Beyond the Brain: exploring causes and effects of head trauma in combat sports

by

Bruno Follmer

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We acknowledge and respect the ləkʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

Supervisory Committee

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Abstract

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Traumatic brain injury, concussion, and subconcussion are different clinical conditions associated with head injury. These conditions share a common origin, mechanical forces directly or indirectly transmitted to the head. In sports, modalities with high exposure to head traumas require further investigation, especially those in which strikes directly to the head are allowed and a determinant of success, such as combat sports. The causes and effects of brain injuries in combat sports such as Mixed Martial Arts, boxing, Muay Thai, and kickboxing are complex and require a comprehensive investigation of many factors. The objective of this dissertation was to explore the main causes that justify combat sports as the main sport sample when it comes to head injury and the effects of chronic exposure to head trauma in this population. Original studies were developed to assess the head injury risk in competition and in training, the level of knowledge of athletes and coaches, and the consequences of chronic exposure to head traumas in the balance function, brain activity, and spinal cord excitability. The risk of a fight ending due to head strikes in competition is directly related to the weight category, and the risk seems to be exacerbated in female athletes. Combat sports athletes are exposed to numerous strikes to the head in simulated fights on a weekly basis in training, when healthcare professionals are absent. During this time that makes up the bulk of exposures, therefore, athletes and coaches are the ones managing potential cases of concussion. However, coaches are not familiar with assessment tools and don't often seek out concussion knowledge. Alarmingly, coaches, often prior athletes themselves, are the main source of concussion knowledge for their athletes. High exposure to head trauma both in competition and training in addition to

poor knowledge and behavior are liable to cause consequences in the nervous system. Athletes chronically exposed to head trauma presented subtle deficits in static balance in the most basic human stance, which is the double-leg over a firm surface. Moreover, while the literature consistently shows impairments in brain function, our study expanded the association between head trauma and nervous system deficits to the least studied component of the nervous system, the spinal cord. While athletic training promotes neuroplastic benefits in spinal cord excitability, these were hindered in a sample of athletes chronically exposed to head traumas. The studies in this dissertation demonstrated that athletes in combat sports are chronically exposed to intentional and repetitive head traumas, and that this exposure is likely associated with long-term functional detriments in balance and spinal cord excitability.

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Dedication

There is no place I'd rather be. I love you, Manoela.

Chapter 1 - Introduction & Literature Review

1.1. Traumatic Brain Injury, Concussion, and Subconcussion: Every Hit Matters

A clinical entity recognized for over a thousand years, the term concussion derives from the Latin "*concussus*", which means violent shock (Mullally, 2017). Despite its millenary clinical history, the investigation of concussion in a systematic way and in the sports context is still relatively recent (McCrory et al., 2017; Turner, 2019). Concussion gained popularity due to the dissemination of cases of brain injuries in athletes in sports with high rates of head impacts, such as American Football and Boxing (Mullally, 2017). Books, films, and articles in various media have leveraged popular and scientific interest in this area. However, concussion is just part of a large spectrum of brain injuries, and of course other forms of brain injury can lead to health damage.

Concussion is a subset of traumatic brain injury (TBI) caused by biomechanical forces transmitted to the head (most often due to a direct impact to the head or body) (Harmon et al., 2019; McCrory et al., 2017). The Glasgow Coma Scale is the instrument used to classify TBIs as mild, moderate, and severe, according to the level of responsiveness for motor and verbal responses (DeCuypere & Klimo, 2012). Concussion is classified as a mild TBI (i.e. Glasgow Coma Scale: 13-15), although the term is considered problematic since there is no consensus that concussion represents the same structural damage as severe injuries, but on a smaller scale (McCrory et al., 2017). Moreover, the term mild can foster the deceptive belief that concussion is a harmless injury. Concussion is considered one of the most complex injuries to be diagnosed, evaluated, and treated (Harmon et al., 2019; Kamins et al., 2017; Langlois et al., 2006;

McCrory et al., 2017), may increase the risk of comorbidities later in life (Izzy et al., 2021), and result in disability, depression, and even suicide (Langlois et al., 2006).

Besides the consistently described acute deficits caused by a concussion, long term impairments associated with a history of concussion have also been reported (Hiploylee et al., 2017; Johnston et al., 2018; Reilly et al., 2020; Wright et al., 2021). Postconcussion syndrome is a recognized condition in which individuals keep experiencing symptoms for longer than the acute phase of the injury (Hiploylee et al., 2017). Moreover, a history of concussions is widely accepted as a risk factor for the degenerative condition chronic traumatic encephalopathy (Montenigro et al., 2015; Omalu et al., 2005). Notwithstanding, the concept of subconcussion (that does not result in known or diagnosed concussion on clinical grounds (Bailes et al., 2013)) has captured scientific interest. If accumulated, repetitive episodes of head impacts with no overt clinical symptom of concussion can also be detrimental (Mainwaring et al., 2018; Rawlings et al., 2020) and even associated with chronic traumatic encephalopathy (Montenigro et al., 2017).

Forces transmitted to the head are a common source of potential short and long-term impairments. The potential outcomes after the event (e.g. head trauma) happens, for single or multiple episodes are illustrated in Figure 1.1. These outcomes (i.e. short- and long-term impairment after concussion and subconcussions) will be further explored in the next sections of the introduction.

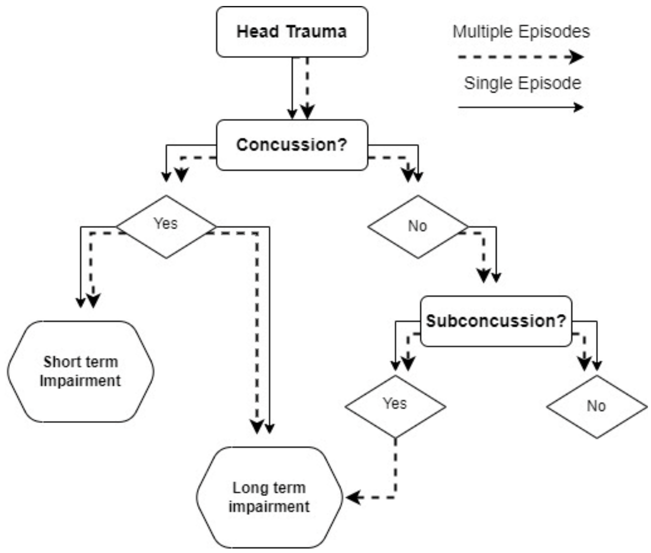

Figure 1.1 Potential outcomes from exposure to single or multiple episodes of head trauma

1.1.1. Concussion Short Term Impairment

The exact structural damage in the brain following a concussion is not completely understood, mainly due to the limitation in extrapolating to humans the evidence that is often obtained in animal models such as in mice (Wojnarowicz et al., 2017). After an impact with forces transmitted to the head, the mechanical stress applied to neurons causes the release of excitatory neurotransmitters that generate changes in the concentrations of regulatory ions, such as calcium, sodium, and potassium. In an attempt to restore homeostasis, there is an increase in glucose utilization by ion pumps, but accompanied by a decrease in cerebral blood flow (Figure 1.2) (Giza & Hovda, 2014). In addition, inflammation, axonal and glial damage, alteration of plasticity, and mitochondrial dysfunction with the production of reactive oxygen species can occur (Bigler, 2018; Giza & Hovda, 2014; Neselius et al., 2015). This energy crisis environment impacts communication between neurons, and is associated with some of the most common clinical symptoms of concussion, such as headache, dizziness, and cognitive and functional deficits (Giza & Hovda, 2014). Reduced animal and human studies warn of greater vulnerability in the brain after a concussive injury, and further injury can result in further metabolic changes and deficits (Giza & Hovda, 2014; Harmon et al., 2019; Kamins et al., 2017; Mullally, 2017; Neselius et al., 2015; Wojnarowicz et al., 2017).

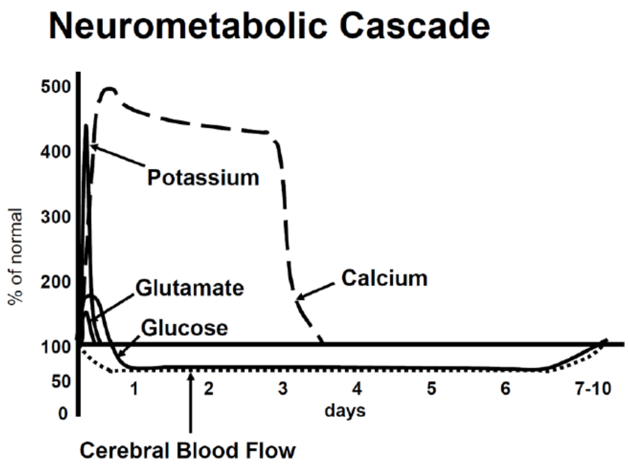

Figure 1.2 Time course of the acute neurometabolic cascade of concussion, from Giza & Hovda (2014)

Despite promising technological advancements, a concussion diagnose is often based on clinical assessments (e.g. self-reported symptoms and functional tests) rather than neuroimaging exams (e.g. magnetic resonance imaging) (Bigler, 2018) or fluid biomarkers (e.g. salivary or blood) (Di Pietro et al., 2021; Hicks et al., 2020). This is because the damage caused by a concussion is usually more explicitly observed in the function, rather than the structure, of the nervous system (Harmon et al., 2019; McCrory et al., 2017). Immediate or delayed onset of symptoms tend to appear within minutes, hours, or even days following the injury (Carney et al., 2014; Harmon et al., 2019; McCrory et al., 2017). Table 1.1 presents all symptoms listed in the Sport Concussion

Assessment Tool (SCAT) developed by the concussion in sport group (Echemendia et al., 2017).

Table 1.1 Symptom evaluation list from the Sport Concussion Assessment Tool 5th edition

Symptoms	
Headache	“Don’t feel right”
Pressure in head	Difficulty concentrating
Neck pain	Difficulty remembering
Nausea or vomiting	Fatigue or low energy
Dizziness	Confusion
Blurred vision	Drowsiness
Balance problems	More emotional
Sensitivity to light	Irritability
Sensitivity to noise	Sadness
Feeling slowed down	Nervous or Anxious
Feeling “in a fog”	Trouble falling asleep

Clinical symptoms are typically expected to spontaneously disappear over 2 to 4 weeks, but there is no consensus in the literature on the exact recovery timeline (Harmon et al., 2019; Kamins et al., 2017; McCrory et al., 2017). Following the injury, immediate disorientation or confusion, impaired balance within 1 day, slower reaction time within 2 days, and impaired verbal learning and memory within 2 days are some of the most consistent and prevalent indicators of concussion in the published literature (Carney et al., 2014). However, the physiological recovery takes longer (Kamins et al., 2017; McCrory et al., 2017), and despite some promising studies with biomarkers (Di Pietro et al., 2021; Hicks et al., 2020), there is still no definitive means to assess when homeostasis is restored. In this sense, a growing literature has explored the lingering effects associated with concussion.

1.1.2. Concussion Long Term Impairment

Although concussion is often featured as a transient injury with short-lived impairment, the long term effects associated with both single and multiple episodes of concussion have been explored. Post-concussion syndrome affects up to approximately 40% of individuals who would fully recover within the initial three months (Bazarian et al., 1999). Headache, difficulty concentrating, fatigue, and dizziness are symptoms usually observed in more than 50% of those experiencing post-concussive syndrome, and the condition may become permanent if recovery has not occurred by three years (Hiploylee et al., 2017). The quantity of symptoms (Hiploylee et al., 2017) and the intensity of initial symptoms (Harmon et al., 2019; McCrory et al., 2017; Schneider et al., 2019) seem to be directly associated with recovery time.

Structurally, some studies have investigated anatomical brain changes *in vivo* in participants with a history of concussion. Diffusion tensor imaging is a technique for investigating such brain changes, particularly white matter abnormalities. Fractional anisotropy is a common measurement used in diffusion tensor imaging studies to assess connectivity in the brain. A systematic review by Kim et al. (2022) concluded that decreased connectivity in the brain (through fractional anisotropy) can be observed not only in the acute phase, but also in the long-term after a concussion. A small sample of retired professional Rugby players with a history of multiple concussions showed differences in brain white matter microstructure compared to individuals with no history of concussion (Wright et al., 2021). In one longitudinal case study, axonal damage (through cerebrospinal fluid neurofilament light protein) was identified up to 9 months after a concussive episode (Neselius et al., 2015), which endorses the consistently longer physiological recovery compared to clinical (Harmon et al., 2019; Kamins et al., 2017; McCrory et al., 2017; Neselius et al., 2015).

Functionally, studies have shown deficits years after clinical resolution of the initial injury. Healthy adults demonstrated reduced postural stability after seven years following the concussion diagnosis (Reilly et al., 2020), whereas American Football and Ice Hockey athletes presented dynamic balance impairment for up to two years (Johnston et al., 2020). It is worth noting that postural control deficits may accumulate with each additional injury (Murray et al., 2019), and recovery of neurological functions is significantly slower after the second episode of concussion (Slobounov et al., 2007). A systematic review investigating retired American Football, boxing, ice hockey, Rugby, and soccer athletes concluded that a history of concussion affects memory, executive and psychomotor functions (Cunningham et al., 2020). In addition to motor and cognitive functional deficits, a 10 years follow-up study associated a history of concussion with long term medical and behavioral comorbidities, such as obesity, hypertension, diabetes mellitus, depression, psychosis, stroke, and epilepsy (Izzy et al., 2021).

The connection between a history of concussive episodes and long term impairment is consistently described especially in retired athletes from modalities with high risk of head impacts. Particularly to this group of athletes, who are chronically exposed to repetitive head impacts, another factor most likely contributes to the occurrence of long term impairment: the silent and undiagnosable subconcussion, previously indicated in Figure 1.1.

1.1.3. Subconcussion

If defining, diagnosing, and recovering from a concussion is problematic, the task becomes even more complex when it comes to subconcussion. There is no official definition for subconcussion, but the term is used for milder forms of head impacts that do not lead to acute deficits in clinical tests or the diagnosis of concussion (Bailes et al., 2013; Mainwaring et al., 2018). Similarly challenging as for concussion, there is no impact force threshold that cause subconcussion. Even without functional impairments and observable symptoms after a single subconcussive impact (i.e. not a concussion), the literature supports that chronic exposure to these impacts to the head has a detrimental effect on brain health and function (Mainwaring et al., 2018; Rawlings et al., 2020).

In order to investigate the effects of repetitive impacts to the head that do not result in known or diagnosed concussion on clinical grounds, studies have focused on acute bouts of subconcussive hits (Hwang et al., 2016; Smirl et al., 2022), comparisons between pre and post sports season (Black et al., 2020; Gong et al., 2018; Shuttleworth-Edwards et al., 2008; Slobounov et al., 2017; Wright et al., 2018), or on (retired or active) athletes from modalities where the exposure to repetitive head impacts is notoriously and chronically high (e.g. American Football, Rugby, ice hockey, boxing, and Mixed Martial Arts) (Amen et al., 2011; Bernick et al., 2015; Casson & Viano, 2019; Lefebvre et al., 2021).

Despite subconcussion being unofficially defined as a cranial impact that does not result in known or diagnosed concussion on clinical grounds (Bailes et al., 2013), bouts of subconcussive hits (i.e. heading a soccer ball) have shown acute transient dysfunction in vestibular processing (Hwang et al., 2016) and dynamic cerebral autoregulation (Smirl et al., 2022). However, participants from both studies were not continuously followed up after the protocols (maximum for 24h in Hwang et al., 2016). Since the onset of clinical symptoms can be delayed, it cannot be ruled out that some participants from these studies actually experienced a concussion. In fact, symptoms severity was elevated after soccer headers and almost 70% of the participants in the Smirl et al., (2022) study experienced an increase in concussion-like symptoms.

Deficits in brain structure (Gong et al., 2018; Slobounov et al., 2017) and function (Slobounov et al., 2017; Wright et al., 2018) were observed in the post season in collision sport athletes with no diagnosed concussion. Furthermore, impairments were exposure-dependent (i.e. the more subconcussive hits, bigger deficit) (Gong et al., 2018; Slobounov et al., 2017; Wright et al., 2018). Amongst university level rugby players, a season worth of head impacts (with no clinically diagnosed concussion) caused balance impairment (Black et al., 2020) and cognitive vulnerability (Shuttleworth-Edwards et al., 2008). Conversely, no impairment in postural control over the course of a competitive football season was observed by Murray et al., (2018), which highlights how findings may differ according to study protocols.

Active or retired athletes from modalities with chronic exposure to head impacts constitute a valuable population to investigate the long term effects of exposure to repetitive head trauma. However, the imminent bias that this sample most likely includes participants with a record of diagnosed concussive episodes must be considered. Repetitive traumas to the head have been associated with decreased cognitive performance (Amen et al., 2011; Bernick et al., 2015), lower brain volume (Bernick et al., 2015), cerebral perfusion (Amen et al., 2011), white matter damage (Lefebvre et al., 2021), and risk of chronic traumatic encephalopathy (Montenigro et al., 2015).

1.2. Population of Interest and Study Designs

The clinical and neuropathological impairments observed in athletes chronically exposed to repetitive head impacts significantly differ according to the sport modality (Casson & Viano, 2019). Therefore, it is pertinent to define a particular audience to specifically address the risks and consequences. The next topics will define and explore the rationale for the population of interest and for the design of each study developed in this dissertation.

1.2.1. Sports-Related Concussion: Incidental Event or Intentional Goal?

Concussion is a global public health issue. In the United States, an estimated 3.8 million injuries occur annually, a likely underestimated number due to the many unreported and undiagnosed episodes (Harmon et al., 2019; Langlois et al., 2006;

Lockrem & Ciocca, 2021). Particularly in sports, managing concussions is complex. Lack of knowledge and inappropriate behavior contribute to an even more challenging scenario. Prevention is the main focus to reduce the number of cases and minimize the acute and chronic burden of this injury. Early identification of visual signs and symptoms, appropriate immediate response, and familiarization with basic assessment tools are critical to the successful management of a potential concussion (Lockrem & Ciocca, 2021; Schneider et al., 2019).

Head injuries and concussions in sports can be related to several factors, such as technical actions of the modality (e.g. heading in soccer), consequence of technical actions (e.g. tackle in American football, body check in ice hockey), accidents (e.g. equestrian fall, collisions), or punishable actions (e.g. helmet to helmet contact or excessive force in American Football and ice hockey) (Pfister et al., 2016; Turner, 2019). However, there are modalities where blows directly to the head are allowed and decisive actions for success.

Boxing, kickboxing, Muay Thai, and Mixed Martial Arts are combat sports in which participants often achieve a win by incapacitating their opponent through blows directly to the head (Neidecker et al., 2019). A knockout (i.e. competitor is unconscious or disoriented) and technical knockout (i.e. competitor is unable to self-defend effectively) are two very common fight outcomes (Buse, 2006; Hutchison et al., 2014; Neidecker et al., 2019), and their operational definitions align with important aspects of the concussion definition (Harmon et al., 2019; McCrory et al., 2017). Moreover, both outcomes are indeed closely associated with the six visual signs strongly associated with concussion diagnose. Table 1.2 presents the visual signs that can be observed immediately at the time of the injury (Davis et al., 2019).

Table 1.2 Visual signs strongly associated with concussion adapted from Davis et al. (2019)

Visual sign	Brief description
Motor incoordination	Instability on feet, loss of balance, staggering, difficulty getting up or walking.
Blank/vacant look	No facial expression or emotion in reference to the athlete’s normal or expected facial expression.
Tonic posturing	Involuntary contraction of limbs or in the cervical region. The musculature becomes stiff in the motion of falling, or on the ground.
Impact seizure	Involuntary, asymmetrical, and irregular rhythmic movement of axial or limb muscles.
Lying motionless	Lying without proposed movement for more than 2 seconds. Not reacting or responding appropriately to stimuli.
No protective action-floppy	Falls to the playing surface without any protective action to mitigate the fall. Loss of muscle tone (in the limbs or neck) before landing.

These signs, with the addition of loss of consciousness, are considered red flags for concussion and the observation of any should indicate immediate removal from the practice (Echemendia et al., 2017; McCrory et al., 2017). In combat sports, however, athletes may be exposed to further damage even after presenting visual signs. The time between the knockout strike and fight stoppage can range from 0 to 20 seconds (3.5s on average), in which the knocked out combatant sustained up to 20 extra strikes (2.6 on average), in addition to a secondary head impact with the fighting environment (e.g. floor, cage, or post) (Hutchison et al., 2014).

In no other sports, athletes are exposed to head impacts as frequently as in combat modalities. Looking at the flowchart presented in Figure 1.1, the likelihood that these athletes will fall into the many possibilities of long term impairment is significantly higher as exposure to the initial event (i.e. head trauma) occurs numerous times on a regular weekly basis. Moreover, the above-mentioned combat modalities are widely practised worldwide, and their contribution to the global burden of concussion in sports must be considered. To explore the special intention, exposure, and reach of combat sports is the main objective of chapter two of this dissertation.

1.2.2. Understanding Risk Exposure, Education, and Behaviour for Prevention

As in any other sport-related injury, prevention is the best way to lessen the burden caused by concussions. Alarmingly, prevention is the least common area of study among the most cited scientific articles in sports-related concussion (McQuivey et al., 2021). In epidemiology, prevention can be classified into three levels and each one is relevant in the sports-related concussion context (Finch, 2006; Schneider et al., 2019). Primary prevention refers to creating strategies that avoid the injury from occurring in the first place. In sports, the main examples are rule changes, protective equipment, and training strategies. Secondary prevention refers to detecting the suspected injury in its initial moments and stopping it from getting worse. In this sense, the identification of visual signs and symptoms followed by the immediate removal from practice contribute to the proper management of suspected cases of concussion. Tertiary prevention encompasses the treatment of the diagnosed injury, therefore the goal is to reduce symptoms, return safely to practice, and restore quality of life.

Primary prevention initiatives are those that have the greatest impact on reducing the burden caused by concussions, as it is understood that most concussions in sport are predictable and preventable (Schneider et al., 2019). Initiatives focused on modifiable intrinsic (e.g. neck strength and return to sport only when fully recovered) and extrinsic (e.g. regulations, stricter rules) risk factors have been implemented in contact sports modalities. For example, regulation of body checks in ice hockey and reducing the number of practices with contact in American Football are efficient strategies to reduce the number of concussions (McCrory et al., 2017; Schneider et al., 2019). However, in combat sports this is challenging since almost all head impacts are intentional (i.e. not punishable because they are within the rules) and a very efficient method of success.

The use of protective equipment is probably the most studied prevention strategy in combat sports. Helmets are effective in reducing the risk of injuries such as cuts, lacerations and punctures, but their effectiveness in preventing concussion is not yet established (Schneider et al., 2019; Tjønndal et al., 2021). As much as the force of the impact is diminished by helmets, they do not impede the movement and shearing forces in the brain inside the skull. Noteworthy, the false sense of protection leads fighters to more aggressive actions (e.g. stronger strikes), and the limited peripheral vision increases the chance of unanticipated impacts. Therefore, the concussion risk may paradoxically increase (Harmon et al., 2019).

In combat sports, education and behavior change are the aspects that can represent the greatest impact in concussion prevention. The education of athletes, coaches, referees, promoters, and the general public has the potential to influence concussion prevention in primary (e.g. modifying risk factors), secondary (e.g. appropriate behaviour after a suspected injury), and tertiary (e.g. treatment and recovery) levels. Despite the awareness that the level of knowledge about concussion is an important factor for prevention (Lockrem & Ciocca, 2021; Schneider et al., 2019), little is known in combat sports and the little that is known is not promising. Combat sport athletes do not fully understand the terms used to describe head injuries and its symptoms, often prefer not to report symptoms to avoid being removed from practice, and return to full contact dangerously too early after a diagnosed concussion (Bennett et al., 2019; Heath & Callahan, 2013; Lystad & Strotmeyer, 2018). While significant knowledge gaps were found in coaches and officials from other contact modalities (Yeo et al., 2020), information remains unknown among combat sports coaches. As a mentor that could directly influence an athlete’s decision to seek medical care or to be removed from practice to avoid further damage, the investigation of coaches’ level of knowledge is crucial in fighting modalities.

Understanding the particular context is imperative for an effective injury prevention strategy (Finch, 2006). Even more so if the context involves intentional hits to the head, such as combat sports modalities like Mixed Martial Arts, boxing, kickboxing, and Muay Thai. The risk exposure in competition and in training, as well as the knowledge and behaviour of athletes and coaches must be comprehensively investigated. These are the objectives of the studies presented in chapters three and four of this dissertation.

1.2.3. Chronic Exposure to Head Trauma and Neuromuscular Function

Athletes from combat sports are chronically exposed to repetitive head trauma. The exposure to an agent for years defines chronicity (Greenamyre & Barrett, 2015), and combat sports athletes (with 5.8 years of experience, range 1-32) are exposed to numerous strikes to the head in the 2.5 (range 1-7) simulated fights they perform weekly (average duration of 63 min per session, range 4-180) (Heath & Callahan, 2013). The long term impairments these athletes are liable to are either due to the acute and transient brain changes from repetitive subconcussions (Di Virgilio et al., 2019), a history of concussion or, most likely, a combination of both.

