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Effect of Ball Inflation Pressure and Padded Headgear on Ball-Head Impacts in Water Polo and Soccer

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UNIVERSITY OF CALIFORNIA,
IRVINE

Effect of Ball Inflation Pressure and Padded Headgear on Ball-Head Impacts in Water Polo and Soccer

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

by

Wyatt Xavier Moscoso

Thesis Committee:
Doctor David J. Reinkensmeyer
Doctor James Hicks
Associate Professor Lorenzo Valdevit

2017

DEDICATION

To

My Family and Friends

In recognition of their unending support

Perfection is not attainable, but if we chase Perfection
We can catch Excellence

-Vince Lombardi

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ABSTRACT OF THE THESIS

Concussions in Water Polo and Soccer

By

Wyatt Xavier Moscoso

Master of Science in Mechanical Engineering

University of California, Irvine, 2017

Doctor David J. Reinkensmeyer

In the sports of water polo and soccer, the effects of ball inflation pressure on head impact forces have received little attention. Determining this relationship may help minimize the results of ball-head contact in these sports and become important for preventing concussion. We studied the effect of ball inflation pressure (35-117 kPa; 5-17 psi) and headgear on head linear impact acceleration and angular velocity using an instrumented, anthropomorphic, test dummy head. Water polo and soccer balls were shot at the forehead at 17.4 to 24.6 m/s (39 to 55 mph), the speeds of the fastest shots in elite water polo, as well as speeds which are typical for heading from goalie punts in competitive soccer. Overinflating the ball beyond the recommended pressure for each sport – 90 to 117 kPa (13 to 17 psi) for water polo, 55 to 76 kPa (8 to 11 psi) for soccer - significantly increased linear impact acceleration by 7% for both water polo and soccer balls ($p < 0.001$). Underinflating the ball from 90 to 69 kPa (13 to 10 psi) for water polo and 55 to 34 kPa (8 to 5 psi) for soccer significantly decreased linear impact acceleration by 8.5% for water polo and 13.5% for soccer ($p < 0.001$). Headgear is shown to reduce impact forces by 22% and angular velocity by 23.5%. These results suggest that appropriately inflating the ball and/or wearing padded headgear may help reduce the prevalence of brain trauma in water polo and soccer.

INTRODUCTION

Approximately 50% of the 3.8 million concussions experienced in the US each year are sports-related [14,18]. Mechanisms of brain injury due to head impact in sports are still not fully understood [17], but impulsive linear and rotational accelerations are widely thought to contribute to brain injury [17,19,21]. Such accelerations may stretch and damage axons within the brain, leading to transient neurologic dysfunction. Even when head impact does not result in immediately observable symptoms of concussion, some studies suggest that repetitive sub-concussive hits in sports cause structural and functional brain changes over time [1,2,22,28]. Recurrent head impacts may be associated with the development of chronic neurodegenerative disorders such as chronic traumatic encephalopathy, and may result in executive dysfunction, memory impairment, depression, apathy, poor impulse control, and eventually, dementia [12,32].

Finding ways to reduce the effects of sub-concussive and concussive hits in sports is, therefore, an important goal, and will likely require attenuating the magnitude of head impact accelerations whenever possible. Soccer and water polo present a unique opportunity because of the nature of the player-ball interaction in these sports. Soccer is the only sport in which players intentionally maneuver the ball with their head. In addition, soccer has the greatest rate of sports-related concussions for women [13]. In water polo, the plane of ball movement is nearly aligned with the players' heads [32], and thus water polo defenders, especially goalies, frequently sustain hits to the head from shots. The first concussion survey of water polo players recently found that 47% of goalies and 36% of all water polo players have experienced at least one concussion, with an average of around two concussions experienced per respondent [5]. Beyond this recent study and the apparent prevalence of concussions seen in the sport, water polo currently suffers from a scarcity of data regarding concussion, exacerbated by the lack of systematic reporting of traumatic brain injury at the club, high school and collegiate levels [5].

Two candidate strategies for reducing ball-head impact are to reduce ball inflation pressure and/or to wear padded headgear. Surprisingly little research has been done on the effect of ball inflation pressure on head impact accelerations in soccer. Studies investigating the role of ball inflation pressures have used experimental [3,29] and theoretical approaches[27]. The results were equivocal showing either ball inflation pressure did not influence impact characteristics or significantly reduced impact forces. There has been no research on the role of ball inflation pressure pertaining to water polo.

