IJSPT

ORIGINAL RESEARCH

UTILIZATION OF IMPACT TESTING TO MEASURE INJURY RISK IN ALPINE SKI AND SNOWBOARD ATHLETES

John Faltus, PT, DPT, SCS, ATC[1]
Brittney Huntimer, PT, DPT, SCS, ATC[2]
Thomas Kernozek, PhD, FACSM[3]
John Cole, BA[4]

ABSTRACT

Background: While studies that have examined the prevalence of musculoskeletal injuries in alpine skiing and snowboarding exist, there has been no discussion of how neurocognitive deficits may influence such injuries. Recent authors have identified a possible link between Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) testing results and the prevalence of musculoskeletal injury in athletic populations. However, no study has specifically examined this in the alpine skiing and snowboard athletes who sustain injury and those that do not.

Hypothesis/Purpose: The purpose was to review injury data and ImPACT test results within the local ski/snowboard population to determine if there was a difference in components of ImPACT test scores between injured and non-injured athletes. It was hypothesized that differences would exist in component scores on ImPACT testing between injured and non-injured athletes.

Study design: Retrospective cohort study

Methods: Injury records and baseline ImPACT testing scores for 93 athletes aged 14-17 participating in a local ski and snowboard club during the 2009-2012 seasons were gathered retrospectively. Injuries documented for the lower and upper extremity included ligament sprains, muscle strains, contusions, dislocation/subluxation, fractures and concussions. Athletes who sustained any of these listed injuries were categorized within the injured athlete group. Each component of ImPACT test scores was compared between gender and for injury status within skiing and snowboarding disciplines using a series of two-way analysis of variance tests.

Results: There was no difference between non-injured and injured females as well as non-injured and injured males in reaction time and visual motor speed (VMS), however there was an interaction between gender and injury status on composite reaction time and visual motor speed, or VMS. The composite reaction time for females was 4.7% faster with injury while males without injury had a composite reaction time that was slower by 5.8%. Females had a 4.1% higher mean VMS score with injury while males had a 14.4% higher VMS score without injury.

Conclusion: Future research may consider prospectively examining neurocognitive testing scores and injury prevalence within the disciplines of snowboarding and both alpine and freestyle skiing.

Levels of Evidence: Level 3

Key Words: Musculoskeletal injury, neurocognitive deficits, neurocognitive testing

[1] Memphis Grizzlies, Memphis, TN, USA
[2] Howard Head Sports Medicine, Edwards, CO, USA
[3] La Crosse Institute for Movement Science, Strzelczyk Clinical Biomechanics Laboratory, Department of Health Professions, Physical Therapy Program, University of Wisconsin-La Crosse, La Crosse, WI, USA
[4] Ski and Snowboard Club Vail, Vail, CO, USA

Acknowledgement

We thank Kim Greene from Vail Valley Medical Center for her contribution in providing ImPACT data records for this study.

No outside funding was received for the completion of this study.

The study protocol was approved by the Institutional Review Board at Vail Valley Medical Center.

The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.

CORRESPONDING AUTHOR

John Faltus,
Memphis Grizzlies,
191 Beale Street, Memphis TN 38103
E-mail: jfaltus@grizzlies.com

INTRODUCTION

Musculoskeletal injuries in skiing and snowboarding are common and have been well documented.[1,2,3,4,5] The prevalence of the types of injuries with these sports varies. Hand, wrist, shoulder and ankle injuries occur at a higher rate in snowboarding whereas knee injuries are more prevalent in skiing.[1,2,3,4,5] It can be assumed that the elements of both sports which often require quick changes in direction involving high limb acceleration during very high-risk maneuvers performed on varied surfaces with changing climate conditions may greatly factor into the incidence of injury. Much of the current literature identifies both neuromuscular and biomechanical mechanisms contributing to such musculoskeletal injuries, specifically regarding non-contact knee injury mechanisms, because these risk factors are thought to be modifiable.[5,6,7]

