Assessment of Brain Injury Risks in Youth Soccer: A Coupled Experimental-Numerical Analysis of Ball Impact.

Nicolas Bourdet, Frank Meyer, Arsène Thouze, Rémy Willinger, Caroline Deck

Abstract This study investigates brain injury risks from soccer ball impacts in young players through a combination of experimental tests and numerical simulations. Using Hybrid III dummy heads, without neck, representing 6- and 10-year-old children, impacts were carried out with eight different soccer balls at varying pressures (0.3-0.8 bar), launched at 50 km/h. Linear and rotational head accelerations, along with calculated intracerebral stress, were used to estimate concussion risk. Results indicate that lighter, softer balls with lower pressures significantly reduce peak accelerations and brain stress, thereby lowering injury risk. In contrast, heavier, stiffer balls at higher pressures produced greater forces, especially during lateral impacts. Age-related differences were minor, although the 10-year-old model showed slightly increased risk. Peak linear accelerations ranged from 30-40 g, dropping to around 20 g with low-pressure soft balls. The average risk of loss of consciousness across all scenarios was estimated at 8.5%. The findings underscore the importance of ball mass and pressure in mitigating head trauma and support the use of lighter, softer, and moderately pressurised balls for youth football. This research contributes to safety guidelines by promoting equipment design tailored to children, aiming to reduce brain injury risks in youth football.

Keywords Brain injury risk, finite element modelling, soccer ball impact, youth soccer.

I. INTRODUCTION

According to the French Football Federation (FFF) [1], for the 2023-2024 season, the total number of registered soccer players reached a record of over 2.3 million, showing notable growth across all categories. Approximately 62% were under 18 years old, representing around 1.4 million young registered players. The act of heading a soccer ball, a common practice in soccer, can have significant implications for young athletes, particularly concerning cognitive and neurological health. Research indicates that repeated headings may result in short-term cognitive deficits, altered brain structure, and potentially increased risk of long-term neurological conditions. The voluntary impact of a soccer ball on the head, known as *heading*, frequently occurs during soccer games and can potentially cause mild to moderate concussion or repeated concussions as referred in [2-3-4]. This issue remains poorly understood, causing increasing concern among professional team managers and parents of young athletes.

The experimental study by [5] investigated how headings in soccer affects cognitive function. The research involved 19 amateur soccer players, including five women, with an average age of 22 years. Participants performed 20 successive headers on a soccer ball propelled at a speed of 10.8 m/s (39 km/h) from a 6 m distance. Cognitive and memory assessments were conducted immediately before and after the heading exercises, along with transcranial magnetic stimulation (TMS) evaluations to measure brain-to-muscle communication and detect signs of concussion. Results indicated a roughly five millisecond increase in brain-to-muscle communication time and a slight reduction in memory performance immediately after a heading. These cognitive changes were temporary, and they dissipated within 24 hours. While none of the players experienced clinical concussions and the study involved a limited sample size, it underscores that even mild head impacts can temporarily affect cognitive functions.

Reference [6] investigated the impact characteristics of modern soccer balls with varying surface materials and panel structures by utilising a kick-robot equipped with a dynamometer. Four types of soccer balls (Cafusa,

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Jabulani, TeamGeist2, and Pelias) were tested at speeds ranging from 15 to 30 m/s to measure their impulsive forces. The results revealed that Cafusa consistently exhibited the lowest maximum impulsive force due to the greater flexibility and higher shock-absorbing properties of its surface material and internal construction. Conversely, Jabulani presented the highest impulse at all tested velocities, attributed primarily to its stiffer internal construction involving machine-stitched panels, enhancing the rigidity of its structure. These findings underscore the substantial influence of soccer ball structural and material characteristics on their dynamic response during kicking, with implications for ball design and performance analysis.

Reference [7] investigated the influence of soccer ball characteristics on ball-to-head contact and associated kinematic variables, by reviewing nine studies. This work highlighted how specific properties of soccer balls (including inflation pressure, mass, structure, size and stiffness) influence head acceleration and forces during heading. Lower inflation pressures consistently reduced peak impact forces and accelerations, suggesting that softer balls could mitigate the magnitude of head response. Similarly, ball mass was directly proportional to impact forces, with lighter balls resulting in lower head accelerations and potentially lower injury risk. While ball size did not consistently alter impact parameters significantly, smaller balls did correlate with shorter impact durations. Ball stiffness also appeared influential, as lower stiffness correlated with reduced impact forces. Additionally, ball material and structural properties, such as water absorption or panel construction, affected impact dynamics, wet balls or stiffer constructions significantly increasing impact forces. Overall, these findings imply that adjusting ball properties, particularly reducing inflation pressure, mass, or stiffness, could effectively reduce the biomechanical burden of soccer heading, thus potentially decreasing injury risk. However, the review emphasised the need for more rigorous and standardised research to establish clear, evidence-based guidelines for soccer ball design that prioritise player safety.

Reference [8] compared head impact data across hockey, American football, and soccer using laboratory simulations with an instrumented Hybrid III dummy head. The results showed that American football impacts generated the highest accelerations and impact energies, often exceeding 150 g, due to high-speed helmet-to-helmet collisions. In hockey, significant impacts came from both sticks and pucks, with concentrated force often directed at the frontal and lateral head regions. In contrast, soccer impacts, primarily from heading the ball, produced much lower accelerations (typically under 50 g), though the cumulative effect of repeated headers remains a concern.

In the study of [9], which examines the risks of brain injuries associated with soccer, particularly regarding headings, it appeared that head loading levels are low, with linear head accelerations below 10g and angular accelerations below 1000 rad/s^2. The author highlights that these values are minimal compared to the thresholds in sports that typically cause head injuries, as linear accelerations ranged from 40 to 60g and the angular acceleration from 3500 to 5000 rad/s^2 for angular acceleration.

In the study by [10], head acceleration events on rugby players caused by ball-to-head impacts accounted for only 0.9% of the 1,622 video-verified incidents. Seventyfive percent of all HAEs (Head Acceleration Events) had a PLA (Peak Linear Acceleration) below 10 g, the overall median PRA (Peak Rotational Acceleration) was 0.6 krad/s^2, and the median PRV (Peak Rotational Velocity) was 7.5 rad/s.

The limitations of these studies are that they focus on peak resultant values and not on the time evolution of kinematics and do not consider the tissue level brain response associated with the risk of concussion. The current research considers an integrated approach combining experimental head responses with numerical simulations to assess the brain injury risk under various impact conditions and also take players' age into consideration. The study does not focus exclusively on purposeful headings but rather on ball impacts occurring during play or training, including intentional headings as well as involuntary or passive impacts, specifically in young players aged 6-to 10-years-old.