The second strategy is the use of padded headgear. Several studies have examined the effect of headgear in soccer with varying conclusions. Some of these studies have suggested that headgear may play a role in attenuating impact for more forceful blows at higher speeds [7,22], while others have concluded that headgear is not effective[21]. There have been no published studies on the effectiveness of padded headgear in reducing impact forces in water polo.

The goal of this study was to determine the effects of ball inflation pressure on impact forces when the ball hits the head at the highest range of speeds expected in water polo and soccer. We also tested whether a padded water polo cap could reduce impact forces, to determine if we could replicate benefits found for padded headgear in soccer. Instead of using theoretical simulations, which make assumptions about the physics of impact,[26] or human subject experiments, which are difficult to justify in the case of delivering repeated hits to the head at high speeds, we used an instrumented, anthropomorphic test dummy head. Such test dummies have undergone years of refinement to improve their bio-fidelity, and are the standard for head impact testing in the transportation industry.

Methods

Apparatus and Experimental Set-up

The experiment consisted of launching water polo and soccer balls inflated to varying pressures at varying speeds at an anthropomorphic test dummy (ATD) head/neck unit (Figure 1, Hybrid III 50th Percentile Male Anthropomorphic Testing Dummy, Humanetics, Plymouth, Michigan). For water polo, a men's ball (Kap7, Irvine, CA) was inflated to 69, 83, 90, 97, 103, and 117 kPa (10, 12, 13, 14, 15, or 17 psi), and thrown at speeds of 17.4, 19.7, 22.3, and 24.6 m/s (39, 44, 50, and 55 mph). The low end of 17.4 m/s was a shot speed typical of elite water polo, while the fastest speed of 24.6 m/s was equivalent to the fastest shots recorded [9,31]. This was corroborated by other literature that found the range of shots to be typically from 14.5 to 25.8 m/s (32 to 57 mph) in an elite environment [36]. For soccer, a men's soccer ball (Size 5, Adidas, Herzogenaurach, Germany) was inflated to 34, 48, 55, 62, and 76 kPa (5, 7, 8, 9, and 11 psi) and thrown at speeds of 17.4, 19.7, and 22.4 m/s (39, 44, and 50 mph). Although these speeds are below the roughly 31 m/s (70 mph) maximum speeds recorded in soccer, heading generally occurs after multiple seconds of ball travel (such as in a punt, where the ball arcs), causing the speed at the time of impact to be close to 20 m/s (45 mph)[6,33].

These speeds were achieved by calibrating the speed setting on a ball launcher (Sidekick Soccer Machine, Seattle Sports Sciences, Seattle, Washington, range 20 to 72 mph) using a radar gun (Tribar Sport Radar Gun, Jugs, Tualatin, Oregon); we also checked speeds using the radar gun throughout the trials. The Sidekick was placed 2.4 m (8 ft) directly in front of the ATD (Figure 1). The radar gun was offset from the line of ball motion with an interior angle of 25 +/- 5 deg, and therefore the measured speeds were adjusted by the reciprocal of the cosine 25 deg to estimate the actual speeds. For the headgear experiment with the water polo ball, a padded water polo cap (Head Guard, Kap7, Irvine, CA) was placed on the dummy head. This silicon cap is designed to be worn under a water polo cap and has padded dimples to absorb impact and disperse forces. The data collected from shots against the dummy head outfitted with the cap was compared to that of hits to the unprotected dummy head to ascertain the efficacy of the headgear in reducing head impact acceleration.

The balls were inflated to the target pressure using an electric air pump with an integrated pressure gauge (Champion Sports Economy Electric Inflating Air Pump, Bronx, New York). A second gauge (Molten Deluxe Digital Air Gauge, Hiroshima, Japan) was used to ensure the ball pressure was accurate between trials.

