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ORIGINAL ARTICLE

The Effect of Wearing Soccer Headgear on the Head Response in Soccer Heading

F.Y. Tan[1], M.H.A. Hassan[1,*], N.H. Johari[1], M.N. Omar[1] and I. Hasanuddin[2]

[1]Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pahang, Malaysia
[2]Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Syiah Kuala, 23111 Banda Aceh, Indonesia

ABSTRACT – Soccer is regarded as the most popular sport in the world, with millions of people actively involved in the game. Being a contact sport in nature, soccer players are susceptible to various kinds of injuries, such as lower extremities muscle injury. In addition to those familiar injuries that soccer players sustain during the game, traumatic brain injury is also a possibility. Head impacts in soccer could be a result of head-to-head impact with an opponent player, a head-to-elbow impact, an impact with the goal post, an impact with the ground, as well as an impact with the soccer ball, which occurs during a heading manoeuvre. Soccer allows the players to use their heads to hit the ball to pass it to a teammate or even perform heading to score a goal. Although soccer heading is perceived as less harmful as compared to head impacts with other hard objects, many studies have shown compelling evidence that this repetitive heading might harm the brain, thereby leading to traumatic brain injury. Protective headgears designed especially for soccer players have been commercially available in the market for some years. However, the effectiveness of these headgears in reducing the impact due to soccer heading has not been well studied. This paper investigates the effectiveness of two commercially available headgears, the Full90 and the ForceField headgear by means of a heading experiment. An anthropometric test device known as Hybrid III head and neck dummy instrumented with an inertial sensor that consists of a triaxial accelerometer and gyroscope installed at the centre of gravity of the head was used in the experiment. A soccer ball launching machine was used to propel the ball at several inbound velocities. Peak linear acceleration (PLA) and peak angular acceleration (PRA) were recorded, and the head injury criterion (HIC) and the rotational injury criterion (RIC) were calculated. It was found that both headgears failed to reduce the linear components of head acceleration but instead increased the HIC (13 – 66% increment) depending on the inbound ball velocity. With respect to the rotational component of head injury, the Full90 headgear was found to reduce the RIC up to 29%, but the ForceField failed to provide a significant reduction of RIC. Overall, both headgears were found to be ineffective in reducing linear and rotational components of head injury, which could be attributed to the headgear design. Improved headgear design and an improved padded foam are needed to protect soccer player's brain while performing soccer heading.

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INTRODUCTION

Soccer is considered the most popular sport in the world, with the participation of millions of people. A publication by the International Federation of Association Football (FIFA) in 2007 revealed that there were some 270 million people actively involved in soccer [1]. That was 15 years ago, and the numbers could have been doubled or tripled by now. In a contact sport like soccer, sustaining injuries is a definite possibility. Soccer players are susceptible to various kinds of injuries, such as ankle injuries, knee injuries, as well as concussions, to name a few [2]. In a study conducted in 2021, soccer was found to result in the highest rate of injury in 1,000 hours of playing [3]. Although some regard soccer as less aggressive as compared to American football or ice hockey, the rate of concussion in soccer is comparable to that of both aforementioned sports [4]–[6].

Concussion in soccer can be a result of head impact with another player's head, elbow, goal post, and ground, as well as impact with the ball when performing soccer heading [7]. It was reported that player-to-player contact is the major cause of concussion in soccer [8]. More than half of the reported concussion cases in soccer happened in soccer-heading encounters [9]. It was also reported in the same study that 41% of concussions in soccer were sustained due to impacts with another player's elbow, arm or hand [9]. With regards to gender, studies have shown that female soccer players have a higher tendency to sustain concussions compared to male players [10]–[12]. Nevertheless, it has been reported that almost 40% of soccer players who have sustained a concussion during a match did not report the incidence, thereby could lead to negative consequences such as a higher tendency to sustain a further concussion in the following matches [13].

Although studies have shown that player-to-player contact is the main cause of concussion among soccer players, the purposeful heading of the ball in soccer is also considered one of the main factors of concussion. The difference between head impacts resulting from player-to-player contact and soccer heading is that a single heading in soccer may not be

***CORRESPONDING AUTHOR** | M.H.A. Hassan | mhasnun@ump.edu.my

harmful, but the repetitive impact might. It was reported that a soccer player may have performed more than 600 headings in a year [14]. Poor neuropsychological performance, such as psychomotor speed, attention task and working memory, has been associated with heading frequency [15], [16]. These are some evidences that suggest repetitive head impact due to soccer heading may be harmful to the brain.

Studies have been conducted to investigate the effect of soccer heading on the brain function of soccer players. The neuropsychological function of soccer players was evaluated using a validated structured questionnaire known as HeadCount-2w, which evaluates the exposure to heading within two weeks [17]. High exposure to soccer heading within a timespan of 12 months was found to impair learning ability among women soccer players [18]. Another study found that recent heading (within two weeks prior to testing) and long-term heading (within 12 months prior to testing) resulted in neuropsychological functions [14]. In addition to HeadCount, other methods of neuropsychological evaluation were conducted, with similar results that demonstrate suspected concussion due to heading and poor working memory among soccer headers that are essential for daily life [19].

