis based on previous work (Harriss et al., 2018b). The appointed researcher also categorized heading events by game scenario (Table 1) as well as head impact location: front, top, back, and side of the head.

2.4. Data analysis

Descriptive statistics for peak linear acceleration and peak rotational velocity are reported as mean and standard deviation. Both linear acceleration and rotational velocity were evaluated using a linear mixed effects model to test whether the game scenario and head impact location predicted head impact magnitude resulting from purposeful heading. Game scenario (pass, shots, free kick, corner, deflection, goal kick, punt, throw-in), and head impact location (top, front, side, back) were entered as fixed effects. Individual differences and game

Table 1
Description of game scenario.

Header Context	Description of game scenario
Corner Kick	A stationary kick taken from the corner of the field after the ball crossed behind the goal line by the defending team
Punt	Kick made by goalie by dropping the ball from the hands and kicking it before it touches the ground. Also called a drop kick by some researchers
Free Kick	Kick from a stationary ball awarded to one team as a penalty for a foul by the opposition
Throw-on	Player throwing the ball in from the sideline
Deflection	Ball was deflected off another player or body location before a header occurred
Pass in Air	Ball was kicked into the air by a player
Shot	Ball was kicked by a player towards the goal by opposing player to score a goal and the defending team headed the ball.

differences were modelled as random effects. To determine the model of best fit, four separate models were tested: null hypothesis, game scenario by head impact location interactions, including their main effects. All statistical analyses were carried out using R (Team, 2016) with linear mixed effects models evaluated using lme4 (Bates et al., 2014) and lmerTest (Kuznetsova et al., 2016). Effect sizes can be misleading and inaccurate when using linear mixed effect modelling, (Bates et al., 2014) and are therefore not reported. Statistical significance was defined using a threshold of 0.05.

3. Results

A total of 434 purposeful headers were identified from video analysis with matching events recorded with microsensors. Overall, the mean linear head acceleration experienced by players was 18.8 (SD 10.2) g, and the mean rotational velocity was 1039.0 (SD 571.3) °/s. The majority of purposeful headers occurred from passes in the air and throw-ins (Table 2). On average, purposeful headers that occurred from shots resulted in the largest linear head acceleration, while corner kicks resulted in the largest rotational velocity (Table 2). In terms of head impact location, headers that occurred on the top of the head resulted in the largest linear acceleration and rotational velocity (Table 3). Most purposeful headers were performed by players using the front of their head. No purposeful headers occurred using the back of the head, and therefore this header location was not considered in the statistical analyses.

The mixed effects model evaluating linear acceleration revealed that game scenario had a statistically significant effect on the linear acceleration that resulted from purposeful headers, compared to the null model [χ^2 (Caccese et al., 2018c) = 37.97, $p = 0.0001$]. Headers that occurred from passes in the air resulted in larger linear head accelerations as compared to deflections [$t(417.79) = -3.88$, $p = 0.0001$], and smaller linear head accelerations as compared to shots [$t(426.93) = 3.70$, $p = 0.002$]. There were no other statistically significant findings for game scenario. Head impact location did not significantly influence linear head accelerations [χ^2 (Black et al., 2016) = 1.81, $p = 0.40$]. There was a statistically significant interaction between head impact location and game scenario on linear head acceleration, since the interaction model fit the data significantly better than the main effects model [χ^2 (Chrisman et al., 2017) = 20.10, $p = 0.02$]. Punts resulted in significantly larger linear head

Table 2
Linear acceleration and rotational velocity resulting from different game scenarios.

Game Scenario	Frequency (%)	Linear Acceleration (g)	Rotational Velocity (°/s)
Pass in air	179 (41%)	19.74 ± 10.86	1098.29 ± 590.95
Throw In	129 (30%)	17.33 ± 6.67	959.22 ± 488.34
Deflection	43 (10%)	12.55 ± 4.02	793.87 ± 521.58
Punt	35 (8%)	20.40 ± 16.14	1021.34 ± 614.82
Shot	20 (5%)	27.35 ± 13.11	1202.30 ± 497.81
Goal Kick	16 (4%)	20.11 ± 6.88	1206.75 ± 765.43
Corner	12 (2%)	22.92 ± 7.21	1447.42 ± 589.80

Table 3

Linear acceleration and rotational velocity resulting from different head impact locations.

