

**A Comparison of Brain Trauma Characteristics from Head Impacts for Lightweight
and Heavyweight Fighters in Professional Mixed Martial Arts**

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Abstract

Athletes competing in the unarmed combat sport of mixed martial arts (MMA) are at an increased risk for long-term neurological consequences due to repetitive head trauma. Mass differentials as well as reported differences in fight styles between Lightweight and Heavyweight fighters in MMA may affect head impact kinematics creating different levels of head injury risk. Factors that influence the risk for head injury include the frequency, magnitude and interval of head impacts. The purpose of this study was to compare differences in frequency, frequency distribution of impact magnitudes, and time interval between head impacts per match between Lightweight and Heavyweight fighters in the Ultimate Fighting Championship (UFC).

Head impacts of 60 fighters were documented from 15 Lightweight and 15 Heavyweight MMA fight videos. Impact type, frequency, and interval were recorded for each fighter, followed by the reconstruction of 345 exemplar impacts in the laboratory using a Hybrid III headform and finite element modeling to determine impact magnitudes. Next, head impacts (punches, kicks, knees and elbows) from fight videos were visually estimated to determine their corresponding magnitude range and establish the frequency distribution of impact magnitudes. The study revealed no significant differences in overall impact frequency and interval between Lightweight and Heavyweight fighters. The frequency distribution of different impact magnitudes was significantly different, with Lightweights sustaining significantly more Very Low, and High magnitude impacts. Overall, both Lightweight and Heavyweight MMA fighters sustain similar impact characteristics as other high-risk athletes including professional boxers and football players. Understanding the different factors that create brain trauma allows for the monitoring, identification, and protection of higher-risk athletes within these two weight classes.

List of Figures

Figure 1. Head impact location reference grid. Impact location: Front Boss-C..... 19

Figure 2. Impact Vector Description 19

Figure 3. The impacting anvil used to simulate punch, kick, and elbow events (A) with layers of foam attached (B) and impact set-up using the HSIS (C). 23

Figure 4. Resultant linear and rotational dynamic response curves for punch anvil impactor matched to compliance of punch-to-head impacts from human punches to a hybrid III headform (Kendall, 2016). 23

Figure 5. The High-speed impacting system (HSIS) consists of a dual rail system mounted on a steel frame, with a steel carriage for the attachment of the impacting mass (A). The carriage is passed through two spinning wheels powered by an electric motor at a desired velocity (B). The final photo on the left demonstrates the launched anvil simulating a shin-to-head impact (C)..... 23

Figure 6. Resultant linear and rotational dynamic response curves for kick anvil impactor matched to compliance of shin-to-head impacts from human kick to a hybrid III headform. 24

Figure 7. Example of pendulum system used to reconstruct elbow-to-head impacts. The hybrid III headform was secured to a low friction-sliding surface located on a table where the height could be adjusted..... 24

Figure 8. Resultant linear and rotational dynamic response curves for elbow anvil impactor matched to compliance of elbow-to-head impacts from human elbow to a hybrid III headform..... 24

Figure 9. Pendulum impacting system consists of a 4 kg metal pendulum frame with an adjustable mass used to reconstruct knee-to-head impacts (A). The (MEP) disc covered with a hemispherical steel cap used to strike the head can be seen in the image to the right (B). 25

Figure 10. Resultant linear and rotational dynamic response curves for knee pendulum impactor matched to compliance of knee-to-head impacts from human knee to a hybrid III headform..... 25

Figure 11. Flow chart depicting methodology to obtain the three objectives of this study (To determine and compare: 1 = Frequency, 2 = interval, 3 = Frequency distribution of MPS between Lightweight and Heavyweight UFC fighters). 30

Figure 12. Total confirmed head impact frequencies from different event types for 30 Heavyweight (HW) and 30 Lightweight (LW) fighters..... 32

Figure 13. Frequency distribution of impact magnitudes for Heavyweight (HW) and Lightweight (LW) fighters. 38

Figure 14. Frequency distribution of head impact magnitudes from punch (a), knee (b), kick (c), and elbow (d) strikes for Heavyweight (HW) and Lightweight (LW) fighters. 39

Figure 15. Image of visual estimation of punch velocity setup with highspeed camera pointed by the yellow arrow positioned orthogonal to the the motions of the athlete (A), and image from broadcast camera positioned behind the highspeed camera (B)..... 67

Figure 16. Frequency of confirmed head impacts, combined confirmed and suspected, and reported significant strikes by Fightmetric (www.ufcstats.com) for Lightweight (A) and Heavyweight fights (B) 68

List of Tables

Table 1. Mass of anvil and pendulum used for impact reconstructions.	22
Table 2. Comparing the frequency of different impact magnitudes between Heavyweight and Lightweights to determine the frequency distribution of head impact magnitudes	26
Table 3. Material properties of the University College Dublin Brain Trauma Model.	27
Table 4. Material characteristics of the brain tissue for the University College Dublin Brain Trauma Model.	28
Table 5. Summary of total frequency and interval of head impacts for Heavyweight (HW) and Lightweight (LW) fighters along with how fights were completed.	31
Table 6. Summary of event characteristics used for the Lightweight (LW) exemplar head impact reconstructions and velocity bucket determination.	33
Table 7. Summary of event characteristics used for the Heavyweight (HW) exemplar head impact reconstructions and velocity bucket determination.	36
Table 8. Comparison of effective mass of punch, elbow, and kicking strikes to body segment parameter calculations.	65
Table 9. Summary of different strike velocities at impact	66

Table of Contents

Contents

Acknowledgements	ii
Abstract	iii
List of Figures	iv
List of Tables	vi
Table of Contents	vii
CHAPTER 1: INTRODUCTION	1
1.1 Problem Statement	1
1.2 Research Question.....	5
1.3 Objective.....	5
1.4 Variables.....	6
1.4.1 Independent Variables	6
1.4.2 Dependent Variables	6
1.5 Experimental Hypothesis.....	6
1.6 Null Hypothesis	6
1.7 Limitations.....	7
1.8 Delimitations.....	8
1.9 Significance.....	8
CHAPTER 2: REVIEW OF LITERATURE	9
2.1 Introduction	9
2.2 Neurological consequences of Head Trauma	10
2.3 Repetitive Head Trauma and Neurological Disease	11
2.4 Head Impact Biomechanics	12
2.4.1 Dynamic Response Measures and Brain Injury	12
2.4.2 Magnitude of Brain Trauma, Dynamic Response and Brain Tissue Deformation	13
2.4.3 Head Impact Events in Combat Sports	14
2.5 Interval between Head Impacts and Duration of Exposure	15
2.6 Summary of literature review	16
CHAPTER 3: METHODOLOGY	17
3.1 Study Design.....	17
3.2 Study Population: Inclusion/Exclusion Criteria	18
3.3 Video Analysis: Head Impact Location Reference Grid	18

3.4 Reconstruction protocol & Impact Compliance	19
3.5 Finite Element Model	26
4. Statistical Analysis	28
4.1 Reliability	28
4.2 Frequency	29
4.3 Frequency Distribution of Different Head Impact Magnitudes	29
4.4 Time Interval Between Head Impacts	30
5.0 Results	31
5.1 Frequency of Head Impacts	31
5.2 Frequency Distribution of Different Head Impact Magnitudes	32
5.3 Time Interval Between Head Impacts	39
6.0 Discussion	40
6.1 Frequency of Head Impacts	40
6.1.1 Frequency of Head Impacts Event Types	41
6.2 Frequency Distribution of Different Head Impact Magnitudes	42
6.3 Time Interval between Head Impacts	45
Conclusion	46
References	47
Appendix	65

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

The sport of mixed martial arts (MMA) involves unarmed combat competition using a combination of techniques from the martial arts, including grappling, submission holds, kicking and striking (UFC.ca). A typical non-championship fight consists of 3 -5 minute rounds, with a rest period of 1 minute between each round. MMA has become a popular sport since its emergence in the 1990s, with over 1 million competitors in the United States (Statistica.com; Lystad *et al.*, 2014). The Ultimate Fighting Championship (UFC), is considered to be the largest MMA organization with the majority of the world's elite mixed-martial artists (Scalia, 2015). As MMA has made its way to the forefront of combat sports, medical groups such as the Canadian Medical Association have voiced concerns about the potential brain injury risks faced by participating athletes from punches, kicks, knees, and elbow strikes to the head (CBC, 2013). Currently, safety regulations vary between sanctioning bodies, but standardized across all 8 weight divisions in the UFC (Flyweight <57 kg, Bantamweight 57 -61.3 kg, Featherweight 61.3 -65.8 kg, Lightweight 65.8 - 70.3 kg, Welterweight 71 -77 kg, Middleweight 77 -83.9 kg, Light Heavyweight 83.9 -93 kg, Heavyweight 93 -120.2 kg). However, reported tactical and physical differences between weight classes in MMA may create differences in brain injury risk between weight classes. The Lightweight division in particular is regarded by experts as one of the most popular and competitive divisions in the UFC (Mackenzie, 2017). In addition, the association between weight class and risk of technical knockout (TKO) has been reported by Hutchison and colleagues (2014), whereby Heavyweights were two times more likely to suffer a technical knockout (TKO) than Lightweights. Heavyweights have been reported to have an injury incidence rate ratio of 1.76 per 1000 minutes of exposure compared to 0.92 for Lightweight fighters (Lystad *et al.*, 2014). This has been attributed to the ability of higher weight-

class fighters to generate a greater punch force in boxing (Walilko *et al.*, 2005). Increases in impacting mass have been reported to significantly affect brain tissue deformation and traumatic axonal injury (Karton *et al.*, 2014; Xu *et al.*, 2016). Time motion analysis research of UFC fights has demonstrated that tactics vary between weight classes, finding that Lightweight fighters spent longer times in high intensity combat situations than Heavyweights in all three rounds (Miarka *et al.*, 2015). High intensity combat situations were defined by Del Vecchio *et al.* (2011) based off of work rates in different positional situations to quantify the effort –pause ratio in a match. With almost half the mass of Heavyweight fighters, it is likely that Lightweights have an increased ability to execute high intensity efforts for longer periods. This appears to be consistent with the fact that Lightweight fighters have been reported to attempt a significantly greater number of head strikes at distance than Heavyweights (where the majority of the fight takes place on average), indicating that fighters in this weight class experience a greater number of head strikes (Miarka *et al.*, 2017). On the other hand, Heavyweight fighters had higher frequencies of head strikes landed and attempted during close-combat clinch situations (Miarka *et al.*, 2017). The position that a fight takes place, whether at distance, clinch, or on the ground, influences the type and frequency of head strikes attempted, since certain strikes such as elbows and knees are easier to land on an opponent in closer combat situations found in the clinch. Lightweight fighters have been reported to spend more time maintaining distance from the opponent, attempting to strike in different positions (i.e. to the head, body, and leg) (Miarka *et al.*, 2017). This indicates that the mechanism of brain injury may differ for athletes depending on weight-class due to differences in time and activity spent during specific positional phases of a fight. Bernick and Banks (2013) have reported that the interaction between weight class and fight exposure in boxers and MMA fighters did not significantly predict changes in brain volume (Bernick & Banks, 2013; Ngai *et al.*, 2008). Ngai and colleagues (2008) found that weight did not statistically increase the likelihood of injuries in a retrospective cohort study of 635 MMA fights. There is no consensus identifying weight class as a

potential risk factor for head injuries in MMA, with Lockwood et al. (2017) stating that data from available studies on brain injuries in MMA were of low quality and lacked homogeneity.

MMA is a combat sport similar to the sport of boxing, where the objective of the contest is for a fighter to score more points or to disable the opponent. Both sports have been reported to have similar head injury rates, ranging from 66-78% in MMA mainly due to lacerations and concussions, and 74-89% in boxing mainly caused by lacerations, concussions, and injuries to the eye (Bledsoe *et al.*, 2006; Lystad *et al.*, 2014; Zazryn *et al.*, 2003). Fights ending in knockouts (KOs) and technical knockouts (TKOs), indicative of a concussion, have been reported to range from 28-46% in MMA and 11-38% in boxing (Bledsoe *et al.*, 2006; Lockwood *et al.*, 2017). Concussions, often referred to as mild traumatic brain injuries (mTBIs), result from high magnitude head rotations causing diffuse strains to brain tissue impairing cellular metabolism (Bailes & Cantu, 2001; Gardner & Yaffe, 2015; Giza & Hovda, 2014; Holbourn, 1943). In addition, the number of KOs among boxers and MMA fighters has been predictive of microstructural brain changes in white matter (Shin *et al.*, 2014). Concussion diagnosis are based on acute clinical symptoms, however, boxers with a history of repetitive mTBIs are also susceptible to chronic neurological injury, commonly coined “punch drunk” (Gardner & Yaffe, 2015; Jordan, 2007, 2014; Martland, 1928; A. C. McKee *et al.*, 2013). Symptoms of cognitive, motor, and behavioral impairments typically present years after the trauma producing activity and the acute symptoms of the initial injury (if any) have ended (Iverson *et al.*, 2015; Jordan, 2014; Martland, 1928; McKee *et al.*, 2013). Axonal degeneration has been found to continue even years after injury in humans, which can result in microtubule breakage and undulation formation indicative of neuropathology (Johnson et al, 2013).