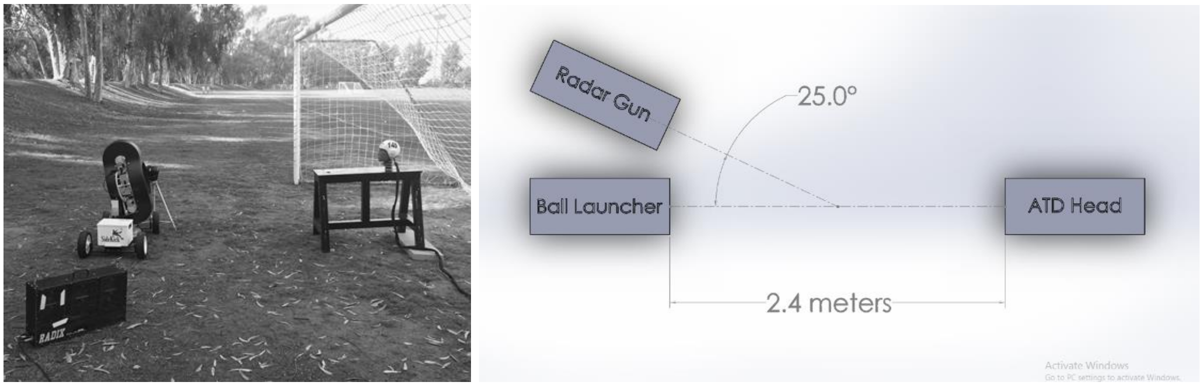

Figure 1. Experimental Setup. A ball launcher was used to throw balls at a test dummy head. Ball speeds were monitored with a radar gun.

The ATD received the ball impacts. Only the neck and head were used in this study. This unit represents a male neck and head of the 50th percentile, and is predominantly used in the field of vehicle crash testing. The neck and skin compliance and mass of the ATD is designed to be biofidelic, especially in the direction of head-on collisions, "accurately simulating the human dynamics moment/rotation flexion and extension response" [15]. The test dummy was bolted to a heavy metal table (Figure 1).

To measure impact acceleration, three linear accelerometers (Model 7264C piezoresistive accelerometers, Endevco, Irvine, CA) were embedded in the dummy head, each with a full-scale range of 2000g, and a frequency response of up to 5000 Hz. To measure angular velocity, three angular rate sensors (Angular Rate Sensor 12k model, DTS, Seal Beach, CA) were used, which have a 12,000 deg/sec range and an SAE class 1000 response with a bandwidth of up to 10,000 Hz [11].

A data acquisition system (32 channel Tracking and Data Acquisition TDAS G5 Model, KARCO, Adelanto, CA) was used to record the six channels of data (the three linear accelerations and three angular rates). The sampling rate was set to 10,000 Hz. Upon receiving an impact, the system recorded accelerometer values from 0.5 seconds before the impact to 1 second after, and a 0.4 second window of data (4000 samples per run) was saved, beginning 0.05s before impact and ending 0.35s after impact. Immediately after each shot, a plot of the data became available for viewing through the software, which allowed the experimenters to check each shot.

Experimental Procedure and Statistical Analysis

Before each of the six throws at each speed and pressure, the data acquisition software performed an automatic re-calibration to ensure the consistency of each run through squib resistance checks and firing of internal loads [11]. During this process, ball pressure was manually verified with the air gage and modified if necessary. Once armed, the experimenter placed a ball in the ball launcher, which was aimed to impact the test dummy in the forehead. An accurate shot to the forehead sent the ball upward into the crossbar/net of a soccer goal placed behind the dummy to catch shots. If the shot missed the forehead, such as with a skim or a facial impact, it was recognized by a combination of aberrant ball flight path (either straight into the goal, or directly back at the experimenter) and a widely variant peak acceleration seen on the computer plot. Misses were deleted and the trial was repeated.

Results were analyzed using three-way (water polo – factors were headgear on/off, shot speed, inflation pressure) or two-way (soccer – factors were shot speed and inflation pressure) analysis of variance (ANOVA). Three clearly anomalous linear acceleration values out of 276 total water polo shots and two anomalous values from the 88 total soccer shots were identified and rejected from the data using a three standard deviation criterion for outliers.