The literature is consistent in describing the impairments caused by chronic exposure to repetitive head impacts in combat sports athletes (Bernick et al., 2015; Casson & Viano, 2019; Schlegel et al., 2021). The nervous system is the main system affected. Laboratorial imaging exams have revealed lower thalamic and caudate volumes (Bernick et al., 2015; Schlegel et al., 2021), decreased cerebral perfusion (Amen et al., 2011), and white matter connectivity deficit in the anterior regions of the corpus callosum and corticospinal tract (Lefebvre et al., 2021). The clinical picture is well associated with the neuropathological (Casson & Viano, 2019), demonstrated by the decreased performance in motor, cognitive, and psychological functions (Amen et al., 2011; Banman et al., 2021; Bernick et al., 2015; Cunningham et al., 2020; Mishra et al., 2019).

While many clinical and laboratorial protocols are valid and sensitive to detect the acute effects of a concussion, there is a growing interest in developing alternative, practical, and reliable tools to assess impairments due to chronic exposure to head impacts. Postural balance, brain activity, and spinal cord excitability are promising parameters that are worth investigating and that could lead to relevant discoveries in the laboratory and clinical settings. The investigation of postural function, brain activity, and spinal cord excitability are the main objectives of the original studies that constitute chapters five and six of this dissertation and will be further introduced in the next topics.

Postural Balance. Postural stability testing has been widely used to assess acute deficits after concussion (Guskiewicz, 2011; Guskiewicz et al., 2001) because it integrates the somatosensory, visual, and vestibular systems (Horak, 2006). Vestibulo-ocular function is crucial for the success of athletes from combat modalities in which evasive and rapid movements are constantly performed (Brown et al., 2022). Among many different protocols to assess postural function, the Balance Error Scoring System (BESS) is the one adopted by the Concussion in Sport Group and the SCAT (Echemendia et al., 2017; McCrory et al., 2017). The BESS is a practical protocol consisting of a series of 20s balance trials in different stances (double-, single-, and tandem-leg) over two surfaces (i.e. firm or foam pad), illustrated in Figure 1.3 (Bell et al., 2011).

Figure 1.3 Traditional Balance Error Scoring System stances: (A) double-, (B) single-, (C) tandem-leg over firm surface (A, B, C, respectively) and over foam pad (D, E, F, respectively) (Bell et al., 2011)

Participants must remain with eyes closed, hands at hips, and bare feet. In the traditional BESS, errors are counted subjectively by the evaluator (e.g. opening the eyes, hands off hips, step, stumble, or fall), whereas the use of a balance board allows for objective measures of center or pressure displacement in the anterior-posterior and medio-lateral axes (Black et al., 2020; Chang et al., 2014; Holmes et al., 2013; Winter, 1995). Mostly due to its practicality and low cost, the integration of the BESS and a balance board has been also implemented to investigate balance deficits after cumulative subconcussive hits to the head (Black et al., 2020; Hwang et al., 2016).

Evidence suggests a progressive vestibular impairment in combat sports athletes (Banman et al., 2021), and the vestibulo-ocular dysfunction may be a result of exposure to repetitive head trauma (Brown et al., 2022). Moreover, there seems to be evidence of accumulation of postural deficits with additional head injury (Murray et al., 2019).

Taken together, the BESS may be a relevant and useful practical tool to examine the long-term impairments caused by chronic exposure to head trauma.

Brain Activity. Studies of brain imaging, function, and biomarkers provide the groundwork for investigating the relationship between head impact and objective measures of dysfunction (Carney et al., 2014; Kamins et al., 2017). While a single episode of concussion does not cause measurable deficit on brain structures (Harmon et al., 2019; McCrory et al., 2017), transient functional impairment (i.e. corticomotor inhibition and altered motor unit recruitment) has been observed after a boxing training session with many subconcussive blows (Di Virgilio et al., 2019). In fact, the effects of the exposure to repetitive and cumulative head trauma are identifiable in many different brain structures and functions (Amen et al., 2011; Bernick et al., 2015; Casson & Viano, 2019; Mishra et al., 2019).

Studies with electroencephalography verified altered amplitude and latency of event-related brain potentials in concussed athletes (Dupuis et al., 2000; Fickling et al., 2019) and in athletes with exposure to repetitive head impacts (Andelinović et al., 2015). Event-related potentials are the synchronous firing of action potentials in the brain as information is processed. Respectively, amplitude and latency relate to the strength and speed of neuronal firing rate (Sur & Sinha, 2009) and are both associated with cognitive function (Andelinović et al., 2015; Dupuis et al., 2000).

The Muse headband is a portable low-cost electroencephalography system and has been proven to be a valid, reliable, and convenient tool to assess event-related brain potentials (Krigolson et al., 2017, 2021). Figure 1.4 shows the MUSE device and typical brain waves recorded from an event-related potential (i.e. N200 and P300) (Krigolson et al., 2021). With a setup done in approximately 10 minutes (Krigolson et al., 2017), the MUSE is a promising laboratory and clinical instrument that can further unveil deficits associated with chronic exposure to head impacts.

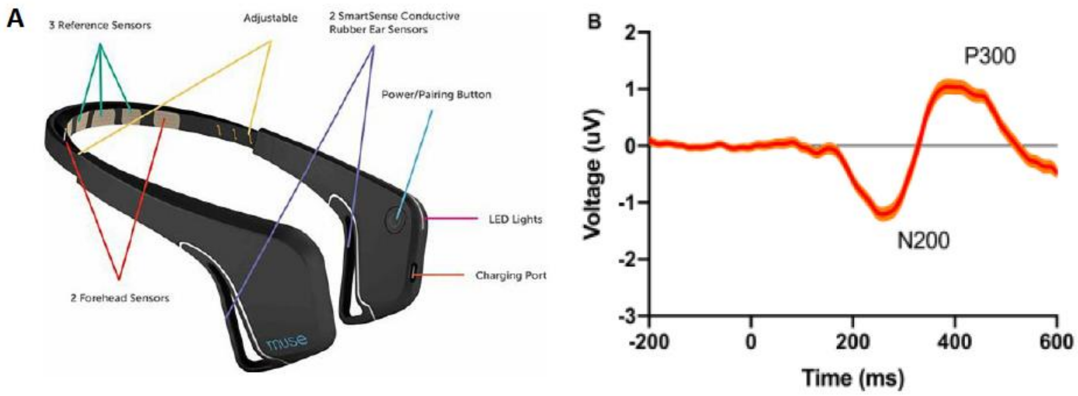

Figure 1.4 The Muse encephalography system (A) and an example of event-related potential brain waves (B) (Krigolson et al., 2021)

Spinal Cord Excitability. Chronic exposure to head impacts affects connectivity and auto regulation in the central nervous system (Mishra et al., 2019; Wright et al., 2018) and is useful for discoveries on supraspinal (i.e. brain) and spinal cord interactions. In particular, the volume of the thalamus seems to be decreased following chronic exposure to repetitive head impacts (Bernick et al., 2015; Bernick & Banks, 2013), a brain structure which integrates cortical and subcortical information (e.g. somatosensory, cognition, learning, and memory functions) (Wolff & Vann, 2019). However, the effects of head injuries on the spinal cord activity remain less studied (Carney et al., 2014; Kamins et al., 2017), yet should be equally considered due to its critical role in transmitting and modulating information to and from supraspinal regions and controlling reflexes regardless of brain control.

Assessment of spinal cord excitability using the Hoffmann (H-) reflex is sensitive for detecting effects caused by head trauma (Katayama et al., 1985) and spinal cord injury (Nozaki et al., 1996). The H-reflex has been widely used in the literature concerning movement control, neurophysiology, and applied physiology (Zehr, 2002). Figure 1.5 illustrates the methodological rationale and physiological mechanisms once the H-reflex is evoked (Aagaardet al., 2002). Following a percutaneously electrical current of the tibial nerve, the evoked action potentials propagate through sensory neurons to the spinal cord. Excitatory postsynaptic potentials elicit action potentials that travel in the α-motoneuron axons toward the muscle recorded as an H-reflex (A). Higher stimulus intensity will cause action potentials to travel directly to the muscle as a motor response (M-wave, B). Further stimulus will propagate action potentials in the α-motoneuron axons towards the spinal cord, colliding and eventually cancelling the reflex response (C and D) (Aagaard et al., 2002; Zehr, 2002).

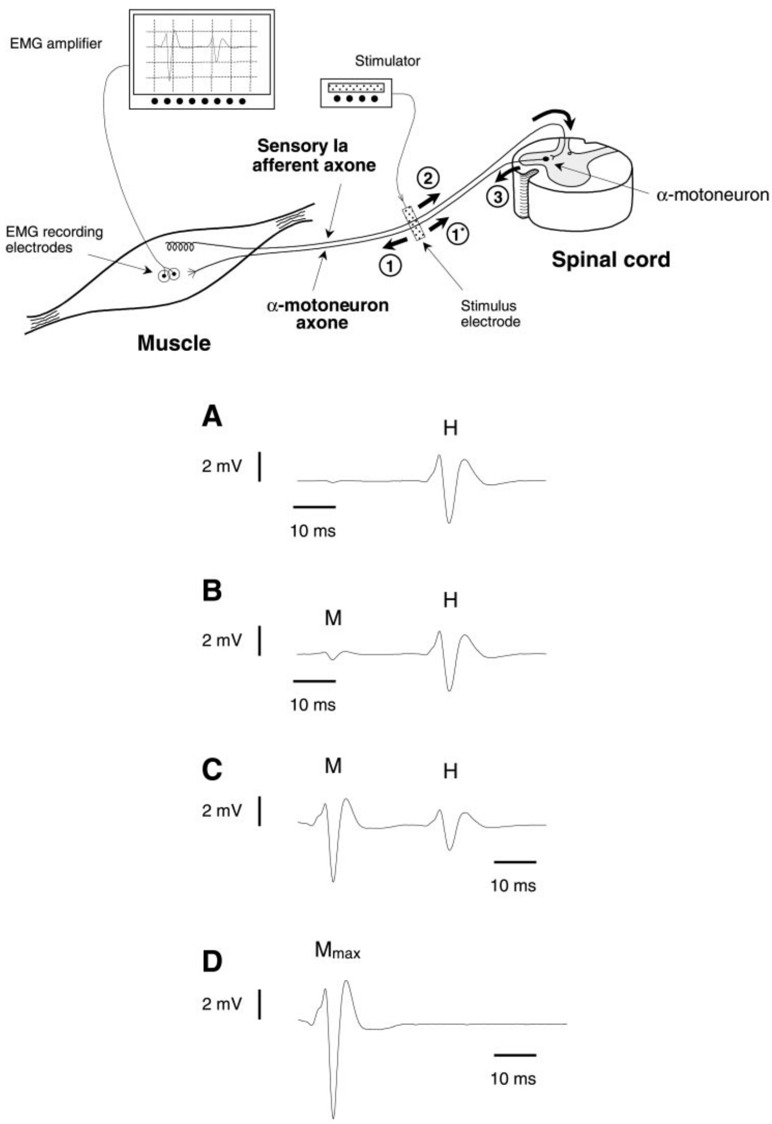

Figure 1.5 The typical Hoffmann reflex response evoked from the tibial nerve electrical stimulation (Aagaard et al., 2002)

The H-reflex is reliable method to analyze modulations of spinal excitability (Grosprêtre & Martin, 2011; Zehr, 2002). In addition to traditional amplitudes (i.e. from H and M waves), bilateral fluctuations have provided information on (ab)normal states associated with the spinal cord excitability (Mezzarane & Kohn, 2002) and plastic changes in the human motor system (Ceballos-Villegas et al., 2017). Responses have been influenced by athletic level (Ceballos-Villegas et al., 2017) and potentially by exposure to head impacts (Black et al., 2020). Therefore, bilateral H-reflex amplitudes and fluctuations are promising biomarkers to investigate the effects of chronic exposure to head impacts in the spinal cord circuitry.

1.2.4. Knowledge Translation

Although knowledge may not directly translate to proper behaviour when it comes to head injuries (Delaney et al., 2018), education must be the first step towards a safer environment and long term health. In combat sports, athletes and coaches must possess a thorough knowledge base regarding concussion including prevention strategies, visual signs, symptoms, and safe return to sport (Nalepa et al., 2017; Neidecker et al., 2019). However, the inability to access sport science research is a real barrier for those involved in sports given that most study findings are disseminated in academic journals and conferences (Pope et al., 2015). In addition to a specialized and not always user-friendly language, academic research is highly consumed by scientists and researchers, not athletes and coaches.

Knowledge translation is a method for closing the gaps from knowledge to practice (Straus et al., 2009), which involves a dynamic and iterative process to ultimate improve health system (Government of Canada, 2012). Communicate scientific findings with the population of interest must be an essential component of the research process (Pope et al., 2015). The knowledge to action framework (Figure 1.6) provides a model for the promotion of the application of research and the process of knowledge translation (Straus et al., 2009).

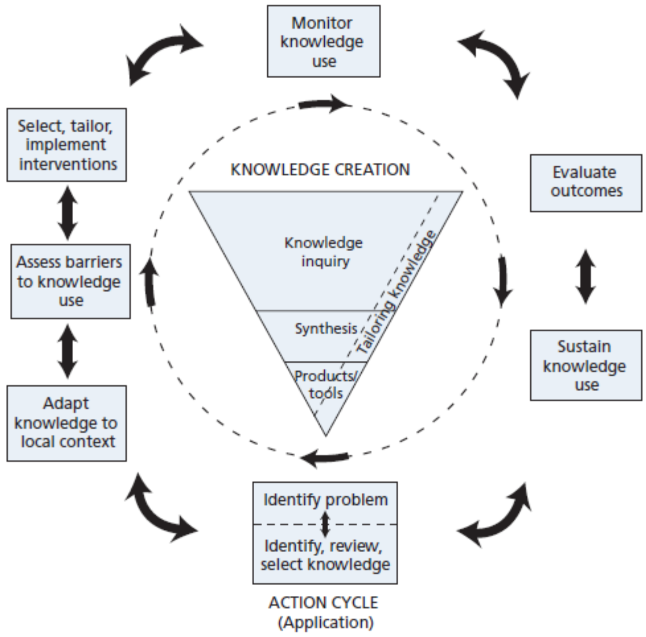

Figure 1.6 The Knowledge to Action framework from Straus et al. (2009)

Knowledge creation (center of the image) includes the completion of primary research, such as the original studies described in chapters 3, 4, 5, and 6 of this dissertation. Synthesis and the production of tools are the next steps, when the scientific literature will be transformed into user-friendly information, directed to particular audiences. This strategy may effectively enhance scholarly knowledge, which can be one of the main barriers to behaviour change (Smith et al., 2015). As previously discussed, the education in concussion and on the harms of head injury among athletes and coaches can be an effective (primary, secondary, and tertiary) prevention strategy to decrease the overall burden in sports. Therefore, chapter seven of this dissertation is composed of blog posts originated from a compilation of scientific manuscripts describing the relevance and consequences of head traumas in sports. All knowledge translation pieces were published in a popular blog of a commercial mainstream magazine (Psychology Today), accessible free of charge, and in user-friendly language.

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Chapter 2 - It's a no Brainer: Combat Sports Should be Ground Zero for Research on Concussion[1]

2.1. Introduction

Many combat sports have as their overt goal the incapacitation of the opponent which is often achieved by blows to the head. While head impact in contact sports like football, rugby, and hockey is accidental and susceptible to sanctioning, strikes directly to the head are intentional and determinants of success in combat sports like Muay Thai, kickboxing, boxing and mixed martial arts (MMA) (Follmer et al., 2019; Neidecker et al., 2019). Yet, combat modalities are often not mentioned among the sports identified with the highest concussion rates. Boxing is found "far behind" equestrian events, Rugby Union, cricket, soccer and other organized college sports (e.g. football and hockey) (Turner, 2019). Data remain limited or unavailable for fighting arts (Harmon et al., 2019).

Fighting has been a sport since at least 648 BC in ancient Greece with Pankration, a discipline that combined wrestling and boxing. Almost a century ago, 'dementia pugilistica' and 'punch drunk' described neurological impairments manifested in long-time boxers. Neuropathological reports on the long-term effects of boxing pre-date those in football (Casson & Viano, 2019).

The popularity and financial power of combat sports have grown exponentially in recent years. Karate joined boxing, wrestling, and taekwondo as an Olympic modality, while kickboxing and Muay Thai associations were granted full Olympic recognition. The

[1] Follmer, B., Zehr, E. P. (2021) It's a no brainer: combat sports should be ground zero for research on concussion. *British Journal of Sports Medicine*; 55(24):1434-1435. doi: 10.1136/bjsports-2021-104519

biggest MMA organization was acquired for over 4 billion dollars, and a boxer and an MMA fighter topped the rankings of the highest-paid athletes of the last decade and in 2021, respectively.

However, this exponential growth in participation and profile has not been matched by equivalent scientific recognition and investigation. The Intention (to neutralize an opponent through head injury), Exposure (the vulnerability of combat fighters to brain trauma) and Reach (across all social strata) of combat sports justify that fighting must be the ground zero when it comes to sports concussion research.

2.1.1. Intention

Strikes directly to the head are intentional and critical to success in combat sports like Muay Thai, kickboxing, boxing and MMA (Follmer et al., 2019). Unlike other sports, fighting often doesn't obey the mandatory immediate removal of the player when signs of concussion are observed (i.e. recognize and remove) (Harmon et al., 2019; Schneider et al., 2019). This allows a brain-injured fighter to receive extra head impacts, from the opponent or the canvas flooring, despite the observation of typical concussion signs (e.g. lying motionless, no protective action, and vacant look) (Harmon et al., 2019). Motor incoordination, disorientation, and symptoms such as dizziness and poor balance may be subtle and insufficient to determine the end of a fight, exposing the combatant to further damage, including life-threatening injuries such as subdural hemorrhage. While there is room for implementing preventive actions, the deliberate intention of inducing brain injury is the biggest risk factor for concussion in combat sports. This is unlikely to change in competition but possibly could in training.

2.1.2. Exposure

Repetitive hits to the head are associated with brain impairment (Casson & Viano, 2019), and in no other sport are athletes as exposed as in fighting. We showed that more than half of heavyweight MMA fights ended with a competitor either unconscious or unable to defend due to head impacts (Follmer et al., 2019). The risk becomes more challenging to track when potential concussive events and actual hours of practice are considered (Harmon et al., 2019). The training routine in combat sports is a source of great concern. Exposure during simulated fights in practice (where medical personnel are absent) far outweighs those during official matches. A weekly frequency of 2.5 simulated fight sessions (range: 1-7) of 63 min each (range: 4-180) has been reported (Heath & Callahan, 2013), which largely surpasses the usual time of official matches in MMA (3 rounds of 5 min) and boxing (12 rounds of 3 min) performed only a few times each year. Competition has greater concussion risk than practice for most sports (Schneider et al., 2019), but not in combat modalities.

2.1.3. Reach

Concussion is a public health issue. Combat sports are easily accessible and widely practised worldwide, whether in higher- or lower- and middle-income countries. Fighting does not require favorable weather, equipment, sophisticated attire, or specific terrain. Weight categories for both sexes allow the inclusion of diverse body types, influencing exposure to head trauma in competition (Follmer et al., 2019). In addition to athletes, a myriad of practitioners, of all ages, seek the educational potential, values, discipline, and health benefits associated with combat sports. There is a lack of data of how many practitioners of boxing, kickboxing, Muay Thai, and MMA exist, which is different to football and ice hockey (8.9 and 3.1million in the US, respectively) (Turner, 2019). It is of utmost importance to investigate the numbers of combat sport practitioners to elucidate the real burden of concussion in contact sports globally.

2.2. Conclusion

The Association of Ringside Physicians published a consensus statement on concussion management in combat sports, which is mostly based on recommendations for non-combat sports and anecdotal evidence (Neidecker et al., 2019). Research evaluating head injuries in combat sports were found to have significant risk of bias, inconsistency, imprecision, very low quality and importance (Lockwood et al., 2018).

The upcoming International Consensus Conference on Concussion in Sport appears timely and will hopefully endorse the importance of better-quality research into concussion in combat sports. It is critical to acknowledge that the Concussion in Sport Group recommendations are poorly implemented in combat sports, due to the very essence of these sports. Combat sport athletes are chronically exposed to intentional and repetitive head impacts, and the real prevalence and global impact of brain injuries in combat sports needs to be addressed.

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Chapter 3 - Head Trauma Exposure in Mixed Martial Arts Varies According to Sex and Weight Class[2]

3.1. Abstract

Background: Brain injury arising from head trauma is a major concern in Mixed Martial Arts (MMA) because knockout (KO) and technical knockout (TKO) are frequent fight outcomes. Previous studies showed a high incidence of match-ending due to strikes to the head but did not perform an investigation considering weight categories and female fights. This study aimed at analyzing match stoppages in MMA and the exposure to head trauma distinguished by the sex and weight categories.

Hypothesis: the heavier the weight class, greater will be the risk and incidence of head trauma exposure regardless of the sex.

Study design: Descriptive epidemiology study.

Level of evidence: Level 3

Methods: Publicly available data of 167 MMA events from 1903 fights between 2014 and 2017 were assessed, comprising eight male and two female weight categories.

Results: The combined KO/TKO rates per 100 athlete-exposures in the middleweight (19.53), light heavyweight (20.8), and heavyweight (26.09) divisions were higher than previously reported for MMA. Whilst a stoppage via KO/TKO occurred in 7.9% of the combats in the female strawweight division, it occurred in 52.1% of the male

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[2] Follmer, B., Dellagrana, R. A., & Zehr, E. P. (2019). Head Trauma Exposure in Mixed Martial Arts Varies According to Sex and Weight Class. *Sports Health*, 11(3), 280–285. doi:10.1177/1941738119827966

heavyweight fights. The male middleweight (OR:1.80; 95%CI:1.26-2.56; p=0.001), light heavyweight (OR:2.00; 95%CI:1.32-3.03; p<0.001) and heavyweight divisions (OR:3.06; 95%CI:2.03-4.61; p<0.001) had an increased risk of KO/TKO due to strikes to the head in 80, 100, and 206%, respectively. The risk in the flyweight division decreased 62% (OR:0.38; 95%CI:0.21-0.68; p=0.001). All categories were compared to the lightweight division. The female bantamweight category presented 221% increased risk in match-ending due to KO/TKO compared to the strawweight (OR:3.21; 95%CI:1.29-7.97; p=0.012). Punches to the head were the major used technique to end a combat via KO/TKO, regardless of sex and weight class.

Conclusion: Head injury risk and incidence varies considerably according to the sex and weight category in MMA.

Clinical relevance: The analysis of head trauma exposure in MMA athletes should be discerned according to sex and weight category.

Keywords: Combat sports; head injuries; brain concussion; traumatic brain injury; chronic traumatic encephalopathy.

3.2. Introduction

Mixed Martial Arts (MMA) is an umbrella term for combat sport that encompasses athletes with backgrounds in several fighting disciplines that mainly involve standing strikes, grappling and locking techniques (Jensen et al., 2017; Lockwood et al., 2018). Despite the increasing popularity of MMA worldwide, numerous medical associations around the globe have called for the banishment of the sport, mainly based on presumed risk of brain injury (Hutchison et al., 2014; Lockwood et al., 2018; Lystad et al., 2014). In response, a cooperative work at different levels has been developing to diagnose, recognize and provide reliable recommendations in order to make the sport safer (Neidecker et al., 2019).

Given that blows directly to the head are an effective way to achieve a win, MMA could report even higher rates of traumatic brain injuries than those assessed in American-style football and ice hockey (Hutchison et al., 2014). Both knockout (KO) (i.e. when a competitor is unconscious or disoriented) and technical knockout (TKO) (i.e. when an athlete is judged to be unable to competently defend himself) are frequent fight outcomes (Buse, 2006; Hutchison et al., 2014; Lockwood et al., 2018). Both outcomes could easily entail concussive events, as sports-related concussion is, among various aspects, a subset of mild traumatic brain injury induced by biomechanical forces that may or may not involve loss of consciousness (McCrory et al., 2017; Neidecker et al., 2019).

Recently, inappropriate representation of the long-term risks of repeated head trauma and concussions in popular culture has gained attention (Zehr & Wright, 2016). The previous studies reporting traumatic brain injury risk in MMA did not consider that there are significant differences between weight categories in several aspects of the fight including strikes landed in the distance, clinch and on the ground (Miarka, Brito, Bello, et al., 2017; Miarka et al., 2015). Moreover, female fights were neither included nor analyzed, which is of utmost importance since there likely exist differences between males and females towards recovery and concussion rates (Hutchison et al., 2017; McDonald et al., 2016; Sicard et al., 2018).

Therefore, the aim of the present study was to perform a comprehensive investigation concerning match stoppages and head trauma risk in MMA fights according to sex and weight classes. This analysis includes percentage of each fight outcome including the incidence of KO and TKO in MMA, the source that resulted in match-ending head traumas and the identification of which sex and weight categories were more susceptible to match-ending due to head traumas.

3.3. Methods

3.3.1. Data Collection

All data collected for the present investigation was obtained from publicly available sources. Every Ultimate Fighting Championship (UFC) matches from 2014 up to 2017 were assessed, comprising a total of 167 events and 1903 fights. Every event within these four years was analyzed. This includes the following: *UFC 169* to *219*, *UFC Fight Night 34* to *123*, *UFC on Fox* from *10* to *26*, *The Ultimate Fighter Finale* from *19* to *26*, *The Ultimate Fighter Finale China*, *The Ultimate Fighter Finale Nations*, and *The Ultimate Fighter Finale Brazil 3*.

