

**Comparison of Frequency and Impact Magnitude of Heading in 1966 and 2018  
International Professional Men's Soccer Matches**

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## **Abstract**

Athletes participating in professional soccer are at an increased risk for long-term neurologic disease due to exposure of repetitive head trauma (MacKay et al., 2019). Recent studies have confirmed cases of dementia and chronic traumatic encephalopathy in retired professional soccer players who played during 1966 (McKee et al., 2014; Hales et al., 2014; Bieniek et al., 2015; Ling et al., 2017; Grinberg et al., 2016). It is suspected that repetitive subconcussive impacts from heading may be a contributing factor to the development of chronic neurological deficits (Matser et al., 1998; Witol & Webbe, 2003). It is unknown if current soccer players are at similar risk of brain trauma. Differences of soccer balls, rules changes, and evolution of the game, may have influenced total frequency and impact magnitude of heading. A comparison of frequency and impact magnitude of heading between 1966 and 2018, highlights the potential risk of chronic neurodegeneration in professional soccer players.

Ten 1966 and ten 2018 FIFA World Cup matches were randomly chosen for video analysis. Total frequency of headers were documented for each game. Header exemplar reconstructions were completed in the laboratory using a 1966 Slazenger Challenge and 2018 Telstar 18 ball. A pneumatic linear impactor and projectile launcher were used to hit the ball and impact a Hybrid III head form to measure dynamic head response. A finite element model was then used to determine heading magnitudes as measured by Maximal Principal Strain (MPS).

The study revealed there were no significant differences in overall frequency of headers between the 1966 and 2018 games. The year 2018 had significantly higher frequency of headers in the medium MPS category while, 1966 had significantly higher frequency in the high category. There were no significant differences of linear acceleration, angular acceleration, and MPS values when comparing the 2018 dry and 1966 dry ball at the same velocity and location. Current athletes who are heading the 2018 Telstar 18 are sustaining similar frequency and magnitudes of heading as athletes in 1966 under the same velocity and impact locations.

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## **CHAPTER 1: INTRODUCTION**

### **1.1 Problem Statement**

According to the Fédération Internationale de Football Association (FIFA), approximately 265 million people participate in soccer worldwide (Kruschewsky, 2014). Soccer is a contact sport where injuries are frequent due to legal and accidental contact (Nielsen & Yde, 1989; Plais et al., 2019; RSC Soccer, 2020). Of these injuries, head injuries are the fifth most common in Major League Soccer (Mandelbaum, 2019). As the popularity of soccer is rising, research and medical professionals have voiced concerns about brain injury in the sport (Nutt, 2016). Potential head impact events include player collisions, falls, and impacts with the soccer ball. Outcomes of these impacts could lead to clinical implications such as skull fractures, concussion, and long-term neurologic disease and deficits. Recently, FIFA had been called upon to improve their concussion awareness and head injury protocols for the 2018 World Cup. However, reports revealed most players who demonstrated two or more signs of concussion following a collision were not evaluated by a sideline healthcare professional (George, 2018; Premkumar et al., 2019). Impact parameters such as frequency and magnitude of impact play a significant role in the influence of brain trauma (Bazarian et al., 2012; Karton & Hoshizaki, 2018; Kuzminski et al., 2018; Post et al., 2017; Zhang et al., 2004). Frequency and magnitude have been associated with chemical, physical, and neuropsychological changes to the brain (Karton et al., 2014; Lipton et al., 2013; Stalnacke et al., 2006). Researchers have reported cases of Chronic Traumatic Encephalopathy (CTE) in retired professional men's soccer players who played between the 1960s to 1980s, with a majority of these individuals competing in 1966 (Bieniek et al., 2015; Grinberg et al., 2016; Hales et al., 2014; Ling et al., 2017). CTE is a progressive degenerative brain disease found in athletes and other individuals with a history of repetitive brain trauma (McKee, et al., 2013; McKee et al., 2015; Omalu, B., 2014; Stern et al.,

2013). With recent media coverage of high-profile retired professional soccer players diagnosed with CTE and other neurodegenerative diseases, there has been an increase in investigations regarding the influence of long-term heading in soccer (BBC, 2019; Magowan, 2020; Nathan, 2017; Nutt, 2016; Senthlingam & Kounang, 2017; Zaitchik, 2018). It is unknown if current soccer players are at the same risk of cumulative head trauma, as differences in soccer balls and game play may influence the exposure of head trauma as described by frequency and magnitude.

Soccer is unique, as it is one of the few sports where players intentionally re-direct the ball with their head, a skill referred to as “heading” (Caccese et al., 2016; Forbes et al., 2016; Spiotta et al., 2012). Heading is the most frequent and repetitive head impact that occurs during soccer games and practices. Studies have identified heading frequency as a predictor of neuropsychological deficits in a range of competitive levels (Downs & Abwender, 2002; Matser et al., 1998; Rutherford et al., 2005; Smolaka, 1984; Webbe & Ochs, 2003; Witol & Webbe, 2003; Zhang et al., 2013). Changes in game play from 1966 to now may have an influence on heading frequency. Personal play styles and coaching influence the type of movement on the field and may increase or decrease the frequency of heading. Additionally, the offside rule changed in 1990, allowing offensive players to be leveled with the last defender, rather than behind (Wallace & Norton, 2014; Yoesting, 2017). This rule change increased the speed of the game by 15%, as characterized by rate of passing and how many times the ball travelled from one side of the field to the other (Wallace & Norton, 2014; Yoesting, 2017). This rule was implemented to provide the offensive team an advantage and may have promoted more heading event opportunities. These changes to the game may influence overall heading frequency and contribute to differences in trauma loads between 1966 and 2018.

Differences in the 1966 and 2018 soccer balls may have an influence on impact magnitude during heading in soccer games. As technology advancements occurred, so did the manufacturing and overall design of the soccer ball. In 1966, the Slazenger Challenge was introduced to professional leagues as the first valve-inflated soccer ball (World Cup Balls, 2020). Now, advanced polyurethane coated textiles and heat-activated adhesive are the standard for soccer ball construction (Plastics, 2020). Many claim soccer balls are safer now due to new materials, which result in lighter balls (Martin, 2014; Sneed, 2014). However, there is little to no mass difference between present soccer balls to ones manufactured before 1970 (Shewchenko et al., 2005c; World Cup Balls, 2020). Furthermore, it is unknown if ball material and overall construction changes are significant when considering brain trauma as soccer ball advancement has been focused on improving play rather than preventing injury (Delaney, 2005; Tysvaer, 1992). Soccer balls made in the 1960s consisted of hand-sewn rubber bladder and genuine leather, allowing them to absorb water during rainy conditions. Shewchenko and colleagues (2005c) identified these older model soccer balls increased in weight up to 47% in wet conditions, which lead to higher dynamic head responses compared to the dry ball. They concluded that dynamic head response can be influenced by ball construction, material, and condition (Shewchenko et al., 2005c). Changes in inbound velocity, angle, impact location, and compliance have been reported to influence the magnitude of head injury (Karton & Hoskizaki, 2018; Oeur et al., 2014; Oeur & Hoshizaki, 2016; Post et al., 2017). Impact magnitude has been identified to have a significant role in head injury in American football, ice hockey, and boxing (Karton & Hoshizaki, 2018; Post et al., 2017; Post et al., 2019; Zetterberg et al., 2006). Since most research has been focussed on high collision contact sports, investigation of head injuries in soccer has been limited.

By examining frequency and impact magnitude of heading, this study will provide insight into brain trauma loads experienced by professional soccer players (Karton & Hoshizaki, 2018). Athletes who participated in professional soccer in 1966 are now presenting with CTE. It is unclear if current soccer players are experiencing the same exposure of cumulative head trauma as players in 1966. Therefore, the purpose of this study is to compare frequency and impact magnitude of heading in international professional men's soccer matches. Total heading frequency, magnitude of heading impacts, and frequency of Maximal Principal Strain (MPS) categories were compared between 1966 and 2018 accounting for historical factors such as type of soccer ball. These comparisons will provide valuable information into the potential risk for current professional men's soccer players.

## **1.2 Research Questions**

1. Are current professional men's soccer players at *similar risk* of head trauma from *heading* as described by frequency and impact magnitude, as players in 1966?
2. Are there differences in impact magnitude of heading between the 1966 Slazenger Challenge and 2018 Telstar 18 under different conditions at varying velocities and locations?

## **1.3 Objectives**

1. To compare overall frequency of headers per game between 1966 and 2018 international professional men's soccer matches.
2. To compare linear acceleration, angular acceleration, and MPS levels of heading between the 1966 Slazenger Challenge and 2018 Telstar 18 under different conditions at varying velocities and locations.

3. To compare frequency of impact magnitudes of heading between 1966 and 2018 international professional men's soccer matches.

## **1.4 Variables**

### **1.4.1 Ball Condition Analysis**

#### **1.4.1.1 Independent Variables**

1. Ball Condition

(a) 2018 Dry (b) 1966 Dry (c) 1966 Wet

2. Impact Velocity

(a) 7m/s (b) 13m/s (c) 17m/s (d) 22m/s (dry only)

3. Location

(a) Front (b) Front Boss (c) Crown (Top)

#### **1.4.1.2 Dependent Variables**

1. Peak Resultant Linear Acceleration

2. Peak Resultant Angular Acceleration

3. Maximal Principal Strain

### **1.4.2 Brain Trauma Load Profile**

#### **1.4.2.1 Independent Variables**

1. Year

(a) 1966 (b) 2018

#### **1.4.2.2 Dependent Variables**

1. Frequency

2. Magnitude (Maximal Principal Strain)

## 1.5 Experimental Hypothesis

1. It is hypothesized that the 1966 Slazenger Challenge wet condition will create higher values of peak resultant linear acceleration, peak resultant angular acceleration, and MPS values than the 1966 Slazenger Challenge dry condition and 2018 Telstar 18 dry condition across all velocities and impact locations.
2. It is hypothesized that the 1966 Slazenger Challenge dry condition will create higher values of peak resultant linear acceleration, peak resultant angular acceleration, and MPS than the 2018 Telstar 18 dry condition at all velocities and locations.