Measuring trauma using magnitude is insufficient to capture a full risk profile. Not only the magnitude, but the frequency (how often the head is impacted), duration (time participated in a sport typically estimated by fight time, career length or number of fights), and the interval (time between head impacts), are risk factors that influence the overall health of the brain. Researchers

have reported that frequent hits to the head, including both concussive and sub-concussive impacts are associated with increased risk for chronic traumatic brain injury etiology (Baugh *et al.*, 2012; Briggs, 2016; Gavett *et al.*, 2011; Jordan, 2007, 2014; McKee *et al.*, 2009; Tagge *et al.*, 2018). Unlike a concussive injury, a sub-concussive injury is mild brain trauma in the absence of the readily observable signs and symptoms of a concussion (Baugh *et al.*, 2012). Boxers have been reported to have changes in levels of blood and cerebrospinal biomarkers after repetitive head impacts following a fight. Elevated levels of neurofilament light polypeptide (NF-L) and total tau (T-tau) reported to be indicative of axonal and central nervous system damage were reported, even in the absence even in the absence of acute symptoms (Neselius *et al.*, 2012; Neselius *et al.*, 2013). Moreover, increasing exposure to repetitive head trauma as measured by the number of professional fights is associated with lower brain volumes and increased impulsiveness in both professional boxers and MMA fighters (Banks *et al.*, 2014; Bernick *et al.*, 2015). The extent of brain damage increases with shorter times between repeated injuries in mice & cell models (Longhi *et al.*, 2005; Meehan *et al.*, 2012; Weber, 2007).

This study utilizes the brain trauma profile method developed by researchers from the Neurotrauma Impact Science Laboratory to characterize cumulative brain trauma sustained while participating in a sport, and includes documenting the frequency of head impacts, magnitude of brain tissue deformation, duration of exposure, and the time interval between impacts (Bernick & Banks, 2013; Hoshizaki *et al.*, 2017; Jordan, 2014; Karton & Hoshizaki, 2018; Zhang *et al.*, 2004). To date, limited evidence exists on evaluating biomechanical characteristics of head impact magnitudes, or on head impact frequencies and intervals sustained by athletes in MMA and associated risk consequences. It was hypothesized that Heavyweight fighters sustain larger impact magnitudes resulting in more severe impacts, while Lightweight fighters experience a higher frequency of head impacts at lower magnitudes. Understanding these risk factors for sustaining brain injury in MMA is valuable for developing guidelines to monitor brain health that can be used

by athletes and regulatory agencies to improve long-term safety in the sport (Bernick & Banks, 2013). The purpose of this study is to document the differences in brain trauma using frequency, magnitude, and interval of head impacts per fight between Lightweight and Heavyweight fighters in the UFC.

1.2 Research Question

Is there a difference in the brain trauma profiles, as characterized by the frequency, frequency distribution of impact magnitudes, and interval, of Lightweight fighters compared to Heavyweight fighters in a professional MMA fight?

1.3 Objectives

1. To compare the frequency of head impacts sustained per fight by Lightweight and Heavyweight fighters in a MMA fight
2. To compare the frequency distribution of different head impact magnitudes, as measured by maximum principal strain, that occur in professional Lightweight and Heavyweight fights
3. To compare the time interval between head impacts that occur within a professional Lightweight and Heavyweight fight

1.4 Variables

1.4.1 Independent Variables

Weight class (2):

- a. Lightweight
- b. Heavy weight

1.4.2 Dependent Variables

1. Frequency of head impacts
2. Frequency distribution of different head impact magnitudes, as measured by Maximum Principal Strain (MPS)
3. Time interval between head impacts

1.5 Experimental Hypotheses

1. Lightweight MMA fighters will sustain a significantly greater frequency of head impacts per fight than Heavyweight fighters will.
2. Heavyweight MMA fighters will have a significantly greater frequency of very high magnitude head impacts, while Lightweight MMA fighters will have a significantly greater frequency distribution of very low - high magnitude head impacts.
3. Lightweight MMA fighters will sustain head impacts at a significantly shorter time interval than Heavyweight MMA fighters.

1.6 Null Hypotheses

1. There will be no difference in the frequency of total head impacts per fight sustained between Lightweight and Heavyweight MMA fighters.
2. There will be no difference in the frequency distribution of different head impact magnitudes of MPS reported from head impact events between Lightweight and Heavyweight MMA fighters.

3. There will be no difference in the time interval between head impacts in Lightweight and Heavyweight MMA fighters.

1.7 Limitations

1. Impacts will be reconstructed using a Hybrid III headform that is not fully biofidelic and may not provide the exact head response (Deng, 1989; Horgan & Gilchrist, 2003; Hubbard & McLeod, 1974; Mertz, 1985).
2. The characteristics of the brain tissue in the Finite Element model used is partially validated based off cadaveric models and may not be fully representative of an adult male (Horgan & Gilchrist, 2003).
3. The data will be collected in a controlled laboratory setting that will not replicate an actual MMA fight. Factors such as fatigue may modify a player's technique and thus change the effective mass of a strike (Gabbett, 2008). It is possible that the striking masses calculated in this study may not fully replicate those in a fight; however, the calculated values remain a good representation of impacting masses (Appendix Table 8).
4. There are limitations to using video analysis, as not all impact locations are visible. Strikes between athletes may not be completely visible due to proximity of body positions in striking exchanges, changes in zoom and camera angle, as well as head positioning in grappling situations.
5. Estimated head impact velocities were visually estimated to establish the frequency distribution of head impact magnitudes of 4 event types (Section 3.4 Reconstruction protocol & Impact Compliance). As a result, estimated impact velocities may vary from those seen in a professional fight.

1.8 Delimitations

1. The impact velocities ranging from 1 m/s - 11 m/s were used in the analysis of impact magnitudes between the 2 weight classes for the 3 most common impact locations (see CHAPTER 3: METHODOLOGY).
2. Only confirmed head impacts that occur in clear view and not partially blocked will be included in the analysis to allow for accurate head impact representation. Nonetheless, suspected head impacts were noted and discussed within the context of overall head impact frequency. Suspected head impacts are described in Section 3.1 Study Design and 5.1 Frequency of Head Impacts.
3. Head impact events that were not designated as one of the four impacting event types (punch, kick, knee, and elbow) were documented as “other” and only included in the total frequency and interval comparisons due to the great variability in these impacting conditions.

1.9 Significance

Studies have evaluated head trauma in mixed martial arts based on reported cases or indicators of traumatic brain injury. None to date however reported the potential effect of a cumulative spectrum of head impacts representative of sub-concussive as well as concussive impacts on the brain. This study aims to identify the mechanical loading scenarios associated with acute and chronic brain injury, such as concussion and chronic traumatic encephalopathy (CTE). Identifying higher-risk athletes provides an opportunity to mitigate the chronic effects of brain trauma through primary prevention techniques.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Introduction

A history of repetitive brain trauma has been identified in individuals diagnosed with CTE (Stern *et al.*, 2011). Athletes participating in contact sports are at risk to sustain repeated concussive and subconcussive blows to the brain which may lead to long-term neurologic sequelae (Omalu *et al.*, 2010; Stern *et al.*, 2011). A systematic review by Lockwood and colleagues (2017) reported that competitors who lost their fight sustained significantly more injuries than winners, with fighters in bouts ending in knockout (KO) or technical knockouts (TKO) incurring more injuries than fighters in bouts ending by submission. Various rates of concussion and other traumatic brain injuries (TBIs) have been reported in MMA, however the incidence of head injury in MMA has yet to be determined without better quality data (Lockwood *et al.*, 2017).

The frequency, magnitude, and time interval between head impact forces along with duration of participation are reported to be risk factors for developing TBI and late-onset neurological disease (Baugh *et al.*, 2014; Gavett *et al.*, 2011; Jordan, 2000, 2013; McKee *et al.*, 2009, 2013; Post *et al.*, 2017). Increased magnitudes of head acceleration and tissue strain are associated with brain tissue injury (Kleiven, 2007; Newman *et al.*, 2000; Zhang *et al.*, 2004). Decreased time intervals between multiple impacts to the head have shown the brain to be more susceptible to injury, and that increasing recovery time between mild TBIs has been reported to lead to positive outcomes (Laurer *et al.*, 2001; Longhi *et al.*, 2005; Meehan *et al.*, 2012; Mychasiuk *et al.*, 2016; Weber, 2007). In boxing and MMA, longer duration of exposure to contact sport is said to increase the risk for cognitive and structural brain changes, psychiatric impairments, and chronic traumatic brain injury (Banks *et al.*, 2014; Jordan, 2013; Shin *et al.*, 2014).

While researchers have associated these factors with increased risk for developing neurological disorders, there is little consensus on how much or how little a role these factors play

in the development of chronic neurological disorders (Baugh *et al.*, 2014; Gardner & Yaffe, 2015; Iverson *et al.*, 2015; Kanthasamy *et al.*, 2017; Meehan *et al.*, 2012; Saulle & Greenwald, 2012; Xu *et al.*, 2016). The following review will examine the neurological consequences of head trauma, and then highlight the risk factors that can lead to brain injury, including repetitive head trauma, head impact magnitude and interval.

2.2 Neurological consequences of Head Trauma

Chronic TBI encompasses a spectrum of disorders associated with single, and repetitive TBIs, including but not limited to dementia pugilistica, chronic postconcussion syndrome, posttraumatic dementia, posttraumatic parkinsonism, and chronic traumatic encephalopathy (CTE) (Jordan, 2014). The only documented case of CTE in MMA to date was made in a professional 25-year-old male MMA athlete, who had only 13 professional fights and experienced 1 knockout loss (Hohler, 2016). CTE is diagnosed post-mortem and has been described as a progressive tauopathy characterized by the accumulation of hyperphosphorylated tau and TDP-43 proteins along with neurodegeneration (Iverson *et al.*, 2015; Jordan, 2014; Kanthasamy *et al.*, 2017; McKee *et al.*, 2013). The clinical presentations (determined retrospectively) that have been linked to the neuropathology include chronic psychiatric problems, dementia, substance abuse, aggression and suicidal behavior, however early stages of CTE can be diagnosed in deceased individuals with no symptoms (Iverson *et al.*, 2015; McKee *et al.*, 2013, 2014). It has been hypothesized that mechanical injury to the axons can trigger a neurodegenerative cascade resulting in pathologic increases in intracellular calcium ions leading to degeneration (Giza & Hovda, 2014; Johnson *et al.*, 2013; Yuen *et al.*, 2009). Genetic factors, age and history of concussive impacts have also been hypothesized to confer different degrees of CTE risk (Jordan, 2007, 2014). Evidence supports that head impacts independent of concussive signs can lead to negative neurophysiological consequences and the onset of CTE. This is consistent with reports of former athletes diagnosed

with CTE with no history of concussion, suggesting that sub-concussive hits may be sufficient to lead to the development of CTE (Baugh *et al.*, 2012; Gavett *et al.*, 2011; Stein *et al.*, 2015). While there have been a number of studies evaluating concussion risk and mild traumatic brain injuries (mTBIs) in mixed martial arts, limited research currently exists regarding the exposure to subconcussive levels of brain trauma (Lockwood *et al.*, 2017; Lystad *et al.*, 2014; Miarka *et al.*, 2017; Ngai *et al.*, 2008).

Additional neurodegenerative disorders have been reported in individuals exposed to repetitive brain injury, and individuals with CTE are at risk for other neurodegenerative diseases (Gardner & Yaffe, 2015; Iverson *et al.*, 2015; Jordan, 2014). Repetitive brain trauma has also been established as a significant risk factor for post-TBI dementias and Parkinson's disease (Gardner & Yaffe, 2015; Kokjohn *et al.*, 2013; Ramos-Cejudo *et al.*, 2018; Weiner *et al.*, 2017). A recent retrospective cohort study has found that previous exposure to a mTBI had a 56% higher rate of developing Parkinson's disease than those without a history of head trauma (Gardner *et al.*, 2018).