Each fight outcome and the source of stoppage were obtained from a specialized and publicly available website (www.sherdog.com), while the official UFC website (www.ufc.com) was used to confirm the weight category for each bout analyzed. Similar data collection procedures were used previously to verify MMA fight outcomes and athletes records (Bernick et al., 2015; Hutchison et al., 2014). When further information was needed, video analysis of the specific bout was performed. The possible fight outcomes in the present study were classified as decision, submission, KO, TKO, disqualification, medical stoppage, and no contest. In addition, both KO and TKO resulting from blows to the head were investigated to identify the source (e.g. punches, elbows, knee, kick, and some combinations) that determined the stoppage.

3.3.2. Weight Categories

The UFC male weight categories assessed in the present study were flyweight (52.1 to 56.7 kg), bantamweight (56.7 to 61.2 kg), featherweight (61.2 to 65.8 kg), lightweight (65.8 to 70.3 kg), welterweight (70.3 to 77.1 kg), middleweight (77.1 to 83.9 kg), light heavyweight (83.9 to 93.0 kg), and heavyweight (93.0 to 120.2 kg). For female weight classes, the strawweight (up to 52.1 kg) and the bantamweight (56.7 to 61.2 kg) divisions were analyzed since these were the two categories with considerable amount of data during the evaluated period. Fights in a catchweight occur when athletes agree to fight in an unofficial weight class and were considered to match the exclusion criteria for the present study. These data were not analyzed regardless of sex, since these fights could have occurred at any weight, and results and conclusion would be affected.

3.3.3. Statistical Analysis

All statistical analysis was performed using SPSS (v.17.0; SPSS Inc., Chicago, IL, USA). Descriptive absolute and relative data are presented for each weight class and also the total of male and female cases. We applied a previous definition for an athlete-exposure (AE) (Hutchison et al., 2014), that is: participation in any competition in which one was exposed to the possibility of an athletic injury (i.e. 1 fight with 2 competitors yields 2 athlete-exposures). Binary logistic regression analyses were performed to verify and compare the odds ratios of a KO/TKO stoppage due to strikes to the head among weight categories for each sex. A significance level of ≤ 5% was set, with 95% confidence intervals (CI).

3.4. Results

3.4.1. Fight Outcomes and KO/TKO sources

A total of 1728 male combats were analyzed. This includes 126 flyweight, 179 bantamweight, 218 featherweight, 350 lightweight, 347 welterweight, 233 middleweight, 137 light heavyweight, and 138 heavyweight combats. For females, a total of 175 fights were analyzed: 101 in the strawweight and 74 in the bantamweight division. The proportions of the main fight outcomes for each weight class are represented in Figure 3.1. Disqualification, no contest, medical stoppage and TKOs that were not directly related to blows to the head (e.g. body kick) were considered as 'other'.

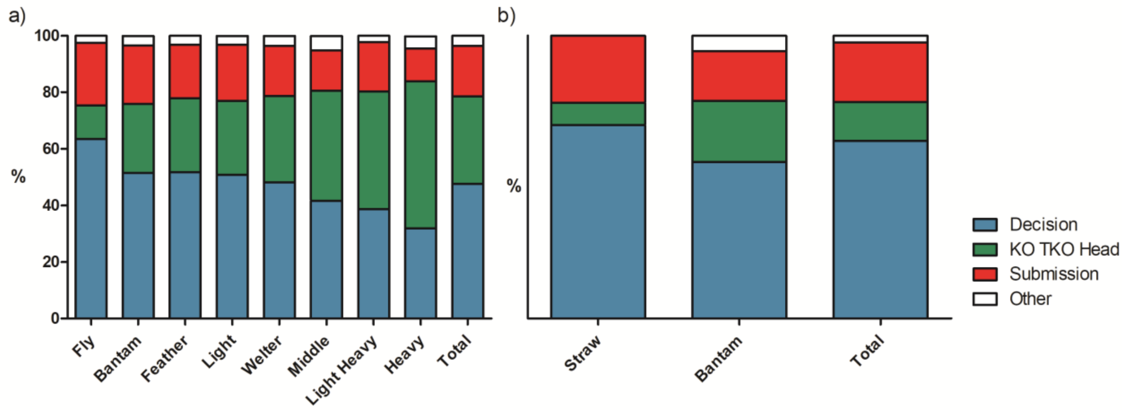

Figure 3.1 Percentage of fight outcomes according to eight male (a) and two female (b) categories

Fighters employed different technique combinations to achieve a referee stoppage during the bouts. Despite the use of the elbow, knee, shin and foot, the hands/fists were the most used parts of the body to obtain a KO/TKO with traumatic blows to the opponent's head. Thus, punches were widely used to end combat, either singly or in combination with other parts of the body, regardless of sex and weight category (Figure 3.2).

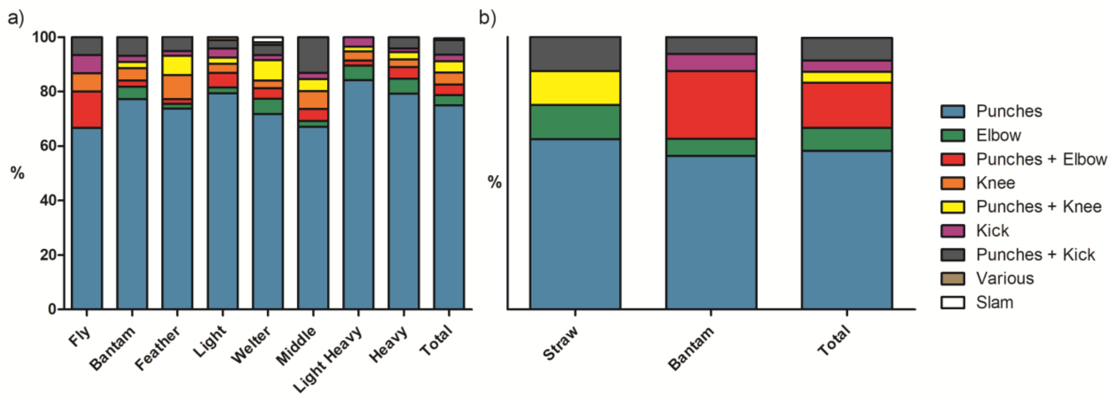

Figure 3.2 Proportion of the source of impact that resulted in knockout (KO) and/or technical knockout (TKO) to the head in each male (a) and female (b) weight category

3.4.2. Athlete-Exposure and Odds Ratios for Head Trauma

The TKO result is commonly associated with blows to the head, however musculoskeletal injuries, lacerations and corner or medical stoppages can also lead to TKOs. The vast majority of TKOs assessed in the present study were due to blows to the head (Table 3.1). Every combat analyzed comprised 2 AEs, which generated a total of 3456 and 350 AEs for male and female, respectively. Table 3.1 demonstrates the proportion of TKO stoppages due to head impact in each weight class, as well as the frequency of KO and combined KO/TKO episodes for every 100 AEs.

Table 3.1 Percentage of technical knockout (TKO) stoppages caused by blows to the head and the incidence of knockout (KO) and KO/TKO per 100 Athletes-Exposures (AEs)

	% TKOs to the head	**100 AEs KO**	**100 AEs KO/TKO to the head**
M Flyweight	70	3.17	5.95
M Bantamweight	93.1	4.75	12.29
M Featherweight	94.1	5.73	13.07
M Lightweight	92.9	5.57	13.14
M Welterweight	93.7	6.63	15.27
M Middleweight	90	7.94	19.53
M Light Heavyweight	100	9.85	20.8
M Heavyweight	95.2	11.59	26.09
M Total	**92.9**	**6.68**	**15.45**
F Strawweight	100	0.99	3.96
F Bantamweight	78.5	3.38	10.81
F Total	**85**	**2**	**6.85**

M = Male; F = Female

The lightweight division was chosen as the reference for the binary logistic regression analysis of the male categories according to previous literature (Hutchison et al., 2014) (Table 3.2). The flyweight was the only category that presented a significantly diminished risk (-62%) of a KO/TKO due to strikes to the head. In contrast, the middleweight, light heavyweight and heavyweight increased the risk of sustaining a KO/TKO outcome caused by strikes to the head by 80, 100 and 206%, respectively. The strawweight division was the reference for the female analysis. Fights of the bantamweight category presented 221% increased risk of a KO/TKO resulting from strikes to the head.

Table 3.2 Odds ratios (OR) for knockout (KO) and technical knockout (TKO) outcomes caused by strikes to the head according to the weight division

	KO/TKO to the head	
	OR (CI95%)	***P***
M Flyweight	0.38 (0.21 – 0.68)	0.001
M Bantamweight	0.91 (0.60 – 1.38)	0.671
M Featherweight	0.99 (0.68 – 1.46)	0.971
M Lightweight*	1.00	----
M Welterweight	1.23 (0.89 – 1.72)	0.213
M Middleweight	1.80 (1.26 – 2.56)	0.001
M Light heavyweight	2.00 (1.32 – 3.03)	<0.001
M Heavyweight	3.06 (2.03 – 4.61)	<0.001
F Strawweight**	1.00	----
F Bantamweight	3.21 (1.29 – 7.97)	0.012

M = Male; F = Female
*Male lightweight division as reference.
**Female strawweight division as reference.

3.5. Discussion

3.5.1. The Relevance of Weight Class and Sex on Head Trauma Risk

Prior investigations reported a general KO incidence of 4.8 and 6.4 per 100 AEs in MMA matches (Buse, 2006; Hutchison et al., 2014). These results are slightly lower than our overall result regardless of the body mass category (6.68). However, our results expand the current medical literature to show that the occurrence of KO and combined KO/TKO varies considerably according to the sex and weight category. Both female's categories and the male flyweight division presented lower values, whereas the results from male's bantam, feather, light, and welterweights were in between those previously assessed and widely disseminated. The odds ratios analysis performed using the lightweight as reference revealed that the middleweight, light heavyweight, and heavyweight divisions presented 80, 100, and 206% increased risk of a match stoppage due to head trauma. Moreover, these three heavier weight classes have achieved values near the upper limit or even higher (Figure 3.1) than the range of KO and TKO prevalence (28.3-46.2% of all matches) previously reported in MMA (Lockwood et al., 2018). Since the present study indicates that heavier categories encompass the larger risks and incidences of KO and TKO, it is reasonable to consider if these athletes had increased chances of suffering from more severe traumatic brain injuries.

Conversely, the scorecard decision was the fight outcome for the vast majority of the male fly (63.4%), bantam (51.4%), feather (51.8%), light (50.8%), and welter weight (48.1%), as well as for the female straw (68.3%) and bantamweight (55.4%) divisions (Figure 3.1). Combats that went to decision presented elevated numbers of total strikes attempted to the head during the standing combat (Miarka et al., 2016), hence athletes involved may be liable to develop symptoms of the chronic exposure to repetitive traumas to the head (Bernick et al., 2015; Zehr & Wright, 2016) and/or subconcussive impacts (i.e. a cranial impact not diagnosed as a concussion) (Mainwaring et al., 2018; Slobounov et al., 2017). Although without perceptive acute symptoms after the bout, repeated evaluations are necessary to diagnose delayed signs and symptoms of concussion (Neidecker et al., 2019). Furthermore, specific recommendations to athletes who underwent an entire combat should be considered, since repetitive traumas to the head have been associated with a decreased cognitive performance (Amen et al., 2011; Bernick et al., 2015), lower brain volume (Bernick et al., 2015), cerebral perfusion (Amen et al., 2011), and risk of chronic traumatic encephalopathy (Manley et al., 2017; McCrory et al., 2017).

Female's fight outcomes presented the same trend as males. The bantamweight showed 221% higher chance of stoppages by KO/TKO than in the strawweight division. Literature has been showing that a special concern in female fighters should be addressed, since females presented greater peak angular acceleration and displacement in the head-neck segment than males (Tierney et al., 2005). Moreover, females also reported several symptoms (McDonald et al., 2016) and presented greater long-term alterations in executive function (Sicard et al., 2018) and a more persistent autonomic nervous system disruption (i.e. reduced heart rate variability) following a concussion compared to males (Hutchison et al., 2017). Then, there is a need for future specific research focused on traumatic brain injuries in female MMA fighters.

3.5.2. The Preferred Technique may not Change, but the Sport Does.

It was previously reported that punches were the most frequently used technique to end an MMA combat via KO and TKO (Buse, 2006; Hutchison et al., 2014). During standing combat, clinch or groundwork, strikes attempted and landed to the head are the most frequent compared to those addressed to the body or legs in male (Miarka, Brito, & Amtmann, 2017) and female (Miarka et al., 2016) MMA fights. Our results confirm that punches accounted for the majority (male 75%, female 58.3%) of blows struck to end a combat by KO and TKO regardless of sex and body mass division (Figure 3.2).

This clear preference for head strikes allows several comparisons between the MMA and Boxing concerning head trauma risks. While both modalities have the head and wrist/hand as the major injured body sites (Jensen et al., 2017; Karpman et al., 2016; Lystad et al., 2014), boxers receive more strikes to the head (Heath & Callahan, 2013), are more likely to experience loss of consciousness (Karpman et al., 2016), and present lower brain volumes than MMA athletes (Bernick et al., 2015).

Some features imported from Boxing have been suggested as alternatives to make MMA a safer sport, like mandatory protective head gear, bigger gloves and the introduction of the 10s rule every time that a competitor is knocked down (Hutchison et al., 2014; Karpman et al., 2016). Considering the abovementioned harsher symptoms presented by boxers compared to MMA fighters, these do not seem to contribute effectively to making the sport safer. However, as in Boxing, MMA rules could consider calling the end of a fight (by TKO) if a combatant is knocked down three times in the same round (Neidecker et al., 2019). Alternatively, the ban on strikes to the head immediately following a knockdown episode, allowing only the submission techniques during a determined period of time might be considered. Above all, fair play and respect for opponents are ethical values that should be encouraged (McCrory et al., 2017). MMA companies could award the fair play of the night instead of, or in addition to, other bonuses (e.g. performance of the night and fight of the night), especially due to the extra strikes and impacts that a fighter experiences unnecessarily after the loss of consciousness in MMA (Hutchison et al., 2014).

3.5.3. Education, Behavior Changes, and Specificity to Evolve

The periods of suspension imposed by commissions following an official fight have no effect on the athlete's training routine (Neidecker et al., 2019), which reinforces the need to educate those directly involved with fighters' training. To date, there is no study showing whether MMA athletes and coaches actually possess any level of knowledge of aspects related to head trauma, brain injury or concussion, which could potentially impact the long-term health status of these athletes. Athletes are an essential part of this education program since the minority reported symptoms of concussion to their coaches in order to keep the training routines (McDonald et al., 2016). Therefore, not only an educational program is needed, but also the urgency for a behavioral change.

The training routine of MMA athletes is likely to include KO and TKO episodes (Heath & Callahan, 2013). Sixty percent of MMA athletes who declared experiencing a concussive event during training returned to competition within a few days, while only 13% sought medical attention (Heath & Callahan, 2013). Moreover, each previous concussion seems to be associated with an increased risk of a next similar event

(Hutchison et al., 2014; Neselius et al., 2015; Zehr & Wright, 2016). Rigorous supervision during training would be recommended, since subconcussive injuries are likely to occur countless times in the 2.5 to 12 weekly sparring sessions reported by MMA athletes (Amtmann, 2004; Heath & Callahan, 2013).

A structured and detailed sport-related concussion record is highly recommended and should include specific information as to previous symptoms of a concussion, length of recovery as well as information about all previous head, face or cervical spine injuries (McCrory et al., 2017). It should also consider the potential differences in concussion rates and recovery between males and females (McDonald et al., 2016), and the imminent influence of the weight category on the head trauma risk and severity, as shown in the present study. Finally, the King-Devick test (Galetta et al., 2011), the Fight Exposure Score (Bernick et al., 2015), and computerized neuropsychological testing (Neidecker et al., 2019) are practical alternatives to diagnose and follow-up after concussive events in MMA, even though brain injury can be present without measurable cognitive impairment (Neselius et al., 2014).

The MMA continues to experience public growth and attracts the attention of medical associations concerned about the safety of the sport (Hutchison et al., 2014; Lockwood et al., 2018; Lystad et al., 2014; Neidecker et al., 2019). However, the majority of the conclusions concerning brain injury and concussion in the literature are still made based on studies with American-style football male players (Mainwaring et al., 2018; Manley et al., 2017), in which the rates of impacts to the head are already known for differing according to the position on the field (Slobounov et al., 2017). Similarly, the sex and weight category must be taken into account for future investigations and recommendations as regards to head trauma analysis in MMA. Ultimately, it is crucial that MMA athletes, coaches, and staffs be educated and follow the guideline for concussion management and return to sport specifically designed to combat sports (Neidecker et al., 2019).

3.5.4. Limitations

Among the limitations of this study, the severity of any injury was not determined. Even though the referee stoppage due to head strikes is a relevant indicator of potentially applied brain injury mechanism, it was not possible to assess the acute and chronic symptoms of sport-related concussion. In addition, the fighters' age and previous KO history were not included in the analysis, which would incorporate relevant elements in the investigation.

3.6. Conclusion

The present study emphasizes the need to consider both sex and weight class when analyzing the incidence of exposure to head trauma in MMA and its severity. The lightest categories were those in which athletes were potentially more susceptible to receive repetitive subconcussive blows to the head. The male middleweight, light heavyweight, and heavyweight categories presented increased incidence and risk of a match-ending with an athlete either unconscious or unable to defend himself. Females presented the same pattern, albeit further evaluation is recommended as regards to specific symptoms, protocols, and recommendations following head trauma in female MMA athletes.

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Chapter 4 - Understanding Concussion Knowledge and Behavior Among Mixed Martial Arts, Boxing, Kickboxing, and Muay Thai Athletes and Coaches[3]

4.1. Abstract

Objectives: In combat sports, strikes to the head are not just incidental but a deliberate and clear determinant of success. Concussion is a complex injury that is poorly understood and inappropriate practices are often observed among athletes and coaches. The purpose of this study was to investigate concussion knowledge and behavior as well as address recommendations for combat sports athletes and coaches. Methods: 70 athletes and 35 coaches from combat sports disciplines completed an online validated survey and personal questionnaire about concussion knowledge, training experience and knowledge translation. Athletes were divided into subgroups for analysis according to sex (male n=55, female n=15), skill level (amateur n=52, professional n=18), and weight classes (<66.2kg: n=25, 66.6 to 77.5kg: n=30, and >78kg: n=15). Results: The likely absence of healthcare professionals during training was confirmed by 68.5% of coaches, and athletes declared that self-diagnosis (79%) and coaches' diagnosis (43.3%) were the most used method of suspected concussion assessment. Merely 5.7% of coaches properly recognized the level of traumatic brain injury a concussion represents, 68.8% were unfamiliar with any sideline assessment tools, and only 14.3% often seek out concussion knowledge. Athletes who were aware of the level of brain injury a concussion represents performed fewer sparring sessions per week (mild: 1.27±1.1; severe: 3.17±2.81; p=.05, *d*=.89) and had a greater likelihood

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[3] Follmer, B., Varga, A. A., Zehr, E. P. (2020) Understanding concussion knowledge and behavior among mixed martial arts, boxing, kickboxing, and Muay Thai athletes and coaches, *The Physician and Sportsmedicine*, 48:4, 417-423, doi:10.1080/00913847.2020.1729668

of reporting concussive episodes. Most professional (55.5%), female (54.5%), and under 66.2kg (50%) athletes returned to full practice within one week following a concussion diagnosis. Conclusions: Relevant key gaps of knowledge and behavior were suggested in combat sports athletes and coaches. The awareness of basic concepts may improve injury reporting and safer behavior in athletes. Knowledge translation strategies with accessible language are recommended for coaches, in particular on how to identify acute symptoms and perform basic assessment.

Keywords: Head injuries; brain concussion; traumatic brain injury; leadership; knowledge translation.

4.2. Introduction

Although classified as a subset of mild traumatic brain injury, concussion is an evolving and serious injury that must be addressed appropriately (Harmon et al., 2019; Saffary et al., 2012). In sports-related concussion, the complexity for a diagnosis (Carney et al., 2014; Harmon et al., 2019; Kamins et al., 2017), resistance to seeking medical assistance (Heath & Callahan, 2013), gaps of knowledge (Bennett et al., 2019; Lystad & Strotmeyer, 2018), and poor behavior (Delaney et al., 2018; Saffary et al., 2012) contribute to the increased likelihood of subsequent injury with potentially devastating consequences (Harmon et al., 2019; McCrory et al., 2017; Yrondi et al., 2017). The issue becomes exponentially more critical when addressing combat sports (e.g. boxing, Muay Thai, and Mixed Martial Arts), where head impacts are not just injuries in passing, but common features in everyday practices (Follmer et al., 2019; Nalepa et al., 2017; Neidecker et al., 2019).

While the management of head injuries during combat sports competition are typically performed by the attending ringside physician (Nalepa et al., 2017; Neidecker et al., 2019), the lack of documented medical monitoring during training sessions often puts coaches in the position of managing concussion (Neidecker et al., 2019). Given the role they are often forced to fulfil, it is a concern that coaches are less qualified than health professionals to recognize and treat a concussion (Lystad & Strotmeyer, 2018). This becomes even more problematic when combined with poor behavior of athletes who often prefer not to report symptoms so as to avoid being removed from practices (Bennett et al., 2019; Delaney et al., 2018; McDonald et al., 2016), and common factors such as fatigue (Coswig et al., 2016; Ghoul et al., 2017) that can contribute to confusion regarding concussion symptoms (Carney et al., 2014; Combs et al., 2019).

Given the complexities of concussion recognition, factual knowledge about concussion may help generate a positive understanding and perspective among athletes and coaches (Bennett et al., 2019; Lystad & Strotmeyer, 2018; Neidecker et al., 2019). While combat sport athletes have a low self-perceived knowledge and show gaps, such as poor understanding of acute symptoms, confusion about the terms used to describe head injury, and a lack of reliability for self-reported episodes (Bennett et al., 2019; Lystad & Strotmeyer, 2018), information involving coaches remains unknown. Coaches who are able to adequately identify the most prevalent and consistent indicators of a concussion (e.g. self-reported symptoms and decreases in cognition, memory, and balance), commonly assessed through practical assessment tools (Albicini & McKinlay, 2018), could reduce the risk of subsequent and serious injuries by referring athletes to medical evaluation.

Thus, there remains a need to further investigate awareness concerning concussion in combat sports. Analysis of athletes should be as specific as possible (Carney et al., 2014; Sicard et al., 2018), whereas it is important to explore what coaches are doing to enhance their knowledge. The purpose of this study was to comprehensively investigate concussion knowledge, behavioral practices, and knowledge translation components among combat sports athletes and coaches.

4.3. Materials and Methods

4.3.1. Participants

Combat sports athletes and coaches within the disciplines of kickboxing, Mixed Martial Arts, boxing, and Muay Thai were the target audience of this study. The first approach of recruitment was through public social media advertisement and email contact with combat sports gyms, associations, athletic commissions, clubs, and other potential institutions. Personal contacts with proven experience and activity in one of the targeted modalities were directly contacted by the team of researchers. To be eligible for the study, athletes and coaches were required to be at least 18 years old and involved in regular training sessions or sanctioned fights within the last two years to be considered active (Lystad & Strotmeyer, 2018). Upon further interest, the specific (i.e. athlete or coach) online document was sent via an electronic link or a personal email. Recruitment and data collection lasted three months.

4.3.2. Materials and Procedures

The online survey included two components: the Rosenbaum Concussion Knowledge and Attitudes Survey – Student Version (RoCKAS-ST) (Rosenbaum & Arnett, 2010) (Appendix A) and a personal questionnaire. Both components were hosted on the online Google Forms platform (Google LLC, Mountain View, CA, USA). A letter of information for implied consent was provided and completion and submission of the questionnaire indicated free and informed consent. The study was approved by the local University's Human Research Ethics Board (protocol number: 18-1115).

The RoCKAS-ST Concussion Knowledge Index (CKI) score, from 0 to 25, is calculated based on correct true/false answers and the accurate identification of symptoms. A higher CKI score is indicative of a greater knowledge. The Concussion Attitude Index (CAI) ranges from 15 to 75. The responses to each of the 15 items are listed on a 5-point Likert scale from “strongly disagree” to “strongly agree”, with a higher score representing a safer attitude towards concussion. Athletes completed both the CKI and CAI, whereas coaches responded only questions related to the CKI.

The athlete personal questionnaire (Appendix B) consisted of 26 questions about demographic and personal characteristics, training experience, history of concussion, and knowledge translation. For the coaches, 30 questions were divided in 3 sections (demographics, coaching experience, and knowledge translation) (Appendix C). The results of questions in which multiple choices were allowed do not add up to 100%. Athlete primary weight class (i.e. most often competed in the last two years) was obtained and categories were aggregated in three groups based on the head trauma exposure profile in competition (Follmer et al., 2019). Weight class (WC) 1 included athletes under 66.2 kg, WC2 from 66.6 kg up to 77.5 kg, and athletes above 78kg were in WC3.

4.3.3. Statistical Analysis

Statistical analysis was performed using SPSS (v.17.0; SPSS Inc., Chicago, IL, USA). Descriptive statistics were used to present absolute and relative outcomes. The assumptions of normality and homogeneity of variances were assessed via Shapiro–Wilk and Levene’s tests, respectively. Comparisons were mainly made between athletes according to sex, skill level, and weigh category. For normally distributed data, t-tests were performed between two independent groups, with ANOVA and Bonferroni post-hoc analysis used to compare three groups. Non-parametric data was verified via Mann Whitney test for two groups or Kruskal Wallis' with Tamhane post-hoc analysis for three groups comparisons. Correlation analysis was performed based on Pearson's coefficient. An alpha level ≤0.05 was set for all analyses, and Cohen's *d* was calculated for effect size estimation (Sullivan & Feinn, 2012).