Neurocognitive testing has become a standard, objective means for assessing changes in cerebral and cortical function associated with concussions and have been used to assist with return-to-play decisions. The reliability and validity of ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing, ImPACT Applications, Inc., Pittsburgh, PA) has been shown in several studies using athletic samples.[8,9,10] Independent studies have demonstrated good reliability of the ImPACT test overall with ICC ranges from.70-.85.[8,10] With regards to the specific components of the total ImPACT score, self-reported symptoms represent the least reliable index while motor processing speed has been reported to be the most reliable.[8,10] Regarding test validity, Maerlender et al[11] reported that the cognitive domains represented from ImPACT testing were shown to have good construct validity compared to neuropsychological tests that are sensitive to cognitive functions associated with mild traumatic brain injury.[11]

Recent authors have investigated a possible link between neurocognitive deficits identified from ImPACT tests and lower extremity injury risk.[12,13] Specifically, composite reaction time >.545 s doubled the risk for injury in collegiate football athletes.[13] It is reasonable to assume that deficits in neurocognitive function may contribute to the occurrence of musculoskeletal injury given recent evidence. A history of concussions in NFL athletes was associated with higher odds of sustaining a musculoskeletal injury.[14] Furthermore, college athletes were found to have increased odds of musculoskeletal injury following return to sport after concussion.[15,16] Deficits in cortically driven reaction time, processing speed, and visual and verbal memory may indicate a diminished capacity for neuromuscular control and predispose an athlete to subsequent injury.[12,13] Maintaining dynamic control during complicated, high velocity athletic movements is contingent on both cortically programmed muscle pre-activation and reflex-mediated muscle contraction. Although many peripheral and segmental reflexive pathways exist, ultimately the cerebral cortex is responsible for planning and regulating all of these motor control processes.[14] Neurocognitive tasks, such as those measuring reaction time, processing speed, visual memory, and verbal memory are indirect measures of cerebral performance.[17] Situational awareness, arousal, and attention are resources that an individual may use to influence those areas of neurocognitive function, and these in turn affect the integration of vestibular, visual, and somatosensory information needed for neuromuscular control.[12,17,18,19]

The purpose was to review injury data and ImPACT test results within the local ski/snowboard population to determine if there was a difference in components of ImPACT test scores between injured and non-injured athletes. It was hypothesized that differences would exist in component scores on ImPACT testing between injured and non-injured athletes.

METHODS

Data for this retrospective cohort study included ImPACT testing scores and injury reports for athletes from a local ski and snowboard club during three competitive seasons. The components of the ImPACT assessment were evaluated as well as the elements of each respective component score which included reaction time (average response speed), verbal memory (attentional processes, learning, and memory within the verbal domain), visual memory (visual attention and scanning, learning and memory), VMS, or visual motor speed (visual processing, learning and memory, and visual-motor response speed), and cognitive efficiency index (CEI). The CEI component of this test examines the interaction between speed and memory and is determined from the symbol-matching task within the ImPACT test. During this component, speed is measured from the number of items correctly identified while accuracy is the number of items correctly identified from the memory portion of this symbol-matching task. The test scores were collected from a local hospital that administered baseline neurocognitive tests. Injury records were collected directly from the local ski and snowboard club. This study protocol was approved by the Vail Valley Institutional Review Board.

Charted records for male and female athletes aged 14-17 participating in the disciplines of alpine skiing, freestyle skiing, and snowboarding during the 2009-12 competitive seasons (October-April) were examined. Records for athletes in this cohort that did not contain the baseline ImPACT testing prior to each competitive season were excluded. Out of roughly 450 athletes, the records for 134 athletes who met the inclusion criteria were included in the data analysis (Table 1). There were 93 documented injuries within this cohort. Injuries documented for the lower and upper extremity included ligament sprains, muscle strains, contusions, dislocation/subluxation, fractures and concussions. Athletes who sustained any of these listed injuries were categorized within the injured athlete group. Athletes who did not sustain an injury but met inclusionary criteria for this study were categorized as non-injured athletes. Informed consent for injury documentation and record keeping was obtained from each athlete and his or her respective legal guardian prior to participation during each season.

