A systematic review of sex differences in concussion outcome: what do we know?

Victoria C. Merritt, Christine R. Padgett & Amy J. Jak

To cite this article: Victoria C. Merritt, Christine R. Padgett & Amy J. Jak (2019): A systematic review of sex differences in concussion outcome: what do we know?, The Clinical Neuropsychologist, DOI: [10.1080/13854046.2018.1508616](https://doi.org/10.1080/13854046.2018.1508616)

To link to this article: <https://doi.org/10.1080/13854046.2018.1508616>

Published online: 08 Jan 2019.

Submit your article to this journal

Article views: 97

View Crossmark data

REVIEW ARTICLE

A systematic review of sex differences in concussion outcome: what do we know?

Victoria C. Merritt^a, Christine R. Padgett^b and Amy J. Jak^{a,c}

^aVA San Diego Healthcare System, San Diego, CA, USA; ^bSchool of Medicine (Psychology), University of Tasmania, Hobart, TAS, Australia; ^cUniversity of California San Diego (UCSD) School of Medicine, Department of Psychiatry, La Jolla, CA, USA

ABSTRACT

Objective: The purpose of this review was to examine sex differences in concussion, or mild traumatic brain injury (mTBI) outcome, updating previous critical reviews of the literature.

Method: Within adult human studies, we reviewed a wide range of concussion outcome variables: prevalence of concussion, injury characteristics, postconcussion symptom trajectories and psychiatric distress, neuropsychological performance, and neuroimaging findings. Sports-related concussion, civilian, and military samples were included in the review.

Results: Given the robust concussion literature, there is a relative paucity of research addressing sex differences following concussion. The majority of available studies focused on sports-related concussion, with fewer studies targeting other civilian causes of concussion or military-related concussion in females. Prevalence of concussion was generally reported to be higher in females than males. Although symptom reporting largely showed a pattern for females to report greater overall symptoms than males, examining individual symptoms or symptom clusters resulted in mixed findings between the sexes. Neuropsychological studies generally showed females performing more poorly than males on measures of visual memory following concussion, though this finding was not consistently reported.

Conclusion: Research examining sex differences in humans following concussion, in general, is in its infancy, and exploration of sex differences in studies outside of the sports concussion domain is particularly nascent. Given the increased prevalence of concussion and potential higher symptom reporting among women, ongoing research is necessary to better understand the role of biological sex on outcome following concussion. Understanding sex differences has important implications for assessment, management, and treatment of concussion.

ARTICLE HISTORY

Received 1 May 2018

Accepted 25 July 2018

KEYWORDS

Mild traumatic brain injury; head injury; gender differences; postconcussion symptoms; neuropsychological outcomes

Introduction

Interest in concussion, or mild traumatic brain injury (mTBI), has escalated in recent decades as a result of the increased awareness of the consequences of such injuries.

CONTACT Amy J. Jak ajak@ucsd.edu VA San Diego Healthcare System (151B), 3350 La Jolla Village Drive, San Diego, CA 92161

© 2019 Informa UK Limited, trading as Taylor & Francis Group

While it is difficult to estimate the true prevalence of concussion, as many may go undetected or are not reported, estimates suggest that of the approximately 2.5 million brain injuries that occur annually (Taylor, Bell, Breiding, & Xu, 2017), around three-quarters are classified as mTBI or concussion (Boyle et al., 2014; Centers for Disease Control and Prevention, 2003, 2015). Concussions affect individuals of all ages and occur not only in sports and military-related settings but also in civilians who have experienced motor vehicle accidents and falls, for example (Carroll et al., 2014; Taylor et al., 2017). Concussions are presently a major public health concern, and questions regarding proper assessment and management of mTBI have dominated the literature for years.

More recently, consensus statements and position papers concerning mTBI/concussion have been published highlighting the importance of considering individual differences, preinjury characteristics, and injury-specific variables as possible modifiers of concussion outcome (Broglio et al., 2014; Giza et al., 2013; Harmon et al., 2013; McCrory et al., 2017). Biological sex is one such variable that has been considered, with emphasis placed on better understanding the extent to which sex modifies, or influences, the nature and course of recovery following mTBI/concussion. Although a growing number of animal studies have indicated that female sex relative to male sex may be protective, leading to reduced mortality and improved cognitive functioning following TBI (Kupina, Detloff, Bobrowski, Snyder, & Hall, 2003; Velosky, Tucker, Fu, Liu, & McCabe, 2017), findings regarding the influence of biological sex on recovery in the broader human concussion literature have been more heterogeneous. The relative importance of this variable, therefore, remains unknown. Developing a better understanding of how sex influences recovery and outcome following mTBI is extremely valuable, though, as concussed individuals may benefit from a more individualized approach to care.

An earlier review of sex differences in TBI outcomes included all severity levels of TBI and only eight studies were available to be included at that time (Farace & Alves, 2000). The main findings from this original review indicated that women demonstrated worse outcome than men in 85% of the variables evaluated. However, authors cautioned that few studies at that time had characterized outcomes by sex, and that future studies would need to better address the extent to which sex impacts recovery and outcome following TBI. Since that time, there has been an increased number of studies evaluating sex differences, with many emphasizing sex differences in the context of sports-related concussion.

The current review aims to update previous critical reviews in the literature by providing a comprehensive summary of our current understanding regarding the influence of sex on mTBI/concussion outcome. We focus specifically on studies evaluating the mild end of the TBI spectrum, covering the following domains: the prevalence of concussion, injury-specific characteristics (such as mechanism of injury or location of injury), baseline and postconcussion symptom trajectories and psychiatric distress, neuropsychological performance, and neuroimaging variables. Given that the majority of available studies for review examined concussed athletes, the findings are largely based on the sports concussion literature, although non-sport civilian studies and military studies will be discussed as available.

Methods

Online databases, including PubMed, PsycINFO, and Google Scholar, were first used to identify relevant articles for the review. After locating articles of interest through online databases, a hand-searching approach of the cited references within each article was conducted to ensure completeness. Articles published or available online from database inception through December 2017 were included in the review. The specific search terms were as follows: 'concussion,' 'mild traumatic brain injury,' 'TBI,' 'head injury,' 'gender,' 'gender differences' 'sex,' and 'sex differences.' Only articles published in English were retained. Additionally, we focused exclusively on studies pertaining to humans, and to limit the confound of neurodevelopmental issues, only studies pertaining to *adult* concussion/mTBI were reviewed. Oftentimes, articles evaluating sports-related concussion included both adolescent/youth and adult (≥ 18 years of age) participants in the same study; under these circumstances, the articles were retained. However, articles were excluded from this review if the study focused exclusively on adolescents/youths. [Table 1](#) summarizes the included studies and highlights key findings from each.

Results

Prevalence of mTBI/concussion

Several empirical studies have examined sex differences with regard to the prevalence or frequency of mTBI/concussion, with the majority of studies focused on athlete populations. Before exploring this literature, it is first relevant to understand that one issue that has complicated making a direct comparison of concussion prevalence between male and female athletes is the sheer number of male athletes relative to female athletes. Given the higher proportion of male sports that traditionally have been studied, it is perhaps not surprising that when examining concussions that occur within the context of athletics, a greater number of concussions were sustained by males than females when all sports were considered together (Giza et al., 2013). However, more recently, investigators have been incorporating additional female sports teams into their analyses, thus causing a shift in the overall injury rates. Black, Sergio, and Macpherson (2017), for example, examined 20 varsity level sports at a Canadian university (with roughly equal representation of male and female sports teams) and reported that more female athletes sustained concussions relative to male athletes. Similar results were also noted in Zuckerman et al. (2015), who examined 25 National Collegiate Athletic Association (NCAA) sports.

Interestingly, when examining sports played by both males and females, there is mounting evidence to suggest that females may experience more concussions than males. Numerous studies evaluating soccer, basketball, and baseball/softball have generally reported higher concussion rates in female athletes relative to male athletes (Covassin, Moran, & Elbin, 2016; Covassin, Swanik, & Sachs, 2003; Delaney, Lacroix, Leclerc, & Johnston, 2002; Dick, Hootman, Agel, & Marshall, 2008; Fuller, Junge, & Dvorak, 2005; Gessel, Fields, Collins, Dick, & Comstock, 2007; Hootman, Dick, & Agel, 2007; Kerr et al., 2017; Roos et al., 2017; Tanveer, Zecavati, Delasobera, & Oyegbile,

Table 1. Summary of studies included in review.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Barnes et al. (1998)	M = 72, F = 65	Epidemiology		Sports-related concussion		Females were less likely than males to have sustained concussions
Bazarian et al. (2010)	M = 782, F = 643	Cross-sectional	3 months	ED presentations	RPCQ, return to normal activities, missed work days	Females were more likely than males to report postconcussive symptoms (in association with greater orthopedic injury); No difference in return to work
Benedict et al. (2015)	Not reported	Cross-sectional	Not reported	Sports and non-sports related concussion (multidisciplinary concussion center)	BESS, K-D, SAC, SCAT3	Females reported more frequent and more severe postconcussive symptoms
Black et al. (2017)	Concussed: M = 33, F = 42	Epidemiology		Sports-related concussion	SCAT, ImPACT	Females were more likely to experience concussion than males, but no differences in symptom and cognitive outcome
Boden et al. (1998)	M = 162, F = 188	Epidemiology		Sports-related concussion		Overall concussion incidence was less in females relative to males
Brainard et al. (2012)	M = 37, F = 51	Epidemiology		Sports-related concussion		Females experienced fewer impacts than males; females also experienced impacts of lesser magnitude relative to males; location of greatest-magnitude impacts was similar for females and males—back of head
Brickell et al. (2017)	M = 86, F = 86	Cross-sectional	<30 months	Military mTBI	NSI and PCL-C	Females reported more frequent PTSD and neurobehavioral symptoms relative to males
Broshek et al. (2005)	M = 94, F = 37	Repeated measures	Baseline and 1-2 days	Sports-related concussion	CRI	Females experienced reduced neurocognitive function and greater cognitive impairment relative to males

