OPEN

A Systematic Review and Meta-Analysis Investigating Head Trauma in Boxing

Robert R. Donnelly, BSc,*† Ukadike Chris Ugbolue, PhD,*† Yang Gao, PhD,‡ Yaodong Gu, PhD,†
Frédéric Dutheil, PhD,§ and Julien S. Baker, PhD‡

Abstract

Objectives: Although physical trauma has been reported in boxing since its inception, boxing still appeals to athletes and spectators. This systematic review and meta-analysis assess both acute and chronic neurological and neuropsychological effects that boxing has on the brain. Further assessments in terms of comparisons of the concussion ratio in boxing to other combat sports, as well as the efficiency of wearing headguards, are also performed. **Data Sources:** This systematic review and meta-analysis used the Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines. The outcomes incorporated included physical chronic abnormalities of the brain, neuropsychiatric, and neurological disorders sustained in amateur or professional boxing, in addition to the safety benefits of boxing headguards. Odds ratios, descriptive statistics, and inferential statistics are also reported. **Main Results:** From the 84 articles reviewed, the 35 included articles suggested that boxers have a significantly elevated risk of sustaining a concussion compared with other combat sports (risk ratio [RR]: 0.253 vs RR: 0.065, $P < 0.001$). From the 631 amateur and professional boxers analyzed, 147 (23.30%) had cavum septum pellucidum, whereas 125 of 411 amateur and professional boxers (30.41%) presented with some form of brain atrophy. Dementia or amnesia was observed in 46 of 71 boxers (61.79%), 36 of 70 (51.43%) had various forms and severities of cognitive disorders, and 57 of 109 (52.29%) displayed abnormal computed tomography or electroencephalogram scan results. Utilization of headguards significantly increased the risk for stoppages in amateur bouts, compared with boxers not wearing a headguard (OR: 1.75 vs 0.53, $P < 0.050$). **Conclusions:** Boxing is a hazardous sport that has the potential to have fatal and negative life-changing results. Because of the limited reliable data regarding the efficiency of boxing headguards, future research should focus on the overall significance that headguards may have for reducing head trauma.

Key Words: boxing, brain, concussion, concussion ratio, combat sports, headguard

(*Clin J Sport Med* 2023;33:658–674)

INTRODUCTION

The sport of boxing consists of participants enduring repeated blunt force trauma to the head and body. Trauma inflicted to the cranium has led to an array of acute, subacute, and chronic neurological and neuropsychological complications, as well as death in the ring. Despite this, the safety of the participants had not been a concern until 1866 when rules banned the use of spikes on the gloves, introduced weight categories, and the 10-second knockout rule.[1] The rules were further amended in 1987 by the World Boxing Association. The association

Submitted for publication January 27, 2022; accepted May 22, 2023.

*From the *Faculty of Sports Science, Ningbo University, Ningbo, China; †School of Health and Life Sciences, Institute for Clinical Exercise & Health Science, University of the West of Scotland, South Lanarkshire, Scotland, United Kingdom; ‡Centre for Health and Exercise Science Research, Department of Sport, Physical Education and Health, Hong Kong Baptist University, Kowloon Tong, Hong Kong; and §CNRS, LaPSCo, Physiological and Psychosocial Stress, University Hospital of Clermont-Ferrand, CHU Clermont-Ferrand, Preventive and Occupational Medicine, WittyFit, Université Clermont Auvergne, Clermont-Ferrand, France.*

The authors report no conflicts of interest.

Conceptualization, R. R. Donnelly, U. C. Ugbolue and J. S. Baker; Data curation, R. R. Donnelly and U. C. Ugbolue; Formal analysis, R. R. Donnelly, U. C. Ugbolue, Y.Gao. and J. S. Baker; Investigation, R. R. Donnelly, U. C. Ugbolue, Y.Gao., Y.Gu., F. Dutheil and J. S. Baker; Methodology, R. R. Donnelly, and U. C. Ugbolue; Project administration, U. C. Ugbolue; Resources, U. C. Ugbolue and Y.Gu.; Software, R. R. Donnelly; Supervision, U. C. Ugbolue; Visualization, U. C. Ugbolue; Writing—original draft, R. R. Donnelly and U. C. Ugbolue; Writing—review and editing, U. C. Ugbolue, Y.Gao., Y.Gu., F. Dutheil and J. S. Baker. All authors have read and agreed to the published version of the manuscript.

No data are available. Data from this study has been acquired from published sources.

Patient consent for publication: Not required.

This study did not involve the use of patients; therefore, ethics documentation was not required.

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

Corresponding Author: Ukadike Chris Ugbolue, PhD, Biomechanics Laboratory, School of Health and Life Sciences, Institute for Clinical Exercise & Health Science, University of the West of Scotland, Lanarkshire Campus Stephenson Place, Hamilton International Technology Park, South Lanarkshire, G72 0LH Scotland, UK (u.ugbolue@uws.ac.uk).

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.cjsportmed.com).

http://dx.doi.org/10.1097/JSM.0000000000001195

reduced the maximum number of rounds in a match from 15 to 12, due to the death of lightweight boxer Duk Koo Kim, who died from acute neurological complications. The cause of death was most likely from an accumulation of blows ending with a knockout. However, in the modern era of boxing, the occurrences of neurological injuries have declined further because of expanded and improved medical and safety precautions, along with more efficient monitoring. Despite these improvements, the risk of traumatic brain injury/injuries (TBI) continue. Research published by Jordan et al[2] observed that approximately 20% of professional boxers develop a chronic traumatic brain injury (CTBI) during their careers, and up to 40% of retired professional boxers were diagnosed with symptoms of chronic brain injury (CBI).[3] Arguably, boxing's most famous practitioner, Muhammad Ali, is the most prominent example of an individual with a boxing-related neurological injury. Ali was diagnosed with the neurodegenerative disorder, Parkinson disease (PD) in 1984, which later contributed to his death in 2016. According to Baird et al,[4] between 1950 and 2007, there have been 339 deaths in professional boxing. In addition, in 2013, the International Boxing Association (AIBA) faced controversy over the changes in the rules in amateur boxing disallowing male senior boxers (participants older than 18 years old) to wear headguards during their bouts. This resulted in controversy due to the increased awareness of head injuries, in conjunction with concussion awareness in sports generally.[5]

A TBI is characterized as a blow or impact to the head interrupting the brain's normal function. Most TBIs are a direct result of the "acceleration-deceleration mechanism."[6] It may occur when the skull has been abruptly and violently struck by an object or when an object has cracked the skull and penetrated the brain tissue.[3] A TBI can be categorized as an mild TBI generally known as a concussion ranging from grade 1 to grade 3 or a CTBI that can be classified as chronic traumatic encephalopathy (CTE).[7] Concussions display almost an instantaneous and short-term reaction from the brain in response to trauma.[8] This display of concussion is usual but not always the case. A CTE is defined as a neurodegenerative disease that can manifest years after the initial incident.[9] This can result in physical shrinking of the brain, which can lead to neurological disorders such as Parkinson disease (PD), dementia, stroke, epilepsy, and seizures.[10] In terms of what is observed postmortem, observations from emerging data suggest that moderate and severe TBIs exhibit a dose–response trend as risk factors for neurodegenerative diseases, including cerebral atrophy.[11,12] In up to 30% of patients who died following a single TBI, the pathological findings showed the presence of diffuse axonal injuries and depositions of amyloid-β aggregates.[13–16] In addition, even a single TBI could induce progressive tau pathology for years after the initial injury, particularly in the presence of diffuse axonal injuries.[17]

Knockouts (KO) are the most common causes of acute neurologic injuries in boxing and are responsible for approximately 10 boxing deaths per year.[18] The loss of consciousness generated by a knockout punch is sudden in onset and generally temporary in duration. A KO is commonly due to a direct and clean strike to the face or jaw, resulting in an acceleration or torque rotational force, which is transferred to the brain. This impairs the cerebellum and brain stem, resulting in imbalance and unsteadiness causing the fighter to be incapable of posture control and defense.[19] Some boxers encounter persistent residual cognitive and physical symptoms, such as temporary short-term memory loss, dizziness, difficulty balancing, and headaches for days or weeks following a boxing bout. This is known as postconcussion syndrome (PCS) or "groggy state." Boxers regularly appear to recover symptomatically and return to their previous physical and cognitive state. However, boxers with longer and intense careers encounter prolonged durations of symptoms. In addition, when PCS becomes more frequent and increases in duration, the risk of chronic problems, including the progression of CTE can occur.[20]

Chronic traumatic brain injury or CTE in boxing, also referred to as "being punch drunk" or "dementia pugilistica," is believed to be the most severe health issue in modern boxing.[21] Chronic traumatic encephalopathy is characterized by a mix of gait and speech disruptions, pyramidal tract dysfunction extrapyramidal features, biochemistry disorders, behaviour or personality changes, and psychiatric disease.[22] In addition, motor impairments consisting of parkinsonism, hyperreflexia, dysarthria, spasticity, and cerebellar ataxia have also been recorded.[23] The distinct neuropsychiatric symptoms include childish behaviour, rage reactions, and mood swings. Chronic traumatic encephalopathy develops slowly or emerges after a brutal bout and typically occurs at the end of a boxer's career or quickly following retirement.[1] In addition, neuropsychological examinations have reported a deterioration in memory, processing information, attention span, and execution of basic functions.[24–26] In the infancy phase of CTE, the symptoms are sometimes temporary and reversible. However, as the neurodegenerative disease progresses, the symptoms become more severe. The pathology of CTE consists of pigmented cell loss, cerebellar tonsillar scarring, cerebral atrophy, cavum septum pellucidum (CSP), and neurofibrillary tangles.[27] However, the neuropathology of CTE can only be conclusively determined during a postmortem neuropathological examination.[28] In addition, there are no International Consensus Criteria or biomarkers of disease that exist and may be used to assist in the clinical examination and determination of CTE.[29,30]

In boxing, the headguard is worn during sparring and previously during amateur boxing bouts. The utilization of headguards in amateur boxing was first introduced in 1984, with the purpose of preventing and decreasing the chances of superficial injuries such as cuts, rather than trauma to the brain.[31] The aim of amateur boxing was to outstrike the opponent. Points are awarded for the volume of punches accurately landed on the opponent. These rules were introduced to limit blows and injuries to the head; the body was targeted due to its large surface area, and the headguards and gloves used were heavily padded.[32] However, as previously mentioned, the AIBA prohibits the use of headguards in competitions. As a result, concerns over participants' safety have increased because the incidence of cuts and brain injuries continue to rise.[31]

Therefore, the rationale and purpose of this systematic review and meta-analysis was to determine the overall long-term injury (ie acute and chronic) of the brain resulting from participation in the sport of boxing. The objectives consisted of analyzing and comparing data outcomes in regard to physical chronic brain abnormalities, such as brain atrophy, and CSP within a population of boxers, along with neuropsychiatric and neurological disorders, for example dementia, amnesia, PD, and ataxic gait impairments (AGIs).