Neurocognitive function assessment was performed prior to each competitive season by administering the ImPACT test. ImPACT is computer software that assesses neurocognitive function and concussion symptoms through a series of six neurocognitive tests. According to the ImPACT Applications, Inc. Technical Manual, these six tests evaluate word recognition, design memory, visual processing and memory, and working memory/visual response speed. From these six tests, five composite scores are produced in the areas of verbal memory, visual memory, reaction time, visual motor speed (VMS) and impulse control. Testing was conducted in a quiet, controlled environment. Following test completion, scores were stored in a secure electronic database in the local hospital's medical records maintained by the director of ImPACT testing. Composite scores from each component (RT, VMS, Verbal, Visual and CEI) were determined from each athlete documented along with injury records, in both paper and electronic form, by the local ski and snowboard club coaching staff and were then used to examine the research question. Testing validity was determined based upon comparison to criterion values for each composite score. Previously established standards for whether a baseline test is invalid include an impulse control composite score greater than 30, processing speed composite score less than 25, reaction time scores greater than .80, verbal memory composite score below 70 and visual memory composite score below 60.[23] Additionally, the ImPACT Applications, Inc. Technical Manual states that the ImPACT report software will automatically generate an indication that a completed baseline test has questionable validity if certain criteria, based upon previously mentioned composite score standards and/or low percentage of correct answers in word and design recognition tasks, are met.

STATISTICAL METHODS

Two-way analysis of variance tests with two between factors (gender – male/female) and injury status (injured/non-injured) were applied separately to each component variable from neurocognitive testing: reaction time, visual motor speed, verbal memory, visual memory and cognitive efficiency index. Alpha was set a priori to 0.05 for each of these tests. Post hoc comparisons were performed as warranted.

Table 1. *Subject Demographics*

	Alpine Skiing	Freestyle Skiing	Snowboarding
Female	50	30	10
Male	28	12	4
Total	**78**	**42**	**14**

Table 2. *Injury by Region*							
	Shoulder	Knee	Hip/Leg	Head/Face/Concussion	Foot/Ankle	Spine	Wrist/Hand
Male	7	6	2	15	4	3	5
Female	4	18	2	16	0	3	8

RESULTS

Of the 93 injuries documented, the majority of these injuries occurred in the lower extremity followed by concussions/head injuries, and upper extremity injuries (Table 2). In regards to testing validity criterion that will be discussed later in this manuscript, ten total athletes (five from injured group and five from uninjured group) scored below the criterion point for verbal memory composite scoring. Eighteen total athletes (7 from injured group and 11 from uninjured group) scored below the criterion point for visual memory composite scoring. Also, two subjects from the uninjured group scored at equal to or slightly greater than this criterion for reaction time. Data which did not meet these criteria was excluded from analysis.

For reaction time, there was no difference based on gender ($F(1,89)=1.97$, $p = .164$) or injury status ($F(1,89)=0.7$, $p = .763$). There was a 2.5% mean difference in reaction time between females and males, with females being slower in reaction time. Reaction time means based on injury status was nearly identical (less than 1% difference between genders). There was an significant interaction between gender and injury status on mean reaction time ($F(1,89)=5.08$, $p=0.027$). Follow up tests indicated that the composite reaction time for females was 4.7% lower with injury ($t(42)=-1.27$, $p=0.210$) while the composite reaction time for males was greater by 5.8% ($t(42)=2.09$, $p=0.045$) (Figure 1).