Results

For the water polo balls thrown at high speed (17.4 -24.6 m/s, 39 – 55 mph) at the test dummy head, there was a significant effect of ball pressure on peak linear impact acceleration (Figure 2A and 2B, ANOVA, F (5, 272) = 8.9, $p < 0.001$) but not on angular velocity (Figure 2C and 2D, ANOVA, F (5, 275) = 0.47, $p = 0.79$). Overinflating the water polo ball to 117 kPa (17 psi) increased the linear impact acceleration by 7%, while underinflating to 69 kPa (10 psi) decreased the linear impact acceleration by 8.5%. There was also a significant effect of wearing the padded headgear on linear impact acceleration (Figure 3A, ANOVA, F (1,272) = 168.4, $p < 0.001$) and on angular velocity (Figure 3B, ANOVA, F (1,275) = 31.6, $p < 0.001$). With padded headgear, the linear impact acceleration was lessened by 22%, while the angular velocity was lessened by 23.5% both on average across all speeds. We observed that linear impact acceleration had a bimodal distribution when plotting a histogram of the z-score of all hits with the padded cap on (Figure 4A), while the distribution was unimodal with the padded cap off (Figure 4B).

For the soccer balls, there was a significant effect of ball pressure on peak linear impact acceleration of the test dummy head (Figure 5A, ANOVA, F (4, 87) = 31.5, $p < 0.001$) but not on angular velocity (Figure 5A and 5B, ANOVA, F (4, 85) = 1.35, $p = 0.26$). Overinflating the soccer ball to 76 kPa (11 psi) increased the linear impact acceleration by 7 %, while underinflating to 34 kPa (5 psi) decreased this acceleration by 13.5%. Only three speeds were tested, and headgear was not applied in the soccer trials.