In addition, concussion rates between boxing and other combat sports, for example, karate and taekwondo, were compared and evaluated, as well as the safety and efficiency of headguards worn during boxing bouts.

METHOD

Search Strategy

This systematic review and meta-analysis used the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Figure 1). To summarize evidence relating to various head trauma within professional and amateur boxing, a search for relevant studies was performed in PubMed, Google Scholar, SAGE Journals, British Journal of Sports Medicine, Research Gate, and Science Direct using the key phrases of "Brain injuries within boxing" and "Efficiency of boxing headguards" from 1962 to 2020. The study included articles that were peer and independently reviewed, which reported data from cohort studies, case studies, or cross-sectional studies. Excluded articles consisted of data not published in English, conference posters, data from interventional studies, along with articles that contained boxing injuries that occur to the head or face, such as cuts or broken bones, and injuries or impairments to the brain that were not directly related to boxing.

Eligibility Criteria

The initial abstracts were analyzed using the search engines using the following principles: (1) data reported on participants who were either current or former professional or amateur

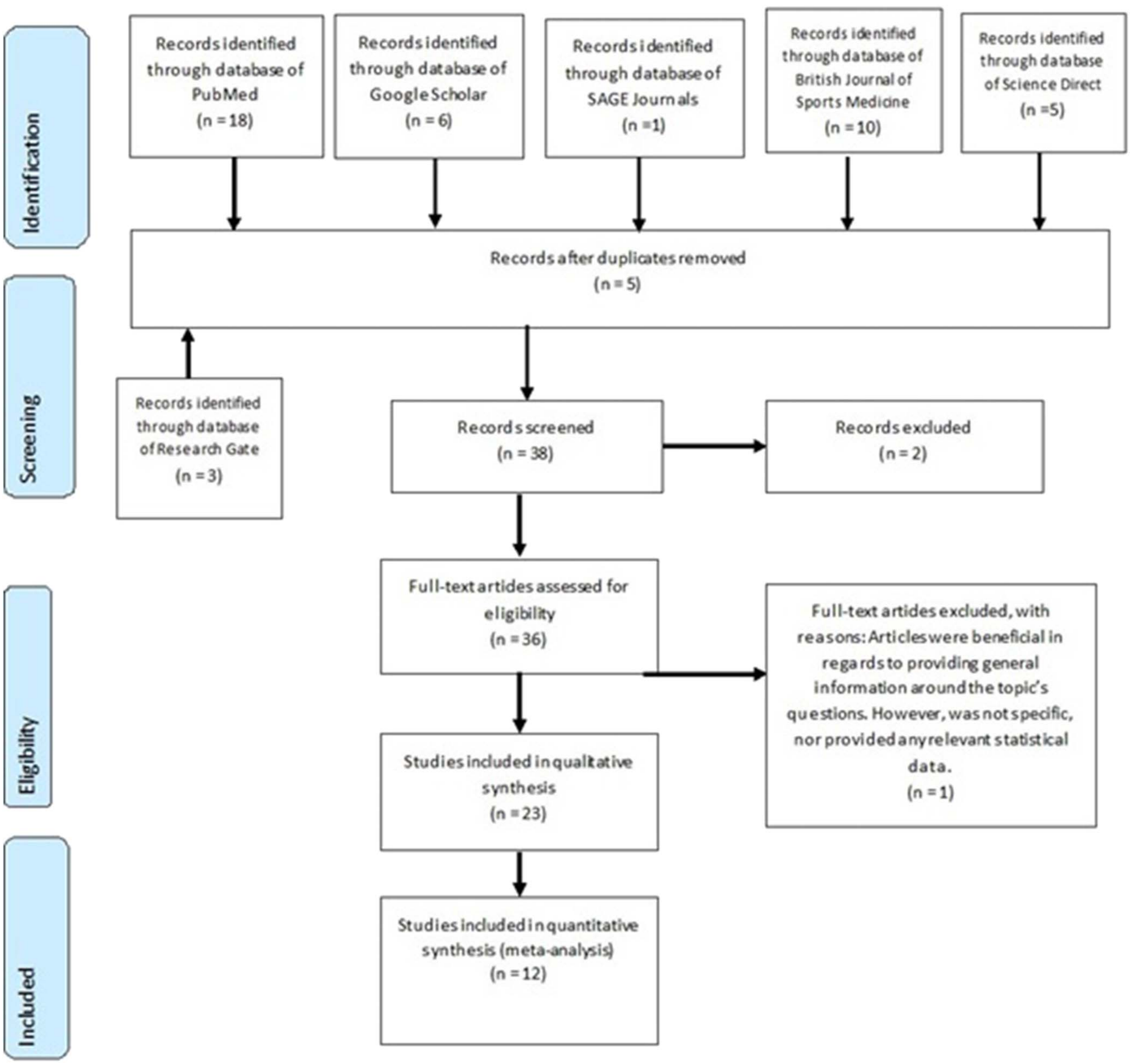

Figure 1. PRISMA Flow Chart showing the search procedures and outputs.

boxers. (2) The boxers had to have at least 5 bouts or career durations of at least 1 year. (3) Data focused on chronic physical brain abnormalities, neuropsychiatric impairment, and neurological impairments within a specific populace evaluated the efficiency of headguards within boxing or compared concussions within boxing with other combat sports.

Eligibility Criteria Rationale

The rationale for the included studies was to execute the objectives of this study, which were to investigate injury to brain in the sport of boxing. Therefore, the participants within the studies were either current or former amateur or professional boxers. The purpose of having a boxing population was to evaluate the risk ratio (RR) of chronic physical brain abnormalities, neuropsychiatric impairment, and neurological impairments within a specific populace, along with evaluating the efficiency of headguards within boxing. This could be completed by comparing the RR of wearing and not wearing a headguard in amateur boxing bouts and sparring. Furthermore, the rationale of comparing the occurrence of concussions between boxing and other combat sports was to determine the safety of boxing by analyzing and contrasting the rate of concussion per 100 participants.

Exclusion Criteria

To determine any prejudice with 1 or more published sources, the Cochrane Risk of Bias Assessment Tool (**Supplemental Digital Content 1**, http://links.lww.com/JSM/A396) was used. Any sources that were identified as having bias were excluded.

Data Extracted

The data extracted included the year of publication, main author/s, study design, populations' training status (amateur or professional), activity type (sparring or bouts), the number of participants, brain injuries sustained, specific anatomical location within the brain (cerebrum, cerebellum, frontal lobe), and the type of neurological or neuropsychological impairment. The outcomes incorporated included physical chronic abnormalities of the brain, neuropsychiatric disorders, and neurological disorders sustained in amateur or professional boxing, in addition to the safety benefits of boxing headguards. These outcomes were then compiled into tables. The data and references obtained were then implemented into the Review Manager 5.4 software (Cochrane Rev Man, Copenhagen, Denmark) to analyze odds ratios (ORs).

Search Results

From the 6 search engines, a total of 52 335 results appeared, and 84 were shortlisted as potentially relevant to this review (Figure 1). After critical evaluation using the relative key phrases, 35 out of the remaining studies with full text were obtained and evaluated, which were then incorporated into this review.

Statistical Analysis

Review Manager 5.4 software (Cochrane Rev Man, Copenhagen, Denmark) was used to accumulate and process all the statistical data from the selected studies. The overall pooled effect was calculated using a fixed-effects meta-analysis method available in Review Manager 5.4 software (Cochrane Rev Man). The data type was dichotomous, and the effect measures were OR, and RR. The fixed-effects method applied was the Mantel–Haenszel (M–H).[33] For the meta-analysis, the fraction of variance due to heterogeneity was estimated by the statistic I^2. The bias of I^2 was calculated by considering whether the number of studies in the meta-analysis was small, that is, based on the Cochrane Library, the median number of studies per meta-analysis is 7 or less.[34] T-tests were also performed to analyze and determine the variation and significance between the comparisons.

Patient and Public Involvement

This is a systematic review and meta-analysis study; therefore, patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

RESULTS

Physical Chronic Brain Abnormalities Because of Boxing

From the 35 studies selected for this review, only 12 were declared suitable in providing sufficient information relating to physical chronic brain abnormalities due to boxing (Table 1).

The results in Figure 2A indicate that only 23.30% suffered from CSP (i.e. 147 of 631 amateur and professional boxers). Figure 2B shows that 30.41% possessed some form of brain atrophy (i.e 125 of 411 amateur and professional boxers).

Chronic Neuropsychiatric and Neurological Disorders within Boxing

A total of 12 study types that provided adequate information in relation to chronic neuropsychiatric or neurological disorders in boxers is presented in Table 2.

The meta-analyses results outlined in Figure 3A indicate that from a total population of 159 current and former boxers, only 86 (54.9%) had either chronic neuropsychiatric (NP) or neurological (NL) disorders related to boxing. The forest plot in Figure 3B demonstrates that 61.79% (i.e 46 of 71 current and former boxers) suffered from varying degrees of dementia or amnesia. Figure 3C illustrates that 51.42% (ie 36 of 70 active and former boxers) possessed various forms and severities of cognitive disorders, such as PD or AGIs, and Figure 3D illustrates that 52.29% (i.e 57 of 109 active and former boxers) possessed abnormal CT or EEG scan results.