Head Impact Location	Frequency	Linear acceleration (g)	Rotational velocity (°/s)
Front	277	18.35 ± 8.50	951.88 ± 550.52
Top	137	19.69 ± 12.23	1215.44 ± 588.56
Side	20	19.41 ± 14.89	1037.66 ± 469.62
Back	0	n/a	n/a

accelerations when completed with the top of the head compared to the front of the head [$t(410.26) = 3.34$, $p = 0.001$].

The mixed effects model evaluating rotational velocity indicated that game scenario had a statistically significant effect on the rotational velocity that resulted from purposeful headers [χ^2 (Caccese et al., 2018c) = 20.84, $p = 0.002$]. Passes in the air resulted in significantly larger rotational head velocities compared to deflections [$t(419.58) = 3.20$, $p = 0.001$] and throw-ins [$t(425.98) = 2.18$, $p = 0.03$]. Furthermore, the rotational head velocity from purposeful headers varied significantly between head impact locations [χ^2 (Black et al., 2016) = 18.15, $p = 0.0001$]. Purposeful headers that occurred at the top of the head resulted in larger rotational velocities compared to the front of the head [$t(429.49) = 4.30$, $p = 0.0001$]. There was no statistically significant difference in rotational velocity between purposeful headers that occurred at the front of the head compared to the side of the head [$t(430.35) = 0.54$, $p = 0.59$]. The game scenario did not significantly influence the rotational head velocity for the different head impact locations [interaction not statistically significant: χ^2 (Chrisman et al., 2017) = 8.89, $p = 0.45$].

4. Discussion

While the United States Soccer Federation implemented heading guidelines with the intent of reducing youth heading exposure [33], there is relatively little information about linear and angular heading kinematics for this age group (Chrisman et al., 2016, 2017; Hanlon and Bir, 2012). Understanding the frequency, magnitude and on-field characteristics of purposeful heading will provide valuable information to soccer federations to develop data-driven models designed to limit youth cumulative heading exposure. We observed that head impact location affected head impact magnitudes; purposeful headers occurring on the top of the head result in larger rotational velocities compared to the front of the head. When considering both game scenario and head impact location, we found that purposeful headers occurring from punts completed with the top of the head had the largest linear head acceleration magnitudes. However, this relationship was not maintained for rotational head velocity where there was no interaction between game scenario and head impact location.

The head impact accelerations experienced by the youth soccer players in our study were comparable to earlier work that quantified purposeful headers during youth soccer scrimmages (Hanlon and Bir, 2012) and games (Chrisman et al., 2016, 2017); however, these studies did not categorize headers by the soccer game scenario. This

component of soccer heading is important as we observed that there were significant differences in impact magnitudes between the various game scenarios. For example, we observed that purposeful headers occurring from deflections result in reduced linear head acceleration and rotational head velocity compared to passes in the air. Such differences in head impact magnitude between the various game scenarios were likely due to varying ball velocities in these situations. For example, controlled laboratory testing has revealed that headers performed with soccer balls projected at 13.4 m/s result in smaller head impact accelerations compared to 22.4 m/s (30.6 ± 6.2 g vs. 50.7 ± 7.7 g, respectively) (Dorminy et al., 2015). As well, soccer ball velocity is reduced when the ball bounces from the ground, or off another player (i.e. deflections), which would lead to a smaller head impact acceleration compared to a pass in the air or goal kick.

One research study suggests that limiting purposeful headers from punts and goal kicks could help reduce the cumulative load of heading in female collegiate soccer (Caccese et al., 2016); however, our findings indicate this strategy may not be effective for youth age groups. Punts and goal kicks occurred infrequently in our study, and therefore do not add substantially to the cumulative heading load experienced by youth players. Passes in the air accounted for the greatest proportion (41%) of purposeful headers performed by youth players, and shots were the only game scenario that resulted in larger head impact acceleration magnitudes. Passing the ball on the ground, rather than in the air could help reduce the number of recorded headers in this study sample by as much as 41%.