In addition to the neuropsychological test, a magnetic resonance imaging (MRI) technique known as diffusion tensor imaging (DTI) was conducted to evaluate the effect of repetitive heading on the player's brain. A study on 37 amateur soccer players has found that repetitive heading could result in abnormal white matter microstructure as well as poor neurocognitive performance [20]. A recent Canadian study has also reached a similar conclusion that repetitive head impacts led to a lower value of fractional anisotropy (FA) in those who had been subjected to repetitive subconcussive head impacts, which suggests a degraded brain function [21]. It was also found that female players experienced more changes in white matter microstructure as a result of soccer heading as compared to male players [22]. This could be attributed to the weaker neck muscle of female players.

Furthermore, computer simulations such as finite element analysis [23] and mathematical models [24] have also been conducted to study the effect of soccer heading on the brain. It was demonstrated that the brain motion induced by soccer heading could be represented by a mass-spring-damper model with acceptable accuracy [24]. A more advanced finite element analysis (FEA) allows the researcher to study in detail the underlying mechanism of brain injury due to soccer heading, such as the influence of ball impact angle on brain deformation. To perform FEA analysis on soccer heading, a validated human head finite element model is required, in addition to a validated finite element model of soccer ball [25].

The objective of this study is to evaluate the effectiveness of two commercial soccer headgear, the Full90 and the ForceField headgears. Both headgears were designed especially for soccer players. However, their performance in reducing the head injury risk when performing soccer heading has not been studied well. The headgears will be tested in simulated soccer heading experiments on an anthropometric test device (ATD) known as Hybrid III head and neck dummy. The head injury predictor (that is, the parameter used to measure the severity of a head impact) used in to evaluate the effectiveness of the headgears are the peak linear acceleration (PLA), peak rotational acceleration (PRA), head injury criterion (HIC), and rotational injury criterion (RIC). The following sections explain the methodology of the study.

METHODOLOGY

Soccer Ball Launching Machine

To perform soccer heading experiment, a soccer ball launching machine that can operate with adjustable speed is needed. The machine was developed in-house, as shown in Figure 1. It utilises a two counter-rotating wheels mechanism to propel the ball forward. The machine comprises Arduino Uno as a microcontroller, an HC-06 Bluetooth module, and two alternating current (AC) motors. The machine is able to launch the ball forward at a speed of 15 – 24 m/s. The AC motor is an economical option; thereby, it is used to spin the wheel. However, the speed of the AC motor cannot be easily controlled. To vary the inbound ball speed, an Android application was developed to switch the motor on and off and release the ball using a stopper mounted to a servo motor, as shown in Figure 1. Varying the delay of which the ball is fed into the machine allows the inbound ball speed to be varied.

The machine was configured to have three modes, with Mode 1 releasing the ball immediately once the motor has reached its maximum speed. Mode 2 and Mode 3 delay the feeding of the ball into the wheel for 1 second and 2 seconds, respectively. Mode 1 produces an average inbound ball velocity of 22.76 m/s, and Mode 2 generates an average inbound velocity of 18.57 m/s and Mode 3 results in a ball velocity of 16.43 m/s. It is essential to use a soccer ball launching machine to ensure the repeatability of the experiment.

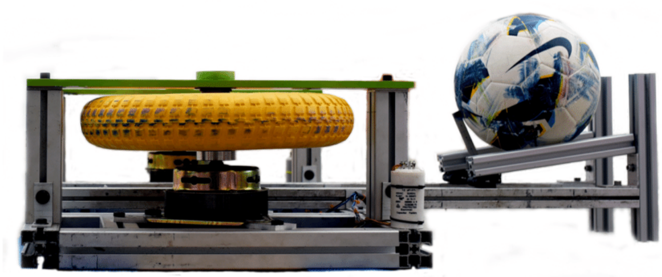


Figure 1. The soccer ball-launching machine

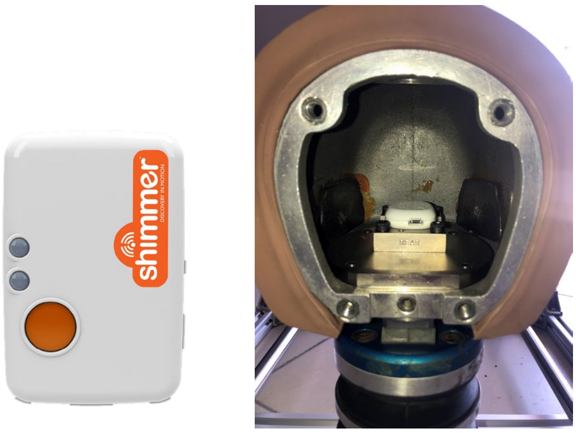
Antropometric Test Device (ATD)

To perform the soccer heading experiment, an anthropometric test device (ATD) known as Hybrid III headform and neckform dummy was used, as shown in Figure 2. Hybrid III represents the 50th percentile male head and neck that weigh 4.54 kg and 1.54 kg, respectively [26]. Hybrid III crash test dummy has been widely used in evaluating the safety performance of passenger cars. In addition, it has been used by many researchers to evaluate the effectiveness of protective helmets in sports [26]–[28]. The dummy is mounted on a platform made of aluminium profiles, and the movement of the dummy is locked in every direction, thereby not allowing it to move back and forth or left and right upon impact. This was done to replicate an actual soccer heading, in which the player is fully aware of the incoming ball. When performing intentional soccer heading, the players usually strengthen their neck muscles and torso to head the ball. Hence, the ATD was fixed on the platform.