Efficiency of Headguards

There was limited information on the effectiveness of headguards in boxing (Table 3). Only 5 appropriate study types were considered suitable to include, and from these 5 study types, 2 provided data on the AIBA 2013 rule change. Davis et al[58] highlighted that there was little difference between using and not using a headguard during amateur bouts. The data compared punches thrown and punches that contacted the head, pre and post the 2013 AIBA rule change. The following outputs were reported: rounds (Pre 2013—headguard: 29; Post 2013—without headguard: 50), total punches thrown expressed as an average (Pre 2013—headguard: 65.2; Post 2013—without headguard: 62.7),

TABLE 1. Overview of all Selected Studies on the Chronic Physical Abnormalities of the Brain Because of Amateur and Professional Boxing

Author (yr)	Data Type	Purpose	Participants' Background	Methods of Measurement	Findings
Lee et al (2020)	Case study	Determine whether combat sports (boxing and martial arts) with CSP and CV possess decreased volumes in brain structures and worse clinical outcomes on mood and cognitive testing	Fighters: 476 (440 male, 36 female. Age: 30.0 ± 8.2 years [range: 18-72 year old]) Control: 63 (57 male, 6 female. Age: 30.8 ± 9.6 years [range: 18-58 year old])	Data collected from 2011 to 2018 on active and retired professional fighters and healthy age-matched controls All controls and fighters underwent MRI scans	Fighters who possessed CV obtain significantly lower mean psychomotor speed (estimated difference, −11.3; 95% CI, −17.4 to −5.2; $P = 0.004$) and lower mean volumes in the supratentorium (estimated difference, −31 191 mm^3; 95% CI, −61 903 to −479 mm^3; $P = 0.05$) Longer CSPV length was associated with lower processing speed (slope, −0.39; 95% CI, −0.49 to −0.28; $P < 0.001$), psychomotor speed (slope, −0.43; 95% CI, −0.53 to −0.32; $P < 0.001$), and lower brain volumes in the supratentorium (slope, −1072 mm^3 for every 1-mm increase in CSPV length; 95% CI, −1655 to −489 mm^3; $P < 0.001$) Fighters with lower WMC possessed lower cognitive complexity
Bernick et al (2015)	Case study	Investigate the relationship between exposure variables, cognition, and MRI brain structural measures in a cohort of professional combatants	Fighters: 224 (131 mixed martial artists and 93 boxers. Age: range from 18 to 44 years, median of 27.7 year old) Control: 22. (age and gender was not described within this study)	MRI scans, along with cognitive function was assessed by a FES and a computer-based battery test that consists of 4 subtests of the CNS vital signs, including verbal memory, symbol digit coding, Stroop test, and a finger tapping test	Estimated reduction of brain volume for boxers relative to MMA fighters were 3.3% [$P = 0.006$] reduction on the thalamus, hippocampus reduction on the left was 2.0% and 4.2% ($P = 0.007$) Estimated reduction of overall brain volumes per year: 0.5% for boxers
Jordan et al (1996)	Case study	Evaluate the neuropsychological impairments that professional boxers develop as a consequence of sparring	Professional boxers: 42 (age: 25.6 year old [Range 19-31 year old]) Total amateur bouts: 55.6 bouts [range: 2-266 bouts]. Amateur losses: 6.2 [range: 1-33 losses] Total professional bouts: 10 bouts [range: 0-36 bouts] Professional losses 3.1 [range: 0-15 losses] Sparring exposure: frequency (d/wk): 3.6 days [range: 1-7 days]. Rounds per sparring session: 6.1 rounds [range: 2-12 round] Total rounds per week: 22.7 rounds [Range: 4-56] Sparring intensity (Marked on a scale of 1-4): 3.0 [Range: 2-4]	Each boxer underwent a CT scan, along with a battery of neuropsychological test. These consisted of estimates of general intelligence, language, constructional skills, memory, visual motor coordination and concept formation, cognitive stability, and flexibility planning	CT scans demonstrated that 17 boxers (40.5%) possessed borderline brain atrophy, 2 boxers had large abnormal CT scans, and 1 abnormal scan exhibited a focal hypodense lesion in the left frontal lobe that was consistent with posttraumatic encephalomalacia. In addition, another scan displayed cerebellar atrophy with an enlarged fourth ventricle, and 6 boxers possessed cavum septum pellucidum (CSP) There was significant correlation in increased exposure to sparring and deterioration of neuropsychological functions ($P < 0.05$)

TABLE 1. Overview of all Selected Studies on the Chronic Physical Abnormalities of the Brain Because of Amateur and Professional Boxing *(Continued)*

Author (yr)	Data Type	Purpose	Participants' Background	Methods of Measurement	Findings
Casson et al (1984)	Case study	Examine the CTE effects boxing has on professional boxers at different levels (journey-men-champions), who have responsible jobs, secondary or college educations, and no history of substance abuse	Ex/professional and golden glove boxers: 18 (age: 36 ± 12.2 year old [range: 18-60 years old]) Total number of bouts: 88.2 ± 65.1 bouts [range: 7-240 bouts] Losses: 9.75 ± 7.9 losses [range: 2-26 losses] Length of career (years): 10.2 ± 5.5 years [range: 1-22 years]	Each boxer under a CT scan, an EEG, a formal neurological examination including mental status, and a battery of neuropsychological tests that consist of trail making test, the digit symbol test, the Wechsler memory test (including both verbal and visual memory), and the Bender Gestalt test	13 of 15 (87%) of ex and active professional boxers possessed abnormal results in at least 2 of the 4 tests (EEG, CT scan, neurological examination, and neuropsychological test battery). All 3 golden glove boxers obtained normal test results across the 4 tests 8 boxers had abnormal CT scans, 1 had cerebral cortical atrophy, 2 possessed central cerebral atrophy, and 5 had generalized cerebral atrophy. A cavum septum pellucidum was noted in 3 of these 8 scans
Ross et al (1983)	Case study	Examine the neurological status and CT appearance of brains' of exprofessional boxer	Exboxers: 40 (age: 46.8 ± 17.1 years old)	38 boxers underwent a CT scan, 24 boxers completed a neurological examination and an EEG, and 24 of these individuals also had a CT scan. CT scans were graded 0-4, 0 implied normal, and 4 implied most abnormal	The information gathered displayed a significant relationship between the number of bouts fought and CT changes ($P = 0.0229$), indicating cerebral atrophy. Positive neurological findings were not significantly correlated with the increase of bouts. EEG abnormalities were significantly correlated with the number of bouts ($P = 0.0582$)
Haaglund and Persson (1990)	Case study	To investigate possible chronic brain damage as a consequence of Swedish amateur boxing	Total number of former amateur boxers: 47 (22 boxers many bouts [HM], and 25 with few bouts [LM]) Age: 33 years old [range 25-44 years old] Career length: HM: 8.3 years [range: 2-17 years]. LM: 3.4 years [range: 1-8 years] Amateur bouts: HM: 54.3 bouts [range: 25-180 bouts]. LM: 5.5 bouts [range: 0-15 bouts] Total number of control group: 50 (25 football players, and 25 track and field athletes.) Age: 33 years old [range 25-44 years old]	All participants underwent EEG examinations, along with measuring brain electric activity mapping (BEAN)	No severe EEG abnormalities were identified in both boxing groups; BEAN findings were not significantly different from the control group. In addition, there were no neurophysiological variables that correlated with the number of amateur bouts, number of lost fights, or duration of a boxing career
Jordan and Zimmerman (1990)	Qualitative comparative analysis	Compare and analyze the differences between CT and MRI scans when examining 21 boxers	Total number of boxers: 21 (16 professionals, 4 amateurs, 1 retired) Age range: 21-66 years old	All participants underwent both CT and MRI scans. CT and MRI scans were then evaluated and compared with each other	11 boxers had normal results on the MRI and CT scans; 7 boxers had abnormal results on the MRI and CT scans; 4 boxers possessed hypodense lesions on CT scans. Out of these 4 boxers, 1 boxer had a dilated sulcus in the left frontal lobe. Another boxer's CT scan demonstrated hydrocephalus and atrophy

TABLE 1. Overview of all Selected Studies on the Chronic Physical Abnormalities of the Brain Because of Amateur and Professional Boxing *(Continued)*

Author (yr)	Data Type	Purpose	Participants' Background	Methods of Measurement	Findings
Jordan et al (1992)	Case study	Analyze 338 active professional boxer's CT scans	Total number of boxers: 338 professional boxers Age: range: 17-46 years old	All participants underwent a CT scan. CT scans were analyzed for the detection of any abnormalities	238 (70%) boxers had normal CT scans, 75 (23%) boxers displayed borderline CT scans, and 25 (7%) boxers possessed abnormal CT scans, 22 of these boxers had brain atrophy. 8 had ventricular atrophy, 6 possessed diffuse atrophy, and 3 boxers had focal lesions of low attenuation persistent along with posttraumatic encephalomalacia. There was no difference in scans between normal, borderline, and abnormal CT scans in regards to age, win/loss record, and number of bouts. Brain atrophy was acknowledged more often within boxers with a large CSP compared with boxers with a small or no CSP ($P < 0.05$). Boxers with abnormal or borderline CT scans who experienced a TKO or KO were slightly older than those with normal CT scans and a history of a TKO or KO (0 ($P < 0.05$)
Carsson et al (1982)	Qualitative short report	Evaluate the neurological effects of knocked out boxers	Total number of boxers: 10 professional boxers Age: 24.9 ± 3.4 years old [range: 20-31 years old] Number of bouts: 20.8 ± 16.3 bouts, [range: 2-52 bouts] Losses: 3.9 ± 2.7 losses [range: 1-11 losses]	All participants under EEG and CT scans	From the information gathered from the CT scans, 5 (50%) of boxers possessed cerebral atrophy and 1 suffered from CSP. EEG scans displayed that 2 boxers had minimal abnormalities
Jordan et al (1992)	Cohort study	Evaluate potential brain injuries within boxing	Total number of boxers: 45 professional boxers	All participants underwent 2 CT scans with a period of 31.3 months [range: 15-48 months] in between scans	Baseline scan: 33 boxers possessed normal CT scan, 9 had borderline brain atrophy, and 1 had moderate-severe brain atrophy; 6 of these 10 possessed CSP, and 2 had focal lesions Follow-up scan: 3 boxers displayed progressive CT changes. 31 boxers had normal CT scans, 10 possessed borderline brain atrophy, and 2 had moderate-serve brain atrophy; 9 of the 12 boxers possessed CSP, and 3 had focal lesions
Aviv et al (2010)	Case study	Identify the quantity and extent of a CSP among professional boxers	Total number of boxers: 164 boxers Control group: 43 control participants	All participants underwent MRI scans	81 boxers possessed medium size CSP, and 13 boxers possessed large size CSP