## 1.6 Null Hypothesis

1. There will be no difference of total frequency of headers per game between 1966 and 2018 international professional men's soccer matches.
2. There will be no difference of *peak resultant linear acceleration* between 1966 Slazenger Challenge and 2018 Telstar 18 *dry condition* across all locations and velocities.
3. There will be no difference of *peak resultant angular acceleration* between 1966 Slazenger Challenge and 2018 Telstar 18 dry condition across all locations and velocities.
4. There will be no difference of *MPS values* between 1966 Slazenger Challenge and 2018 Telstar 18 dry condition across all locations and velocities.
5. There will be no difference of *peak resultant linear acceleration* between 1966 Slazenger Challenge *dry and wet conditions* across all locations and velocities.
6. There will be no difference of *peak resultant angular acceleration* between 1966 Slazenger Challenge *dry and wet conditions* across all locations and velocities.
7. There will be no difference of *MPS* between 1966 Slazenger Challenge *dry and wet conditions* across all locations and velocities.

8. There will be no difference of *peak resultant linear acceleration* between 1966 Slazenger Challenge *wet condition* and Telstar 18 *dry condition* across all locations and velocities.
9. There will be no difference of *peak resultant angular acceleration* between 1966 Slazenger Challenge *wet condition* and Telstar 18 *dry condition* across all locations and velocities.
10. There will be no difference of *MPS* between 1966 1966 Slazenger Challenge *wet condition* and Telstar 18 *dry condition* across all locations and velocities.
11. There will be no difference of frequency in the very low *MPS* category between 1966 and 2018 International Professional men's soccer matches.
12. There will be no difference of frequency in the low *MPS* category between 1966 and 2018 International Professional men's soccer matches.
13. There will be no difference of frequency in the medium *MPS* category between 1966 and 2018 International Professional men's soccer matches.
14. There will be no difference of frequency in the high *MPS* category between 1966 and 2018 International Professional men's soccer matches.
15. There will be no difference of frequency in the very high *MPS* category between 1966 and 2018 International Professional men's soccer matches.

## **1.7 Limitations**

1. Velocities that were used in header exemplar reconstructions are based on existing soccer literature. The average velocity of each heading scenario will be used for exemplar heading reconstructions. Four velocities were used for dry conditions (7m/s, 13m/s, 17m/s, and 22m/s) and three velocities (7m/s, 13m/s, and 17m/s) were used for wet conditions due to the limitations of laboratory equipment.

2. One soccer ball for each year was used, the 1966 Slazenger Challenge and the 2018 Telstar 18. Since only one ball of each model was tested, variability in construction and material may influence dynamic head response and magnitude measures (World Cup Balls, 2020).
3. Header exemplar reconstructions were completed with a Hybrid III head and neckform. It is made of metal and rubber which represents geometry and inertial properties of the human head. Head responses may not be exact to real-life events (Deng, 1989; Horgan & Gilchrist, 2003).
4. Characteristics of brain tissue in the Finite Element model is partially validated based on cadaveric models, therefore assumptions are made in the model regarding material behaviour of brain tissue. Since the University College Dublin Brain Trauma Model (UCDTM) is tested against cadaveric data, responses may not be true to the living human brain under the same dynamic impact (Horgan & Gilchrist, 2003).
5. There are limitations when using video analysis, as not all heading events and contact moments are visible. The wide angle and view of the soccer footage is meant to capture the entire field, making it difficult to document the exact heading location. Therefore, the total confirmed heading frequency is conservative (Babbs, 2001).

## **1.8 Delimitations**

1. Only two balls were chosen to undergo impact testing: 1966 Slazenger Challenge and 2018 Telstar 18. Some players may have participated in soccer with different soccer balls, however, since these two were the official match balls of FIFA World Cup in their respective years, these balls were chosen for testing.

2. Only men's FIFA World Cup matches were used to analyze heading profiles for the two years. The videos were collected from an external website. Training time and practices were not included in heading frequency as information was not provided per player.

## **1.9 Significance**

Professional soccer players who participated in 1966 are now presenting with neurodegenerative diseases such as CTE (Hales et al., 2014; Bieniek et al., 2015; Grinberg et al., 2016; Ling et al., 2017). It is unknown if current soccer players are at the same risk of cumulative brain trauma as players in 1966. Research has documented repetitive sub concussive impacts such as heading has an association with long term neurological disease (Matser et al., 1998; Witol & Webbe, 2002; Zhang et al., 2013). Additionally, it is proposed different soccer ball models create varying impact magnitudes which could influence brain trauma loads of soccer players. This study aims to compare frequency and impact magnitude of heading during professional game play between 1966 and 2018 to understand differences in brain trauma loads.

## **CHAPTER 2: REVIEW OF LITERATURE**

### **2.1 Neurologic Disease in Soccer**

Chronic traumatic brain injury covers a range of disorders associated with single and repetitive impacts. Trauma to the brain over time can cause physical and neuropsychological degeneration (Timofeev et al., 2011). Neural disorders associated with long-term consequences of exposure of trauma include dementia puglistica, post-traumatic parkinsonism, post-traumatic dementia, and CTE (Jordan, 2013). CTE is a progressive degenerative brain disease found in athletes, military veterans, and other individuals with a history of repetitive brain trauma (McKee, et al., 2013; McKee et al., 2015; Omalu, B., 2014; Stern et al., 2013). McKee and colleagues (2013) examined post-mortem brains from a cohort of subjects with a history of mild

traumatic brain injuries, and 64 out of 85 had a form of CTE. This research involved 94% athletes and 32% military veterans. The spectrum of tau pathology ranged in severity starting in the frontal neocortex to severe tauopathy affecting widespread brain regions. Depending on trauma exposure, magnitude, and trauma type, stages of CTE were varied with additional diagnosis such as motor neuron disease, Alzheimer's disease, Lewy body disease, and frontotemporal lobar disease (McKee et al., 2013). MacKay and colleagues (2019) conducted a retrospective cohort study comparing mortality from neurodegenerative disease among former professional soccer players to the general population. They found soccer players are three and a half times higher than the general population to die from neurodegenerative brain disease (MacKay et al., 2019). CTE has been associated mostly with boxers and American football athletes due to high velocity impacts; however, there is now evidence for the inclusion of repetitive low velocity impacts (Kondo et al., 2015; Karton & Hoshizaki, 2018; Stalnacke et al., 2006). Studies have shown long-term trauma exposure of repetitive low velocity impacts have similar outcomes to one severe event (Karton & Hoshizaki, 2018; Bahrami et al., 2016). This suggests similar neurological risks are associated with cumulative effect of repetitive trauma to neural tissues. Early studies have documented neurologic abnormalities in professional soccer players (Matser et al., 1998; Sortland & Tysvaer, 1989; Tysvaer & Lochen, 1991; Tysvaer & Storli, 1981; Tysvaer & Storli, 1989). In 1989, Sortland & Tysvaer identified central cerebral atrophy in former soccer players and speculated the cause was due to repetitive small head injuries associated with heading. Similarly, Tysvaer & Lochen (1991) completed an extensive battery of psychologic tests on the National Football Team of Norway. They identified mild to severe neuropsychological deficits in 81% of players. They concluded their findings indicated some degree of permanent brain alteration due to repeated trauma from heading the ball (Tysvaer

& Lochen, 1991). As technology advancements occurred, so did identifying brain injury. Recent studies used post-mortem examinations to identify varying degrees of brain abnormalities. While there is not a well-defined relationship between neurological pathologies and soccer, recent studies have explored the possibility of this association (Bieniek et al., 2015; Grinberg et al., 2016; Hales et al., 2014; Ling et al., 2017; McKee et al., 2014). Ling and colleagues (2017) examined 13 retired professional soccer players between the years 1980-2004 with progressive cognitive impairments. Six cases consented for post-mortem examinations and neuropathology showed septal abnormalities for all individuals, and four cases of confirmed CTE. They concluded their findings were associated with exposure to repetitive head impacts from head-to-player collisions and heading the ball thousands of times throughout their professional careers (Ling et al., 2017). Hales and colleagues (2014) examined a 16-year professional soccer player from the United Kingdom with tau pathology distributed throughout the brain, brainstem, and spinal cord. Observations of highly characteristic sulcal and vascular deposition of tau pathology were due to physical and shear stresses from the patient's brain encountered with head injuries. Many other physical and chemical characteristics of the brain indicated CTE (Hales et al., 2014). Furthermore, a study conducted by Grinberg and colleagues (2016) examined an 83-year-old retired soccer player with no history of concussion and had typical Alzheimer-type dementia. This individual played as a professional centre-back for 21 years, retiring at the age of 39. After his death at 83 years an entire neuropathological examination was done. This revealed mixed pathology including widespread CTE, moderate Alzheimer's disease, hippocampal sclerosis, and TDP-43 proteinopathy (Grinberg et al., 2016). Research has identified neurological deficits and disease in retired soccer players. The cause of these brain abnormalities are not well understood;

however, the speculation of the contribution of long term exposure of low magnitude repetitive impacts, such as heading has been consistent.