Increasing exposure to repetitive head trauma as measured by number of professional fights and years of fighting were also associated with lower brain volumes and increased impulsiveness in both professional boxers and MMA fighters (Banks *et al.*, 2014; Bernick *et al.*, 2015; Shin *et al.*, 2014). The number of knockouts among boxers and MMA fighters has been reported to be predictive of microstructural brain changes in white matter (Shin *et al.*, 2014). Olympic boxers who sustained repetitive head trauma were found to have elevated levels of biomarkers for central nervous system damage after a bout, and thought to be associated with increased risk of chronic brain injury (Neselius *et al.*, 2012, 2013).

2.3 Repetitive Head Trauma and Neurological Disease

The evidence linking repetitive head trauma to chronic brain injury initially stems from 1928, when Martland noted that particularly slugging boxers who took significant head punishment

as part of their fighting style were suffering from “punch drunk”. Martland (1928) describes the neurocognitive status of 23 professional boxers, detailing early symptoms of slight unsteadiness in gait, mental confusion, slowing of muscular action and then the progression in severe cases to characteristics of parkinsonian syndrome (Martland, 1928). This neuropsychiatric syndrome was later termed dementia pugilistica by Millspaugh in 1937, and was further reported in boxers by other researchers (Corsellis *et al.*, 1973; Millspaugh, 1937). Evidence emerged that the neuropathology and clinical symptoms of dementia pugilistica were not unique to boxers, but could be seen in individuals including a woman who had been repeatedly battered, a person with autism that had a history of head banging behavior (Hof *et al.*, 1991; Roberts *et al.*, 1990). The term chronic traumatic encephalopathy (CTE) has been adopted to describe the unique neurological deterioration that results from repetitive head trauma, whereas dementia pugilistica is considered a subtype of CTE reserved for boxers (Iverson *et al.*, 2015; Jordan, 2014; McKee *et al.*, 2009; Stern *et al.*, 2011).

2.4 Head Impact Biomechanics

2.4.1 Dynamic Response Measures and Brain Injury

The relationship between mechanical parameters of an event and risk of injury has been the focus of a number of papers (Karton *et al.*, 2014; Oeur *et al.*, 2014; Oeur & Hoshizaki, 2016). Higher magnitudes of peak linear and rotational head acceleration of the head during an impact, has been associated with increased risk of mTBI and TBI (Gennarelli *et al.*, 1982; King *et al.*, 2003; Kleiven, 2013; Newman *et al.*, 2000; Post *et al.*, 2017; Zhang *et al.*, 2004). Linear acceleration has been linked to intracranial pressure gradients, and shown to be associated with focal head injuries such as skull fractures, and traumatic brain injuries such as subdural hematoma (Gurdjian *et al.*, 1963; Holbourn, 1943; Kleiven, 2013; Ommaya & Gennarelli, 1974; Thomas *et al.*, 1966). Concussion and diffuse axonal injuries (DAIs) have been associated with high head rotations causing diffuse strains to a

larger area of brain tissue (Biasca, 2002; Gennarelli *et al.*, 1982). While there has been success in managing focal type injuries in professional sports due to current helmet testing designs and certifications (T. B. Hoshizaki & Brien, 2004), athletes in professional MMA do not wear head protection.

2.4.2 Magnitude of Brain Trauma, Dynamic Response and Brain Tissue Deformation

The magnitude of a head impact event is influenced by the event's unique impacting characteristics such as mass, velocity, location, and compliance (Bernick *et al.*, 2015; Karton *et al.*, 2014; Oeur *et al.*, 2014; Oeur & Hoshizaki, 2016; Oeur, 2018). As the impact parameters such as location, mass, velocity, and compliance change, the resulting dynamic response curves vary creating different levels of injury risk (Gennarelli *et al.*, 1982; Karton *et al.*, 2014; Oeur *et al.*, 2014; Oeur & Hoshizaki, 2016; Oeur, 2018; Ommaya *et al.*, 1966). Impact location, defined by the site and angle of the impact, has been shown to have an influence on the resulting brain response and head injury (Gennarelli *et al.*, 1982; Oeur *et al.*, 2014; Ommaya *et al.*, 1966; Walsh *et al.*, 2012; Walsh *et al.*, 2011). Noncentric impacts, as well as side and rear impacts have been shown to have high angular accelerations, while impacts to the front and side had the highest linear accelerations. The effect of the impactor mass also plays a role on the dynamic response. Karton *et al.* (2014) found a positive relationship between increases in mass and increases in dynamic response. Experimental animal research also confirmed that weight increase of the impactor produced a graded injury in animal mouse models (Xu *et al.*, 2016). The overall stiffness (compliance) of the impactor also influences the effects of the dynamic response of the head, and the severity of the brain injury (Oeur & Hoshizaki, 2016; Oeur, 2018). The influence of increasing velocity results in an increased dynamic response magnitude (Gurdjian *et al.*, 1963; Oeur, 2018; Rousseau *et al.*, 2009).

Finite Element (FE) models of the brain provide brain tissue strain measures, taking into account the time history of the linear and angular acceleration curves (King *et al.*, 2003; Ommaya *et*

al., 1966; Post *et al.*, 2017). Thus, finite element modeling allows for the interpretation of linear and rotational loading curves and how they influence the response of neural tissue. This has led researchers to investigate the relationship between brain tissue strain with injury (Zhang *et al.*, 2004). Maximum principal strain (MPS) is commonly used to represent brain deformation and has been identified as a possible indicator of brain injury (Gagnon & Ptito, 2017; Kleiven, 2002, 2007; Willinger & Baumgartner, 2003; Zhang *et al.*, 2004). Bartsch *et al.* (2012) found that in equivalent impacts, punches with MMA gloves induced higher rotational velocity than the boxing glove equivalent. Kendall (2016) reconstructed knock-out punches from MMA fighters and reported that impacts resulting in an average MPS value of 50% strain corresponded to 80% risk for concussive injury.

2.4.3 Head Impact Events in Combat Sports

Brain trauma in MMA most commonly results from punches, kicks, knees, and elbows to the head. Little biomechanical research involving the risk to brain injury caused by these types of head impact events exists. Much of the literature involving brain tissue deformation and impact parameters include sports such as football and hockey. It is important to consider other combat sports research that would be relevant to MMA.

A biomechanical study of full-contact karate reported that hand protectors and foot padding did not reduce violent acceleration of the headform from kicks and punches to the head (Schwartz *et al.*, 1986). Striking techniques have been reported to increase effective impact mass in boxing and football (Viano *et al.*, 2007; Viano *et al.*, 2005; Walilko *et al.*, 2005). The effective mass of an impact is a measure of the body's inertial contribution to the transfer of momentum during a collision. Smith and Hamill (1986) noted that higher skilled boxers generated greater momentum even though the hand was not travelling at a higher velocity. Well trained martial artists can generate higher effective mass palm strikes of 2.62kg compared to 1.33kg from non-practitioners

by tightening appropriate muscles immediately before and during impact (Neto *et al.*, 2007). This coincides with findings that the transfer of momentum of the punching arm, rather than that of the other body segments, to its target contributes to 95% of the impulse (Nakano *et al.*, 2014). Walilko *et al.*, (2005) examined the punch force generated by Olympic boxers from five different weight classes. Higher weight class boxers were found to generate high punch force, in which punch force was the strongest predictor of severity outcomes. Super heavyweight (91-100kg) boxers generated punch forces with an average of 4345N compared to 2625N by Middleweights (75kg) (Walilko *et al.*, 2005). Impact punch velocities have been reported between 7 – 12 m/s (Atha *et al.*, 1985; Viano *et al.*, 2005; Walilko *et al.*, 2005).

2.5 Interval between Head Impacts and Duration of Exposure

The effect of inter-injury interval between impacts has been previously studied in animal and cell models attempting to replicate repetitive injuries in humans. In one study, cumulative damage was observed in hippocampal cells that were subjected to mild stretch injuries at either 1hr or 24hr time intervals, with the extent of damage increasing with shorter times between repeated injuries (Weber, 2007). The effect of interval injury was made even more apparent when hippocampal cells subjected to very low levels of stretch (10%) were not damaged after 1-hour intervals, but induced cell damage was observed when the experiment was repeated at 2 minute intervals (Slemmer & Weber, 2005). Experiments involving mice models have found cognitive impairment in mice was exacerbated when the time interval between concussive head impacts was within 3 to 5 days (Longhi *et al.*, 2005). Meehan and colleagues (2012) impacted rats with concussive blows to the head at varying time intervals per day, week, or month, and found that when multiple concussions were sustained daily, the effects on cognition may be permanent. However increasing the time interval between concussions attenuated the effects on cognition.

These findings suggest that a level of injury sustained within a certain timeframe or vulnerable period may cause cumulative brain damage (Prins *et al.*, 2013). Time interval of head impacts may be influenced by the differences in the time spent performing high versus low intensity actions, or the amount of strikes attempted within a given timeframe. Heavyweight fighters have been reported to spend on average 121s and 46s performing low and high intensity actions respectively. This is in contrast to Lightweight fighters who spend on average 170s and 150s performing low and high intensity actions (Miarka *et al.*, 2015). Heavyweights have been reported to attempt significantly fewer head strikes (14) compared to Lightweights (24) (Miarka *et al.*, 2017). The time interval between head impacts during an MMA bout has not been investigated to date.

While the duration of a career has been proposed as an increased risk for CTE in boxing and football, it is still poorly defined (Jordan, 2013; McKee *et al.*, 2013). A major challenge in attempting to describe duration of a career in combat sports is that factors such as out of competition sparring, number of knockouts sustained, average number of fights per year, and total number of fights may be influential when analysing the duration of a fighting career (Bernick & Banks, 2013). Modern boxing as initially defined by the Queensberry Rules, and professional football played in the National Football League are well established sports, but in the modern sport of MMA, the bouts in the UFC fought under the unified rules were established in 2000 (Sherdog.com), with a limited number of fighters retired. For this study, duration of activity was studied within the context of a single professional MMA fight.

2.6 Summary of literature review

Physical and tactical differences between Lightweight and Heavyweight fighters suggest a possible difference in their respective brain trauma profiles. Examining brain trauma profiles for different weight classes will provide a better understanding of the relationship between weight class and risk of brain injury in MMA. To understand the differences in brain trauma sustained

between different weight classes in MMA, it is important to analyse the risk factors associated with brain injury, and their neurological consequences. Exposure to repetitive sub-concussive and concussive head impacts, higher impact magnitudes, and a decreased amount of time sustained between impacts have been discussed as head injury predictors for acute and chronic negative neurological consequences. These risk factors have been poorly described in the context of weight classes in MMA due to the infancy of the sport and lack of available research.

CHAPTER 3: METHODOLOGY

3.1 Study Design

The aim of this study was to determine if differences in impact frequency, frequency distribution of head impact magnitudes, and time interval between impacts exist between Lightweight and Heavyweight fighters. Head impacts for 60 fighters were documented from 15 Lightweight and 15 Heavyweight MMA fight video footage; impact locations were determined by dividing the head into 8 (45°) separations in the transverse plane and 3 elevations within the sagittal plane (Figure 1). Head impacts from video footage were documented as either confirmed or suspected head impacts. Confirmed impacts were defined by meeting the following three conditions:

- i) An impact is certain and results in visible motion of the head
- ii) The impact type is clear
- iii) The estimated moment of impact can be identified

Suspected head impacts included partially blocked strikes or as impacts seen on screen where head contact location was not visible. Exemplar impacts of each event (punch, kick, knee, and elbow) were selected for reconstruction to determine impact magnitudes (Figure 3-Figure 10, Table 6).

Impact locations were established based on documented video analysis of the top three impact locations. Impact velocities and striking masses cited in the literature were used for reconstructions (Table 1 and Appendix Table 9). Reconstructions were completed three times for each event type at a given location and velocity, and the average MPS of the three trials was used to establish the MPS value of that impact. In the cases where there was equal representation of impacts leading to more than top three locations, additional reconstructions were completed to represent those locations. A total of 345 impact reconstructions were completed. Velocities of documented head impacts corresponding to MPS values of reconstructed impacts were visually estimated from video sequences to determine the frequency distribution of different head impact magnitudes. Impact interval was determined to be the average time between head impacts for each fighter in each weight class.

3.2 Study Population: Inclusion/Exclusion Criteria

The populations studied were current Lightweight and Heavyweight fighters who fought in a 3-round fight in the UFC. To capture the most current spectrum of trauma profile, fight footage from the 2017-2018 calendar year collected through the UFC's extensive fight library was used. Heavyweight and Lightweight competitors must be within the cut-off weight limits at the time of their official weigh ins before competition.