TABLE 1. Overview of all Selected Studies on the Chronic Physical Abnormalities of the Brain Because of Amateur and Professional Boxing *(Continued)*

Author (yr)	Data Type	Purpose	Participants' Background	Methods of Measurement	Findings
Katse et al (1982)	Case study	Examine the neurological and psychological affect boxing has on the brain	Total number of boxers: 14 (8 amateur boxers, and 6 professional boxers.) Amateur boxers: age: 31 years old [range: 19-53 year old] Number of bouts: mean: 129 bouts Losses: 28 losses Professional boxers: age: 38 [range: 29-53 years old] Number of bouts: Mean: 148 bouts Number of losses: 35 losses	Each boxer had a neurological examination, and 12 boxers psychological examination. This included Wechsler adult intelligence scale and Wechsler memory scale. In addition, Wisconsin card-sorting test, trial-making test, Benton visual retention test, and the Purdue pegboard test were also incorporated; 6 boxers underwent an EEG (2 professional boxers, and 4 amateur boxers), and 5 boxers had a CT scan (4 professional boxers and 1 amateur boxer)	EEG results were abnormal for 6 boxers. Abnormalities were theta focus in 2 boxers, diffuse in 3 boxers, and paroxysmal theta in 1 boxer CT scans displayed brain atrophy in 3 (50%) of the professional boxers, CSP was acknowledged in 2 professionals and 1 amateur

FES, fight exposure score; WMC, working memory capacity.

punches landed expressed as a bout average (Pre 2013—headguard: 7.6; Post 2013—without headguard: 10), and punches landed to the head expressed as a bout average (Pre 2013—headguard: 6.3; Post 2013—without headguard: 8.9). There were no significant differences between the Pre 2013—headguard and the Post 2013—without headguard (P = 0.380). The RRs of punches landed to the head were 0.82 and 0.89 for the Pre 2013—headguard and Post 2013—without headguard, respectively. However, there was an average 25% increase in punches landed per bout and an average 30% increase in punches landed to the head.

Furthermore, the data reported by Loosemore et al, displayed that overall, stoppages due to blows to the head significantly decreased by 53.49% without using headguards, and stoppages per 1000 hours also significantly decreased by 57.09% without using headguards. Specifically, in their study comparing the stoppages due to contacts to the head pre and post 2013 AIBA rule change, the following outputs were reported: rounds (Pre 2013—headguard: 14 880; Post 2013—without headguard: 50), overall stoppages (Pre 2013—headguard: 43; Post 2013—without headguard: 62.7), stoppages per 10 000 rounds (Pre 2013—headguard: 28.9; Post 2013—without headguard: 10), and stoppages per 1000 hours (Pre 2013—headguard: 57.8; Post 2013—without headguard: 8.9). There were significant differences between the Pre 2013—headguard and the Post 2013—without headguard (P = 0.030). The RRs of stoppages were 1.75 and 0.53 for the Pre 2013—headguard and Post 2013—without headguard, respectively. When comparing concussions in boxing to other combat sports, karate and taekwondo were the most appropriate sports with data sets that provided adequate statistical information. This statistical information was used to determine the concussion and RRs of boxing, karate, and taekwondo. The concussion rate per 100 participants for taekwondo were reported as 0.8,[59] 1.2,[60] and 0.4.[61] For karate, the concussion rate per 100 participants were 0.4,[62] 0.9,[63] and 2.8.[64] For boxing, the concussion rate per 100 participants were 41.5,[65] 20.4,[66] and 14.0.[67] The concussion rates per 100 adult participants were between 0.4 and 1.2 for taekwondo, 0.4 and 2.8 for karate, and 14 and 41.5 for boxing. The RR for boxing was 0.253, whereas that for other combat sports was 0.065.

DISCUSSION

This systematic review and meta-analysis evaluated and compared published studies on chronic physical, neuropsychiatric, and neurological brain abnormalities that can occur within a combined amateur and professional boxing population, the risk of sustaining a concussion in boxing compared with other combat sports, and the efficiency of headguards to determine the overall safety of both amateur and professional boxing.

Prevalence of Physical Chronic Brain Abnormalities

Cavum septum pellucidums are benign growths of cystic midline cavities that are situated between the lateral ventricles and pass through the foramina of Monro.[68] The specific cause for the development of CSP is unclear. However, one theory is that the accumulation of repetitive trauma to the skull causes this physical brain abnormality.[69] Symptoms of a large CSP are seizures, headaches, changes in behaviour, learning difficulties, and deteriorated vision.[70]

Brain/cerebral atrophy can occur due to traumatic injuries to the head and is classified as the degeneration of cerebral tissue and neurons and supporting cells, for example, astrocytes, oligodendrocytes, connecting fibers, causing the brain to shrink over time. If the overall decreased volume of the brain is significant enough, the individual can suffer psychiatric impairments, cognitive deficits, and neurodegenerative diseases, such as dementia.[71] Decrease in brain volume is not dependent on brain atrophy, many brains with CTE do not have atrophy. However, CTE is related to cellular and connecting fiber injury, noted by tau and amyloid-β accumulation.

The probability of boxers developing CSP or brain atrophy, along with the symptoms that accompany these physical abnormalities was significantly low (OR: 0.13, $P < 0.001$ vs OR: 0.20, $P < 0.001$). An OR <1 suggests that the exposure (boxing) is associated with lower odds of outcome (CSP or brain atrophy). These findings support the statistical data from MacPherson and Teasdale[72] that diagnosed 55 of 1000 participants (5.5%) with CSP. The researchers concluded that the presence of CSP almost absolutely depicts an insistent congenital anomaly of no clinical significance, and besides from routine observation, CSP alone should not affect the career of a boxer. However, evidence from Jordan et al[41] illustrated that boxers with CSP possess decreased brain volumes and psychomotor ability and are 14% more likely to have brain atrophy. Therefore, from the data presented in this study in regards to physical chronic brain abnormalities, it is clear that these types of abnormalities can occur in a boxing population. However, there is lack of clarity on the overall impact these types of injuries have on a boxer's health, and thus, further research is required in this field.

Prevalence of Chronic Neuropsychiatric and Neurological Disorders

The awareness of neuropsychiatric and neurological disorders is infamously associated with boxing due to the exposure the disorders receive from popular boxing-related films and from iconic former professional boxers who suffered from dementia pugilistica, PD, and AGI, such as Muhammad Ali and Jake LaMotta. These disorders may be identified and associated with abnormal CT and EEG scans. However, from the data gathered from the studies that focused on chronic neuropsychiatric and neurological disorders, there was no significant difference ($P = 0.510$), nor any significant probability (OR: 1.19) between boxers possessing abnormal or normal CT or EEG scans. This trend continues because there was no significance ($P = 0.770$) to confirm that boxers will develop PD or AGI. However, the possibility of boxers developing these disorders was elevated compared with boxers developing abnormal CT or EEG scans (OR: 2.58 vs OR: 1.19). Despite this, there was a significantly greater likelihood (OR: 2.58, $P < 0.005$) that boxers would suffer from dementia in their lifetime. Research conducted by Roberts et al[27] explained the prevalence of dementia in boxers; their study outlines that repeated trauma to the brain increases the neurofibrillary tangles in the cortex and production of β-amyloid protein, which are both factors responsible for the development of dementia in individuals. These factors may alternatively be markers of dementia and provide evidence demonstrating the dangers of boxing and the potential consequences of having a career in the sport.

Headguards

Headguards in boxing apparently decrease the risk of injury and the data presented here agrees with this injury prevention strategy. The results highlight that the implementation of

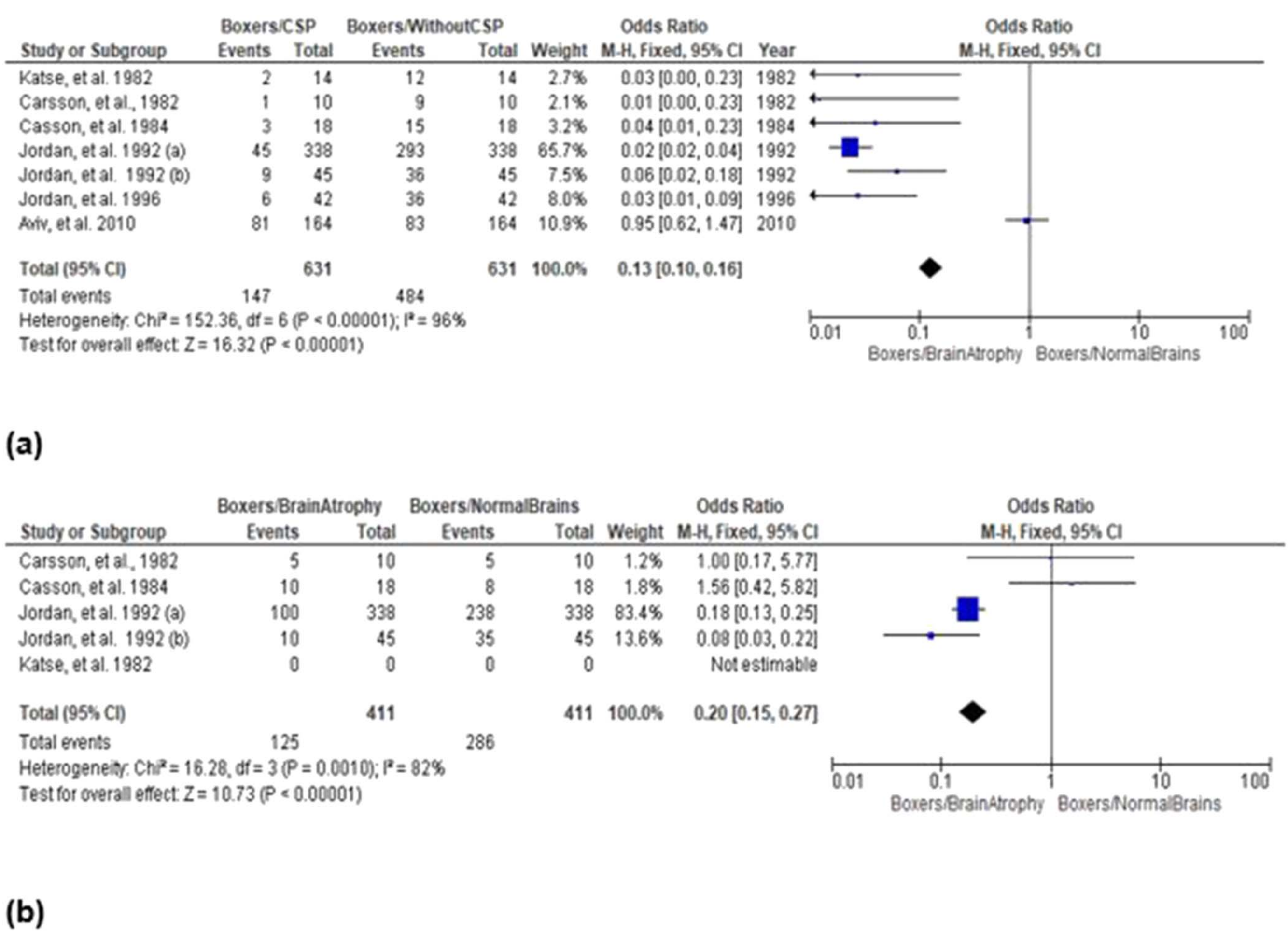

Figure 2. Forest plot showing (A) CSP results in a boxing population and (B) brain atrophy results in a boxing population.