II. METHODS

This study employs a rigorous combination of experimental testing and numerical simulation to assess brain injury risks in youth soccer heading. The methodology was designed to simulate realistic ball impacts on child players under controlled conditions, ensuring precision and reproducibility. By using advanced instrumentation, diverse ball types, and validated computational models, the approach provides comprehensive insights into head response. The primary aim of this study was to assess brain injury risk, specifically concussion, associated with heading in youth soccer, in order to inform the design of safer, age-appropriate sports equipment. Hereafter the experimental and modelling procedures are outlined.

Experimental Testing Setup

The experimental apparatus was meticulously designed to replicate realistic soccer ball impacts on human heads under controlled laboratory conditions. A GLOBUS ball launcher was employed and calibrated to catapult balls at a constant velocity of 13.9 m/s (50 km/h). This system ensured accurate and repeatable impacts for robust data collection. The impacts were conducted on Hybrid III dummy heads specifically designed to represent the heads of a 6-years-old child and a 10-years-old child. Each dummy head was equipped with advanced instrumentation to capture detailed kinematic data during impacts.

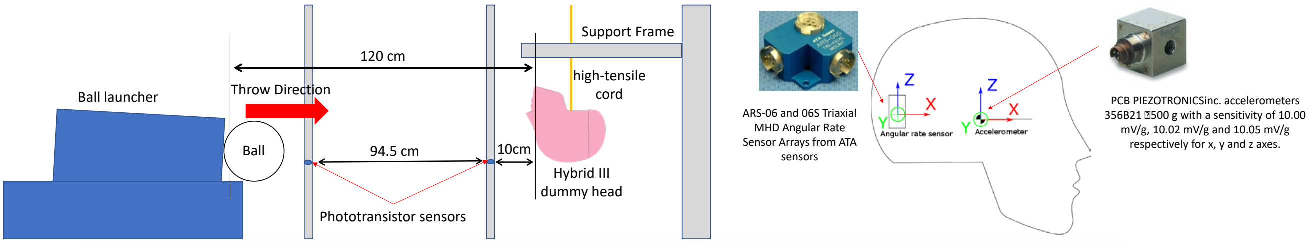

Fig. 1. Representation of the experimental device for throwing a ball against a Hybrid III head.

The instrumentation used in this study was carefully selected to capture precise head kinematic data during ball impacts against the dummy heads. Each Hybrid III dummy head was equipped with triaxial accelerometers (PCB PIEZOTRONICS 356B21), located at the headform center of gravity, to measure linear accelerations along the x, y, and z axes, with a sensitivity of approximately 10.0 mV/g per axis. Additionally, triaxial angular velocity sensors (ATA Sensor ARS-06) recorded rotational velocities around the three principal axes, providing crucial data on the rotational dynamics of the head, as illustrated in Fig. 1. The sensors were connected to a CompactDAQ data acquisition system by National Instruments, featuring two 24-bit analog-to-digital converter modules (NI 9234 and NI 9239). This system allowed for a high sampling rate of 25,600 Hz per channel, ensuring fine temporal resolution and capturing detailed motion characteristics during each impact. This advanced instrumentation enabled the accurate quantification of both linear and angular kinematics essential for assessing head injury risks.

The test configuration was designed to ensure precise and repeatable soccer ball impacts on Hybrid III dummy heads under controlled conditions. The dummy head was suspended using a high-tensile cord, allowing it to move freely upon impact, avoiding neck effect, while being stabilized with positioning aids to maintain consistent orientation before impact. The soccer ball launcher was placed 120 cm away from the dummy head to ensure accurate targeting and uniform impact force. High-speed cameras were positioned perpendicularly to the ball's trajectory to capture detailed visual data of the impact event. Phototransistor sensors, spaced 94.5 cm apart along the ball's path, measured the time taken for the ball to travel between them, enabling accurate velocity calculations before impact, as illustrated in Fig. 1. To ensure accurate ball speed measurements, preliminary checks were conducted using high-speed camera tracking data. Impacts were conducted for both frontal and lateral configurations, replicating real-world heading scenarios. Each test setup maintained controlled experimental conditions to assess brain injury risks across different ball types and pressures. Tests for each configuration were repeated five times. A CORA-type statistical evaluation [11] was employed to verify the repeatability of the tests by comparing the entire time-history of the signal.

TABLE I.
LIST OF THE EIGHT TESTED BALLS WITH CORRESPONDING PRESSURES.

ID	Type of ball	Size	Mass [g]	The two manufacturer-specified inflation pressures [bar]
BALL-1	Softball Light - size 5	5	278.5	0.8; 0.6
BALL-2	Reference ball - size 4	4	360.7	0.8 ; 0.6
BALL-3	Reference ball light - size 5	5	350.9	0.8 ; 0.6
BALL-4	Reference ball with soft component - size 5	5	439.3	0.8 ; 0.6
BALL-5	Softball low mass and low pressure - size 5	5	284.5	0.3 ; 0.6
BALL-6	Reference ball - size 5	5	422.6	0.8 ; 0.6
BALL-7	Reference ball softer - size 5	5	427	0.8 ; 0.6

Eight different soccer ball types were tested to represent a wide range of properties commonly encountered in youth and professional soccer. These included lightweight options such as soft balls, as well as standard and heavier models. Each ball was tested under two pressure conditions, ranging from 0.3 bar (low pressure) to 0.8 bar (high pressure), to evaluate the influence of ball mass and internal pressure on head injury risks. The tested balls, with the two inflation pressures specified by the manufacturers, are detailed in TABLE I. The variations in size, weight, and pressure were designed to simulate real-world differences in ball characteristics and their potential effects on head dynamic response, as studied in the study [12-13]. The diversity in ball types allowed for comprehensive analysis of their impact on kinematic responses and brain injury probabilities in young players.

Brain FE Model and Injury Metric

This study is based on Strasbourg University FE Head Model (SUFEHM) (illustrated in Fig. 2), which is a numerical model of the human head, including realistic brain and skull material laws, and which permits the computation of tissue level brain response under impact. Validation of this head model was provided in earlier studies [8-9], against local brain motion data [10-11], as well as against intracranial pressure data [12-13]. Further to the model validation, 109 real-world head trauma cases have been simulated with this head model to derive brain injury criterion in terms of intracerebral Von Mises Stress (VMS) to predict moderate concussion or short coma, known as AIS2+ (Abbreviate Injury Scale) injuries. Based on an in-depth Logistic Regression [14-15] analysis of different computed intracerebral parameters as well as by considering different percentiles, the Nagelkerg parameter that expresses the quality of the regression showed that maximum brain VMS was the most appropriate metric to predict moderate concussion. The proposed brain injury tolerance limit for a 50% risk of this reversible brain injury has been established at 37 kPa [16-17]. The equation of the brain tolerance curve obtained with the Binary Logistic method for the computed VMS extracted from SUFEHM is recalled in Eq. (1) and plotted in Fig. 2. As the option was chosen to consider the best mathematical fit instead of forcing at zero, this curve does not show a zero risk for zero stress.

$$Risk = \frac{1}{1 + e^{3.178 - 0.087.VMS}} \quad (1)$$

where VMS is the maximum value of brain Von Mises Stress in kPa.