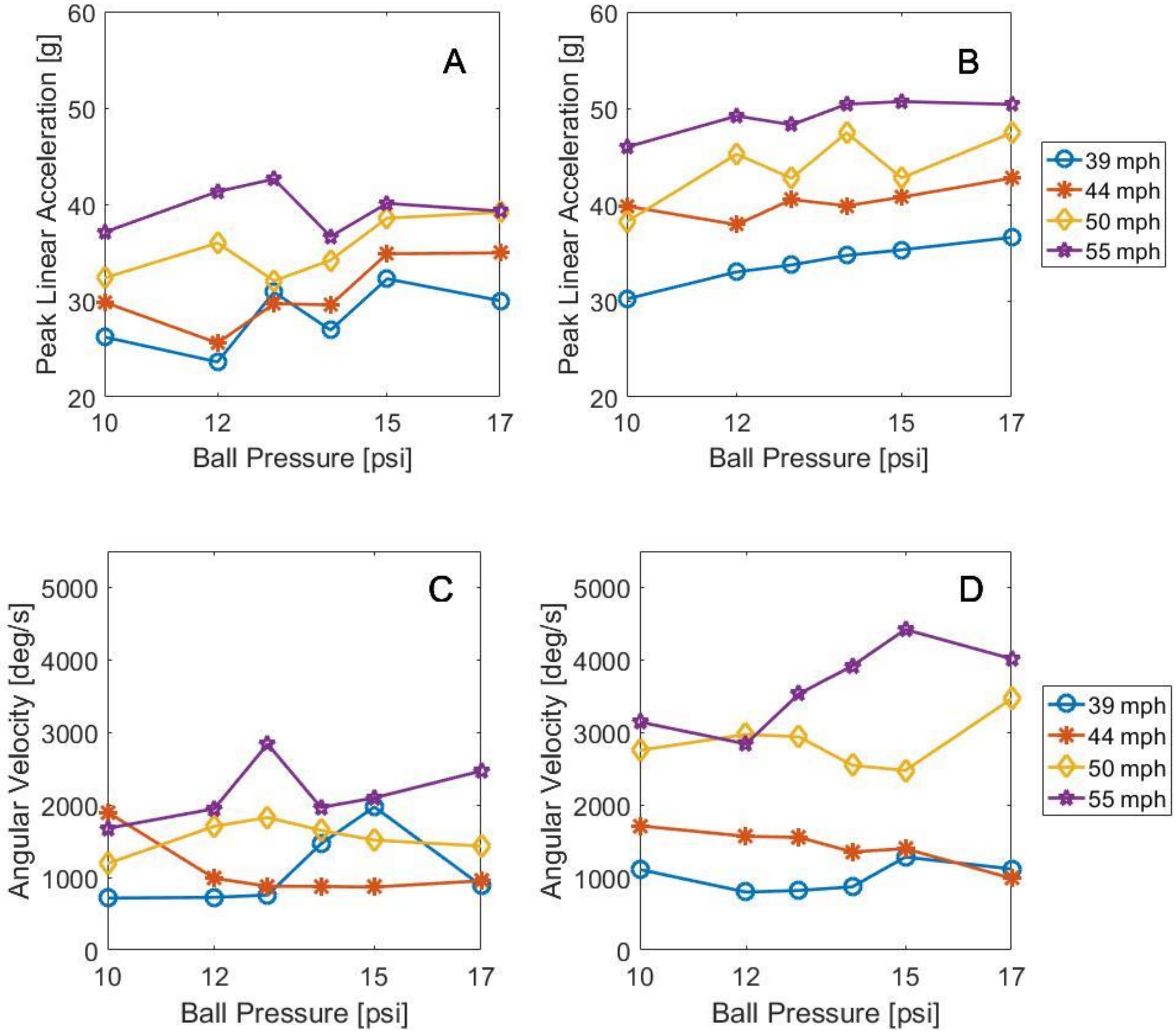

Figure 2. Top Row: Average linear impact acceleration as a function of water polo ball pressure for all four speeds, with (A) and without (B) padded headgear. Bottom Row: Average angular velocity as a function of water polo ball pressure for all four speeds, with (C) and without (D) padded headgear.

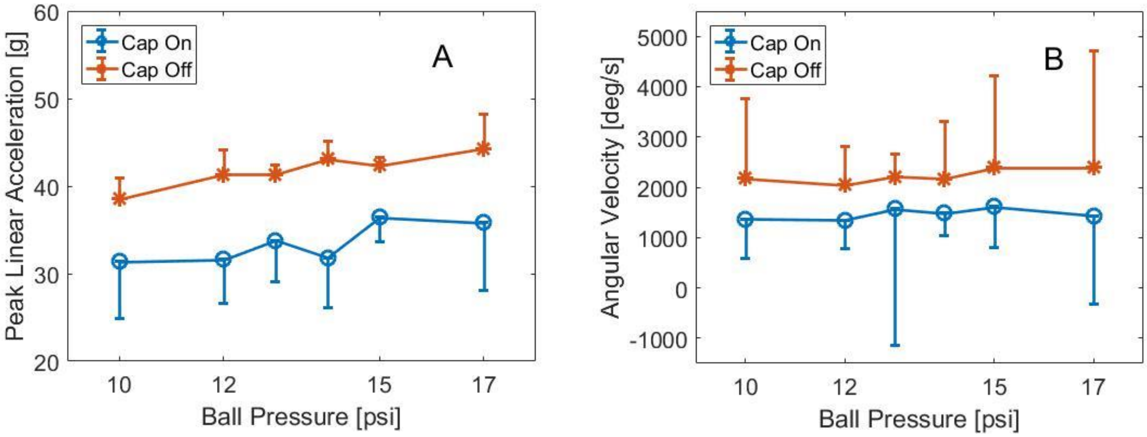

Figure 3. Average linear impact acceleration (A) and angular velocity (B) for all speeds combined as a function of ball pressure, with and without padded headgear, for water polo. Error bars show one standard error.