(continued)

Table 1. Continued.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Brown et al. (2015)		Meta-analysis				Females were more likely to report symptoms at baseline
Chamard et al. (2013)	F = 20 (concussion = 10, no concussion = 10)	Cross-sectional	18.9 months (mean)	Sports-related concussion	Neurometabolic and microstructural alterations	Concussed females had lower hippocampal and primary motor myo-inositol; concussed females had greater white matter diffusivity and reduced fractional anisotropy in corpus callosum Concussed females had reduced mean diffusivity and radial diffusivity in the corpus callosum, as compared to non-concussed females
Chamard et al. (2016)	M = 57 (mTBI = 47, control = 10), F = 33 (mTBI = 22, control = 11)	Cross-sectional	6 months	Sports-related concussion	White matter in corpus callosum and corticospinal tract	Female soccer players with concussion history had slower reaction times than males
Colvin et al. (2009)	M = 93, F = 141	Cross-sectional	9 days (median)	Sports-related concussion	ImPACT	Overall, females sustained a higher percentage of concussions during games than males; highest concussion injury rate was in women's soccer and men's lacrosse
Covassin et al. (2003)	See article	Cohort		Sports-related concussion		Females more likely to report symptoms at baseline than males No differences between males and females on postconcussive symptoms
Covassin et al. (2006)	M = 651, F = 558	Cross-sectional	Baseline	Sports-related concussion	ImPACT	
Covassin et al. (2007)	M = 41, F = 38	Repeated measures	Baseline, approx. 2 and 8 days	Sports-related concussion	ImPACT	

(continued)

Table 1. Continued.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Covassin et al. (2010)	M = 100, F = 88	Retrospective	Baseline with prior concussion (grouped by number of previous concussions) Baseline, 2, 7, and 14 days	Sports-related concussion	ImPACT	Females performed better than males on visual memory after multiple concussions
Covassin et al. (2012a)	M = 203, F = 93	Repeated measures		Sports-related concussion	ImPACT and BESS	Females performed worse than males on the visual memory composite; females endorsed more postconcussive symptoms than males
Covassin et al. (2012b)	M = 1104, F = 512	Cross-sectional	Baseline	Sports-related concussion	ImPACT, BDI-II	Females performed better on the verbal memory composite than males; females endorsed greater cognitive, emotional, and sleep symptoms compared with males
Covassin et al. (2013)	M = 39, F = 56	Repeated measures	Baseline and 8 days	Sports-related concussion	ImPACT	Females experienced greater visual impairment than males postconcussion
Covassin et al. (2016)	M = 779, F = 903	Epidemiology		Sports-related concussion		Females had higher rates of concussion in specific sports (baseball/softball, basketball, ice hockey, and soccer) compared to males; females took longer to recovery than males in all sports except lacrosse
Dougan et al. (2014)	Meta-analysis			Sports-related concussion		Females had poorer neurocognitive outcomes initially
Ellemberg et al. (2007)	F = 22 (concussion = 10, no concussion = 12)	Cross-sectional	6–8 months	Sports-related concussion	CVLT, Ruff selective attention, BTA, SDMT, SCWT	Concussed females had slower processing speed than non-concussed females

(continued)

Table 1. Continued.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Fakhrian et al. (2014)	F = 18 (concussion =10, no concussion =8)	Cross-sectional	Not reported	General population	White matter abnormalities and ImPACT	Compared to females and non-concussed males, concussed males had significantly lower fractional anisotropy bilaterally in the uncinate fasciculus
Henry et al. (2015)	M = 42, F = 24	Repeated measures	Initial assessment within 7 days of injury, then 3 and 4 weeks postinjury	Sports-related concussion	ImPACT, PCSS, DHI	No difference in recovery, although at 4 weeks postinjury, males were more likely to <i>not</i> report symptoms
Iverson et al. (2011)		Epidemiology		Military mTBI	NSI and neuropsychiatric diagnosis (using ICD-10)	After controlling for blast exposure, females were more likely to report higher levels of somatosensory, vestibular, and cognitive symptoms than males with TBI
King (2014a)						Approximately half of the studies reviewed found females had greater risk of chronic postconcussive symptoms (measured 3–6 years post-mTBI)
King (2014b)						Females were more likely to report postconcussive symptoms at 12–18 months post-mTBI relative to males
Kontos et al. (2012a)	M = 51, F = 24	Repeated measures	Baseline, 2, 7, and 14 days	Sports-related concussion	ImPACT, PCSS, BDI	No sex differences in PCSS total score or depression levels; females performed more poorly than males on ImPACT visual memory, otherwise no sex

(continued)

Table 1. Continued.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Kontos et al. (2012b)	Concussed: M = 961, F = 477	Case series	1–7 days	Sports-related concussion	PCSS	differences on ImPACT cognitive composites Females reported higher levels of the affective symptom cluster than males
Lippa et al. (2018)	M = 79, F = 79	Cross-sectional	<30 months	Military mTBI	NSI, PCL-C, Abbreviated Injury Scale	Females with TBI reported greater somatosensory symptoms, but only when PTSD was also present
Mihalik et al. (2013)	M = 241, F = 55	Repeated measures	Baseline, time of injury, days 1, 2, 3, 5, 7, and 90	Sports-related concussion	BESS, SAC, GSC	Concussed females experienced greater postconcussive symptoms than males during acute recovery
Moore et al. (2010)	M = 83, F = 75	Cross-sectional	>1 year	General population	CANTAB	Females performed better than males on visual memory 12 months after concussion; no other differences
Preiss-Farzanegan et al. (2009)	M = 144, F = 71	Cross-sectional	3 months	Sports-related concussion	RPCQ	Adult, but not pediatric, females with concussion reported greater postconcussive symptoms
Scott et al. (2015)	M = 94, F = 75	Cross-sectional	11.1 years (mean)	ED presentations	Self-reported anxiety or major depressive disorder (internalizing), offending behavior or substance abuse dependence (externalizing) SCAT and PCSS	Females who reported childhood TBI had greater internalizing problems than males, while males had greater externalizing problems than females
Shehata et al. (2009)	M = 190 (non-concussed = 116, concussed = 74), F = 70 (non-concussed = 51, concussed = 19)	Cross-sectional	Baseline	Sports-related concussion		Females reported more symptoms at baseline than males

(continued)

Table 1. Continued.

Author	N (M, F)	Study type	Time point(s)	Population	Measures	Key findings
Tanveer et al. (2017)	M = 362, F = 333	Cross-sectional	1 day to 4 weeks	Sports-related concussion	IMPACT and PCSS	Concussed males reported greater loss of consciousness; amnesia, and confusion, whereas females reported greater overall postconcussive symptoms
Tsushima et al. (2009)	M = 62, F = 40	Retrospective; cross-sectional	2 years	General population	Halstead-Reitan Neuropsychological Battery	No significant differences in neuropsychological performance at 2 years post-mTBI, although females over 30 years old performed worse than males on two measures—Category Test and Trails A

M: male; F: female; BDI: Beck Depression Inventory; BESS: Balance Error Scoring System; BTA: Brief Test of Attention; CANTAB: Cambridge Neuropsychological Test Automated Battery; CRI: Concussion Resolution Index; CVLT: California Verbal Learning Test; DHI: Dizziness Handicap Inventory; GSC: Graded Symptom Checklist; IMPACT: Immediate Post-Concussion Assessment and Cognitive Testing; K-D: King-Devick; NSI: Neurobehavioral Symptom Inventory; PCL-C: Posttraumatic Stress Disorder Checklist – Civilian Version; PCSS: Post-Concussion Symptom Scale; RPCQ: Rivermead Post-Concussion Symptoms Questionnaire; SAC: Standardized Assessment of Concussion; SCAT: Sport Concussion Assessment Tool; SCAT3: Sport Concussion Assessment Tool: 3rd Edition; SDMT: Symbol Digits Modalities Test; SCWT: Stroop Color Word Test.

2017; Zuckerman et al., 2015). However, two older studies, both evaluating the frequency of concussion in soccer players, found the opposite pattern—that is, men were more likely than women to have sustained concussions (Barnes et al., 1998; Boden, Kirkendall, & Garrett, 1998).

In sports beyond soccer, basketball, and baseball/softball, more equivocal findings have been reported. With regard to ice hockey, several studies showed no significant differences with respect to concussion prevalence between male and female athletes (Dick et al., 2008; Kerr et al., 2017; Schick & Meeuwisse, 2003), whereas one study documented more concussions in females (Covassin et al., 2016) and another study documented fewer concussions in females (Zuckerman et al., 2015) relative to males. As for concussion rates in lacrosse, a similar pattern emerged, with some evidence to suggest no sex differences exist (Covassin et al., 2003; Kerr et al., 2017), one study showing females having higher rates of concussions than males (Zuckerman et al., 2015), and a final study demonstrating fewer concussions sustained by females relative to males (Covassin et al., 2016).

