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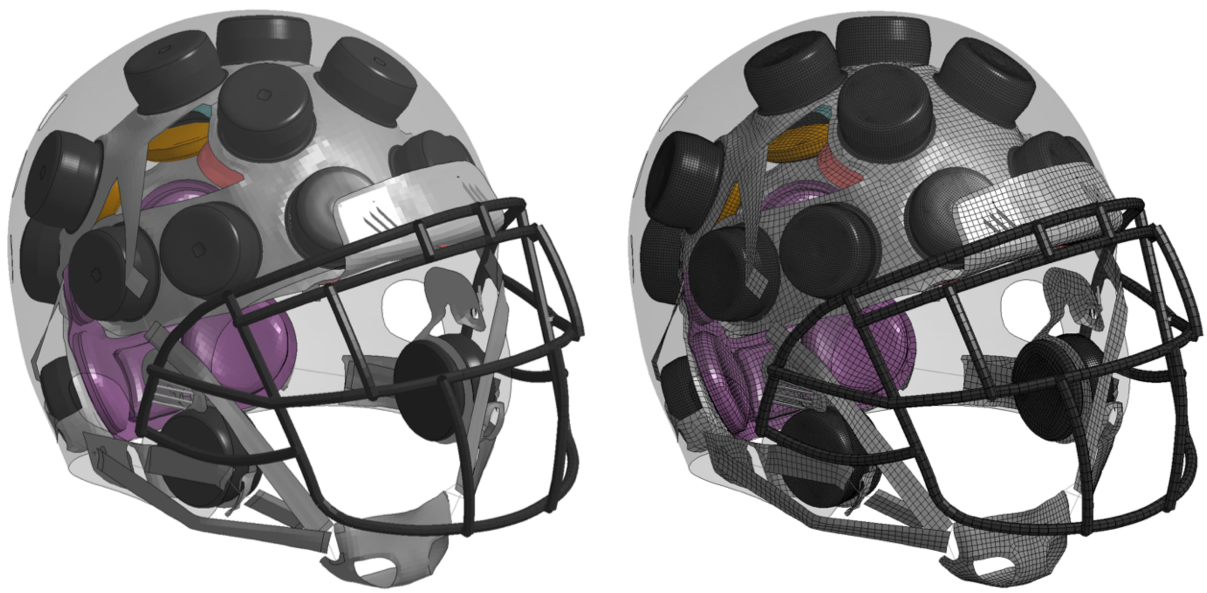
12/12/19
Independent Study

Modeling Head Impacts to Improve Understanding of the Mechanics of Traumatic Brain Injury in Sport

Traumatic brain injury is one of many types head injuries that occurs in sports, but it is also one of the most dangerous due to the possible long-term consequences on brain function. This has prompted sporting leagues such as the NFL and the UFC to alter rules and invest large amount of money into further research to increase the safety of its athletes. Our knowledge of brain injuries is slowly evolving because of the complexity and the vast inner mechanisms of neural tissue. In this paper I will evaluate how impact location, kinetics and interface with the head/headgear change the rotational and linear kinematics of the head in two specific sports: American football and Boxing/Mixed Martial arts. This analysis of the observable head impact will be used to predict the behavior and deformation of the brain and neural tissue within the skull. These two sports have highlighted specifically because of the highly public concussion issue in football that has been has shed light on another long-term brain disease, chronic traumatic encephalopathy (CTE). Boxing/MMA will also be evaluated because of how the sport relies on head contact as a goal of competition and the recent rise of the UFC's popularity as a sporting league as well as the high mortality rate among boxers in competition, there have been 339 deaths between 1950 and 2007 with mean age being 24±3.8 years old (Baird, 2010). In addition to my analysis of head impacts, I will propose theoretical ideas into future areas of research.