3.3 Video Analysis: Head Impact Location Reference Grid

Impact location was documented based on a similarly established reference system previously adopted by Kendal (2016) to determine head impact locations (Figure 1). Impact vectors to the head in MMA are characterized by a wide range of possibilities, however to account for this variability, possible impacts were classified into 6 different impact vectors at 45 degrees similar to previously published impact vector locations (Figure 2) (Stojsih, 2010; Walsh *et al.*, 2011). Video

data were collected by a single evaluator who later reanalyzed 7 fight videos after a minimum of 1 week between analyses to ensure intra-rater reliability (see 4.1 Reliability).

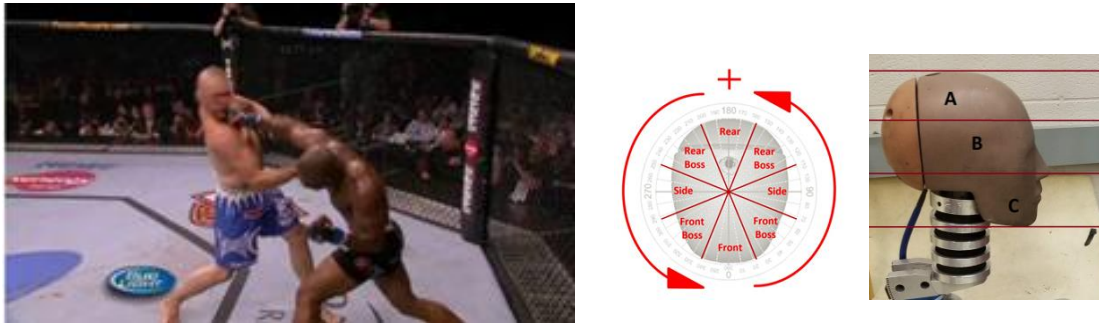


Figure 1. Head impact location reference grid. Impact location: Front Boss-C

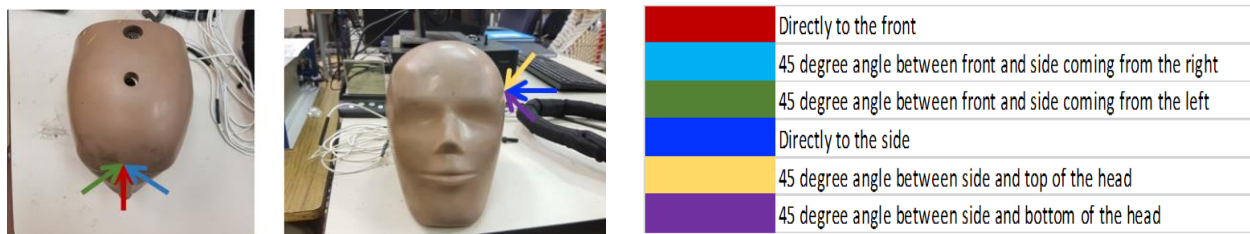


Figure 2. Impact Vector Description

3.4 Reconstruction protocol & Impact Compliance

The impact compliance of a punch with a MMA style glove has been documented (Kendall, 2016). The use of Dempster’s rigid body segmental mass calculations for establishing the striking mass was found to be comparable to studies reporting effective mass of punch, elbow, and kicking strikes (Atha et al., 1985; Dempster & Gaughran, 1967; Philippe Rousseau & Hoshizaki, 2015a; Sidthilaw, 1996; P. K. Smith & Hamill, 1986; Paul K. Smith, 2008; Walilko, 2005a) (Appendix Table 8). The mass of the anvil and pendulum used was adjusted using metal weights to represent the two different striking masses reported in Table 1. The impacting anvil used to simulate punch, elbow and kick strikes was instrumented with varying densities and layers of foam (Figure 3), while a 3.81

cm modular elastomer programmer (MEP) disc covered with a hemispherical steel cap (Figure 9) previously used in another study (Ignacy, 2017) was used to simulate knee striking events. Three-dimensional dynamic response data was collected from multiple knee and elbow trials to a Hybrid III headform by an experienced kickboxer. Compliance data were determined from a single, standing kick-to-head strike to the Hybrid III headform since the participant experienced a large amount of discomfort from the impact, thus having to terminate further trials. Acceptable compliance for the impacting conditions were determined by matching the dynamic response curve shapes and impact durations (Figure 4, Figure 6, Figure 8, Figure 10). Head impact reconstructions of punches and kick strikes to a Hybrid III dummy head were completed using a high-speed impacting system (HSIS), while elbow and knee strikes used a pendulum system to launch the appropriate impactor at a Hybrid III headform (Figure 5, Figure 7, and Figure 9).

The top impact locations for both weight classes (60 fighters in total) were determined from video analysis for punch, kick, knee, and elbow strikes. Next, exemplar impact reconstructions were represented at a range of velocities starting at 1 m/s up to 11 m/s, reported to be the average velocity from knockouts professional boxers can sustain (Cournoyer, 2019). The tested velocities were event specific and based on previously reported kinematic studies in other sports (Appendix Table 8). Dynamic response data collected from these impact reconstructions were input into the University College Dublin Brain Trauma Model (UCDBTM) finite element (FE) model to determine brain tissue strains. Once brain tissue strains were determined for the spectrum of impact velocities for different events, velocity categories were established based on impact event and location to corresponding strain values of very low, low, medium, high, and very high (Table 2). After velocity ranges were established, head impacts (punches, kicks, knees and elbows) from fight videos were visually estimated to determine which velocity category an impact belongs to and its corresponding MPS category.

In this study, a visual estimation approach was used, where the velocity of head impacts from different events (punch, kick, knee, and elbows) were estimated from the Lightweight and Heavyweight professional fights. Before velocity estimations from fight videos were completed, the visual estimation method was validated against punch speeds calculated using a HighSpeed Imaging PCI-512 Fastcam camera (Photron USA Inc., San Diego, CA, USA). An amateur kickboxer volunteered to perform 37 different punches (jabs, crosses, hooks, uppercuts, and hammerfists) with a range of velocities on a boxing bag set up in the lab while being recorded using a high-speed camera as well as a broadcast camera placed at Octagon height level (1.8m) (Appendix Figure 15). Punches were the strike of choice used to visually estimate and validate. This is because they were the most common strikes landed and varied the most, comprising of many different orientations. A senior researcher calculated the striking velocities using the high speed camera. Next, a trained amateur kickboxer blinded to the results of the high-speed camera estimated which velocity category each punch belonged to. The blinded amateur kickboxer was trained to view video recordings of the broadcast camera and visually identify impact velocity categories for each punch type. The velocity categories used were: 0-2 m/s, 2-4 m/s, 4-6 m/s, and 6+ m/s. The training was as follows: 15 video sequences of punches from the recorded data set that covered the range of possible velocities were analyzed by the kickboxer, while given recurrent feedback from the senior researcher comparing estimated velocities with the high-speed camera results. The kickboxer then created a written description on the range of possible velocities dependent on punch type (jab, cross, hook, uppercut, and hammerfist), and then estimated 37 different punch types recorded in the lab. Velocity measurement reliability was assessed using Cronbach's alpha (3.1 Statistical Analysis). A flowchart depicting the methodology protocol is shown in Figure 11.

Table 1. Mass of anvil and pendulum used for impact reconstructions.

Impact Parameters	Description of Value used	Impact Velocities Tested	Value used
<p>Striking mass (Punch)</p> <p>(Kendall, 2016; Walilko <i>et al.</i>, 2005)</p>	<p>Mean for weight class (Anthropometric data of Professional Boxers)</p>	<p>1, 3, 5, 7, 9, 11 m/s</p>	<p>Lightweight: 3.35 kg</p> <p>Heavyweight: 4.6 kg</p>
<p>Striking mass (Kick)</p> <p>(Dempster's Segmental mass)</p>	<p>Dempster's Body Segment Parameters (Leg Knee to ankle center)</p>	<p>3, 5, 7, 9 m/s</p>	<p>Lightweight: 3.32 kg</p> <p>Heavyweight: no head kicks were observed</p>
<p>Striking mass (Knee)</p> <p>(Dempster's Segmental mass)</p>	<p>Dempster's Body Segment Parameters (Hip to knee center)</p>	<p>1, 3, 5, 6.5 m/s</p>	<p>Lightweight: 7 kg</p> <p>Heavyweight: 12 kg</p>
<p>Striking mass (Elbow)</p> <p>(Dempster's Segmental mass)</p>	<p>Dempster's Body Segment Parameters (Glenohumeral joint to elbow center)</p>	<p>1, 3, 5, 6.5 m/s</p>	<p>Lightweight: 1.97 kg</p> <p>Heavyweight: 3.37 kg</p>



Figure 3. The impacting anvil used to simulate punch, kick, and elbow events (A) with layers of foam attached (B) and impact set-up using the HSIS (C).

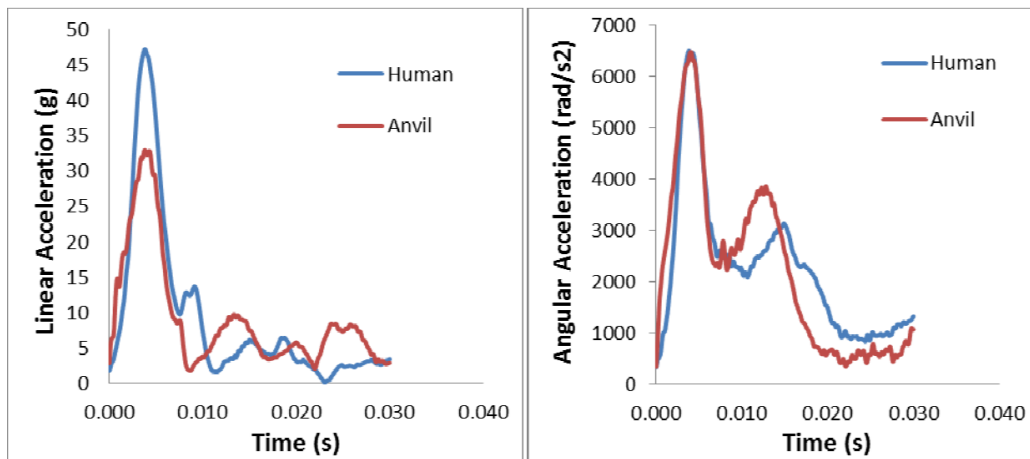


Figure 4. Resultant linear and rotational dynamic response curves for punch anvil impactor matched to compliance of punch-to-head impacts from human punches to a hybrid III headform (Kendall, 2016).



Figure 5. The High-speed impacting system (HSIS) consists of a dual rail system mounted on a steel frame, with a steel carriage for the attachment of the impacting mass (A). The carriage is passed through two spinning wheels powered by an electric motor at a desired velocity (B). The final photo on the left demonstrates the launched anvil simulating a shin-to-head impact (C).

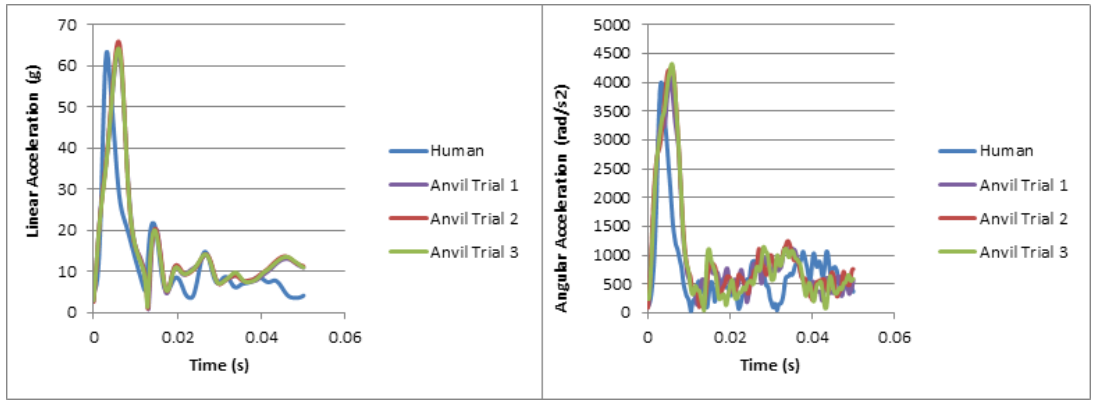


Figure 6. Resultant linear and rotational dynamic response curves for kick anvil impactor matched to compliance of shin-to-head impacts from human kick to a hybrid III headform.

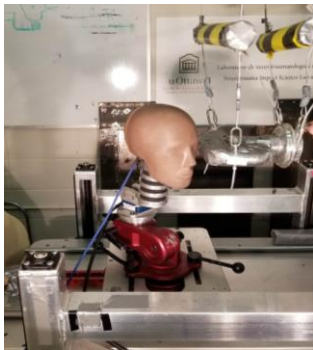


Figure 7. Example of pendulum system used to reconstruct elbow-to-head impacts. The hybrid III headform was secured to a low friction-sliding surface located on a table where the height could be adjusted.