In studies examining the prevalence or incidence of TBI in other civilian samples (i.e. non-sports concussion studies), it was much more common for investigators to consider mild, moderate, and severe TBI samples altogether and report sex differences for overall injury prevalence. Given the focus of concussion/mTBI in the present review, we do not provide a comprehensive synopsis of these articles herein, as they are beyond the scope of the review. Instead, to briefly summarize, recent data from the Centers for Disease Control and Prevention (2016) indicate that rates of TBI were much greater for men than women between the years 2001 and 2010. Analogous findings were documented in a meta-analysis by Frost, Farrer, Primosch, and Hedges (2013) who examined prevalence rates of TBI in the general adult population. Their meta-analysis revealed that men were more than twice as likely to have experienced a TBI as women.

With regard to studies evaluating sex differences in the prevalence/incidence of military mTBI, there appear to be no studies examining this as a primary outcome. However, some researchers provided information pertaining to sex differences when describing the characteristics of the sample under investigation. For instance, Schneiderman et al. (2008), in their examination of military personnel following deployment to Operation Iraqi Freedom (OIF) and/or Operation Enduring Freedom (OEF), reported a similar rate of mTBIs sustained by males and females. Specifically, among those deployed in both conflicts, 12% of males and 12% of females experienced mTBI. More recently, Hendricks et al. (2013) reported that the rate of having a positive TBI screen in OIF/OEF service members was about double for males (23.1%) than females (10.7%); however, this encompassed all TBI severity and did not include comprehensive TBI evaluation, only screening.

Injury characteristics

In addition to evaluating concussion prevalence by sex, some investigators have examined injury characteristics such as the magnitude and location of head impacts as a function of sex. Brainard et al. (2012) studied collegiate ice hockey players and

compared males and females on the frequency, magnitude, and location of head impacts. The authors showed that male hockey players experienced a greater number of impacts than female hockey players and were more likely than females to experience impacts of greater magnitude. With respect to injury location, Brainard et al. (2012) showed that although there were minor differences in injury location by sex (with females experiencing a greater number of left and right side-of-the-head impacts than males), the location of greatest-magnitude impacts was similar for both males and females—the back of the head.

As for injury mechanism, Barnes et al. (1998) examined elite soccer players and reported that the most common form of injury in their sample for both males and females was player-to-player contact. Fuller et al. (2005), who also evaluated elite soccer players, utilized a more fine-grained approach to examining mechanism of injury; their findings showed that the most common causes of concussion in males and females were use of the upper extremity and head-to-head contact, with males more often experiencing the former and females more often experiencing the latter. In a study of lacrosse players, Lincoln et al. (2007) found that the most common injury mechanism for males was player-to-player contact, whereas the most common injury mechanism for females was contact with an object (i.e. stick, ball). Finally, Rosene et al. (2017) assessed male and female ice hockey players and reported that player-to-player contact was the most common mechanism of injury for both sexes, followed by surface contact. However, a greater proportion of males sustained their concussions by player contact whereas more females experienced concussions through surface contact.

Postconcussion symptoms and psychiatric distress

Among the variables receiving a substantial amount of research attention are postconcussion symptoms. Although the majority of published studies on this topic fall within the context of sports concussion, the civilian and military TBI literatures have also begun examining sex differences with respect to symptom reporting. In addition to postconcussion symptoms, assessment of psychiatric symptoms is also relevant, given the burgeoning literature establishing a connection between concussion/mTBI and mental health symptoms (for example, see Kerr et al., 2014; MacDonald et al., 2017; Morissette et al., 2011). Below, study results will be described according to the population of interest (i.e. sports concussion, other civilian studies, and military studies), as well as when symptoms were assessed relative to the concussive event. Broadly, studies evaluating symptoms at baseline (preconcussion) will be discussed first, followed by studies examining symptoms in the acute and postacute phases of injury.

Baseline assessments

To begin, within the sports concussion literature, there appears to be some evidence showing that female athletes may report higher ‘postconcussive’ symptoms than male athletes upon baseline testing. In a study of NCAA college athletes, Covassin et al. (2006) found that females overall reported more ‘postconcussion’ symptoms at baseline than males. When evaluating individual symptoms, females were significantly

more likely than males to endorse 14 of the 22 individual symptoms evaluated on the Post-Concussion Symptom Scale (PCSS). In another study of male and female college athletes, Shehata et al. (2009) found similar results using the Sport Concussion Assessment Tool (SCAT). In addition to evaluating the mean total symptom score, they also evaluated other symptom indices such as the median total symptom score and the percent of males and females having a total symptom score of '0.' They demonstrated that females had greater mean and median total symptom scores, and that a greater proportion of males exhibited total symptom scores of '0' (47.4% of males had a total symptom score of '0' compared to 24.3% of females). Additionally, Kontos, Elbin et al. (2012b) examined symptom clusters derived from the PCSS and established that females endorsed greater cognitive-sensory, sleep-arousal, vestibular-somatic, and affective symptoms than males at baseline.

Examining the sports-related concussion literature via meta-analysis, Brown, Elsass, Miller, Reed, and Reneker (2015) found that females were 43% more likely than males to report *any* symptom associated with concussion at baseline, and in particular, females were more likely to report preconcussion symptoms of headache, poor concentration, vision/hearing concerns, and mood and sleep symptoms. Additionally, at baseline, females had significantly higher total symptom scores than males; however, Brown and colleagues concluded that this difference was not clinically significant.

Few studies within the sports-concussion literature have evaluated sex differences with respect to baseline (premorbid) psychiatric distress. Yang et al. (2007) was perhaps the first group to examine whether sex differences are associated with baseline symptoms of depression in a sample of NCAA college athletes; they revealed that female athletes had a higher risk of experiencing depressive symptoms relative to male athletes. In contrast to these findings, Covassin, Elbin, Larson, and Kontos (2012b), who examined high school and college athletes, showed that there were no significant differences between male and female reports of depressive symptoms at baseline. They also found no sex differences for overall postconcussion symptoms at baseline, but when examining symptom cluster scores, females endorsed greater cognitive, emotional, and sleep symptoms than males (with no significant differences found for the somatic/migraine symptom cluster).

Acute concussion assessments

With regard to symptoms endorsed acutely after a concussive event, anywhere between 1 and 14 days postinjury, numerous studies within the sports-concussion literature have established that females endorse greater postconcussion symptoms than males (Broshek et al., 2005; Colvin et al., 2009; Covassin, Elbin, Bleecker, Lipchik, & Kontos, 2013; Covassin, Elbin, Harris, Parker, & Kontos, 2012a; Mihalik et al., 2013). Additionally, in an examination of a civilian concussion sample who sustained injuries by a variety of mechanisms (including sports, motor vehicle accidents, and falls, etc.) and were evaluated in the acute period following concussion (most participants were tested within 48 hr of referral), females reported a higher number and severity of post-concussive symptoms than males (Benedict et al., 2015). Although individuals as young as 10 were included in the sample, the average age was 35 and so we have reported the results here.

Not all studies, though, have documented such clear sex differences in the acute phase following injury. The meta-analysis by Brown et al. (2015), referenced above, also evaluated postconcussion symptom reporting following concussion. Their findings revealed that only one individual symptom—confusion—differed between males and females postinjury, with females actually having lower odds than males of endorsing confusion. Furthermore, although the meta-analysis found that overall symptoms (total symptom score) were greater for females than males postinjury, they again concluded that the difference was not clinically meaningful (2015).

Next, Kontos et al. (2012b) compared male and female symptom reports (gathered 1–7 days postinjury) across four postconcussion symptom clusters—cognitive-fatigue-migraine, affective, somatic, and sleep—and only found sex differences for the affective symptom cluster, with females endorsing greater symptoms than males. Another study by Kontos and colleagues (Kontos, Covassin, Elbin, & Parker, 2012a) examined postconcussion symptoms and depressive symptoms at 2, 7, and 14 days following sports concussion, and found no sex differences for both total postconcussion symptoms and depression symptoms. Covassin, Schatz, and Swanik (2007) examined postconcussion symptom reporting in a sample of college athletes and also found no sex differences in total symptoms between males and females when evaluated at two time points postinjury—approximately 3 and 10 days postconcussion. However, the investigators documented that concussed males reported more vomiting and sadness than concussed females, with no other individual symptom differences reported between the sexes. Similar to Covassin et al. (2007), Tanveer et al. (2017) found that males were more likely than females to experience specific symptoms; these included loss of consciousness, retrograde and anterograde amnesia, and confusion. However, females experienced greater overall postconcussion symptoms (total symptom score) than males (Tanveer et al., 2017).

Postacute concussion assessments

While the above studies documented acute sex differences in symptom reporting, other studies have examined whether males and females differ with regard to symptom reporting in the postacute phase of injury. Among 1,425 individuals (of which almost half were female) who presented to an emergency department, females were more likely to have higher postconcussive symptom endorsement than males at 3 months postinjury (Bazarian, Blyth, Mookerjee, He, & McDermott, 2010). However, other bodily injuries, in addition to concussion, notably contributed to higher postconcussive symptom scores in this sample. Despite this higher symptom endorsement by females, return to work and other activities did not differ between females and males.

Age may also be a relevant variable when examining sex differences, as adult females with sports-related concussion had higher Rivermead Post-Concussion Symptoms Questionnaire scores 3 months postinjury than adult males, though this difference was not present in children (Preiss-Farzanegan, Chapman, Wong, Wu, & Bazarian, 2009). Specific symptoms more highly endorsed by females included headache, dizziness, fatigue, irritability, and concentration difficulties. Sport specific variables or other demographics did not better account for any differences (Preiss-Farzanegan et al., 2009). Finally, a systematic review of prolonged postconcussive

symptoms also found females at higher risk for elevated symptom reporting at 12–18 months post mild head injury, relative to males (King, 2014b). At 3–6 years post-mTBI, only half (two out of four) of the correlational studies found that females were at higher risk for ‘permanent’ postconcussive symptoms (King, 2014a).