## **2.2 Sub concussive Impacts**

Research has identified repetitive low-magnitude brain trauma can result in similar pathological outcomes as one severe event (Bahrami et al., 2016; Karton & Hoshizaki, 2018). Brain strain levels as low as 5-15% have been associated with functional impairment (Karton & Hoshizaki, 2018; Kondo et al., 2015; Stalnacke et al., 2006). Recent studies have identified changes in white matter structure and neuronal activity in athletes following a season in a contact sport who did not receive a concussion diagnosis (Bahrami et al., 2016; Bazarian et al., 2012; Breedlove et al., 2012; Koerte et al., 2012; Kuzminski et al., 2018). Koerte and colleagues (2012) reported changes in white matter integrity in varsity university ice hockey players during one season of play. When compared to preseason data, postseason images showed higher traces of radial and axial diffusivity. Rat models were used to explore the effect of impacting magnitude on neurological, cardiovascular, and histopathological responses (Dixon et al., 1991). It was found that higher impacting velocities produced greater acute and chronic neurological and histopathological alterations with cerebrum structural damage (Dixon et al., 1991). Greater axonal injury has been found with an increase of impacting velocity (Yan, 2013; Lighthall, et al., 1990). Axons in white matter have been reported to be vulnerable to injury resulting from mechanical loading of the brain during a traumatic event. Recent evidence reports brain injuries may induce long-term neurodegeneration of axons years after the initial injury and play a role in the development of dementia-like pathological changes (Johnson et al., 2013). Research has documented cumulative effect of repetitive head trauma show similar neurological risks to single high velocity impacts.

### **2.3 Frequency of Heading and Neurological Deficits**

Frequency of head impacts have been associated with chemical, physical, and neuropsychological changes to brain tissue (Lipton, 2013; Stalnacke et al., 2004). On average a player heads the ball 6 to 12 times during each game, performing an estimated 5250 headers throughout a 15-year professional career (Auger et al., 2020; Smolaka, 1984; Tysvaer & Storli, 1981). Several researchers have identified a relationship between frequency of heading and neurocognitive impairments (Matser et al., 1998; Smolaka, 1984; Tysvaer & Storli, 1981; Witol & Webbe, 2002). Witol & Webbe (2002) investigated heading frequency as a predictor of neuropsychological deficits between soccer players at different levels (high school, amateur, and professional) and a control group with individuals who do not play soccer. They reported the group identified as ‘high frequency headers’, had lower attention, concentration, cognitive flexibility, and general intellectual functioning when compared to the group with no soccer heading (Witol & Webbe, 2002). Similarly, Matser and colleagues (1998) compared amateur soccer players to swimming and track athletes. They found soccer players exhibited impaired performances in memory, planning, and visuoperceptual processing when compared to the control athletes. The researchers hypothesized the cause may be due to repetitive heading soccer players perform during training and games (Matser et al., 1998).

Short-term and long term exposure to heading have been reported to be associated with physical and biological changes in athletes (Kuzminski et al., 2018; Lipton et al., 2013; Stalnacke et la., 2004) Kuzminski and colleagues (2018) assessed white matter changes during a single high school football season. They reported decreases in fractional anisotropy in the fornix-stria terminalis and cingulum hippocampus, which were related to impact frequency. They highlighted their findings of white matter injury and alterations in white matter tracts were

detectable only after one season of play (Kuzminski et al., 2018). In a study by Lipton and colleagues (2013), they investigated the association of soccer heading with subclinical evidence of traumatic brain injury by quantifying heading in the prior 12 months. They found that heading was associated with lower fractional anisotropy at three locations in temporo-occipital white matter, concluding heading is associated with abnormal white matter microstructure (Lipton et al., 2013). Stalnacke and colleagues (2004) explored serum concentrations of two biochemical markers of brain tissue damage, S-100B and neurone-specific enolase (NSE), in male soccer players in relation with the game. Blood samples were taken before and after a competitive game while also recording the number of headers and trauma events that occurred. Results identified S-100B and NSE was significantly raised. Furthermore, changes in S-100B concentrations were statistically significantly correlated to the number of headers performed in the game (Stalnacke et al., 2004). Research has identified physical and chemical brain abnormalities in athletes who sustain multiple impacts to the head.

#### **2.4 Interval and Exposure of Heading**

Interval between head impacts is measured as the time between each impact (Karton & Hoshizaki, 2018). Continued exposure to brain trauma without optimal recovery may result in chronic impairment of essential neuronal pathways and potentially promote cell death (Jessen et al., 2015; Peng et al., 2016). Exposure of trauma is defined as the amount of time a player is in the traumatic inducing environment (Karton & Hoshizaki, 2018). When considering soccer, number of games and career duration are variables that influence total brain trauma exposure. There is limited documentation for player's game history prior to the 1990s. Currently, professional European soccer players participate an average of 54 games a season, including league play and external tournaments (Soccer Base, 2020). There is no documentation of the

specific number of games each player participated in 1966; however, the average career length of professional British soccer players was 20 years. Players who are now retiring have a similar average professional career length of 19 years (Soccer Base, 2020; World Football, 2020; Web Archive, 2020). Additionally, childhood experience and pre-professional soccer training and games would contribute to total brain trauma exposure, however, this is difficult to quantify as each player has a different background.

## **2.5 Magnitude of Head Trauma in Soccer**

Magnitude of an impact event is influenced by the event's specific characteristics which include mass, velocity, location, compliance, and angle (Karton et al., 2014; Oeur et al., 2014; Oeur & Hoshizaki, 2016). When impact parameters are altered, changes in resulting dynamic response curves vary creating different levels of injury risk. An increase in inbound mass has been found to show increases in both linear and angular acceleration (Karton et al., 2014). Additionally, variations in impact location and angle also influence dynamic head response outcomes. According to Oeur and colleagues (2014), impact angles greater than 15° at the front and side location will result in significant differences for MPS values when compared to 0°, 5°, and 10°. Furthermore, it was noted that increasing compliance decreases dynamic head response and MPS (Oeur & Hoshizaki, 2016; Fahlstedt, 2016). Studies have identified increased stiffness of impact material contributes to larger dynamic head accelerations (Shewchenko et al., 2005c). Shewchenko and colleagues (2005c) identified head response reductions up to 15% were observed between different ball constructions and year models. They reported soccer heading, dynamic head response can be influenced by ball construction, material, and model of the ball (Shewchenko et al., 2005c). Variations in these parameters will produce differences in magnitude as measured by Maximal Principal Strain (MPS). Brain tissue deformation

measurements such as brain stress and strain, have been proposed as a better injury predictor for risk of brain injury than linear or angular acceleration alone (King et al., 2003; Post & Hoshizaki, 2015; Zhang et al., 2004). Using finite element (FE) analysis, MPS has been identified as a variable that has close association with strain in the brain tissue (Bain & Meaney, 2000; Kleiven, 2007; Margulies & Thibault, 1992; Post & Hoshizaki, 2015; Zhang et al., 2004).

There have been a number of studies investigating the implications of heading a soccer ball with a biomechanics focus (Bauer et al., 2001; Harriss et al., 2018; Harriss et al., 2019; Harriss et al., 2020; Naunheim et al., 2000; Shewchenko et al., 2005a; Shewchenko et al., 2005b; Shewchenko et al., 2005c). Harriss and colleagues (2019) explored purposeful heading in youth soccer and concluded impact magnitudes from heading depend on game scenario and head impact location. Headers performed at the top of the head resulted in larger rotational velocities compared to the front of the head (Harriss et al., 2019). Shewchenko and colleagues (2005c) explored different soccer balls during heading by manipulating ball mass, pressure, size, and models. They found ball mass reductions of 35% resulted in decreased head responses between 23-35%. This study concluded differences in soccer ball characteristics can influence dynamic head response (Shewchenko et al., 2005c). Multiple studies documented ball velocities between 7 to 25m/s depending on soccer scenario; bounce, secondary header, throw-in, pass kick, corner kick, punt, and goalie kick (Bauer et al., 2001; Cerrah et al., 2012; Kawamoto et al., 2007; Kirkendall et al., 2001; Levendusky et al., 1985; Levendusky et al., 1987; Linthorne & Everett, 2006; Peacock et al., 2017; Stoner, 1980; Shewchenko et al., 2005c, Self, 2006). However, recent studies exploring dynamic head responses during heading use impact velocities lower than experienced in professional soccer games (Bauer, 2001; Naunheim, 2003a; Naunheim, 2003b; Shewchenko et al., 2005a, Shewchenko et al., 2005b, Shewchenko et al., 2005c.).

Implementation of realistic velocities will influence overall dynamic head responses and provide a better understanding of brain trauma exposure sustained by soccer players.

## **2.6 Soccer Balls**

In 1855, soccer balls were created with a rubber bladder and leather covering. Prior ball construction consisted of an inflated animal's bladder to allow the ball to keep its spherical shape (Delmy, 2017; Shewchenko et al., 2005c). Improvements to the ball occurred over the years to provide consistency and durability. Today, requirements are set for all soccer balls by FIFA in the Laws of the Game, where all balls must have a circumference of 680-720mm, mass of 410-450g, inflation pressure of 0.6-1.1 bar, and constructed of suitable cover material (FIFA, 2020). Recently, materials used in soccer ball construction have developed significantly, improving the exterior covering. This helped decrease water absorption and degradation, a common problem with the older generation balls (R. Dehnert & P.R. Dehnert, 1989). The 2018 Telstar 18 was used during the 2018 World Cup in Russia and is the current soccer ball used by professional players at international events (FIFA, 2020; World Cup Balls, 2018). This ball is constructed of advanced polyurethane coated textiles and heat-activated adhesive, creating a waterproof soccer ball (Plastics, 2020). For the 1966 England World Cup, the Slazenger Challenge was introduced as the first valve-inflated soccer ball played at an international event (Delmy, 2017). This revolutionized the game as it employed consistent game play. The Slazenger Challenge consisted of a rubber bladder, genuine leather, and hand sewn allowing it absorb water during rainy conditions (Delmy, 2017; Shewchenko et al., 2005c; World Cup Balls, 2018). When waterlogged, leather balls weighing at 450g become 25% heavier with corresponding increased impact on contact with the head (Babbs, 2001). Shewchenko and colleagues (2005c) examined old and new soccer balls under varying conditions. Researchers identified the wet ball condition

experienced increases in peak force likely due to the increase in mass. They also noted ball construction was of interest as balls that were sewn were noted to absorb a greater percentage of water than molded balls. However, these researchers documented that the older generation soccer balls used in their study were visibly degraded and could have influenced the absorption of water (Shewchenko et al., 2005c). The evolution of soccer ball technology has been focused on improving game play, however, it is unknown if advancements are significant when considering risk of brain trauma exposure.