VMS scores were not different between gender ($F(1,89)=0.48$, $p=0.490$) or injury status ($F(1,89)=1.55$, $p = .216$). VMS mean scores between genders with nearly the same (less than 1% difference between genders). Based on injury status VMS differed by 4.1% with injury yielding slightly higher scores. There was a significant interaction between gender and injury status on VMS scores ($F(1,89)=5.65$, $p = .027$). Follow up tests indicated that the females had a 4.1% higher mean VMS scores with injury ($t(42)=0.80$, $p=0.426$) whereas the males had a 14.4% higher VMS score without injury ($t(47)=-2.55$, $p=.014$) (Figure 2).

Verbal memory scores were not different between gender ($F(1,89)=0.51$, $p = .476$) or injury status ($F(1,89)=0.84$, $p = .363$). Mean verbal scores based on gender was 84.7 ± 12.5 for males and 83.5 ± 11.3

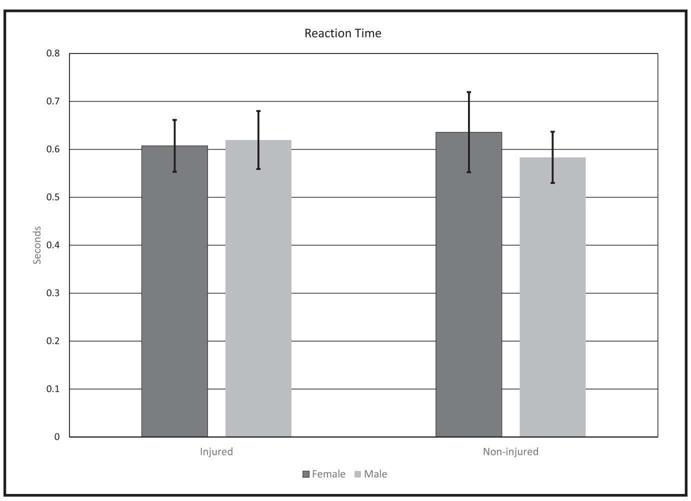

Figure 1. *Mean and standard deviation for reaction time (RT) for injured and non-injured males and females.*

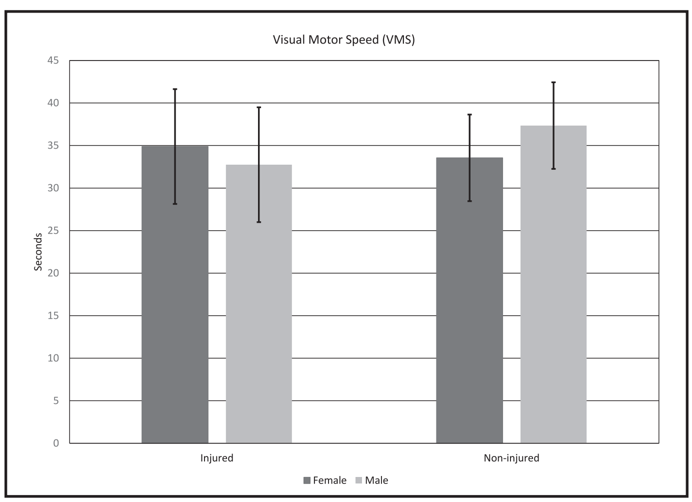

Figure 2. *Mean and standard deviation for visual motor speed (VMS) for injured and non-injured males and females.*

for females. Similarly, the means on injury status for verbal scores were only 2.1% different with injury being slightly larger. There was also no interaction between gender and injury status for verbal scores ($F(1,89)=0.05$, $p = .822$). Means for verbal scores changed based on injury status was smaller by 2% while males were smaller by 3.5%.

Visual memory scores were not different between gender ($F(1,89)=1.46$, $p = .231$) or injury status ($F(1,89)=0.17$, $p = .679$). Mean visual scores were 4.6% higher in females compared to males. Injury status similarly had little influence on mean visual scores with 73.4 ± 13.9 for females and 73.1 ± 16.4 for males. There was also no interaction between gender and injury status for verbal scores ($F(1,89)=0.10$, $p = .750$). Mean visual scores were 5.2% lower with injury for females and nearly 2% lower for males.