Investigators have also studied psychiatric distress in the postacute phase of injury. Scott et al. (2015) examined psychosocial functioning, including rates of depression and anxiety, substance use disorders, and internalizing and externalizing problems/behaviors in male versus female adults with a history of childhood TBI. When examined as adults, females who had sustained childhood TBI of any severity had greater internalizing problems than males, while males had greater externalizing problems than females (Scott et al., 2015). Although an interesting finding, it is not fully understood whether these differences are uniquely related to the history of TBI, or whether there are baseline differences in internalizing and externalizing behaviors that may then be amplified or exacerbated following TBI.

Military studies

Concussion has always been a prevalent issue in the military and attention to it heightened during the wars in Iraq and Afghanistan as blast and combat related concussions increased. Despite concussion being a signature injury of these wars, focus on mTBI in female military personnel and Veterans has been notably lacking. Given that females make up only approximately 15% of active duty military (Department of Defense, 2015), they have often been excluded from military TBI research. As a result, sex differences have often not been reported given the low frequency of women in this unique population. More recently, though, studies have begun addressing the role of sex on TBI outcomes, generally focusing on the presence of postconcussion symptoms and psychiatric distress.

Iverson et al. (2011) conducted one of the largest examinations of sex differences in military concussion. She and her colleagues examined sex differences in psychiatric diagnoses and neurobehavioral symptom reporting between males and females in a large, retrospective study of over 12,000 Iraq and Afghanistan Veterans who underwent TBI assessment within the VA system. All severities of TBI were included, though statistically, mTBI makes up the vast majority of all TBIs reported. They found that females with a history of TBI were less likely to have PTSD or substance use diagnoses, relative to males, but were more likely to carry a diagnosis of depression, anxiety, or comorbid depression and PTSD. However, PTSD, anxiety, and substance use sex differences did not remain after controlling for blast exposure. Neurobehaviorally, females were more likely to report higher levels of somatosensory, vestibular, and cognitive (but not affective) symptoms than males on the Neurobehavioral Symptom Inventory (NSI).

In a more recent study of a matched sample of 86 female and 86 male service members with a history of mTBI who were evaluated within 2 years postinjury, females reported more neurobehavioral and PTSD symptoms than males (Brickell et al., 2017). Follow-up analyses revealed that sex differences were greatest for the neurobehavioral symptoms of sensitivity to light, change in taste/smell, change in appetite, nausea, poor sleep, and fatigue. As for PTSD symptoms, sex differences were most pronounced

for poor concentration, trouble remembering a stressful event, and disturbing memories/thoughts/images. However, after controlling for PTSD symptoms, injury details, other bodily injuries, and symptom validity, postconcussion symptom reporting was much more equivalent between males and females (Lippa et al., 2018); female service members with both a history of TBI and PTSD reported only more somatosensory symptoms than males, with no other symptom reporting differences.

Neuropsychological outcomes

The majority of literature relating to sex differences in neurocognitive function following mTBI/concussion has focused on sports-related concussion, and typically has utilized the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) computerized program, which measures neurocognitive performance across verbal memory, visual memory, reaction time, and processing speed domains, as well as post-concussion symptoms (discussed previously). As will be shown below, there are some findings that suggest there may be sex-related differences in specific domains, however, there does not appear to be a consistent pattern of impairment between sexes.

The cognitive domain most frequently identified as being associated with sex-related differences is visual memory, with some evidence of greater impairment in females than males in the acute recovery period (Covassin et al., 2007; Kontos et al., 2012a). In a further study, it was also reported that visual memory impairment was greater in females relative to males 8 days after injury, even after controlling for body mass index (Covassin et al., 2013). Most recently, Tanveer et al. (2017) examined ImPACT performance and analogously reported worse visual memory scores in females compared to males when examined acutely following concussion. No sex differences were identified for the remainder of the ImPACT cognitive variables. Notably, the participants studied by Tanveer and colleagues were relatively younger than the studies reviewed above, ranging in age between 10 and 20; nevertheless, the study was included in the present review given that a subset of the sample comprised college athletes.

Interestingly, contradictory results were found when exploring the influence of multiple concussions. Covassin, Elbin, Kontos, and Larson (2010) found that males with a history of multiple concussions actually fared worse than females on some ImPACT cognitive tasks. Specifically, females with three or more concussions performed better than males with three or more concussions on the visual memory composite. Additionally, females with two and three or more concussions performed better than males with similar concussion histories on the verbal memory composite. The authors suggest this may indicate that female sex hormones are protective in the event of sports-related concussion. However, given the differences in muscle mass and other sports-related factors such as acceleration and stabilization (Tierney et al., 2005), it is also possible that severity of concussion may differ between sexes and this effect becomes evident when concussions accumulate. Such a relationship could explain the contradictory results between the Covassin et al. (2010) study and other studies reviewed above. Finally, Colvin et al. (2009) studied male and female soccer players and found that females who had sustained a prior concussion had slower reaction

times on ImPACT testing than males, and found a trend for females having poorer memory and processing speed scores relative to males.

Others have used computerized programs other than ImPACT to explore sex differences in sports-related concussion outcomes. Broshek et al. (2005), using a computerized package that predominantly measured reaction time and processing speed (the Concussion Resolution Index), compared baseline performance to postconcussion performance (approximately 3–4 days postinjury) using reliable change index scores. It was found that female athletes had greater reductions in neurocognitive function following concussion, and also were 1.5 times more likely than males to experience cognitive impairment. Accounting for helmet use did not notably impact results.

In another study, Ellemberg, Leclerc, Couture, and Daigle (2007) examined female soccer players. At 6–8 months after a single lifetime concussion, concussed females were compared to age-matched females who had never experienced a concussion. In this postacute period, the concussed females had significantly slower processing speed than non-concussed females. There were no significant differences in other cognitive domains (including memory, attention, and executive functioning). This sample was small, with only 10 concussed and 12 non-concussed female soccer players, but they utilized a more comprehensive neuropsychological battery, as opposed to brief computerized testing used by most other studies. Other strengths included assessment of number of 'headers' that did not result in concussion; these subconcussive incidents were also found to be equivalent between concussed and non-concussed groups. These athletes did not, however, have baseline testing; while this avoids practice effects or motivations to do poorly on baseline testing to positively impact return to play decisions in the future, it limits interpretability of change postconcussion. Finally, this study did not compare male and female performance, thus, it is not possible to determine whether the deficits experienced by the concussed females were greater than would be expected in males.

A meta-analysis of the neurocognitive outcomes associated with sports-related concussion also explored the role of sex differences (Dogan, Horswill, & Geffen, 2014). The authors reported that females consistently experienced poorer neurocognitive outcomes during the initial recovery period (within 1–10 days postinjury), and this was particularly apparent when baseline measures had been obtained. Furthermore, deficits appeared to be more pronounced in adults. The authors noted that there was a lack of research exploring sex-differences in the postacute recovery period, and therefore it was not possible to determine whether the observed sex differences in the acute recovery period extended to later recovery.

To date, few studies have explored the role of sex in post-mTBI neurocognitive function outside of the sports concussion literature. Moore, Ashman, Cantor, Krinick and Spielman (2010) compared performance of males and females with mTBI on tasks of processing speed, executive functioning, and visual memory using the Cambridge Neuropsychological Test Automated Battery (CANTAB). All participants were evaluated at least 1 year postinjury. Differences between males and females were only found in visual memory, where females outperformed males. This finding aligns with the results of Covassin et al. (2010), who found similar deficits where multiple concussions had occurred, but contradicts a number of other findings (Covassin et al., 2012a; Covassin

et al., 2007, 2013; Kontos et al., 2012a), where males outperformed females in this domain during the initial recovery phase. In another study examining civilian adults approximately 2 years following mTBI, there were virtually no sex differences in neuropsychological functioning on the Halstead-Reitan neuropsychological battery (Tsushima, Lum, & Geling, 2009); however, females over 30 performed more poorly than males on the Category Test and Trails A.

Concussion recovery

Concussion 'recovery' has been conceptualized in numerous ways in the literature, but generally studies have associated recovery with time—that is, the number of days to return to regular activities or how long it took to become asymptomatic following concussion, for example. Black et al. (2017) evaluated symptom and cognitive recovery in collegiate athletes representing a wide range of sports. In their study, recovery was assessed using the SCAT (or SCAT2) and the ImPACT computerized battery. The main outcomes evaluated were (1) the number of days from the concussion to symptom resolution as per SCAT/SCAT2 and (2) the number of days from the concussion to cognitive recovery as per ImPACT test performance. When outcomes were compared by sex, Black et al. (2017) reported no sex-related differences with respect to both symptom and cognitive recovery. Similarly, Henry et al. (2015) also found no differences between males and females regarding cognitive recovery, but did find that at 4 weeks postinjury, males were more likely than females to be asymptomatic. Finally, Covassin et al. (2016) reported that females in some sports, but not all, had greater time loss from their sports as compared to males.