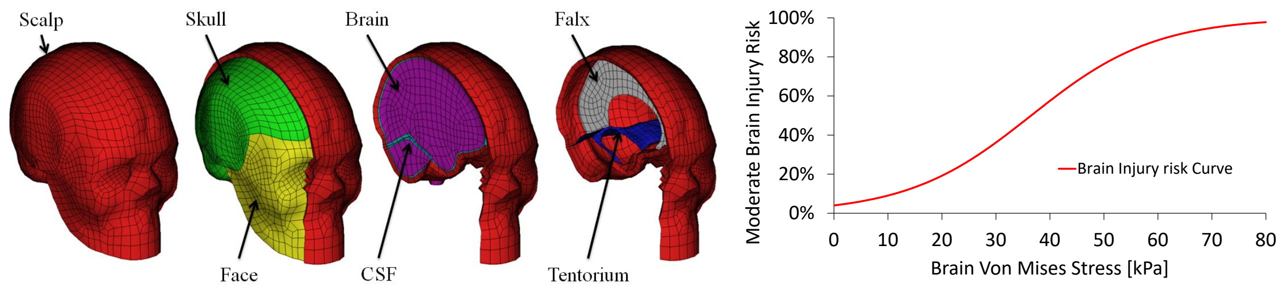

Fig. 2. Illustration of the different parts of the Head Finite Element Model and the related brain tolerance curve.

Coupled Experimental and Numerical Method for Evaluating Ball Impact

The testing protocol involved a total of 40 experimental impact tests for each type of ball. Two headform models were used to represent children aged 6 and 10 years old, allowing for the assessment of age-related differences in head response. Each ball was tested at two different internal pressure levels to evaluate the influence of inflation pressure on impact dynamics. Additionally, two distinct impact locations were selected (frontal and lateral) based on common heading scenarios in youth soccer, as illustrated in Fig. 3. To ensure repeatability and reliability of the results, five repetitions were conducted for each unique configuration, resulting in a robust dataset for analysis.

Each experimental test of ball impact on the Hybrid III head form generated six loading curves (three linear accelerations and three rotational velocities) which are then used as input data for numerical simulations employing a finite element head model. This simulation process allows for the calculation of intracerebral stress distributions and the evaluation of brain tissue deformation, providing a detailed assessment of the brain's biomechanical response and the associated injury risk for each impact scenario. This combined approach allows for a comprehensive assessment of brain injury risk associated with each specific impact condition.

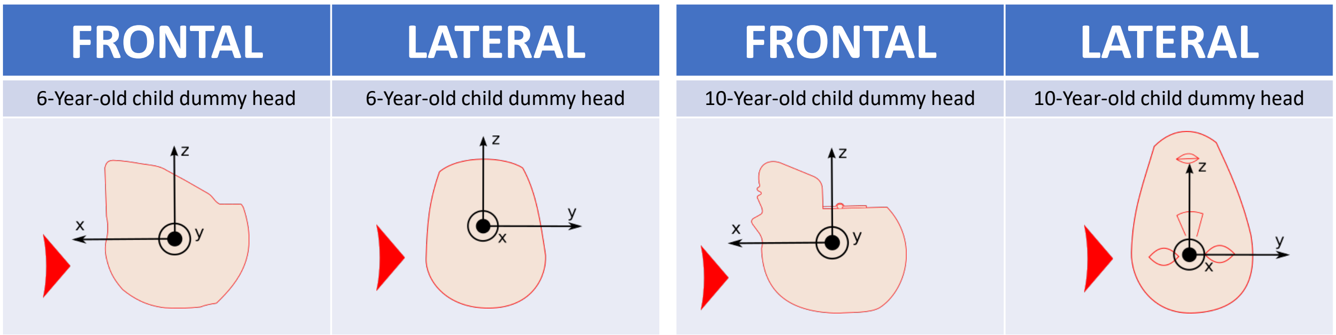

Fig. 3. Illustration of the Four Ball Impact Configurations on a 6-Year-Old and 10-Year-Old Dummy Head

III. RESULTS

The study involves a comprehensive assessment of soccer ball impacts on the head, considering multiple key parameters to analyse head injury risk in young players. A total of eight different soccer balls were tested at a speed of 50 km/h, with two pressure levels per ball to evaluate their influence on impact dynamics as detailed in TABLE I. The experiments included two age groups, represented by 6-year-old (6Y) and 10-year-old (10Y) Hybrid III dummy heads, ensuring age-specific risk assessments. Additionally, two impact locations (frontal and lateral) were examined to capture variations in head response depending on the point of contact. This experimental design resulted in 80 unique impact configurations, for which 6D kinematic data (linear and angular accelerations over time) were recorded to permit numerical simulations. To ensure data reliability, each configuration was tested five times, bringing the total number of experimental trials to 400, allowing for robust statistical validation and reproducibility of results. These variations in ball size, mass, and pressure allowed for a detailed analysis of their effects on linear acceleration, rotational acceleration, and brain injury risks during soccer-related head impacts.

Fig. 4 and Fig. 5 provide a visual representation of the impact dynamics of various soccer balls on the Hybrid III dummy heads (6Y and 10Y) under controlled conditions. These images illustrate the differences in deformation, kinematic response, and impact distribution for each tested ball type. Each impact was conducted at a velocity of 13.9 m/s (50 km/h), with the ball striking the dummy head in both frontal and lateral configurations.