Figure 2. Hybrid III headform and neckform

Inertial Sensor

To measure the severity of head impact due to soccer heading, Shimmer3 200g inertial sensor (Shimmer, Ireland) as shown in Figure 3(a), was used. The sensors consist of a tri-axial accelerometer with the capability to measure linear acceleration up to ±200 g and a gyroscope that can measure angular velocity up to ±2,000 degree/s. The sensor was placed inside the Hybrid III head at its centre of gravity, as depicted in Figure 3(b). The capability of the inertial sensor to measure linear acceleration up to 200 g makes it suitable to measure head impact in soccer heading. Both accelerometer and gyroscope record the data at 1,000 Hz. The data was streamed to a laptop via Bluetooth.



(a) (b)

Figure 3. (a) Shimmer3 200g inertial sensor. (b) Sensor installed at the centre of gravity of the Hybrid III head

Experimental Setup

The experiment was conducted outdoors due to the rebound of the ball after impact. The soccer ball launching machine was slightly elevated and placed near the Hybrid III head dummy (approximately 1 metre away) and positioned accordingly such that the ball propelled by the machine would hit the forehead of the head dummy, as shown in Figure 4. For each ball launching mode mentioned earlier, ten trials were performed for every condition. Only the trials in which the ball hits the centre of the forehead were considered acceptable. Otherwise, the experiment was repeated.

Figure 4. The experimental setup

The inbound ball velocity was measured using an iOS application, SpeedClock – Video Radar developed by Sten Kaiser. The application utilises the iPhone slow-motion camera function that records the footage at 240 frames per second. The application tracks the movement of the ball in each frame, as shown in Figure 5. The diameter of the ball (which is 22 cm) was used as the basis to measure the distance the ball travels. The application converts this distance travelled by the ball in pixels into metre, thereby calculating the velocity of the ball by dividing this distance by the time taken. To measure the ball velocity, we chose the last five frames just before the ball hit the dummy head. The accuracy of this application was proven to be comparable to that of timing lights [29]. We found that the use of the SpeedClock application is satisfactory in a soccer heading experiment.

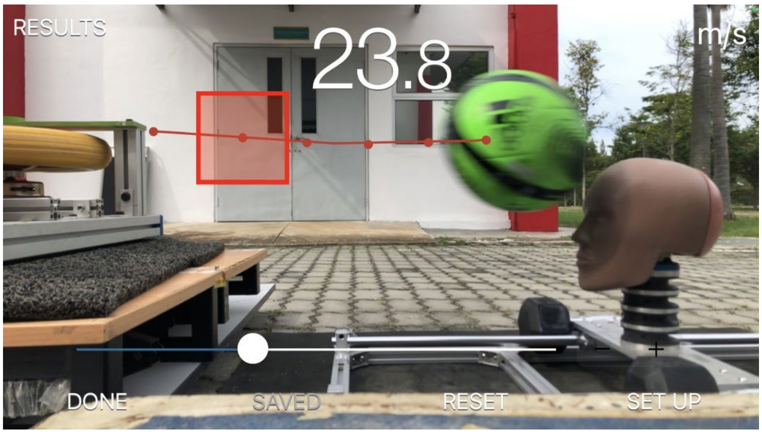


Figure 5. Measurement of the ball inbound velocity in SpeedClock application

Headgear Tested

The objective of this study is to evaluate the effectiveness of commercial soccer headgear. Two commercial soccer headgears were tested in this study, namely the ForceField and the Full90 headgear. Both of them were not commercially available in Malaysia, so they were bought from Amazon.com. Figure 6 illustrates both headgears. The experiment was also conducted on the head dummy without wearing any headgears. This serves as the 'control group' or the baseline in evaluating the effectiveness of both headgears. This study is only limited to evaluating the performance of both headgears in soccer heading situations. The effectiveness of the headgears in an impact with objects other than soccer balls is beyond the scope of this study.

(a) (b)

Figure 6. (a) ForceField headgear. (b) Full90 headgear

Data Analysis

As mentioned earlier, the data recorded by the inertial sensor was streamed to a laptop, which was then used for further analysis. Since the output of linear acceleration generated in all three axes was in millivolts (mV), to obtain linear accelerations in m/s^2, the values of linear acceleration need to be converted in MATLAB. This was achieved by exporting the uncalibrated data from the 200g accelerometer. Then, the Shimmer3 200g sensor was placed on the surface such that the positive x-axis is pointing in the direction of the gravity vector (vertically up), hence pointing away from the direction of the gravity vector (vertically down). These steps were repeated for both the remaining y-axis and z-axis to obtain the offset, sensitivity, and alignment matrices. After that, the calibration parameters were applied to the uncalibrated accelerometer output using the available calibration code to derive a calibrated 200g accelerometer output into m/s^2.