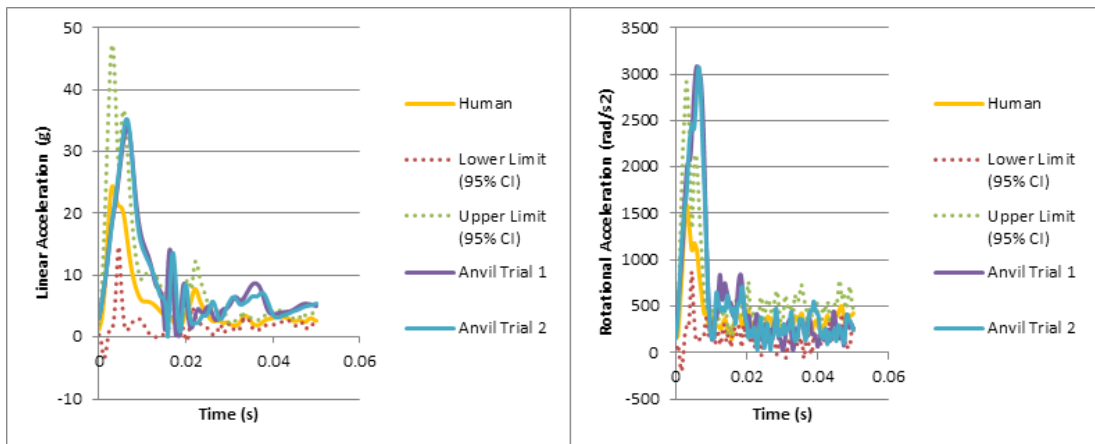


Figure 8. Resultant linear and rotational dynamic response curves for elbow anvil impactor matched to compliance of elbow-to-head impacts from human elbow to a hybrid III headform.

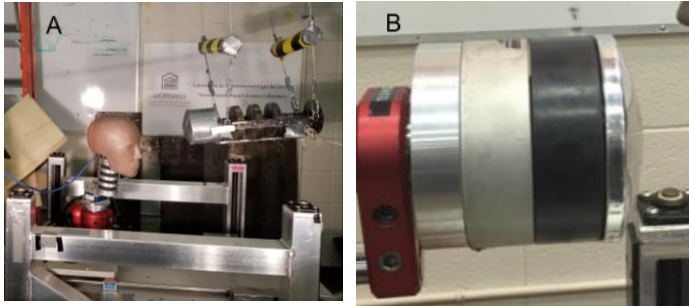


Figure 9. Pendulum impacting system consists of a 4 kg metal pendulum frame with an adjustable mass used to reconstruct knee-to-head impacts (A). The (MEP) disc covered with a hemispherical steel cap used to strike the head can be seen in the image to the right (B).

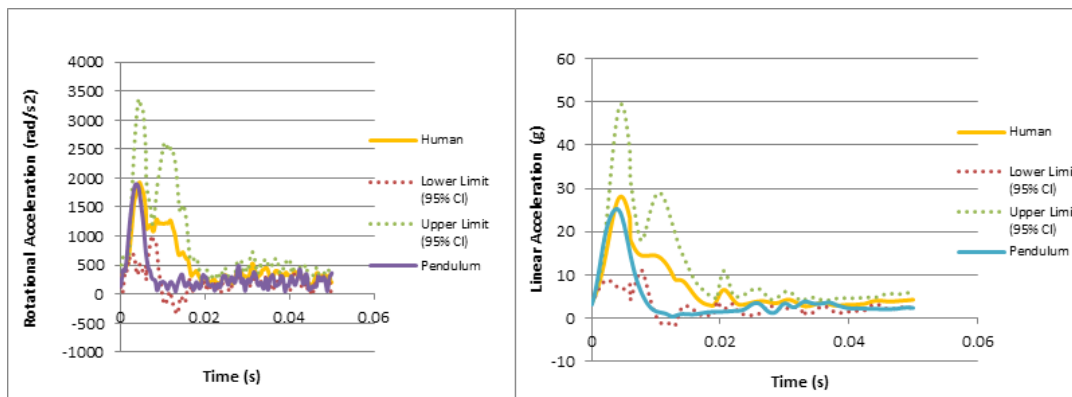


Figure 10. Resultant linear and rotational dynamic response curves for knee pendulum impactor matched to compliance of knee-to-head impacts from human knee to a hybrid III headform.

Table 2. Comparing the frequency of different impact magnitudes between Heavyweight and Lightweights to determine the frequency distribution of head impact magnitudes

Category*
Very low MPS: <8%
Low MPS: 8%-16.9%
Medium MPS: 17%-25.9%
High MPS: 26%-34.9%
Very High MPS: >35%

*(Bain & Meaney, 2000; Cournoyer, 2019; Karton *et al.*, 2016; Karton & Hoshizaki, 2018; Kleiven, 2007; Patton *et al.*, 2013; Rousseau, 2014; Viano *et al.*, 2005; Zanetti *et al.*, 2013; Zhang *et al.*, 2004).

3.5 Finite Element Model

Three-dimensional loading curves from exemplar impacts were applied to the University College Dublin Brain Trauma Model (UCDBTM) to determine maximum principal strain (MPS).

Material properties and brain tissue characteristics of the model can be found are shown in Table 3 and Table 4. The geometry of the brain model was established from computed tomography (CT) and magnetic resonance imaging (MRI) of a human cadaver, and was validated based on cadaveric impact tests as well as reconstructions of traumatic brain injuries (Doorly & Gilchrist, 2006; Horgan & Gilchrist, 2003). This version of the UCDBTM has approximately 26 000 elements and the components that make up the model include the scalp, skull, pia, falx, tentorium, cerebrospinal fluid, grey and white matter, cerebellum, and brainstem (Horgan & Gilchrist, 2003; 2004).

Table 3. Material properties of the University College Dublin Brain Trauma Model.

Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m³)
Scalp	16.7	0.42	1000
Cortical Bone	15000	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	15000	0.5	1000
Grey Matter	Linear viscoelastic	0.49	1060
White Matter	Linear viscoelastic	0.49	1060

Table 4. Material characteristics of the brain tissue for the University College Dublin Brain Trauma Model.

Material	Shear Modulus (kPa)		Decay Constant (GPa)	Bulk Modulus (s ⁻¹)
	G ₀	G _∞		
Cerebellum	10	2	80	2.19
Brain Stem	22.5	4.5	80	2.19
White Matter	12.5	2.5	80	2.19
Grey Matter	10	2	80	2.19

The mechanical properties of brain tissues have been characterized as viscoelastic in shear, resulting in time-varying stiffness depending on how fast a stress is applied and the duration the tissue is under load. The compressive nature of the brain tissue was defined as elastic. Shear characteristic of the viscoelastic brain was represented by the equation:

$$G(t) = G_{\infty} + (G_0 - G_{\infty})e^{-\beta t}$$

where G_{∞} is defined as the long-term shear modulus, G_0 is the short-term shear modulus, and β is the decay factor (Horgan & Gilchrist, 2003).

4. Statistical Analysis

4.1 Reliability

To ensure intra-rater reliability of the recording of head impact events, 7 fights (3 lightweight and 4 heavyweight) were randomly selected and reanalyzed at 2 different occasions with a minimum of 7 days between analyses.

A two-way mixed, intraclass correlation coefficient (ICC) was used to calculate the intra-rater reliability, with an ICC between 0.75-0.90 indicating a 'good' agreement and ≥ 0.90 indicating an 'excellent' agreement (Koo & Li, 2016). The intra-rater reliability for the identification of the head impact events was determined to be 'excellent' (ICC = .974) for this study. Velocity scale items were used from 1-4 representing 0-2, 2-4, 4-6, and 6+ m/s respectively for determination of Cronbach's alpha used to measure the consistency of visual estimation scale in determining impact velocity. The alpha coefficient was determined to be 0.91, indicating a high internal consistency between the High Speed Fastcam camera and the visual estimation method (Bland & Altman, 1997).

4.2 Frequency

The frequency of confirmed head impacts was initially determined per fight. However, fight time durations were not related due to referee stoppages of knockouts and submissions. As a result, the frequency data were reported in terms of number of strikes per minute of competition. Mann-Whitney *U* tests were conducted to compare the total frequency, strikes per minute, and frequency of head impacts by event types between Lightweight and Heavyweight fighters.

4.3 Frequency Distribution of Different Head Impact Magnitudes

A Chi-squared (χ^2) test was completed on the frequency distribution of different head impact magnitudes between Lightweight and Heavyweight fighters to assess whether there was a significant association between weight class and the number of head impacts within a certain magnitude range. A Cramer's *V* (ϕ_c) was used to describe the strength of association between weight class and frequency distribution, with $\phi_c \geq 0.3$ and $\phi_c \geq 0.5$ indicating 'moderate' and 'strong' associations respectively (Cohen, 1988). Mann-Whitney *U* tests were conducted to compare frequency differences in each MPS category between the two weight classes.

4.4 Time Interval Between Head Impacts

A Mann-Whitney U test was completed to compare differences in the average time between head impacts sustained for Lightweight and Heavyweight MMA fighters.

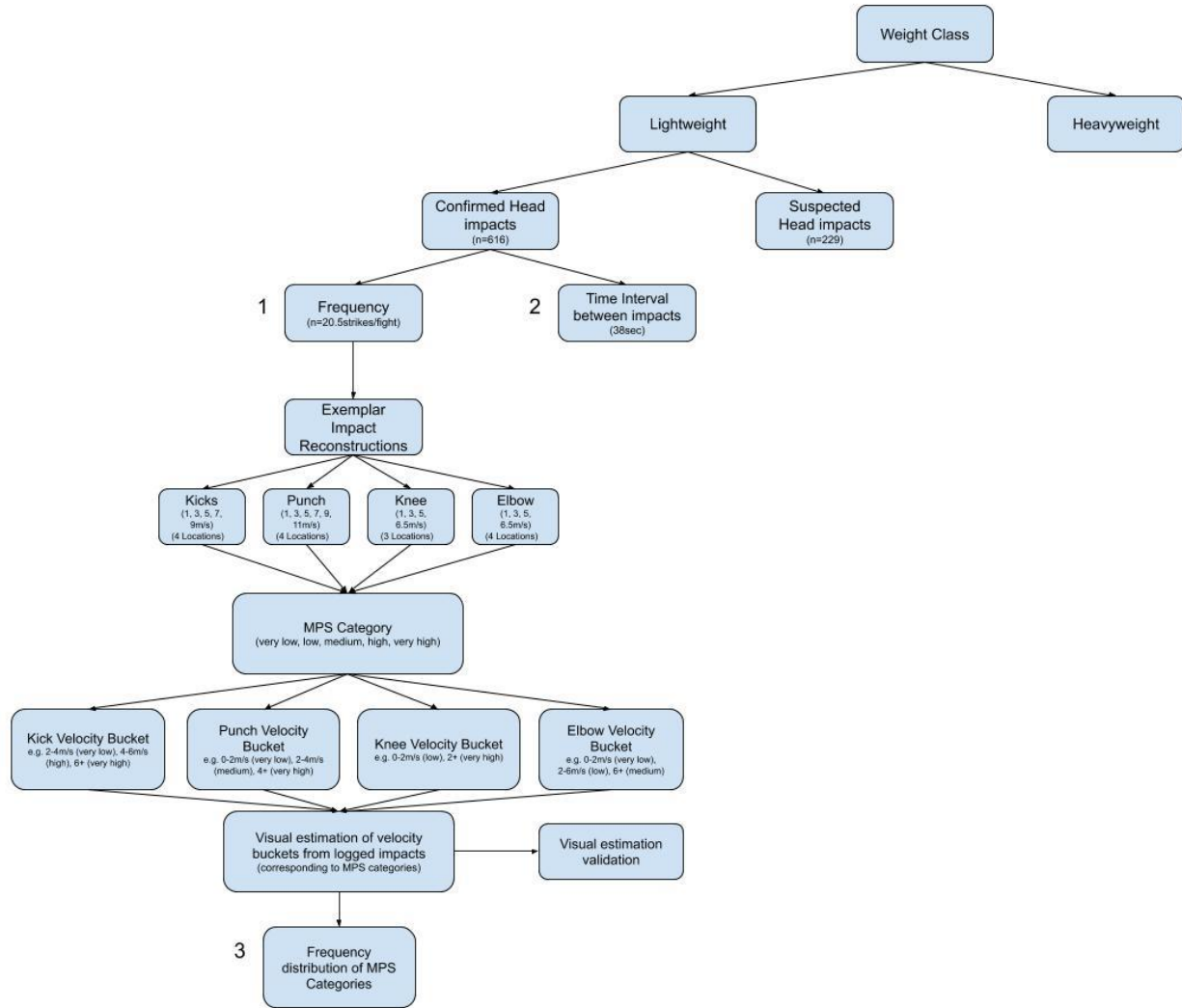


Figure 11. Flow chart depicting methodology to obtain the three objectives of this study (To determine and compare: 1 = Frequency, 2 = interval, 3 = Frequency distribution of MPS between Lightweight and Heavyweight UFC fighters).