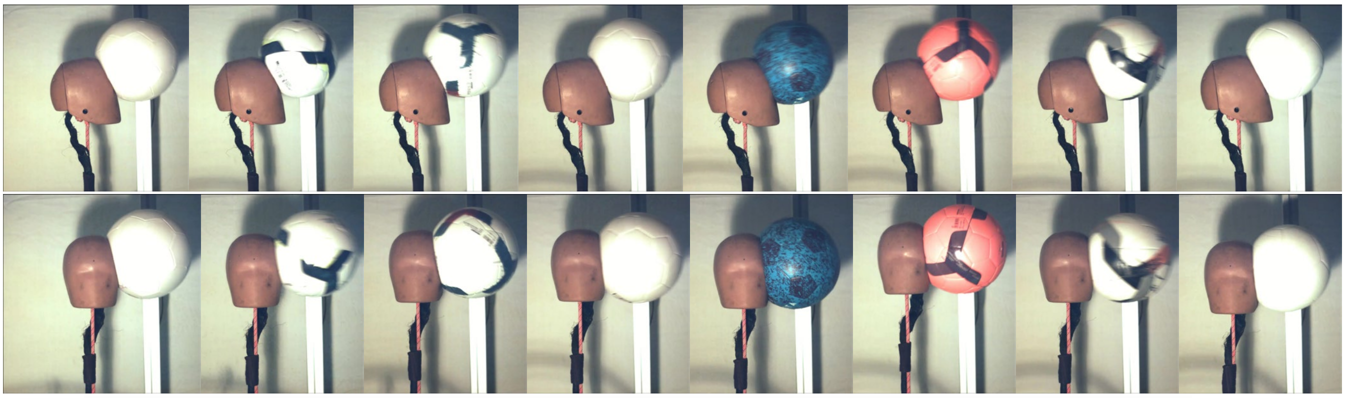

Fig. 4. Representation of the eight ball impacts in frontal and lateral on a 6Y Hybrid III dummy head.

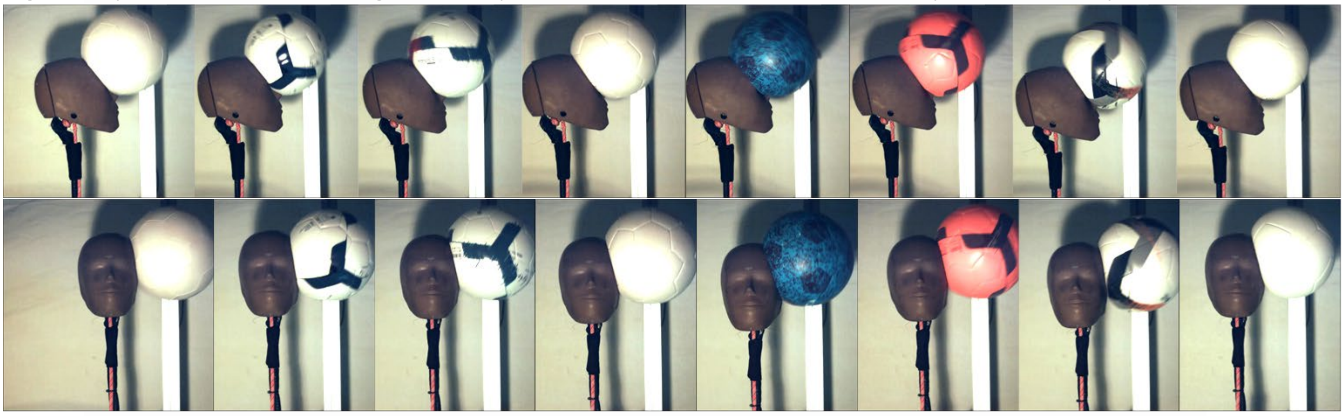

Fig. 5. Representation of the eight ball impacts in frontal and lateral on a 10Y Hybrid III dummy head.

In this section, the experimental results are presented for each ball type and each impact condition in terms of maximum linear acceleration, maximum angular acceleration, and maximum angular velocity, directly obtained from the experimental impact tests. Following each impact, numerical simulations of the brain's response were performed to calculate the maximum shear stress within the brain tissue and assess the associated brain injury risk. These values are also reported for each ball and each impact condition to provide a comprehensive evaluation of impact severity and potential injury outcomes.

The results showed that impact velocity can vary by approximately 5% around 50 km/h, with observed speeds ranging from 48.3 km/h to 52.2 km/h. Additionally, the location of impact points on the head proved to be highly consistent. By comparing the complete time histories of the signals, the linear acceleration curves, rotational accelerations, and angular velocities demonstrated excellent reproducibility, as confirmed by the CORA evaluation results [11], with scores ranging from 0.95 to 0.99. When focusing on the variability of peak values, linear accelerations showed lower variability, ranging between 4 and 5 g, and angular velocities varied by 2 to 3 rad/s. However, angular accelerations exhibited higher variability, ranging from 1 to 2.5 krad/s². This increased variability in angular acceleration is attributed to the relatively low angular velocity. Figure 6 illustrates an example of trace data for a frontal impact on a 6-year-old head form with BALL-1 pressurised to 0.6 bar replicated five times.

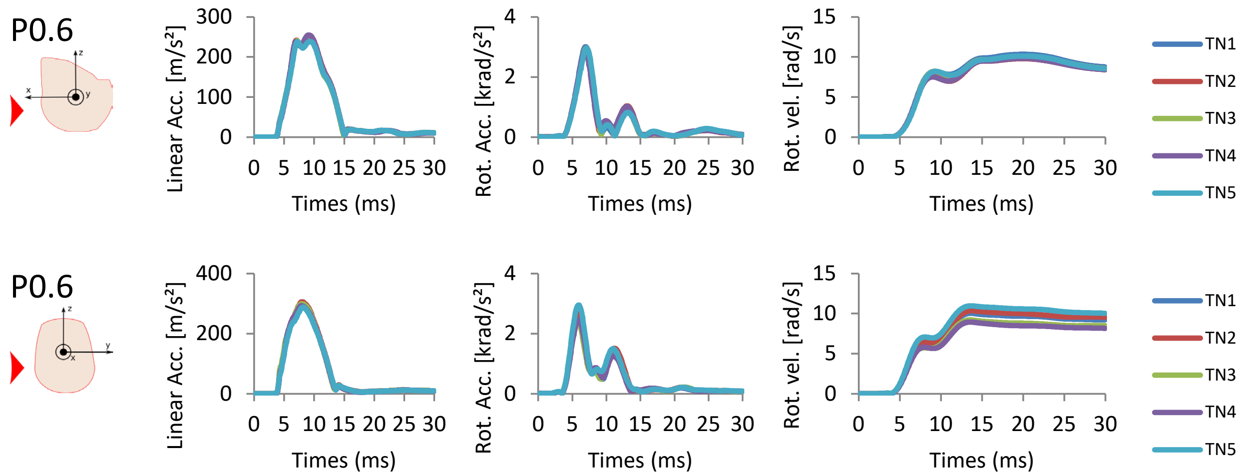

Fig. 6. Example of trace data in terms of resultant values for a frontal and lateral impacts on a 6-year-old head form with BALL-1 pressurised at 0.6 bar, replicated 5 times.