4.4. Results

4.4.1. Demographics and Training Information

From 114 initial responses, 4 athletes were excluded due to age and 5 by not being considered active. The descriptive demographic data of 70 combat sports athletes and 35 coaches is presented in Table 4.1. The modalities athletes declared to have competed in and coaches were involved with were kickboxing (70 and 74.3%), Muay Thai (62.9 and 60%), boxing (57.1 and 60%), and Mixed Martial Arts (38.6 and 37.1%). While 94.3% of the coaches had previous competitive athletic experience, 68.6% of athletes were currently involved in combat sports coaching activities, especially female (80%) and professional (94.4%) fighters. Most athletes (73%) had over 5 years of combat sports training and more than 10 career fights (72.9%), while 60% of coaches had more than 10 years of experience coaching athletes at professional (45.7%), international (14.3%), national (17.1%), provincial (5.7%), regional (2.9%), and recreational (14.3%) levels.

Table 4.1 Absolute and relative (%) frequencies of demographic data from participants

Athletes (n=70)		Coaches (n=35)	
Sex		**Sex**	
Male	55 (78.6)	Male	29 (82.9)
Female	15 (21.4)	Female	6 (17.1)
Skill Level		**Age (yo)**	
Amateur	52 (74.3)	25 to 34	12 (34.3)
Professional	18 (25.7)	35 to 44	13 (37.1)
Weight Class		Older than 45	10 (28.6)
1 (under 66.2kg)	25 (35.8)	**Highest level of education**	
2 (66.6 > 77.5kg)	30 (42.8)	Less than high school	1 (2.9)
3 (above 78kg)	15 (21.4)	High school diploma	8 (22.9)
Age (yo)		Incomplete college	8 (22.9)
18 to 24	8 (11.4)	Undergraduate degree	10 (28.6)
25 to 34	48 (68.6)	Graduate degree	8 (22.9)
35 to 44	13 (18.6)	**Locality**	
Older than 45	1 (1.4)	North America	31 (88.6)
Locality		Oceania	2 (5.7)
North America	64 (91.4)	Europe	1 (2.9)
Oceania	4 (5.7)	Asia	1 (2.9)
Europe	2 (2.9)		

Athletes and coaches declared 2.1±1.7 (range 0-10) and 1.9±0.8 (range 1-5) sparring sessions per week, respectively, with no differences between athlete subgroups. Male, amateur, WC1, and WC3 athletes declared a range of 0-10, whereas females, professionals, and WC2 declared 0-4 weekly sparring sessions. Athletes and coaches rated the intensity of strikes to the head during regular sparring sessions as extremely light (5.7% and 0%), light (21.4 and 37.1%), moderate (64.3 and 54.3%), and heavy (8.6 and 8.6%), with no differences between athlete subgroups. A correlation was found between frequency and intensity of sparring sessions for males ($p<.01$, $r=.40$), amateurs ($p<.01$, $r=.45$), WC1 ($p<.01$, $r=.51$), and WC2 athletes ($p=.03$, $r=.37$).

Coaches declared that their athletes always (31.4%), often (20%), sometimes (17.1%), almost never (22.9%), or never (8.6%) use protective headgear during sparring sessions. Among the 40% of the coaches who believe that headgear can protect athletes from a concussion, only 50% of those coaches always require its use.

4.4.2. Concussion Knowledge Scores

The CKI of athletes and coaches, and athletes' CAI are presented in Figure 4.1. No differences were found between scores when comparing athlete subgroups.

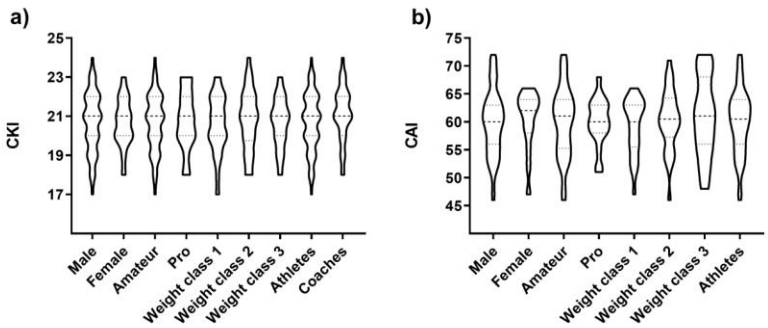

Figure 4.1 Participants Concussion Knowledge Index (CKI) (a) and Concussion Attitude Index (CAI) (b)

Self-perceived knowledge about concussion was obtained using a scale from 0 (nothing) to 10 (excellent). Female athletes rated their knowledge higher than males, the only significant difference between the subgroups (Table 4.2). Coaches' score was positively correlated with CKI ($p<.01$, $r=.52$), whereas no correlation was found in the other subgroups.

Table 4.2 Self-perceived knowledge about concussion in combat sports athletes and coaches

	Mean±SD	**Range**	**95%CI**
Male (n=55)	5.89±1.82*	1 - 10	5.39 – 6.38
Female (n=15)	6.93±1.57	2 - 8	6.05 – 7.8
Amateur (n=52)	6.05±1.96§	1 - 10	5.51 – 6.60
Pro (n=18)	6.22±1.26	3 - 8	5.59 – 6.85
Weight class 1 (n=25)	6.24±2.22#	1 - 10	5.32 – 7.15
Weight class 2 (n=30)	5.93±1.61	2 - 8	5.32 – 6.53
Weight class 3 (n=15)	6.2±1.42	3 - 8	5.41 – 6.98
Athletes (n=70)	6.1±1.8	1 - 10	5.67 – 6.52
Coaches (n=35)	6.54±1.46	4 - 10	6.04 – 7.04

*Different from Female ($p=.04$; $d=.61$); §Compared with Pro ($p=.74$; $d=.1$); #Compared with Weight classes 2 and 3 ($p=.81$).

Professional athletes (11.2%), WC2 fighters (10%), and coaches (5.7%) showed the lowest percentage of the correct response (i.e. mild) when questioned “what level of brain injury do you think a concussion is?” (Figure 4.2). Further analysis revealed that athletes who are properly aware that a concussion represents a mild traumatic brain injury reported fewer sparring sessions per week (range 0-3) compared to those who responded severe (range 0-10) (mild: 1.27±1.1, 95%CI: 0.53 – 2.01 vs severe: 3.17±2.81, 95%CI: 1.73-4.62; p=.05, *d*=.89).

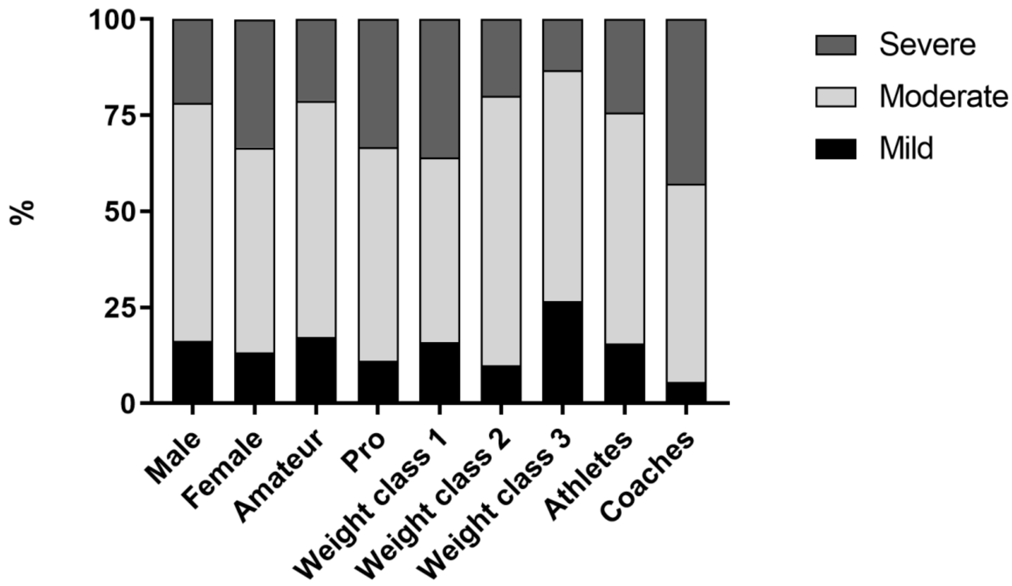

Figure 4.2 Distribution of responses for the level of brain injury a concussion represents

4.4.3. Concussive Episodes and Training Practices

Almost all the athletes who answered a concussion is a moderate (97.6%) or severe (94.1%) brain injury reported they had not had any concussive episodes in the past year, while this proportion dropped to 63.6% of those who responded mild. Similarly, the percentage of individuals having reported the occurrence of a concussion in their entire career was higher in the mild group (63.6%) compared to the moderate (45.2%) and severe (52.9%).

Essentially half of the coaches (51.4%) reported having athletes with at least one episode of diagnosed concussion in training, and 31.4% witnessed the occurrence of loss of consciousness. More athletes declared episodes of suspected (72.9%) than diagnosed (50%) concussion, where self-diagnosis (79%) was the most used method of suspected concussion assessment, followed by the coach diagnosis (43.3%), other staff member (24.5%), and other teammate (22.6%) (multiple responses were allowed).

Coaches confirmed that the presence of a licensed health professional during training sessions is rare (never or almost never: 68.5%; sometimes: 22.9%; often: 8.6%), unlike during competition (always: 85.7%). Medical clearance (94.3%) was the most common criterion to decide whether an athlete who was diagnosed with a concussion should return to full practice, followed by coach evaluation (54.3%), athlete self-reported symptoms (51.4%) and the use of a recognized return to fight protocol (34.3%). Return to full practice within one week of the concussion diagnosis was declared by 41% of athletes, and the proportion was higher among professional (55.5%), female (54.5%), and WC 1 (50%) fighters.

4.4.4. Knowledge Translation

Athletes indicated coaches as their main source (70%) to gather knowledge about concussion, followed by mass media (64.3%), teammates (54.3%), scientific journals (42.9%), and workshops/seminars (18.6%). However, 31.4% of coaches declared never or almost never getting information to increase knowledge about concussion, whereas 54.3 and 14.3% do it sometimes or often, respectively. They indicated lack of time (51.4%), inability to access (51.4%) and interpret (42.9%) academic research, sport science literature is not user friendly (34.3%), lack of interest (14.3%), and lack of money (5.7%) as the main barriers to acquiring evidence-based knowledge about concussion. Colleagues (65.7%), mass media (57.1%), and textbooks (54.3%) were indicated by coaches as their main sources of information about concussion.

For 80% of the coaches, educational videos lasting 3 to 5 min (42.9%), 2 to 3 min (25.7%), more than 5 min (22.9%), or 1 to 2 min (8.6%) would be the most effective method for translating scientific literature. Computer based learning programs (68.6%), interactive oral presentations (54.3%), and educational infographic (40%) were also cited. Coaches have declared their interest in some specific topics to be educated on (Figure 4.3a), and their level of familiarity with the sideline assessment tools for concussion (Figure 4.3b).

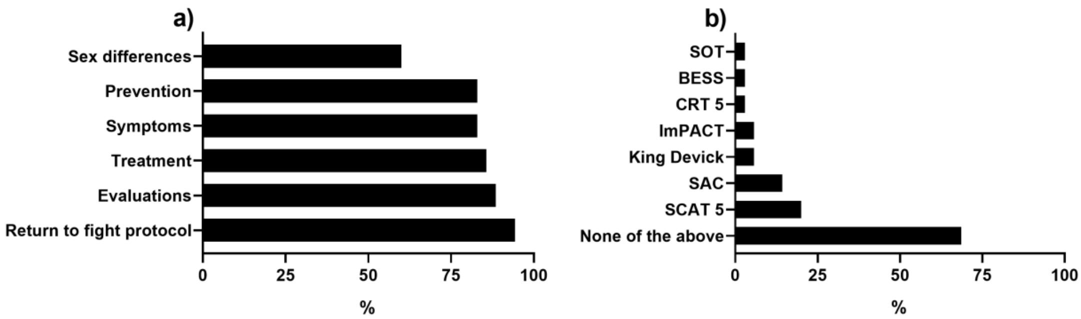

Figure 4.3 Educational topics of interest (a), and the instruments to assess concussion which combat sports coaches are familiar with (b)

4.5. Discussion

This study suggests that respondent coaches in combat sports were often involved in concussion management due to the rare presence of healthcare professionals during practice. However, significant knowledge gaps were identified, and respondent coaches stated that they rarely seek information from reliable sources. Alarmingly, combat sports athletes indicated coaches as their primary source of concussion knowledge. Knowledge gaps and poor behavior were observed in some of the athlete subgroups.

4.5.1. Concussion Knowledge and Behavior

Participants achieved high scores in the RoCKAS-ST survey (i.e. CKI and CAI), without difference among athlete subgroups, as previously seen in Muay Thai fighters (Lystad & Strotmeyer, 2018). Despite high reliability demonstrated elsewhere (Caron et al., 2018; Rosenbaum & Arnett, 2010), both the CKI and CAI are insensitive in discriminating knowledge and attitude levels among combat athletes. Self-reported knowledge scores were also relatively high, as previously seen with other athletes (Bennett et al., 2019). However, this is the first study to perform subgroup analysis.

The accuracy and level of updating of some CKI questions deserve consideration. The supposedly true statement “an athlete who gets knocked out after getting a concussion is experiencing a coma” should be viewed with reservations because of its wording in regards to concussion diagnosis (Carney et al., 2014) and coma assessment (Teasdale et al., 2014). Also, “after 10 days, symptoms of a concussion are usually completely gone” is supposedly true, yet objectively outdated. Although prevalent and consistent indicators of concussion are observed particularly within the first couple of days after injury (Carney et al., 2014), the majority of injured athletes recover, from a clinical perspective, within the first month of injury (McCrory et al., 2017). Moreover, considering this item as true might potentially translate into a false generalization given the consensus that physiological recovery extends beyond the clinical (Carney et al., 2014; Kamins et al., 2017; McCrory et al., 2017). For the CAI, the ease in recognizing the safest response for each question is likely the reason for high scores in this study and others (Caron et al., 2018; Lystad & Strotmeyer, 2018).

Knowledge may not necessarily transfer to proper behavior (Delaney et al., 2018), and it was highlighted here when female athletes rated their perceived knowledge higher than males but have shown questionable behavioral practices. Professional, female, and WC1 fighters reported the highest likelihood of returning to full practice within a week of a diagnosed concussion. Our data adds to others who also suggest an incidence of a likely premature return to practice after a head injury (Bennett et al., 2019; Heath & Callahan, 2013). While motivation of professional fighters for a quick return appears to be mainly intrinsic, (e.g. career aspirations and desire to win) (Bennett et al., 2019), female motivation is associated with the perception that the injury was not serious and the desire not to be removed from practice (McDonald et al., 2016). Early return to sport can be especially dangerous for lighter and female athletes, as they are often exposed to more blows to the head and for a longer duration in official bouts (Follmer et al., 2019; Miarka et al., 2016). Women are also shown to present greater short-term impairment (Covassin et al., 2007) as well as more persistent alterations in executive function (Sicard et al., 2018) and autonomic nervous system disruption (Hutchison et al., 2017) following a concussion compared to men.

A greater incidence of suspected than diagnosed concussion was suggested, reinforcing the concept that athletes fail to seek medical attention (Delaney et al., 2018; Heath & Callahan, 2013). In this sense, a coach must use the lead role to inform athletes that concussion symptoms should not be overlooked or hidden, the “toughness” culture need to be avoided, and the habit of not seeking medical care abolished (Heath & Callahan, 2013; Saffary et al., 2012).

4.5.2. Sparring and Training Practices

Sparring is a common type of training session where combat sports athletes simulate a real fight featuring moderate to high-intensity movements (Coswig et al., 2016; Ghoul et al., 2017), representing a high likelihood of head trauma (Heath & Callahan, 2013; Ravdin et al., 2003). The indicated overall moderate intensity of the strikes to the head contributes to understanding why the training routine in combat sports is a cause of concern. Although a subjective measure, the self-assessment of head strike intensity can be a useful tool to control sparring sessions, by matching intensity between training partners and avoiding unnecessary hardness. Also, most respondent coaches reported having at least one episode of an athlete experiencing a diagnosed concussion in training. Even without a specific force reference threshold for concussion (Harmon et al., 2019), it may be prudent for athletes and coaches to be educated as to the risks of excessive sparring in terms of frequency and intensity given that the exposure to countless mild and repetitive head impacts is detrimental to the nervous system (Fickling et al., 2019; Mainwaring et al., 2018).

A considerable proportion of the respondents believe that headgear shows significant protection against concussion. Despite that, however, only half of these coaches required its mandatory use in sparring. The inconsistency as to the efficacy of headgear may factor into why they do not always require their athletes to wear head protection. Headgear has been shown to lessen the transmitted impact and prevent skull trauma, intracranial bleeding, and cosmetic damage, but its effectiveness in preventing concussion has not been clinically proven (Harmon et al., 2019; McIntosh & Patton, 2015; Saffary et al., 2012). Concern also exists that the use of protective equipment in sport encourages more aggressive actions which paradoxically increase the potential for injury (Hagel & Meeuwisse, 2004; Harmon et al., 2019).

Although the healthcare professional should provide guidance on acute evaluation and return to practice (Harmon et al., 2019), their absence in training sessions confirms that coaches are often in the position of managing concussions in combat sports (Neidecker et al., 2019). Moreover, training time far exceeds competition time, which allows countless opportunities for head injuries in practice. However, 68.6% of the combat sports coaches were not familiar with any sideline assessment tool used to monitor the most prevalent indicators of a concussion (Albicini & McKinlay, 2018; Carney et al., 2014). The instrument participants were more familiar with was the Sport Concussion Assessment Tool 5, a comprehensive sideline assessment but designed for use by physicians and licensed healthcare professionals (Albicini & McKinlay, 2018; McCrory et al., 2017). The suitable options for coaches, which do not rely on a medically trained appraiser (Albicini & McKinlay, 2018; McCrory et al., 2017), were familiar to a vast minority of the sample. For instance, the King-Devick test is a simple, accurate and reliable method (Albicini & McKinlay, 2018), even used in combat athletes (Galetta et al., 2011), albeit recognized by 5.7% of the coaches. Also, the Balance Error Scoring System is an accessible and sensitive test to detect balance impairment after a concussive episode (Albicini & McKinlay, 2018; Bell et al., 2011) but familiar to merely 2.9% of the respondent coaches.

Sideline evaluations are a critical early measure to identify a high-risk individual who could be protected from further injury (Harmon et al., 2019; Saffary et al., 2012). If properly educated and trained, coaches in combat sports modalities could provide the first screening of symptom checklist, cognitive and balance assessments following a potential concussive event (Harmon et al., 2019). Special attention must be given to the influence of aspects such as non-pathological transient features (e.g. fatigue) (Carney et al., 2014; Combs et al., 2019) and sex (Combs et al., 2019) in test results and in symptom reporting.

4.5.3. Future Directions

Our study indicated that athletes and coaches are frequently involved with the suspected concussion assessment (Neidecker et al., 2019). At issue are the suggested significant gaps of knowledge athletes have displayed here and elsewhere (Bennett et al., 2019; Lystad & Strotmeyer, 2018) and the shortage of investigation with combat sports coaches. For instance, difficulty speaking, panic attacks, and reduced breathing rate were highly indicated by athletes and coaches as symptoms likely to be experienced after a concussion, yet these are not typical indicators of concussion (Carney et al., 2014; Rosenbaum & Arnett, 2010). This draws attention to the possible confusion between acute symptoms and the potential chronic effects of successive head injuries, often related to mental health, emotional disturbances, and chronic diseases (Langlois et al., 2006; McCrory et al., 2017; Saffary et al., 2012; Yrondi et al., 2017).

The inclusion of relevant definitions has been suggested to improve the accuracy of reports of prior head trauma (Bennett et al., 2019). Our results showed that only 15.7 and 5.7% of combat sports athletes and coaches, respectively, were aware that a concussion represents a mild traumatic brain injury. Further analysis revealed that the athletes who responded correctly have declared more concussive episodes in the past year and less frequently that they have never had a concussion. Moreover, these athletes perform fewer sparring sessions per week compared to those who recognize a concussion as a severe traumatic brain injury. This suggests that by understanding a concussion as a mild injury, therefore more likely to occur, athletes would reflect this knowledge by reducing exposure in training.

A large proportion of coaches (42.9%), WC1 (36%), female (33.3%), and professional (33.3%) fighters acknowledged a concussion as a severe traumatic brain injury. The extent of the misconception concerning the level of traumatic brain injury a concussion represents is unknown and beyond this investigation. However, this could be at the root of the misunderstanding that a concussion occurs only after harsh episodes, such as those involving loss of consciousness. Therefore, it might be crucial to promote in combat sports the well-documented fact that a concussion usually does not involve loss of consciousness (Carney et al., 2014; McCrory et al., 2017).

While most athletes declared coaches as their primary source of information about concussion, coaches rely commonly on colleagues and mass media, and have stated that gaining knowledge about concussion is not a regular practice. Coaches confirmed the difficulty with scientific literature access and interpretation (Pope et al., 2015). Using popular media as a source should be viewed with caution due to its inconsistent (Berg et al., 2014) and inappropriate (Zehr & Wright, 2016) representations of concussion. Therefore, athletes obtain information from coaches, but coaches present significant gaps and rarely seek knowledge from reliable sources. Alternatively, the Association of Ringside Physicians (Neidecker et al., 2019) have been providing a scientific-based, though accessible approach to concussion management in combat sports. Results from the present study might provide insightful and specific subgroup information to better address educational strategies for combat sports athletes. Also, brief educational videos ranging from 2 to 5 min and computer-based learning programs appear to be the preferred methods by coaches.

The results of the present study may be considered preliminary until a more representative sample is investigated. Given the recruitment methods applied (e.g. email and social media), the true potential sample size could not be estimated and there is a plausible bias that the most educated individuals volunteered to participate. Nevertheless, athlete demographics in this study were similar to previous studies that investigated concussion knowledge in combat sports athletes: mostly men, aged 25 to 34 and composed primarily of amateurs fighters (Bennett et al., 2019; Lystad & Strotmeyer, 2018).

4.6. Conclusion

Coaches in combat sports are often forced into managing concussion, but fail to recognize symptoms and are unfamiliar with available evaluation tools. The acknowledgment that a concussion represents a mild traumatic brain injury might positively reflect on athlete knowledge and behavior. There is a need for a specific, reliable, and sensitive tool to assess awareness in this population, while female, professional, and lighter athletes who potentially need more education to improve knowledge and behavior. The risks of excessive sparring and the benefits and limitations of protective head equipment is also recommended for future educational efforts.

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Chapter 5 - Effects of Chronic Exposure to Head Impacts on the Balance Function of Combat Sports Athletes[4]

5.1. Abstract

We investigated static and dynamic balance in combat sport athletes chronically exposed to head impacts. MMA, boxing, kickboxing, and Muay Thai athletes exposed (AE: n=19; 14 men, 5 women; 30.2±4.5yrs; 1.76±0.1m; 75±9.2kg) to head impacts were compared to athletes non-exposed (AnE: n=25; 18 men, 7 women; 25.1±3.2yrs; 1.78±0.1m; 77.4±10.3kg), and control individuals (CON: n=23, 13 men, 10 women; 25.5±5.8yrs; 1.75±0.1m; 70.4±12kg). Static balance was assessed using the Balance Error Scoring System, and dynamic function by center of pressure shift and reactive object tracking. A low-cost balance board was used for both protocols. AE performed worse than CON (0.01±0.006 vs 0.006±0.003; p=0.02, d=0.75) in the ellipse area of sway for double-leg stance in firm condition ($F_{2,62}$=3.94, p=0.02, η^2=0.11). Static center of pressure and dynamic balance did not differ among groups. The integration of a balance board and a widely used clinical protocol unveiled differences in the ellipse area of static postural sway in the double-leg stance over a firm surface in athletes chronically exposed to head impacts. The combined use of practical, objective, and clinically relevant test protocols is encouraged to detect lasting deficits in static and dynamic balance as a result of chronic exposure to repetitive head impacts.

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5.2. Introduction

Concussion is often defined as a transient injury resulting in short-lived impairment of neurological function that often may resolve spontaneously (Harmon et al., 2019; McCrory et al., 2017). Unfortunately, this definition discounts the potential seriousness of concussion. In sports, although some studies do not show deficits in the long-term outcomes of collision sports (Deshpande et al., 2020; Savica et al., 2012), a history of head trauma is often associated with long-term neurological deterioration (Amen et al., 2011; Bernick et al., 2015; Casson & Viano, 2019; Martland, 1928) reflected in clinical features such as decreased cognitive and sensorimotor functions (Banman et al., 2021; Bernick et al., 2015; Cunningham et al., 2020; Mainwaring et al., 2018; Rawlings et al., 2020). While most clinical assessments focus on acute management of concussion, scientific interest has grown on practical tools to verify lasting damage associated with a history of concussion (Johnston et al., 2018; Reilly et al., 2020) or repetitive episodes of head impacts with no overt clinical symptoms (i.e. subconcussion) (Mainwaring et al., 2018; Rawlings et al., 2020).

