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ORIGINAL ARTICLE

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Force experienced by the head during heading is influenced more by speed than the mechanical properties of the football

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There are growing concerns about the risk of neurodegenerative diseases associated with heading in football. It is essential to understand the biomechanics of football heading to guide player protection strategies to reduce the severity of the impact. The aim of this study was to assess the effect of football speed, mass, and stiffness on the forces experienced during football heading using mathematical and human body computational model simulations. Previous research indicates that a football header can be modeled as a lumped mass mathematical model with elastic contact. Football headers were then reconstructed using a human body modeling approach. Simulations were run by independently varying the football mass, speed, and stiffness. Peak contact force experienced by the head was extracted from each simulation. The mathematical and human body computational model simulations indicate that the force experienced by the head was directly proportional to the speed of the ball and directly proportional to the square root of the ball stiffness and mass. Over the practical range of ball speed, mass, and stiffness, the force experienced by the head during football heading is mainly influenced by the speed of the ball rather than its mass or stiffness. The findings suggest that it would be more beneficial to develop player protection strategies that aim to reduce the speed at which the ball is traveling when headed by a player. Law changes reducing high ball speeds could be trialed at certain age grades or as a phased introduction to football heading.

KEYWORDS

biomechanics, computational modeling, head injury

1 | INTRODUCTION

There are growing concerns about the risk of several neurodegenerative diseases associated with heading in football.[1] The bulk of research on the effects of football heading has resulted in contradictory and inconclusive findings.[2] However, a recent retrospective cohort study was undertaken comparing mortality from neurodegenerative disease among professional soccer players with that among matched controls from the general population.[3] The study identified that although professional football players lived longer than the general population and were at less risk of death from ischemic heart disease and lung cancer, they were roughly 3.5 times more likely to die from neurodegenerative disease, including 5.1 times more likely to die from Alzheimer's disease and 4.3 times more likely to die from motor neuron disease.[3] The former findings agree with the strong evidence base that participation in sport has lifelong mental and physical health benefits as well as the general consensus that exercise is preventative medicine and crucial to public health.[4] However, the fear of short- and long-term health consequences from football heading could prevent children and the young adult population participating in football.[1] Therefore, not only are there concerns that football heading can lead to long-term neurodegeneration, there is a possible wider effect that it can reduce overall football participation among the general population and thus have an adverse effect on public health. As a result of the study,[3] the Football Association issued new guidance on heading in youth football training.[5] The guidance advised no heading in primary school age pupils and a graduated approach to heading in children aged between 12 and 16 during training. Additionally, footballs should be age appropriate sized and at the lowest pressure authorized in the Laws of the Game.[5]

A proactive approach to football heading would be to identify player protection strategies that reduce the severity of a header impact without considerable changes to the dynamics of the game. An essential first step is to further understand the biomechanics of football heading. Nuanheim et al[6] found that available headgear for football heading illustrated poor ability to attenuate impact during typical football header reconstructions with a dummy headform. Nuanheim et al[6] explained that the difference in stiffness between the compliant football and head leaves the head nearly undeformed during a header (no headgear), while the football deforms considerably. For a header with headgear, since the football is already compliant relative to the head, the relatively small deformation of the headgear is ineffective at attenuating the impact.

Most footballs can be broken down into four main layers or components: bladder, fabric, foam, and skin.[7] A football experiences thousands of impacts of varying severity in a single football match and is expected to have a lifetime of several years.[7] The football must be within established ranges for circumference, weight, and internal pressure while meeting FIFA standards for shape deviation, water absorbency, rebound and internal pressure, shape, and size retention.[7] Manufacturers also place considerable importance on aerodynamic stability for long shots.[7] The football may provide an opportunity to reduce the forces experienced during heading through design manipulation. However, this is a delicate balance and it is important to not disrupt the dynamics and skills of the game and a theoretical assessment of the potential gains from this approach is missing.