In the meantime, the gyroscope measures the angular velocity in all three axes. Therefore, to obtain the angular accelerations in each respective axis, the values of angular velocities were numerically differentiated. To avoid accumulation of errors, the angular velocities were initially filtered using the Butterworth filter prior to the differentiation. This was applied by using add-ins in Microsoft Excel developed by Wassenbergh (2007), where a cut-off frequency of 167 Hz was applied, which corresponds to one-sixth of the sampling rate of the Shimmer sensor of 1024 Hz. This is based on the Nyquist theorem stating that, to avoid losing information from the signal, it is necessary to sample at a sampling rate that is equal to twice the frequency of the signal because signals contain high-frequency components. Finally, the resultant linear and angular accelerations were calculated.

The data obtained from the experiment were further used to calculate the linear impact severity indexes Head Injury Criterion (HIC) and rotational impact severity indexes Rotational Injury Criterion (RIC) during the time of impact by using Microsoft Excel using the following equations:

$$HIC_{15} = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_0^t a_{lin}(t)dt \right]^{2.5} \right\} max \tag{1}$$

$$RIC_{15} = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_0^t a_{rot}(t)dt \right]^{2.5} \right\} max \tag{2}$$

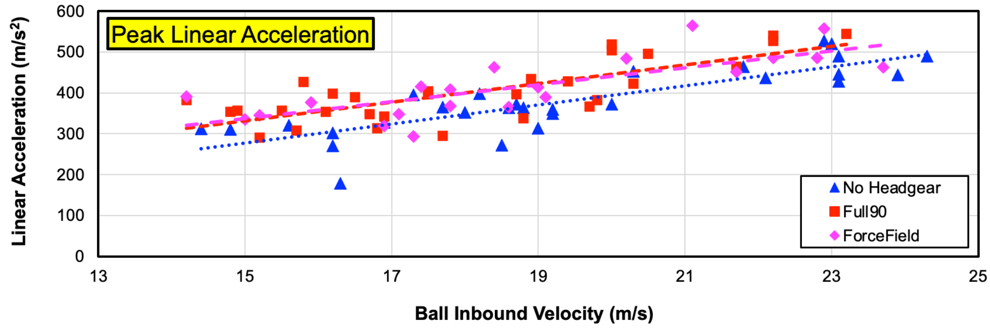
where a_{lin}(t) represents linear acceleration in g while and a_{rot}(t) represents rotational acceleration in rad/s^2 as a function of time, respectively, and $t_2 - t_1$ represents the time span of 15 ms, which the HIC and RIC were differentiated [30].

RESULTS AND DISCUSSION

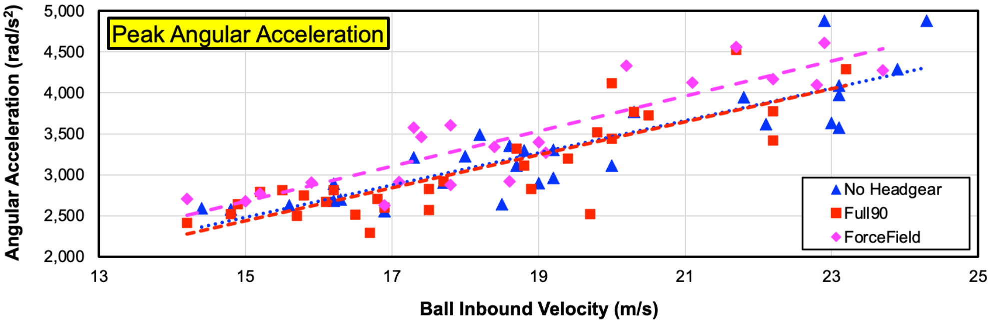
The aim of this study is to evaluate the effectiveness of two commercial soccer headgears, namely ForceField and Full90 headgear. Soccer heading experiments were conducted on an ATD, Hybrid III head and neck dummy which was mounted on a custom-made test rig. The experiments were grouped into three categories, that is without wearing headgear, wearing ForceField headgear, and wearing Full90 headgear. The first category (without headgear) serves as the baseline for the evaluation of the protective performance of the headgears. Four parameters were measured and analysed to evaluate the protective performance of the headgears, which are the peak linear acceleration (PLA), peak angular acceleration (PRA), maximum head injury criterion (HIC_{max}) and maximum rotational injury criterion (RIC_{max}).

The conventional way to evaluate the severity of the head injury is by measuring the peak linear and angular accelerations experienced by the head upon impact. Figure 7(a) and Figure 7(b) show both PLA and PRA experienced by the Hybrid III head dummy upon soccer ball impact. In both figures, it is obvious that the PLA and PRA increase with the increase of ball inbound velocity, which is straightforward. Interestingly, in Figure 7(a), it can be seen that the PLA increases slightly when wearing both headgears as compared to not wearing headgear. This is evident across the range of inbound velocities tested. This result is not what have been expected prior to the experiment. We speculate this is due to the compression and expansion of padded foam used in both headgears. Upon impact with the soccer ball, which can also be considered as a soft object, the ball compressed. The compression of ball will then compress the padded foam. After a few milliseconds, the padded foam expands and returns to its original thickness, while the ball also expands and rebounds after the impact. The impact of the ball and padded foam can be visualised as the impact of two springs. When two springs impact each other, it seems like two springs are connected in series. The total deformation is then the sum of the deformation of the ball and the padded foam. This in turn, may result in a slight increase in the PLA, as seen in Figure 7(a).