## **2.7 FINITE ELEMENT MODEL**

Finite Element (FE) models of the brain quantify brain tissue strain sustained during an impact through the analysis of linear and rotational acceleration curves (Horgan & Gilchrist, 2003; King et al., 2003; Ommaya et al., 1966; Post et al., 2017). These models allow for interpretation of the influence of dynamic head response on neural tissue during a traumatic event. FE models provide further representation of intra-cranial response after a head impact that dynamic head response cannot provide alone. MPS is a metric used to quantify brain deformation and has been identified as an indicator of brain injury (Kleiven, 2007; Patton et al., 2012, Post et al., 2012). Research completed on reconstructions of injury events have estimated a 50% risk of sustaining a concussion from MPS values of 19-27% found in gray and white matter (Zhang et al., 2004; Kleiven, 2007; Patton et al., 2013).

## **CHAPTER 3: METHODOLOGY**

### **3.1 Video Analysis**

#### **3.1.1 Inclusion/Exclusion Criteria**

Video footage of ten 1966 and ten 2018 men's FIFA World Cup matches were included in this study. Two games were randomly selected from the finals, semifinals, quarterfinals, round of 16, and group stage to capture a full range of gameplay. Since there was no round of 16 in 1966, four games were randomly selected from the group stage (Footballia, 2020). The criteria used for a *confirmed header*: was a player making direct forward contact with the ball using the head and clearly visible within the video (Rahnama et al., 2003). Suspected head impacts are impact events that are thought to have occurred, but the point of contact was obstructed in some way and could not be confirmed (Chen et al., 2020; Khatib, 2019; Paiement, 2020 Post et al., 2019). All other impacts to the head were documented and recorded, but not included in the analysis. Additional time due to injuries and referee pauses were included in the analysis, however, extra time was excluded.

#### **3.1.2 Data Collection**

The twenty games were obtained through the website Footballia.net. WM Capture 8 was used to record the footage from the website. When a head impact was identified the video was clipped using WM Capture 8 and in an excel file the time stamp was documented along with a detailed description of the event (Figure 1). Each header was categorized into one of the following heading scenarios: bounce, secondary header, throw-in, kick, corner kick, punt, and goalie kick (Caccese et al., 2016). Definitions for each heading scenario is contained in Table 1. For the scope of this study only confirmed heading events were included in the frequency count (Harriss et al., 2018).

## Figure 1

*Video of 1966 and 2018 FIFA World Cup Matches*



**Table 1**

*Heading Scenario Definitions*

<b>Scenario</b>	<b>Definition</b>
Bounce	Header in which the ball made contact with the ground before the athlete headed the ball
Secondary Header	Header in which another player headed the ball prior to the athlete heading the ball
Throw-In	Header off a throw-in from the sidelines
Pass Kick	Header in which another athlete on the field kicks the ball during game play
Corner Kick	Header off a corner kick
Punt	Header in which the goalkeeper drop kicks the ball
Goalie Kick	Header off a goal kick on the ground

*Note.* (Caccese et al., 2016)

## 3.2 Equipment

### 3.2.1 Hybrid III Head form and Neck form

A male 50<sup>th</sup> percentile Hybrid III head form was used for all header exemplar reconstructions (Figure 2). It has a mass of 4.54 +/- 0.01 kg and is equipped with nine Endevco 7264C-2KTZ-2-300 accelerometers arranged in a 3-2-2-2 array. The head form is regularly used in research and is considered to be representative of the human head (Post et al., 2015). The head form was attached to a Hybrid III neck form. The neck form is composed of an internal braided steel cable connecting individual rubber disks. The Hybrid III neck form was chosen to simulate the heading skill as the asymmetric compliant design in the anterior aspects reduces resistance in extension when compared to flexion (Walsh et al., 2018).

#### Figure 2

*50<sup>th</sup> Percentile Hybrid III head form and neck form*



### 3.2.2 Pneumatic Linear Impactor

The pneumatic linear impactor used in this study is depicted in Figure 3. It consists of a compressed air tank, air cylinder, air release valve, and impactor rod. The air cylinder propels the impact rod by discharging the air pressure via a control valve. The air pressure is monitored using a pressure gauge connected to the compressed air tank. An adjustable sliding table is at the end of the linear impactor where the head and neck form are attached.

**Figure 3**

*Pneumatic Linear Impactor*



### **3.2.3 Projectile Launcher**

The projectile launcher is an attachment of the pneumatic linear impactor (Figure 4). The impactor rod was rotated downwards to allow attachment of the projectile launcher canon at the top. The projectile launcher used the same compressed air tank, air cylinder, air release valve, and has adjustable table at the end where the head and neck form are attached.

**Figure 4**

*Projectile Launcher*



### 3.2.4 Soccer Balls

The 1966 Slazenger Challenge was obtained through World Cup Balls, a company that constructs replicas of World Cup soccer balls from 1930 to 1966 (Figure 5). This ball was composed of a rubber bladder, genuine leather, and hand stitched, following the soccer ball construction protocols of 1966. The 2018 Telstar 18 was obtained from Spedster Sports, a company that had the FIFA World Cup Russia 2018 official match ball in stock (Figure 5).

**Figure 5**

*Soccer Balls*



*Note.* 1966 Slazenger Challenge (left), 2018 Telstar 18 (right)

### 3.2.5 Data Filtering and Processing

There are nine Endevco 7264C-2KTZ-2-300 accelerometers [Endevco, San Juan Capistrano CA] arranged in a 3-2-2-2 array within the Hybrid III head form. For the header exemplar reconstructions, accelerometer data were sampled at 20 KHz and a low pass filter of 1000 Hz was applied to obtain clean linear and angular acceleration curves. Accelerometer signals were passed through a TDAS Pro Lab system before being processed by TDAS software (DTS, Seal Beach, CA).

### 3.2.6 Finite Element Model

Three-dimensional linear and rotational loading curves from heading exemplar impacts were applied to the University College Dublin Brain Trauma Model (UCDBTM) to determine Maximal Principal Strain (MPS). This model was established from computed tomography (CT) and magnetic resonance imaging (MRI) of an adult male and was validated based on cadaveric impacting tests (Doorly & Gilchrist, 2006; Hardy et al. 2001; Horgan & Gilchrist, 2003; Nahum et al., 1977). This model has approximately 26, 000 hexahedral elements divided into sections including the scalp, skull, dura, cerebral spinal fluid (CSF), pia, falx, tentorium, cerebral hemispheres, cerebellum and brainstem (Horgan & Gilchrist, 2003; 2004). Tables 2 and 3 display the material properties and characteristics of the UCDBTM.

**Table 2**

*Material properties of the University College Dublin Brain Trauma Model*

<b>Material</b>	<b>Young's Modulus (MPa)</b>	<b>Poisson's Ratio</b>	<b>Density (kg/m<sup>3</sup>)</b>
Scalp	16.7	0.42	1000
Cortical Bone	15 000	0.22	2000
Trabecular Bone	1000	0.24	1300
Dura	31.5	0.45	1130
Pia	11.5	0.45	1130
Falx	31.5	0.45	1140
Tentorium	31.5	0.45	1140
CSF	15 000	0.5	1000
Grey Matter	Linear viscoelastic	0.49	1060
White Matter	Linear viscoelastic	0.49	1060

**Table 3***Material characteristics of the brain tissue components for the University College Dublin Brain**Trauma Model*

Material	Shear Modulus (kPa)		Decay Constant (Gpa)	Bulk Modulus ( $s^{-1}$ )
	$G_0$	$G_\infty$		
Cerebellum	10	2	80	2.19
Stem	22.5	4.5	80	2.19
White Matter	12.5	2.5	80	2.19
Grey Matter	10	2	80	2.19

**3.2.7 Brain Strain Categories**

Five categories of brain strain have been identified to represent different levels of brain tissue trauma. Each category has clinical significance based on neurochemical and physical changes to the brain (Karton & Hoshizaki, 2018). MPS values were calculated using the UCDBTM to classify each impact into a trauma category.

