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The relationship between executive function and concussion symptom history in Brazilian professional mixed martial arts athletes

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Abstract

Introduction: A concussion is a trauma caused by the impact of the brain against the skull, which can result in minor injuries with significant physiological and psychological consequences. Symptoms observed include sleep disturbance, vertigo, headache, and photophobia. In the psychological context, perturbations are observed, such as, depression and anxiety and altered mood. Changes in attention, concentration, language, and executive function (EF), which can be divided into working memory, inhibitory control, and cognitive flexibility.

Objective: The aim of this study was to investigate which executive functions are associated with concussions symptoms reported by mixed martial arts (MMA) athletes.

Method: The Five Points Test and the Trail Making Test were used to evaluate cognitive flexibility. Inhibitory control, solving problem, and working memory were evaluated using the Stroop Test, the Tower of Hanoi, and Digit Span tasks, respectively. Self-reported concussion symptom history was assessed using the Sport Concussion Assessment Tool (SCAT); athletes reported post-concussion symptoms for early and later phases. Tests were administered to 16 professional MMA athletes. A stepwise multiple linear regression was calculated to predict combined concussion symptom history using EF test scores as the independent variables.

Results: The Five Points Test, the Tower of Hanoi, and the Trail Making Tests were strongly related to concussion symptom history. The model explained 61.4% of the variance in symptom history. The strongest correlation between symptoms history and EF was with the Trail Making test (Part B).

Conclusion: Frontal regions of the brain are responsible for cognitive flexibility and problem solving. Therefore, it makes sense that these executive functions are two of the most affected as MMA athletes receive a large number of impacts in this area.

Key words: concussion; cognition; executive function; mixed martial arts; professional athlete

Introduction

In the last few decades, many studies have investigated the neuropsychological consequences of brain concussions in contact sports, such as football (Omalu et al., 2005), soccer (Dias, Ávila, Rocha, Pinto, & Ribeiro, 2014; Tarnutzer, Straumann, & Brugger, 2017), rugby (Hume et al., 2016), hockey (Renton, Howitt, & Marshall, 2019), kickboxing (Melo & Filgueiras, 2018), and boxing (Förstl, Haass, Hemmer, Meyer, & Halle, 2010; Jamora et al., 2017; Payman, Yates, & Cullum, 2018; Shahid, Verma, & Youngblood, 2018). Despite growing interest in this area, little is known about the neuropsychological consequences experienced by mixed martial arts (MMA) athletes in terms of their executive functions, which are fundamental cognitive processes utilized in everyday living (Diamond, 2013).

Executive functions (EFs) are separated into two groups: low-order and high-order EFs. The low-order EFs, considered the main EFs, include inhibitory control, working memory, and cognitive flexibility. Inhibitory control refers to control of processes such as attention, emotion, and behavior. In other words, it is the ability to control automatic or impulsive responses. Working memory is related to the manipulation of relevant information stored in memory. Cognitive flexibility is the ability to alternate between different perspectives. The high-order EFs consist of planning and problem solving. Planning involves the identification and management of the steps and resources required to achieve a goal. As its name suggests, problem solving is the cognitive process related to the ability to find solutions to problems (Diamond, 2013; Friedman & Miyake, 2017; Miyake & Friedman, 2012; Miyake et al., 2000; Morris & Ward, 2005; Nowrangi, Lyketsos, Rao, & Munro, 2014; Barbey, Colom, & Grafman, 2013; Newman, Carpenter, Varma, & Just, 2003). Another important aspect of cognition is processing speed, which is related to ability to perform cognitive tasks quickly and fluently. A fast processing speed enables more resources to be available to further evaluate information (Primi & Nakano, 2015; Clay et al, 2019; Tourva, Spanoudis, & Demetriov, 201; Salthouse, 1996; Gorman et al., 2016).