Previous work also indicates that repetitive long-range headers, can negatively influence cognitive functions. For example, soccer players who perform a greater number of long-range headers have slower reaction times on pointing tasks compared to players with fewer long-range headers (Koerte et al., 2017). However, other work shows no negative changes in computerized neurocognitive functioning among both male and female youth soccer players (Kontos et al., 2011). It is possible that repetitive exposure to specific purposeful headers, such as long-range kicks, may be more likely to impair cognitive functioning in youth soccer players. Accordingly, limiting the number of purposeful headers that youth players perform from long-range passes in the air could reduce their overall heading exposure.

Previous work has identified differences between head impact location and the magnitude of head impact accelerations in female youth soccer players (Hanlon and Bir, 2012). Our findings demonstrate that purposeful headers performed using the top of the head result in larger rotational velocities compared to the front of the head, while headers performed using the side of the head did not influence rotational head velocity magnitude compared to the front of the head. These results indicate that players should be trained to execute proper heading technique, impacting the ball with the front of their heads, as this reduces the magnitude of the linear head impact accelerations. In contrast, improper heading technique (i.e. headers performed with the top of the head) can result in larger rotational velocities as well as shear forces (Elkin et al., 2018). These findings support US Soccer's stance that reducing overall head impact exposure in soccer, rather than only concussive impacts, is an important aspect of policy development and player safety (Yang and Baugh, 2016).

There are some limitations to the current study that should be acknowledged. The impact magnitudes in this paper are based on sensor data rather than predictions for the head center of mass. This study only quantified head impact accelerations for female youth soccer players during soccer games, and not practices. This study provides meaningful data about purposeful heading for a population that is notably absent in head injury literature; however, we cannot make any comparisons between sexes or different soccer leagues/calibers. Recent findings suggest that heading may cause greater head injury in female soccer players compared to males (Rubin et al., 2018), and accordingly these findings are pertinent to this at-risk population. The data presents both the linear and angular head impact kinematics for different game

scenarios and head impact locations, but we do not report head impact exposure per player. A comparison paper presents information on the different game scenarios and head impact location per player for purposeful headers (Harriss et al., 2018a). Our study only quantified impacts that resulted from purposeful headers, and did not consider non-header impacts. Non-header impacts occur infrequently compared to purposeful heading events (Lamond et al., 2018), and therefore may not substantially contribute to overall head impact exposure. However, unintentional headers may pose a greater risk of CNS symptoms than intentional headers (Stewart et al., 2017). It is important to recognize that non-header impacts, such as player to player contact, would be a separate focus for rule changes compared to intentional heading.

Our findings show that purposeful heading in female youth soccer is a common activity, that occurs from various game scenarios, but predominately passes in the air and throw-ins. While similar impact magnitudes were recorded from each of the various scenarios, limiting headers from passes in the air could help reduce youth heading exposure by up to 41%. Furthermore, while most headers were performed using the front of the head, players still use the top of their head for almost one-third of purposeful headers. This is a concern because the rotational head velocity was larger for headers performed with the top of the head compared to the front of the head. Coaching strategies should focus on methods for limiting the number of headers that players perform, perhaps by encouraging players to avoid heading passes in the air, but also educate players on heading technique to reduce cumulative heading burden.

Ethics approval

This study was approved by the Health Sciences Research Ethics Board at the University of Western Ontario.

Conflicts of interest

There are no conflicts of interest to disclose.