**Table 4***Brain strain categories based on MPS*

Category	Maximal Principal Strain
Very Low	<8%
Low	8-16.9%
Medium	17-25.9%
High	26-34.9%
Very High	35%<

*Note.* (Bain & Meaney, 2000; Cournoyer, 2019 ; Karton & Hoshizaki, 2018; Kleiven, 2007; Patton et al., 2013; Viano et al., 2005; Zhang et al., 2008)

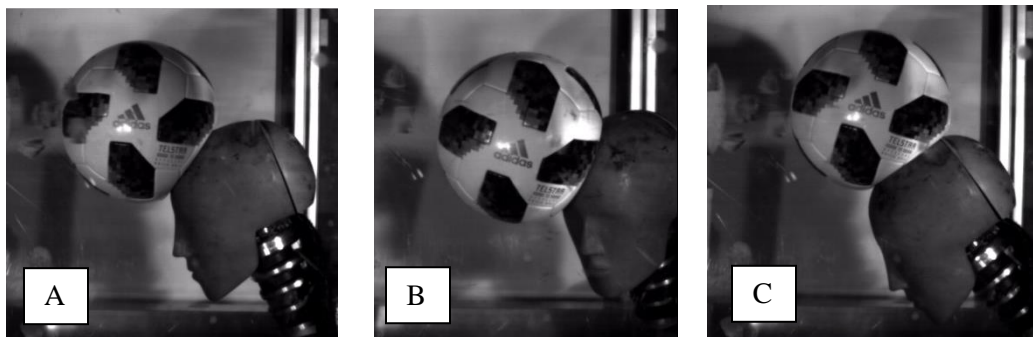
### 3.3 Exemplar Header Reconstruction

#### 3.3.1 Impact Parameters

Impact parameters for header exemplar reconstructions were determined from video analysis and existing soccer literature. Impact locations were identified through video analysis. There were a total of 6 impact locations including front, front boss, side, top, rear, and rear boss. The three most prominent header locations were front, front boss, and top and therefore these three locations were used for exemplar header reconstructions (Figure 6). Velocities used were based on heading scenarios that were documented in soccer (Table 5). The identified heading scenario in the video analysis was attached an average velocity based on existing documented soccer velocities (Table 5). The soccer balls were inflated to 10 PSI, within FIFA's Laws of the Game (FIFA, 2020). Three impacts were conducted per header reconstruction to obtain linear and angular acceleration data. Refer to Table 6 for impact parameters including ball, angle, pressure, condition, location, and velocity.

**Figure 6**

*Header Impact Locations*



*Note.* A) Front B) Front Boss C) Top

**Table 5***Literature Review to Determine Ball Velocities*

<b>Scenario</b>	<b>Literature</b>	<b>Average Velocity</b>	<b>Velocity</b>
Bounce	6m/s, 8m/s – Shewchenko et al., 2005 6.8±0.5m/s - Bauer et al., 2001	6.93m/s	<b>7m/s</b>
Secondary Header	6m/s, 8m/s – Shewchenko et al., 2005 6.8±0.5m/s - Bauer et al., 2001		
Throw-In	11.7m/s, 12.4m/s – Cerrah et al., 2012 13.4m/s – Linthorne & Everett, 2006	12.5m/s	<b>13m/s</b>
Pass Kick	17.88m/s – Levendusky et al., 1987 18.3m/s – Levanon & Dapena, 1998 16m/s, 21m/s – Kawamoto et al., 2017	16.93m/s	<b>17m/s</b>
Corner Kick	12m/s – Self et al., 2006 16m/s – Linthorne & Everett, 2006		
Punt	20m/s – Stoner, 1980; Kirkendall et al., 2001 25m/s – Stoner, 1980; Kirkendall et al., 2001 22.7m/s – Peacock et al., 2017	21.74m/s	<b>22m/s</b>
Goalie Kick	25m/s – Stoner, 1980; Kirkendall et al., 2001 16m/s – Self et al., 2006		

**Table 6***Impact Parameters for Header Exemplar Reconstructions*

<b>Ball</b>	<b>Angle (°)</b>	<b>Pressure (PSI)</b>	<b>Condition</b>	<b>Location</b>	<b>Velocity (m/s)</b>			
					<b>7</b>	<b>13</b>	<b>17</b>	<b>22</b>
2018	15°	10	Dry	F				
				FB				
				TOP				
1966	15°	10	Dry	F				
				FB				
				TOP				
			Wet	F				
				FB				
				TOP				

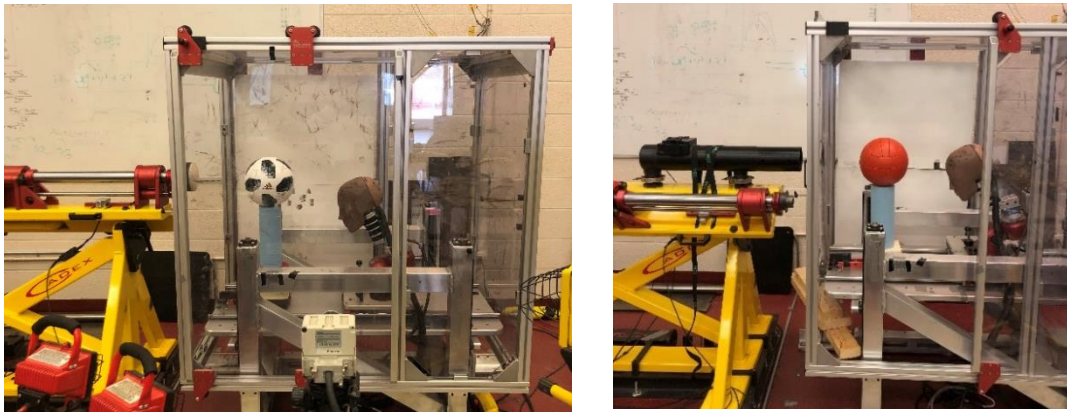
*Note.* For the 1966 wet condition 22m/s was not achieved due to equipment limitations

### 3.3.2 Reconstruction Set Up

The appropriate soccer ball was placed on a cylinder platform between the impactor and the Hybrid III head form. The impactor contacted the ball and the ball impacted the head form at the desired location (Figure 7). Velocities at 7m/s and 13m/s the linear impactor was used, whereas the projectile launcher was used for 17m/s and 22m/s (Figure 7). The projectile launcher propelled a weighted softball into the soccer ball and the soccer ball impacted the head form. A high-speed camera was used to confirm the velocity while accelerometers inside the head form measured resulting linear and angular acceleration curves. For safety a plexi-glass enclosure was placed around the sliding table to protect researchers from the soccer ball's ricochet off the head form (Figure 7).

#### Figure 7

##### *Header Exemplar Reconstruction Set Up*



*Note.* Pneumatic Linear Impactor set up (left) and the Projectile Launcher set up (right)

### 3.3.3 Weighing and Pressure Check

Each soccer ball was weighed and pressure checked at each velocity change. A Starfit scale was used with a small cylinder cardboard cut-out to ensure the ball did not roll when measuring the weight (Figure 8). A hand pump was used to inflate the soccer balls (Figure 9). A

built-in pressure gauge at the top of the hand pump ensured the soccer balls were filled to 10 PSI; within FIFA's Laws of the Game (FIFA, 2020).

### Figure 8

#### *Weight Measurement Apparatus*



*Note.* Scale (left), 1966 Slazenger Challenge ball on scale (middle), and 2018 Telstar 18 ball on scale (right)

### Figure 9

#### *Pressure Gauge and Inflation Method*



*Note.* Hand pump with pressure gauge (right) and an example of pressure check and inflation method of the 2018 Telstar 18 ball

### 3.3.4 Wet Ball Procedures

Tap water was used to fill a large bucket about three quarters full. Both soccer balls were placed in the water filled bucket and a concrete slab wrapped in plastic was placed on top of both balls to ensure full submersion (Figure 10). Every thirty minutes the balls were taken out of the water, wiped down and weighed. This occurred for a total of three times at the thirty, sixty, and ninety minute time marks. Refer to Appendix A: Methods for weight measuring increments. The balls were submerged for a total of ninety minutes, the same amount of time as a professional soccer game. After ninety minutes the weight of the soccer ball was chosen as the *target weight* for impacts for the wet condition. The 2018 Telstar 18 ball did not change in weight after ninety minutes and therefore, did not undergo wet condition testing. The 1966 Slazenger Challenge ball's weight did change and underwent testing at three velocities (7m/s, 13m/s, 17m/s) and three head impact locations (front, front boss, and top). Before each impact the ball was submerged in the water bucket to reach the target weight and pressure checked to ensure consistency throughout each trial.

**Figure 10**

*Wet Method Submersion Technique*



*Note.* Soccer ball in water filled bucket (left) and concrete slab wrapped in plastic placed on top of the soccer ball to ensure submersion (right)

### 3.3.5 Coefficient of Restitution

Coefficient of Restitution (COR) was obtained for the 1966 Slazenger Challenge ball dry, wet, and 2018 Telstar 18 dry. Since the 2018 Telstar 18 did not uptake water from the wet ball procedure, only the dry ball was used to determine COR. Initial and final velocities of the ball was determined using high speed camera footage. The initial velocity was obtained three frames before impact to the ground and the final velocity was three frames after impact when the ball completely left contact with the ground. Each ball was dropped from 2 metres height for three trials. The mean of the trials was the final COR for that ball. See Figure 11 for the Coefficient of Restitution equation.

#### Figure 11

*Coefficient of Restitution Equation*

$$C_R = \frac{V}{u}$$

*Note.* This is a variation of the Coefficient of Restitution equation of a ball bouncing off a flat, stationary surface. Where  $V$  is the final velocity after impact and  $u$  is the initial velocity before impact (Haron & Ismail, 2012; Schwager & Pöschel, 2007)

### 3.4 Statistical Analysis

When evaluating all statistical analysis were completed using IBM SPSS software. Non-parametric Mann Whitney U test was conducted to compare total frequency per game between 2018 and 1966 matches. A two-way MANOVA was used to compare linear acceleration, angular acceleration, and MPS values across the variations of the ball conditions. And lastly, four Mann-Whitney U tests were used to compare frequency differences in each MPS category between 2018 and 1966.