A similar observation is seen for PRA, as shown in Figure 7(b). The Full90 headgear was found to produce almost the same PRA as the baseline condition, as observed from the generated trendline. The Forcefield headgear, on the other hand, again produces slightly higher PRA compared to not wearing headgear condition. While PLA might be attributed to the deformation of two soft objects, namely the ball and the padded foam, PRA is a different story. The increase in PRA for ForceField headgear may result from the headgear design. The ForceField headgear is technically a headband, with a padded foam on the front placed inside the headband (refer to Figure 6(a)). The Full90 headgear, however, is a more robust headgear, as shown in Figure 6(b) and fits nicely on the head with less movement compared to the ForceField headgear that prone to significant movement upon ball impact due to its design, which is in the form of a headband. This movement, when being impacted by the ball, may result in slight amplification of the head rotation, as observed in Figure 7(b).



(a)



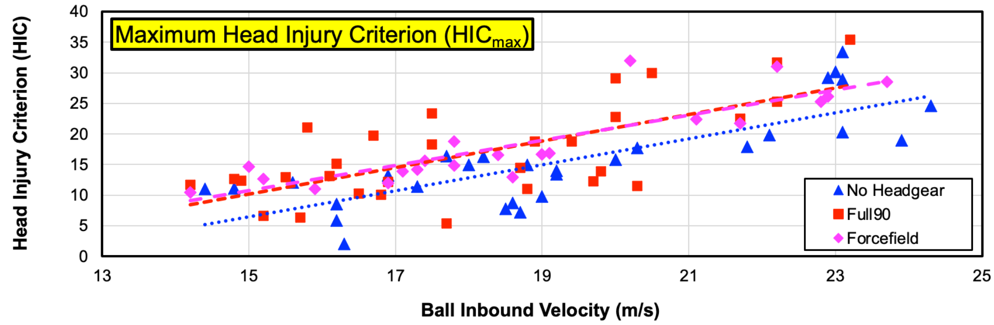
(b)

Figure 7. Performance of the headgears at (a) peak linear acceleration and (b) peak angular acceleration

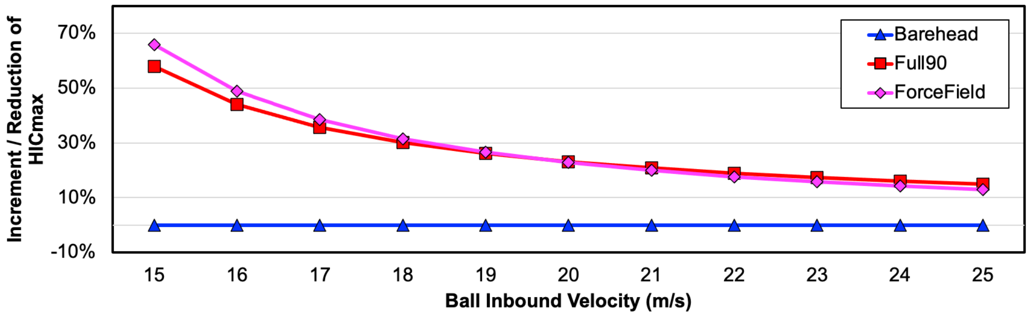
As the research in head injury evolves, many head injury predictors have been introduced to evaluate the severity of head impacts. One of the most common head injury predictors, which until now is still used in assessing the head injury in the automotive industry, is the Head Injury Criterion (HIC). There are two common HIC calculations used, which are within a timespan of 36 milliseconds, known as HIC_{36}, and within a time span of 15 milliseconds, that is known as HIC_{15}. In this study, HIC_{15} was used and calculated using Eq. (1), as shown in the previous section. As the calculation of HIC is derived from the linear accelerations, thereby HIC represents the severity of head injury based on the linear components.

Figure 8(a) shows the maximum HIC in all three conditions: no headgear, wearing ForceField headgear, and wearing Full90 headgear. Similar to what was observed with the PLA, wearing both headgears did not reduce the HIC, instead, it result in a slight increase in maximum HIC value. We believe that this finding is due to the same reason as what have been discussed previously, that is the impact of two deformable bodies (the ball and the padded foam in the headgear) has resulted in an impact of two springs connected in series, thereby slightly amplify the HIC value when wearing the headgear as compared to the baseline. The trendline of both headgears fall on almost the same line, which suggests that both headgears have similar behaviour upon soccer ball impact, thereby producing an almost similar response. One could contemplate that both headgears might have been using padded foam with similar mechanical properties, if not the same.

When looking at the percentage of increment of HIC against the inbound ball velocity, as shown in Figure 8(b), it is evident that the smaller the ball inbound velocity, the worse the protective performance of both headgears in terms of HIC. Both headgears exhibit negative exponential protection against the linear component of head impact, with the performance increasing as the inbound velocity increases. At a simulated low inbound velocity of 15 m/s, wearing Full90 headgear increases the HIC to 58%, while wearing the ForceField headgear increases the HIC to 66%, as compared to the baseline. As the inbound velocity increases, the effect of wearing the headgear becomes less apparent. At the simulated impact ball impact of 25 m/s, the effect of wearing both headgears approaches a 10% difference from the baseline. This could be due to the fact that at higher inbound velocity, the force generated by the ball impact compresses the padded foam fully, thereby making the presence of the headgear nearly ineffectual.