Head kinematic magnitudes (linear accelerations, rotational velocities, and rotational accelerations) are frequently used in brain injury metrics, and these kinematics are largely driven by the location and magnitude of the contact forces experienced by the head during an impact event.[8] One study using instrumented mouthpieces found that median head peak linear accelerations, rotational velocities, and rotational accelerations in female youth football were 9.4 g, 4.1 rad/s, and 689 rad/s^2, respectively.[9] The study also found that the head kinematics ranged up to 40.6 g, 15.3 rad/s, and 3078 rad/s^2. By comparison, the average values reported in the literature for concussions in adult males are roughly 100 g, 33 rad/s, and 5000 rad/s^2.[8] Shewchenko et al[10] utilized MADYMO human body model simulations and human subject trials to assess the effect of football mechanical properties on head response. Human body model simulations based on Newtonian mechanics allow sport impacts to be reconstructed in a highly controlled environment.[11] The approach can enable researchers to assess the influence of mechanical, structural, and contact properties (eg, mass, stiffness, and friction) and initial conditions (eg, velocity) on simulation outputs. The human subject trials indicated that head linear and angular accelerations measured using an instrumented mouthpiece ranged from 11.9-22.0 g and 1020-2580 rad/s^2, respectively, for controlled headers at football speeds of 7.2-8.0 m/s. Shewchenko et al[10] found that football mass reductions up to 35% resulted in decreased head responses up to 23%-35% for the model and subject trials. Football pressure reductions of 50% resulted in head response reductions up to 10%-31% for the model and subject trials.

To reduce the impact severity of a given header, we would want to reduce the contact force experienced by the head during the impact. However, the relationship between peak force and football mass, stiffness, and speed has not been adequately assessed. The aim of this study was to develop a predictive lumped mass mathematical model (hereafter "mathematical model") that assessed the effect of football speed, mass, and stiffness (influenced by football pressure and material properties)[10,12] on the forces experienced during football heading. Football headers were then reconstructed using human body model simulations to assess the predictions of the mathematical model.

2 | METHODS

2.1 | Mathematical model

Previous research has illustrated that the difference in stiffness between the compliant football and head leaves the head nearly undeformed during a header.[6] Additionally, compression and drop-testing found footballs to be primarily elastic in nature at a range of football pressures.[10,12] This indicates that a football header can be modeled as a predictive lumped mass model with elastic contact (Equation 1; see Appendix A for derivation).

$$F_{Head} = v\sqrt{mk} \quad (1)$$

where F_{Head} is the peak force experience by the head. v is the velocity of the football at impact. m and k are the mass and stiffness of the football, respectively.

2.2 | Human body model

The MADYMO ellipsoid human body model was used for simulating contact forces during the football header reconstructions. The model comprises of 52 rigid bodies connected by kinematic joints with ellipsoids for surface representation and contact evaluation.[11] The model was originally developed for vehicle-pedestrian impact modeling and validated for numerous blunt impact locations.[13-18] The model provides reasonable predictions for head translations, rotations, head impact time, and head impact velocity in pedestrian collisions.[19] The model has been used to assess head accelerations and neck forces in automotive research.[20-22] Additionally, MADYMO multibody human body models have been used as a tool for investigating head kinematics during headers in football[10] and impacts in rugby and Australian rules football.[8,11,23-25] A recent analysis identified that the MADYMO pedestrian model is considered suitable for preliminary impact analysis in sport, with a focus more on trends than absolute values of kinematic and dynamic predictions..[26]

2.3 | Football header reconstructions

The average player head-neck orientation and football velocity angle identified by Shewchenko et al[10] were simulated for the football header reconstruction (Figure 1). Using a customized Matlab script together with the MADYSCALE function, the model mass, moments of inertia, and height were scaled based on the average UK male (175.3 cm and 83.6 kg, respectively).[27] The coefficient of friction for head-to-football contact was set at 0.5.[28] Head-to-football contact evaluations were applied using the average football stiffness (35.4 kN/m) reported for a dry football at 0.8 bar[10] and the built-in MADYMO contact stiffness function for the head. The football mass was set at 0.403 kg and radius at 0.11 m to represent a dry football at 0.8 bar.[10] The moment of inertia was calculated based on a hollow sphere.[29] All simulations were run with a maximum level of muscle activation represented by locking all of the human body model joints. The locked joint condition results in the joints remaining rigid representing maximum bracing. The simulations were run for 35 ms to provide sufficient time for peak force values to be reached. An integration time step of 1e-5 s was used.