## CHAPTER 4: RESULTS

### 4.1 Video Analysis

The results for heading frequency per game (Appendix B: Results) were categorized into each heading scenario; bounce, secondary header, throw-in, kick, corner kick, punt, and goalie kick. Non-header impacts represented 3.6% of all head impacts in 2018 and 2.6% in 1966. The results for frequency of head impact location per game (Appendix B: Results) were categorized: front, front boss, top, side, rear, and rear boss. Furthermore, the results of frequency used to inform physical reconstructions and MPS categories were displayed by specific location, scenario, and assigned velocity (Table 7).

**Table 7**

*Frequency of Heading Scenario across Velocity and Location per Game*

Heading Scenario		Bounce/ Secondary Header			Throw-In			Kick/Corner Kick			Punt/Goalie Kick		
Velocity		7m/s			13m/s			17m/s			22m/s		
Location		F	FB	T	F	FB	T	F	FB	T	F	FB	T
Year	Game												
2018	1	39	3	0	7	0	0	43	6	0	19	3	0
	2	18	2	0	0	0	0	21	7	2	7	1	0
	3	24	1	0	4	1	1	47	2	3	28	1	4
	4	18	1	0	2	0	0	29	4	3	8	1	1
	5	23	3	0	0	0	0	28	2	3	12	2	0
	6	37	6	5	6	1	1	63	5	3	15	1	3
	7	22	0	0	6	1	1	46	1	0	10	1	0
	8	29	0	1	10	0	0	38	2	1	20	1	0
	9	21	1	0	8	1	0	38	3	1	6	0	2
	10	32	0	0	6	0	1	50	4	2	12	1	1
1966	1	23	1	1	3	0	1	37	6	2	11	2	1
	2	28	3	0	5	0	1	65	7	3	26	1	2
	3	19	3	0	1	0	0	36	8	2	19	0	3
	4	22	1	1	1	0	0	72	7	8	17	1	2
	5	35	4	3	2	0	1	55	8	6	17	1	1
	6	19	1	0	4	0	1	29	8	1	13	0	0
	7	14	0	0	2	0	0	60	4	2	4	0	0
	8	31	1	2	5	0	0	53	2	0	14	0	2
	9	20	1	0	6	0	0	57	2	1	10	1	0
	10	21	0	0	4	0	0	53	3	1	6	2	0

*Note.* For Location (F=Front, FB=Front Boss, T=Top)

## 4.2 Total Frequency of Headers

Total frequency of heading was completed for ten 2018 and ten 1966 men's FIFA World Cup games. Two games were randomly selected from the finals, semifinals, quarterfinals, round of 16, and group stage. In 1966 there was no round of 16, and therefore, 4 games were randomly selected from the group stage. The results of the Mann-Whitney U test indicated there was no significant difference (Table 8) of total heading frequency between 2018 (M=97.8, SD=27.7) and 1966 (M=105.1, SD=23.2) U=42, p=0.579.

**Table 8**

*Total Frequency of Headers per Game*

<b>Games</b>	1	2	3	4	5	6	7	8	9	10	<b>Average</b>	<b>SD</b>	<b>Total</b>
<b>2018</b>	121	58	117	68	73	148	90	104	88	111	97.8	27.7	978
<b>1966</b>	88	141	91	134	133	76	87	111	98	92	105.1	23.2	1051

*Note.* See Appendix B: Results, for breakdown of heading frequency soccer scenarios

## 4.3 Magnitude of Headers

The 2018 Telstar 18 and 1966 Slazenger Challenge were used to impact the Hybrid III head form under variations of location (front, front boss, top), velocity (7m/s, 13m/s, 17m/s, 22m/s), and condition (dry, wet) to measure peak resultant linear acceleration, peak resultant angular acceleration, and MPS values. The 2018 ball did not have a wet condition because it did not uptake water as noted in the methods. A two-way MANOVA was completed to compare linear acceleration, angular acceleration, and MPS values for the header exemplar reconstructions. Tables 9, 10, 11, and 12 display the average and standard deviation of each dependant variable across different locations and ball conditions per velocity. The results indicated there was a statistically significant main effect of ball condition on the combined dependent variables,  $F(27, 130)=27.668$ ;  $p<0.001$ ; Wilks'  $\Lambda=0.190$ . At 7m/s and 13m/s velocities

there were no statistically significant differences of peak resultant linear acceleration, peak resultant angular acceleration, and MPS values across ball condition for each location (Table 9, 10). The only exception was peak resultant angular acceleration at 13m/s at the top location for 1966 wet condition was significantly lower than 2018 dry and 1966 dry,  $p < 0.001$  (Table 10). At 17m/s peak resultant linear and peak resultant angular acceleration were significantly lower across all locations for 1966 wet condition when compared to 2018 dry and 1966 dry,  $p < 0.001$  (Table 11). Additionally, the MPS value for the top location of 1966 wet was significantly lower than 2018 dry and 1966 dry,  $p < 0.002$ . At 22m/s there was no statistically significant differences for peak resultant linear acceleration, peak resultant angular acceleration, and MPS values between the 2018 dry and 1966 dry front and top location (Table 12). However, 1966 dry peak resultant linear and peak resultant angular acceleration at the front boss location was significantly lower than 2018 dry,  $p = 0.027$ ,  $p < 0.001$ .

**Table 9**

*Dynamic Head Response and MPS of 7m/s Header Exemplar Reconstructions*

Location	Ball	Condition	Peak Resultant	Peak Resultant	Maximal Principal
			Linear Acceleration (g)	Angular Acceleration (rad/s <sup>2</sup> )	Strain (%)
Front	2018	Dry	9.5 (0.5)	853.6 (45.4)	5.2 (0.3)
	1966		9.1 (0.2)	831.5 (68.5)	5.7 (0.1)
	1966	Wet	10.2 (0.4)	1078.8 (119.5)	7.4 (0.7)
Front boss	2018	Dry	10.6 (0.2)	1094.6 (64.7)	8.8 (0.2)
	1966		9.8 (0.4)	995.5 (18.0)	8.2 (0.8)
	1966	Wet	11.43 (0.6)	1501.0 (372.2)	10.8 (1.3)
Top	2018	Dry	7.7 (0.5)	955.0 (77.4)	4.6 (0.1)
	1966		8.0 (0.4)	971.1 (50.1)	5.1 (0.2)
	1966	Wet	9.5 (0.4)	966.4 (31.4)	6.3 (0.1)

*Note.* Brackets indicate standard deviation.

**Table 10***Dynamic Head Response and MPS of 13m/s Header Exemplar Reconstructions*

Location	Ball	Condition	Peak Resultant	Peak Resultant	Maximal Principal
			Linear Acceleration (g)	Angular Acceleration (rad/s <sup>2</sup> )	Strain (%)
<b>Front</b>	2018	Dry	19.2 (0.1)	2060.4 (10.4)	10.8 (0.5)
	1966		19.2 (0.2)	2108.7 (19.9)	11.0 (0.4)
	1966	Wet	23.27 (0.7)	2582.1 (60.9)	12.7 (0.3)
<b>Front boss</b>	2018	Dry	19.8 (0.9)	2874.8 (583.5)	17.2 (1.9)
	1966		20.4 (0.3)	2619.7 (383.4)	16.4 (1.1)
	1966	Wet	23.8 (0.2)	2918.43 (60.2)	21.5 (0.4)
<b>Top</b>	2018	Dry	15.8 (0.6)	2187.8 (46.4)	11.8 (1.1)
	1966		15.7 (0.2)	2064.7 (61.8)	10.7 (0.9)
	1966	Wet	6.7 (0.9)	869.8 (116.7)*	6.9 (0.2)

*Note.* \* indicates significance. Brackets indicate standard deviation.

**Table 11***Dynamic Head Response and MPS of 17m/s Header Exemplar Reconstructions*

Location	Ball	Condition	Peak Resultant	Peak Resultant	Maximal Principal
			Linear Acceleration (g)	Angular Acceleration (rad/s <sup>2</sup> )	Strain (%)
<b>Front</b>	2018	Dry	26.1 (1.5)	2946.4 (110.6)	14.5 (1.5)
	1966		26.7 (1.8)	3100.5 (152.2)	15.2 (0.6)
	1966	Wet	11.0 (4.1)*	720.6 (309.8)*	8.4 (3.4)
<b>Front boss</b>	2018	Dry	30.1 (0.8)	4162.6 (191.8)	24.0 (0.6)
	1966		30.57 (0.4)	4802.07 (579.3)	27.2 (2.3)
	1966	Wet	20.8 (11.2)*	2094.2 (899.5)*	18.7 (5.9)
<b>Top</b>	2018	Dry	24.4 (0.7)	3109.4 (144)	14.6 (0.2)
	1966		22.07 (2.7)	3334.87 (279.4)	14.6 (1.5)
	1966	Wet	6.80 (0.46)*	767.37 (245.2)*	6.8 (2.2)*

*Note.* \* indicates significance. Brackets indicate standard deviation.

**Table 12***Dynamic Head Response and MPS of 22m/s Header Exemplar Reconstructions*

Location	Ball	Condition	Peak Resultant	Peak Resultant	Maximal
			Linear Acceleration (g)	Angular Acceleration (rad/s <sup>2</sup> )	Principal Strain (%)
Front	2018	Dry	38.8 (1.4)	4898.4 (307.8)	23.7 (1.2)
	1966		38.8 (1.0)	4760.3 (248.8)	26.7 (0.4)
Front boss	2018	Dry	42.1 (1.9)	6489.8 (283.4)	33.1 (3.8)
	1966		33.17 (6.9)*	5253.80 (644.5)*	28.8 (4.1)
Top	2018	Dry	35.1 (2.6)	5068.2 (89.4)	21.7 (2.7)
	1966		30.8 (1.5)	4578.3 (106.0)	23.0 (1.8)

*Note.* \* indicates significance. Brackets indicate standard deviation.