The high-speed video images provide valuable visual evidence of the variations in ball deformation, head displacement, and energy transfer during impact, depending on the ball's mass, internal pressure, and material properties. These visual observations complement and strengthen the experimental results shown in Fig. 7, illustrating how different ball characteristics influence head kinematics and injury risk.

Softballs, such as BALL-1 and BALL-5, show substantial deformation upon impact. This greater deformation allows the ball to absorb and dissipate energy more effectively, resulting in lower peak acceleration values.

In contrast, standard and heavier balls, represented by BALL-2, BALL-4, BALL-7, and BALL-8, demonstrate limited deformation during collisions. The stiffer behaviour of these balls results in higher impact forces being transmitted to the head, increasing both linear accelerations and rotational motion. This effect is particularly noticeable during lateral impacts, where the head experiences more pronounced displacement and twisting forces, elevating the risk of concussion.

The images also highlight the role of ball pressure. Comparison between low-pressure conditions (0.3-0.6 bar) and high-pressure conditions (0.8 bar) reveal significant changes in ball stiffness and impact severity. Higher-pressure balls are less compliant, generating sharper impacts and greater head accelerations, while lower-pressure balls soften the collision and reduce kinematic response.

Overall, these visual analyses reinforce the experimental findings and clearly demonstrate how the combination of ball mass, pressure, and material composition can influence head dynamics and the associated risks of brain injury in young athletes as it further demonstrated and detailed hereafter.

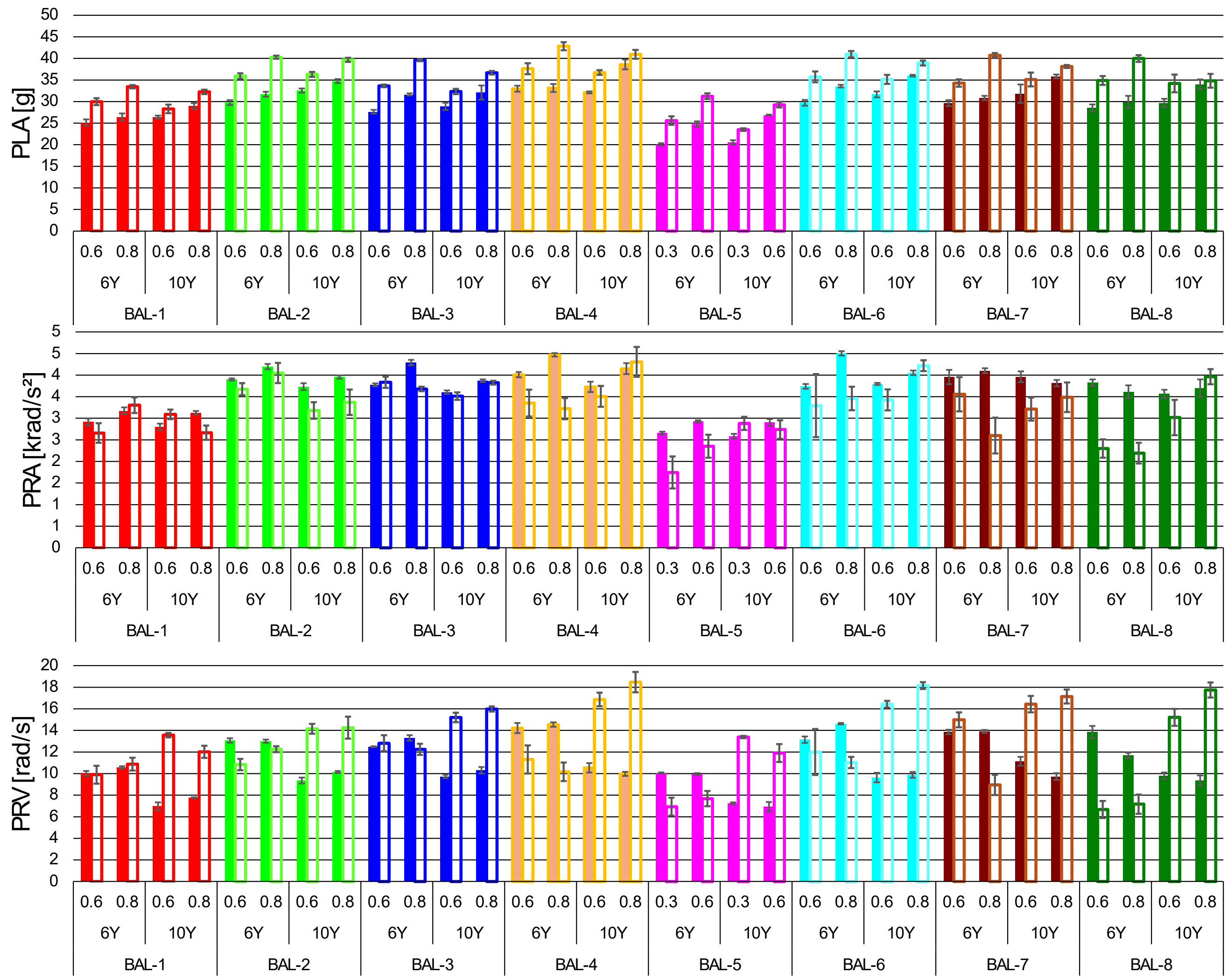

Fig. 7. Illustration of the average resultant PLA (Peak Linear Acceleration), PRV (Peak Rotational Velocity) and PRA (Peak Rotational Acceleration) for Different Balls and Dummy Heads (solid bar in FRONTAL impact, Empty bars LATERAL impact).