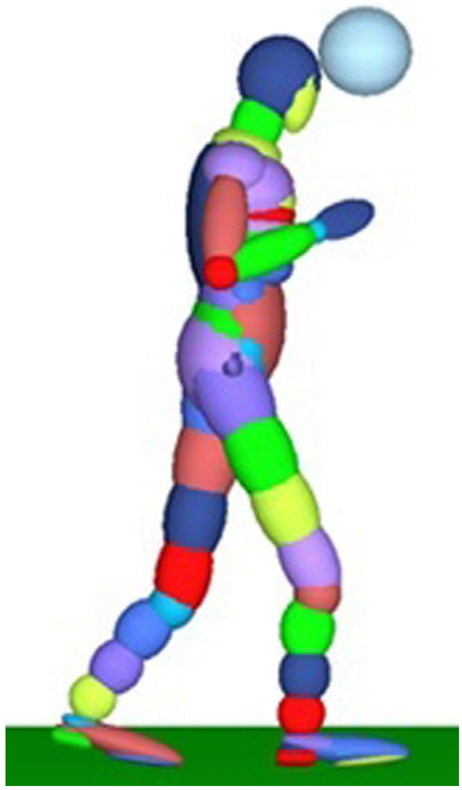

FIGURE 1 MADYMO human body model football header reconstruction

2.3.1 | Speed analysis

The highest speed football a player would voluntarily head is believed to be 85 km/h (23.6 m/s) and from a goal kick.[30] However, most headers occur at football speeds less than 65 km/h (18.1 m/s).[30] Therefore, the speed of the football was varied from 2 to 24 m/s in increments of 2 m/s. The football mass and stiffness remained constant at 0.403 kg and 35.4 kN/m.

2.3.2 | Mass analysis

The football mass tested by Shewchenko et al[10] ranged from 0.299 to 0.604 kg. Therefore, the mass of the football was varied from 0.25 to 0.65 kg in increments of 0.05 kg. The football speed and stiffness remained constant at 10 m/s and 35.4 kN/m.

2.3.3 | Stiffness analysis

The football stiffness tested by Shewchenko et al[10] at 0.8 bar ranged from 25.9 to 43.7 kN/m. Therefore, the stiffness of the football was varied from 25 to 45 kN/m in increments of 2 kN/m. The football speed and mass remained constant at 10 m/s and 0.403 kg.

2.4 | Data analysis

The peak elastic contact force experienced by the head was extracted from each simulation. Based on Equation 1, a one-term power series model given by $y = ax^b$ where a and b are constants was fitted to the mathematical and simulation results using the MATLAB "fit" function for the speed, mass, and stiffness analysis.

2.5 | Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of the human body model and football properties on the predicted peak force based predominantly on a protocol developed by Fréchède and Mcintosh.[23] The simulations were run with a low- and high-level parameter value for each parameter (Table 1). For the human body model head contact stiffness, the simulations were run at a low level of -20% contact stiffness and a high level of +20% contact stiffness. Low- and high-level stiffness conditions were established by decreasing/increasing the slope of the force vs displacement relationship for the head in the human body model.[11] To gain a generalized understanding of the influence of neck strength, simulations were run using an unlocked neck joint condition. The condition results in the joints of the neck being free to articulate within the physiological range of motion with minimal resistance and thus represent minimal neck strength.[11] To assess the influence of head velocity, the simulations were run with the unlocked neck joint condition with an initial head velocity of 2.84 m/s at contact.[10]

3 | RESULTS

3.1 | Speed analysis

The mathematical model illustrates that the force experienced by the head is directly proportional to the speed of the football, indicated by coefficient $b = 1$ ($y = ax^b$) in Figure 2A. Coefficient b differs by 3% in the MADYMO simulation results ($b = 1.03$). However, separately $b = 1$ between 2-20 m/s and 20-24 m/s though the gradients of the lines are different for these two intervals (Figure 2A). For the mathematical model, the coefficient $a = 119.4$ is based on the square root of the product of the football mass and stiffness ($\sqrt{mk}$) which is higher than the MADYMO simulation results ($a = 102.4$).

TABLE 1 Parameters for the sensitivity analysis with the low and high levels

Parameter	Original	Low level	High level
Ball velocity angle	33°	28°	38°
Friction	0.50	0.35	0.65
Head stiffness	±0%	−20%	+20%
Head angle	−20°	−15°	−25°
Human body model mass	83.6 kg	73.6 kg	93.6 kg
Head velocity	0 m/s	N/A	2.84 m/s
Neck strength	Maximum	Minimum	N/A