To analyze this impact, I will be utilizing classical mechanical physics equations based on Newton's laws. Newtons second law: $\vec{F}_{net} = \sum_i \vec{F}_i = \sum_i m\vec{a}_i$ will be the base upon how we observe all impacts as well as Newton's first law of inertia and third law of reactionary forces. This will provide the base for my evaluations of linear kinematics of the head after impact. Because I am analyzing a three dimensional object moving and rotating in all three planes of motion I will also be using the angular corollary to Newton's second law: $\vec{\tau}_{net} = \sum_i \vec{\tau}_i = \sum_i I\vec{\alpha}_i = \sum_i(\vec{F}_i \times \vec{r}_i)$ to see how the point of impact will affect the rotation of the skull in the transverse, sagittal and frontal planes of motion. When analyzing specific interaction between a glove and head or a helmet to helmet hit, I will be utilizing the impulse equation: $\Delta p = F\Delta t = m\Delta v$ of how long the interaction lasts and how an increased or decreased time will affect the force applied to the head. Other factors that are considered in each impact evaluation will be the counteracting force and torque on the head from neck musculature that will cause the deceleration to the initial impulse. Each collision is not entirely elastic and there will be some loss of mechanical energy to deformation of gloves, helmets, face and possible the bone and connective tissue as well so the entire impact force will not be transmitted entirely to the brain. Because the brain itself is held in place with cranial meninges and held in cerebrospinal fluid, these anatomical structures will also take part in decelerating the brain as it moves inside the cranium. To model this, I will incorporate a driven the dampened harmonic oscillation differential equation with an impulse function as the driving force to display the head impact. $m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = g_{\Delta t}(t)$. Where m is mass of the brain, b is the friction coefficient, k is the spring constant and $g_{\Delta t}(t)$ is the impulse function that is equal to the force delivered over the given Δt. After the Δt, the driving force is equal to zero causing the oscillation to dampen. The differential equation above will not be solved due to the complexity and dependency on each component involved, I will only be using it to describe and predict how the brain will accelerate and how this will affect the brain's impact with the inside of the skull.

In American Football, rules have evolved to protect players from head to head contact as well as implemented stricter concussion policies. This has helped decrease the frequency of severe head injuries, but they are still prevelent. Two main type of impacts occur to the head area, from a player tackling another and leading with a body part (head, shoulder, etc.) into the other players head or having a head impact the ground. Starting with the player to player contact, both players wear shoulder pads and helmets. The padding in the helmet is used to absorb some mechanical stress and increase the force application time (Figure 1). This gear is implemented to