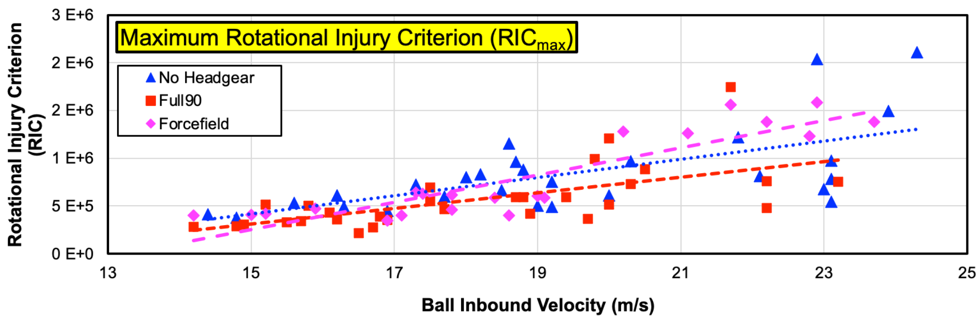
(a)



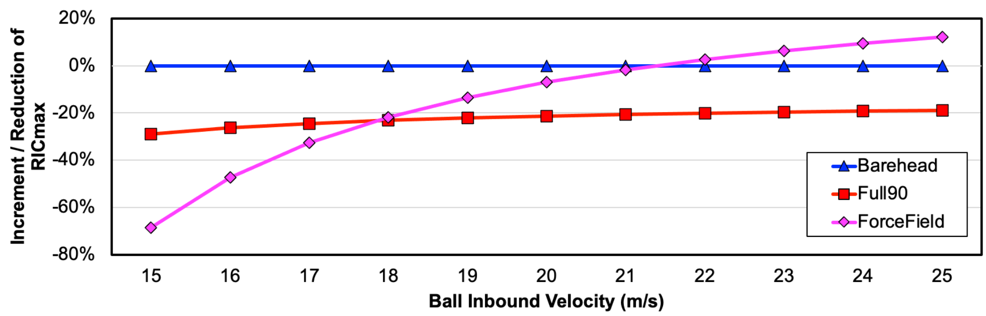
(b)

Figure 8. Comparison of (a) maximum Head Injury Criterion (HIC_{max}) and (b) percentage of increment/reduction of HIC_{max} when wearing the headgears as compared to the baseline

The head rotation has been considered to produce more brain response than translational (linear) component, thereby is more harmful to the brain [27], [31], [32]. Therefore, in addition to HIC, we have also calculated the rotational injury criterion (RIC), which is derived mainly from the angular accelerations of the head. The RIC, calculated using Eq. (2), provides important information on the protective performance headgears against a more injurious rotational head acceleration, as depicted in Figure 9(a). When it comes to RIC, the trendlines for both headgears are different than that of HIC. It can be seen that at lower inbound ball velocity, both headgears were able to reduce the RIC. Full90 headgear demonstrates a reduction of RIC across the range of ball inbound speed tested. However, for the ForceField headgear, it is evident that it is only effective at lower ball inbound velocity. While approaching higher ball inbound velocity, the headgear not only becomes ineffective at reducing the RIC but also slightly increases the RIC value.



(a)



(b)

Figure 9. Comparison of (a) maximum Rotational Injury Criterion (RIC_{max}) and (b) percentage of increment/reduction of RIC_{max} when wearing the headgears as compared to the baseline

The findings can be clearly seen in Figure 9(b), which plots the percentage of reduction or increment of RIC when wearing both headgears compared to the baseline. It is apparent that the Full90 headgear provides a steady reduction of RIC within a range of 20-30% across all inbound ball velocities. However, the ForceField has a totally different trend. At lower inbound velocity, the ForceField headgear provides a significant reduction of RIC of nearly 70%. However, the percentage of reduction of RIC lessens drastically, and upon exceeding inbound velocity of 21 m/s, the ForceField headgear becomes useless in terms of RIC reduction. As mentioned earlier, this could be due to the design of the ForceField headgear, which is in form of a headband, that is very prone to moving upon impact. This speculation could be corroborated by the fact that the Full90 headgear perform better since its design provides a better fit to the head, thus preventing it from moving erratically upon impact.

Both headgears were tested and analysed in terms of their protection against the linear and rotational component of head injury. It has been established that the rotational component of head impact is more injurious than the linear components since rotational motion tends to induce a higher degree of brain motion. In terms of the translational (linear) component, which is analysed by means of PLA and HIC, it was found that both head injury indicators show a similar trend. The results demonstrated that wearing both headgears not only did not reduce the translational head motion but also increased it. This was not hypothesised prior to the experiment. However, it was conjectured that this was the result of an impact between two deformable objects (the ball and the padded foam inside the headgear), which may have caused the slight amplification of the translational head motion.