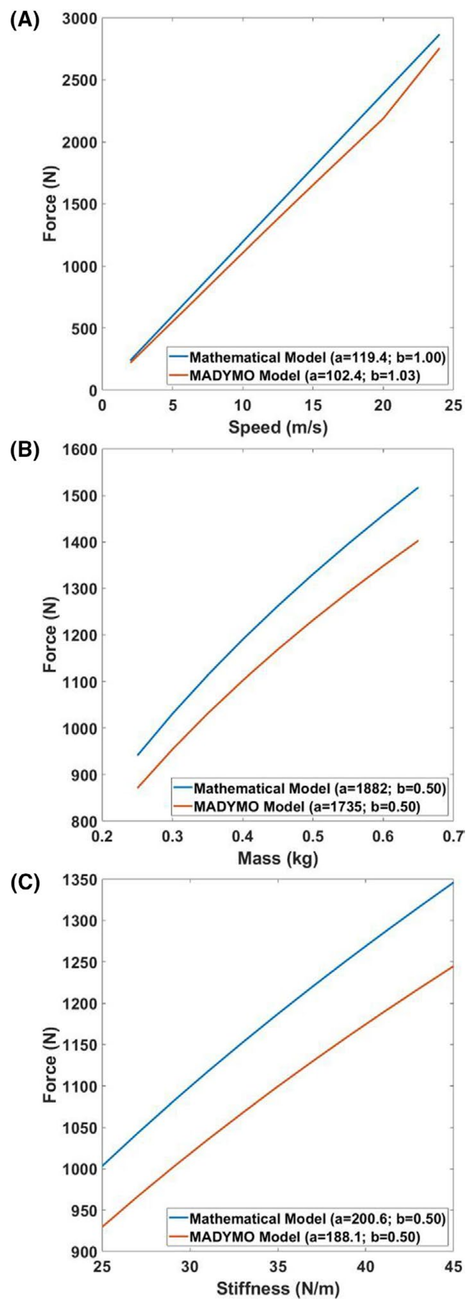

FIGURE 2 The effect of football (A) speed, (B) mass and (C) stiffness on the peak force experienced by the head during the football header reconstructions with coefficients a and b from the power series model ($y = ax^b$)