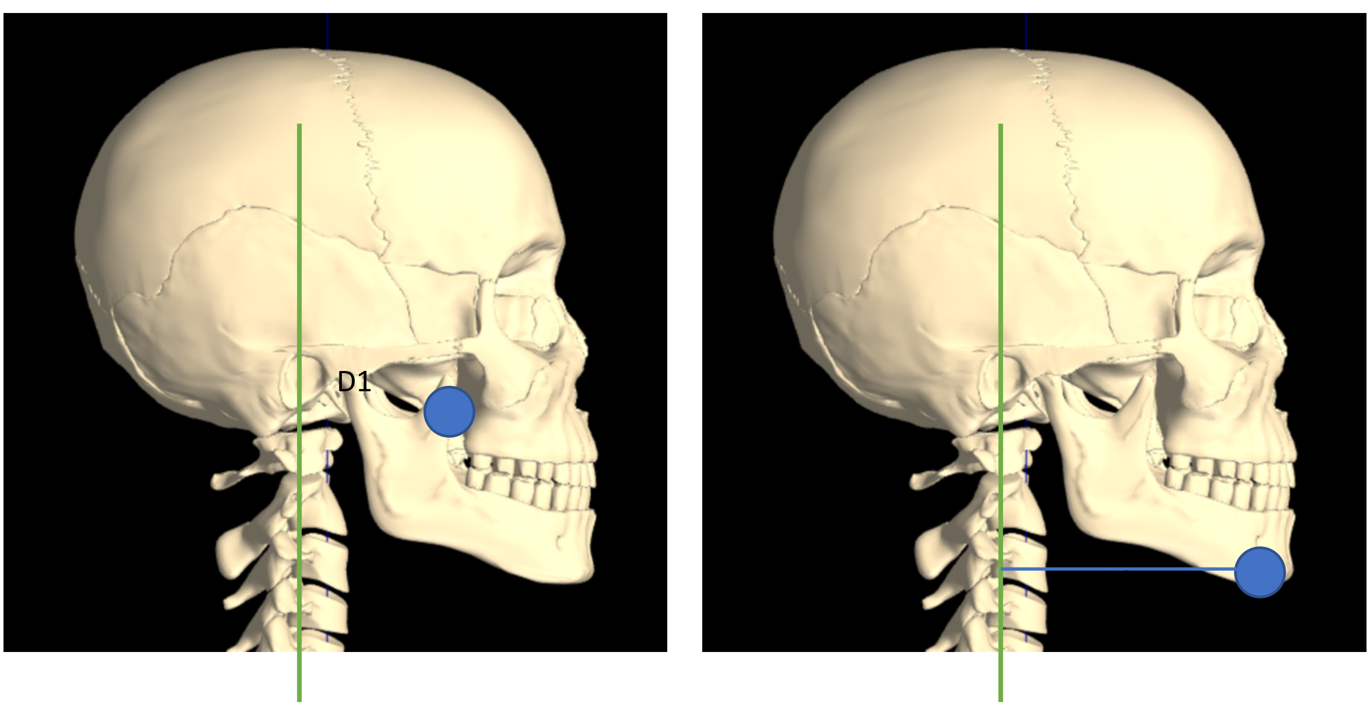


reduce injuries of players, but also increases the mass of each player when modeled as a projectile. The average weight of defensive players is between 200 and 300 pounds, depending on position. (Figure 1: Helmet design incorporate padding under shell to decrease linear acceleration) With pads and helmets on this can increase another 10-15 pounds. On the other side, the player who is being hit the pads and helmet will increase their mass and their moment of inertia. As a defensive player launches into an offensive player for a tackle, they can be modeled as a projectile with an acceleration and mass that will collide with the offensive player at a point of impact. The location of the impact will affect the linear and rotational accelerations.

A hit near the base of the head (closer to the occipitoatlantal joint) will have a much smaller moment arm for torque on the players head leading to lower rotational acceleration in the transverse plane. However, rotation in the frontal and sagittal plane incorporate moment arms to each individual intervertebral joint in the neck leading to rotational acceleration in sagittal or frontal planes. This is due to the close proximity the impact is to the skulls center of mass, leading to higher amounts of linear translation of the cranium in direction of force application and more production of torque in the neck to decelerate the head. These impacts can occur at very high collision relative velocities between players as they are moving towards each other. Both players have high momentum due to large masses and velocities ($p = mv$). As they collide the momentum of the head can change at a an extremely fast rate. Looking at impulse, the change in momentum with the respect to time will be the force applied. The helmet and padding are designed to increase this interaction time by dissipating some of the mechanical energy. However, due to the massive momenta of players and using the entire body as a projectile, a large amount of force is still transmitted to the head. This is also found by Mazdak et al. (2017) in their computational modelling of American football head to head impacts. They found the highest amount of translational acceleration in the frontal plane by the head moving right to left or left to right depending on the side of impact. They also found that the highest amount of rotational acceleration occurred posterior-anterior and inferior-superior. This means there was less rotation left to right/right-left in the transverse plane. When tackling in American football the goal is to stop the opposing player where they are hit, which leads to more direct contact and less contact at an angle which is consistent with findings of higher translational accelerations than rotational. When using this to predict brain trauma, the impulse force will be much higher due to described effects of using the entire body to hit, but the angle the force is applied at will lead to an oscillation that causes a high amount of compression force. Looking at the differential equation, $m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = g_{\Delta t}(t)$. The values m, b and k are all specific to the anatomical characteristics of the brain and other neural tissue, so a larger $g_{\Delta t}(t)$ exterior force function will cause higher accelerations and velocity of the brain within the cranium. This means the impact of the brain into the cranium will cause compression and deformation of the neural tissue leading to high likelihood of damage. Head impacts with the ground present a similar issue, as the head accelerates toward the ground, there is an almost immediate change in momentum as the head impacts the ground due to the inability of the ground to move. This change of momentum is often larger, and the direction of impact is straight on. The brain will continue to accelerate once the head hits the ground causing the brain to impact the area of the cranium that hit the ground. This impact force then causes the translational oscillation as described before. Overall, impacts in football lead to a larger amount of translational movement of the head and brain rather than rotational. This leads to increased compressional forces as opposed to shear or torsional.

Moving into combat sports, I will be highlighting how the different gloves effect the impact and energy transfer as well as in MMA the utilization of kicks, elbow and knees to the head. Boxing has been around for a much longer time than MMA leading to more diverse studies and research into the sport and the injuries that come with it. The first description of CTE in boxers as reported in 1928 (Bernick, 2013) but consistent research into the subject has not been established until recently. Mixed Martial Arts have seen a massive rise in popularity over the past 5-6 years, this has also allowed the investment into safety and health for their fighters. In the world's largest and most popular fighting league, the UFC, the Nevada State athletic commission screened ringside physician reports and found that from January 2016 through July 2018, a total of 291 injuries were recorded in 285 fights from nine different weight divisions. It was found that head injuries accounted for 67% of injuries and were the most common injury (Fares, 2019). The study conducted by Fares also emphasizes that from a trendline analysis, as the weight division increases, the rate of knockouts, overall injuries and head injuries increase.