TABLE 2. Overview of all Selected Studies on the Chronic Neuropsychiatric and Neurological Disorders Because of Amateur and Professional Boxing

Author (yr)	Study Type	Purpose	Participants' Background	Methods of Measurement	Findings
Johnson (1969)[46]	Case study	Examine the neuropsychiatric effects of head injuries sustained in former boxers	Exboxers: 17 (16 professional and 1 amateur) Age: 54 ± 8.5 [range: 35-64 years old] Bouts: all participants had 200-300 bouts between them	Participants underwent EEGs, AEG, and cognitive assessments	11 exboxers possessed amnesia 3 suffered from dementia 5 had morbid jealousy 4 had rage reactions, generally accompanied with pathological intoxication, and 2 had psychosis Cognitive assessments displayed slow information processing speed and memory difficulties
Jordan et al (1997)[21]	Case study	Assess the relationship between CTBI and APOE genotype in boxers	Professional boxers: 30 boxers Age: 48.9 ± 16.2 years old [range: 23-76 years old] Bouts: 30.0 ± 36.8 professional bouts [ange: 0-162 professional bouts]	All participants underwent APOE genotyping, behavioural and neurologic examinations. APOE was examined in relationship of CTBI. A 10-point clinical rating scale (0-9), a CBI scale was created to monitor the severity of CTBI associated with boxing	11 boxers had normal CBI scores 12 displayed mild impairments 4 were moderately deficit 3 possessed were severely impaired Boxers who had more with ≥12 professional bouts displayed significantly higher CBI scores than boxers with less than 12 professional bouts ($P < 0.001$) All boxers who possessed a severe impairment possessed at least 1 APOE e4 allele. Findings indicate that boxers who possess APOE e4 allele and have more than 12 professional bouts may be more likely to suffer from server chronic neurologic deficits
Dominic et al (2017)[47]	Case study	To determine the prevalence and elements of risk of PD within retired Filipino boxers	Exprofessional boxers: 21 exboxers Age: 38.19 ± 2.75 years old	All participants were screened for PD through the utilization of the motor part of the MDS—UPDRS	17 (80.95%) of boxers possessed PD. 10 (58.82%) had asymmetric PD. 10 boxers (58.82%) suffered for PD within the upper extremities 6 (35.29%) suffered from PD within the upper and lower extremities, and only 1 (5.88%) had PD within the lower extremities PD within boxers were significantly increased ($P = 0.0480$) with the number of losses, along with the number of knockouts suffered
Spillane (1962)[48]	Observational study	Describe the neurological deficits of 5 exprofessional boxers	Exprofessional boxers: 5 exboxers Age: 48.8 ± 11.8 years old [range: 33-69 years old] Professional bouts: all boxers had more than 200 bouts each	All participants had a PEG, and 2 had neurological examinations	Boxer 1 possessed progressive dysarthria, ataxic gait, AD, impairment of intelligence. Pneumoencephalogram (PEG) findings displayed an absence of the septum pellucidum Boxer 2 possessed progressive dysarthria, ataxia, right hemiparesis, right optic atrophy, and impaired intelligence. PEG displayed CSP. Boxer 3 suffered from progressive dementia along with serve dementia, and ataxia tremors. PEG revealed CSP, and enlarged lateral ventricles Case 4 possessed normal a PEG and neurological examination results Boxer 5 suffered from progressively worsening dysarthria, dragged his left leg. Neurological examinations displayed no dementia, but poor concentration, and PEG was normal. An autopsy revealed mental deterioration due to the degeneration of the left cerebral and cerebellar hemispheres

TABLE 2. Overview of all Selected Studies on the Chronic Neuropsychiatric and Neurological Disorders Because of Amateur and Professional Boxing *(Continued)*

Author (yr)	Study Type	Purpose	Participants' Background	Methods of Measurement	Findings
Mawdsley, and Ferguson (1963)[49]	Observational and case study	Examine the neurological diseases within boxers	Exprofessional boxers: 10 exboxers Age: 55.9 ± 8.9 years old [range: 33-69 years old] Professional bouts: 232.4 ± 175.6 bouts [range: 80- 600 bouts]	Every participant underwent clinical examinations	All boxers had some form of tremors, ranging from 1 limb to all 4, 8 exboxers possessed CSP 5 displayed EEG abnormalities 9 had abnormal AEGs 3 suffered from dementia 4 had grossly defected memories 6 had ataxic gaits and 8 had speech impairments, ranging from slurring words to dysarthria
Casson et al (1984)[38]	Case study	Examine the CTE affects boxing has on professional boxers a different levels (journey-men-champions), who have responsible jobs, secondary or college educations, and no history of substance abuse	Ex/professional and golden glove boxers: 18 (age: 36 ± 12.2 years old [range: 18-60 years old]) Total number of bouts: 88.2 ± 65.1 bouts [range: 7-240 bouts] Losses: 9.75 ± 7.9 losses [range: 2-26 losses] Length of career (years): 10.2 ± 5.5 years [range: 1-22 years]	Each boxer under a CT scan, an EEG, a formal neurological examination including mental status, and a battery of neuropsychological tests that consist of trail making test, the digit symbol test, the Wechsler memory test (including both verbal and visual memory), and the Bender Gestalt test	5 boxers possessed abnormal neurological examinations and 3 suffered from a memory loss, disorientation, and confusion 1 exboxer had an impaired recent memory without any confusion or disorientation 1 exboxer had an organic mental syndrome, and 1 exboxer had cortical release phenomena All boxers had abnormal Bender Gestalt test, verbal delay, verbal immediate results 11 boxers had visual delayed abnormalities 10 had abnormal trail making test results and 7 possessed abnormal digit symbol results
Drew et al (1986)[50]	Case study	Examine the neuropsychological deficits in active professional boxers	Professional boxers: 19 (age: 23.4 ± 2.95 years [range: 18-25 years old]) Amateur career: 52.8 ± 55.98 bouts [range: 1-195 bouts]. Losses: 5.2 ± 4.7 [range: 0-15 losses] Professional career: 13.7 ± 13.08 bouts [range: 0-37]. Losses: 3.8 ± 2.88 [range: 0-10] Control: 10 (age: 23.9 ± 2.59 years [range: 19-28 years old])	QNST, the RMT, and the HRNTB. Subtests within the QNST involved rapidly reversing Repetitive hand movements, finger to nose, thumb, and finger circle, tandem walk, and single foot stand. RMT was used to measure overall memory index. HRNTB consisted of subtest such as aphasia screening test, trails test, fingertip number writing Seashore rhythm, tactile performance test (TPT), finger tapping, and category test	Boxers who possessed a higher number of professional bouts and losses had a higher correlation of memory, cognitive, sensory motor impairments, along with cerebellar vestibular dysfunctions
Brooks et al (1987)[51]	Case study	Examine the neuropsychological affects within amateur boxers	Amateur boxers: 29 (age: 21 ± 3.1 years old. [range: 15-27 years old]); amateur bouts 26.2 ± 22.2 [range: 2-96]. Losses: 8.6 ± 7.4 [range: 0-32] Control: 19 (age: 21 ± 3.0 years old)	Cognitive test procedures included 3 subtests that consists of learning and memory, information processing and motor skill, and intelligence	There was no significant differences between the boxers and control group in terms of verbal intelligence, nor was there any significant predictors of impaired cognitive performance
Kaste et al (1982)[45]	Case study	Examine the neurological and psychological affect boxing has on the brain	Total number of boxers: 14 (8 amateur boxers, and 6 professional boxers.) Amateur boxers: age: 31 years old [range: 19-53 years old] Number of bouts: mean: 129 bouts Losses: 28 losses	Each boxer had a neurological examination, and 12 boxers psychological examination. This included Wechsler adult intelligence scale, and Wechsler memory scale. In addition, Wisconsin card-sorting test, trial-	One professional boxer had abnormal neurological results, apraxia and slight unsteadiness, along with slight slowness and uncertainty in mental functions EEG results were abnormal for 6 boxers Abnormalities were theta focus in 2 boxers, diffuse in 3 boxers, and paroxysmal theta in 1 boxer. Mean IQ (112 ± 15) was slightly above the normal national average (100 ± 15)

TABLE 2. Overview of all Selected Studies on the Chronic Neuropsychiatric and Neurological Disorders Because of Amateur and Professional Boxing *(Continued)*