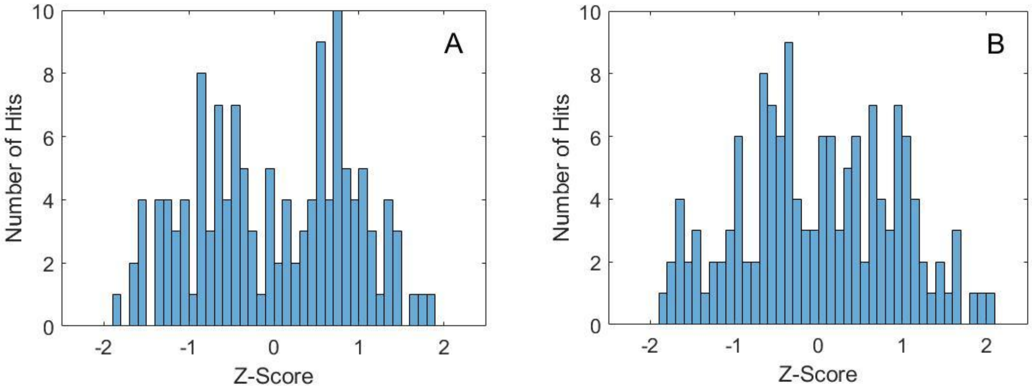

Figure 4. Histogram of linear impact acceleration Z-Scores with (A) and without (B) padded headgear. Z-score was calculated as $(V - \bar{V})/\sigma_v$ where V is the linear impact acceleration of the hit, $\bar{V}$ is the mean impact acceleration across all hits in the condition (headgear on or off), and σ_v is the standard deviation of the hits. Note the bimodal distribution of hits when the headgear was on, likely due to whether the ball hit squarely on the padded dimples on the cap.

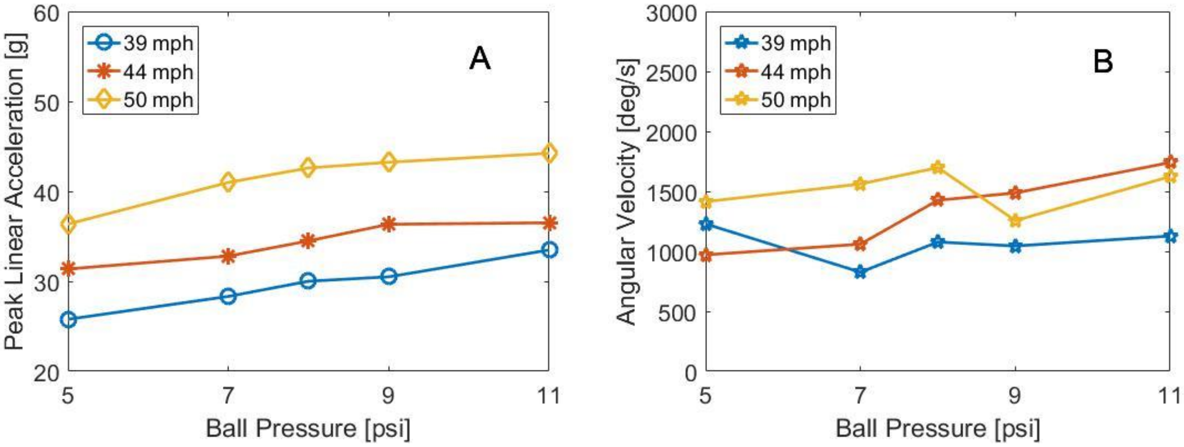

Figure 5. Average linear impact acceleration (A) and angular velocity (B) as a function of ball pressure using a soccer ball over three tested speeds.

Discussion

Finding ways to reduce the effects of sub-concussive and concussive hits to the head in water polo and soccer is an important goal for protecting players. Here, using an instrumented, anthropomorphic test dummy, we found that reducing ball inflation pressure reduced the effects of head impacts for both water polo and soccer balls thrown at high speeds, in terms of the impulsive linear accelerations caused by the hit. The padded water polo cap also reduced head impact linear accelerations and angular velocities.

Effect of Ball Pressure

In this study, the reductions in linear head impact acceleration due to ball pressure changes were relatively small, ranging from ~5-15%. It is difficult to directly compare these results to previous experiments due to the differences in ball pressure, speeds, and experimental approaches[3,29]. However, the size of the reduction in general agreed with or exceeded those found in previous experiments, supporting the finding that reducing ball pressure indeed reduces linear impact acceleration of the head, and that the reduction may be greater at higher speeds.