A concussion is a trauma resulting from an impact to the head or any other part of the body where the shock rattles the brain against the skull (Dias et al., 2014). This reverberation can be understood as abrupt acceleration and deceleration of the brain (Förstl et al., 2010; Ianof et al., 2014) perturbing brain cells (Omalu et al., 2005) and resulting in damaging physiological and psychological consequences. Psychophysiological consequences include sleep disturbance, photophobia, headache, and vertigo (Dias et al., 2014; Ellis, Leddy, & Willer, 2015; Ianof et al., 2014; Leddy, Baker, Haider, Hinds, & Willer, 2017). It is important to highlight that although loss of consciousness is frequently associated with concussions, it is not always a consequence of brain trauma (Dias et al., 2014). Additional psychological manifestations of concussion are: onset of depression and anxiety, and changes in general mood**,** attention, concentration, language, and executive function (Ellis et al., 2015; Melo & Filgueiras, 2018; Melo et al., 2018; Mez et al., 2017; Moore et al., 2016).

Outside the context of sports, many studies (Lambregts et al., 2017; Whiting, Deane, Simpson, Mcleod, & Ciarrochi, 2017) have shown a relationship between concussions and poor performance on neuropsychological tests, as well as the development of mood disorder symptoms. Kaup et al. (2019) conducted a study with retired military veterans to compare the neuropsychological profile of those who suffered brain trauma and needed medical attention versus those who did not suffer significant trauma. The results showed that veterans who suffered brain trauma were more likely to develop symptoms of depression and substance abuse, in addition to presenting a deficit in processing speed and executive function. Kochhann and Zimmermann (2014) conducted a study of 81 hospital patients with brain trauma, ages 18 to 72, finding that this damage was associated with inhibitory control deficits. Pereira et al. (2016) observed similar results in a study of 96 adults who suffered mild or severe brain trauma. The greater the severity of trauma, the more cognitive deficits appeared. Specifically, deficits in inhibitory control, episodic memory, initiation, and verbal planning were observed.

In context of sport, Omalu and colleagues (2005) were among the first to document a case of a retired professional American football player who displayed neurodegenerative changes because of brain trauma. This case included symptoms of Parkinson's disease, mood disorders, difficulties with memory, and impaired judgement. Subsequently, Omalu, Bailes, Hammers, and Fitzsimmons (2010) studied five cases of retired

American football players who committed or attempted suicide, where head trauma was identified as a risk factor. This association was also observed by Abreu, Cromartie, and Spradley (2016). Mez and colleagues (2017) studied 202 donated brains, including 111 brains of former National Football League (NFL) players. In line with other studies (Abreu, Cromartie, & Spradley, 2016; Montenigro et al., 2017; Omalu, Bailes, Hammers, & Fitzsimmons, 2010; Omalu et al., 2005; Aaron M Yengo-kahn, Johnson, Zuckerman, & Solomon, 2016), they found a relationship between brain trauma and psychological changes. These included onset of anxiety, depression and mood disorders, incidences of outbursts and violent behavior, as well as disorders involving language, memory, attention and executive function.

Such findings are not limited to American football, but are evident in almost all sports with forceful physical contact. For instance, Dias and colleagues (2014) reported a concussion case in soccer where the athlete presented with symptoms of dysarthria, severe headache and amnesia, but fortunately returning to practice after short-term symptoms resolved. Ling et al. (2017) described cases of retired soccer players who reported symptoms of anxiety, depression, irritability, memory disorder, and impulsivity following a concussion. In these cases, athletes also developed dementia associated with the brain trauma.

In boxing, a study showed that out of the 291 injuries sustained during championships 48% were concussions (Payman et al., 2018). In addition to cognitive, mood, and behavioral disorders, the incidence of brain trauma can lead an athlete to die in the ring (Förstl et al., 2010) or develop serious medical conditions. Payman et al. (2018) reported cases of dementia in retired boxers that were probably caused by distal factors related to concussion (such as alcohol and family history). Shahid et al. (2018) reported a case of a previously healthy amateur boxer who developed diabetes insipidus shortly after suffering a concussion. Jamora et al. (2017) collected data from seventeen retired boxers and observed a relationship between the number of concussions suffered and the onset of Parkinson's symptoms. Additionally, in kickboxing, a boxing variant, Melo and Filgueiras (2018) found a relationship between symptoms of depression and concussions.