A common practice for evaluating deficits of somatosensory, visual, and vestibular integration following a concussion is the use of balance tests (Bell et al., 2011). Results can rely on a subjective error counting system (e.g. the Balance Error Scoring System - BESS) (Bell et al., 2011) or on objective analysis like the center of pressure sway (Cavanaugh et al., 2005). Although balance impairments from acute head injuries may resolve within a few days (Guskiewicz, 2011), deficits in static balance can persist for years after a concussion (Reilly et al., 2020). This can also be seen in dynamic postural control, where athletes diagnosed with a concussion within the last two years presented deficits compared to a control group (Johnston et al., 2020). The evidence for effects of repetitive subconcussive head impacts on balance function after a competitive season of contact modalities is variable with findings supporting presence (Black et al., 2020) and absence (Murray et al., 2018) of alterations.

The effects on balance function of chronic exposure to repetitive head impacts remains largely unknown. While head injuries are commonly found in contact and collision sports modalities (McCrory et al., 2017), combat sports like boxing, kickboxing, Muay Thai, and Mixed Martial Arts (MMA) stand out (Follmer & Zehr, 2021). In addition to the high risk of competitive fights ending due to head traumas (i.e. with an athlete either unconscious or defenceless) (Follmer et al., 2019), there is the exposure to countless head impacts during training (i.e. 2 simulated fights per week) (Follmer et al., 2020).

While the link between exposure to head traumas and neurological damage in fighters is well established (Casson & Viano, 2019; Martland, 1928), early detection of long-term impairments using practical instruments could be clinically relevant. Therefore, the objective of this study was to investigate static and dynamic balance function in an athletic population chronically exposed to repetitive head impacts. It was hypothesized that balance function would be impaired in athletes chronically exposed to head impacts.

5.3. Materials and Methods

5.3.1. Participants

Sixty-seven participants from both sexes, 18 to 40 years of age, were recruited for this study and grouped as athletes exposed (AE) or non-exposed (AnE) to head impacts, and a control of non-athlete individuals without a history of chronic exposure to head impacts (CON) (Table 5.1). Athletes from AE and AnE had to be actively involved in regular training sessions or competition in their given sport within the last two years (Follmer et al., 2020). Participants from the CON group had no more than the 150-300 minutes per week of moderate- to vigorous-intensity physical activity recommended by the Canadian Society for Exercise Physiology (*Canadian Society for Exercise Physiology - Home*, n.d.).

Table 5.1 Participants' demographics

	Athletes Exposed (AE)	**Athletes non Exposed (AnE)**	**Control (CON)**	**Total Sample**
N (men/women)	19 (14/5)	25 (18/7)	23 (13/10)	67 (45/22)
Age (years)	30.2±4.5	25.1±3.2	25.5±5.8	26.7±5
Height (m)	1.76±0.1	1.78±0.1	1.75±0.1	1.77±0.1
Weight (kg)	75±9.2	77.4±10.3	70.4±12	74.3±11

AE participants were involved in combat modalities as MMA (n=5), boxing (n=10), kickboxing (n=7), and Muay Thai (n=1) for 10±5.5 years, with 15±14 amateur or professional fights. Their training consisted of 5.2±1 sessions and 11.2±4.9 hours per week. Seven participants reported a total of eight diagnosed concussions in a lifetime, while three others reported one episode each of a suspected concussion. Participants from AnE were involved in modalities such as rowing (n=5), triathlon (n=4), jiu jitsu (n=4), crossfit (n=4), weightlifting (n=3), volleyball (n=2), diving (n=1), running (n=1), and cycling (n=1) for 6.1±3.2 years. Their training consisted of 5.6±0.9 sessions and 14±5.7 hours per week. Twelve participants declared a training history, more than 3 years ago, in modalities with exposure to head impacts (i.e. rugby, hockey, kickboxing, football, lacrosse). Nine participants reported 14 diagnosed concussions in a lifetime, while one declared a single suspected concussion. Individuals from CON were involved in weekly moderate to vigorous physical activity for less than 60 min (n=2), 60 to 150 min (n=8), or 150-300 min (n=13), in activities such as jogging, soccer, biking, hiking, tennis, and weightlifting. Participants exercised 3.7±1 days a week and for 49.4±16 minutes per session. Seven participants reported one diagnosed concussion each in a lifetime, with no suspected concussions.

General exclusion criteria included having suffered a diagnosed concussion within the past three months (Fox et al., 2008; Guskiewicz et al., 2001) or experiencing any head impacts during the three days prior to assessment (Guskiewicz et al., 2001; McCrory et al., 2017). Any condition that might affect balance also resulted in exclusion. These included lower body injury (Fox et al., 2008), visual, vestibular or neurological disorder (Fox et al., 2008; McCrory et al., 2017), or any known metabolic disorder affecting somatosensation (i.e. diabetes) (Walley et al., 2014). Participants were required to abstain from caffeine intake (McNerney et al., 2014) and exercise on the day of examination to control for the effect of fatigue (Fox et al., 2008; Ghoul et al., 2017). All participants signed a consent form before performing data collection and completed a questionnaire with personal and demographical information according to their group. This study was approved by the University's Human Research Ethics Board (protocol 19-0434).

5.3.2. Balance Tests

A commercially available balance board (BB; Nintendo, Kyoto, Japan) was interfaced with a computer using customized software (LabVIEW 2011 National Instruments, Austin, TX, USA), and data sampled at 100 Hz (Holmes et al., 2013). Keeping in mind translation to future real-world use, the BB was chosen due to its accessibility, validity (r=0.99), reliability (ICC=0.88), and relatively low cost (Chang et al., 2014).

During the static balance task, participants performed one trial of 20s for each stance (i.e. double-, single-, and tandem-leg) of the BESS (Bell et al., 2011). All three stances were performed barefoot, with eyes closed, hands on the hips, and on the BB board (firm condition) and repeated with a medium density foam (Airex Balance Pad Elite 81002, 50.08 cm x 40.64 cm x 6.35 cm) placed over the BB (foam condition) (Figure 5.1). All participants confirmed that they had never performed the BESS protocol. Centre of pressure (CoP) was defined according to Winter (Winter, 1995) and calculated from the BB output. The excursion of CoP in the medio-lateral (CoP_{ML}) and antero-posterior

(CoP_{AP}) directions, as well as the total path length (CoP_T) were calculated (Appendix D). The area of sway was calculated from the 95% confidence interval of the ellipse (Reilly et al., 2020).

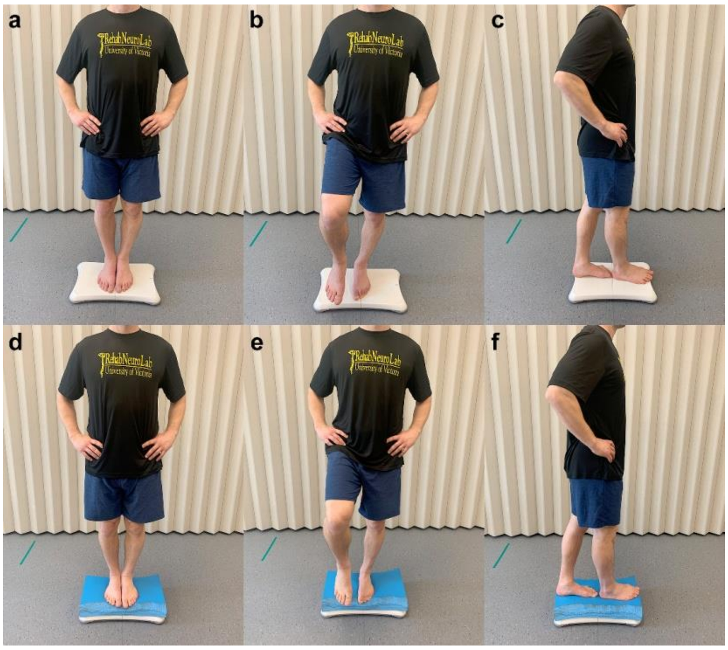

Figure 5.1 Double-, single-, and tandem-leg stances over the firm (a,b,c, respectively) and foam (d,e,f, respectively) conditions using the balance board

In the dynamic assessment, each participant stood barefoot on the BB, feet at shoulder width, eyes open, hands on the hips, in front of a laptop screen at chest height which displayed the CoP as a white dot. Upon the initiation of a trial, a target dot (red) appears on the screen and moves in random sequence among eight cardinal and ordinal directions (Figure 5.2). Participants were instructed to shift their weight on the BB so that the CoP meets the target on the screen as quickly and accurately as possible. Following the familiarization set, participants completed five trials (Black et al., 2020; Sun et al., 2019). The averaged time to reach target (tTarget), time to return to center from target (tCenter), and their computed sum (tTotal) were obtained and analyzed (Black et al., 2020; Sun et al., 2019).

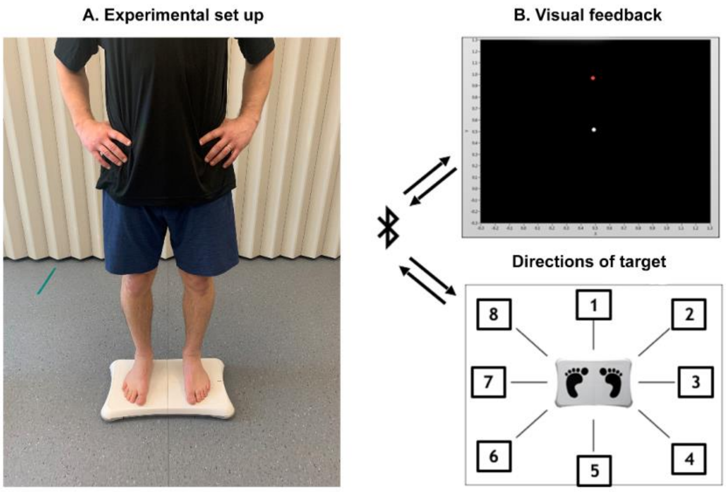

Figure 5.2 Participant position (a) and balance board setup (b) for the dynamic test. Participants shift their center of pressure (white dot) to match a target (red dot) (adapted from Sun et al., 2019)

5.3.3. Statistical Analysis

Statistical analysis was performed using SPSS (v.24, Armonk, NY: IBM Corp) with the level of significance set at $p<0.05$. Prior to comparisons, extreme outlier data points were excluded if they exceeded three magnitudes of the interquartile range beyond the first and third quartiles (Mowbray et al., 2018). Data normality and homogeneity of variances were tested using Shapiro-Wilk and Levene tests, respectively. Normally distributed variables were compared between the three groups via analysis of variance (ANOVA) and post-hoc of Tukey HSD. A Box-Cox method of transformation was performed when ANOVA assumptions were not met (Vélez et al., 2015), which was the case in the firm surface double-leg CoP_T and foam surface double-leg CoP_{ML}, CoP_{AP}, CoP_T, as well as single-leg CoP_{ML} and CoP_T.

5.4. Results

From 1206 data points collected (i.e. 67 participants x 3 stances x 2 conditions x 3 CoP variables), 21 outputs (1.75% from total) were identified as outliers (3 outputs from AE firm condition, 1 from firm and 5 from foam condition for AnE, and 6 data points in firm and foam conditions each for CON).

Figure 5.3 presents results from the static balance on the firm surface. No difference was observed between groups in the double-leg (CoP_{ML} ($F_{2,62}$=1.1, p=0.33, η^2=0.03), CoP_{AP} ($F_{2,62}$=1.34, p=0.26, η^2=0.04), CoP_T ($F_{2,61}$=2.72, p=0.07, η^2=0.08)), single-leg (CoP_{ML} ($F_{2,63}$=0.7, p=0.49, η^2=0.02), CoP_{AP} ($F_{2,63}$=0.34, p=0.71, η^2=0.01), CoP_T ($F_{2,63}$=0.32, p=0.72, η^2=0.01)), or tandem-leg stances (CoP_{ML} ($F_{2,64}$=0.74, p=0.48, η^2=0.02), CoP_{AP} ($F_{2,64}$=1.55, p=0.22, η^2=0.04), CoP_T ($F_{2,64}$=1.22, p=0.3, η^2=0.03)).

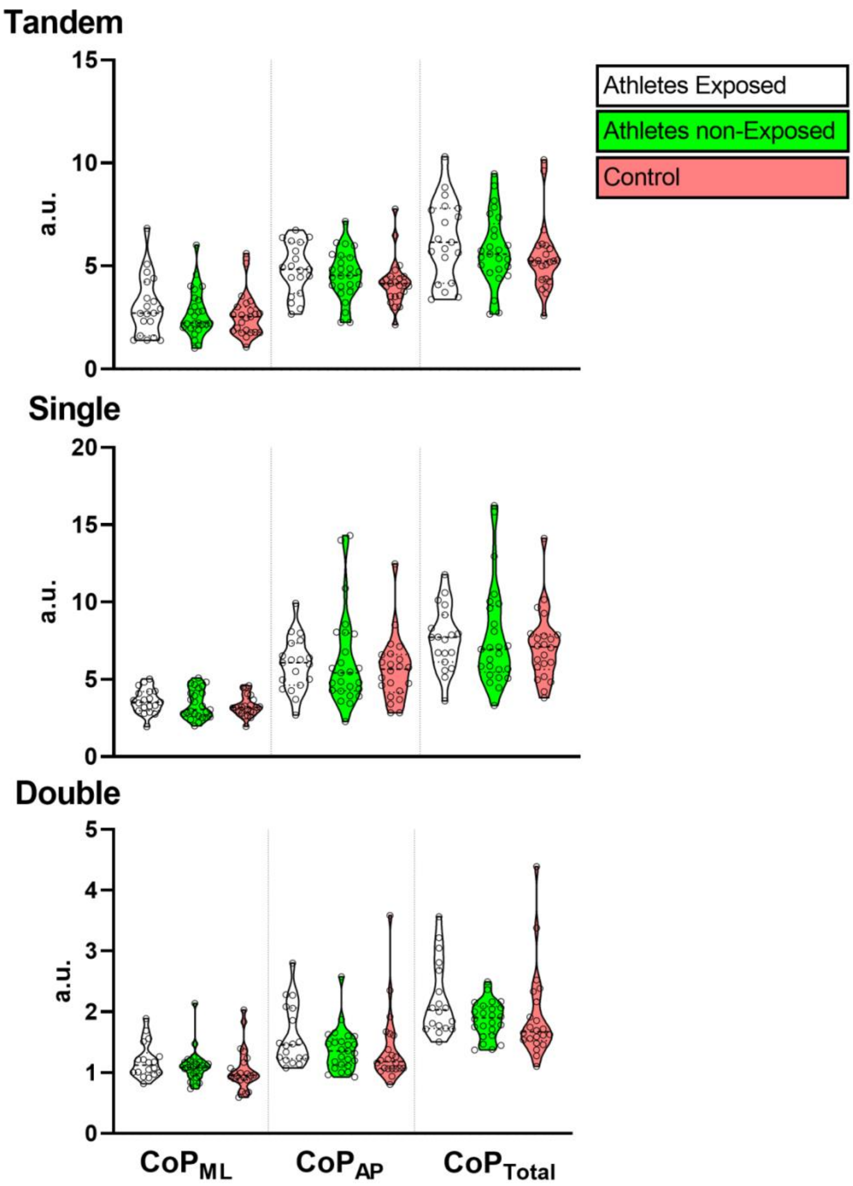

Figure 5.3 Static balance in double-, single-, and tandem-leg stances over a firm surface

Similarly, no differences were observed in the foam surface (Figure 5.4) in the double-leg (CoP_{ML} ($F_{2,64}$=0.16, p=0.84, η^2=0.0), CoP_{AP} ($F_{2,64}$=0.91, p=0.4, η^2=0.03), CoP_T ($F_{2,64}$=0.66, p=0.51, η^2=0.02)), single-leg (CoP_{ML} ($F_{2,63}$=0.48, p=0.62, η^2=0.01), CoP_{AP} ($F_{2,63}$=0.43, p=0.64, η^2=0.01), CoP_T ($F_{2,63}$=0.21, p=0.8, η^2=0.01)), or tandem-leg stances (CoP_{ML} ($F_{2,62}$=0.58, p=0.56, η^2=0.02), CoP_{AP} ($F_{2,61}$=0.14, p=0.86, η^2=0.0), CoP_T ($F_{2,61}$=0.05, p=0.94, η^2=0.0)).

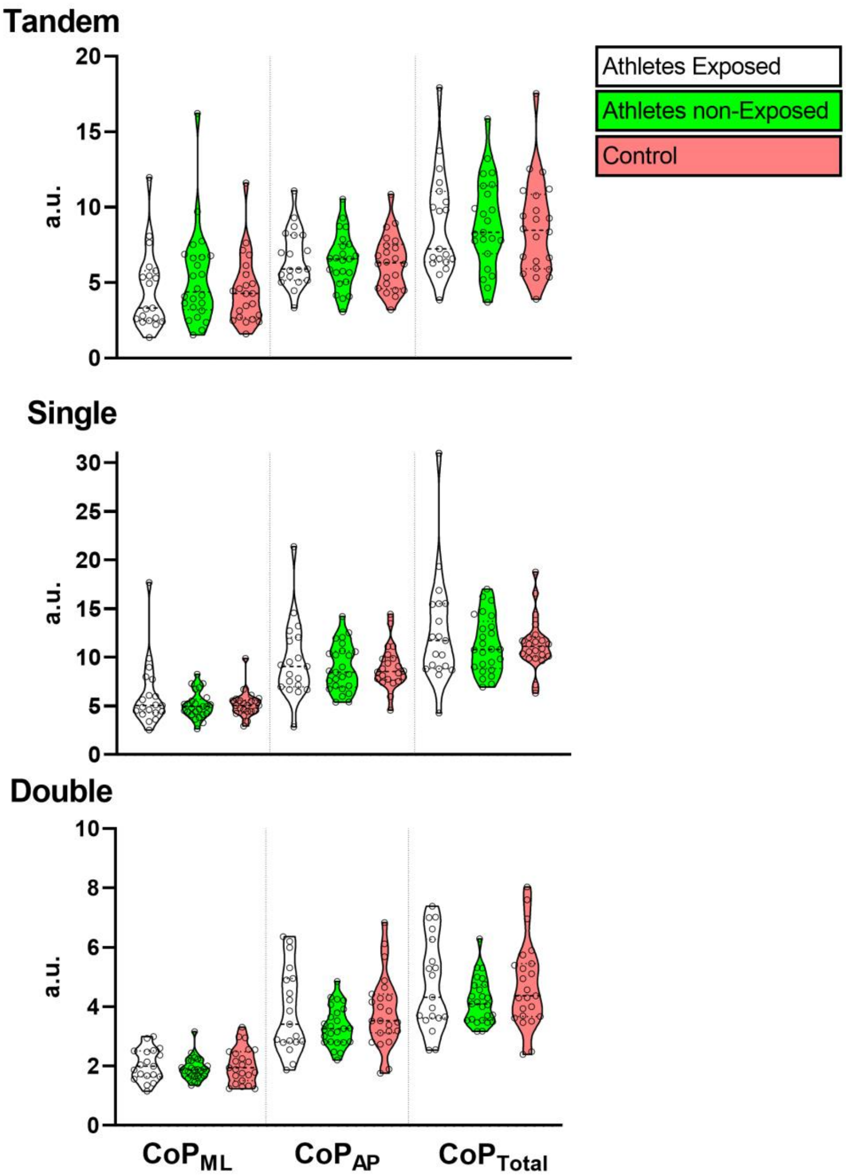

Figure 5.4 Static balance in double-, single-, and tandem-leg stances over a foam surface

The analysis of the area of 95% confidence ellipse revealed a difference in the double-leg stance firm condition ($F_{2,62}$=3.94, p=0.02, η^2=0.11), where AE had greater values than CON (0.01±0.006 vs 0.006±0.003; p=0.02, d=0.75) (Figure 5.5). No other difference was observed between groups (Firm condition single: $F_{2,61}$=0.34, p=0.71, η^2=0.01; and tandem-leg: $F_{2,62}$=0.49, p=0.61, η^2=0.01; Foam condition double: $F_{2,62}$=1.1, p=0.33, η^2=0.03; single: $F_{2,62}$=0.12, p=0.88, η^2=0.01; and tandem-leg: $F_{2,62}$=1, p=0.35, η^2=0.03).

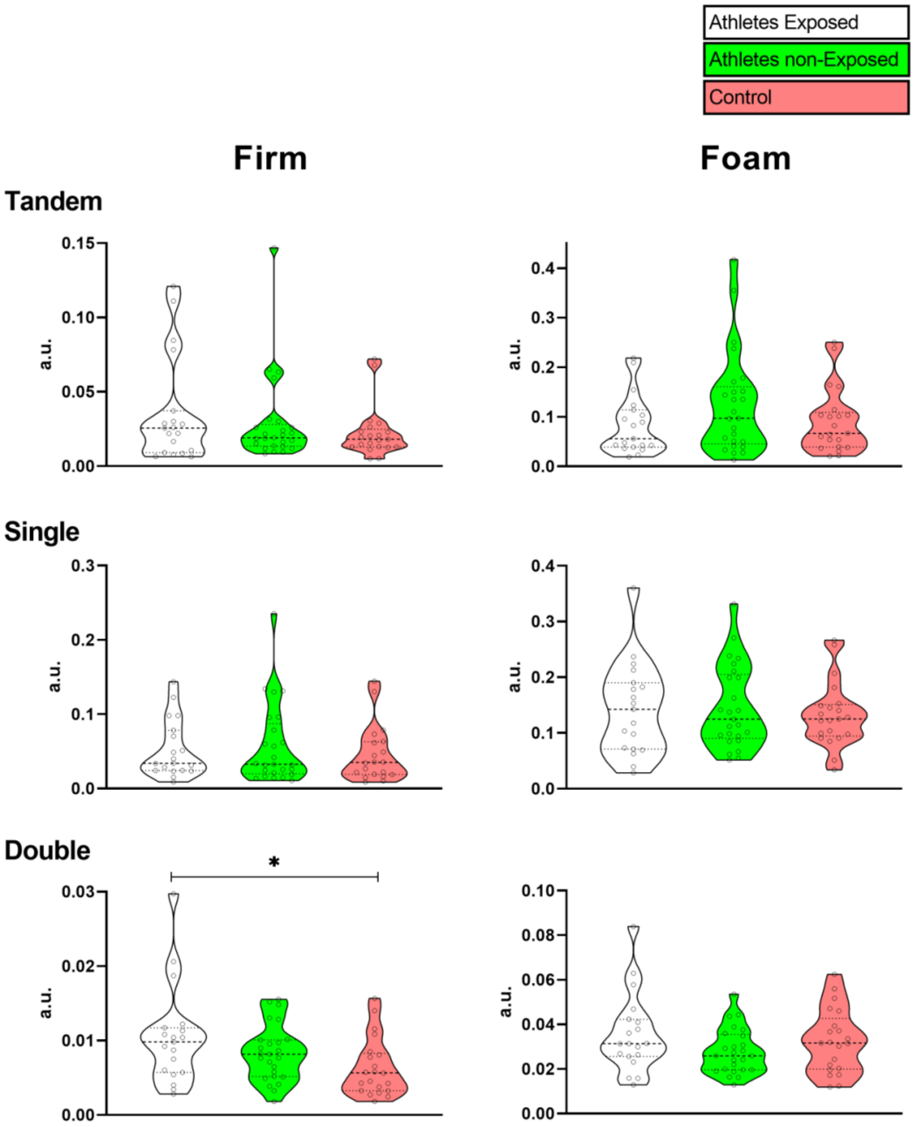

Figure 5.5 Ellipse area of sway in double-, single-, and tandem-leg stances over firm (left) and foam (right) surfaces

In the dynamic balance assessment, there were no differences between groups in tTarget ($F_{2,64}$=0.59, p=0.55, η^2=0.02), tCenter ($F_{2,64}$=2.35, p=0.7), or tTotal ($F_{2,64}$=0.67, p=0.51, η^2=0.02) (Figure 5.6).

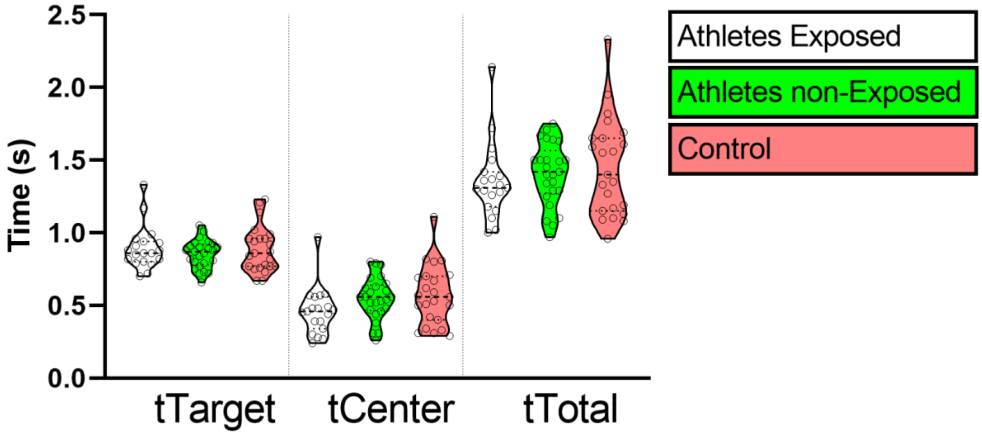

Figure 5.6 Dynamic balance performance in time to reach target (tTarget), return to center (tCenter) and total time taken (tTotal)

5.5. Discussion

This study used a practical and accessible tool to analyze the balance function of athletes chronically exposed to head impacts. While balance protocols have been mainly utilized acutely to determine if a concussion forced compensatory actions to maintain static postural stability (Reilly et al., 2020), deficits may accumulate with each additional injury (Murray et al., 2019). Athletes chronically exposed to repetitive head impacts presented greater elliptical area of static postural sway in the double leg stance in the firm condition compared to active control individuals. This adds to the literature showing similar deficits in the acute phase after a concussion (Dorman et al., 2015; Guskiewicz et al., 2001) and following a history of concussion (Reilly et al., 2020).