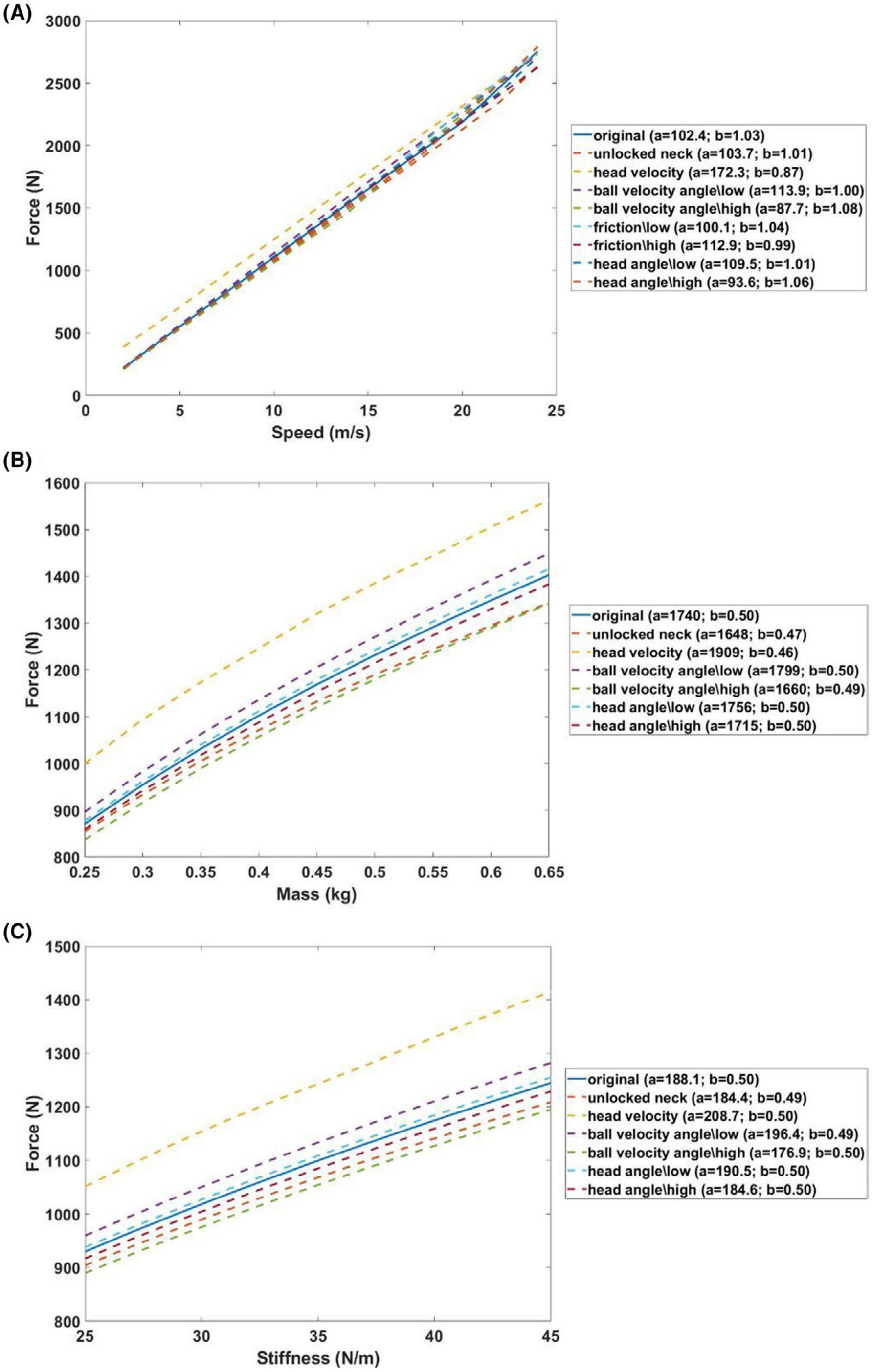

FIGURE 3 The influence of the human body model and football parameters on the predicted peak force experienced by the head for the (A) speed, (B) mass, and (C) stiffness analysis with coefficients a and b from the power series model ($y = ax^b$). Parameters with negligible influence on the coefficients a and b (<0.5% difference) compared to the original simulations were not plotted

3.2 | Mass analysis

The mathematical and MADYMO simulation model illustrates that the force experienced by the head is directly proportional to the square root of the mass of the football, indicated by coefficient $b = 0.5$ ($y = ax^b$) in Figure 2B. For the mathematical model, the coefficient $a = 1882$ is based on the football speed multiplied by the square root of the football stiffness ($v\sqrt{k}$) which is higher than the MADYMO simulation results ($a = 1735$).

3.3 | Stiffness analysis

Similarly, the mathematical and MADYMO simulation model illustrates that the force experienced by the head is directly proportional to the square root of the stiffness of the football, indicated by coefficient $b = 0.5$ ($y = ax^b$) in Figure 2C. For the mathematical model, the coefficient $a = 200.6$ is based on the football speed multiplied by the square root of the football mass ($v\sqrt{m}$) which is higher than the MADYMO simulation results ($a = 188.1$).

3.4 | Sensitivity analysis

The sensitivity analysis indicates that the human body model and football parameters influence the predicted peak force experienced by the head (Figure 3). For the speed and mass analysis, the head velocity parameter plays the most significant role. For the stiffness analysis, the head velocity parameter plays the most significant role for coefficient *a,* while neck strength (unlocked neck) and football velocity angle are the only two parameters that influence coefficient *b* ($b = 0.49$ for both).

4 | DISCUSSION

Mathematical and human body computational model simulations indicate that the force experienced by the head during football heading is influenced more by the speed of the ball than its mass or stiffness. The findings provide initial guidance for the development of player protection strategies on the basis that reducing the force experienced by the head could reduce the potential adverse effects of heading on brain health.[1,3] However, there is clearly a need for prospective longitudinal studies taking into account concussion history and overall head impact exposure to draw this conclusion.[31] Additionally, there is a need for more research on the head impact exposure from heading in football at youth, amateur and elite level.

The offset for coefficient *b* in the speed analysis and *a* for all analyses between the mathematical model and human body computational model simulation results is believed to be due to the human body model head not being a rigid flat surface as depicted in the mathematical model (Appendix A). Minor deformation of the head was represented in the simulations. Additionally, the curvature of the head combined with a non-zero incidence angle of the football reduced the elastic contact force and caused contact friction resulting in some kinetic energy of the football being converted into rotational kinetic energy. The abovementioned factors reduced the elastic contact force on the head and thus coefficient *a* and *b*.