5.0 Results

5.1 Frequency of Head Impacts

Comparison of the total frequency of impacts revealed no significant differences ($p=0.21$) between the two weight classes. Both Heavyweight and Lightweight fighters sustained 2.7 strikes/minute on average, and had an average fight time of 9 minutes 53 seconds and 9 minutes 36 seconds respectively (Table 5). Moreover, no significant differences were found when comparing frequency of event types using the nonparametric Mann-Whitney U test.

Table 5. Summary of total frequency and interval of head impacts for Heavyweight (HW) and Lightweight (LW) fighters along with how fights were completed.

	Strikes/min *mean **median (range)	Time between impacts/fight *mean **median (range)	Average Fight Time (SD)	Number of fights ending in KO/TKO	Number of fights ending in decision	Number of fights ending in submission
HW	*2.7 **1.7 (0 -12.6)	*35 sec **26 sec (1 -117 sec)	9 min 53 sec (5 min 07 sec)	9 out of 15	4 out of 15	2 out of 15
LW	*2.7 **1.7 (0 -16.1)	*38 sec **34 sec (3 -105 sec)	9 min 36 sec (5 min 50 sec)	8 out of 15	6 out of 15	1 out of 15

The frequency of confirmed head impact events are reported by impact event type in Figure 12. A combined total of all head impact events yielded a total of 570 and 608 impacts to the head for 30 Heavyweight and 30 Lightweight fighters respectively. The most common impact events

were punches to the head, accounting for 76% (435/570) for Heavyweights, and 82% (500/608) for Lightweights.

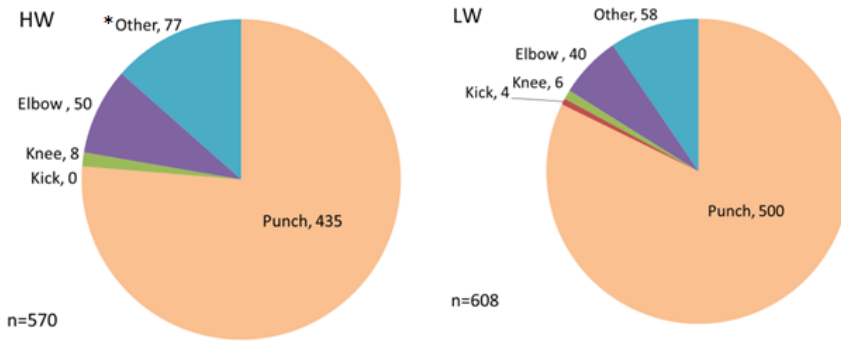


Figure 12. Total confirmed head impact frequencies from different event types for 30 Heavyweight (HW) and 30 Lightweight (LW) fighters.


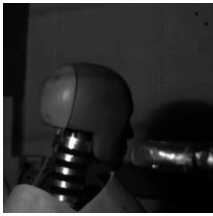

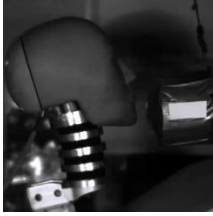
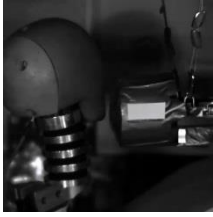
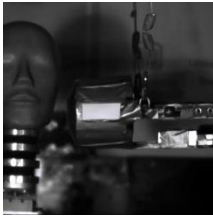
*other impacts denote head impacts that were not punches, kicks, knees, and elbows. These impacts were only included in the total frequency and interval comparisons due to the great variability in these impacting conditions

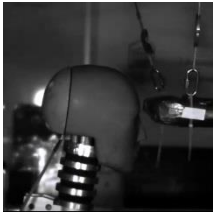

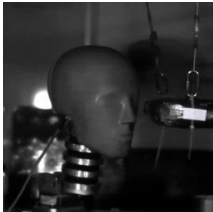
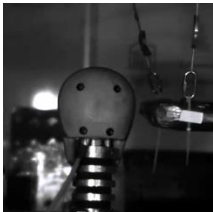
5.2 Frequency Distribution of Different Head Impact Magnitudes

The magnitudes of MPS from exemplar impact reconstructions, as well as visual estimation velocity buckets are provided in Table 6 and Table 7. The frequencies of these visually documented head impacts of different magnitude MPS are presented in Figure 13. Lightweight fighters were found to sustain a significantly greater number of very low ($p=0.049$) and high ($p=0.005$) magnitude MPS impacts than Heavyweight fighters. When separating frequency of head impacts based on event type (Figure 14), Lightweight fighters sustained a significantly greater number of high ($p<0.001$) magnitude MPS from punches, while Heavyweight fighters sustained a significantly greater number of high ($p=0.007$) magnitude MPS from elbows.

Table 6. Summary of event characteristics used for the Lightweight (LW) exemplar head impact reconstructions and velocity bucket determination.






Event	Location	Exemplar Impact	Tested Velocities (m/s)	Measured MPS	MPS Category	Visual Estimation Velocity Category (m/s) and corresponding MPS category
Kick (LW)	Front Boss C _(D)		3, 5, 7, 9	0.16, 0.29, 0.46, 0.59	L, H, VH, VH	2-4 (L), 4-6 (H), 6+ (VH)
	Side A _(B45)		3, 5, 7, 9	0.12, 0.27, 0.40, 0.51	L, H, VH, VH	2-4 (L), 4-6 (H), 6+ (VH)
	Side B _(D)		3, 5, 7, 9	0.12, 0.21, 0.28, 0.38	L, M, H, VH	2-4 (L), 4-6 (M), 6-8 (H), 8+ (VH)
	Side C _(B45)		3, 5, 7, 9	0.16, 0.27, 0.38, 0.53	L, H, VH, VH	2-4 (L), 4-6 (H), 6+ (VH)
Punch (LW)	Front B _(D)		1, 3, 5, 7, 9, 11	0.06, 0.10, 0.20, 0.39, 0.53, 0.68	VL, L, M, VH, VH, VH	0-2 (VL), 2-4 (L), 4-6 (M), 6+ (VH)




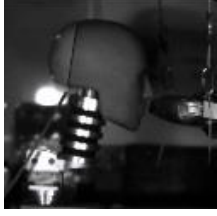


	Front $C_{(D)}$		1, 3, 5, 7, 9, 11	0.07, 0.21, 0.24, 0.33, 0.52, 0.69	VL, M, M, H, VH, VH	0-2 (VL), 2-6 (M), 6-8 (H), 8+ (VH)
	Front Boss $C_{(D)}$		1, 3, 5, 7, 9, 11	0.08, 0.25, 0.39, 0.56, 0.79, 0.77	VL, M, VH, VH, VH, VH	0-2 (VL), 2-4 (M), 4+ (VH)
	Side $C_{(D)}$		1, 3, 5, 7, 9, 11	0.05, 0.20, 0.29, 0.45, 0.76, 0.88	VL, M, H, VH, VH, VH	0-2 (VL), 2-4 (M), 4-6 (H), 6+ (VH)
Knee (LW)	Front $C_{(B45)}$		1, 3, 5, 6.5	0.10, 0.25, 0.29, 0.40	L, M, H, VH	0-2 (L), 2-4 (M), 4-6 (H), 6+ (VH)
	Front Boss $C_{(B45)}$		1, 3, 5, 6.5	0.12, 0.36, 0.60, 0.74	L, VH, VH, VH	0-2 (L), 2+ (VH)
	Side $C_{(B45)}$		1, 3, 5, 6.5	0.10, 0.24, 0.44, 0.54	L, M, VH, VH	0-2 (L), 2-4 (M), 4+ (VH)


Elbow (LW)	Front B _(D)		1, 3, 5, 6.5	0.05, 0.11, 0.16, 0.25	L, VL, VL, M	0-2 (VL), 2-6 (L), 6+ (M)
	Front Boss A _(D)		1, 3, 5, 6.5	0.05, 0.14, 0.23, 0.38	VL, L, M, VH	0-2 (VL), 2-4 (L), 4-6 (M), 6+ (VH)
	Front Boss B _(D)		1, 3, 5, 6.5	0.05, 0.11, 0.19, 0.23	VL, L, M, M	0-2 (VL), 2-4 (L), 4+ (M)
	Side B _(D)		1, 3, 5, 6.5	0.05, 0.09, 0.14, 0.25	VL, L, L, M	0-2 (VL), 2-6 (L), 6+ (M)

Impact vectors: (D) direct impacts & (B₄₅) impacts coming from 45° below the horizontal
 VL = very low, L = Low, M = Medium, H = High, VH = Very High

Table 7. Summary of event characteristics used for the Heavyweight (HW) exemplar head impact reconstructions and velocity bucket determination.

Event	Location	Exemplar Impact	Tested Velocities (m/s)	Measured MPS	MPS Category	Visual Estimation Velocity Category (m/s) and corresponding MPS category
Punch (HW)	Front C _(D)		1, 3, 5, 7, 9, 11	0.07, 0.20, 0.24, 0.38, 0.52, 0.69	VL, M, M, VH, VH, VH	0-2 (VL), 2-6 (M), 6+ (VH)
	Front Boss C _(D)		1, 3, 5, 7, 9, 11	0.07, 0.23, 0.38, 0.59, 0.80, 1.01	VL, M, VH, VH, VH, VH	0-2 (VL), 2-4 (M), 4+ (VH)
	Side B _(D)		1, 3, 5, 7, 9, 11	0.05, 0.11, 0.22, 0.41, 0.57, 0.69	VL, L, M, VH, VH, VH	0-2 (VL), 2-4 (L), 4-6 (M), 6+ (VH)
Knee (HW)	Front Boss* A _(D)		1, 3, 5, 6.5	0.14, 0.40, 0.63, 0.79	L, VH, VH, VH	0-2 (L), 2+ (VH)
	Front Boss* A _(L45)		1, 3, 5, 6.5	0.11, 0.32, 0.51, 0.66	L, H, VH, VH	0-2 (L), 2-4 (H), 4+ (VH)

	Front Boss* $C_{(D)}$		1, 3, 5, 6.5	0.14, 0.35, 0.59, 0.78	L, VH, VH, VH	0-2 (L), 2+ (VH)
	Front Boss* $C_{(B45)}$		1, 3, 5, 6.5	0.15, 0.36, 0.62, 0.80	L, VH, VH, VH	0-2 (L), 2+ (VH)
	Front $C_{(D)}$		1, 3, 5, 6.5	0.18, 0.46, 0.68, 0.80	M, VH, VH, VH	0-2 (M), 2+ (VH)
Elbow <small>(HW)</small>	Front $C_{(D)}$		1, 3, 5, 6.5	0.06, 0.24, 0.29, 0.35	VL, M, H, VH	0-2 (VL), 2-4 (M), 4-6 (H), 6+ (VH)
	Side $A_{(D)}$		1, 3, 5, 6.5	0.05, 0.16, 0.26, 0.47	VL, L, M, VH	0-2 (VL), 2-4 (L), 4-6 (M), 6+ (VH)
	Front Boss $A_{(D)}$		1, 3, 5, 6.5	0.05, 0.17, 0.30, 0.56	VL, L, H, VH	0-2 (VL), 2-4 (L), 4-6 (H), 6+ (VH)

	Front Boss $C_{(D)}$		1, 3, 5, 6.5	0.07, 0.22, 0.29, 0.54	VL, M, H, VH	0-2 (VL), 2-4 (M), 4-6 (H), 6+ (VH)
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*The impact vector orientation for knee-to-head impacts to the Front Boss location had equal representation, therefore both were reconstructed. Impact vectors: (D) direct impacts, (L_{45}) impacts coming from 45° to the left & (B_{45}) impacts coming from 45° below the horizontal
VL = very low, L = Low, M = Medium, H = High, VH = Very High