Out of all the combat sports, MMA presents a higher number of matches that are interrupted due to concussions, the most reported injury (Buse, 2006; García & Malcolm, 2010; Oliveira, 2013). MMA, also known as extreme fighting, cage fighting, and “no holds barred” sport fighting, can trace its roots to around 648 BC, if not earlier. It combines techniques of different martial arts: boxing, karate, judo, kung-fu, taekwondo, jiu-jitsu, and others. The fight is decided by a knockout or submission, and the techniques that are more effective for securing victory also frequently cause concussion in the opponent (Buse, 2006; Jensen, Maciel, Petrigliano, Rodriguez, & Brooks, 2017; Lystad, Gregory, & Wilson, 2014; Oliveira, 2013; Rainey, 2009; Slowey, Maw, & Furyk, 2012).

The repeated experience of concussion in MMA (Curran-sills & Abedin, 2018, Hutchison, Lawrence, Cusimano, & Schwizer, 2014) can be especially dangerous for the neurological health of an athlete. However, there is evidence that even with a single concussion there is a risk of progressive brain changes over a short period of time (Mayer et al., 2015, 2017). As with studies in American football, soccer and boxing, research in MMA has pointed to an association between brain trauma and declining processing speed, memory, inhibitory control, and attention (Banks et al., 2014; Bernick et al., 2015; Hubbard et al., 2018; Lockwood, Frape, Lin, & Ackery, 2018; Mayer et al., 2015, 2017). For instance, Lim, Ho, and Ho (2019) reported the case of a former MMA athlete who arrived at a clinic in 2010 with complaints of memory and concentration difficulties. This male MMA athlete, age 40, fought MMA for 10 years and was an instructor for 5 years. Concussion episodes were recurrent during his time in the sport. During physical examination, he presented with hand tremors and coordination problems. An MRI showed slight asymmetry in his parahippocampal structures. The patient reported increased irritability, distraction, and fatigue. In addition, the patient reported difficulties in maintaining employment due to memory and concentration problems. Indeed, a neuropsychological assessment identified a deficit in working memory. Years later, a follow-up neuropsychological assessment showed a progressive decline in attention, memory, and executive functions. Such studies reveal the complexity of effects of single versus multiple exposure to brain trauma, along with short-term and long-term effects to executive functions.

Although these findings highlight that MMA athletes experience a high incidence of concussions and suffer the consequence of neuropsychological impairment, there remains a limited number of studies that investigate the specific cognitive effects of concussion in this sport. Thus, the aim of this study was to investigate which executive functions are associated with concussion-related symptoms in professional MMA athletes.

Methods

Participants

This study consisted of a convenience sample of 16 male professional MMA athletes between the ages of 21 and 34 years old (M = 26.19; SD = 4.3). Their education ranged from 9 to 16 years (M = 11.81; SD = 2), and each athlete participated in at least three national or international matches. The athlete's tenure in combat sports varied between 3 and 21 years (M = 7.87; SD = 5.18), and the numbers of fights varied between 3 and 32 (M = 12.5; SD = 8.56).

Instruments

The Sport Concussion Assessment Tool (SCAT) was developed in 2004 at the Second International Conference on Concussion in Sport to evaluate concussions in sport in an objective and standardized way. SCAT accesses neurocognitive and neurological functions, as well as concussion symptoms including amnesia, loss of consciousness and other physiological and psychological changes (Yengo-kahn et al., 2016). The instrument is divided in three scales, two to assess symptoms of concussion (early and late symptoms) using a Likert scale ("0 – None" to "6 – Severe") and one for medical evaluation by doctors and neuropsychologists. As the medical evaluation needs to be completed immediately following a concussion; however, the present study used only the symptom scales, where athletes were asked to share their concussion symptoms history by using the prompt: “Please, respond about these symptoms for each instance you can recall that you were knocked down, felt drowsy, and/or had a loss of consciousness after a hit to your head”. The interview was conducted by a trained neuropsychologist who recorded the athlete’s responses according to the SCAT’s instructions. Although SCAT assesses the severity of symptoms after concussion, the present study used this instrument to assess the self-reported history of concussion symptoms, asking the athlete to recall all instances of head trauma suffered during sports practice.