Variables from the static assessment (i.e. CoP path lengths and elliptical area) have been associated with poorer postural stability after a concussion (Guskiewicz et al., 2001; Reilly et al., 2020). Although only one variable in the present study showed statistical significance, a few particularities must be considered. The BESS protocol is widely performed by clinicians (Bell et al., 2011), recommended by specialists (McCrory et al., 2017), and it can provide useful information on the effects of subconcussions even in such a fundamental posture for humans (i.e. double-leg stance) when integrated with a portable and low cost balance board (Black et al., 2020). Moreover, our static protocol was composed by a single-task, whereas other studies detected similar outcomes only when performing double-task protocols (Carney et al., 2014; Dorman et al., 2015), which is believed to exacerbate stability deficits (Register-Mihalik et al., 2013). Although static balance may be seen as not sufficiently challenging and sensitive to detect changes in higher level athletes (Johnston et al., 2017), it remains to be investigated whether alternative protocols can reveal static balance impairments associated with chronic exposure to head impacts in an athletic population. Agility, coordination, and strength are fundamental aspects in the training routine of combat sport athletes (Andrade et al., 2019), which may have influenced the performance in the most challenging stances and conditions of the present study.

Besides dual-task situations, sensorimotor control deficits post-clinical recovery from concussion may be more pronounced during dynamic tasks (Johnston et al., 2017, 2020; Register-Mihalik et al., 2013). Additionally, repetitive head impacts may be associated with vestibulo-ocular deficits (Miyashita & Ullucci, 2020), and postural control impairments are greater in concussed participants specifically under divided attention conditions (Register-Mihalik et al., 2013). Although our dynamic protocol involved a cognitive and visual component of tracking the dot and a motor response of shifting the center of pressure, no difference was observed between athletes with different levels of exposure to head impacts. Also, our protocol did not detect any influence of athletic background between AnE and CON, which was expected given its influence on object tracking and balance (Bell et al., 2011; Black et al., 2020).

Some reasons for the lack of differences in dynamic balance should be considered. The cognitive and visual task of tracking the dot may have been too simple for a young sample without any acute impairment. Previous evidence showed no dynamic balance impairment in a sample of athletes with a history of concussion for more than two years (Johnston et al., 2020). Although the influence of a history of concussion was not the goal of the present investigation, only one participant from AE and one from AnE declared a diagnosed concussion within the last two years. Also, the sensitivity of the instrument has to be considered. When the same dynamic balance test protocol (i.e. YBT) was applied to assess a sample with history of concussion, the study that relied on an analogue measurement tool did not find performance impairment (Merritt et al., 2017), while another using more objective and sensitive measures (i.e. inertial sensor technology) did (Johnston et al., 2020). Therefore, in order to verify deficits in dynamic balance in an athletic population chronically exposed to head impacts, future efforts must ensure a minimum level of task complexity and also rely on sensitive instruments for data collection.

The literature is consistent in reporting structural and functional neurological impairments associated with long-term exposure to head impacts, especially in combat sports (Bernick et al., 2015; Casson & Viano, 2019; Martland, 1928). These athletes are involved in up to 10 simulated fights per week (Follmer et al., 2020), each session lasting around an hour (Heath & Callahan, 2013), where countless blows to the head are received in moderate intensity (Follmer et al., 2020). Such training routine is associated with acute and transient brain changes, which is suggested to originate long-term impairments (Di Virgilio et al., 2019). Participants from AE declared more than 5 years of training for modalities where head strikes are a clear determinant of success (i.e. MMA, boxing, kickboxing, and Muay Thai). These characteristics all together matched the definition of chronicity adopted by the present study, where participants from AE were exposed for years to the influence of an agent (e.g. head impacts) that originates from outside the genome (Greenamyre & Barrett, 2015).

For the benefit of future investigations, the limitations of the present study and some recommendations must be explored. Although controlled by athletic background and exposure to head impacts, participants were not matched by concussion history or time since the last diagnosed concussion, which would ideally come from medical records rather than self-reported. The sample size was limited by demographic boundaries and restrictions caused by a global pandemic. In addition, we performed a single data collection (i.e. cross sectional), whereas prospective longitudinal studies with larger samples that periodically assess postural control would be ideal to unveil deficits associated with repetitive head impacts (i.e. subconcussion). While our protocols and instrument detected difference in only one variable, it is emphasized the importance of developing practical, objective, time-efficient, low-cost, and clinically relevant alternatives to accurately assess how postural control may be affected by chronic exposure to head impacts (Register-Mihalik et al., 2013).

5.6. Perspective

Our study potentially adds to the growing evidence that exposure to concussion or subconcussive hits can produce lasting deficits in static stability. A simple and widely used clinical balance protocol integrated with a low-cost balance board showed differences in the ellipse area of postural sway in the double-leg stance over a firm surface in a group of athletes chronically exposed to head impacts. No differences were observed in the dynamic balance assessment. Alternative static and dynamic practical protocols using objective instruments should be encouraged due to their clinical relevance to detect impairments in the balance function of athletes chronically exposed to repetitive head impacts.

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Chapter 6 - Brain Event-Related Potentials and Spinal Cord Reflex Excitability in Athletes Chronically Exposed to Head Traumas.

6.1. Abstract

Dysfunctions caused by chronic exposure to head trauma are widely described for the brain, whereas effects on the spinal cord remain understudied. Protective neuroplasticity caused by athletic training per se must be considered when evaluating decrements in athletes chronically exposed to head traumas. We assessed brain event-related potentials and spinal cord reflex excitability of individuals with and without athletic training and chronic exposure to head traumas. Participants were allocated in groups of combat and contact athletes exposed to head traumas (AE: n=14; 28.9±7 yo; trained for 11.2±5.3 yrs), athletes from various modalities non-exposed to head trauma (AnE: n=14; 24±3.7 yo; trained for 5.4±3 yrs), and a control group of non-athletes non-exposed to head trauma (CON: n=14; 24.6±4.5 yo). Brain event-related potentials (N200 and P300) were assessed using a portable electroencephalogram system and a neurocognitive task (go-no-go), while Hoffmann (H-) reflexes were evoked from both legs to assess spinal cord reflex excitability. No differences were observed between groups for latencies and amplitudes of brain event-related potentials (N200 and P300) and H-reflex amplitudes (Hmax/Mmax) ($p>0.05$). Bilateral H-reflex fluctuations that rely on the integrity between supraspinal and spinal cord networks were different between groups ($X^2(2,n=42)=6.04$, $p=0.04$), demonstrated by the increased values of cross-covariance between legs in AnE compared to AE ($U=47$, $p<0.05$) and CON ($U=57$, $p<0.05$). This result extends to the spinal cord the association between head trauma and disruptions in the function within the nervous system. Chronic exposure to

subconcussive head trauma likely interferes with beneficial effects associated with athletic training.

6.2. Introduction

A traumatic brain injury results from forces transmitted to the head due to a direct or indirect impact and is classified as mild, moderate, or severe according to the acute level of responsiveness (DeCuypere & Klimo, 2012). Concussion (i.e. a subset of mild traumatic brain injury) presents well-established acute clinical symptoms (Carney et al., 2014; Harmon et al., 2019), and a growing literature supports that a history of concussion can lead to chronic neurological impairments (Bazarian et al., 1999; Cunningham et al., 2020; Hiploylee et al., 2017; Kim et al., 2022; Wright et al., 2021). Alarmingly, insidious head trauma that does not result in diagnosed concussion (i.e. subconcussion) (Bailes et al., 2013) can also cause harm to the nervous system if repetitive and accumulated (Di Virgilio et al., 2019; Gong et al., 2018; Slobounov et al., 2017; Wright et al., 2018). Therefore, head traumas of varied severities seem to be the common origin for many neurological deficits regardless of clinical classification.

Biomarkers and functional brain imaging studies provide the groundwork for investigating the relationship between head trauma and objective measures of dysfunction (Carney et al., 2014; Fickling et al., 2019; Kamins et al., 2017). A history of chronic exposure to head traumas is consistently associated with decreased brain volume (Bernick et al., 2015), cerebral perfusion (Amen et al., 2011), and white matter integrity (Mishra et al., 2019). Potentially related to this, electroencephalographic (EEG) data and more specifically event-related brain potentials (ERP) to a given stimulus (e.g. a neurocognitive task), are reduced following acute concussion (Clayton et al., 2020; Dupuis et al., 2000; Fickling et al., 2019) and in exposure to repetitive subconcussive impacts (Andelinović et al., 2015). The amplitude and latency of these ERP components can provide specific information about a spectrum of brain functions. For example, the P300 ERP component is associated with attentional-cognitive processes (Dupuis et al., 2000; Ghosh Hajra et al., 2016; Krigolson et al., 2021). The Muse, a commercially available, low-cost and user-friendly mobile EEG system, has been shown to be able to measure ERPs in real world environments (Krigolson et al., 2017, 2021; Fickling et al., 2020) and its use to verify changes caused by chronic exposure to head traumas is clinically promising but little explored.

In contrast to measures in the brain, effects within the spinal cord arising from concussion-related trauma remain less studied (Black et al., 2020; Carney et al., 2014; Kamins et al., 2017), yet should be equally considered due to the critical role in transmitting information to and from the brain and controlling reflexes regardless of supraspinal control. Assessment of spinal cord excitability using the Hoffmann (H-) reflex is sensitive for detecting alterations caused by head trauma (Katayama et al., 1985) and spinal cord injury (Nozaki et al., 1996). Bilateral H-reflex fluctuations have been employed as an index of plastic changes in the human motor system (Ceballos-Villegas et al., 2017). Evidence suggests a supraspinal regulation of bilateral H-reflex fluctuations (Nozaki et al., 1996) and that cumulative head impacts may alter spinal cord excitability (Black et al., 2020). While it is scientifically grounded that nervous system disruptions caused by head trauma have consequences beyond where the mechanical blow occurs, the effects of chronic exposure to such trauma on spinal cord reflex excitability require further investigation.

Athletes from contact and combat sports are chronically exposed to cumulative head trauma (Follmer & Zehr, 2021; Mullally, 2017) and form an appropriate model to explore discoveries in central nervous system interactions. However, athletic training background per se is a factor that may cause neuroplasticity in the brain (Lefebvre et al., 2021) and spinal cord (Ceballos-Villegas et al., 2017; Maffiuletti et al., 2001). Therefore, the objective of this study was to assess event-related potentials in the brain and spinal cord reflex excitability of individuals with and without athletic training and chronic exposure to head traumas.

6.3. Methods

6.3.1. Participants

Forty-two participants of both sexes volunteered for this study. Participants were allocated in groups according to their athletic background and chronic exposure to head trauma: athletes exposed (AE), athletes non-exposed (AnE), and a control group (CON) of active individuals non-exposed to head traumas. AE were trained in kickboxing (n=5), boxing (n=4), mixed martial arts (n=3), rugby (n=3), Muay Thai (n=1), and hockey (n=1) for 11.2 $\pm$ 5.3 years. AnE were trained in cross fit (n=4), jiu jitsu (n=3), triathlon (n=2), running (n=1), cycling (n=1), volleyball (n=1), soccer (n=1), and rowing (n=1) for 5.4 $\pm$ 3 years. CON participants were recreationally involved in weight training (n=9), running (n=6), walking (n=4), tennis (n=2), cycling (n=2), yoga (n=2), non-contact karate (n=1), bowspring (n=1), jiu jitsu (n=1), rock climbing (n=1), swimming (n=1), hiking (n=1), and basketball (n=1) and were not involved in any competitive sport within the past two years. Table 6.1 presents data from demographics, training routine, and concussion history for each group.

Table 6.1 Descriptive information, activity characteristics, and concussion history of the participants.

	Athletes Exposed (n=14, men=11)	Athletes non-Exposed (n=14, men=8)	Control (n= 14, men= 9)
Age (years)	28.9±7	24±3.7	24.6±4.5
Height (m)	1.78±0.1	1.77±0.1	1.73±0.07
Weight (kg)	78.1±15.9	74.7±11.8	72.5±9.4
Training routine	5.43±0.7 sessions; 13.9±9.8h weekly	5.14±1 sessions; 10.9±3.9 h weekly	60-150 min (n=5), 150-300 min (n=8), 300+ min (n=1) weekly
Concussion history	n=8; 21 episodes	n=5; 8 episodes	n=5; 5 episodes

Being actively involved in regular training and competition in a given sport within the last two years was an inclusion criterion for AE and AnE participants, and an exclusion criterion for the CON group (i.e. non-athletes). General exclusion criteria included having a diagnosed concussion within the past three months or any visual, vestibular, or neurologic disorder (Guskiewicz et al., 2001). Caffeine intake and prior exercise on the day of the examination were not allowed. Participants provided written and informed consent prior to involvement in the protocol and filled out a questionnaire applicable to their respective group to gather demographic information. This study was approved by the University's Human Research Ethics Board (protocol 19-0434). Upon consent, participants underwent testing protocols for assessment of brain ERPs and spinal cord reflex excitability, in this order.

6.3.2. Brain Event-Related Potentials

Participants were seated in a quiet room to complete a standard go-no-go task on an Apple iPad mini (Apple Inc., Cupertino, CA, US) while using the 2016 Muse EEG system (InterAxon Inc., Toronto, ON, Canada). The Muse device was set up on the participant's forehead so that electrode locations where matched to where they would be on the standard 10-10 layout (Krigolson et al., 2017). Participants were oriented to hold the iPad with both hands and remain still while performing the neurocognitive task (i.e. go-no-go).

During the go-no-go task participants were asked to react (i.e. touch the screen) to a random series of blue (i.e. go) (MATLAB RGB value = [0 0 255]) and green (i.e. no go) (MATLAB RGB value = [0 255 0]) colored circles for 800–1.200 ms in the center of a dark gray screen (MATLAB RGB value = [108 108 108]) (Krigolson et al., 2021). A black (MATLAB RGB value = [0 0 0]) fixation cross was presented for 300 to 500 ms prior to the onset of the first circle and in between the presentation of subsequent circles. Participants were not informed that the green circles appeared less frequently (no go: 25%) than the blue circles (go circles: 75%). Four blocks of 60 trials were performed by each participant.

Data were processed offline in MATLAB using EEGLAB (Delorme & Makeig, 2004) and custom written scripts (github.com/Neuro-Tools). The continuous EEG data offline was not re-referenced as our event-related potential analysis was focused on the two posterior Muse electrodes (TP9 and TP10) that were referenced appropriately at the time of recording to electrode FPz. Continuous data were filtered with a dual pass Butterworth filter with a pass band of 0.1 to 30 Hz then with a 60 Hz notch filter. To increase signal-to-noise ratio, the number of trials was doubled by assuming the activity in bilateral electrodes are mirrored but slightly different in tasks that elicit an oddball. As such, there were 480 trials for each of “pooled” frontal and posterior electrodes. Our ERP analysis focused on the pooled posterior electrode based on previous work (Krigolson et al., 2017, 2021).

After filtering, epochs of data from 200 ms before to 600 ms after stimulus onset (go, no-go) were extracted from the continuous EEG data and were baseline corrected using the 200 ms preceding stimulus onset. An artifact rejection algorithm was then implemented. As a result of this procedure, segments that had an absolute difference of more than 60 uV were discarded (M = 12.7% [7.9%, 17.6%]). Segments were then averaged for the go and no-go trials for each participant and a difference waveform was constructed by subtracting the average control (i.e. go) from the average oddball (i.e. no-go) waveform. Grand average ERP were generated by averaging all conditional (go, no-go) and difference waveforms for each participant. At the participant level, N200 and P300 potential component amplitudes and latencies were quantified by finding the local minimal (N200: 150 to 300 ms) and local maximal (P300: 300 to 600 ms) voltage amplitudes and latencies.

6.3.3. Spinal Cord Excitability

Participants were seated in a chair with their feet strapped to an apparatus mounted on the floor. Knee angle was kept between 50-60° of flexion throughout the protocol (0° = full extension). Electromyography was collected using bipolar surface electrodes on both the right and left legs. Electrodes were placed bilaterally on the tibialis anterior, soleus, and vastus lateralis muscles, with the grounding electrodes placed on both the right and left patella. Percutaneous electrical stimulation electrodes were placed in the popliteal fossa at the midpoint of the knee crease line (Özyurt et al., 2018) and square wave (1ms) electrical stimuliwere delivered to the tibial nerve using a Digitimer constant current stimulator (Mendtel, NSW, Australia). Recordings were sampled at 5 kHz, amplified (500 times for the soleus and 5000 times for the other muscles) and filtered (10-1000 Hz for soleus and 100-300 Hz for others) (P511 Grass Instruments, AstroMedInc, West Warwick, RI, USA). Recruitment curves were collected from each leg, where stimulation intensity was progressively increased until at least three maximal M-waves (Mmax) were obtained (Klimstra & Zehr, 2008). The H-reflex with the largest peak-to-peak amplitude (Hmax) was also obtained.

H-reflex amplitude fluctuations. Bilateral H-reflexes were evoked from 510 stimuli applied with pseudo-random intervals (1 to 3s) simultaneously in both legs. The stimulation intensity was adjusted to elicit reflex waveforms between 50% and 80% of Hmax obtained on the ascending limb of the recruitment curve (Grosprêtre & Martin, 2011; Zehr, 2002). The first 10 sweeps were discarded to remove the initial transient modulation potentially influenced by homosynaptic depression (Mezzarane et al., 2017; Mezzarane & Kohn, 2002). The remaining 500 sweeps were analyzed by calculating the coefficient of variation (CV) (i.e. ratio of standard deviation over the mean) and the cross-covariance (CCV) peak at zero lag of the H-reflex amplitude sequence between left and right legs using the method developed by Mezzarane & Kohn (2002). Latencies were determined as the time interval between the beginning of the 1ms stimulus to the peak of the compound muscle action potential for the M and H waves (Mallik & Weir, 2005).

After completion of the 510-stimulation sequence, another recruitment curve was collected from each leg. In order to calculate ratios and amplitudes for this study, Hmax was defined as the maximum H reflex amplitude obtained from either recruitment curve before or after the 510-stimulation sequence. The Mmax was calculated from the average of the three largest M waves recorded across either the recruitment curve before or after the 510-stimulation sequence for each leg (Noble et al., 2019).

6.3.4. Statistical Analysis

All statistical analysis was performed using SPSS (v.24, Armonk, NY: IBM Corp) and G*Power (v.3.0.10) with the level of significance set at $p<0.05$. Data normality and homogeneity of variances were tested using Shapiro-Wilk and Levene tests, respectively. If normally distributed, variables were compared between the three groups via analysis of variance (ANOVA) and Tukey HSD post-hoc. If ANOVA assumptions were not met, non-parametric Kruskal Wallis and Mann Whitney post-hoc tests were performed. Paired t-tests were used for comparisons within groups. Effect sizes were calculated using Cohen's *d*. Extreme outlier data points were excluded if they exceeded three magnitudes of the interquartile range beyond the first and third quartiles (Mowbray et al., 2018). Data are displayed using scatter dot plots representing individual values, while group means and standard deviations (SD) or median and confidence intervals (CI) are used to show measures of central tendency and dispersion for parametric and non-parametric analysis, respectively.

6.4. Results

Data from amplitude and latency of ERP waves N200 and P300 are presented in Figure 6.1. There was no difference between groups for N200 (Amplitude: $F_{2,39}$=0.18, p=0.83, η^2<0.01; Latency $F_{2,39}$=2.17, p=0.12, η^2=0.1) or P300 (Amplitude $F_{2,39}$=0.01, p=0.99, η^2<0.01; Latency $F_{2,39}$=0.61, p=0.54, η^2=0.03).

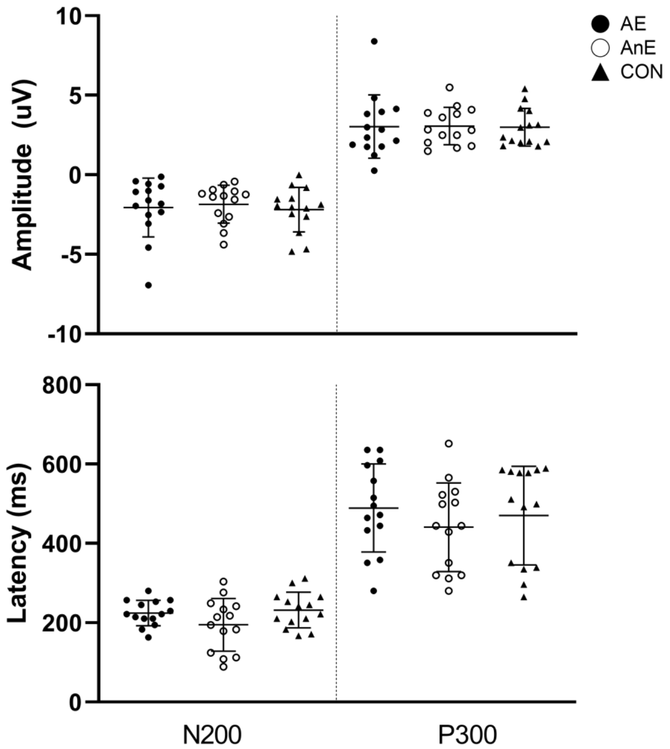

Figure 6.1 Brain ERP for N200 and P300 amplitudes (top) and latencies (bottom) are shown for athletes exposed (AE - closed circles), athletes non-exposed (AnE - open circles), and Control (CON - triangles).

Figure 6.2 presents the Hmax/Mmax ratios from the three groups in both legs. No differences were observed between groups for right ($F_{2,39}$=1.42, p=0.25, η^2 = 0.06) and left legs ($F_{2,39}$=0.86, p=0.42, η^2 = 0.04), nor within groups for right vs left leg (p>0.05).

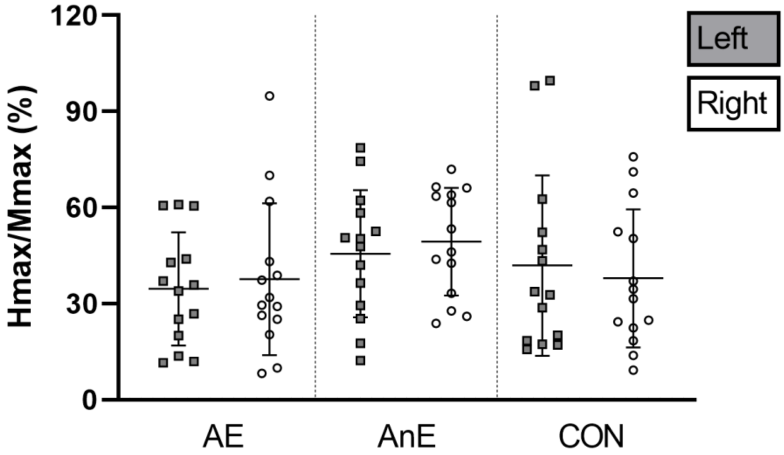

Figure 6.2 Spinal cord Hmax/Mmax ratios for left (grey squares) and right (open circles) legs in athletes exposed to head trauma (AE), athletes non-exposed (AnE), and control group (CON). Data are Mean±SD and individual values.

There was no difference between groups for the right ($F_{2,38}$=2.83, p=0.07, η^2=0.12) and left legs ($F_{2,38}$=2.9, p=0.06, η^2=0.13) H-reflex latency. AE presented a larger latency for the right compared to the left leg (p=0.01, *d*=0.8), whereas no difference was found in AnE and CON (p>0.05) (Figure 6.3). Ratios between H-reflex and M-wave latencies were AE: 1.83±0.11, AnE: 1.75±0.1, CON: 1.81±0.12 for the right leg ($F_{2,38}$=2.18, p=0.12, η^2=0.1), and AE: 1.76±0.13, AnE: 1.78±0.1, CON: 1.82±0.15 for the left leg ($F_{2,38}$=0.82, p=0.44, η^2=0.04). Data from one CON participant matched the outlier criterion and was excluded from the latency analysis.

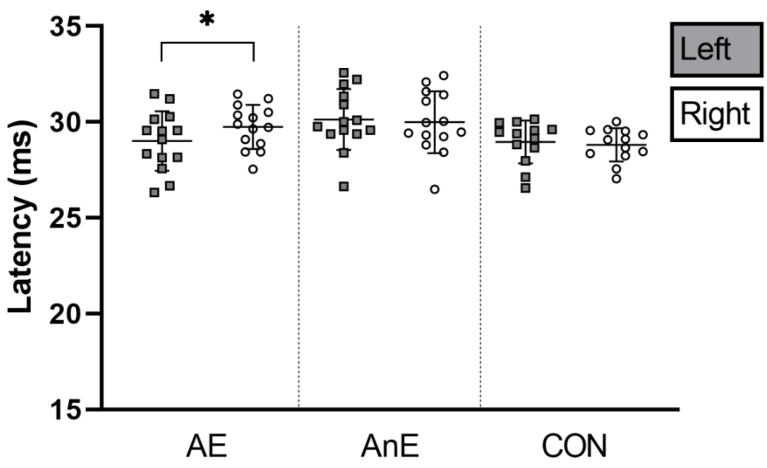

Figure 6.3 Comparison of H-reflex latency between groups (AE vs AnE vs CON) and within groups (right vs left leg). *=p<0.05

Figure 6.4 presents results from the H-reflex CV. No differences were observed between groups for right ($F_{2,39}$=0.13, p=0.87, η^2<0.01) and left legs ($F_{2,39}$=0.67, p=0.51, η^2=0.03), nor within groups for right vs left leg (p>0.05).