Author (yr)	Study Type	Purpose	Participants' Background	Methods of Measurement	Findings
			Professional boxers: age: 38 [range: 29-53 years old] Number of bouts: mean: 148 bouts Number of losses: 35 losses	making test, Benton visual retention test, and the Purdue pegboard test were also incorporated; 6 boxers underwent an EEG (2 professional boxers and 4 amateur boxers), and 5 boxers had a CT scan (4 professional boxers and 1 amateur boxer)	However, 12 boxers took a longer time in the trail making test, compared with average performance times
Thomassen et al (1979)[52]	Qualitative comparative analysis	Display possible neurological consequences of amateur boxing	Total number of boxers: 53 amateur boxers Number of bouts: 76 ± 44 bouts [range: 19-209 bouts] Losses: 30 ± 16 losses [5-82 losses] Career length: 8 ± 3 years [range: 3-16 years] Control group: 53 former football players	Neurological, neuropsychological, and EEG examinations were completed on all participants	EEG results and neurological examinations did not display any significant differences between the 2 groups. Neuropsychological findings displayed a significant difference between the 2 groups ($P < 0.05$), as boxers possessed more dysfunctions in the motor function of the left hand, memory, and expressive speech
Bernick et al (2015)[36]		Investigate the relationship between exposure variables, cognition, and MRI brain structural measures in a cohort of professional combatants	Fighters: 224 (131 mixed martial artists and 93 boxers. Age: range from 18 to 44, median of 27.7 years old) Control: 22 (age and gender was not described within this study.)	MRI scans, along with cognitive function was assessed by a FES and a computer-based battery test that consists of 4 subtests of the CNS vital signs, including verbal memory, symbol digit coding, Stroop test, and a finger tapping test	Fighters who had more professional fights or an increased FES tended to have lower brain volumes, specifically the caudate and thalamus. In addition, processing speed declined in relationship to decreased thalamic volumes, along with increased fighting exposure. Increased scores on a FES used to reflect exposure to repetitive head trauma were linked with greater probability of possessing a cognitive impairment
McLatchie et al (1987)[53]		Examine evidence of abnormal neuronal dysfunction within active amateur boxers	Amateur boxers: 20 (age: 26 ± 8.1 years old [range: 18-49 years]). Amateur bouts: 61.8 ± 56.8 [range: 4-200 bouts]	Participants underwent an EEG and a CT scan. Neuropsychological function was assessed by means of clinical psychometric procedures and computer administered tests, such as the Wechsler memory scale	7 (35%) of participants displayed neurological abnormalities The most notable of these consisted of extensor plantar responses, and deterioration of rapid alternating movement of the hands and forearm Abnormal neurological examination significantly correlated with increasing number of fights ($P < 0.05$ Mann–Whitney *U* test) EEG abnormalities within 8 (40%) of participants were detected, many displayed local slow wave activity unrelated to any relevant medical history, and 2 displayed fast transients or discharges. However, did not possess a history of seizures 4 of the 8 EEG abnormalities (50%) also possessed an abnormal clinical examination Abnormalities within EEG significantly correlated with age ($P < 0.05$ Mann–Whitney *U* test), as the younger the participant, the increased likelihood of obtaining an abnormal EEG. CT scans were normal 9 (45%) of the boxers had poor performances on 2 or more clinical measurements

AEG, air encephalogram; APOE, apolipoprotein E; HRNTB, Halstead–Reitan neuropsychological test battery; MDS, Movement Disorder Society; PEG, pneumoencephalogram; QNST, quick neurological screening test; RMT, Randt memory test; UPDRS, Movement Disorder Society—Unified Parkinson's Disease rating Scale.

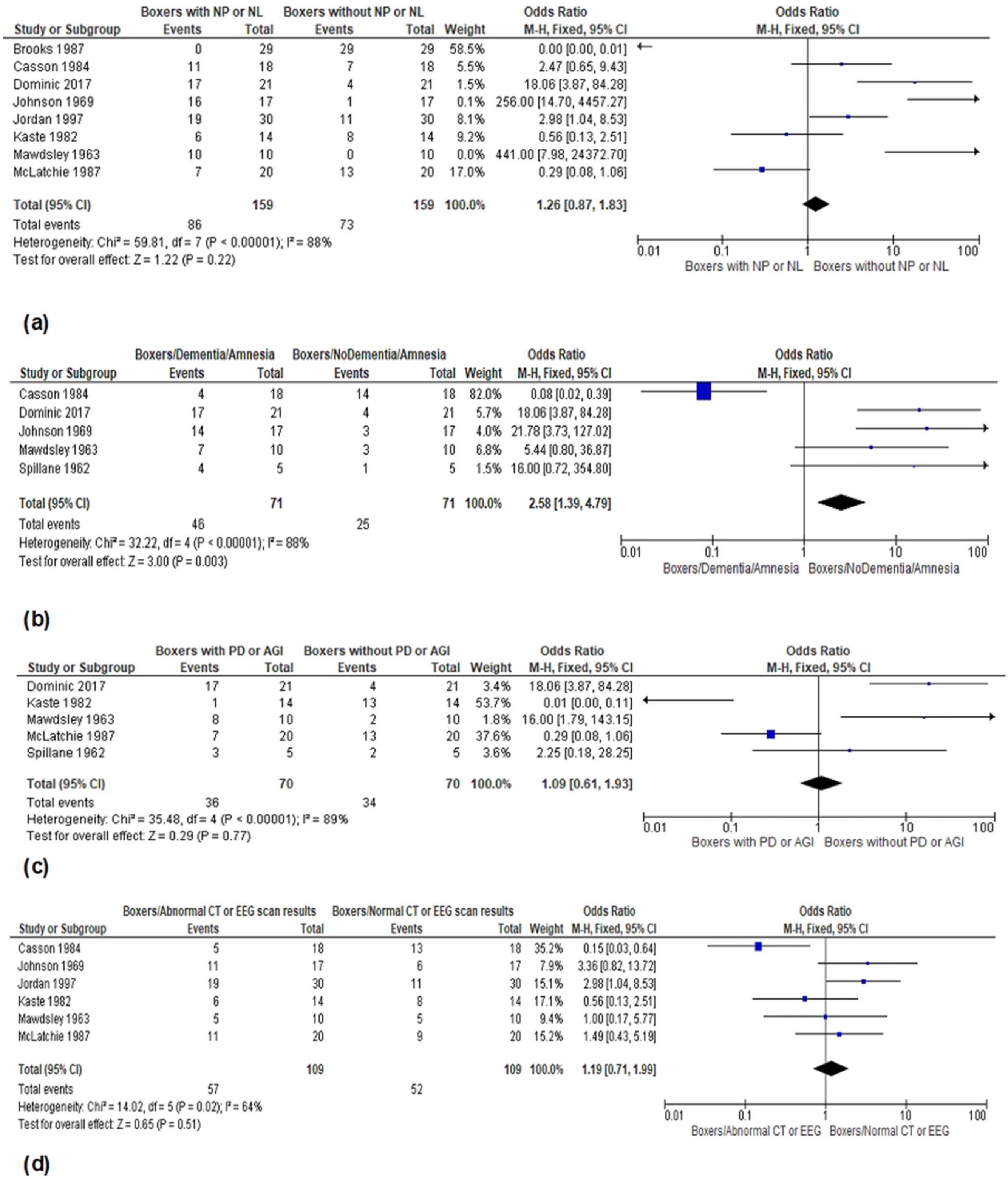

Figure 3. A display of forest plots showing (A) boxers who possess either NP or NL. (B) Boxers who possess dementia or amnesia. C, Boxers who possess PD or AGI, and (D) Boxers with abnormal CT or EEG scan results.

headguards reduced the peak linear and angular acceleration of a punch, along with decreasing impacts to the skull, therefore lowering the trauma delivered to the brain and, theoretically, making boxing safer as a sport. Although data were limited on the efficiency of headguards in boxing, it conflicted with this theory because the results established that there was no significant difference ($P > 0.050$) pre and post 2013 rule change in terms of risk of punches to the head (OR: 0.82 vs OR: 0.89). In addition, the pre-2013 rule change had a significant increased risk (RR: 1.75, $P < 0.005$) of a bout

TABLE 3. Overview of Selected Studies on the Impact of Headguards in Boxing

Author (yr)	Study Type	Purpose	Participants' Background	Methods of Measurement	Findings
McIntosh, and Patton (2015)[54]	Qualitative	Evaluate the impact energy attenuation performance on a variety of headguards designed for combat sports	Boxing headguards: Adidas (AIBA), and Top Ten Boxing (AIBA)	Lateral drop tests at 0.4, and 0.6 meters onto a flat rigid anvil, and a comparative reduction in peak headform acceleration with headguard only and glove only tests at 0.6, and 0.8 meters on a flat rigid anvil	Top Ten Boxing headguard possessed superior performance in comparison to the Adidas (AIBA). Mean peak acceleration was on average at all heights was between 32% and 40% lower at all meters for the Top Ten model compared with the Adidas boxing model
McIntosh, and Patton (2015)[55]	Qualitative	Examine the effects of headguards on head impact dynamics and injury risk	Boxing Headguards: Adidas (AIBA), and Top Ten Boxing (AIBA)	Linear impact was devised, and a variety of impacts was delivered to an instrumented Hybrid III head and neck system both with and without an AIBA approved headguards Impacts at selected speeds between 4.1 and 8.3 m/s were undertaken. The impactor mass was approximately 4 kg and an interface comprising a semirigid "fist" with a glove was used	Results displayed that linear and angular accelerations in 45 degrees forehead and 60 degrees jaw impacts were reduced by the headguards
Davis et al (2017)[56]	Cross-sectional observational study	To analyze and compare the effect of the rules change in 2013 on amateur boxing of discarding headguards	Pre-2013: 39 elite male amateur boxers Age: 25.1 ± 3.6 years old Post-2013: 60 elite male amateur boxers Age: 23.5 ± 2.8 years old	Analyze and compare over 10 finals and 19 semifinals bouts of the 2012 London Olympic Games to 10 finals, 20 semifinals, and 20 quarterfinals bouts of the 2015 Doha World Championships	Total punches thrown bout average: Pre-2013 = 65.2 ± 19.7 punches (range: 60.0 - 70.4 punches) Post-2013 = 62.7 ± 19.5 punches (range: 58.2-67.2 punches) Punches landed bout average: Pre-2013: 7.6 ± 5.9 punches (range: 6.0-9.1 punches). Post-2013: 10.0 ± 5.1 punches (range: 8.9-11.2 punches) Punches to the head bout average %: Pre 2013: 2013: 6.3 ± 5.4 punches (range: 6.0-6.5 punches) Post-2013: 8.9 ± 6.4 punches (range: 8.7-9 punches) Referee stop time(s) bout average: Pre 2013: 15.2 ± 10.7 s (range: 12.4-18.0 s) Post-2013: 11.7 ± 7.3 s (range: 10.0-13.4 s)
Loosemore (2016)[57]	Cross-sectional observational study	Analyze the alterations of the new rule of by the International Boxing Association (AIBA) to remove headguards from its competitions	All amateur boxers from the Milan 2009, Baku 2011, and Almaty 2013 world championships Age and number of bouts were not included in the study	Examine the number of stoppages due to blows to the head by comparing WSB, without headguards, to other AIBA competitions with headguards. Along with examining the last 3 world championships: 2009 and 2011 (with headguards) and 2013 (without headguards)	Rounds with headguard: 14 880 rounds Rounds without headguards: 13 992 rounds Stoppages with headguards: 45 stoppages Stoppages without headguards: 23 stoppages Cuts wit headguard: 45 cuts Cuts without headguard: 273 cuts Stoppages per 1000 rounds: with headguard = 28.9, without headguard = 16.5 Stoppages per 1000 hours: with headguards: 57.8, without headguards: 33.0