Neuroimaging

Very few sex-based differences in neuroimaging outcomes following concussion have been explored and represents an area in need of increased study. In a small study of 10 female athletes who had sustained a concussion compared to 10 non-concussed female athletes, the concussed athletes (at least 7 months postinjury) showed lower levels of myo-inositol in the hippocampi and primary motor cortices and higher white matter mean diffusivity and lower fractional anisotropy (FA) in the corpus callosum as compared to the non-concussed athletes (Chamard et al., 2013). Another study by the same group (Chamard, Lefebvre, Lassonde, & Theoret, 2016) compared 10 female concussed athletes (evaluated 6 months postinjury) to 8 non-concussed female athletes and similarly found that the concussed females showed lower mean diffusivity and radial diffusivity in the corpus callosum compared to the non-concussed females. In a final study that evaluated both sexes, females showed relative sparing of the uncinate fasciculus following mTBI as compared to males; males had significantly lower FA bilaterally in the uncinate fasciculus than concussed females or non-concussed controls (Fakhran, Yaeger, Collins, & Alhilali, 2014). Male sex and uncinate fasciculus FA also predicted persistent postconcussive symptoms and time to symptom resolution. Given the extremely limited work in this area, definitive or even preliminary conclusions

about any sex-specific differences in neuroimaging markers after concussion cannot be reached.

Discussion

The present review evaluated what we currently know about sex differences following concussion, or mTBI, with a focus on the following domains: prevalence of concussion, injury characteristics, postconcussion symptoms and psychiatric distress, neuropsychological outcomes, and neuroimaging. The majority of the available studies for review pertained to sports-related concussion, with fewer studies examining sex differences in mTBI/concussion outcome in other civilian and military populations. Thus, any conclusions that can be made regarding sex differences is largely based on findings from within the sports-concussion literature.

Overall, the current evidence suggests that females may be more vulnerable to concussion than males in a sports setting, but that males encounter a greater number of TBIs than females in the general adult population (i.e. non-sports concussion setting). Soccer, basketball, and baseball/softball—specific sports played by both males and females—had the most consistent findings regarding rates of concussion, with females experiencing proportionally more concussions than males. However, other sports, including ice hockey and lacrosse, showed more equivocal findings regarding concussion prevalence. As for non-sport populations, there was limited data on the prevalence of mTBI/concussion specifically. Instead, concussion rates were generally reported as a function of all TBI severities, with findings supporting the opposite pattern as what was observed in the sports-concussion literature—more TBIs are sustained by males than females. Additional research is needed to better understand the factors that increase females' vulnerability to concussion in sports, and future studies should specifically examine whether sex differences exist regarding the prevalence of mTBI/concussion in civilian and military populations. Although females make up a small component of active duty military forces, they are the fastest growing segment seeking VA care (Frayne et al., 2014); nonetheless, examination of sex differences following concussion in military or Veteran samples remains notably limited in the existing literature, and represents an area of much needed research.

As for injury characteristics, there appears to be insufficient data to support any clear sex differences regarding head impact data and mechanism of injury. Only one study evaluated head impacts, and although findings support a greater number and magnitude of impacts in males than females, it is important to recognize that findings were based on a specific sport (ice hockey) and therefore may not generalize to other sports or civilian and military populations. Regarding mechanism of injury, within the sports-concussion literature, player-to-player contact and object/surface contact appear to be the most common forms of injury experienced by both males and females; although minor differences may exist between the sexes with regard to the proportion of males and females experiencing each mechanism, taken together, there do not appear to be substantial sex differences in this domain. Additionally, findings pertaining to recovery rates were also rather ambiguous, though the available data do not suggest any overt sex differences with regard to concussion recovery. Given the

limited data available for review, future studies should more specifically address whether males and females differ with respect to recovery and functional outcomes, such as days of school or work missed following concussion, or length of time to return to play.

The domains receiving the greatest research attention to date regarding sex differences were postconcussion symptoms and neuropsychological outcomes. Regarding symptom reporting, although not definitive, the data suggest a stronger likelihood for females to endorse greater symptomatology than males. Interestingly, this finding was reported across concussed athletes, civilians, and military personnel, as well as across time (i.e. baseline assessment and postinjury assessment). It is possible that sex differences in response styles may account for the apparent greater symptom reporting in females. That is, perhaps males are underreporting symptoms and females are accurately reporting symptoms, or it may be that females are more willing to report post-concussive symptoms than males. The influence of environmental or cultural norms, or more simply *gender* differences, on male and female symptom reporting patterns has long been referenced as a possible explanation or cause of differing symptoms between the sexes (Granito, 2002; Lovell et al., 2002). Given this possibility, the data reviewed above raises the question as to the extent to which biological sex differences versus gender differences contributes to postinjury outcomes. Furthermore, with regard to symptom reporting, more thought needs to be given as to whether or when sex-based norms should be used for postconcussion symptom interpretation, and when implemented, how this would impact clinical outcome.

Related to this is other work demonstrating the non-specificity of postconcussion symptoms; specifically, there is a burgeoning literature establishing that traditional 'postconcussion symptoms' are commonly endorsed by non-concussed populations including college students and community volunteers, as well as patients with preexisting medical or psychiatric conditions (Asken et al., 2017; Garden & Sullivan, 2010; Iverson & Lange, 2003; Smith-Seemiller, Fow, Kant, & Franzen, 2003; Wang, Chan, & Deng, 2006). This in itself is not surprising given the broad nature of postconcussion symptoms, but highlights the need to be cautious not to infer causation from reported postconcussion symptomatology.

Another interesting possibility for further consideration is how hormonal systems, neural architecture, and musculature/biomechanical systems differ between the sexes and may impact response to concussion and/or contribute to the sex differences in outcomes (i.e. symptom reporting) following concussion. The Brown et al. (2015) meta-analysis hypothesized that at least some difference in symptom reporting is a result of phase of menstrual cycle in which the injury was sustained and/or when symptoms were reported, but animal studies have documented overall sex differences as opposed to just hormonal cycle based ones (Velosky et al., 2017). Interestingly, in a study evaluating *healthy* participants, Hu et al. (2013) examined sex differences in the context of brain metabolic networks and showed that female brains, compared to male brains, have *higher* metabolic demands in posterior regions such as the occipital cortex and posterior parietal cortex, as well as the thalamus and hippocampus, whereas female brains have *lower* metabolic demands relative to male brains in anterior regions such as the frontal cortex and anterior parietal cortex. It is therefore

possible that these metabolic differences at baseline may lead to differential symptom reporting between males and females, and that these differences are exacerbated postinjury. Furthermore, although our review found some evidence for postinjury sex differences with regard to neuroimaging findings, future studies will need to more comprehensively examine sex differences at baseline and postconcussion to understand whether the differences observed postinjury are a result of baseline sex differences or if these differences are exacerbated postinjury.

With regard to other pathophysiological and biological aspects of concussion, a very recent study of neural architecture of TBI revealed that female axons were smaller with fewer microtubules and were subsequently at higher risk to break and/or exhibit greater axonal pathology following injury than male axons following an equivalent force from simulated TBI (Dolle et al., 2018). Additionally, previous research has established that females have weaker neck muscles compared to males and consequently may experience greater angular acceleration of the head/neck (Barnes et al., 1998; Tierney et al., 2005, 2008). It is possible that these factors may result not only in a differential risk of concussion but also in the experience of postconcussion symptoms for males and females.

As for the neuropsychological findings, it appears that differences between neurocognitive function of males and females are mostly limited to increased deficits for females in visual memory in the acute recovery phase. However, given the limitations of the available findings, additional research is needed, especially for long-term recovery and non-sports concussion mTBIs. Further, recruiting participants who are in mid to late adulthood, and who are more sedentary, will clarify the relationship between sex and mTBI/concussion in terms of neurocognitive outcomes.

There are also a number of factors that should be considered when interpreting the literature regarding sex differences in cognitive functioning. First, the differences reported postinjury may reflect preexisting individual differences. For example, Covassin et al. (2006) compared male and female athletes' baseline performance on the ImPACT battery, and found that females outperformed males on verbal memory, whereas males outperformed females on visual memory. Similar findings have also been reported in healthy participants (Weiss, Kemmler, Deisenhammer, Fleischhacker, & Delazer, 2003). Thus, there is evidence that males and females may perform differently on cognitive tasks prior to injury. However, it must be noted that there were no differences in baseline ImPACT scores, stratified by sex, in the Covassin et al. (2007) study described above. Furthermore, Broshek et al. (2005) noted that in their sample, males had a higher frequency of learning disabilities (LD) and attention-deficit/hyperactivity disorder (ADHD) (Broshek et al., 2005). While they excluded individuals who reported LD or ADHD, others have not reported the presence of LD or ADHD. Given prevalence of LD and ADHD is known to be higher in males, and is known to impact neurocognitive function (Seidman, 2006), it may be advisable to report and control for these factors when exploring sex differences in this population.

Additionally, as stated previously, most of the research reported herein has recruited young athletes, which may reduce generalizability. For example, it is well established that neuroplasticity influences recovery after injury, and that neuroplasticity decreases with age, and there is emerging evidence that both exercise and sex-

differences impact plastic processes (Voss, Thomas, Cisneros-Franco, & de Villers-Sidani, 2017). Expanding mTBI research to older adults and particularly older women is much needed. The aging of the population is contributing to the steady increase in TBI-related emergency room visits from older adults, with rates of emergency room visits following mTBI rising exponentially every decade after age 65 (Albrecht et al., 2016). In older adults, the incidence of mTBI in females was higher than that of males (Albrecht et al., 2016); these findings further highlight the need to study mTBI in older adults more broadly, but specifically in older women, as most work to date has been conducted on concussions sustained by younger cohorts. Caution must therefore be applied in extending the current findings to older and/or less active individuals, where neuroplasticity may be reduced.