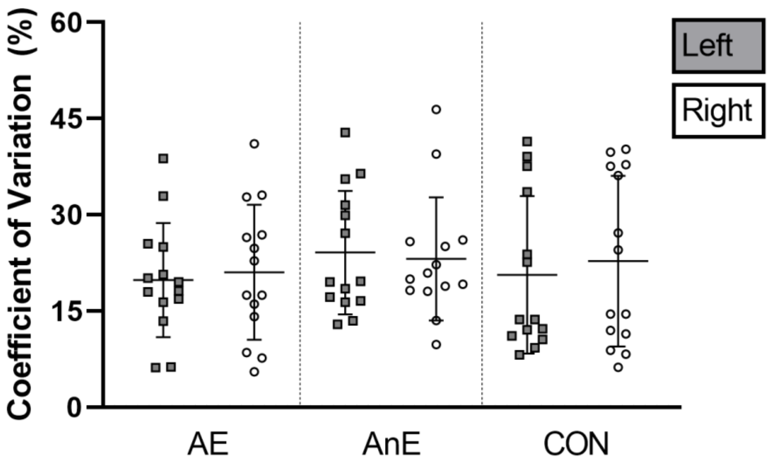

Figure 6.4 H-reflex coefficient of variation for both legs across the three groups. Data are Mean±SD and individual values.

The CCV data failed ($p<0.05$) the Levene's equality of homogeneity test. Due to this heterogeneity of variances non-parametric analysis was performed. The peak of the CCV at the zero lag of the sequence was different between groups ($X^2(2,n=42)=6.04$, $p=0.04$) such that AnE was greater compared to AE ($U=47$, $p<0.05$) and CON ($U=57$, $p<0.05$), as presented in Figure 6.5.

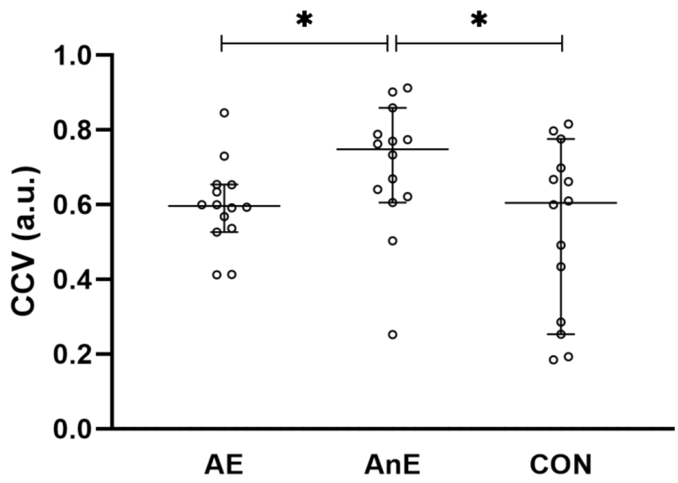

Figure 6.5 Median±95%CI and individual values of CCV peak at zero lag from athletes exposed (AE), non-exposed (AnE), and control (CON). *=p<0.05.

H-reflex amplitudes during the 500 sweeps were consistent across groups and ranged from 58.75±18.1% (CON) to 64.24±11.3 (AnE) of Hmax for the right leg (24.1±16.9 to 32±13.3% of Mmax, respectively). For the left leg, H-reflex amplitudes ranged from 61.9±8.3% (AE) to 68.8±29.9 (CON) of Hmax (22.6±11.2 to 27±17.4% of Mmax, respectively). M-wave amplitudes (as a percentage of Mmax) for the right and left legs, respectively, were AE: 24.2±18.9 and 37.7±19.7, AnE: 17.5±15.1 and 23.7±17.7, CON: 21.9±14.1 and 27.2±22.7.

6.5. Discussion

Our study investigated brain ERPs and spinal cord reflex excitability in three groups with different levels of athletic training and exposure to head traumas. A measure of spinal cord excitability that relies on supraspinal regulation differentiated the groups while effects of chronic exposure to head traumas on brain potentials were not significant. The description and interpretation of the findings, methodological considerations, and suggestions for future studies are discussed below.

6.5.1. Brain event-related activity

Event-related potentials are widely used as a proxy for brain functions. The N200 and P300 potentials are well-established for marker cognitive fatigue and visuo-spatial attention (Ghosh Hajra et al., 2016; Krigolson et al., 2021). The P300 seems to be a particularly sensitive biomarker for concussion with the degree of impairment strongly associated with the severity of concussion clinical symptoms (Dupuis et al., 2000). In addition, P300 has shown persistent change even after clinical clearance (Fickling et al., 2019) that can last for one week to six months after the injury (Dupuis et al., 2000). Results from our study did not show differences in amplitude or latency of N200 and P300 across samples with different athletic training and exposure to head trauma. This may indicate that brain ERPs can be more sensitive and clinically relevant in the acute phase of the injury, while patients are still symptomatic (Dupuis et al., 2000; Fickling et al., 2019).

Although our sample of AE did not present any differences compared to AnE and CON, the behavior of P300 in non-concussed individuals exposed to repetitive subconcussive hits warrants further investigation. Longer P300 latency and smaller amplitude have been observed in a group of soccer players exposed to repetitive mild impacts to the head, which supports the idea that subconcussive hits may produce measurable cognitive deficit through brain activity (Andelinović et al., 2015). Acute and transient brain changes occur frequently in modalities with high exposure to head traumas (e.g. combat sports) (Di Virgilio et al., 2019), and the chronic exposure to these acute changes is the most reasonable mechanism underlying well-established long-term impairments in brain function and structure (Amen et al., 2011; Bernick et al., 2015; Cunningham et al., 2020; Di Virgilio et al., 2019; Gong et al., 2018).

An aspect of our study that may be considered for future investigations is the use of the valid and user-friendly Muse EEG mobile system (Krigolson et al., 2017). Different from most systems, this device can be setup in less than 10 minutes and provide reliable and valid EEG data, including ERP (Krigolson et al., 2017, 2021; Fickling et al., 2020). The Muse mobile EEG system could be incorporated as a tool to monitor acute changes in P300 in athletic samples exposed to (sub)concussions with potential use for diagnosis and recovery. Personal baselines of P300 to establish individual's healthy brain function have been suggested and are clinically relevant to detect impairments after dysfunctions such as a concussion (Clayton et al., 2020; Ghosh Hajra et al., 2016). Nonetheless, some confounding factors must be controlled when evaluating P300, such as participants' level of cognitive fatigue at the moment of the assessment (e.g. how many hours they had been awake prior to testing and how many hours they had slept the night before) (Krigolson et al., 2021). Such confounding factors should be controlled for in future studies and may have compromised the true implications of chronic exposure to head impacts in the P300 results.

6.5.2. Spinal Cord H-reflex Amplitude and Latency

The H-reflex has been widely used in the literature concerning movement control, neurophysiology, and applied physiology as a convenient tool to explore different conditions and disorders (Özyurt et al., 2018; Pearcey et al., 2017; Zehr, 2002). The ratio between the maximum H reflex and M wave is an index for the level of reflex excitability of the motor pool and reflects the facilitation of the transmission between the afferent and efferent neurons (Pearcey & Zehr, 2019, 2020). Our results showed no difference in Hmax/Mmax ratio between groups of athletes and non-athletes, or according to the exposure to head trauma. Although athletes performing aerobic sports usually present higher Hmax/Mmax ratios than sedentary individuals, power-type athletes can present decreased reflex excitability compared to sedentary subjects (Maffiuletti et al., 2001). Upon review of our sample, the majority of participants from AE and AnE (except for 2 triathletes, 1 runner, and 1 cyclist) were trained in modalities that rely on both aerobic and anaerobic energy systems, which may justify the lack of differences compared to the CON group here. There is little related knowledge about Hmax/Mmax ratios in athletes chronically exposed to head trauma. Although no difference was observed between the groups of athletes, larger sample sizes that allow further subgroup analyses (e.g. by modality, amount of exposure to head trauma, and previous history of concussion) may be required to fully appreciate potential effects of chronic exposure to head trauma on Hmax/Mmax ratio.

All three groups evaluated in our study presented latencies close to the normative values for the soleus H-reflex (Burke, 2016), and no difference was observed between groups. Slower corticomotor latencies evoked by transcranial magnetic stimulation have been observed in a group of concussed athletes and were positively correlated with the number of concussive episodes (Stokes et al., 2020). Therefore, it seems that head trauma can affect transmission along the corticospinal pathway, but whether the spinal reflex transmission efficiency is a sensitive marker of chronic exposure to head trauma requires further investigation.

Athletes chronically exposed to head impacts presented longer latency in the right compared to the left leg. Most factors that influence latency are differences between subjects, such as limb length and age (Burke, 2016), which would not justify the differences within the AE group. The relative composition of motor unit types within distinct motor pools (e.g. soleus motor units have smaller diameter than gastrocnemius) can also affect the latency (Grosprêtre & Martin, 2011), but only data systematically collected from different muscles (i.e. soleus and gastrocnemius) would justify the difference in AE. Combat sports athletes constituted the majority of the AE group sample (10 out of 14). They were all right-handed and use a fighting stance with their left limbs ahead as a first line of defense. We further analyzed AE subgroups of combat sports (i.e. involved in fighting modalities) and confirmed the difference between legs ($p<0.01$, $d=0.9$), which was not confirmed ($p=0.41$, $d=0.4$) in the four AE from contact modalities (i.e. rugby and hockey). This anecdotal relationship between voluntary reaction time and H-reflex latency may partially explain the differences found within AE, particularly in combat sports athletes.

6.5.3. H-reflex Bilateral Fluctuations were Sensitive to Head Trauma Exposure

Our data suggests that athletes exposed to concussion have alterations in the CCV that characterize fluctuations in H-reflex excitability between legs, but not in CV within legs. The CCV represents a dynamic property which enables the detection of bilateral fluctuations and exposes temporal linkages between the legs, whereas the CV indicates the variability of the H-reflex amplitude within each leg (Mezzarane et al., 2017; Mezzarane & Kohn, 2002). Among other mechanisms, the strength of H-reflex amplitude fluctuations may be mediated by descending regulation from supraspinal centres, likely including brainstem and cortical regions. For example, the strength of bilateral H-reflex fluctuation is altered by the performance of voluntary or rhythmic motor tasks with the arms and legs (Mezzarane et al., 2017).

It had been previously shown that athletes present increased CCV peak values compared to non-athletes (Black et al., 2020; Ceballos-Villegas et al., 2017), which is supported by the differences we found between AnE and CON. However, no difference was observed between AE and CON, even though AE reported twice as many years of athletic training than AnE. Moreover, AnE presented higher values of CCV compared to AE. Therefore, our CCV result seems to endorse the concept that exposure to subconcussive hits may counteract some beneficial effects associated with athletic training (Follmer et al., 2021; Lefebvre et al., 2021). Despite the many positive health outcomes widely known, participation in some sports modalities can present the risk of head injury as a by-product (Follmer & Zehr, 2021). Although CCV may not yet present a well-established relationship with health outcomes, it has been shown that neurologically intact subjects presented more synchronous (i.e. higher values of CCV) bilateral fluctuation of H-reflex between legs compared with individuals with spinal cord injury (Nozaki et al., 1996).

Our results did not show any difference in CV related to the sampled leg, either within groups (i.e. right vs left legs) or between groups. A previous study with female rugby varsity athletes did not find differences between legs either, but their CV values were approximately 50% higher than those found in a non-athletic population (Black et al., 2020; Mezzarane et al., 2017). It was suggested that either athletic training or exposure to head impacts could affect this measure. Based on our findings, the variability of H-reflex waves within each leg (here represented by the CV) does not appear to be associated with athletic training or chronic exposure to head impacts.

Studies in reduced animal preparations suggest that concussive injury can produce suppression of sensory transmission at the spinal cord level (Katayama et al., 1985). This concept has been expanded to humans and descending influences from supraspinal centres modulate slow fluctuations in the H-reflex amplitudes (Mezzarane et al., 2017; Mezzarane & Kohn, 2002; Nozaki et al., 1996). Our study is the first to suggest that chronic exposure to head traumas may hinder the positive effects that athletic training has on CCV shown elsewhere (Black et al., 2020; Ceballos-Villegas et al., 2017). An alternative interpretation of our findings is that the history of diagnosed concussions could have caused the buffer in CCV response, given that participants from the AE group reported more concussive episodes (21) than AnE (8) and CON (5). Either by regular exposure to subconcussive hits in training and competition, or by a history of diagnosed concussions, or probably by the accumulation of events regardless of clinical classification, our findings support the detrimental link between head traumas and central nervous system function and highlight the need for multiple levels of analysis to detect subtle changes. We also underscore the need for composite measures to assess neurological integrity in concussion.

6.6. Conclusion

Chronic exposure to head trauma seemed to hinder the neuroplastic adaptation caused by athletic training in spinal cord excitability. Athletes non-exposed to head trauma presented increased synchronicity of bilateral H-reflexes compared to non-athletes as well as to athletes with high exposure to head traumas. Our findings support the link between head traumas and disruptions in the nervous system and extend this to include effects on spinal cord excitability. Although no statistical differences were observed, the use of brain event-related potentials to detect long-term impairment with user-friendly and portable electroencephalography is clinically promising and requires further investigation. Such approaches should also include multiple measurement and assessment tools to enable detection of subtle changes.

6.7. References

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Chapter 7 - Sharing Science Knowledge is a Superpower

7.1. Concussion in Combat Sports is an Iceberg Under the Ring

Ignorance sent the Titanic to its doom, knowledge can save combat athletes.

“But this ship can’t sink!”—Bruce Ismay, managing director of the White Star Line commenting on the Titanic

“She’s made of iron, sir! I assure you, she can. And she will. It is a mathematical certainty.”—Thomas Andrews, shipbuilder and architect of the Titanic
—Dialogue from the feature film Titanic (1997)

It’s helpful to learn from the past. On April 15, 2022, we will mark the 110th anniversary of the sinking of the “unsinkable” Titanic (‘*Titanic*’, 2022). This event has become a classic example of how arrogance and disdain can lead to devastating and long-lasting consequences. Ship builders and regulators learned and created protocols and innovations for safer construction and navigation.

Over a decade later, in 1928 Harrison Martland wrote about combat sports causing brain damage. His paper “Punch Drunk” was the first clear statement on the existence and dangers of concussion in combat sports (Martland, 1928). Unlike lessons from icebergs in the North Atlantic, however, in the ten decades that followed Martland’s warning very little has changed in combat sports. Still many disdain research and safety by saying, essentially, that the goal of fighting is precisely to cause that kind of injury, so who cares? Well, we all should.

As with the surface of the sea obscuring what lies beneath, what you see on the surface of the ring in combat sports such as Boxing and Mixed Martial Arts is one athlete trying to incapacitate the other, often by strikes directly to the head. This essence definitely increases the risk of what lies beneath - brain injury. But this doesn't mean we shouldn't care. On the contrary, we must worry even more. What is visible on the surface of the ring represents only the tip of an iceberg of dangerous aspects that need to be cautiously revealed and explored.

Bruno Follmer and I wrote an opinion article in the British Journal of Sports Medicine about this. It's a no brainer: combat sports should be ground zero for research on concussion addresses the special Intention, Exposure, and Reach that differentiate combat sports from all other modalities when it comes to head injuries (Follmer & Zehr, 2021) (Figure 7.1).

Figure 7.1 The iceberg of intention, exposure, and reach under the ring of combat sports

7.1.1. Combat Sports Include the Intention to Hit the Head

Intention. In most sports the intention is to score points, like in soccer, football, hockey, and basketball. Head impacts are, therefore, concerning and uncommon events, even subject to sanctioning. Experts say athletes must be removed at the first suspicion of concussion - for example with the observation of motor incoordination, vacant look, and loss of consciousness. The intention is way different in fighting. Head impacts are the most common event in striking modalities, and often a fight continues even if one (or both) athletes present visual signs of concussion. “If in doubt sit them out” is the main motto for concussion prevention in sports, but not easily applicable in fighting.

7.1.2. Combat Athletes are Exposed to Too Many Concussive Events in Training

Exposure. Professional fighters compete only a few times per year, oversight by ringside physicians and medical care. Despite the clear risk in competition, the exposure to head impacts in training is the most worrisome. One of our previous studies showed that fighters are exposed to numerous hits to the head in 2 simulated fights per week in training (Follmer et al., 2020). That’s more than 100 simulated fights per year! Given that medical presence is rare in the gym, athletes and coaches are the ones managing potential concussions, even though there is a vicious cycle of concussion ignorance among them (*The Vicious Cycle of Concussion Ignorance in Combat Sports | Psychology Today Canada*, n.d.). The real danger to these athletes’ brains occurs in the darkness and depths of the gym and not in the bright of the spotlights and pay-per-view events.

7.1.3. Combat Sports Have Universal Appeal and Reach

Reach. Combat sports are popular all over the world, regardless of social class or financial status. Different from other sports, fighting does not require favorable weather, sophisticated equipment and attire, or a specific terrain for practice. Weight classes account for the inclusion of distinct body types for both sexes. Also, it only takes two to tango- and to fight. Historically, fighting has been a sporting event since at least 648 BC in ancient Greece with Pankration (Buse, 2006). Nowadays, the popularity and wealth of combat sports companies and athletes draw many young people into these waters. Aside from the competitive level, a plethora of inexperienced practitioners are driven by the discipline and health benefits of combat modalities, but susceptible to head injury as a by-product. The contribution of combat sports to the overall concussion burden in sports is likely underestimated given the deep and global reach of these modalities.

7.1.4. When Ignorance is the Problem, Education is Always the Answer

Education is the most powerful tool we have to dodge the iceberg. Unfortunately, recent interest and scientific discoveries have not reached the general public nor combat sports athletes and coaches. The lack of knowledge and perpetuation of bad practices is clear. In the 60's, Muhammad Ali's coach reported that "*Ali believed that suffering was an important part of his preparation for a fight, that a man could build up tolerance for blows to the head and body in much the same way that you one might build up tolerance for spicy food"* (Eig, 2017). MMA superstar Wanderley Silva always trained with the firm belief that he would get more resistant if repetitively hit in the head during training. Recently, he admitted suffering from chronic concussion symptoms (*Wanderlei Silva*, 2019). When navigating these risky waters, education in concussion can lead to a change of direction that can ultimately change the destination of many combat sports athletes.

Whether by omission or disdain, failing to acknowledge the depths of head trauma in combat sports will permit foundering on the solid and dangerous iceberg of ignorance that clearly exists. While all involved in combat sports must seek better and more reliable sources of information about head injuries, scientists must learn to communicate better with their target audience. The next consensus statement on concussion in sport appears in a timely manner to endorse the relevance of combat sports modalities and better guide those who already or intend to navigate these waters. So far, we have barely touched the surface, especially around prevention. Yet, regardless of our perspectives, danger lurks in the depths and the only way to defeat the danger is by changing our practices.

Just as the danger to ships from icebergs lies just under the surface of the water, the dangers to combat sports athletes lies under the skin just beneath the surface of the skull. The Titanic unknowingly sailed towards its doom. Unlike that ill-fated voyage, we have lots of evidence for the risks and dangers of head trauma and concussion in combat sports and clear ways to implement changes in practice. Unlike the Titanic, this ship doesn't have to sink.

7.2. What's With Wonder Woman and Concussion?

Women, both humans and superhuman, face unique challenges with concussion.

Wonder Woman is arguably the most powerful hero in the DC Universe, despite her relatively smaller size compared to Superman, Batman, and beyond. Just as the dangerous power and potential of superheroes come in all sizes and shapes, it is dangerous to assume all concussions are created equal. No matter who you are or what biological sex or gender you identify with, when you are engaged in contact sport you are exposed to concussion risk. Concussion, or to use the accidentally dismissive yet commonly applied term of “mild traumatic brain injury,” requires individualized management given the multiple aspects influencing treatment and recovery.

Just like Wonder Woman's powers, abilities, and challenges, studies have been showing that men and women present significant differences at all levels of concussion management, from exposure to recovery (Figure 7.2). But just as almost all major superheroes have been men, research studies have been typically done with men only. There is a huge gap in understanding related to women. But that’s probably fine, right? Women have mostly been neglected as participants in physiological research since, well, pretty much the very beginning (Liu & Mager, 2016). Instead, it seems women are often just thought of as slightly smaller versions of men, which is, of course, incorrect. Differences due to sex and gender must be carefully addressed when it comes to health. It is simply part of the process of understanding variability instead of the search for universals.

Figure 7.2 Women, both humans and superhuman, face unique challenges with concussion

While women are generally healthier and have a longer life expectancy than men in North America (*Mars vs. Venus*, 2010), women are more susceptible to certain health conditions. These include stroke, osteoarthritis, and mental health issues like depression and anxiety (*What Health Issues or Conditions Affect Women Differently than Men?*, n.d.). While both have been neglected, a clear example where women need a specific approach is concussion in combat sports.

Bruno Follmer, a Ph.D. trainee at the University of Victoria, Rodolfo Andre Dellagrana from Federal University of Santa Catarina in Brazil, and I analyzed almost

2000 MMA fight outcomes from Ultimate Fighting Championship (UFC) bouts. Our study was the first to differentiate head trauma exposure for men and women in MMA and what we found was stunning.

The incidence of a fight ending due to head strikes was compared across the male and female weight categories. We showed that fights in the female bantamweight division (56.7 to 61.2kg) had a 221% increased risk compared to the strawweight (up to 52.1kg) (Follmer et al., 2019).

For the female weight categories, there is about a 9kg difference between the upper limit weights for bantamweight and strawweight. To find a similar ~200% increased risk in men the weight difference was more than 5 times larger (50kg) and contrasted heavyweights (up to 120kg) compared to the lightweights (up to 70.3kg). This adds to the recurring technical mismatch in some fights with women, such as the recent boxing match that resulted in a gruesome 7-second knockout (*CBSSports.Com*, n.d.).

When studied in laboratory conditions of acceleration mimicking whole body impacts, women have higher acceleration and larger displacement in the head-neck segment than men (Tierney et al., 2005). This is important because muscles surrounding the neck can decrease acceleration and, therefore, the forces that are transmitted to the brain. Also, during baseline assessment after concussive impact exposure, women often endorse more symptoms, and at a higher severity than do men. This makes the concussion diagnosis more difficult and suggests additional approaches are needed.

The recovery process after a concussion seems to take longer in women. Evidence suggests more persistent disruption in executive function (like paying attention, planning, focusing, and regulating emotions) (Sicard et al., 2018) and in the autonomic nervous system (involuntary actions) in women (Hutchison et al., 2017). Migraine and visual memory impairment are also particularly common in women (Merritt et al., 2019). The issue becomes even more dangerous in multiple episodes because female athletes with a history of concussions can have reduced cerebral blood flow compared to women with only one concussion, a result that was not found in men (Hamer et al., 2020).

Despite efforts to include a more explicit study of women in all domains, a huge gap remains in concussion research and clinical practice. A recently published review exploring neurological consequences of repetitive head impacts analyzed studies from 1930 up to the 2000s (Casson & Viano, 2019). In this comprehensive summary, not a single case involving female athletes was described.

Beyond the poor representation in superhero movies, women have been neglected in science and medicine. This neglect has huge negative implications for health and wellness. Using the explicit example here, the dismissive attitude that women are just little men when it comes to concussion management has to be forcefully refuted. The increase in female participation in fighting sports (*Wonder Woman in the Ring*, n.d.), and the recent female superhero empowerment movies (*Captain Marvel and Superhero Empowerment | Psychology Today Canada*, n.d.) (including both *Wonder Woman* and *Wonder Woman 1984*) are reasons to believe that the media exposure and cultural recognition is growing. Scientific exploration and medical management must continue to match and support the real difference between women and men.

7.3. The Vicious Cycle of Concussion Ignorance in Combat Sports:

Dangerous misconceptions about brain injury go round and round the ring

Getting your bell rung. Taking a 'knock on the noggin'. Taking it on the chin. Getting your lights knocked out. These are all terms used to describe contact to the head that could lead to concussion. They are used in a way that is not positive or useful but instead minimizes the importance and danger of brain injury. These phrases underscore the lack of understanding that many have about the severity of so-called "mild traumatic brain injury"—concussion. They help feed an ethos of "Why should we care? Don't fighters try to give each other concussions anyway?"

Knowledge transfer from one generation to the next often occurs orally from teacher to student, elder to youth, or coach to athlete. Learning directly from those who came before us, and then sharing that expertise with others, can be an effective means of passing along information. While this form of communication is often essential and beneficial, it can also exacerbate misconceptions and perpetuate anecdotal (and often incorrect) evidence.

In sport, the coach-athlete relationship involves educating and training the next generation of athletes. This relationship can be especially strong and powerful in combat sports, but it is problematic when it comes to concussion. The consensus definition of sport-related concussion is a traumatic brain injury induced by biomechanical forces (McCrory et al., 2017). According to this definition, concussive head injury may:

- be caused either by a direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head;

- result in the rapid onset of short-term impairment of neurological function that resolves spontaneously (but may evolve over hours);
- result in neuropathological changes, but the acute clinical signs and symptoms are largely a functional disturbance rather than a structural injury and cannot be imaged effectively;
- produce clinical signs and symptoms that may or may not involve loss of consciousness.