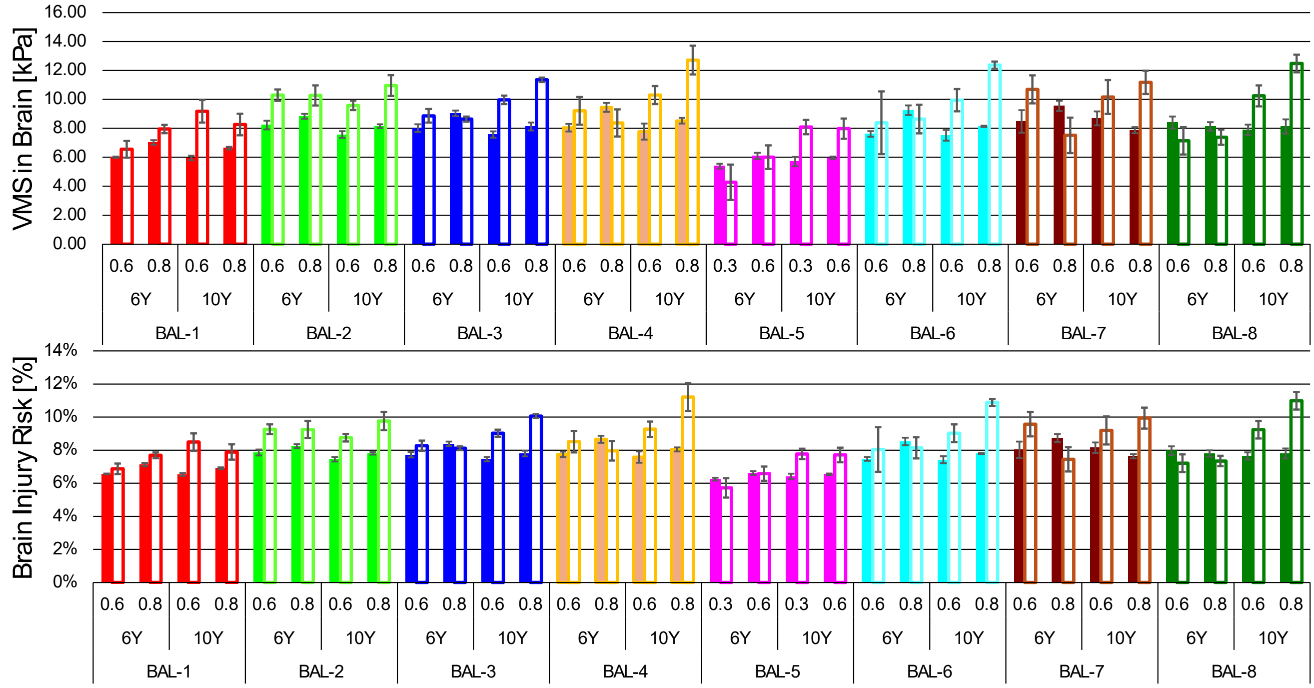

Fig. 8. Illustration of the Average brain VMS and the associated brain injury risk in terms of loss of consciousness for Different Balls and Dummy Heads (solid bar in FRONTAL impact, Empty bars LATERAL impact).

Fig. 7 and Fig. 8 present the kinematic in terms of resultant values and injury risk data for frontal and lateral impacts on 6-year-old (6Y) and 10-year-old (10Y) Hybrid III dummy heads across eight different soccer balls at two pressure levels (0.3-0.8 bar) and a 50 km/h impact velocity. The key parameters analysed include peak linear acceleration (PLA), peak rotational acceleration (PRA), peak rotational velocity (PRV), maximum Von Mises Stress (VMS) in brain, and the associated brain injury risk in terms of loss of consciousness computed from the VMS value according to equation (1). The results show that softer and lighter balls, such as BALL-5 and BALL-1, produced the lowest PLA values, confirming their suitability for reducing head impact forces. Among these, BALL-5 at 0.3 bar had the lowest PLA (20.1 g) and PRA (2657 rad/s²) in frontal impact, significantly decreasing impact severity and reducing brain injury risk to 6.2% only. Conversely, heavier balls like BALL-2, BALL-4, BALL-6, and BALL-7 resulted in higher head accelerations, increasing concussion risk. BALL-4 at 0.8 bar, in lateral impact, recorded the highest PRV (18.5 ± 0.9 rad/s) and maximum VMS in the brain (12.7 kPa). The PLA values exceeded 40 g for some high-pressure balls.

Ball pressure had a significant impact on acceleration values, as increasing the pressure from 0.6 bar to 0.8 bar consistently resulted in higher PRA values, amplifying head trauma risk. For example, in the case of BALL-6, PRA increased from 3739 rad/s² at 0.6 bar to 4504 rad/s² at 0.8 bar, demonstrating that pressure significantly affects impact severity. Similarly, BALL-2 also showed a notable increase in acceleration values when pressure was raised, confirming that higher pressure increases the likelihood of concussion and brain injury risks. On the other hand, low-pressure configurations (0.3-0.6 bar) led to reduced rotational acceleration and lower VMS values, lowering the probability of brain trauma. This indicates that reducing ball pressure is an effective measure to mitigate head impact forces and prevent injuries in youth soccer.

The results also provide insight into the differences between the 6- and 10-year-old dummy heads. While the 10Y dummy heads exhibited slightly lower PRA and PRV values compared to the 6Y heads, the overall differences remained marginal (~1-2%). This suggests that both age groups are similarly vulnerable to head impacts, reinforcing the need for safety measures across all young players.

Using simulations of brain response, the computed VMS provided insight into the stress distribution within the brain tissue during impact. The results indicated that higher-pressure and heavier balls resulted in greater intracranial stress, increasing the risk of brain injury.

In terms of concussion probability, the lowest risks (5.7%-6.6%) were observed with Softballs (BALL-1, BALL-5) at lower pressures under lateral impact versus (6.2%-6.6%) under frontal impact. In contrast, heavier and high-pressure balls (BALL-4, BALL-6, BALL-7) lead to the highest risk values (8.5%-8.7% for frontal and 10.9%-11.2% for lateral), indicating a substantial risk of brain injury with pressure heavy balls.

In general, the risk of loss of consciousness is slightly higher in case of lateral impacts than under frontal impacts, as illustrated in Fig. 7 and Fig. 8. The balls that present the lowest risk are BALL-1 and BALL-5. These balls, due to their reduced mass and lower internal pressure, generate lower linear and rotational accelerations, thereby minimising intracerebral stress and reducing the probability of concussion. This observation confirms the protective advantage of using soft, low-pressure balls, particularly in youth soccer, where head safety is a primary concern.

Fig. 9 and Fig. 10 show the average risks of loss of consciousness as a function of ball mass, indicated by colour, and their pressure, represented by symbols (a square for the lower pressure and a circle for the higher pressure). It is clearly observed that lighter balls present lower risks, particularly for front impacts. For balls weighing between 350 g and 450 g, the trend is more nuanced.

Under lateral impacts, a ball impact on a 10-year-old dummy head at higher pressure presents a greater risk of loss of consciousness compared to impacts at lower pressure. Interestingly, the opposite trend is observed for the 6-year-old dummy head, where lower pressure leads to slightly higher risk under lateral impacts.

For frontal impacts, the risks associated with high and low pressure are approximately the same, regardless of the dummy head impacted. This highlights that while mass remains a dominant factor, the effect of pressure is more complex and varies depending on impact location and head size, emphasising the need for careful regulation of both ball mass and pressure in youth soccer.