<u>The Tower of Hanoi</u>, an instrument with three pins and different sized disks, was used to measure problem solving ability (Brião & Campanholo, 2018). The test begins with a sequence of disks on the first pin with the objective being to move the disks to repeat the initial sequence on the last pin. The rules include only moving one disk at a time and not placing a larger disk on top of a smaller disk. The time and number of movements to complete the sequence on the last pin are used to evaluate problem solving. The present study used five discs requiring a minimum of thirty-one movements to reach the final goal. In this study, only the time to complete the test was used as a score, not the number of movements, to measure the level of problem solving ability (Ahonniska, Ahoren, Aro, & Lyytinen, 2000).

<u>The Stroop Test</u> was used to assess inhibitory control (Diamond, 2013; Friedman & Miyake, 2017b; Miyake & Friedman, 2012). It consists of displaying names of various colors, where the font color differs from the displayed color name. For example, the word "blue" is displayed in yellow font. Thus, the athlete had to select the option corresponding to the font color (yellow). Consequently, it is necessary to inhibit the impulse to select the option that corresponds to the displayed word in order to correctly select the option corresponding to the font color. An electronic version of the Stroop Test was used - the application Speed Color (Genesio, 2014) in “time attack” mode. The app presented incongruent words at the top of screen and nine colored

squares at the bottom, where the athlete needed to select the square that corresponded to the font color. Athletes had 30 seconds to correctly match the incongruent words and colored squares. The wrong answers were subtracted from the number of correct answers to generate the final score.

The Five Point Test is a nonverbal fluency test that assesses cognitive flexibility (Lopes-Silva, Starling-Alves, Moura, & Haase, 2017). It consists of drawing figures by connecting five points in a square, without lifting the pen from the paper and without intersecting back through a line that has already been drawn. The test has a total of forty squares. Athletes were instructed to make different figures in each square during a three-minute period. The score was calculated by subtracting the wrong answers from the correct answers. If a figure was repeated, the first appearance was counted as correct and the following appearance counted as incorrect.

The Trail Making Test (TMT) was used to assess cognitive flexibility and processing speed (Salvador, Martins, Moura, & Haase, 2017; Moll, Oliveira-Souza, Moll, Bramati, & Andreioulo, 2002). The test is divided into part A and part B. Part A requires one to connect a sequence of numbers from one to 25 as quickly as possible, which assesses visual searching ability. Part B assesses cognitive flexibility and consists of alternating sequences of numbers and letters as quickly as possible. The Parker-O'Brien and Associates electronic version of the TMT was used (Parker-O'Brien and Associates, 2013a, 2013b). The score of the test was the time it took the athlete to complete each part of the TMT.

The Forward- and Backward-digit Span Tasks were used to assess short-term memory and working memory, respectively (Diamond, 2013; Melo & Filgueiras, 2019). Forward-digit Span consists of repeating items in the order they were presented. Backward-digit Span, in contrast, consists of memorizing the items presented and repeating them in reverse order. Consequently, the Forward-digit Span only requires memorization of the presented items. Conversely, the Backward-digit Span requires the athlete to use working memory, as the athlete has to memorize the items and mentally manipulate the information in order to repeat the items in the reverse order. An electronic version of the span tasks was used (UCLA, 2014). The score corresponds to the number of items that athletes could remember in eight rounds of testing.

Procedure

Athletes were recruited from martial arts academies in Rio de Janeiro. They received a free and informed consent form outlining the study objectives. Those who signed the consent form agreeing to participate in this study continued with assessments. This study was approved by the Ethics Committee of Rio de Janeiro State University. Participants completed a sociodemographic questionnaire. In order to answer the SCAT items, the participants were interviewed by one of the authors (RM) about all concussion episodes during MMA practice they could recall. Then participants performed each of the following EF tests. All data was collected in a single laboratory session. The test order was: 1) the Tower of Hanoi, 2) the electronic version of the Stroop test, 3) the Five Points Test, 4) the Trail Making Test (TMT), parts A and B, and 5) an electronic version of the Forward- and Backward-digit Span test.