Boxing utilizes heavier, more padded gloves than compared to MMA. The boxing glove weight is agreed upon by the fighters before the fight. Normal professional gloves weigh 8-10oz and are made from leather with padding underneath. In boxing, the impact to the head is caused from throwing punches, these punches can come in from a multitude of different angles causing both translational and rotational movement of the head on impact. Atha et al. conducted a study on punch force data of a heavyweight boxer and found that the hand speed reached a peak velocity of 8.9 m/s and a peak impact force of 4096 Newtons. Other studies have found punch force data to range between 3453N and 4800N for elite level boxers (Smith, 2000). This means boxers are delivering a very high impact force to the head of other boxers. Impacts of punches that have a line of force application that is closer to the center of mass will create translational acceleration similarly to what was described above in football head impacts. What is different in



(Figure 2: Torque increase based on impact location, D2 > D1 images from KineMan3D) boxing is the placement of punches farther away rom the center of mass near the jaw that can cause a much faster rotational acceleration of the head. (Figure 2). This force

applied to the chin will greatly increase the torque around the neck due to the increased distance from the axis of rotation. Two distinct types of punches, and uppercut which would apply a force on the inferior part of the chin directed upwards would snap the head back causing rotational acceleration in the sagittal plane and a hook which would land on the lateral side of the chin with a line of force application that would cause the rotation to be in the transverse plane. Some of the mechanical energy is dissipated by the gloves and the soft tissue of the face but the brain will oscillate from the interaction between the cranium and the brain itself. Due its rotational nature, the differential equation is modified: $I\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K\theta = (g_{\Delta t}(t) \times \vec{r})$. Where I is the moment of inertia, B is the rotational damping coefficient and K is the rotational component to spring constant. The exterior force is also modified to represent the torque applied. This increase of torque on the head will lead to larger rotational acceleration and impact force of the brain and the cranium causing increased compression and possible torsional loading. This head trauma continues in the fight until either someone is knocked out or both boxers last 12 rounds. This can lead to acute trauma and possible lethal complications during and post-fight due to the high number of hits to the head.

In mixed martial arts, strikes to the head are very similar to boxing regarding fist striking except MMA gloves are lighter (4oz.) and do not provide as much padding. However, more than just hand strikes are allowed in MMA. Kicks, knees and elbows are also allowed, presenting an increased threat to possible traumatic brain injury. Compared to a punch, a kick will be thrown slower but with a larger amount of the person's body weight behind it. These kicks have a greater momentum than punches and with no protective gear can cause a lower time of force application and higher impulse meaning a larger amount of force is translated to the head and consequently increased compressional forces on the brain. This is also true with jumping knees to the head and even with elbows. Research into the dynamics of kicks, elbows and knees in MMA has not been investigated and could provide a clearer picture into how to keep MMA athletes safe when competing.

Recreating environments and assessing key biomechanical inputs are only part of the research needed to understand traumatic brain injuries and sport. Further research needs to be done into how the brain responds physiologically to these impacts as well as research into technology that can help prevent them in the future. This bridge between biomechanics and pathology is necessary to see if the model that shows high stress in one area of the brain is consistent with the symptoms and injury for that area. The described motion and impact described in the paper are only effective if they can be used to help identify locations of brain trauma and understand how our brain reacts to loading in vivo to improve health and safety. To build upon the biomechanical model itself, the exact mechanical properties of neural tissue need to be evaluated, current research shows a vast variance among populations studied and does not have a defining value (Meaney 2014). From an anatomical view, different areas of the brain have different proportions of myelination, axon proportion or cell body proportion. For example, a hit to the back of the head near the cerebellum will have a completely different effect and mechanical loading that a hit to the top of the head near the frontal cortex due to the cerebellum having a much larger neuron density than the cerebral cortex. How the tissue responds to different types of forces, i.e. shear, and torsional should also be further investigated due the combination of tensile and compressive forces. A trend in biomechanical modeling has been the incorporation of computational models. In a study by Mazdak et al. they developed a model for brain deformation that incorporated the difference in anatomical structures within the brain and how it deformed in response to types of loading. Computational modelling provides a highly controlled environment that does not rely on the need for cadavers or in vivo experiments. It also allows recreation of head trauma to view how the model responds and data found is accurate due to advanced computing simulation. However, it is limited due to the parameters set by the researchers, if these parameters are not accurate then the results will be inaccurate and un useable. Because there is still much uncertainty about in vivo properties of brain tissue, data that models provide cannot be totally relied upon. As progress is made in the field of neurology, these models will be updated and to incorporate such findings to provide a reliable simulations and prediction for future technology to enhance the safety of athletes and help decline the number of traumatic brain injuries that occur.

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