TABLE 3. Overview of Selected Studies on the Impact of Headguards in Boxing *(Continued)*

Author (yr)	Study Type	Purpose	Participants' Background	Methods of Measurement	Findings
Dau et al (2006) [32]	Qualitative	Measure the effectiveness of current headguards	AIBA approved headguard	Impact was recorded from 27 amateur boxers and was exerted onto the Hybrid III head and neck system both with and without an AIBA approved headguard	Punch force(N): with headguard: 2815.59 Without headguard: 4260.51 Punch velocity (m/s): with headguard: 9.57 m/s Without headguard: 8.43 m/s Peak angular acceleration (rad/ s^2): with headguard: 5534.78 Without headguard: 9164.10 Peak linear acceleration (g's): With headguard: 51.79 Without headguard: 78.04

AIBA, Amateur International Boxing Association; WSB, World Series Boxing.

stopping due to a blow to the head compared with post 2013 (RR 0.53). These results can be used to highlight the case that headguards are potential strike targets for boxers during bouts and have a larger surface area, therefore, increasing the number of punches attempted to the head, thus explaining the increased stoppages pre 2013. It may also be concluded that headguards promote punches to the head, subsequently increasing head trauma, rather than reducing head trauma.

Concussions in Boxing Compared with Other Combat Sports

There is always a risk of injuries involved in contact sports, and the risk of injury is undoubtedly elevated when participating in combat sports. Injuries to the head are responsible for 74% to 96% of the total injuries in boxing, with various grades of concussions being accountable for up to 75% of these injuries.[73] However, professional boxing is almost a different sport from amateur boxing, with different rules, equipment, and motivation to participate. Most importantly, there is a substantially greater cumulative risk of injury in youth to amateur to professional boxing, due to increased volume and force of strikes to the head over a longer duration career. When comparing the incidence of concussions in amateur boxing[66] to professional boxing,[65] amateur boxing was significantly safer than professional boxing ($P > 0.05$, concussions per 100 amateur boxing bouts 0.33/100 vs concussions per 100 professional boxing bouts 2.62/100). The smaller number of concussions in amateur boxing could be due to shorter bout durations and stricter safety considerations, such as the use of headguards and more padded boxing gloves. However, findings by Matser et al[74] depicted that amateur boxers still possess a 13% minimum chance of sustaining a concussion during a bout.

Research has illustrated that concussions in karate can occur once every 1156 matches or 0.43/1000 participants,[75] whereas a study completed by Koh et al[76] concluded that boxing possesses the highest frequency of concussions compared with other contact sports. The results in this review support these claims because the data accumulated illustrates that boxing contains a significantly higher risk of sustaining a concussion compared with other combat sports (OR: 0.253 vs 0.065, $P < 0.001$). This increases the potential occurrence of acute traumatic brain injuries, which can subsequently lead to CTBI. However, a study completed by Pappas[77] compared the total amount of injuries between boxing, wrestling, and martial arts between the years 2002 to 2005. Their results revealed that boxing has a lower injury rate compared with wrestling ($P = 0.003$), and only 3.2% of injuries sustained in boxing were concussions.

Limitations

Several limitations were noted when conducting this review and meta-analysis. There was insufficient research regarding headguard efficiency, and all headguard-related sources evaluated different aspects of the headguard, therefore not concluding the effectiveness and benefits of using a headguard in boxing. Moreover, some research articles within this review did not include a baseline, control, or age of the boxers, bouts, wins, losses, or knockouts suffered, consequently creating a wide variety of external factors that can potentially influence the reliability and validity of the results. Furthermore, there was no female representation within this review because there was very little data available for physical chronic brain abnormalities or chronic neuropsychiatric and neurological disorders in female amateur or professional boxers. This limited the potential of this study to highlight any gender discrepancies, including whether gender affects the development of brain-related disorders due to boxing or increases vulnerability to concussive events. All but 1 of the forest plots produced in this meta-analysis had less than 10 studies. Funnel plot methodology and Egger's regression intercept[78,79] were not calculated to assess the risk of publication bias. This was because in the study by Sterne and colleagues, it was stipulated that "as a rule of thumb, tests for funnel plot asymmetry should not be used when there are fewer than 10 studies in the meta-analysis because test power is usually too low to distinguish chance from real asymmetry."

CONCLUSIONS

The safety of amateur and professional boxing has been a concern for many years and has prompted debate on whether the rules should be altered or if the sports should be banned completely. This systematic review and meta-analysis does not attempt to encourage nor discourage the participation in amateur or professional boxing because this is a personal choice for individuals. The rationale behind accumulating data on both professional and amateur boxers and merging the findings into 1 outcome was to highlight the probability of the potential dangers and consequences of boxing and to outline the injuries that can be inflicted on the brain. The research in this review highlights that most of the strikes landed in either professional or amateur bouts are to the head, therefore risking the possibility of sustaining a concussion and potential brain disorder, regardless of the boxing level. In addition, most amateur boxers possess an extensive and lengthy career before turning professional. This summarizes the possible risks associated with a long-term boxing career for an amateur boxer considering progressing toward a professional career.

From the results presented here, boxing has the potential to be a very dangerous sport because participants possess a greater risk of sustaining a concussion compared with any other contact and combat sports that were reviewed in this study. In addition, professional boxing was significantly more dangerous than amateur boxing. Despite this, the findings also indicate that boxing may not be as dangerous as the media portrays and that the probability of boxers suffering from brain atrophy, PD, or AGI are all relatively low. However, these findings need further confirmation because in the CSP and dementia related data, some of the information gathered on brain atrophy, PD, and AGI did not contain baseline measures such as length of career, number of bouts, or knockouts.

Our results indicate that boxing is a hazardous sport and has the potential to have fatal and negative life-changing consequences. Although there are many multiple factors that can influence the severity of head injuries sustained by boxers, there is little research in the literature regarding the efficiency of boxing headguards, thus making it difficult to determine with confidence the overall significance that headguards may or may not have in reducing head trauma during boxing.

ACKNOWLEDGMENTS

The authors acknowledge the support from the Key R&D Program of Zhejiang Province China (2021C03130), Public Welfare Science and Technology Project of Ningbo, China (2021S133), Zhejiang Province Science Fund for Distinguished Young Scholars (R22A021199).

References

1. Mendez MF. The neuropsychiatric aspects of boxing. *Int J Psychiatry Med*. 1995;25:249–262.
2. Jordan BD. *Chronic Traumatic Brain Injury Associated With Boxing*. New York, NY: Thieme Medical Publishers, Inc.; 2000:179–186.
3. Agarwal N, Thakkar R, Than K. *Sports Related Head Injury*. American Association of Neurological Surgeons; 2021. Available at: https://www.aans.org/Patients/Neurosurgical-Conditions-and-Treatments/Sports-related-Head-Injury#:~:tex=In%20several%20studies%2C%2015%2D40,some%20degree%20of%20brain%20damage. Accessed July 10, 2023.
4. Baird LC, Newman CB, Volk H, et al. Mortality resulting from head injury in professional boxing: case report. *Neurosurgery*. 2010;67:E519–E520.
5. Murray IR, Murray AD, Robson J. Sports concussion: time for a culture change. *Clin J Sport Med*. 2015;25:75–77.
6. Graham DI, Luntos P. Greenfield's neuropathology. *Eur J Neurol*. 2002; 9:705.
7. Blennow K, Hardy J, Zetterberg H. The neuropathology and neurobiology of traumatic brain injury. *Neuron*. 2012;76:886–899.
8. McCrory P, Feddermann-Demont N, Dvořák J, et al. What is the definition of sports-related concussion: a systematic review. *Br J Sports Med*. 2017;51:877–887.
9. Baugh CM, Robbins CA, Stern RA, et al. Current understanding of chronic traumatic encephalopathy. *Curr Treat Options Neurol*. 2014;16: 306.
10. Townsend A. *Repeated Boxing Head Injuries Cause Brain Shrinkage*. MedicineNet Health News; 2020. Available at: https://www.medicinenet.com/boxing_head_injuries_cause_brain_shrinkage/news.htm. Accessed January 08, 2020.
11. Ding K, Marquez de la Plata C, Wang JY, et al. Cerebral atrophy after traumatic white matter injury: correlation with acute neuroimaging and outcome. *J Neurotrauma*. 2008;25:1433–1440.
12. Warner MA, Youn TS, Davis T, et al. Regionally selective atrophy after traumatic axonal injury. *Arch Neurol*. 2010;67:1336–1344.
13. Chen XH, Johnson VE, Uryu K, et al. A lack of amyloid β plaques despite persistent accumulation of amyloid β in axons of long-term survivors of traumatic brain injury. *Brain Pathol*. 2009;19:214–223.
14. Roberts G, Gentleman S, Lynch A, et al. Beta amyloid protein deposition in the brain after severe head injury: implications for the pathogenesis of Alzheimer's disease. *J Neurol Neurosurg Psychiatry*. 1994;57:419–425.
15. Sherriff F, Bridges L, Sivaloganathan S. Early detection of axonal injury after human head trauma using immunocytochemistry for β-amyloid precursor protein. *Acta Neuropathol*. 1994;87:55–62.
16. Uryu K, Chen X-H, Martinez D, et al. Multiple proteins implicated in neurodegenerative diseases accumulate in axons after brain trauma in humans. *Exp Neurol*. 2007;208:185–192.
17. Katsumoto A, Takeuchi H, Tanaka F. Tau pathology in chronic traumatic encephalopathy and Alzheimer's disease: similarities and differences. *Front Neurol*. 2019;10:980.
18. Ling H, Hardy J, Zetterberg H. Neurological consequences of traumatic brain injuries in sports. *Mol Cell Neurosci*. 2015;66:114–122.
19. Morrison RG. Medical and public health aspects of boxing. *JAMA*. 1986; 255:2475–2480.
20. Heilbronner RL, Bush SS, Ravdin LD, et al. Neuropsychological consequences of boxing and recommendations to improve safety: a National Academy of Neuropsychology education paper. *Arch Clin Neuropsychol*. 2009;24:11–19.
21. Jordan BD, Relkin NR, Ravdin LD, et al. Apolipoprotein E epsilon4 associated with chronic traumatic brain injury in boxing. *JAMA*. 1997; 278:136–140.
22. McCrory P. Boxing and the brain. Revisiting chronic traumatic encephalopathy. *Br J Sports Med*. 2002;36:2.
23. Jordan BD. Neurologic aspects of boxing. *Arch Neurol*. 1987;44: 453–459.
24. Carlsson GS, Svärdsudd K, Welin L. Long-term effects of head injuries sustained during life in three male populations. *J Neurosurg*. 1987;67: 197–205.
25. Ross RJ, Casson IR, Siegel O, et al. Boxing injuries: neurologic, radiologic, and neuropsychologic evaluation. *Clin Sports Med*. 1987;6:41–51.
26. Jordan B, Jahre C, Hauser W, et al. CT of 338 active professional boxers. *Radiology*. 1992;185:509–512.
27. Roberts GW, Allsop D, Bruton C. The occult aftermath of boxing. *J Neurol Neurosurg Psychiatry*. 1990;53:373–378.
28. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *J Neuropathol Exp Neurol*. 2009;68:709–735.
29. Stern RA, Daneshvar DH, Baugh CM, et al. Clinical presentation of chronic traumatic encephalopathy. *Neurology*. 2013;81:1122–1129.
30. Mez J, Stern RA, McKee AC. Chronic traumatic encephalopathy: where are we and where are we going? *Curr Neurol Neurosci Rep*. 2013;13:407.
31. Dickinson P, Rempel P. Prohibiting headgear for safety in amateur boxing? Opinion of the Canadian boxing community: an online poll. *Sports Med-Open*. 2016;2:1–11.
32. Dau N, Chien HC, Sherman D, et al. *Effectiveness of Boxing Headgear for Limiting Injury*. Blacksburg, VA: Annual Conference of the American Society of Biomechanics; 2006.
33. Higgins JP, Thomas J, Chandler J, et al. *Cochrane Handbook for Systematic Reviews of Interventions Version 6.2 (Updated February 2021)*. John Wiley & Sons; 2021.
34. von Hippel PT. The heterogeneity statistic I 2 can be biased in small meta-analyses. *BMC Med Res Methodol*. 2015;15:35–38.
35. Lee JK, Wu J, Bullen J, Banks S, et al. Association of cavum septum pellucidum and cavum vergae with cognition, mood, and brain volumes in professional fighters. *JAMA Neurol*. 2020;77:35–42.
36. Bernick C, Banks SJ, Shin W, et al. Repeated head trauma is associated with smaller thalamic volumes and slower processing speed: the Professional Fighters' Brain Health Study. *Br J Sports Med*. 2015;49:1007–1711.
37. Jordan BD, Matser EJ, Zimmerman RD, Zazula T. Sparring and cognitive function in professional boxers. *Phys Sportsmed*. 1996;24:87-98.
38. Casson IR, Siegel O, Sham R, et al. Brain damage in modern boxers. *JAMA*. 1984;251:2663–2667.