An experimental study using a paradigm in which soccer balls were dropped from a height of 6 m onto a force plate reported an increase in impact force when ball pressure was increased from 62 to 83 kPa (9 to 12 psi) [3]. Using a theoretical model of a child's head, simulations suggested that soccer ball inflation pressure, varied from 69 to 97 kPa (FIFA requires ball pressure to be in the range 59 to 108 kPa [8.5 to 15.6 psi]), did not influence impact characteristics during simulated soccer heading, at velocities simulated from 0.1 to 30 m/s (0.2 to 67 mph) [27]. This was somewhat unexpected, as the same study performed material testing experiments exhibiting increases in soccer ball stiffness when the ball pressure increases. A more realistic simulation found that overinflating a ball designed for a standard 83 to 110 kPa (12 to 16 psi) increased linear impact acceleration by 9% and rotational acceleration by 7%, while underinflating the ball from 82.7 to 41.4 kPa (12 to 6 psi) resulted in 31% and 24% reductions in linear impact and rotational accelerations, respectively [29]. In the same study, three human participants executed a passing scenario using frontal heading two times each while wearing an intraoral acceleration sensor. A ball pressure decrease from 80 to 60 kPa (11.6 to 8.7 psi) reduced linear acceleration by 10%, but increased rotational acceleration by 15%. An increase from 80 to 110 kPa (11.6 to 16 psi) increased accelerations by 12% and 13%, respectively. In sum, for soccer balls, variations in ball inflation pressure within the regulation range have been reported to alter impact accelerations by approximately 10%. In these simulation and human participant studies, the ball was delivered at relatively low speeds (6 to 7 m/s, 13.4 to 15.6 mph), which are not representative of impact speeds when heading a goal kick or corner kick, the scenarios of greatest concern. In high-level competitive environments, elite water polo athletes can shoot balls well over 17.9 m/s (40 mph) [9]. The effects of high speed throws in water polo on head impact accelerations have been previously unstudied.

Effect of Headgear

Concerning padded headgear, which we only tested for water polo balls, highly significant drops of over 20% were found for both linear impact acceleration and angular velocity of the ATD head. This is the first study of headgear in water polo to our knowledge. A direct comparison to soccer headgear studies is difficult because of the different balls, speeds and protocols, as well as a different design of the headgear, but the magnitude of reduction in our study is larger than the 12-16% average reported from previous studies [7,8]. For example, several studies examined the effect of headgear in soccer at higher speeds of 15.4 to 15.6 m/s (34 to 35 mph) [7,22]. The tested speeds were close to the maximum speed of 17.9 m/s (40 mph) that a soccer player may encounter when heading a ball [16]. Broglio et al. shot balls at 3 different headgears applied to a force platform and found a 12.5% reduction in peak acceleration from headgear application [7]. Naunheim et al. applied a soccer headband to a testing dummy and found that headgear tested was not effective at attenuating impact at low speeds, but suggested further research at higher speeds, as roughly a 15% reduction was found at the highest speed, while all other speeds had little to no reduction[22]. Another study found none of the headgear they tested was effective at reducing the acceleration from ball impact, but suggested headgear could be helpful in head-to-head or other non-ball-related impacts [37]. Niedfeldt et al. also proposed a potential concern with headgear – namely, that athletes may have a false sense of security and feel compelled to strike the ball harder, thus incidentally raising the risk of head injury [24]. Currently, no standards exist for soccer headgear devices [24]. Manufacturers use different materials ranging from dense cell foam to hard plastic encased in terry cloth, which may account for variability in their effectiveness in protecting against more severe impacts [8]. One experiment involving headgear on rugby players ascertained that headgear had no effect on concussion prevalence [20]. To our knowledge, no studies have been done regarding headgear in water polo, and padded headgear is prohibited in NCAA water polo matches, because no scientific evidence has proven headgear to reduce injury risk [23]. In general, few studies have been conducted with respect to the physiological demands and dangers of water polo, even though the game has been played for over a century [30].

The larger acceleration reduction we measured due to the padded cap may be due to the higher speeds we tested, the higher stiffness of the water polo ball, or the greater functionality of the headgear. Regardless, the present study begins to fill in the paucity of data at the highest level of competitive speeds in water polo, showing that the padded headgear does provide significant reduction of head impacts and should be considered for adoption. The decision to at least explore use of padded headgear in water polo seems clear given that water polo players already wear headgear that protects their ears, and therefore the gear change is relatively minimal.

An interesting finding was that the linear head impact acceleration had a bimodal distribution when headgear was applied, compared to a distribution with a single mode without the padded cap. We believe this was due to the dimpled nature of the padding on the cap we tested. Some hits likely directly landed on one of the padded nodes while others hit in-between nodes. Caps with more continuous padding may produce consistently larger acceleration reductions, resulting in an average reduction even greater than the 20% observed here.