CEI scores were not different between gender ($F(1,89)=0.41$, $p = .526$) or injury status ($F(1,89)=0.02$, $p = .882$). Female and male mean CEI values differed by 5% while injury status had little influence on mean CEI scores (2.7% difference). There was also no interaction between gender and injury status for verbal scores ($F(1,89)=0.77$, $p = .383$). Mean CEI scores were 8.9% higher for females with injury while males had a 6.4% greater CEI with injury.

DISCUSSION

The current study investigated whether there was a difference in each component of ImPACT testing based on gender and injury status. Results indicated interaction between gender and injury status on composite reaction time and VMS (Figures 1 and 2). There was no difference in ImPACT scores and injury prevalence in the adolescent ski and snowboard population based the results of the current study.

While lower extremity injuries accounted for 34% of total injuries in the data collection, concussions were also a commonly documented injury in this ski and snowboard population (Table 2). The occurrence of concussion injuries in this population as well as possible effects on neurocognition must be considered given recent attention provided to this topic in the literature. There appears to be a relationship between age, gender and concussion outcomes including symptoms to component scores from ImPACT testing and postural stability.[24] Iverson et al demonstrated decreased performance on specific components of the ImPACT test, specifically verbal memory, visual memory, visual motor speed and reaction time after sustaining a concussion.[24] Diminished performance in these component score categories may indicate delayed neurocognitive recovery and could impact physical performance as well.[23] Deficits in neurocognitive measures such as sustained auditory attention, visual motor processing speed, reaction time and postural stability may hinder physical performance and could lead to increased risk of musculoskeletal injuries and concussion.

High school athletes appear to take longer to recover from concussion injury than collegiate athletes. Iverson et al reported that 37% of concussed high school athletes were still clinically symptomatic on two or more neurocognitive measures reported on the ImPACT test including verbal memory, visual memory, and reaction time at 10 days after a concussion compared to impairments in visual motor speed that resolved in five days after sustaining a concussion in collegiate athletes.[24] Covassin et al suggested that high school athletes had a poorer performance than college athletes on verbal and visual memory scores on the ImPACT test after sustaining a concussion injury.[20] Their results suggest that on average, neurocognitive impairments may persists for 10-21 days after a concussion for high school athletes compared to 5-7 days for neurocognitive recovery in collegiate athletes.[20] Meehan et al reported on a study of 2041 high school athletes and found that up to 23% of concussed athletes continued to demonstrate difficulties on cognitive tasks three weeks after injury.[21] Given the high percentage of concussion injuries in the study, special consideration of neurocognitive deficits in these ski and snowboard athletes with a history of concussion and the possible effect of these deficits on performance must be further examined, especially if compromised neurocognitive function may contribute to elevated injury risk.

Previous authors have identified delayed reaction time with injuries in the lower extremity with a defined prediction value (≥.565) based upon ImPACT reaction time composite scores.[12,13] This prediction value represents the reaction time composite score in milliseconds for determining injury risk. In the case of the studies referenced, athletes who had a delayed reaction time, greater than 0.57 milliseconds, were found to be at greater risk for musculoskeletal injury. In comparison to the results, injured female and male athletes had an average reaction time of .61 and .62 ms, respectively. Non-injured female and male athletes had an average reaction time of .64 and .58 ms, respectively. These findings may indicate that a reaction time of .57 ms may not be a good predictor of injuries in the ski and snowboard population. Furthermore, interaction effects between genders and both injured and non-injured populations should be further investigated across different sports. The predictive nature of other composite scores within ImPACT has not been established.