With regards to the rotational head motion, the severity of head injury was evaluated based on the PRA and RIC, as shown in Figure 7(b) and Figure 9(a), respectively. The PRA and RIC, however, did not exhibit a similar trend as what has been observed in the translational component. In terms of PRA, it was found that the ForceField headgear resulted in an increase in PRA, which may have been caused by the movement of the headgear upon soccer ball impact. This is attributed to the design of the headgear, that is in form of a headband, which did not fit tightly on the ATD’s head, thereby is susceptible to excessive movement upon impact. The Full90 headgear, on the other hand, was found to have no effect on the PRA, which is demonstrated by its trendline that falls almost exactly on the trendline of the baseline condition. In terms of the RIC, it further demonstrates the unsteady behaviour of using the ForceField headgear, which is showcased by its mixed protective performance and significant reduction of RIC at lower inbound velocity, but drastically changed as the inbound velocity increases. Exceeding 21 m/s inbound velocities resulted in a totally useless protection from the ForceField headgear in terms of RIC. However, the Full90 headgear demonstrated a steady reduction of RIC at an average of 20% across the inbound velocities tested.

Our results reveal that both headgears were ineffective in protecting the head against the translational motion. Not only that, wearing the headgears has slightly increased the translational head motion. With respect to the rotational head motion, the Full90 headgear was able to reduce 20% of the RIC, but not the PRA. The ForceField headgear, however, was found to be ineffective in protecting the head against rotational motion. To summarise, it can be seen that both headgears did not provide any significant reduction of head motion due to soccer heading. The headgears may be effective in protecting the head against impact with hard objects, such as another player’s head, goalpost, or elbow. However, both headgears were ineffective in protecting the head from an impact with the soccer ball.

CONCLUSIONS

This study aims to evaluate the effectiveness of soccer headgear in reducing the risk of sustaining a concussion in soccer heading. Soccer heading experiments were conducted in three conditions: without wearing headgear (baseline), wearing the Full90 headgear, and wearing the ForceField headgear. The severity of the head injury was measured using four parameters, that are peak linear acceleration, peak rotational acceleration, maximum head injury criterion, and maximum rotational injury criterion. Both headgears were not only found to be ineffective in protecting the head against a translational component of head injury but also wearing the headgears has resulted in an increase in translational head motion. With respect to the rotational component of head injury, both headgears were also ineffective in reducing the PRA, although the Full90 headgear was able to reduce the RIC by 20%. Overall, it was demonstrated that both headgears were not effective in reducing the risk of sustaining a head injury in the event of soccer heading. The headgears could be effective in an impact with a hard, rigid object, but not with a soft, deformable object like the soccer ball. A new headgear design that could reduce both the translational and rotational head motion upon soccer ball impact is needed to ensure the safety of soccer player’s brain when performing soccer heading.

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REFERENCES

[1] FIFA, “FIFA Big Count 2006: 270 million people active in football,” *FIFA Communications Division, Information Services*, 31 May, 2007.

[2] C. G. Koutures and A. Gregory, “Clinical report - Injuries in youth soccer,” *Pediatrics*, vol. 125, no. 2, pp. 410–414, 2010.

[3] P. Prieto-González, J. L. Martínez-Castillo, L. M. Fernández-Galván, A. Casado, S. Soporki, and J. Sánchez-Infante, "Epidemiology of sports-related injuries and associated risk factors in adolescent athletes: An injury surveillance," *International Journal of Environmental Research and Public Health*, vol. 18, no. 9, 2021.

[4] J. Mooney, M. Self, K. ReFaey, G. Elsayed, G. Chagoya, J. D. Bernstock *et al.*, "Concussion in soccer: A comprehensive review of the literature," *Concussion*, vol. 5, no. 3., pp.1-16, 2020.

[5] V. E. Wahlquist and T. W. Kaminski, "Purposeful heading in youth soccer: A review," *Sports Medicine*, vol. 51, no. 1., pp. 51-64, 2021.

[6] V. Hubertus, N. Marklund, and P. Vajkoczy, "Management of concussion in soccer," *Acta Neurochirurgica*, vol. 161, no. 3. 2019.

[7] M. H. A. Hassan, Z. Taha, I. Hasanuddin, and M. J. Mohamed Mokhtarudin, "Concussion in soccer," in *SpringerBriefs in Applied Sciences and Technology*, no. 9789811302701, 2018, pp. 1–9.

[8] R. D. Comstock, D. W. Currie, L. A. Pierpoint, J. A. Grubenhoff, and S. K. Fields, "An evidence-based discussion of heading the ball and concussions in high school soccer," *JAMA Pediatrics*, vol. 169, no. 9, pp. 830–837, 2015.

[9] T. E. Andersen, Á. Árnason, L. Engebretsen, and R. Bahr, "Mechanisms of head injuries in elite football," *British Journal of Sports Medicine,* vol. 38, no. 6, pp. 690–696,2004.

[10] U. Dave, J. Kinderknecht, J. Cheng, K. Santiago, B. Jivanelli, and D. I. Ling, "Systematic review and meta-analysis of sex-based differences for concussion incidence in soccer," *Physician and Sportsmedicine*, vol. 50, no. 1. pp. 11–19, 2022.

[11] A. R. Weiner, J. R. Durbin, S. R. Lunardi, A. Y. Li, T. C. Hannah, A. J. Schupper *et al.*, "Incidence and severity of concussions among young soccer players based on age, sex, and player position," *Orthopaedic Journal of Sports Medicine*, vol. 10, no. 1, pp. 1-8, 2022.

[12] J. B. Caccese, T. A. Buckley, R. T. Tierney, W. C. Rose, J. J. Glutting, and T. W. Kaminski, "Sex and age differences in head acceleration during purposeful soccer heading," *Research in Sports Medicine*, vol. 26, no. 1, pp. 64–74, 2018.