At 85 km/h (23.6 m/s), the goal kick appears to cause the highest speed football a player would voluntarily head in a match scenario.[30] Goal kick law changes could provide an opportunity to reduce the maximum football speeds at which players head the ball at. For example, this could include replacing goal kicks with throws/roll-outs or head-height rules at certain age grades as part of a phased introduction to heading. However, rule changes can lead to unintended consequences and increased injury rates, and thus, head impact exposure and injury monitoring would be essential.[32] Additionally, more research is needed to understand phase of play-specific football speeds at which headers occur. A new goal kick law trial where the ball is in play once kicked and can be played before leaving the penalty area was introduced in 2019/20.[33] This increases the options available to the goalkeeper encouraging short passes along the ground, rather than longer, higher speed kick-outs. The International Football Association Board increased the sanction for illegal play involving contact with an opponents' head to a red card which appeared to reduce head injury risk.[34]

Football mass and stiffness are influenced by football pressure and material properties. Previous research found that reducing a football pressure from 0.8 to 0.4 bar reduced the contact stiffness by 50% but had negligible influence on the mass. This provides an opportunity to reduce the force experienced by the head during football heading through football redesign, though much greater relative reductions are needed. For example, to reduce the force experienced by the head by 50%, we would need to reduce the football stiffness or mass or the product of the two (mass multiplied by stiffness) by 75%. A reduction of football speed of only 50% is needed for the same effect. However, reductions to the football stiffness and mass may reduce the speed at which the ball can be kicked and influence the aerodynamics which could have the added benefit of reducing header speeds. Aerodynamic stability and effects on player kicking and control technique would need to be considered.

The main limitation of this study is that a stationary head with maximal neck strength was simulated which is unrealistic in football. Though the principal findings were not influenced by a sensitivity analysis that assessed minimal neck strength and head speed, the interpretation of the results of this study should focus more on the trends identified than the absolute values of force prediction.[26] Future work should focus on human trials and field-based research using instrumented mouthpieces and footballs to gain accurate values of kinematic and dynamic predictions.[35] Human body models could be further validated for sports impacts using motion capture laboratory trials and/or real-world impact modeling using multiple camera view video footage.[36-38] The model used in this study is a passive model, and hence, active neck muscles could not be simulated or assessed. The development of active human body models has become a promising prospect in sport impact analysis.[39] These models enable active muscle behavior to be exhibited by the model during an impact scenario. However, the models require muscle activation parameters as initial conditions which are not yet fully known but could be measured through motion capture laboratory trials with electromyography (EMG).[39] For future work, motion capture laboratory trials and field-based research could be explored to assess the influence of neck strength as well as neck strengthening programmes in combating the severity of football headers. Additionally, instrumented mouthpieces combined with wither 2D/3D video calibration techniques or instrumented footballs could be used to assess the effect of ball speed on head response in real match scenarios.[40]

5 | PERSPECTIVE

The mathematical and human body computational model simulations indicate that the force experienced by the head was directly proportional to the speed of the ball (3% difference between mathematical and human body model results) and directly proportional to the square root of the ball stiffness and mass. The force experienced by the head during football heading appears to be mainly influenced by the speed of the ball rather than its mechanical properties. The findings suggest that it would be more beneficial to develop player protection strategies that aim to reduce the speed at which players head the ball at. These strategies could be introduced and trialed at certain age grades or as a phased introduction to football heading. For example, this could include replacing goal kicks which result in the highest heading ball speeds with throws or head-height rules at certain age grades as part of a phased introduction to heading.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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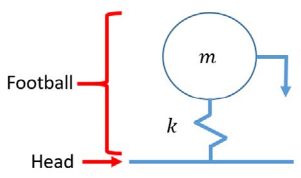
APPENDIX A

Derivation of the football header lumped mass model with elastic contact.



m = Football Mass
k = Football Stiffness
ω_n = Football Natural Frequency
x = Football Displacement
v = Football Velocity
a = Football Acceleration
F_{Head} = Peak Force Experienced by Football/Head

Spring mass system to represent head impact:

$$m\ddot{x}(t) + kx(t) = 0; \qquad \omega_n = \sqrt{\frac{k}{m}}$$

$$x(t) = x(0)\cos(\omega_n t) + \frac{\dot{x}(0)}{\omega_n}\sin(\omega_n t)$$

for known $x(0) = 0$ and $\dot{x}(0) = v$;

$$x(t) = \frac{v}{\omega_n}\sin\omega_n t$$

$$\dot{x}(t) = v(t) = v\cos\omega_n t$$

$$\ddot{x}(t) = a(t) = -v\,\omega_n \sin\omega_n t = -v\sqrt{\frac{k}{m}}\sin\omega_n t$$

$$F(t) = -v\sqrt{mk}\,\sin\omega_n t$$

$$F_{Head} = v\sqrt{mk}$$