#### 4.4 Frequency of Magnitude of Headers

Frequency of MPS values of header exemplar reconstructions were binned into the five MPS categories (Table 13). Four Mann-Whitney U tests were conducted to determine if a difference in frequency of headers existed between 2018 and 1966 in each MPS category. There was no frequency for the very high category, therefore, no statistical analysis was performed. It was determined there were no significant differences of frequency in the very low,  $U=40.6$ ,  $p=0.481$ , and low,  $U=28.5$ ,  $p=0.105$  MPS categories. The statistical results showed 2018 had significantly higher frequency in the medium category,  $U=0$ ,  $p<0.001$ , whereas 1966 had significantly higher frequency in the high category,  $U=0$ ,  $p<0.001$  (Figure 12).

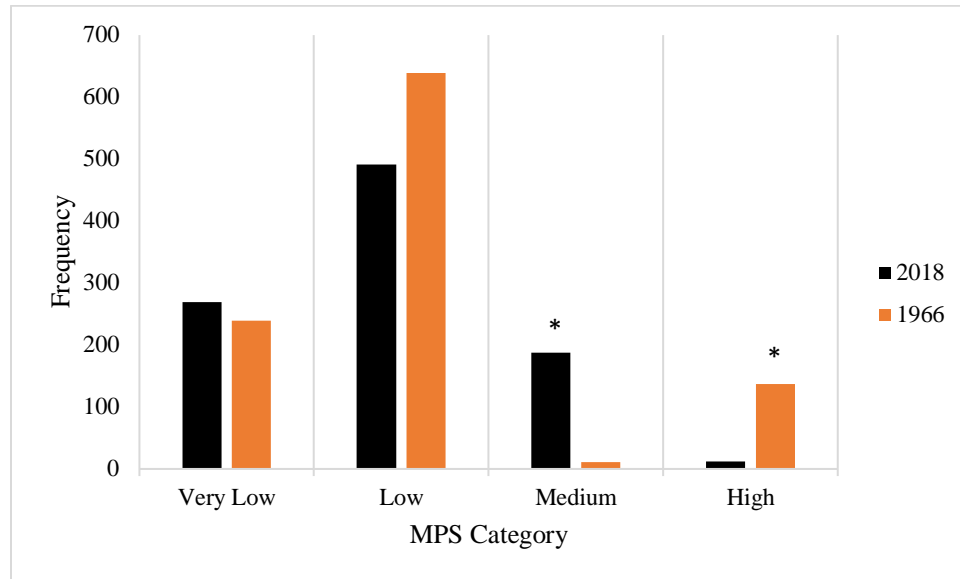
**Table 13***Frequency of MPS values of Headers per Year*

	Very Low <8.0%	Low 8.0-16.9%	Medium 17-25.9%	High 26-34.9%	Very High >35%
<b>2018</b>	269 (8.5)	491 (49.2)	188 (18.8)*	12 (1.2)	0
<b>1966</b>	239 (7.2)	639 (14.9)	11 (1.1)	137 (7.0)*	0

*Note.* \* indicates significance. Brackets indicate standard deviation

**Figure 12**

*Comparison of MPS Category Distribution of Heading Frequency*



\* indicates significance

#### **4.5 Coefficient of Restitution**

Coefficient of Restitution (COR) was measured for the 2018 Telstar 18 dry and 1966 Slazenger Challenge ball dry and wet. The results show no difference of COR across the ball conditions (Table 14).

**Table 14**

*Coefficient of Restitution for Soccer Balls*

<b>Ball</b>	<b>Condition</b>	<b>Coefficient of Restitution</b>
2018 Telstar 18	Dry	0.82
1966 Slazenger Challenge	Dry	0.84
1966 Slazenger Challenge	Wet	0.81

*Note.* Refer to Figure 11 for the Coefficient of Restitution Equation

## **CHAPTER 5: DISCUSSION**

This study compared frequency and impact magnitude of headers between 2018 and 1966 international professional men's soccer matches. More specifically, this study compared total heading frequency, soccer balls influence on head response under varying head conditions, and frequency of MPS categories between 2018 and 1966. These comparisons can provide valuable information into the potential head injury risk for current professional men's soccer players.

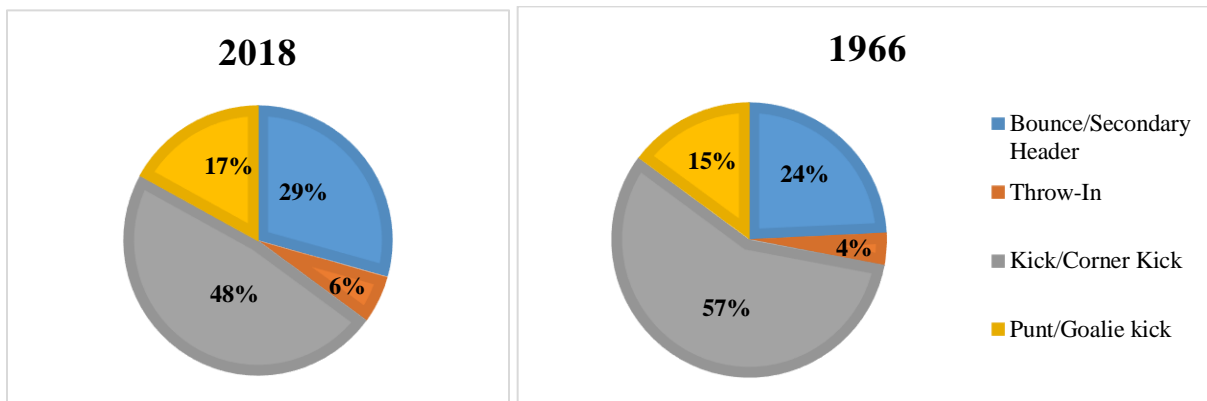
### **5.1 Frequency of Heading**

Overall frequency of headers between ten 2018 ( $M=97.8$ ,  $SD=27.7$ ) and ten 1966 ( $M=105.1$ ,  $SD=23.2$ ) soccer matches were not statistically significant. Frequency of head impacts are important when considering brain trauma as research has reported an association between frequency of impacts and changes in white matter, biomarkers, and metabolic responses (Kuzminski et al., 2018; Lipton et al., 2013; Stalnacke et al., 2004). Heading is the most repetitive and frequent impact to the head experienced by soccer players with research reporting this skill associated with neurologic issues (Matser et al., 1998; Smodlaka, 1984; Tysvaer & Storli, 1981; Witol & Webbe, 2002). Both short-term and long-term exposure to heading have been reported to be associated with physical and biological changes in the brain (Kuzminski et al., 2018; Lipton et al., 2013; Stalnacke et al., 2004). These results demonstrate today's players experience similar frequencies of head trauma from headers when compared to the 1966 players and may be at the same level of risk for neurologic disease and cognitive deficits (Hales et al., 2014; Bieniek et al., 2015; Grinberg et al., 2016; Ling et al., 2017). In terms of the frequency of heading scenarios there was a similar distribution between 2018 and 1966 (Figure 13). In 1966, 57% of heading scenarios were kicks and corner kicks, when compared to 48% in 2018. This 9% difference was the largest difference when comparing heading scenarios between 1966 and 2018

matches. This indicates overall play styles, rules changes, and evolution of the game over the years have not influenced the total frequency of headers and distribution of heading scenarios.

**Figure 13**

*Frequency Distribution of Heading Scenarios*



## 5.2 Magnitude of Headers

Magnitude of a heading impact event is influenced by the event's specific characteristics which include mass, velocity, location, compliance, and angle (Karton et al., 2014; Oeur et al., 2014; Oeur & Hoshizaki, 2016). When impact parameters are changed, resulting resultant linear acceleration and resultant angular acceleration curves vary creating different levels of injury risk. Each year was defined by the soccer ball that was used for the FIFA World Cup of that year. In 2018 Russia, the 2018 Telstar 18 was the official match ball, and for 1966 England World Cup, the 1966 Slazenger Challenge was used. These soccer balls represented the compliance and mass of these impacts. The 2018 Telstar 18 and 1966 Slazenger Challenge were tested under variations of location (front, front boss, top), velocity (7m/s, 13m/s, 17m/s, 22m/s), and condition (dry, wet), to measure linear acceleration, angular acceleration, and MPS values.

It was hypothesized that the 1966 Slazenger Challenge dry condition would create higher values of linear acceleration, angular acceleration, and MPS than the 2018 Telstar 18 dry condition across all velocities and locations. It was found at 22m/s front boss location for the

1966 dry, angular acceleration was significantly lower than the 2018 dry (Table 13). This may be due to the location, as front boss is inherently variable (Oeur & Hoshizaki, 2016; Oeur et al., 2021). With the combination of high velocity and the unique exterior stitching of the 1966 ball, angular acceleration could have decreased at the 22m/s velocity. However, at 7m/s, 13m/s, and 17m/s between the 2018 dry and 1966 dry there were no significant differences for linear acceleration, angular acceleration, and MPS values across all locations (Table 10, 11, 12). These results are important as it demonstrates there were no differences in head impact magnitude for the current international standard soccer ball when compared to the hand-sewn leather soccer ball used in 1966. Current athletes who are heading the 2018 Telstar 18 are sustaining similar head impact magnitudes as athletes in 1966 under the same condition, velocity, and impact location.