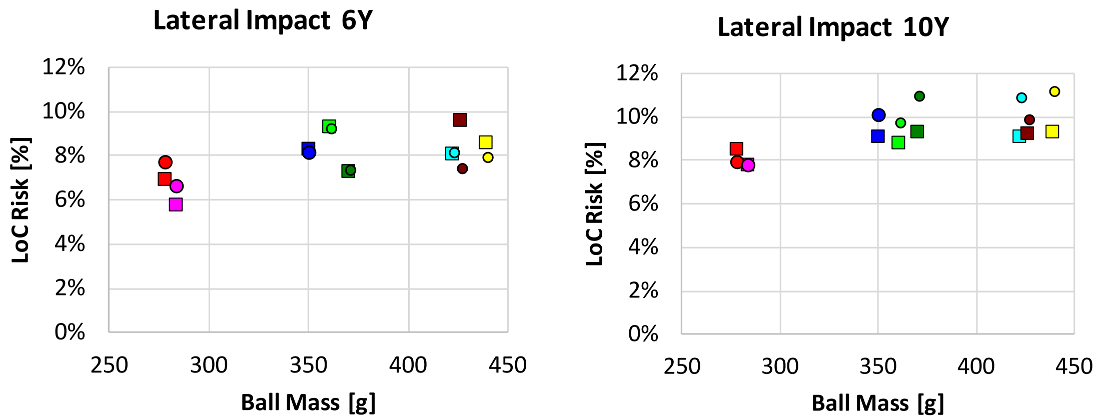

Fig. 9. Representation of loss of consciousness risks by head type under lateral impact as a function of ball mass (☐Low pressure: 0.3 - 0.6 bar; ○ High pressure: 0.6 - 0.8 bar).

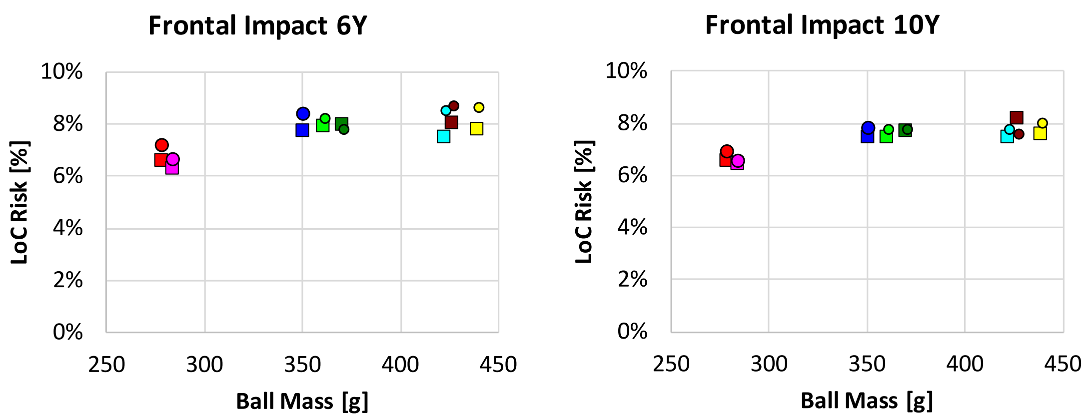

Fig. 10. Representation of loss of consciousness risks by head type under frontal impacts as a function of ball mass (☐Low pressure: 0.3 - 0.6 bar; ○ High pressure: 0.6 - 0.8 bar).

The average results in terms of loss of consciousness risk for each ball, calculated from the mean value of the maximum VMS in the brain across all frontal and lateral impacts at both pressure levels, vary slightly depending on the child's age. The average risks are marginally higher for the 10-year-old head compared to the 6-year-old head, although this difference remains very small given the experimental uncertainties.

The average maximum brain VMS values are computed for each ball, considering all impact configurations and both pressure conditions, along with the associated loss of consciousness risks. With the exception of BALL-1 and BALL-5, which show the lowest risk levels, the loss of consciousness risks for the other six balls are approximately 8.5%, highlighting the influence of ball properties on head injury severity.

IV. DISCUSSION

This study offers a comprehensive biomechanical evaluation of how soccer ball properties influence head impact severity in young players. Through controlled impact tests and numerical brain simulations, we demonstrated that softer, lower-pressure balls (e.g., BALL-1 and BALL-5) significantly reduce peak linear and rotational accelerations as well as intracranial stress, thereby decreasing concussion risk. Lateral impacts consistently produced more severe kinematic responses than frontal ones, reinforcing the importance of accounting for impact direction in injury risk assessments. Notably, differences between 6- and 10-year-old dummy head forms were minimal, suggesting that all youth players, regardless of age within this range, are similarly vulnerable to impact forces, supporting uniform safety regulations across youth categories.

These findings align with a growing body of evidence that heading or in general ball head impact, even when sub-concussive, can cause transient neurological disruptions. References [24-25] reported that repeated heading leads to immediate concussion-like symptoms, cognitive impairments, and altered brain-muscle communication. The study [26] further showed that postural stability is compromised after repetitive heading, effects that may accumulate with frequent exposure. While the study [27] found no evidence of reduced brain volume in habitual headings, biochemical studies such as [28] revealed increases in neurofilament light, a marker of axonal damage, after heading, pointing to subtle, possibly long-term neurological effects. These findings, together with our data, strengthen the case for limiting exposure to high-intensity ball-head impacts in youth.

Importantly, our results add nuance to the debate on whether ball material properties or speed play the dominant role in head loading. While our data highlight the role of pressure and mass in modulating kinematic response, the study by [29] offers critical complementary insight: using mathematical and human body models, they demonstrated that ball speed is the most influential factor in determining peak force to the head, more so than mass or stiffness. Their simulations indicated a direct linear relationship between speed and force, with only a square-root dependence on ball stiffness and mass. This suggests that reducing ball velocity during headers may yield the greatest protective effect. Such findings support strategies like rule modifications to limit high-speed aerial plays (e.g., rethinking goal kick rules or heading restrictions during certain phases of play), which could lower exposure to dangerous impact conditions without requiring radical changes to equipment.

The importance of equipment specifications is also reinforced by studies such as [12-26], and the recent review by [7], which show that lowering ball pressure within the allowed FIFA range reduces impact severity. FIFA's technical guidelines already recommend lighter and smaller balls for younger players (e.g., Size 3 or 4 for U-12), and our results validate these policies by showing marked reductions in PLA, PRA, and brain stress with low-pressure balls. Given that heavier, high-pressure balls caused the most severe impacts in our study, particularly BALL-4, BALL-6, and BALL-7, mandating pressure checks and restricting overinflation could be a simple yet effective injury prevention measure.