39. Ross RJ, Cole M, Thompson JS, Kim KH. Boxers—computed tomography, EEG, and neurological evaluation. *JAMA*. 1983;249:211–213.
40. Haglund Y, Persson H. Does Swedish amateur boxing lead to chronic brain damage? 3. A retrospective clinical neurophysiological study. *Acta Neurol Scand*. 1990;82:353–360.
41. Jordan BD, Zimmerman RD. Neurological Injuries in Boxers: The Use of Tests-Reply. *JAMA*. 1990;264(12):1532–1533.
42. Jordan BD, Jahre C, Hauser WA, et al. Serial computed tomography in professional boxers. *J Neuroimag*. 1992;2:181–185.
43. Casson IR, Sham R, Campbell EA, et al. Neurological and CT evaluation of knocked-out boxers. *J Neurol Neurosurg Psychiatry*. 1982;45:170–174.
44. Aviv RI, Tomlinson G, Kendall B, et al. Cavum septi pellucidi in boxers. *Can Assoc Radiol J*. 2010;61:29–32.
45. Kaste M, Vilkki J, Sainio K, et al. Is chronic brain damage in boxing a hazard of the past? *Lancet*. 1982;320:1186–1188.
46. Johnson J Organic psychosyndromes due to boxing. *Br J Psychiatry*. 1969;115:45–53.
47. Jamora RDG, Shiong Shu LL, Cenina ARF, et al. Parkinsonism among retired Filipino boxers. *Basal Ganglia*. 2017;10:1–3.
48. Spillane JD. Five boxers. *Br Med J*. 1962;2:1205–1210.
49. Mawdsley C, Ferguson F. Neurological disease in boxers. *Lancet*. 1963; 282:795–801.
50. Drew RH, Schuyler BA, Templer DI, et al. Neuropsychological deficits in active licensed professional boxers. *J Clin Psychol*. 1986;42:520–52.
51. Brooks N, Kupshik G, Wilson L, et al. A neuropsychological study of active amateur boxers. *J Neurol Neurosurg Psychiatry*. 1987;50:997–1000.
52. Thomassen A, Juul-Jensen P, de Fine Olivarius B, et al. Neurological, electroencephalographic and neuropsychological examination of 53 former amateur boxers. *Acta Neurol Scand*. 1979;60:352–362.
53. McLatchie G, Brooks N, Galbraith S, et al. Clinical neurological examination, neuropsychology, electroencephalography and computed tomographic head scanning in active amateur boxers. *J Neurol Neurosurg Psychiatry*. 1987;50:96–99.
54. McIntosh AS, Patton DA. The impact performance of headguards for combat sports. *Br J Sports Med*. 2015;49:1113–1117.
55. McIntosh AS, Patton DA. Boxing headguard performance in punch machine tests. *Br J Sports Med*. 2015;49:1108–1112.
56. Davis P, Connorton A, Driver S, et al. The activity profile of elite male amateur boxing following the 2013 rule changes. *J Streng Cond Res*. 2017;32. 10.1519/JSC.0000000000001864.
57. Loosemore M. The Pathophysiology of Boxing Injuries; Student thesis: Doctoral Thesis › PhD. 2018. Accessed November 01, 2015.
58. Davis P, Waldock R, Connorton A, et al. Comparison of amateur boxing before and after the 2013 rules change and the impact on boxers' safety. *Br J Sports Med*. 2018;52:741–746.
59. Pieter W, Fife GP, O'Sullivan DM. Competition injuries in taekwondo: a literature review and suggestions for prevention and surveillance. *Br J Sports Med*. 2012;46:485–491.
60. Pieter W, Zemper ED. Incidence of reported cerebral concussion in adult taekwondo athletes. *J R Soc Promot Health*. 1998;118:272–279.
61. Oler M, Tomson W, Pepe H, et al. Morbidity and mortality in the martial arts: a warning. *J Trauma*. 1991;31:251–253.
62. Stricevic MV, Patel MR, Okazaki T, et al. Karate: historical perspective and injuries sustained in national and international tournament competitions. *Am J Sports Med*. 1983;11:320–324.
63. Zetaruk M, Violan M, Zurakowski D, et al. Injuries in martial arts: a comparison of five styles. *Br J Sports Med*. 2005;39:29–33.
64. McLatchie GR, Davies JE, Culley J. Injuries in karate: a case for medical control. *J Trauma*. 1980;20:956–958.
65. Jordan BD, Campbell EA. Acute injuries among professional boxers in New York State: a two-year survey. *Phys Sportsmed*. 1988;16:87–91.
66. Porter M, O'Brien M. Incidence and severity of injuries resulting from amateur boxing in Ireland. *Clin J Sport Med*. 1996;6:97–101.
67. Welch MJ, Sitler M, Kroeten H. Boxing injuries from an instructional program. *The Physician and Sportsmedicine*. 1986;14:81–89.
68. Shtaya A, Hettige S. Cavum septum pellucidum causing obstructive hydrocephalus in a toddler. *Pediatric Neurosurgery*. 2019;54:416–418.
69. Gardner RC, Hess CP, Brus-Ramer M, et al. Cavum septum pellucidum in retired American pro-football players. *J Neurotrauma*. 2016;33:157–161.
70. GARD. *Genetic and Rare Diseases Information Center; Absence of Septum Pellucidum*; 2016. https://rarediseases.info.nih.gov/diseases/9253/absence-of-septum-pellucidum. Accessed February 2023.
71. Misquitta K, Dadar M, Tarazi A, et al. The relationship between brain atrophy and cognitive-behavioural symptoms in retired Canadian football players with multiple concussions. *Neuroimage: Clin*. 2018;19:551–558.
72. Macpherson P, Teasdale E. CT demonstration of a 5th ventricle–a finding to KO boxers? *Neuroradiology*. 1988;30:506–510.
73. Loosemore M, Lightfoot J, Palmer-Green D, et al. Boxing injury epidemiology in the Great Britain team: a 5-year surveillance study of medically diagnosed injury incidence and outcome. *Br J Sports Med*. 2015;49:1100–1107.
74. Matser EJ, Kessels AG, Lezak MD, et al. Acute traumatic brain injury in amateur boxing. *Phys Sportsmed*. 2000;28:87–92.
75. Arriaza R, Cierna D, Regueiro P, et al. Low risk of concussions in top-level karate competition. *Br J Sports Med*. 2017;51:226–230.
76. Koh JO, Cassidy JD, Watkinson EJ. Incidence of concussion in contact sports: a systematic review of the evidence. *Brain Injury*. 2003;17: 901–917.
77. Pappas E. Boxing, wrestling, and martial arts related injuries treated in emergency departments in the United States, 2002-2005. *J Sports Sci Med*. 2007;6:58–61.
78. Egger M, Davey Smith G, Schneider M, et al. Bias in meta-analysis detected by a simple, graphical test. *BMJ*. 1997;315(7109):629–634.
79. Sterne JA, Sutton AJ, Ioannidis JP, et al. Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*. 2011;343:d4002.