It was also hypothesized that the 1966 Slazenger Challenge wet condition would create higher values of linear acceleration, angular acceleration, and MPS when compared to 1966 dry condition across all velocities and impact locations. It was found at 13m/s the 1966 wet ball measured significantly lower angular acceleration at the top location when compared to the 2018 dry and 1966 dry (Table 11). Furthermore, the 1966 wet condition showed significantly lower linear and angular acceleration measures when compared to the 2018 dry and 1966 dry at 17m/s across all locations (Table 12). This was interesting as the weight of the ball for the wet condition increased from 410 grams to 595 grams after 90 minutes of water submersion (Appendix A). The increased weight of the 1966 ball under the wet condition did not increase dynamic head response measures as expected. Studies that have explored older model soccer balls and completed wet conditions have documented an increase in dynamic head response with an increase in soccer ball weight (Shewchenko et al. 2005c). Shewchenko and colleagues

(2005c) identified older model soccer balls increased in weight up to 47%, which lead to higher dynamic head responses compared to the dry ball. However, this study used real participants with mouth guard accelerometers and tested at velocities of 6m/s and 8m/s. Coefficient of Restitution was measured for all three ball conditions and showed there was no significant difference between the 2018 dry, 1966 dry, and 1966 wet (Table 14). This means there were no differences in transfer of energy between the two soccer balls under wet and dry conditions. A trend was noticed in these results for the 1966 wet ball, as the velocity was increased, generally linear acceleration, angular acceleration, and MPS values decreased. From high-speed video analysis, it was observed that the combination of the geometry of the Hybrid III head form, the 1966's wet condition, and high velocity, the ball would slide off the head form rather than providing a direct force impact. Furthermore, the action of heading in real life games are slightly different than the exemplar header reconstructions in the lab. One factor is the head form is not moving towards the ball as players would during a header. Additionally, players often redirect the ball by moving their head from one side to the other; the head form in the lab was stationary until impact. These factors could have influenced the impacting force resulting in the overall lower dynamic head responses from the wet condition.

### **5.3 Frequency of Magnitude of Headers**

Frequency of MPS values of header exemplar reconstructions were distributed into five MPS categories (Table 13). There was no frequency for the very high category, therefore no statistical analysis was performed. It was found there were no significant differences of frequency in the very low and low MPS categories. The results showed 2018 had significantly higher frequency in the medium category, whereas, 1966 had significantly higher frequency in the high category (Figure 12). The average frequency for 2018 (M=188 SD=18.8) games for the

medium MPS category was higher than 1966 (M=11 SD=1.1) across all games (Table 13). In 1966 (M=137 SD= 7) the average frequency of the high MPS category was higher than 2018 (M=12 SD=1.2) across all games (Table 7). This was due to the ball magnitudes measured in the header exemplar reconstructions, the linear and angular accelerations of the 1966 ball at 22m/s for the front location created higher dynamic response than the 2018 ball, creating a higher MPS value and assigning the frequency heading to the high category for punt/goalie kick (Table 15). The frequency of the headers for the 1966 punt/goalie kicks front location, were binned into the high category when the 2018 frequency was binned into the medium category (Table 16).

**Table 15**

*Heading Scenario MPS Category Distribution across Location per Year*

Heading Scenario	Bounce/ Secondary Header			Throw-In			Kick/Corner Kick			Punt/Goalie Kick		
Velocity	7m/s			13m/s			17m/s			22m/s		
Location	F	FB	T	F	FB	T	F	FB	T	F	FB	T
Year												
2018	VL	L	VL	L	M	L	L	M	L	M	H	M
1966	VL	L	VL	L	L	L	L	H	L	H	H	M

*Note.* For Location (F=Front, FB=Front Boss, T=Top) VL=Very Low, L=Low, M=Medium, H=High

**Table 16**

*Heading Frequency of Heading Scenario across Location per Year*

Heading Scenario	Bounce/ Secondary Header			Throw-In			Kick/Corner Kick			Punt/Goalie Kick		
Velocity	7m/s			13m/s			17m/s			22m/s		
Location	F	FB	T	F	FB	T	F	FB	T	F	FB	T
Year												
2018	263	17	6	49	4	4	403	36	19	137	12	10
1966	232	15	7	33	0	4	517	55	26	137	7	11

*Note.* For Location (F=Front, FB=Front Boss, T=Top)

The MPS values between 2018 at 22m/s for front location (M= 23.7%, SD=1.2%) and 1966 (M=26.7%, SD=0.4%) were not statistically significant, however, the medium category was defined as MPS values between 17-25.9% and the high category was defined as 26-34.9%. The 2018 was binned at middle of the medium MPS category while the 1966 was binned at the low end of the high MPS category. Both MPS values of 2018 and 1966 provided similar clinical significance as research reports an estimated 50% risk of sustaining a concussion from MPS values of 19-27% found in gray and white matter (Zhang et al., 2004; Kleiven, 2007; Patton et al., 2013).

## **CHAPTER 6: CONCLUSION**

The purpose of this study was to compare frequency and impact magnitude of heading in 2018 and 1966 international professional men's soccer matches. This was completed by comparing total frequency of heading, magnitude of headers, and frequency of magnitude levels of headers. The results revealed no differences for total frequency of headers between 2018 and 1966 matches. When comparing peak resultant linear acceleration, peak resultant angular acceleration, and MPS values there were no significant differences at 7m/s, 13m/s, and 17m/s between the 2018 Telstar 18 and 1966 Slazenger Challenge under dry conditions at front, front boss, and top locations. However, for 1966 wet ball condition the peak resultant linear acceleration, peak resultant angular acceleration, and MPS values decreased from the interaction of the head form and ball under wet conditions at high velocities. For frequency magnitudes, the results revealed 2018 had significantly higher frequency in the medium MPS category, whereas 1966 had significantly higher frequency in the high MPS category. This study reported that present day players sustain similar impact magnitudes as players heading the ball in 1966. Future studies should focus on including accidental contacts and collisions to provide a complete brain

trauma profile of a soccer player. Institutions and sports media outlets with access to video footage should also consider analyzing their video and include heading count per player as this information is important regarding repetitive head trauma. Given the global popularity of soccer, the results of this study provide a better understanding of the risk factors for chronic neurologic disease associated with heading the ball, allowing players to make informed decisions involving repetitive heading.

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## APPENDICES

### Appendix A: Methods

**Table 17**

*Wet Ball Weight Increments*

<b>Ball</b>	<b>Minutes of Water Submersion</b>	<b>0mins</b>	<b>30mins</b>	<b>60mins</b>	<b>90mins</b>
2018		427g	427g	427g	427g
1966		410g	581g	593g	595g

## Appendix B: Results

**Table 18**

*Header Frequency of Soccer Scenarios per Game*

<b>Year</b>	<b>Game</b>	<b>Bounce</b>	<b>Secondary Header</b>	<b>Throw -In</b>	<b>Kick</b>	<b>Corner Kick</b>	<b>Punt</b>	<b>Goalie Kick</b>
<b>2018</b>	1	12	31	7	45	5	2	19
	2	11	9	0	26	4	0	8
	3	9	16	6	48	5	2	31
	4	5	14	2	34	4	0	9
	5	16	10	0	29	4	0	14
	6	17	31	9	68	4	1	18
	7	8	14	8	45	3	0	12
	8	9	21	10	40	3	0	21
	9	14	8	7	40	4	3	12
	10	10	22	7	50	8	0	14
	<b>Total</b>	111	176	56	425	44	8	158
<b>1966</b>	1	10	15	4	42	3	8	6
	2	12	19	6	69	6	19	10
	3	9	13	1	42	1	12	10
	4	5	19	1	76	1	8	12
	5	20	22	3	63	3	11	8
	6	10	10	5	33	5	4	9
	7	6	9	2	64	2	3	1
	8	14	20	6	51	6	6	10
	9	12	9	6	53	6	7	4
	10	12	9	5	55	5	2	6
	<b>Total</b>	110	145	39	548	53	80	76

**Table 19***Header Frequency of Impact Location per Game*

<b>Year</b>	<b>Game</b>	<b>Front</b>	<b>Front Boss</b>	<b>Top</b>	<b>Side</b>	<b>Rear</b>	<b>Rear Boss</b>
<b>2018</b>	1	108	12	0	1	0	0
	2	46	10	2	0	0	0
	3	103	5	8	1	0	0
	4	55	5	7	0	1	0
	5	63	6	4	0	0	0
	6	120	13	13	1	1	0
	7	83	4	1	2	0	0
	8	96	3	3	2	0	0
	9	78	6	2	2	0	0
	10	99	6	4	2	0	0
		<b>Total</b>	851	7	44	11	2
<b>1966</b>	1	73	10	6	0	0	0
	2	124	11	6	0	0	0
	3	73	12	6	0	0	0
	4	110	9	13	2	0	0
	5	108	14	11	0	0	0
	6	66	8	2	0	0	0
	7	80	4	2	1	0	0
	8	103	3	4	1	0	0
	9	93	4	1	0	0	0
	10	83	4	3	2	0	0
		<b>Total</b>	913	79	54	6	0

**Table 20***MPS Level Distribution Frequency of Headers per Game*

<b>Year</b>	<b>Game</b>	<b>Very Low</b>	<b>Low</b>	<b>Medium</b>	<b>High</b>	<b>Very High</b>
2018	1	39	53	25	3	0
	2	18	27	14	1	0
	3	24	56	35	1	0
	4	18	35	13	1	0
	5	23	34	14	2	0
	6	42	79	24	1	0
	7	22	53	12	1	0
	8	30	49	22	1	0
	9	21	47	12	0	0
	10	32	59	17	1	0
1966	1	24	45	1	19	0
	2	28	77	2	27	0
	3	19	42	3	27	0
	4	23	82	2	25	0
	5	38	68	1	26	0
	6	19	36	0	21	0
	7	14	64	0	8	0
	8	33	59	2	16	0
	9	20	65	0	13	0
	10	21	58	0	11	0