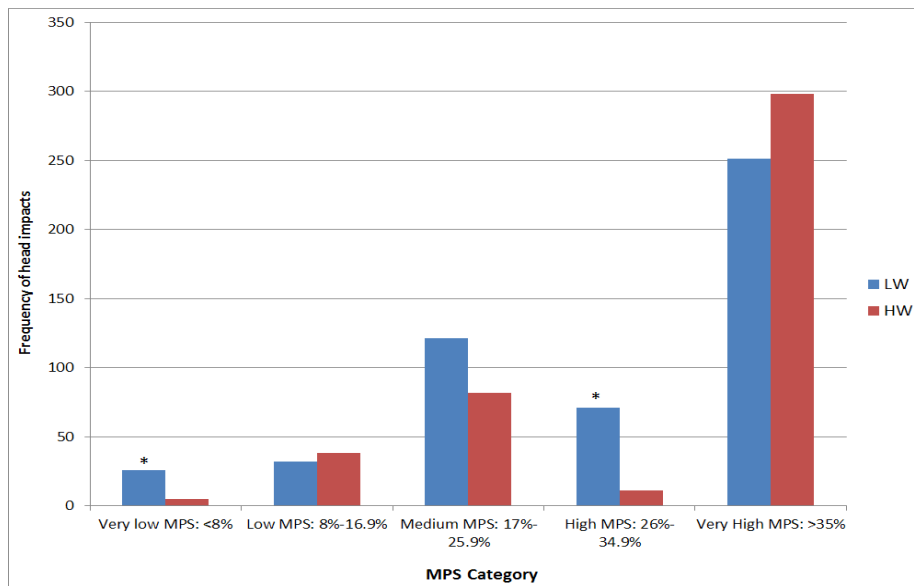
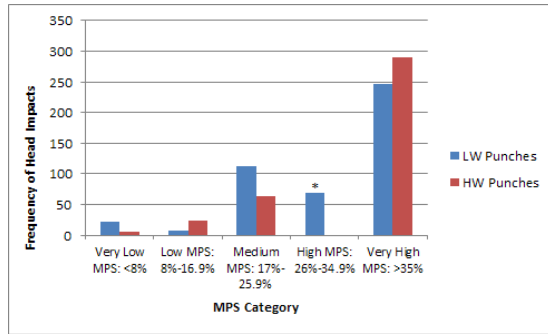
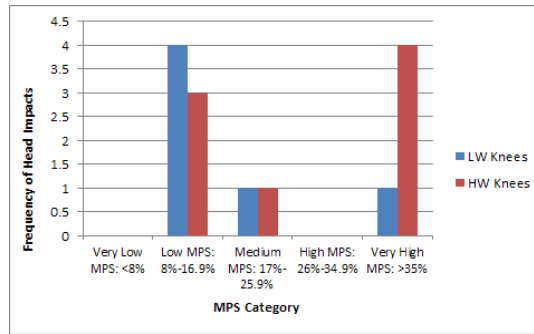


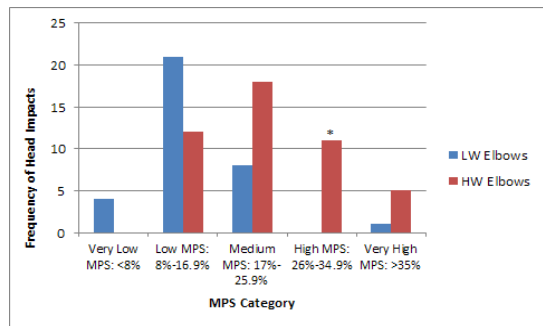
Figure 13. Frequency distribution of impact magnitudes for Heavyweight (HW) and Lightweight (LW) fighters.



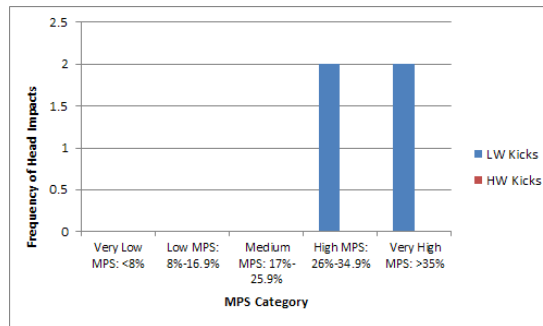
a)



b)



c)



d)

Figure 14. Frequency distribution of head impact magnitudes from punch (a), knee (b), kick (c), and elbow (d) strikes for Heavyweight (HW) and Lightweight (LW) fighters.

5.3 Time Interval Between Head Impacts

Comparison of the time interval between impacts revealed no significant differences ($p=0.39$) between the two weight classes. The average time between head impacts sustained in a MMA fight by Lightweight and Heavyweight fighters is 38 seconds and 35 seconds respectively (Table 5).

6.0 Discussion

This research project compared brain trauma characteristics between fighters in two weight classes in Mixed Martial Arts. More specifically, the purpose of this study was to compare the differences in frequency, frequency distribution of impact magnitudes, and time interval of impact events per match between Lightweight and Heavyweight MMA fighters. Understanding these brain trauma characteristics can provide information to administrators, professional healthcare teams, and fighters to best manage and mitigate the risk for long-term brain injury.

6.1 Frequency of Head Impacts

Heavyweight and Lightweight fighters did not significantly differ in the frequency of sustained head impacts per fight. On average, fighters were reported to experience 2.7 strikes to the head per minute of fight time (an average of 20 and 19 strikes per Lightweight and Heavyweight MMA fight respectively). These frequency estimates may in fact, represent a conservative estimate due to the specificity of the inclusion criteria and limitations of video analysis. Head impacts metrics from UFC Stats reported a greater number of head impacts in 13 out of 15 Lightweight fights and 11 out of 15 Heavyweight fights, which indicates that the estimates from this research are likely conservative (Appendix Figure 16). Conservative estimates may be attributed to limitations in video footage since not all impacts were visible, as well as the specificity of the confirmed head impact criteria methodology utilized. In other collision sports, the long-term effects of repetitive brain injury have been documented in boxing and professional football players (McKee *et al.*, 2009).

Boxers have been reported to sustain an average of 5.3 strikes/min, almost double the amount reported in this study on MMA fighters (Cournoyer, 2019; Stojisih, 2010). In a review of 60 fights (ranging from Flyweight – Lightweight), boxers were reported to receive, on average 175 total punches per fight versus 58 for MMA fighters (Bernick *et al.*, 2015). This is likely because boxers are limited to punching the body, in particular the head to end a fight while MMA fighters

can utilise other combat skills to win their match by submission without hits to the head. In American College Football, the frequency of head impacts can be position dependent, and range from 6-26 impacts per game (Crisco *et al.*, 2010, 2011; Mihalik, 2007; Montenegro *et al.*, 2017). Furthermore, boxers and football players can experience thousands of sub-concussive head impacts over the course of a single season (McKee *et al.*, 2009). MMA fighters in this study were found to sustain similar levels of repetitive head impacts to football players, 20 and 19 strikes per fight on average in Lightweight and Heavyweights respectively. As the sport continues to grow in popularity and research, there is concern that professional MMA will also become associated with long-term brain trauma.

6.1.1 Frequency of Head Impacts Event Types

When analyzing the breakdown of head impact event types, punches were the most commonly landed event types for both weight classes. This is likely a result of MMA fights start standing, and punches can be thrown at a variety of angles, velocities, and distances. Moreover, punches can be strung together in combinations, making them an ideal attack to inflict damage on an opponent. This study found no significant differences in the frequency of head impacts from kick, knee and elbow strikes between Lightweight and Heavyweight fighters. Of the four event types (punch, kick, knee, elbow) analyzed, elbow-head events were the second most common, followed by knee and kick-head. It is likely that as the difficulty of landing an event on the opponent increases, the frequency of the event decreases for both weight classes. The difficulty of landing an event on the opponent may vary based on the execution time, energy expenditure, and skill of the athlete. Researchers have reported that martial artists had shorter execution times for punches than kicks, making it more difficult for the opponent to defend against (Chaabène *et al.*, 2015). Kicking techniques have also been reported to require greater physical exertion than punches,

indicating that the lower frequencies reported in this study may have been a means for athletes to conserve energy (Imamura et al., 1997).

Heavyweight fighters are reported to present a higher frequency of strikes landed and attempted in clinch combat, a component of stand up fighting where fighters incorporate grappling techniques with shorter-range strikes such as elbows and knees (Miarka et al., 2017; Trial & Wu, 2014). Lightweight fighters have almost half the total body mass compared to Heavyweight fighters, which along with reported differences in body composition likely results in a greater ability to execute high intensity efforts such as head kicks (Miarka *et al.*, 2015; Sterkowicz-Przybycień & Franchini, 2013). While previous studies have reported differences between times spent in different positional phases of a fight, this study found that this had no overall bearing on the frequency of total head impacts sustained.

6.2 Frequency Distribution of Different Head Impact Magnitudes

Lightweight fighters were reported to sustain a significantly greater frequency of Very Low and High MPS category impacts. This is due to the frequency of different event types and their impact magnitudes between the two weight classes. When separating frequency of impact magnitudes by event type, High (26 - 34.9% MPS) magnitude strikes were a result of punches and kicks in Lightweight fights while elbow to head impacts were the sole cause of High (26 - 34.9% MPS) magnitude strikes in Heavyweight fights (Figure 14). Punch events differed in their impacting mass, velocity and location. Exemplar punches to the side of the head were to the mandibular region for Lightweight fighters (Table 6). In comparison to Heavyweight fighters, these exemplar punches were further away from the center of gravity of the head for this location. The larger moment arm created resulted in High MPS strains at 2 - 4 m/s impact velocities, but Medium MPS in Heavyweights. Exemplar punches to the front of the head only differed in mass between the two

weight classes. As a result, lighter mass punches from Lightweights resulted in High MPS strains at 6 - 8 m/s impact velocities, but Very High MPS in Heavyweights.

The significant differences in Very Low (<8% MPS) magnitude strikes were a result of punches and elbows in Lightweight fights and punch events in Heavyweights (Figure 13, Figure 14). Although not quantified, the greater frequency of Very Low MPS strikes in Lightweights is likely due to the differences in fight strategy between the two weight classes. It was observed that Lightweight fighters used Very Low MPS punches in many instances as a distraction to set up larger magnitude punches. This was most often seen during groundwork combat where Heavyweight fighters focused on landing more singular larger magnitude impacts compared to the more active offence of Lightweights. Previous time-motion analysis studies have reported that lighter weight classes tended to be more active, and spend more time in ground combat situations than heavier weight categories (Miarka *et al.*, 2015).

Measuring impact magnitude using shear strains from an input force is associated with injury severity, where higher levels of strain are associated with an increased risk for neurological injuries (Gennarelli *et al.*, 1982; Kleiven, 2007, 2013; McAllister *et al.*, 2012; Thibault *et al.*, 1990). It is postulated that brain injury occurs along a graded spectrum (from low to high strain levels) rather than injury versus no injury (Hoshizaki *et al.*, 2017). Low-magnitude head impacts have the potential for inducing protein molecular changes absent of symptoms, leading to cellular dysfunction and neuronal loss (Hoshizaki *et al.*, 2017; McKee *et al.*, 2009, 2013; Omalu *et al.*, 2005; Weber, 2007). Higher magnitude concussive impacts resulting in metabolic impairment of the neurons and the presence of symptoms have been typically relied on as a way to document injury and monitor recovery (Giza & Hovda, 2014; Kleiven, 2007; Lockwood *et al.*, 2017; Lystad *et al.*, 2014; Neidecker *et al.*, 2019; Zhang *et al.*, 2004). Yet, neurological injuries sustained from head impacts do not always manifest through clinical symptoms. Relying solely on observable symptoms is insufficient in monitoring injury and recovery of athletes. Concussive level impacts are capable of

inducing axonal degeneration despite cognitive recovery, and cellular damage can even occur in the absence of symptoms (Creed *et al.*, 2011; Hoshizaki *et al.*, 2017). While research is ongoing, understanding the characteristics that describe head impacts which lead to brain trauma and how they contribute to chronic brain injury is essential. Bridging this gap in knowledge and developing a personalized fighter index to monitor cumulative brain trauma as previously suggested by Bernick and Banks (2013) can improve long-term safety in the sport.

American football players and boxers are two high-risk populations for chronic traumatic brain injury, and have been commonly studied using impact reconstructions for understanding the risk for neurological consequences of different head impact magnitudes (Bernick *et al.*, 2015; Cournoyer, 2019; Jordan, 2000, 2014; Kleiven, 2007; McKee *et al.*, 2009; McKee *et al.*, 2014; Zanetti *et al.*, 2013; Zhang *et al.*, 2004). Strain values of 9-11% have been documented in head impact reconstructions of American Football linemen with no reported symptoms (Zanetti *et al.*, 2013). Impact reconstructions of typical punches from boxers that did not result in loss of consciousness had MPS magnitudes that ranged from 28-47% (Cournoyer, 2019). In NFL Football, reconstructed head impacts reported strain levels that ranged from 19-26% produced a 50% probability of concussion (Kleiven, 2007; Zhang *et al.*, 2004). These athletes can sustain thousands of impacts over a single season, and therefore the cumulative effects of all impact magnitudes likely explains the higher association for cTBI than in other populations (Bernick *et al.*, 2015; Crisco *et al.*, 2011; McKee *et al.*, 2009).