Data Analysis

The early- and late-phase symptoms of concussions were summed to generate the total self-reported concussion symptom history, which was the dependent variable. The executive function tests were the independent variables in a stepwise multiple linear regression analysis calculated using R data analysis software (R Package, Vienna, Austria).

Results

Means and standard deviations were calculated for all demographic variables, including years of practice and the executive function tests, which are presented in Table 1. Normality of all variables was tested using the Kolmogorov-Smirnov test, and no significant difference was found, leading to the assumption that the variables are normally distributed.

INSERT TABLE 1 ABOUT HERE

The stepwise multiple linear regression showed a significant difference between the final model and the null hypothesis. The ANOVA statistics comparing the null hypothesis and the suggested output from the stepwise regression were $F(5,10)=5.767$; $p<0.001$; $f^2=1.591$; power=0.772. According to the effect size rule established in Aguinis et al. (2005), a $f^2\geq0.35$ means high effect and power≥0.80 is an adequate power of the test. The ANOVA of the multiple linear regression presented a high effect with moderate power. However, the smallest sample size in the literature to reach the acceptable power of 80% was 17 participants, one less than this study's sample size. The coefficient of determination of the model revealed high levels of explained variance ($r^2=0.614$). The intercept and the coefficients of stepwise regression for each variable included in the model are depicted in Table 2. The EF tests associated with history of concussion were the 5 Points tests (both $p < .001$, the Tower of Hanoi test ($p = .022$), and the Trail Making Tests (Parts A and B; $p = .017$ and <.001, respectively). The Stroop test and the Forward- and Backward-digit Span tests did not predict self-reported concussion symptom history.

INSERT TABLE 2 ABOUT HERE

Discussion

In the present study, we aimed to understand which facets of executive function would be associated with concussion symptoms in MMA athletes. For this, we calculated self-reported concussion symptom history by summing the early and late symptoms scores of SCAT, which was the dependent variable. The executive function tests were the predictor variables. We also examined whether length of practice and the age of athlete (both in years) were related to symptom history. According to the present results, symptom history is tightly associated with the scores from the Tower of Hanoi, the Trail Making Test parts A and B, and the 5 Points Test. The Stroop test and the Forward- and Backward-digit Span tests did not predict concussion symptom history. This means that the executive functions most affected by brain trauma suffered during MMA practice are problem solving (Brião & Campanholo, 2018), processing speed (Salvador et al., 2017), and cognitive flexibility (Lopes-Silva et al., 2017; Salvador et al., 2017), respectively.

The literature shows evidence of a strong association between concussions and deficits in executive function, in and out of the context of sport (Ling et al., 2017; Pereira et al., 2016; Tarnutzer et al., 2017). Consistent with our results, Moore et al. (2016) found a relationship between concussions and low problem solving ability, in addition to a deficit in inhibitory control in children who retired from sport training due to head trauma. Another finding in sport is from Lim et al. (2019), they identified progressive cognitive impairments in a former MMA athlete. This former MMA athlete had poor performance in a processing speed task, in addition to deficits in memory, planning, and attention**.** Hume et al. (2016) found similar results when investigating the impact of prior concussions on cognition. They compared groups of former elite rugby athletes with former non-contact sport athletes. The results showed that the group with concussion history had the worse performance in processing speed and cognitive flexibility, measured by the CNS-VS test battery.

Outside of sport, Whiting et al.(2017) investigated cognition after a brain trauma. Results showed that people who suffered from concussions presented deficits in cognitive flexibility. Kaup et al. (2019) investigated the cognition of older military veterans with concussion history. These veterans presented a significant deficit in processing speed when compared to older veterans without concussion history. A study conducted by Lambregts et al. (2017) found that a number of participants with head injury presented with deficits in processing speed, inhibitory control, cognitive flexibility, and memory.

Significance of executive functions

Given that executive functions are fundamental skills in everyday life (Diamond, 2013), deficits in executive function can negatively affect the ability to do daily tasks and even interpersonal relationships. This is because thoughts and attitudes, such as each new situation, require good management of cognitive skills. Each executive function has an important purpose in our lives.