So, concussive injuries don’t require head contact, produce deficits that arise quickly and are usually brief, can’t be seen using conventional imaging, and don’t need to involve getting "knocked out". But do people active in combat sports, where concussion risk is quite high, actually know any of this? Recently we published a study called ‘Understanding concussion knowledge and behaviour among mixed martial arts, boxing, kickboxing, and Muay Thai athletes and coaches’ in the journal The Physician and Sports Medicine. We found that two-thirds of these martial artists said their coaches were their primary means of gathering knowledge about head injury and concussion. Coaches said they mostly relied on other coaches to collect and share information (Follmer et al., 2020).

Alarmingly, as many as 86% of coaches declared they ‘never’ or only ‘sometimes’ seek information to increase their knowledge of head injury. The reality that almost all coaches were prior athletes, and that many athletes were currently involved in coaching activities, exposes a cyclical pattern of concussion knowledge in which athletes rely on poorly informed coaches and in turn become poorly informed trainers themselves. This ignorance is trapped in a vicious cycle and never escapes the ring.

Transmitting correct information is critical when dealing with the serious and disabling injury of concussion. I have previously shared how my own post-concussive symptoms altered my capacities and led to a self-reflection of the new me. Our study demonstrates that fighters are exposed to head traumas in fight simulations, or so-called sparring sessions, typically twice a week. This information alone should be enough to focus extra attention on the risks these athletes face. Health-care professionals are rarely present during training, coaches have significant knowledge gaps and are unfamiliar with concussion assessment tools, and athletes usually do not report symptoms to avoid removal from a practice or a competition. This shows the importance of spreading reliable information on head injury knowledge, assessment, and management in combat sports.

One member of the lab who is directly involved in the professional combat sports community has seen firsthand that combat sports athletes and coaches think loss of consciousness is a prerequisite for concussion. This is a myth: Loss of consciousness may or may not occur in a concussive incident. He recalled attending a fight event at which an athlete approached him. This fighter had been fiercely knocked unconscious and stated that he could now take part in our study since he had finally suffered his first concussion. But he had already many other concussions if one were using the appropriate definitions.

Many combat sports athletes, like the one in the anecdote and those in our study, believe a major injury is required to produce concussion. In our example, the athlete was also a coach, in which role he likely considers the occurrence of concussion among his students through the same lens and is likely passing that misconception on to the next generation of athletes, some of whom will become coaches, thus perpetuating the cycle of incorrect knowledge. Ignorance in the ring goes round and round.

Another key misconception identified in our study was on the level of brain injury a concussion is thought to represent. Very few athletes and coaches correctly understood that a concussion represents a mild traumatic injury. Interestingly, those athletes who believed a concussion represents a severe brain injury reported engaging in more sparring sessions per week and fewer indicated they had suffered a concussion in the past year relative to those who understood the actual level of severity a concussion represents. This finding introduces how education on even basic concepts may help, as the understanding of this general idea led to safer behaviour and likely a more realistic perception of concussion occurrence. Therefore, big changes appear to be achievable through small steps.

However, the vicious cycle of transferring incorrect knowledge and dangerous attitudes regarding concussion can be a challenging one to overcome. In our study coaches declared that scientific literature is neither easy to access or to interpret, and this cannot be underestimated. The use of short educational videos, computer-based learning programs, and infographics directed toward a lay audience were noted as the ideal forms of communication requested by combat sports coaches. These strategies represent the concept of knowledge translation, a process of dynamic and interactive strategies used to improve communication between researchers and knowledge users. As scientist, researcher, and martial artist, I believe it is important to acknowledge that alternative educational means must be produced to communicate effectively with different audiences. This was the main reason I started writing books more than a decade ago.

Beliefs are pervasive, and people want to adhere to ideas that make them comfortable. This can create a chain of inaccurate information that has a greater likelihood of reinforcing rather than correcting itself when information is passed from one generation to the next. By spreading accessible concussion information that promotes good practices and efforts from all parties, hopefully a vicious cycle of ignorance can become a virtuous cycle of knowledge.

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Chapter 8 - Summary

The objective of this dissertation was to explore causes and effects of head trauma in sports. To address such a broad topic, various projects were developed to answer specific research questions towards the ultimate goal of producing a coherent and relevant body of literature. While chapter one reviewed the literature concerning the main topics of this dissertation, chapters two to seven presented original materials produced by the author during the doctoral program. A summary of the main findings of this dissertation is presented next.

8.1. Understanding the Causes of Head Trauma in the Target Audience

Concussion is a trendy popular and scientific topic. Traditionally recognized as a condition of short-lived impairments, long-lasting effects have also been consistently associated with diagnosed concussion (Hiployleeet al., 2017). However, concussion is just one of the possibilities that may arise after mechanical forces are directly or indirectly transmitted to the head (i.e. head trauma). As illustrated in Figure 1.1, head trauma is the original event that will likely cause impairment, even when no concussion is clinically diagnosed. Although problematic, the term subconcussion easily conveys the concept of head traumas below diagnostic thresholds for concussion. Despite not causing acute impairments after a single episode (therefore not a concussion), sub threshold damage accumulates from repetitive subconcussions and can cause long-term deterioration of functions and structures of the nervous system and increase the risk of neurodegenerative diseases (Rawlings et al., 2020).

Considering this scenario, no other population is at greater risk than those constantly exposed to head trauma. In sports, we need the utmost concern for modalities where strikes to the head are allowed and a clear determinant for success. Chapter two of this dissertation explored the intention, exposure, and reach of combat sports when it comes to head trauma. Worldwide, practitioners and athletes from modalities such as Mixed Martial Arts, boxing, kickboxing, and Muay Thai are consistently exposed to intentional strikes to the head (Follmer & Zehr, 2021). This manuscript emphasized how the real prevalence and global impact of brain injury in combat sports needs to be appreciated and further investigated. Therefore, the next chapters of this dissertation were aimed at assessing the risk in competition and in training, as well as the knowledge level of athletes and coaches involved in combat sports.

Chapter three objectively investigated the risk exposure in combat sports competition, particularly in Mixed Martial Arts. Moreover, distinguishing the risk according to weight classes and sex was a novel approach in the literature, and results clearly endorsed its relevance. The combined rate of knockouts and technical knockouts (i.e. when combatants are either unconscious or unable to self-defend, respectively) in heavier athletes was greater than previously reported in the literature, whereas lighter athletes were exposed to longer matches and more non match-ending strikes. Heavier female fighters showed a 221% increased risk of match-ending due to head trauma compared to a 9 kg lighter weight class. Similar increase in risk (i.e. 206%) was observed for male fighters from categories 50 kg apart (Follmer et al., 2019). This study clearly showed that the analysis of head trauma exposure in combat sports competition must be distinguished according to weight class and sex.

While findings from competition are relevant, arguably the largest head injury risk fighters are exposed to occurs during training. Chapter four investigated training practices and level of knowledge of combat sports athletes and coaches. A high frequency of exposure to head trauma (i.e. 2 simulated fights per week) and the absence of health-care professionals in training were identified. Therefore, athletes and coaches are the first line of management of potential concussive episodes during training. Alarmingly, athletes and coaches presented significant gaps of knowledge and behavior, as well as a dangerous cyclic pattern of perpetuating poor practices (i.e., athletes rely on their coaches for concussion knowledge, and coaches are former athletes) (Follmer et al., 2020). The need to bridge the gap between scientific material and knowledge users was evident after the study.

To address the issue of science communication with the target audience in accessible and comprehensible manner, three blog posts were elaborated based on the findings from the abovementioned original studies. Chapter seven of this dissertation is composed of three knowledge translation materials published in blog form at Psychology Today magazine. Using an analogy with the tragic and preventable sinking of the Titanic, the first explores the importance of recognizing the insidious elements that justify combat sports as the most relevant modalities when it comes to brain injury. Making parallels with the famous super-hero character Wonder Woman, the second analyzes sex-related differences and the unique challenges that women face with concussion, from exposure to recovery. Finally, the third examines the knowledge transfer from one generation to the next in combat sports and how to transform the current vicious cycle of concussion ignorance into a virtuous cycle of knowledge.

8.2. Effects of Chronic Exposure to Head Trauma

Findings from chapters two, three and four endorsed that combat sports athletes constitute an appropriate sample to investigate the long-term effects of chronic exposure to head trauma. Two original studies in this dissertation investigated the effects of chronic exposure to head traumas, one focused on the balance function and the other in brain and spinal cord activity.

Balance deficit is one of the most prevalent symptoms observed in concussed individuals. Evidence supports that balance deficits can occur not only in the acute phase, but also long time after the diagnosed episode (Guskiewicz, 2011). Furthermore, repetitive subconcussive hits to the head are also associated with balance function impairment. Our study from chapter five contributed to the growing evidence that exposure to concussive and subconcussive hits can produce lasting deficits in static balance. A group of athletes chronically exposed to head impacts presented larger area of postural sway in the most basic stance from the Balance Error Scoring System test (i.e. double-leg stance over a firm surface) (Follmer et al., 2021). Our study also highlighted the importance of integrating a sensitive measurement tool (i.e. balance board) with a clinically relevant and widely used practical protocol for balance assessment. Prospective longitudinal studies to periodically assess balance function are recommended for future designs, as well as the use of sensitive tools to detect subtle deficits associated with exposure to head trauma.

Functional and structural deficits in the brain are the most investigated and reported outcomes in studies on concussion (Kamins et al., 2017). However, head injuries' repercussions are not limited to where the mechanical force is applied (i.e. the head). The spinal cord also constitutes the central nervous system and has been considerably understudied. The original study developed in chapter six of this dissertation investigated brain event-related potentials and spinal cord reflex excitability in groups of individuals with different levels of athletic fitness and exposure to head trauma. Bilateral reflex fluctuations, a spinal cord reflex measure that relies on supraspinal regulation, was sensitive to the exposure to head impacts. Our results confirmed that athletic population presents more synchronous bilateral reflex fluctuations, assessed by the coefficient of cross co-variance of the Hoffmann reflex. However, the group of athletes that was also chronically exposed to head traumas (i.e. from combat and contact sports) did not present the same result. Therefore, chronic exposure to head trauma seemed to hinder the neuroplasticity adaptation caused by athletic training in the spinal cord excitability.

8.3. Final Remarks

The studies developed in this dissertation indicate a high risk of exposure to brain injury (e.g. concussion and subconcussion) in combat sports training and competition, combined with deficient knowledge and unsafe behavior of athletes and coaches. This conjuncture of factors represents a liable scenario for long-term impairments due to chronic exposure to head traumas, such as the ones in balance function and spinal cord excitability demonstrated in this dissertation.

Primary prevention will always be the most impactful approach to decrease the concussion burden in sports. However, it is important to recognize that in combat modalities the implementation of strategies will be challenged the inherent nature of the sport. Therefore, education and proper behavior of all involved in fighting modalities is of utmost importance to promote an effective change, starting in the training room. As the popularity of combat sports and scientific interest for concussion continue to rise, it is imperative to bridge the gap between theory and practice. The recommendations of safer practices emphasized in research must reach the target audience.

While researchers must keep investigating epidemiological data, developing protocols, and issuing recommendations, it is crucial to objectively assess the effectiveness of different means of communication with the target audience. On the other hand, athletes, coaches, and anyone involved in sports modalities with high risk of head injury must be open to absorbing knowledge and making behavioral changes. The only path for a safer environment in an inherently harmful sport is through awareness and collective efforts that allow for minimizing risk exposure when it is possible to do so.

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Appendix A. RoCKAS-ST

RoCKAS-ST

NOTE: The phrase "Return to play/competition" refers to being cleared to play in both practice and games.

Section 1

DIRECTIONS: Please read the following statements and circle TRUE or FALSE for each question.

1	There is a possible risk of death if a second concussion occurs before the first one has healed.	TRUE	FALSE
2	Running everyday does little to improve cardiovascular health.	TRUE	FALSE
3	People who have had one concussion are more likely to have another concussion.	TRUE	FALSE
4	Cleats help athletes' feet grip the playing surface.	TRUE	FALSE
5	In order to be diagnosed with a concussion, you have to be knocked out.	TRUE	FALSE
6	A concussion can only occur if there is a direct hit to the head.	TRUE	FALSE
7	Being knocked unconscious always causes permanent damage to the brain.	TRUE	FALSE
8	Symptoms of a concussion can last for several weeks.	TRUE	FALSE
9	Sometimes a second concussion can help a person remember things that were forgotten after the first concussion.	TRUE	FALSE
10	Weightlifting helps to tone and/or build muscle.	TRUE	FALSE
11	After a concussion occurs, brain imaging (e.g., CAT Scan, MRI, X-Ray, etc.) typically shows visible physical damage (e.g., bruise, blood clot) to the brain.	TRUE	FALSE
12	If you receive one concussion and you have never had a concussion before, you will become less intelligent.	TRUE	FALSE
13	After 10 days, symptoms of a concussion are usually completely gone.	TRUE	FALSE
14	After a concussion, people can forget who they are and not recognize others but be perfect in every other way.	TRUE	FALSE
15	High-school freshmen and college freshmen tend to be the same age.	TRUE	FALSE
16	Concussions can sometimes lead to emotional disruptions.	TRUE	FALSE
17	An athlete who gets knocked out after getting a concussion is experiencing a coma.	TRUE	FALSE
18	There is rarely a risk to long-term health and well-being from multiple concussions.	TRUE	FALSE

Section 2

DIRECTIONS: Please read each of the following scenarios and circle TRUE or FALSE for each question that follows the scenarios.

Scenario 1:
While playing in a game, Player Q and Player X collide with each other and each suffers a concussion. Player Q has never had a concussion in the past. Player X has had 4 concussions in the past.

1	It is likely that Player Q's concussion will affect his long-term health and well-being.	TRUE	FALSE
2	It is likely that Player X's concussion will affect his long-term health and well-being.	TRUE	FALSE

Scenario 2:
Player F suffered a concussion in a game. She continued to play in the same game despite the fact that she continued to feel the effects of the concussion.

3	Even though Player F is still experiencing the effects of the concussion, her performance will be the same as it would be had she not suffered a concussion.	TRUE	FALSE

Section 3

DIRECTIONS: For each question circle the number that best describes how you feel about each statement.

		Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
1	I would continue playing a sport while also having a headache that resulted from a minor concussion.	1	2	3	4	5
2	I feel that coaches need to be extremely cautious when determining whether an athlete should return to play.	1	2	3	4	5
3	I feel that mouthguards protect teeth from being damaged or knocked out.	1	2	3	4	5
4	I feel that professional athletes are more skilled at their sport than high-school athletes.	1	2	3	4	5
5	I feel that concussions are less important than other injuries.	1	2	3	4	5
6	I feel that an athlete has a responsibility to return to a game even if it means playing while still experiencing symptoms of a concussion.	1	2	3	4	5
7	I feel that an athlete who is knocked unconscious should be taken to the emergency room.	1	2	3	4	5
8	I feel that most high-school athletes will play professional sports in the future.	1	2	3	4	5

Section 4

DIRECTIONS: For each question read the scenarios and circle the number that best describes your view. (For the questions that ask you what *most athletes* feel, base your answers on how you think MOST athletes would feel.)

	Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
Scenario 1: *Player R suffers a concussion during a game. Coach A decides to keep Player R out of the game. Player R's team loses the game.*					
1 I feel that Coach A made the right decision to keep Player R out of the game.	1	2	3	4	5
2 Most athletes would feel that Coach A made the right decision to keep Player R out of the game.	1	2	3	4	5
Scenario 2: *Athlete M suffered a concussion during the first game of the season. Athlete O suffered a concussion of the same severity during the semifinal playoff game. Both athletes had persisting symptoms.*					
3 I feel that Athlete M should have returned to play during the first game of the season.	1	2	3	4	5
4 Most athletes would feel that Athlete M should have returned to play during the first game of the season.	1	2	3	4	5
5 I feel that Athlete O should have returned to play during the semifinal playoff game.	1	2	3	4	5
6 Most athletes feel that Athlete O should have returned to play during the semifinal playoff game.	1	2	3	4	5
Scenario 3: *Athlete R suffered a concussion. Athlete R's team has an athletic trainer on the staff.*					
7 I feel that the athletic trainer, rather than Athlete R, should make the decision about returning Athlete R to play.	1	2	3	4	5
8 Most athletes would feel that the athletic trainer, rather than Athlete R, should make the decision about returning Athlete R to play.	1	2	3	4	5
Scenario 4: *Athlete H suffered a concussion and he has a game in two hours. He is still experiencing symptoms of concussion. However, Athlete H knows that if he tells his coach about the symptoms, his coach will keep him out of the game.*					
9 I feel that Athlete H should tell his coach about the symptoms.	1	2	3	4	5
10 Most athletes would feel that Athlete H should tell his coach about the symptoms.	1	2	3	4	5

Section 5

DIRECTIONS: Think about someone who has had a concussion. Check off the following signs and symptoms that you believe someone may be likely to experience AFTER a concussion.

✓		✓	
	Hives		Feeling in a "Fog"
	Headache		Weight Gain
	Difficulty Speaking		Feeling Slowed Down
	Arthritis		Reduced Breathing Rate
	Sensitivity to Light		Excessive Studying
	Difficulty Remembering		Difficulty Concentrating
	Panic Attacks		Dizziness
	Drowsiness		Hair Loss

Appendix B. Athlete Questionnaire

Demographic Questionnaire - Combat Sports Athletes

Completion of this questionnaire is not mandatory. If you choose to do so, please provide true answers for each item so that we can generate meaningful research which will contribute to the development of this area of knowledge. Questions are single choice answers. We will inform you when multiple choice is allowed. Don't forget to inform the participant ID.

SECTION: PERSONAL INFORMATIONS

What is your age?

- o Under 18 years old
- o 18-24 years old
- o 25-34 years old
- o 35-44 years old
- o ≥ 45 years old

What is your ethnicity?

- o Caucasian
- o African-American
- o American Indian or Alaskan Native
- o Asian
- o Native Hawaiian or other Pacific islander
- o Some other ethnicity (please specify)
- o Prefer not to answer

What is your gender?

- o Female
- o Male

What is the highest level of school you have completed or the highest degree you have received?

- o Less than high school degree
- o High school degree or equivalent (e.g., GED)
- o Some college but no degree
- o Associate degree
- o Bachelor degree
- o Graduate degree

SECTION: TRAINING EXPERIENCE

What is the amount of experience you have in general sports training?

- 0-2 years
- 3-5 years
- 6-9 years
- ≥ 10 years

What is your sports status in your current modality?

- Professional
- Amateur

What is the amount of training experience do you have in your actual sport modality?

- 0-2 years
- 3-5 years
- 6-9 years
- ≥ 10 years

Which is your primary weight class (most often competed) in the last two years?

- Under 70kg
- From 70kg up to 84 kg
- More than 85 kg

How many training sessions per week do you have full contact (with strikes to the head) with other trainer partners (like a sparring session)?

- None
- 1
- 2
- 3
- 4 or more

SECTION: HISTORY OF CONCUSSION

Did you already have a diagnosed concussion by a licensed healthcare professional (doctor or nurse)?

- Yes
- No

If you answered yes in the previous question, please answer the next three questions:

Was it a sports-related concussion?

- Yes
- No
- I don't know

How many diagnosed concussions did you have in your entire career?

- 1

- 2
- 3
- ≥ 4

Did you ever return to full practice (no limitations) within one week following the diagnosis?

- Yes
- No

Did you already have a suspected concussion? (Do not consider those diagnosed by a doctor)

- Yes
- No

If you answered yes in the previous question, please answer the next two questions:

How many suspected concussions did you have in your entire career?

- 1
- 2
- 3
- ≥ 4

Who did the diagnosis of the suspected concussion? (Multiple choice allowed)

- Coach / Trainer
- Other staff member (ex: fitness coach, physiotherapist, massage therapist)
- Other team mate / partner
- Other health staff member (ex: nurse, pharmacists, athletic therapists)

SECTION: CONCUSSION KNOWLEDGE

Rate your self-perceived knowledge about concussion in a scale from 0 (zero- nothing) to 10 (ten- excellent):

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Do you believe would you know what to do when someone gets a concussion?

- Yes
- No

Whence did you obtain information about concussion and/or brain injury? (Multiple choice allowed)

- By myself (searching in general media)
- From educational programs held by professionals
- From my coaches
- From my team mates
- Other source, please specify which here: ………………………………
- I believe I do not possess basic knowledge of sports-related concussion or brain injury.

Do you know where should you search to get reliable information on sports-related concussion?

- Yes
- No

Was this the first time you answered the survey RoCKAS-ST?

- Yes
- No

If you answered "No" in the last question, please provide the number of times you've completed the RoCKAS-ST:

- 1
- 2
- 3 or more.

Appendix C. Coach Questionnaire

Demographic Questionnaire - Combat Sports Coaches

Completion of this questionnaire is not mandatory. If you choose to do so, please provide true answers for each item so that we can generate meaningful research which will contribute to the development of this area of knowledge. Questions are single choice answers. We will inform you when multiple choice is allowed. Don't forget to inform the participant ID.

SECTION: PERSONAL INFORMATIONS

What is your age?
- 18-24 years old
- 25-34 years old
- 35-44 years old
- ≥ 45 years old

What is your ethnicity?
- Caucasian
- African-American
- American Indian or Alaskan Native
- Asian
- Native Hawaiian or other Pacific islander
- Some other ethnicity (please specify)
- Prefer not to answer

What is your gender?
- Female
- Male

What is the highest level of school you have completed or the highest degree you have received?
- Less than high school degree
- High school degree or equivalent (e.g., GED)
- Some college but no degree
- Associate degree
- Bachelor degree
- Graduate degree

<u>SECTION: TRAINING EXPERIENCE</u>

What is the amount of experience you have in general sports training as a coach?

- 0-2 years
- 3-5 years
- 6-9 years
- ≥ 10 years

What is your sports status in your current modality as a coach?

- Professional
- Amateur

What is the amount of coaching experience do you have in your actual sports modality?

- 0-2 years
- 3-5 years
- 6-9 years
- ≥ 10 years

How many training sessions per week do you have with full contact (with strikes to the head) between your athletes (like a sparring session)?

- None
- 1
- 2
- 3
- 4 or more

Did you already witness an athlete suffering a concussion diagnosed by a licensed healthcare professional (doctor or nurse)?

- Yes
- No

What criteria do you consider when deciding the return to full practice of an athlete who has suffered a concussion? (Multiple choice allowed)

- Medical clearance
- Athlete's self reported symptoms
- Clearance obtained from other staff member
- Your own evaluation

Within how long do you allow an athlete to return to full practice after a concussive event?

- Within 1 week
- Never before 1 week
- Within 1 month
- More than 1 month
- I don't know

Which one of these professionals do you have regularly on the sideline during <u>trainings</u>? (Multiple choice allowed)

- Doctor

- Nurse
- Other health staff member (ex: pharmacists, athletic therapists, chiropractor)
- Other staff members (ex: assistant coach, fitness coach, physiotherapist, massage therapist)

Which one of these professionals do you have regularly on the sideline during competitions? (Multiple choice allowed)

- Doctor
- Nurse
- Other health staff member (ex: pharmacists, athletic therapists, chiropractor)
- Other staff members (ex: assistant coach, fitness coach, physiotherapist, massage therapist)

Athletes under your supervision are used to training with protective headgears:

- Always – every session
- Only in sessions with higher chances of impacts to the head
- Never

SECTION: CONCUSSION KNOWLEDGE

Rate your self-perceived knowledge about concussion in a scale from 0 (zero- nothing) to 10 (ten- excellent):

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Do you believe would you know what to do when someone gets a concussion?

- Yes
- No

Whence did you obtain information about concussion and/or brain injury? (Multiple choice allowed)

- By myself (searching in general media)
- From educational programs held by professionals
- From my coaches
- From my team mates
- Other source, please specify which here: ……………………………….
- I believe I do not possess basic knowledge of sports-related concussion or brain injury.

Do you know where should you search to get reliable information on sports-related concussion?

- Yes
- No

Do you know the SCAT5 (Sport Concussion Assessment Tool)?

- Yes
- No

Do you know the CRT5 (Concussion Recognition Tool)?

- Yes
- No

Was this the first time you answered the survey RoCKAS-ST?

- Yes
- No

If you answered "No" in the last question, please provide the number of times you've completed the RoCKAS-ST:

- 1
- 2
- 3 or more.

Appendix D. Center of Pressure calculation

Equation 1. Center of Pressure X (CoP_X):

$$CoP_X = \frac{F_{TR} + F_{BR}}{\left(F_{TR} + F_{BR} + F_{TL} + F_{BL}\right)}$$

Equation 2. Center of Pressure Y (CoP_y):

$$CoP_y = \frac{F_{TL} + F_{TR}}{\left(F_{TR} + F_{BR} + F_{TL} + F_{BL}\right)}$$

Equation 3. Center of Pressure medial-lateral path length (CoP_{ML})

$$CoP_{ML} = \Sigma\left|\left(CoP_X(n+1) - CoP_X(n)\right)\right|$$

Equation 4. Center of Pressure anterior-posterior path length (CoP_{AP})

$$CoP_{AP} = \Sigma\left|\left(CoP_y(n+1) - CoP_y(n)\right)\right|$$

Equation 5. Centre of Pressure total path length (CoP_T)

$$CoP_T = \Sigma\sqrt{[CoP_X(n) - CoP_X(n+1)]^2 + \left[CoP_y(n) - CoP_y(n+1)\right]^2}$$

F_{BL} = Force sensor bottom left

F_{BR} = Force sensor bottom right

F_{TL} = Force sensor top left

F_{TR} = Force sensor top right