Baillargeon et al provided evidence that sports concussion may specifically affect working memory processes in all age groups.[22] However, adolescents displayed more cognitive impairments than children and adults after sustaining a sports related concussion. Previous authors have also demonstrated that gender may have an effect on recovery from a concussion. Covassin et al reported that after sustaining a concussion, female collegiate athletes demonstrated significantly worse on visual memory compared to males.[20] Similarly, it has been reported that concussed female athletes had slower reaction times and more post-concussion symptoms compared to males. Gender differences in cognitive function after a concussion may be attributed to hormone differences specifically estrogen and progesterone, weak musculature, anatomic differences and cerebrovascular organization. With regards to gender, the study showed interaction effects between injured females and non-injured males in the categories of reaction time and visual motor speed. Injured female athletes in our study scored lower by 4.7% in the reaction time category. However, a history of concussion was not considered in this category during analysis.

Neurocognitive testing is an important component in both the assessment and management of sports-related concussion. Typically, baseline testing is used as a comparative measure to determine an athlete's readiness to return to sport when neurocognitive function is assessed following a concussion. ImPACT was the neurocognitive testing platform used for baseline testing in this study and has been shown to be a valid measure for examining deficits in reaction time, processing speed, working memory, attention and concentration.[9,24] In addition, ImPACT has shown specificity and sensitivity in identifying neurocognitive deficits following a concussion.[9,24] For the purposes of this study, ImPACT scores were used solely to investigate possible differences between baseline scores and in-season injury occurrence.

Despite studies indicating the usefulness of ImPACT in identifying neurocognitive deficits following a concussion, the validity of baseline testing has and should be further examined. As previously mentioned, some of the athletes who initially met the inclusion criteria in this study had invalid test scores, likely due to either delayed or slower response times to tasks or completing the test too quickly. Subsequently, the data that did not meet validity criteria were excluded. There are some factors that must be considered when performing computerized neurocognitive assessment testing. Athletes may also intentionally score lower on baseline testing in order to score higher on follow-up testing should they sustain a concussion injury during the competitive season and possibly return to competition sooner. In addition, despite that ImPACT is widely used and accepted, reliability and validity of scores between age groups requires further investigation. It was determined that the age group of 14-17 would be used for this study due to it being the largest cohort within the local ski and snowboard club as well as consideration given to the cognitive development of adolescents who may not score as drastically than on testing during earlier adolescent years. A reliability study investigating the use of ImPACT within a similar cohort found that online baseline ImPACT testing is a stable measure of neurocognitive performance for high school athletes across a one-year time period.[8] Furthermore, it was recommended that high school athletes complete updated baseline testing every two years to account for any changes in neurocognitive performance.[8] While it was difficult to control for all the previously mentioned variables, data for athletes who did not complete baseline testing prior to the start of their competitive season was excluded from this study. Invalid testing scores based upon generated ImPACT results for the cohort in this study were also excluded from data collection. In some of these cases, seasonal athletes had completed ImPACT testing at home prior to relocation to the training center. Lack of attention focused on testing due to cell phone music or television use while completing neurocognitive testing likely resulted in invalid scores.

Athletes presenting with various neurocognitive deficits may benefit from a rehabilitative program which integrates training strategies focused on improving reaction time, processing speed and ability to maintain postural stability in an environment which challenges balance and motor control. A rehabilitation program that addresses the neurocognitive deficits in a snowboard athlete has been outlined.[25] The dynamic and aerial nature of disciplines within both snowboarding and alpine skiing as well as environmental factors must also be considered. While the results of our study did not find difference in reaction time with increased injury risk, it may be prudent to integrate reactionary training activities into pre-season conditioning and in-season strength and on-hill sessions to address any potential neurocognitive deficits that may exist. Furthermore, it may be useful for athletes to be evaluated for movement impairments, which may potentially increase their risk for musculoskeletal injury. Functional movement screening tools have been effectively used to identify compensatory movement patterns and increased injury risk in the athletic population.[26,27] Strength and conditioning programs which combine elements of neurocognitive training and corrective exercise designed to address movement impairments may provide robust outcomes in both improving neurocognitive function and movement efficiency in the athletic population. The results of the study do not specifically indicate differences in neurocognitive testing components and injury risk, but rather interaction affects between genders. However, neurocognitive deficits recognized on ImPACT can be addressed in training programs, which consider both the musculoskeletal and neurocognitive components of injury in both genders in the ski and snowboard population. Further research is needed to determine whether this aforementioned training approach can improve neurocognitive function and decrease injury risk in the ski and snowboard population.