[13] N. Nelson and C. Albright, "Injury reporting in collegiate soccer players and the impact of non-reporting," *Internet Journal of Allied Health Sciences and Practice,* vol. 18, no. 4, pp. 1–5, 2020.

[14] C. F. Levitch, M. E. Zimmerman, N. Lubin, N. Kim, R. B. Lipton, W. F. Stewart, *et al.*, "Recent and long-term soccer heading exposure is differentially associated with neuropsychological function in amateur players," *Journal of the International Neuropsychological Society*, vol. 24, no. 2, pp. 147–155, 2018.

[15] W. F. Stewart, N. Kim, C. Ifrah, M. Sliwinski, M. E. Zimmerman, M. Kim *et al.*, "Heading frequency is more strongly related to cognitive performance than unintentional head impacts in amateur soccer players," *Frontiers in Neurology*, vol. 9, no. APR, pp. 1–10, 2018.

[16] D. Bruno and A. Rutherford, "Cognitive performance in former professional football (soccer) players is affected by estimated heading frequency," *Alzheimer's & Dementia*, vol. 17, no. S10, pp. 1-1, 2021.

[17] M. L. Lipton, C. Ifrah, W. F. Stewart, R. Fleysher, M. J. Sliwinski, M. Kim *et al.*, "Validation of HeadCount-2w for estimation of two-week heading: Comparison to daily reporting in adult amateur player," *Journal of Science and Medicine in Sport,* vol. 21, no. 4, pp. 363-367, 2018.

[18] K. Ye, R. Fleysher, R. B. Lipton, M. E.Zimmerman, W. F. Stewart, M. J. Sliwinski *et al.*, "Repetitive soccer heading adversely impacts short-term learning among adult women," *Journal of Science and Medicine in Sport,* vol. 25, no. 11, pp. 935–941, 2022.

[19] J. Ashton, G. Coyles, J. J. Malone, and J. W. Roberts, "Immediate effects of an acute bout of repeated soccer heading on cognitive performance," *Science and Medicine in Football,* vol. 5, no. 3, pp. 181–187, 2021.

[20] M. L. Lipton, N. Kim, M. E. Zimmerman, M. Kim, W. F. Stewart, C. A. Branch *et al.*, "Soccer heading is associated with white matter microstructural and cognitive abnormalities," *Radiology*, vol. 268, no. 3, pp. 850–857, Sep. 2013.

[21] G. Lefebvre, S. Guay, E. Chamard, G. Theaud, E. de Guise, B. A. Bacon, *et al.*, "Diffusion tensor imaging in contact and non-contact university-level sport athletes," *Journal of Neurotrauma*, vol. 38, no. 5, pp. 529–537, 2021.

[22] T. G. Rubin, E. Catenaccio, R. Fleysher, L. E. Hunter, N. Lubin, W. F. Stewart *et al.*, "MRI-defined white matter microstructural alteration associated with soccer heading is more extensive in women than men," *Radiology*, vol. 289, no. 2, pp. 478–486, 2018.

[23] M. H. A. Hassan and Z. Taha, "Finite element analysis of soccer heading," in *Procedia Engineering*, vol. 112, pp. 46–51, 2015.

[24] Z. Taha, M. H. A. Hassan, and I. Hasanuddin, "Analytical modelling of soccer heading," *Sadhana - Academy Proceedings in Engineering*, vol. 40, no. 5, pp. 1567–1578, Aug. 2015.

[25] Z. Taha and M. H. A. Hassan, "A reaction-force-validated soccer ball finite element model," *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, vol. 231, no. 1, pp. 43–49, 2017.

[26] J. M. Clark, T. B. Hoshizaki, and M. D. Gilchrist, "Assessing women's lacrosse head impacts using finite element modelling," *Journal of The Mechanical Behavior of Biomedical Materials*, vol. 80, no. January, pp. 20–26, 2018.

[27] J. M. Clark, T. A. Connor, A. Post, T. B. Hoshizaki, and M. D. Gilchrist, "The influence of impact surface on head kinematics and brain tissue response during impacts with equestrian helmets," *Sports Biomechanics*, vol. 20, no. 6, pp. 737–750, 2021.

[28] R. A. Oeur, M. D. Gilchrist, and T. B. Hoshizaki, "Parametric study of impact parameters on peak head acceleration and strain for collision impacts in sport," *International Journal of Crashworthiness*, vol. 0, no. 0, pp. 1–10, 2019.

[29] R. Stanton, M. Hayman, N. Humphris, H. Borgelt, J. Fox, L. D. Vecchio *et al.*, "Validity of a smartphone-based application for determining sprinting performance," *Journal of Sports Medicine*, vol. 2016, pp. 1–5, 2016.

[30] M. Dunn, D. Davies, and J. Hart, "Effect of football size and mass in youth football head impacts," in *Proceedings*, vol. 49, no. 1, p. 29, 2020.

[31] S. Kleiven, "Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are," *Frontiers in Bioengineering and Biotechnology*, vol. 1, no. 15, pp. 1–5, 2013.

[32] A. Post, A. Oeur, B. Hoshizaki, and M. D. Gilchrist, "An examination of American football helmets using brain deformation metrics associated with concussion," *Materials & Design,* vol. 45, pp.653-662, 2013.