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References

- Bates, D., Mächler, M., Bolker, B., Walker, S., 2014. Fitting linear mixed-effects models using lme4. *J. Stat. Software* 67 (1), 1–48.
- Black, A.M., Macpherson, A.K., Hagel, B.E., et al., 2016. Policy change eliminating body checking in non-elite ice hockey leads to a threefold reduction in injury and concussion risk in 11- and 12-year-old players. *Br. J. Sports Med.* 50 (1), 55–61. <https://doi.org/10.1136/bjsports-2015-095103>.
- Breedlove, E.L., Robinson, M., Talavage, T.M., et al., 2012. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J. Biomech.* 45 (7), 1265–1272. <https://doi.org/10.1016/j.jbiomech.2012.01.034>.
- Caccese, J.B., Buckley, T.A., Tierney, R.T., et al., 2018a. Head and neck size and neck strength predict linear and rotational acceleration during purposeful soccer heading. *Sports BioMech.* 17 (4), 462–476. <https://doi.org/10.1080/14763141.2017.1360385>.
- Caccese, J.B., Buckley, T.A., Tierney, R.T., Rose, W.C., Glutting, J.J., Kaminski, T.W., 2018b. Sex and age differences in head acceleration during purposeful soccer heading. *Res. Sports Med.* 26 (1), 64–74. <https://doi.org/10.1080/15438627.2017.1393756>.
- Caccese, J.B., Lamond, L.C., Buckley, T.A., Glutting, J., Kaminski, T.W., 2018c. Linear acceleration in direct head contact across impact type, player position, and playing scenario in collegiate women's soccer. *J. Athl. Train.* 53 (2), 115–121. <https://doi.org/10.4085/1062-6050-90-17>.