At the professional level, MMA fighters from both weight classes are capable of consistently generating a range of tissue-damaging forces to the head at similar impact magnitudes and frequencies of boxers and football players. The majority of head impacts in both weight classes fell in the Medium and Very High MPS categories, with impacts above >35% being the most common. Head impacts of high magnitudes are inherent in the sport, as the objective is to inflict the most damage to an opponent. The temporal and mandibular region were the most common impact

locations in both weight classes, as to induce knockouts - a primary objective in the sport. Impacts to these locations can induce high rotational accelerations leading to brain injury due to shear strains of the tissue (Gennarelli *et al.*, 1982; Hodgson *et al.*, 1983; Walsh *et al.*, 2011).

6.3 Time Interval between Head Impacts

Researchers have implicated a high frequency and short time interval of repetitive head impacts with an increased risk for experiencing a second mild Traumatic Brain Injury (mTBI). Studies from animal models have found that after a primary mTBI causing impact, there is a duration of glutamate exposure resulting in an energy crisis and impaired cellular function (Giza & Hovda, 2014). The biological vulnerability for a subsequent concussion at a lower magnitude impact is attributed to the duration of this cellular energy crisis within the brain (Giza & Hovda, 2014; Guskiewicz *et al.*, 2003). It was reported in mice models that the brain was more vulnerable to a second impact of similar or different magnitude if the second injury occurred 24hrs after the first (Laurer *et al.*, 2001). Even low levels of mechanical stretch which did not cause significant cell damage when exposed at 1-h intervals did induce cell damage when repeated at 2 min intervals (Slemmer *et al.*, 2005). Moreover, researchers using rodent models of TBI have stated that the effects of a second mTBI may be synergistic, rather than additive due to cerebral vulnerability after the initial insult (Giza & Hovda, 2014; Laurer *et al.*, 2001). As a result, additional impacts that take place within this proposed window of vulnerability may result in cognitive dysfunction that otherwise could have been avoided with sufficient recovery time after the initial injury (Longhi *et al.*, 2005). Research on the effect of time between head impacts on humans is limited. However, Broglio and colleagues (2017) found concussed high school football players had higher impact densities, defined as the total magnitude of a number of impacts over time, than Control athletes. This study found no significant differences in the time interval between head impacts: 35 seconds for Heavyweights and 38 seconds for Lightweights. This time interval is even shorter than what researchers have found to cause cellular damage, and from higher levels of strain. Shortening the

time of rounds in a fight and allowing for appropriate recovery time after a fight is important for mitigating the increased risk for repeat injuries.

Conclusion

The objective of this study was to compare the brain trauma characteristics for impacts to the head between Lightweight and Heavyweight fighters in professional mixed martial arts. This was completed by determining the frequency of head impacts, frequency distribution of different head impact magnitudes, and time interval between impacts in 15 Lightweight and 15 Heavyweight fights. There were no differences in the overall frequency of head impacts, and time interval between the two weight classes. However, the frequency distribution of impact magnitudes was significantly associated with weight class. Lightweight fighters sustained significantly higher number of Very Low (<8% MPS) and High (26-34.9% MPS) magnitude impacts to the head. Heavyweights sustained a significantly larger number of High (26-34.9% MPS) magnitude elbows to the head, while Lightweights sustained a significantly larger number of High (26-34.9% MPS) magnitude punches.

This study reported that fighters competing in these two weight classes sustain similar head impact characteristics. Head impact characteristics in this study were similar to what has been reported in boxing and American Football, two sports commonly associated with high head trauma and chronic traumatic brain injury (cTBI). Given the violent nature of the sport, determining the risk factors for long-term neurological disease will ultimately empower athletes with the knowledge to make informed decisions about participation. Moreover, understanding the risk factors can aid in diagnostic or predictive tools and assist administrators and trainers to best regulate the sport.

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Appendix:

Table 8. Comparison of effective mass of punch, elbow, and kicking strikes to body segment parameter calculations.

Reference	Weight of athlete	Effective punch mass measured	Effective elbow mass measured	Effective kick mass measured	Dempster's Body Segment Parameter Calculation
(Walilko et al, 2005) ^a	Flyweight (50kg)	2.3 (1.1) kg			2.80 kg
	Light welterweight (63kg)	2.7 (1.1) kg			3.50 kg
	Middle weight (75kg)	0.8 (0.2) kg ^d			4.10 kg
	Super heavyweight (90-110kg)	5.0 (2.4) kg			5.60 kg ^b
(Smith & Hamill, 1986) ^c		3.0-5.0 kg			
(Smith, 2008)	72.5 kg	4.9 kg			4.06 kg
(Atha <i>et al.</i> , 1985)	90 kg	6 kg			5.04 kg
(Rousseau & Hoshizaki, 2015)	88.5 kg (9.5kg)	-----	4.8 (1.7) kg		4.96 kg
(Sidthilaw, 1996)	80 kg			12.9 kg	12.88 kg

^a Found significance ($p < 0.05$) in effective mass with respect to weight

^b Calculated for a 100 kg person

^c Athlete mass could not be determined

^d Effective mass calculated was considerably low, this was attributed to dorsal flexion of wrist upon impact

The effective mass of an impact is a measure of the body's inertial contribution to the transfer of momentum during a collision. Smith and Hamill noted that higher skilled boxers generated greater momentum even though the hand was not travelling at a higher velocity (1986). Well trained martial artists may achieve higher effective masses by tightening appropriate muscles immediately before the impact (Neto *et al.*, 2007). This coincides with findings that the transfer of momentum of the punching arm, rather than that of the other body segments, to its target attributes to 95% of the impulse (Nakano *et al.*, 2014).

Table 9. Summary of different strike velocities at impact

Study	Population	Type of Head Impact	Reported velocity (m/s)
(Walilko, 2005)	Olympic boxers	Unspecified frontal area punch	9.14 ± 2.06
(Viano <i>et al.</i> , 2005)	Olympic boxers	Unspecified punch (Forehead)	8.2 ± 1.5
		Punch (Hook)	11.0 ± 3.4
		Unspecified punch (Jaw)	9.2 ± 1.7
		Punch (Uppercut)	6.7 ± 1.5
(Stojsih <i>et al.</i> , 2010)	Amateur boxers	Hook	11 ± 3
		Jab	9 ± 3
		Cross	9 ± 1
(Kendall, 2016)	Professional MMA fighters	Unspecified punch	6.5 ± 0.7
(Ignacy, 2017)	Elite men's rugby	Knee	4.44 ± 0.0401
(Sidthilaw, 1996)	Amateur Muay Thai Fighters	Roundhouse Kick (kickboxing bag)	6.8 ± 1.2
		Knee (low level kick)	
		(medium level kick)	3.3 ± 0.7
		(high level kick)	3.3 ± 0.6
			2.6 ± 0.5
(Gavagan & Sayers, 2017).	Muay Thai Beginners	Roundhouse Kick	7.22
(Chinnasee <i>et al.</i> , 2018)	Muay Thai Beginners	Knee	4.15 ± 1.3
(Park, 1989)	Taekwondo	Kick (front kicks)	6.9-7.58
(Hwang, 1987)	Amateur Taekwondo	Kick (front kicks)	10.3-11.7
(C. D. Jordan, 1973)	Karate	Kick (3 different types of karate kicks)	5.2, 6.5, 5.5
(Powell, 1989)	Karate	Kick (3 different types of karate kicks)	3.8, 4.3, 4.7
(Withnall, 2005)	FIFA Football	Elbow	1.3-5.3 ± 1.67

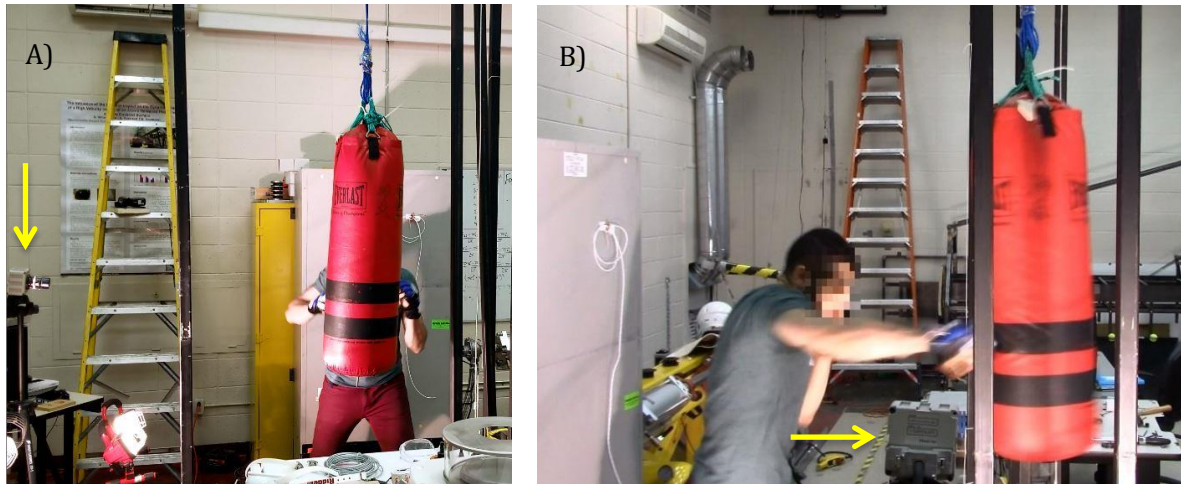


Figure 15. Image of visual estimation of punch velocity setup with highspeed camera pointed by the yellow arrow positioned orthogonal to the the motions of the athlete (A), and image from broadcast camera positioned behind the highspeed camera (B).

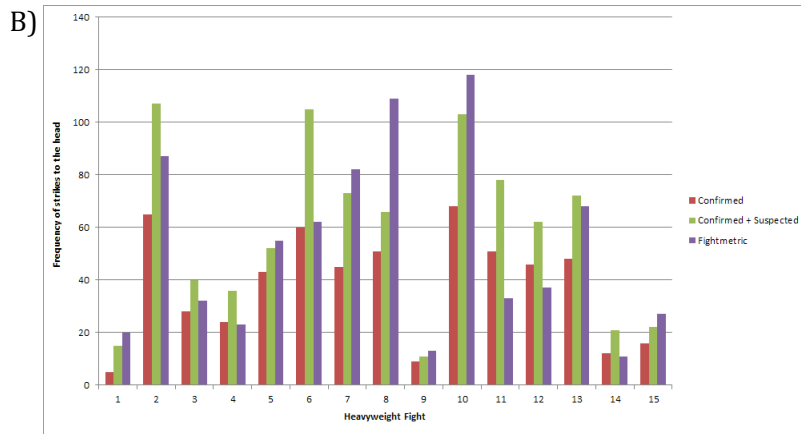
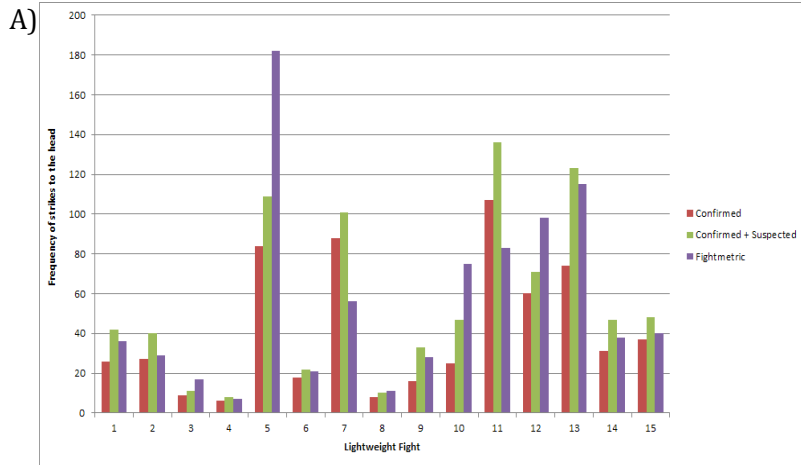


Figure 16. Frequency of confirmed head impacts, combined confirmed and suspected, and reported significant strikes by Fightmetric (www.ufcstats.com) for Lightweight (A) and Heavyweight fights (B)