Other areas in which concussion in females is notably underexamined is within the context of intimate partner violence (IPV). Although extremely limited data is available, one investigation found almost 68% of physically abused women had sustained an mTBI at the hands of their partner (Valera & Berenbaum, 2003), with a high likelihood of multiple mTBI incidents (Kwako et al., 2011). The TBIs sustained in the context of IPV lead to cognitive (Valera & Berenbaum, 2003) and altered brain functional connectivity (Valera & Kucyi, 2017). Female Veterans also report higher rates of IPV than non-Veterans (Dichter, Cerulli, & Bossarte, 2011), demonstrating an intersection of two understudied populations in the concussion literature. Further study of concussion in women who have or are experiencing IPV is warranted, as impact of and recoveries from both physical and psychological trauma will be uniquely intertwined in females in this context.

A final area yet to be explored in relation to sex differences in mTBI is the potential for interaction with genes known to influence postinjury recovery. A number of genes have been identified as influencing recovery after TBI (Davidson, Cusimano, & Bendena, 2015; Weaver, Chau, Portelli, & Grafman, 2012), and there is evidence of sex-gene interactions in relation to neurobiological and general outcomes after injury (Lopez et al., 2016; Ost et al., 2008). However, there is limited evidence of sex $\times$ gene interactions in the context of cognitive function, with only one study in TBI to date. Myrge et al. (2016) found that a number of genes associated with dopamine pathways interacted with sex in relation to cognitive recovery at 6 and 12 months after severe TBI. Thus, at present, there are no published findings in relation to mTBI, and only limited research in more severe TBI; as such, this represents another area in need of future research.

A number of methodological factors should also be taken into account when considering the extant findings related to sex differences in cognitive functioning following sports-related concussion. Firstly, as noted by Dougan et al. (2014), there is a lack of evidence relating to postacute recovery. The majority of studies have focused on the first 2 weeks of recovery, and it appears from the limited evidence (Moore et al., 2010) that the effect of sex differences on outcome may differ during later phases of recovery. A further consideration is the use of ImPACT, which has both advantages and disadvantages. Consistent use of the same measures allows better comparison between studies, and the ImPACT program has been reported to be valid and reliable by some studies (Nakayama, Covassin, Schatz, Nogle, & Kovan, 2014; Schatz, 2010;

Schatz, Pardini, Lovell, Collins, & Podell, 2006). However, there is also evidence that the alternate forms used in ImPACT are not always equivalent (Resch, Macciocchi, & Ferrara, 2013), and that it may be less reliable than other neurocognitive tests (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Resch et al., 2013). Finally, almost no study utilized performance or symptom validity measures, and examining sex differences with regard to validity is an area of much needed research.

Summary and conclusion

In conclusion, research examining sex differences in humans following concussion, in general, is in its infancy, and exploration of sex differences in studies outside of the sports concussion domain is particularly nascent. Thus, there is substantial need for additional research to be conducted in this area to better understand the influence of biological sex on concussion recovery and outcome. This review highlights what we currently know about sex differences following concussion, and provides avenues for future exploration.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the US Army Medical Research and Material Command and the US Department of Veterans Affairs [Chronic Effects of Neurotrauma Consortium] under Award No. W81XWH-13-2-0095 and I01 RX002076. The US Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick MD 21702-5014, is the awarding and administering acquisition office. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the US Government, or the US Department of Veterans Affairs, and no official endorsement should be inferred. The funding agencies had no role in data collection, analysis, or manuscript development.

ORCID

Christine R. Padgett <http://orcid.org/0000-0003-4398-4268>

References

- Albrecht, J. S., Hirshon, J. M., McCunn, M., Bechtold, K. T., Rao, V., Simoni-Wastila, L., & Smith, G. S. (2016). Increased rates of mild traumatic brain injury among older adults in us emergency departments, 2009-2010: Mild traumatic brain injury in older adults. *The Journal of Head Trauma Rehabilitation*, 31(5), E1–E7. doi:10.1097/HTR.000000000000190
- Asken, B. M., Snyder, A. R., Clugston, J. R., Gaynor, L. S., Sullan, M. J., & Bauer, R. M. (2017). Concussion-like symptom reporting in non-concussed collegiate athletes. *Archives of Clinical Neuropsychology*, 32(8), 963–971.
- Barnes, B. C., Cooper, L., Kirkendall, D. T., McDermott, T. P., Jordan, B. D., & Garrett, W. E. (1998). Concussion history in elite male and female soccer players. *The American Journal of Sports Medicine*, 26(3), 433–438.

- Bazarian, J. J., Blyth, B., Mookerjee, S., He, H., & McDermott, M. P. (2010). Sex differences in outcome after mild traumatic brain injury. *Journal of Neurotrauma*, 27(3), 527–539.
- Benedict, P. A., Baner, N. V., Harrold, G. K., Moehringer, N., Hasanaj, L., Serrano, L. P., ... Flanagan, S. R. (2015). Gender and age predict outcomes of cognitive, balance and vision testing in a multidisciplinary concussion center. *Journal of the Neurological Sciences*, 353(1), 111–115.
- Black, A. M., Sergio, L. E., & Macpherson, A. K. (2017). The epidemiology of concussions: Number and nature of concussions and time to recovery among female and male Canadian Varsity Athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, 27(1), 52–56.
- Boden, B. P., Kirkendall, D. T., & Garrett, W. E. (1998). Concussion incidence in elite college soccer players. *The American Journal of Sports Medicine*, 26(2), 238–241.
- Boyle, E., Cancelliere, C., Hartvigsen, J., Carroll, L. J., Holm, L. W., & Cassidy, J. D. (2014). Systematic review of prognosis after mild traumatic brain injury in the military: Results of the international collaboration on mild traumatic brain injury prognosis. *Archives of Physical Medicine and Rehabilitation*, 95(3), S230–S237. doi:10.1016/j.apmr.2013.08.297
- Brainard, L. L., Beckwith, J. G., Chu, J. J., Crisco, J. J., McAllister, T. W., Duhaime, A.-C., ... Greenwald, R. M. (2012). Gender differences in head impacts sustained by collegiate ice hockey players. *Medicine and Science in Sports and Exercise*, 44(2), 297–304.
- Brickell, T. A., Lippa, S. M., French, L. M., Kennedy, J. E., Bailie, J. M., & Lange, R. T. (2017). Female service members and symptom reporting after combat and non-combat-related mild traumatic brain injury. *Journal of Neurotrauma*, 34(2), 300–312.
- Broglio, S. P., Cantu, R. C., Gioia, G. A., Guskiewicz, K. M., Kutcher, J., Palm, M., & McLeod, T. C. V. (2014). National Athletic Trainers' Association position statement: Management of sport concussion. *Journal of Athletic Training*, 49(2), 245–265.
- Broglio, S. P., Ferrara, M. S., Macciocchi, S. N., Baumgartner, T. A., & Elliott, R. (2007). Test-retest reliability of computerized concussion assessment programs. *Journal of Athletic Training*, 42(4), 509–514.
- Broshek, D. K., Kaushik, T., Freeman, J. R., Erlanger, D., Webbe, F., & Barth, J. T. (2005). Sex differences in outcome following sports-related concussion. *Journal of Neurosurgery*, 102(5), 856–863. doi:10.3171/jns.2005.102.5.0856
- Brown, D. A., Elsass, J. A., Miller, A. J., Reed, L. E., & Reneker, J. C. (2015). Differences in symptom reporting between males and females at baseline and after a sports-related concussion: A systematic review and meta-analysis. *Sports Medicine*, 45(7), 1027–1040. doi:10.1007/s40279-015-0335-6
- Carroll, L. J., Cassidy, J. D., Cancelliere, C., Côté, P., Hincapié, C. A., Kristman, V. L., ... Hartvigsen, J. (2014). Systematic review of the prognosis after mild traumatic brain injury in adults: Cognitive, psychiatric, and mortality outcomes: Results of the international collaboration on mild traumatic brain injury prognosis. *Archives of Physical Medicine and Rehabilitation*, 95(3), S152–S173. doi:10.1016/j.apmr.2013.08.300
- Centers for Disease Control and Prevention. (2003). Report to congress on mild traumatic brain injury in the *United States: Steps to prevent a serious public health problem*. Retrieved from Atlanta, GA.
- Centers for Disease Control and Prevention. (2015). Report to congress on traumatic brain injury in the *United States: Epidemiology and rehabilitation*. Retrieved from Atlanta, GA.
- Centers for Disease Control and Prevention. (2016). *Rates of TBI-related emergency department visits, hospitalizations, and deaths by sex—United States, 2001–2010*. Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.
- Chamard, E., Lassonde, M., Henry, L., Tremblay, J., Boulanger, Y., De Beaumont, L., & Théoret, H. (2013). Neurometabolic and microstructural alterations following a sports-related concussion in female athletes. *Brain Injury*, 27(9), 1038–1046.
- Chamard, E., Lefebvre, G., Lassonde, M., & Theoret, H. (2016). Long-term abnormalities in the corpus callosum of female concussed athletes. *Journal of Neurotrauma*, 33(13), 1220–1226.