- Caccese, J.B., Lamond, L.C., Buckley, T.A., Kaminski, T.W., 2016. Reducing purposeful headers from goal kicks and punts may reduce cumulative exposure to head acceleration. *Res. Sports Med.* 24 (4), 407–415. <https://doi.org/10.1080/15438627.2016.1230549>.
- Chrisman, S., Mac Donald, C., Friedman, S., et al., 2016. Head impact exposure during a weekend youth soccer tournament. *J. Child Neurol.* 31 (8), 971–978. <https://doi.org/10.1177/08830738166634857>.
- Chrisman, S.P.D., Ebel, B.E., Steiny, E., Lowry, S.J., Rivara, F.P., 2017. Head impact exposure in youth soccer and variation by age and sex. *Clin. J. Sport Med.* <https://doi.org/10.1097/JSM.0000000000000497>.
- Collins, C.L., Fletcher, E.N., Fields, S.K., et al., 2014. Neck strength: a protective factor reducing risk for concussion in high school sports. *J. Prim. Prev.* 35 (5), 309–319. <https://doi.org/10.1007/s10935-014-0355-2>.
- Diakogeorgiou, E., Miyashita, T.L., 2018. Effect of head impact exposures on changes in cognitive testing. *Orthop J Sports Med* 6 (3) 2325967118761031. <https://doi.org/10.1177/2325967118761031>.
- Dorminy, M., Hoogeven, A., Tierney, R.T., Higgins, M., McDevitt, J.K., Kretzschmar, J., 2015. Effect of soccer heading ball speed on S100B, sideline concussion assessments and head impact kinematics. *Brain Inj.* 29 (10), 1158–1164. <https://doi.org/10.3109/02699052.2015.1035324>.
- Eckner, J.T., Oh, Y.K., Joshi, M.S., Richardson, J.K., Ashton-Miller, J.A., 2014. Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *Am. J. Sports Med.* 42 (3), 566–576. <https://doi.org/10.1177/0363546513517869>.
- Elkin, B.S., Gabler, L.F., Panzer, M.B., Siegmund, G.P., 2018. Brain tissue strains vary with head impact location: a possible explanation for increased concussion risk in struck versus striking football players. *Clin. Biomech.* <https://doi.org/10.1016/j.clinbiomech.2018.03.021>.
- Gutierrez, G.M., Conte, C., Lightbourne, K., 2014. The relationship between impact force, neck strength, and neurocognitive performance in soccer heading in adolescent females. *Pediatr. Exerc. Sci.* 26 (1), 33–40. <https://doi.org/10.1123/pes.2013-0102>.
- Hanlon, M., Bir, A., 2012. Real-time head acceleration measurement in girls' youth soccer. *Med. Sci. Sports Exerc.* 44 (6), 1102–1108. <https://doi.org/10.1249/MSS.0b013e3182444d7d>.
- Harriss, A., Walton, D.M., Dickey, J.P., 2018a. The number of purposeful headers female youth soccer players experience during games depends on player age but not player position. *Sci. Med. Football In Press.* <https://doi.org/10.1080/24733938.2018.1506591>.
- Harriss, A., Walton, D.M., Dickey, J.P., 2018b. Direct player observation is needed to accurately quantify heading frequency in youth soccer. *Res. Sports Med.* 26 (2), 191–198. <https://doi.org/10.1080/15438627.2018.1431534>.
- Janda, D.H., Bir, C.A., Cheney, A.L., 2002. An evaluation of the cumulative concussive effect of soccer heading in the youth population. *Int. J. Inj. Contr. Saf. Promot.* 9 (1), 25–31. <https://doi.org/10.1076/icsp.9.1.25.3324>.
- Kawata, K., Liu, C.Y., Merkel, S.F., Ramirez, S.H., Tierney, R.T., Langford, D., 2016. Blood biomarkers for brain injury: what are we measuring? *Neurosci. Biobehav. Rev.* 68, 460–473. <https://doi.org/10.1016/j.neubiorev.2016.05.009>.
- Koerte, K., Nichols, E., Tripodis, Y., et al., 2017. Impaired cognitive performance in youth athletes exposed to repetitive head impacts. *J. Neurotrauma* 34 (16), 2389–2395. <https://doi.org/10.1089/neu.2016.4960>.
- Kontos, A.P., Dolese, A., Elbin, R.J., Covassin, T., Warren, B.L., 2011. Relationship of soccer heading to computerized neurocognitive performance and symptoms among female and male youth soccer players. *Brain Inj.* 25 (12), 1234–1241. <https://doi.org/10.3109/02699052.2011.608209>.
- Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2016. *Imertest: Tests in Linear Mixed Effects Models R Package Version 2.0-33*.
- Lamond, L.C., Caccese, J.B., Buckley, T.A., Glutting, J., Kaminski, T.W., 2018. Linear acceleration in direct head contact across impact type, player position, and playing scenario in collegiate women's soccer players. *J. Athl. Train.* 53 (2), 115–121. <https://doi.org/10.4085/1062-6050-90-17>.
- Lipton, M.L., Kim, N., Zimmerman, M., et al., 2013. Soccer heading is associated with white matter microstructural and cognitive abnormalities. *Neuroradiology* 268 (3), 850–857. <https://doi.org/10.1148/radiol.13130545>.