While the present study provides insights into head injury risks associated with soccer ball impacts in young players, several limitations should be acknowledged. The experiments were conducted using Hybrid III dummy heads, which, although widely used for biomechanical testing, cannot fully replicate the complex anatomical and physiological properties of a real human head, including variations in soft tissues, skull elasticity, and cerebrospinal fluid dynamics. Nevertheless, the methodology couples the experimental tests with numerical simulations using finite elements of the human head. The use of the numerical model aims at evaluating the brain injury risk by considering the skull as a non-deformable structure. It must be mentioned here that the brain FE model used in this study represents a standard adult head and was not scaled to children's heads. The reason is that brain mechanical properties and injury thresholds are supposed to be similar and that scaling down the model's geometry may affect computation results. Therefore, only the influence of children's head mass and moment of inertia on brain injury risk was considered in the present study. Furthermore, the brain injury risks examined in this study are based on real-world road accident data, with a threshold corresponding to a brief loss of consciousness, classified as AIS2. This injury severity level and its associated symptoms have been linked to brain von Mises (VM) stress in previous studies [22-23-31]. The present study hypothesizes that intra-cerebral VM stress remains a relevant metric, even under lower loading conditions.

Another limitation is that all tests were performed at a fixed impact speed of 50 km/h, which may not cover the full range of velocities encountered in real soccer matches, where heading speeds and accidental ball impacts vary significantly. The choice of an impact velocity of 50 km/h for this study is grounded in observations and measurements reported in several studies of soccer play dynamics, which identify this speed as representative of typical ball velocities encountered during headers and accidental impacts in youth and amateur soccer matches. According to [19-21], ball velocities during professional and competitive matches can range from 40 to 60 km/h during headings or short passes, with peaks up to 80-100 km/h for powerful shots. However, for youth categories, the average ball speeds are notably lower, typically between 30 and 55 km/h, given differences in player strength, ball mass, and game conditions. The study by [34] also highlights that the mean velocity of soccer balls during heading drills performed by adolescents falls within the range of 40 to 55 km/h, depending on age group and ball properties. Similarly, [35] indicate that ball impacts during youth play frequently reach 45-50 km/h when delivered by standard kicks or passes, providing a realistic basis for simulating typical in-game scenarios. Moreover, [36] emphasise that for realistic laboratory replication of soccer impacts, test protocols generally adopt velocities between 45 and 60 km/h, ensuring that results are directly applicable to on-field situations without underestimating potential risks. In conclusion, selecting 50 km/h as the reference impact speed in this study corresponds to the reasonable ball speed encountered by youth players in real match conditions. This choice allows the experimental setup to realistically simulate typical headings and ball-head collisions experienced in children's soccer, making the results directly relevant for injury risk evaluation and equipment safety recommendations.

Another limitation of the proposed approach is the boundary condition of the head. Indeed, the controlled nature of the laboratory environment does not account for in-game variables, such as player movement, neck muscle activation, neck stiffness, and unanticipated impact angles, which can influence head response and injury risk. Moreover, only frontal and lateral impacts were studied. Other impact locations, such as oblique angles or top-of-head impacts, may also present different biomechanical responses and were not included in this analysis. According to [35], neck muscle activation prior to impact can significantly reduce head acceleration, as a tensed neck absorbs and redistributes forces. This factor cannot be replicated in static dummy head tests, where the neck is passive and does not react to incoming impacts. Additionally, impact angles in real matches are rarely perfectly frontal or lateral; oblique impacts introduce complex rotational forces and are associated with higher concussion risk according to [37]. In this study, the headform is freely suspended by a rope from its base to eliminate the influence of neck dynamics. Although this setup allows for standardised and reproducible measures and simplifies the complexity of real-life situations. As a result, it may either underestimate or overestimate the true injury risk by not accounting for factors such as neck stiffness, muscle activation, and reactive movements that occur during actual play but can approach accidental situations for which unexpected impacts occur. In addition, in the present study the influence of the ball property on the impression to the player when kicking it with the foot has not been considered. Adoption of a softer ball with lower inflation pressure may face hurdles from players who want characteristics of faster ball.

By recognising these limitations, future research can aim to incorporate more complex impact scenarios, broader age ranges, player-specific physiological factors, and longitudinal studies to fully understand and mitigate head injury risks in youth soccer, especially when repeated concussion is considered.

V. CONCLUSION

This study highlights that the severity of head impacts during ball collisions is strongly influenced by the ball's mass and internal pressure. Lower-mass and lower-pressure balls are associated with significantly lower peak accelerations and reduced risks of loss of consciousness, particularly under frontal impacts. Conversely, heavier and more rigid balls tend to increase both linear and rotational accelerations, resulting in higher biomechanical loads to the brain and greater injury risk. The age of the child also has a slight influence, with older children's headforms (10-year-old) exhibiting marginally higher risks compared to younger ones (6-year-old). These findings emphasise the importance of carefully selected ball characteristics, particularly for use with young children, to minimise head injury risks. In particular, using lighter, softer, and moderately pressurised balls can significantly contribute to safer play conditions in youth sports. Indeed, the results showed that peak linear accelerations (PLA) generally range between 30 and 40 g, with the exception of a soft ball with low mass, which shows lower values around 20 g at a pressure of 0.3 bar. Maximum rotational velocities are observed between 10 and 15 rad/s. Higher ball pressure and greater mass are associated with increased PLA, rotational accelerations, and consequently, a higher risk of loss of consciousness. Overall, lateral impacts present slightly higher risks compared to frontal impacts. The balls associated with the lowest risk levels are a light softball with a low-mass and low-pressure softball. The analysis highlights that lighter balls tend to produce lower risks, particularly in frontal impacts, while for medium-weight balls (between 350 and 450 grams), higher pressure can increase risks, especially in lateral impacts on 10-year-old headforms. In contrast, the opposite trend is observed for 6-year-old headforms. When considering all configurations, except for the lighter, the average risk of loss of consciousness across the other balls is around 8.5%.

The findings emphasise that adopting lightweight, moderately pressurised balls can significantly contribute to safer sporting environments for children. This research lays the groundwork for developing science-based equipment standards and regulatory recommendations aimed at injury prevention. Ultimately, this study highlights the importance of tailoring sports equipment design to the physiological characteristics of young athletes, ensuring both performance and safety in youth sports practice.

Finally, an original experimental versus numerical approach was applied to assess brain injury risk in case of heading as it often happens in soccer playing. To the author's knowledge it is the first time that not just global head kinematic parameters are considered but also tissue level metrics and injury risk. Proposed results should be considered for the estimation of brain injury risk in case of unique impact but can also be the basis of future research towards repeated concussion.

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VII. REFERENCES

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