A limitation of this study is that athletes between the ages of 14- 17 were utilized. Data for athletes younger than 14 or older than 17 was not included in the analysis and, thus limited the cohort size. Findings from this study cannot necessarily be generally applied to ski and snowboard athletes outside of the inclusionary age group. Previous research has also suggested that computer based neurocognitive testing such as the ImPACT test may not be as reliable and valid for younger athletes secondary to changes in cognitive function that occur with brain development.[28] Computer based neurocognitive testing such as the ImPACT test are often utilized for efficiency and may provide better measurements of cognitive function related to reaction time and the speed of information processing. Furthermore, computerized neurocognitive testing also allows athletes to serve as their own control and the data can be compared to a baseline score if the test was taken prior to a concussion or data can also be compared to normative samples. However, normalized samples are often based on the older athletes and may be less generalizable to younger athletes. McCrory suggested that cognitive maturation may be greatest in those under the age of 15 years and then plateaus to an adult level of performance.[28] This may suggest that comparing neurocognitive testing to baseline cognitive performance may be problematic with athletes less than 15 years of age. This may also support the need for more frequent baseline testing of younger athletes because their baseline function changes with age. Concussions and/or musculoskeletal injuries from seasons prior to 2009-12 were not considered as exclusionary criteria primarily due to lack of documentation records of these conditions prior to the 2009 season. This could be a limitation of this study as well since a plausible argument could be made that prior concussions and/or musculoskeletal injury could influence the likelihood of future injury as has been suggested in previous research.[14,15,16] Additional research would be needed to support this theory as it applies to the population in this study. Lastly, another limitation of this study is that it is a retrospective study with a convenience sample. Future research should consider including ski and snowboard athletes from both the amateur and professional ranks, both within and outside of the age groups included in this study, in a prospective manner where both ImPACT results and injury data can be compared from season to season within disciplines as opposed to a group of seasons collectively.

CONCLUSION

In summary, the current findings indicate an interaction between gender and injury status in the categories of reaction time and visual motor speed. More research is needed to determine whether a correlation between neurocognitive deficits and musculoskeletal injury exists in the ski and snowboard population. Future research should compare ImPACT results and injury data between seasons and among a wider range of age groups and disciplines. Further investigation is needed to determine if interaction effects exist between genders and both injured and non-injured athletes within neurocognitive testing in various sports.