Impact Reduction Mechanisms

Reductions in linear acceleration are to be expected from an energy analysis of the ball impact. With lower ball pressures, the ball is allowed to deform more easily, so more energy is dissipated into the ball rather than being imparted to the head due to the lower coefficient of restitution [32]. The converse is true for higher ball pressures. Furthermore, the spongy cap would be expected to increase the duration of the impact and momentum transfer, which also decreases the peak acceleration [22]. However, the finding that ball pressure did not have a significant effect on angular velocity was somewhat unexpected. At least one previous study did find an effect [29], and we are uncertain as to the reason that ours did not. One possibility is that the vertical location of ball contact on the ATD head varied across all trials due to variability in the ball launcher; indeed, we had to discard some throws that did not hit the dummy head squarely. This variability would likely not affect peak linear acceleration since all hits were ensured visually to be frontal impacts. However, this could create variance in the moment about the center of mass of the head and therefore angular velocity, which was not as easy to verify visually, perhaps making the changes in angular velocity due to ball inflation pressure changes more difficult to detect.

Enough to Make a Difference?

The reductions in impact acceleration measured in this study were modest but statistically significant. It is unclear how they might translate to reductions in traumatic brain injury, as the threshold of energy required to trigger a traumatic brain injury, and even the metric with which to measure this threshold, is a topic of debate. One study characterized traumatic brain injury onset in terms of brain shear stress, with the threshold ranging from 11 kPa to 16.5 kPa [34]. Another experiment used intracranial pressure as the criterion for comparison, and proposed a 235 kPa threshold for serious or fatal injury [35]. Using intracranial pressure as a precursor to concussion, translational acceleration had a greater influence on intracranial pressure than rotational acceleration [38]. Translational and rotational acceleration are widely accepted criteria, with thresholds of 61-144 g's and 4168-

12,832 rad/s^2 being suggested (Zhang et al., 2004), or, in another case, a rotational acceleration threshold of 1800 rad/s^2 [25,38]. Others postulate that the criterion should be based on impact duration and peak acceleration studied in tandem, with 80-90 g's sustained for more than 4 ms causing concussion [14]. However, it is unlikely that there is a precise threshold, but rather head injury results as a complex function of several physical factors. Furthermore, most head impacts in sports typically do not result in the clinical syndrome of concussion [28]; instead, these impacts can be described as sub-concussive hits, or head impacts which induce no readily observable symptoms. Several studies have shown that repetitive sub-concussive hits in contact sports have the ability to cause neurophysiological changes that accumulate from one season to the next and consequently produce structural and functional brain changes over time [1,2,28]. Although an exact criterion for concussion onset remains elusive, consistently reducing head impacts by even a small amount by underinflating the ball or wearing padded headgear might reduce both the cumulative effects of sub-concussive hits and the chance of concussion.

Limitations and Future Studies

The use of an ATD provides an ethical approach for delivering repeated impacts to the head at high speeds. While the shape, mass, and compliance of the ATD head and neck are highly engineered to be biofidelic, it remains a simplification of a human head. For example, it cannot emulate varying neck tension, which is an important factor relating to neck strength and player readiness that can influence head acceleration [4,10]. In addition, while the data suggests that ball deflation and padded headgear have a consistent positive effect across the speeds we tested, the experiment should be repeated for a greater range of speeds since impacts likely occur more frequently at lower speeds.

The results of this study suggest a few avenues for further exploration. One important direction is to study the effect of inflation pressure and headgear on head impacts during game play, which is possible with wearable acceleration sensors. In our view, the present study provides ample justification to take this next step. An interesting question is how deflating the ball to the low end of the regulation range in soccer and water polo affects game play, including shot speeds and accuracies. Optimization of headgear is another area of interest indicated by this study. Better designed headgear has the potential to reduce head impact acceleration even further while minimizing changes to the dynamics of the games; the opportunity is particularly clear for water polo, since players already wear protective headgear. Varying the direction of impact is a topic of interest, as literature suggests that direction has a correlation to lesion type and severity [26].

Conclusion

The results of this study support the concept that reducing ball inflation pressure can significantly reduce ball-head impacts in soccer and water polo, at least for high speed throws. Furthermore, for the first time, this study presents evidence that padded headgear can reduce ball-head impacts forces in water polo, a sport that only recently was rigorously documented to have a high prevalence of concussion [5]. Our evidence suggests that further study and possible application of these methods will contribute to decreasing the incidence of head injuries in these uniquely dangerous sports.

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