- Lynall, R.C., Clark, M.D., Grand, E.E., et al., 2016. Head impact biomechanics in women's college soccer. *Med. Sci. Sports Exerc.* 48 (9), 1772–1778. <https://doi.org/10.1249/MSS.0000000000000951>.
- McCuen, E., Svaldi, D., Breedlove, K., et al., 2015. Collegiate women's soccer players suffer greater cumulative head impacts than their high school counterparts. *J. Biomech.* 48 (13), 3720–3723. <https://doi.org/10.1016/j.jbiomech.2015.08.003>.
- Moore, R.D., Lepine, J., Elleberg, D., 2017. The independent influence of concussive and sub-concussive impacts on soccer players' neurophysiological and neuropsychological function. *Int. J. Psychophysiol.* 112, 22–30. <https://doi.org/10.1016/j.ijpsycho.2016.11.011>.
- Muise, D.P., MacKenzie, S.J., Sutherland, T.M., 2016. Frequency and magnitude of head accelerations in a canadian interuniversity sport football team's training camp and season. *Int. J. Athl. Ther. Train.* 21 (5), 36–41. <https://doi.org/10.1123/ijatt.2016-0005>.
- Mussack, T., Dvorak, J., Graf-Baumann, T., Jochum, M., 2003. Serum s-100b protein levels in youth amateur soccer players after controlled heading and normal exercise. *Eur. J. Med. Res.* 8 (10), 457–464.
- Naunheim, R.S., Bayly, P.V., Standeven, J., Neubauer, J.S., Lewis, L.M., Genin, G.M., 2003. Linear and angular head accelerations during heading of a soccer ball. *Med. Sci. Sports Exerc.* 35 (8), 1406–1412. <https://doi.org/10.1249/01.MSS.0000078933.84527.AE>.
- Paus, T., 2010. Growth of white matter in the adolescent brain: myelin or axon? *Brain Cogn.* 72 (1), 26–35. <https://doi.org/10.1016/j.bandc.2009.06.002>.
- Poole, V.N., Breedlove, E.L., Shenk, T.E., Abbas, K., Robinson, M.E., Leverenz, L.J., Nauman, E.A., Dydak, U., Talavage, T.M., 2015. Sub-concussive hit characteristics predict deviant brain metabolism in football athletes. *Dev. Neuropsychol.* 40 (1), 12–17. <https://doi.org/10.1080/87565641.2014.984810>.
- Press, J.N., Rowson, S., 2017. Quantifying head impact exposure in collegiate women's soccer. *Clin. J. Sport Med.* 27 (2), 104–110. <https://doi.org/10.1097/JSM.0000000000000313>.
- Reynolds, B.B., Patrie, J., Henry, E.J., et al., 2016. Practice type effects on head impact in collegiate football. *J. Neurosurg.* 124 (2), 501–510. <https://doi.org/10.3171/2015.5.JNS15573>.
- Rowson, S., Duma, S.M., Beckwith, J.G., et al., 2012. Rotational head kinematics in football impacts: an injury risk function for concussion. *Ann. Biomed. Eng.* 40 (1), 1–13. <https://doi.org/10.1007/s10439-011-0392-4>.
- Rubin, T.G., Catenaccio, E., Fleysher, R., et al., 2018. MRI-defined white matter microstructural alteration associated with soccer heading is more extensive in women than men. *Radiology* 289 (2), 478–486. <https://doi.org/10.1148/radiol.2018180217>.
- Ruestow, P.S., Duke, T.J., Finley, B.L., Pierce, J.S., 2015. Effects of the nfl's amendments to the free kick rule on injuries during the 2010 and 2011 seasons. *J. Occup. Environ. Hyg.* 12 (12), 875–882. <https://doi.org/10.1080/15459624.2015.1072632>.
- Self, B.P., Beck, J., Schill, D., Eames, C., Knox, T., Plaga, J., 2016. Head accelerations during soccer heading. In: *The Engineering of Sport 6*. Springer, New York, NY, pp. 81–86. https://doi.org/10.1007/978-0-387-46051-2_15.
- Shewchenko, N., Withnall, C., Keown, M., Gittens, R., Dvorak, J., 2005. Heading in football. Part 2: biomechanics of ball heading and head response. *Br. J. Sports Med.* 39 (Suppl. 1), i26–32. <https://doi.org/10.1136/bjism.2005.019042>.
- Stewart, W.F., Kim, N., Ifrah, C.S., et al., 2017. Symptoms from repeated intentional and unintentional head impact in soccer players. *Neurology* 88 (9), 901–908. <https://doi.org/10.1212/WNL.0000000000003657>.
- Teas, R., 2016. *Rstudio: Integrated Development for R*. RStudio, Inc., Boston, MA.
- USAClubSoccer, 2016. *Recognize to Recover. Implementation Guidelines for Us Soccers Player Safety Campaign Concussion Initiatives- Heading for Youth Players*. [cited 2017 December].
- Yang, Y.T., Baugh, C.M., 2016. Us youth soccer concussion policy heading in the right direction. *Jama Pediatrics* 170 (5), 413–414. <https://doi.org/10.1001/jamapediatrics.2016.0338>.
- Zhang, M.R., Red, S.D., Lin, A.H., Patel, S.S., Sereno, A.B., 2013. Evidence of cognitive dysfunction after soccer playing with ball heading using a novel tablet-based approach. *PLoS One* 8 (2), e57364. <https://doi.org/10.1371/journal.pone.0057364>.