REFERENCES

1. Bladin C, McCrory P, Pogorzelski A. Snowboarding injuries. *Sports Med.* 2004;34:133-138.
2. Davidson T, Laliotis A. Alpine skiing injuries: a nine-year study. *West J Med*. 1996;164:310-314.
3. Davidson T, Laliotis A. Snowboarding injuries: a four-year study with comparison with alpine ski injuries. *West J Med*. 1996;164:231-237.
4. Dohjima T, Sumi Y, Ohno T, et al. The dangers of snowboarding: a 9-year prospective comparison of snowboarding and skiing injuries. *Acta Orthop*. 2001;72:657-660.
5. Idzikowski J, Janes P, Abbott P. Upper extremity snowboarding injuries: ten-year results from the Colorado snowboard injury survey. *Am J Sports Med*. 2000;28:825-832.
6. Hewett T, Myer G, Ford K, Heidt R, Colosimo A, McLean S, van den Bogert A, Paterno M, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33:492-501.
7. Powers C. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther.* 2010;40:42-51.
8. Elbin R, Schatz P, Covassin T. One-year test-retest reliability of the online version of ImPACT in high school athletes. *Am J Sports Med*.2011;39:2319-2324.
9. Schatz P, Pardini J, Lovell M, et al. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsych*. 2006;21:91-99.
10. Schatz P. Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *Am J Sports Med*. 2010;38:47-53.
11. Maerlender A, Flashman L, Kessler A, Kumbhani S, Greenwald R, Tosteson T, McAllister T.. Examination of the construct validity of ImPACT computerized test, traditional, and experimental neuropsychological measures. *Clin Neuropsychol*. 2010;24:1309-1325.
12. Swanik C, Covassin T, Stearne D, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35: 943-948.
13. Wilkerson G. Neurocognitive reaction time predicts lower extremity sprains and strains. *Int J Athl Ther Train.* 2012;17:4-9.
14. Pietrosimone B, Golightly Y, Mihalik J, Guskiewicz K. Concussion frequency associates with musculoskeletal injury in retired NFL players. *Med Sci Sports Exerc.*2015;47:2366-2372.
15. Brooks MA, Peterson K, Biese K, Sanfilippo J, Heiderscheit B, Bell D. Concussion increases odds of sustaining a lower extremity musculoskeletal injury after return to play among collegiate athletes. *Am J Sports Med.* 2016;44:742-747.
16. Lynall R, Mauntel T, Padua D, Mihalik J. Acute lower extremity injury rates increase concussion in college athletes. *Med Sci Sports Exerc.*2015;47:2487-2492.
17. Andersen M, Williams J. Athletic injury, psychosocial factors and perceptual changes during stress. *J Sports Sci.* 1999;17:735-741.
18. Negahban H, Hadian M, Salavati M, et. al. The effects of dual-tasking on postural control in people with unilateral anterior cruciate ligament injury. *Gait & Posture.* 2009;30:477-481.
19. Teel E, Register-Mihalik J, Blackburn J, Guskiewicz K. Balance and cognitive performance during a dual-task: preliminary implications for use in concussion assessment. *J Sci Med Sport.* 2013;16:190-194.
20. Covassin T, Elbin RJ, Harris W, Parker T, Kontos A.. The role of age and sex in symptoms, neurocognitive performance, postural stability in athletes after concussion. *Am J Sports Med.*2012;40: 1303-1312.
21. Meehan W, Taylor A, Proctor M. The Pediatric Athlete: Younger athletes with sports-related concussion. *Clin Sports Med.* 2011;30:133-x.
22. Baillargeon A, Lassonde M, Leclerc S, Ellemberg D. Neuropsychological and neurophysiological assessment of sport concussion in children, adolescents and adults. *Brain Injury*.2012;26:211-220.

23. Lovell M. Clinical Interpretation Manual. ImPACT Web site. http://www.impacttest.com/interpretation.php. Accessed March 16, 2015.
24. Iverson G, Gaetz M, Lovell M, et al. Relation between subjective fogginess and neuropsychological testing following concussion. *J Int Neuropsych Soc*. 2004;10:904-906.
25. Faltus J. Rehabilitation strategies addressing neurocognitive and balance deficits following a concussion in a female snowboard athlete: a case report. *Int J Sports Phys Ther.* 2014;9:232-241.
26. Chorba R, Chorba D, Bouillon L, Overmyer C, Landis J. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *North Am J Sports Phys Ther.* 2010;5:47-54.
27. Kiesel K, Plisky P, Voight M. Can serious injury in professional football be predicted by a preseason functional movement screen. *North Am J Sports Phys Ther.* 2007;2:147-152.
28. McCrory P, Collie A, Anderson V, Davis G. Can we manage sport related concussion in children the same as in adults? *Br J Sports Med*. 2004;38:516-519.