Inhibitory control is the ability to inhibit automatic or impulsive reactions, allowing one to maintain focus and concentration (Miyake et al., 2000). It also gives one the ability to control one's thoughts, feelings and behaviors which allows one to choose how and when to act (Diamond, 2013). There are different types of inhibitory control: inhibitory control of attention, cognitive inhibition, and self-control. Inhibitory control of attention is what allows one to focus only on what one chooses or needs, blocking out any other stimuli (Miyake et al., 2000; Diamond, 2013). During a fight, MMA athletes need a high level of concentration to avoid the opponent's blows and thus reducing the risk of injury, especially head injury. Therefore, it is necessary to silence the surrounding stimuli (audience noise, narrators, etc.) using inhibitory control of attention that allows one to focus on only what is needed.

Cognitive inhibition is related to regulating unpleasant memory or thoughts, as well as blocking out previous knowledge that may interfere with the acquisition of new information. Self-control involves having discipline to perform tasks, even if they are boring tasks or there are distractions. In addition, self-control is related to resisting temptation (e.g., not eating sweets when on a restricted diet) and postponing gratifications for a greater reward (e.g., postponing a moment of leisure to train for a fight; Diamond, 2013).

Working memory involves monitoring and coding information by relevance according to the task to be performed. In one's working memory, information is stored and worked gradually. It allows individuals to mentally manipulate information even when stimuli are unfamiliar. In addition, any mathematical operation that is completed mentally requires the use of working memory. The same is true when one thinks of a to-do list, when one translates something, or when one needs to connect information to reach a conclusion. Working memory differs from short-term memory because short-term memory only stores information for a period of time and working memory mentally manipulates information received (Diamond, 2013; Miyake et al., 2000).

Cognitive flexibility refers to the ability to switch between spatial or interpersonal perspectives, alternating tasks, mental sets, or calculations. It is strongly related to inhibitory control and working memory as changing perspective requires inhibiting prior knowledge in order to be open to new information and to mentally work with it. Another aspect of cognitive flexibility is related to viewing things from various perspectives, considering possible alternatives for accomplishing something. In addition, it is also associated with being flexible to meet demands and admitting when one makes a mistake (Diamond, 2013; Miyake et al., 2000). In the study by Whiting et al. (2017), they found that cognitive flexibility was impaired due to brain trauma in addition to a deficit that implies poor problem solving ability.

Regarding high-order executive functions, problem solving can be understood as an interaction between the subject and the environmental demands, which requires a mental representation of a problem and an outline of the necessary steps to solve it. An outline of ways to reach a goal refers to another cognitive skill: planning (Morris & Ward, 2005; Primi & Nakano, 2015). Working memory seems to directly imply the ability to plan as it is necessary not only to access information contained in memory, but also managing this information to reach an effective solution (Morris & Ward, 2005; Primi & Nakano, 2015).

Processing speed, another important aspect of cognition, is a skill related to how quickly an individual processes various types of information. It is considered essential for the performance of other cognitive skills, especially working memory, due to its relationship with stimulus processing time. Thus, a deficit in processing speed could suggest poor performance in other cognitive functions (Clay et al, 2019; Tourva, Spanoudis, & Demetriov, 201; Salthouse, 1996; Gorman et al, 2016).

Neurophysiological implications

The brain works through intricate neural connections that facilitate interaction between different brain regions (Zanto & Gazzaley, 2013; Cole et al., 2013). Neuroimaging studies show the regions most associated with executive functions are the frontal, parietal and cerebellar lobes (Nowrangi et al., 2014). During training and fights, MMA athletes receive several blows to the head, especially in the most frontal and lateral regions of the head (Jensen et al., 2017; Hutchison et al., 2014). The relationship found in this study between concussion symptoms and deficits in cognitive flexibility, processing speed, and problem solving may possibly be due to damage to specific brain regions. In a study by Moll and colleagues (2002), a strong association was found between the prefrontal cortex and cognitive flexibility. The study was conducted using fMRI during completion of the TMT test. Data indicated substantial activation of the prefrontal, dorsolateral, and medial cortices; areas having important influences on cognitive flexibility. Activation of the prefrontal cortex is also associated with processing speed (Barbey et al., 2015; Whiting et al., 2017) and problem solving (Newman et al., 2003).