- Colvin, A. C., Mullen, J., Lovell, M. R., Vereeke West, R., Collins, M. W., & Groh, M. (2009). The role of concussion history and gender in recovery from soccer-related concussion. *The American Journal of Sports Medicine*, 37(9), 1699–1704.
- Covassin, T., Elbin III, R. J., Larson, E., & Kontos, A. P. (2012b). Sex and age differences in depression and baseline sport-related concussion neurocognitive performance and symptoms. *Clinical Journal of Sport Medicine*, 22(2), 98–104.
- Covassin, T., Elbin, R., Bleecker, A., Lipchik, A., & Kontos, A. P. (2013). Are there differences in neurocognitive function and symptoms between male and female soccer players after concussions? *The American Journal of Sports Medicine*, 41(12), 2890–2895.
- Covassin, T., Elbin, R., Harris, W., Parker, T., & Kontos, A. (2012a). The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *The American Journal of Sports Medicine*, 40(6), 1303–1312.
- Covassin, T., Elbin, R., Kontos, A., & Larson, E. (2010). Investigating baseline neurocognitive performance between male and female athletes with a history of multiple concussion. *Journal of Neurology, Neurosurgery & Psychiatry*, 81(6), 597–601.
- Covassin, T., Moran, R., & Elbin, R. (2016). Sex differences in reported concussion injury rates and time loss from participation: An update of The National Collegiate Athletic Association Injury Surveillance Program from 2004–2005 through 2008–2009. *Journal of Athletic Training*, 51(3), 189–194.
- Covassin, T., Schatz, P., & Swanik, C. B. (2007). Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery*, 61(2), 345–351.
- Covassin, T., Swanik, C. B., Sachs, M., Kendrick, Z., Schatz, P., Zillmer, E., & Kaminaris, C. (2006). Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *British Journal of Sports Medicine*, 40(11), 923–927.
- Covassin, T., Swanik, C. B., Sachs, M., Kendrick, Z., Schatz, P., Zillmer, E., ... Stearne, D. J. (2006). Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *British Journal of Sports Medicine*, 40(11), 923–927. doi:10.1136/bjsm.2006.029496
- Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex differences and the incidence of concussions among collegiate athletes. *Journal of Athletic Training*, 38(3), 238–244.
- Davidson, J., Cusimano, M. D., & Bendena, W. G. (2015). Post-traumatic brain injury: Genetic susceptibility to outcome. *Neuroscientist*, 21(4), 424–441. doi:10.1177/1073858414543150
- Delaney, J. S., Lacroix, V. J., Leclerc, S., & Johnston, K. M. (2002). Concussions among university football and soccer players. *Clinical Journal of Sport Medicine*, 12(6), 331–338.
- Department of Defense. (2015). *2015 Demographics: Profile of the military community*. Retrieved from <http://download.militaryonesource.mil/12038/MOS/Reports/2015-Demographics-Report.pdf>
- Dichter, M. E., Cerulli, C., & Bossarte, R. M. (2011). Intimate partner violence victimization among women veterans and associated heart health risks. *Womens Health Issues*, 21(4 Suppl), S190–S194. doi:10.1016/j.whi.2011.04.008
- Dick, R. W., Hootman, J. M., Agel, J., & Marshall, S. W. (2008). Concussion rates and gender in NCAA competitions. *Medicine & Science in Sports & Exercise*, 40(5), S231.
- Dolle, J. P., Jaye, A., Anderson, S. A., Ahmadzadeh, H., Shenoy, V. B., & Smith, D. H. (2018). Newfound sex differences in axonal structure underlie differential outcomes from in vitro traumatic axonal injury. *Experimental Neurology*, 300, 121–134. doi:10.1016/j.expneurol.2017.11.001
- Dougan, B. K., Horswill, M. S., & Geffen, G. M. (2014). Athletes' age, sex, and years of education moderate the acute neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society*, 20(1), 64–80.
- Ellemborg, D., Leclerc, S., Couture, S., & Daigle, C. (2007). Prolonged neuropsychological impairments following a first concussion in female university soccer athletes. *Clinical Journal of Sport Medicine*, 17(5), 369–374.
- Fakhran, S., Yaeger, K., Collins, M., & Alhilali, L. (2014). Sex differences in white matter abnormalities after mild traumatic brain injury: Localization and correlation with outcome. *Radiology*, 272(3), 815–823. doi:10.1148/radiol.14132512

- Farace, E., & Alves, W. M. (2000). Do women fare worse: A metaanalysis of gender differences in traumatic brain injury outcome. *Journal of Neurosurgery*, 93, 539–545.
- Frayne, S. M., Phibbs, C. S., Saechao, F., Maisel, N. C., Friedman, S. A., Finlay, & Haskell, S. (2014). *Sourcebook, women veterans in the Veterans Health Administration: Volume 3, Sociodemographics, utilization, costs of care, and health profile*. Washington, DC: Women's Health Evaluation Initiative, Women's Health Services, Veterans Health Administration, Department of Veterans Affairs.
- Frost, R. B., Farrer, T. J., Primosch, M., & Hedges, D. W. (2013). Prevalence of traumatic brain injury in the general adult population: A meta-analysis. *Neuroepidemiology*, 40(3), 154–159.
- Fuller, C., Junge, A., & Dvorak, J. (2005). A six year prospective study of the incidence and causes of head and neck injuries in international football. *British Journal of Sports Medicine*, 39(Suppl 1), i3–i9.
- Garden, N., & Sullivan, K. A. (2010). An examination of the base rates of post-concussion symptoms: The influence of demographics and depression. *Applied Neuropsychology*, 17(1), 1–7. doi:10.1080/09084280903297495
- Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training*, 42(4), 495–503.
- Giza, C. C., Kutcher, J. S., Ashwal, S., Barth, J., Getchius, T. S., Gioia, G. A., ... Manley, G. (2013). Summary of evidence-based guideline update: Evaluation and management of concussion in sports Report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology*, 80(24), 2250–2257.
- Granito Jr, V. J. (2002). Psychological response to athletic injury: Gender differences. *Journal of Sport Behavior*, 25(3), 243–259.
- Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., ... Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: Concussion in sport. *British Journal of Sports Medicine*, 47, 15–26.
- Hendricks, A. M., Amara, J., Baker, E., Charns, M. P., Garner, J. A., Iverson, K. M., ... Lew, H. L. (2013). Screening for mild traumatic brain injury in OEF/OIF deployed US military: An empirical assessment of VHA's experience. *Brain Injury*, 27(2), 125–134. doi:10.3109/02699052.2012.729284
- Henry, L. C., Elbin, R., Collins, M. W., Marchetti, G., & Kontos, A. P. (2015). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*, 78(2), 232–241.
- Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training*, 42(2), 311–319.
- Hu, Y., Xu, Q., Li, K., Zhu, H., Qi, R., Zhang, Z., & Lu, G. (2013). Gender differences of brain glucose metabolic networks revealed by FDG-PET: Evidence from a large cohort of 400 young adults. *PLoS One*, 8(12), e83821. doi:10.1371/journal.pone.0083821
- Iverson, G. L., & Lange, R. T. (2003). Examination of “postconcussion-like” symptoms in a healthy sample. *Applied Neuropsychology*, 10(3), 137–144.
- Iverson, K. M., Hendricks, A. M., Kimerling, R., Krengel, M., Meterko, M., Stolzmann, K. L., ... Lew, H. L. (2011). Psychiatric diagnoses and neurobehavioral symptom severity among OEF/OIF VA patients with deployment-related traumatic brain injury: A gender comparison. *Women's Health Issues*, 21(4), S210–S217.
- Kerr, Z. Y., Evenson, K. R., Rosamond, W. D., Mihalik, J. P., Guskiewicz, K. M., & Marshall, S. W. (2014). Association between concussion and mental health in former collegiate athletes. *Injury Epidemiology*, 1(1), 28.
- Kerr, Z. Y., Roos, K. G., Djoko, A., Dalton, S. L., Broglio, S. P., Marshall, S. W., & Dompier, T. P. (2017). Epidemiologic measures for quantifying the incidence of concussion in National Collegiate Athletic Association sports. *Journal of Athletic Training*, 52(3), 167–174.
- King, N. S. (2014a). Permanent post concussion symptoms after mild head injury: A systematic review of age and gender factors. *NeuroRehabilitation*, 34, 741–748.

- King, N. S. (2014b). A systematic review of age and gender factors in prolonged post-concussion symptoms after mild head injury. *Brain Injury*, 28(13–14), 1639–1645.
- Kontos, A. P., Covassin, T., Elbin, R., & Parker, T. (2012a). Depression and neurocognitive performance after concussion among male and female high school and collegiate athletes. *Archives of Physical Medicine and Rehabilitation*, 93(10), 1751–1756.
- Kontos, A. P., Elbin, R., Schatz, P., Covassin, T., Henry, L., Pardini, J., & Collins, M. W. (2012b). A revised factor structure for the post-concussion symptom scale: Baseline and postconcussion factors. *The American Journal of Sports Medicine*, 40(10), 2375–2384.
- Kupina, N. C., Detloff, M. R., Bobrowski, W. F., Snyder, B. J., & Hall, E. D. (2003). Cytoskeletal protein degradation and neurodegeneration evolves differently in males and females following experimental head injury. *Experimental Neurology*, 180(1), 55–73.
- Kwako, L. E., Glass, N., Campbell, J., Melvin, K. C., Barr, T., & Gill, J. M. (2011). Traumatic brain injury in intimate partner violence: A critical review of outcomes and mechanisms. *Trauma Violence Abuse*, 12(3), 115–126. doi:10.1177/1524838011404251
- Lincoln, A. E., Hinton, R. Y., Almquist, J. L., Lager, S. L., & Dick, R. W. (2007). Head, face, and eye injuries in scholastic and collegiate lacrosse: A 4-year prospective study. *The American journal of Sports Medicine*, 35(2), 207–215.
- Lippa, S. M., Brickell, T. A., Bailie, J. M., French, L. M., Kennedy, J. E., & Lange, R. T. (2018). Postconcussion symptom reporting after mild traumatic brain injury in female service members: Impact of gender, posttraumatic stress disorder, severity of injury, and associated bodily injuries. *The Journal of Head Trauma Rehabilitation*, 33(2), 101–112.
- Lopez, M., Efron, P. A., Ozrazgat-Baslanti, T., Zhang, J. Y., Cuschieri, J., Maier, R. V., & Brakenridge, S. C. (2016). Sex-based differences in the genomic response, innate immunity, organ dysfunction, and clinical outcomes after severe blunt traumatic injury and hemorrhagic shock. *Journal of Trauma and Acute Care Surgery* 81(3), 478–485. doi:10.1097/TA.0000000000001113
- Lovell, M. R., Collins, M. W., Maroon, J. C., Cantu, R. C., Hawn, M. A., Burke, C. J., & Fu, F. (2002). Inaccuracy of symptom reporting following concussion in athletes. *Medicine & Science in Sports & Exercise*, 34(5), S298.
- MacDonald, C. L., Barber, J., Jordan, M., Johnson, A. M., Dikmen, S., Fann, J. R., & Temkin, N. (2017). Early clinical predictors of 5-year outcome after concussive blast traumatic brain injury. *JAMA Neurology*, 74(7), 821–829. doi:10.1001/jamaneurol.2017.0143
- McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., ... Castellani, R. J. (2017). Consensus statement on concussion in sport—The 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*. Published Online First: 26 April 2017. doi:10.1136/bjsports-2017-097699
- Mihalik, J. P., Register-Mihalik, J., Kerr, Z. Y., Marshall, S. W., McCrea, M. C., & Guskiewicz, K. M. (2013). Recovery of posttraumatic migraine characteristics in patients after mild traumatic brain injury. *The American Journal of Sports Medicine*, 41(7), 1490–1496.
- Moore, D. W., Ashman, T. A., Cantor, J. B., Krinick, R. J., & Spielman, L. A. (2010). Does gender influence cognitive outcome after traumatic brain injury? *Neuropsychological Rehabilitation*, 20(3), 340–354.
- Morrisette, S. B., Woodward, M., Kimbrel, N. A., Meyer, E. C., Kruse, M. I., Dolan, S., & Gulliver, S. B. (2011). Deployment-related TBI, persistent postconcussive symptoms, PTSD, and depression in OEF/OIF veterans. *Rehabilitation Psychology*, 56(4), 340–350.
- Myrka, J. M., Failla, M. D., Ricker, J. H., Dixon, C. E., Conley, Y. P., Arenth, P. M., & Wagner, A. K. (2016). A dopamine pathway gene risk score for cognitive recovery following traumatic brain injury: Methodological considerations, preliminary findings, and interactions with sex. *Journal of Head Trauma Rehabilitation*, 31(5), E15–E29. doi:10.1097/HTR.000000000000199
- Nakayama, Y., Covassin, T., Schatz, P., Nogle, S., & Kovan, J. (2014). Examination of the test-retest reliability of a computerized neurocognitive test battery. *The American Journal of Sports Medicine*, 42(8), 2000–2005.
- Ost, M., Nylen, K., Csajbok, L., Blenow, K., Rosengren, L., & Nellgard, B. (2008). Apolipoprotein E polymorphism and gender difference in outcome after severe traumatic brain injury. *Acta Anaesthesiologica Scandinavica*, 52(10), 1364–1369. doi:10.1111/j.1399-6576.2008.01675.x

- Preiss-Farzanegan, S. J., Chapman, B., Wong, T. M., Wu, J., & Bazarian, J. J. (2009). The relationship between gender and postconcussion symptoms after sport-related mild traumatic brain injury. *PM&R*, 1(3), 245–253.
- Resch, J. E., Macciocchi, S., & Ferrara, M. S. (2013). Preliminary evidence of equivalence of alternate forms of the ImPACT. *The Clinical Neuropsychologist*, 27(8), 1265–1280.
- Roos, K. G., Wasserman, E. B., Dalton, S. L., Gray, A., Djoko, A., Dompier, T. P., & Kerr, Z. Y. (2017). Epidemiology of 3825 injuries sustained in six seasons of National Collegiate Athletic Association men's and women's soccer (2009/2010–2014/2015). *British Journal of Sports Medicine*, 51(13), 1029–1034.
- Rosene, J. M., Raksnis, B., Silva, B., Woefel, T., Visich, P. S., Dompier, T. P., & Kerr, Z. Y. (2017). Comparison of concussion rates between NCAA division I and division III men's and women's ice hockey players. *The American Journal of Sports Medicine*, 45(11), 2622–2629.
- Schatz, P. (2010). Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *The American Journal of Sports Medicine*, 38(1), 47–53. doi:10.1177/0363546509343805
- Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology*, 21(1), 91–99.
- Schick, D. M., & Meeuwisse, W. H. (2003). Injury rates and profiles in female ice hockey players. *The American Journal of Sports Medicine*, 31(1), 47–52.
- Schneiderman, A. I., Braver, E. R., & Kang, H. K. (2008). Understanding sequelae of injury mechanisms and mild traumatic brain injury incurred during the conflicts in Iraq and Afghanistan: Persistent postconcussive symptoms and posttraumatic stress disorder. *American Journal of Epidemiology*, 167(12), 1446–1452.
- Scott, C., McKinlay, A., McLellan, T., Britt, E., Grace, R., & MacFarlane, M. (2015). A comparison of adult outcomes for males compared to females following pediatric traumatic brain injury. *Neuropsychology*, 29(4), 501–508. doi:10.1037/neu0000074
- Seidman, L. J. (2006). Neuropsychological functioning in people with ADHD across the lifespan. *Clinical Psychology Review*, 26(4), 466–485. doi:10.1016/j.cpr.2006.01.004
- Shehata, N., Wiley, J., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. (2009). Sport concussion assessment tool: Baseline values for varsity collision sport athletes. *British Journal of Sports Medicine*, 43(10), 730–734.
- Smith-Seemiller, L., Fow, N. R., Kant, R., & Franzen, M. D. (2003). Presence of post-concussion syndrome symptoms in patients with chronic pain vs mild traumatic brain injury. *Brain Injury*, 17(3), 199–206.
- Tanveer, S., Zecavati, N., Delasobera, E. B., & Oyegbile, T. O. (2017). Gender differences in concussion and postinjury cognitive findings in an older and younger pediatric population. *Pediatric Neurology*, 70, 44–49.
- Taylor, C. A., Bell, J. M., Breiding, M. J., & Xu, L. (2017). Traumatic Brain Injury–Related Emergency Department Visits, Hospitalizations, and Deaths — United States, 2007 and 2013. *MMWR. Surveillance Summaries*, 66(9), 1–16. doi:10.15585/mmwr.ss6609a1
- Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training*, 43(6), 578–584.
- Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segment dynamic stabilization during head acceleration. *Medicine and Science in Sports and Exercise*, 37(2), 272–279.
- Tsushima, W. T., Lum, M., & Geling, O. (2009). Sex differences in the long-term neuropsychological outcome of mild traumatic brain injury. *Brain Injury*, 23(10), 809–814.
- Valera, E., & Kucyi, A. (2017). Brain injury in women experiencing intimate partner-violence: Neural mechanistic evidence of an “invisible” trauma. *Brain Imaging and Behavior*, 11(6), 1664–1677. doi:10.1007/s11682-016-9643-1
- Valera, E. M., & Berenbaum, H. (2003). Brain injury in battered women. *Journal of Consulting and Clinical Psychology*, 71(4), 797–804.

- Velosky, A. G., Tucker, L. B., Fu, A. H., Liu, J., & McCabe, J. T. (2017). Cognitive performance of male and female C57BL/6J mice after repetitive concussive brain injuries. *Behavioural Brain Research*, 324, 115–124. doi:[10.1016/j.bbr.2017.02.017](https://doi.org/10.1016/j.bbr.2017.02.017)
- Voss, P., Thomas, M. E., Cisneros-Franco, J. M., & de Villers-Sidani, É. (2017). Dynamic brains and the changing rules of neuroplasticity: Implications for learning and recovery. *Frontiers in Psychology*, 8, 1657.
- Wang, Y., Chan, R. C., & Deng, Y. (2006). Examination of postconcussion-like symptoms in healthy university students: Relationships to subjective and objective neuropsychological function performance. *Archives of Clinical Neuropsychology*, 21(4), 339–347.
- Weaver, S. M., Chau, A., Portelli, J. N., & Grafman, J. (2012). Genetic polymorphisms influence recovery from traumatic brain injury. *Neuroscientist*, 18(6), 631–644. doi:[10.1177/1073858411435706](https://doi.org/10.1177/1073858411435706)
- Weiss, E. M., Kemmler, G., Deisenhammer, E. A., Fleischhacker, W. W., & Delazer, M. (2003). Sex differences in cognitive functions. *Personality and Individual Differences*, 35(4), 863–875.
- Yang, J., Peek-Asa, C., Corlette, J. D., Cheng, G., Foster, D. T., & Albright, J. (2007). Prevalence of and risk factors associated with symptoms of depression in competitive collegiate student athletes. *Clinical Journal of Sport Medicine*, 17(6), 481–487.
- Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: Incidence, recurrence, and mechanisms. *The American Journal of Sports Medicine*, 43(11), 2654–2662.