Long-term exposure to head trauma in MMA

No relationship was found between years of sport practice and the concussion history. This differs from the literature that highlights a significant relationship between these variables. Melo and Filgueiras (2018) found a relationship between years of practice and concussion history when comparing amateur and elite kickboxers showing that the longer the athletic career, the greater the concussion history. Similarly, Renton, Howitt and Marshall (2019) conducted a study with hockey players, where a significant relationship was found between years of practice and concussion history. The explanation for this finding is that athletes with longer athletic careers would have more exposure to the risk of concussion.

There are four possible hypotheses to explain why the results about years of practice differ from the literature. The first hypothesis considers the number of hours of practice per week. Second, the participants may have been able to develop an ability to avoid blows to the head, unlike athletes from other close contact sports, like hockey (Renton, Howitt, & Marshall, 2019). Certainly, a key objective of MMA is to avoid head traumas that could lead to a knockout. The third hypothesis relates to the ceiling effect, as the sample only consisted of elite athletes, all at the same level of technical ability, which was in contrast to previous findings. For instance, the sample from Melo and Filgueiras (2018) included both elite and amateur kickboxers. The fourth hypothesis is that the sample size was not adequately powered to find results consistent with the literature.

Limitations and future research

One limitation of the present study is that data were cross-sectional, being collected all in one day. In the literature, there is a lack of longitudinal studies on MMA athletes investigating the long-term risks of concussions. Another limitation is the sample of the present study. Our sample included 16 athletes, a quantity that is not representative of the population. We also did not include a comparison group of age-matched controls, which might inform about any effects of aging. Therefore, further studies are needed to investigate the consequences of concussions on the executive functions of MMA athletes and how these develop over time.

Conclusion

In recent decades, studies on concussion in sport have gained increased visibility because these injuries result in the development of neuropsychological deficits, and they are also associated with increased risk of death due to severe brain trauma. Our findings suggest that due to the high incidence of concussions, MMA athletes tend to suffer deficits in executive function. More specifically, the executive functions most associated with concussion symptoms were cognitive flexibility, processing speed, and problem solving. This finding is in line with previous studies that have investigated the consequences of concussion on executive function in and out of sports. MMA does not appear to be different from boxing in terms of neuropsychological risks for athletes, as concussions can result in the development of dementia and depression symptoms. Therefore, careful monitoring of important indices of executive function in mixed martials arts may be important for both athletic success, health, and vitality both in the short-term and long-term – even well after retirement.

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Data and Code Availability

The dataset and R code presented in this study is available open access at the Open Science Framework. It can be found at: https://doi.org/10.17605/OSF.IO/BSQJT.

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Table 1 Mean and standard deviation of demographic variables and executive functions tests.

Variables	Athletes (n=16)	
	M	***SD***
Demographic Data		
Age (y)	26.19	4.31
Education (y)	11.81	2.00
Years of Practice	7.88	5.19
Number of Fights	12.5	8.56
Total concussion symptom history	36.69	23.39
ExecutiveFunctioningTests		
Tower of Hanoi	358.50	237.31
5 Points – Repeated	3.12	0.96
5 Points - Different	5.75	2.79
Foward-DigitSpan	6.31	1.01
Backward-DigitSpan	5.69	1.14
Trail Making Test – Part A	22.00	6.50
Trail Making Test – Part B	54.58	31.71
Stroop	19.25	6.17

Table 2 Results of multiple linear regression to predict total concussion symptom history.

Intercept and Coefficients of Regression				
Executive Functions Tests	*ß*	*SE*	*T-Test*	*P*
5 Points – Repeated	14.283	4.949	2.886	0.001
5 Points - Different	4.492	1.517	2.961	0.001
Tower of Hanoi	-0.023	0.018	-1.287	0.022
Trail Making Test – Part A	-0.927	0.632	-1.466	0.017
Trail Making Test – Part B	0.604	0.144	4.179	<0.001
Intercept	-37.772			

Note: The Stroop Test and Forward- and Backward-digit Span tests were not significant and were dropped in the stepwise analysis.