



Effectiveness of a Computerized Cognitive Training Program for Reducing Head Impact Kinematics in Youth Ice Hockey Players

Melissa S. DiFabio^{†1} and Thomas A. Buckley^{‡2,3}

¹Department of Biomedical Engineering, University of Delaware, Newark, DE, USA; ²Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE, USA; ³Biomechanics and Movement Science Interdisciplinary Program, University of Delaware, Newark, DE, USA

[†]Denotes graduate student author, [‡]Denotes professional author

ABSTRACT

International Journal of Exercise Science 14(1): 149-161, 2021. Cognitive training (CT) is an effective technique to improve neurological performance, but has not been investigated as a head impact primary prevention strategy. The purpose of this study was to investigate the CT's effectiveness in reducing head impact kinematics in youth ice hockey players. Twenty youth were divided into two groups: a CT and Control group. The CT group performed two 30-minute sessions of IntelliGym CT weekly for 20 weeks and the control group performed two 30-minute sessions weekly evaluating hockey videos. The dependent variables, number of head impacts, cumulative linear acceleration (CLA) and rotational acceleration (CRA) and mean linear and rotation peak acceleration, were compared with repeated measures ANOVAs, with post-hoc for main effect of time for each group, between the first and second half of the season. There were significant interactions for number of head impacts ($p = 0.014$) and CLA ($p = 0.043$) and post-hoc testing identified reductions in the second half of the season for the CT, but not control, group. There were no interactions for CRA, mean peak linear acceleration, and mean peak rotational acceleration. These preliminary results suggest CT may be an effective primary prevention strategy to reduce head impacts and cumulative linear acceleration in youth ice hockey players.

KEY WORDS: Concussion, mild traumatic brain injury, injury prevention, subconcussive impacts

INTRODUCTION

Ice hockey is a popular sport with over a million North American players annually and participation rates steadily increasing; however, concerns have been raised over hockey related concussions and repetitive head impacts (RHI) (22, 29). The nature of ice hockey includes fast skating, legal body contact (i.e., checking), and unintentional contacts with hard objects (e.g., ice, boards) resulting in considerable overall injury risk with up to $\frac{3}{4}$ of players suffering an injury during the course of a season (63). Furthermore, concussions are a common hockey injury (10 - 15%) and the concussion rate (up to 21.5 per 1,000 athlete exposures) is comparable to other collision sports (20, 21, 31). However, this may still underrepresent the true incidence rate as

many concussions likely go unreported (2, 24, 36, 37). While concussions have received considerable attention and leagues have worked to update concussion diagnostic and management protocols. RHI, sometimes referred to as “subconcussive blows,” are hits to the head which commonly occur in collision sports but without clinically observed neurological dysfunction (1, 9). RHIs, independent of concussion, have been speculated to be associated with later life neuropathological deficits including chronic traumatic encephalopathy (38, 44, 60). Adolescents have different physiological responses and longer recovery from concussion than adults or children. However, less is known about adolescent’s response to RHI particularly when they occur during critical neurological development periods (44, 51, 60).

There is inconsistent evidence related to neuropathological effects of RHI, but a single non-concussive head impact generally does not cause cellular damage (1). Animal models have suggested that multiple RHIs may result in neuropathology including injured axonal integrity and acute neuroinflammatory response with repeated impacts over a short period of time (1, 3, 55, 57). Furthermore, earlier first exposure to RHI may be a contributing factor to later life behavioral and structural deficits (60, 61), but are not seen in collegiate athletes (10, 11). Numerous human neuroimaging studies have repeatedly identified neurological changes in American adolescent football players, but few studies exist in reference to ice hockey (6, 50, 58, 64, 65). In collegiate ice hockey players, RHI, independent of concussion, has been associated with altered white matter integrity and decreased N-acetylaspartate (33, 48). While no dose response or threshold for RHI is currently well accepted in the scientific literature, Montenigro has proposed a cumulative head impact index and suggested RHIs exceeding this threshold elevates the risk of cognitive and behavioral impairments in later life (44). Regardless of a specific threshold, the pattern of emerging evidence supports the recommendation of reducing RHI in collision sports (1).

Injury prevention models are divided into primary (preventing an injury before it occurs), secondary (reducing the effects of an injury), and tertiary (lessening long term effects) (53). In sports injury approaches, primary prevention mechanisms generally involving increasing player strength, rule changes, heightened rule enforcement, or reduced full contact practice times which have shown mixed results in reducing RHI and concussions (8, 13,17-19, 32, 34, 43, 54, 59, 62). Specific to ice hockey, delaying body checking until age 13 has reduced injury risk; however, this is doesn’t protect teenage participants (4, 19, 28). While primary prevention strategies to reduce head impacts in hockey are limited, one potential approach which has received limited investigation is cognitive training (CT). CT typically refers to training core cognitive abilities with the goal of improving performance on other cognitive tasks through the concept of broad training by utilizing complex computer games (30, 56). These interventions are generally effective at improving performance on the trained task with limited translation to other tasks or overall cognitive performance (5, 56). However, some evidence supports the use of complex computer games to improve skilled performance (e.g., flight performance) when attentional control is the training program target (26). The CT goal utilized herein was to improve attention allocation weighting (e.g., strategy) during a complex computer game presenting high concurrent demands (26). This approach has successfully demonstrated transfer of skills and attentional allocation during military flight training after 20 training sessions lasting

ten hours; however, it is unknown if this approach would be effective at reducing head impacts in sports (23, 26, 38).

While many questions regarding RHI impact kinematics remain unresolved, it is generally agreed that fewer RHI likely reduces potential risks (1, 44). A potential primary prevention strategy of computerized CT could be beneficial in reducing RHI. Therefore, the purpose of this study was to investigate the effectiveness of a CT program in reducing head impact kinematics in youth ice hockey players. We hypothesized that cognitive training would be effective at reducing the number and magnitude of head impacts over the course of a youth ice hockey season.

METHODS

Participants

Two youth ice hockey teams (U16 and U18) were recruited and 22 male youth ice hockey players, out of 35 potential players, agreed to participate in the study. The participants were randomly divided into the Cognitive Training (CT) group (age: 15.5 ± 0.6 years, height: 1.73 ± 0.06 m, weight: 67.8 ± 25.8 kg) and a control group (age: 16.1 ± 0.9 years, height: 1.78 ± 0.1 m, weight: 73.7 ± 9.2 kg). No anthropometric group differences were found ($p > 0.05$). The inclusion criteria was any active participant on one of the teams. Participants were excluded if they quit the team during the season ($N = 2$, non-injury related). All participants provided informed consent if over 18 or informed assent and parental consent if under 18 as approved by the institutional review board. The study adhered to the ethical policies set forth by the editorial board (45).

Protocol

The computerized CT was performed with the Hockey IntelliGym (Applied Cognitive Engineering, Pine Brook, NJ, USA) program. Hockey IntelliGym was developed to match perceived sport skills with training components in the game through a modified version of the Space Fortress CT protocol which has been effectively utilized across diverse populations (5, 16, 25, 26, 30). During the CT program, two five-player teams, consisting of one human player and nine artificial intelligence virtual players, compete to shoot a bomb into the opponents "home gate" which requires collaboration amongst teammates and overcoming opponents (25). This video game like environment emphasizing attentional skills, situational awareness, and attentional resources in dual task gaming environments with up to 80 parameters per game round (Figure 1).

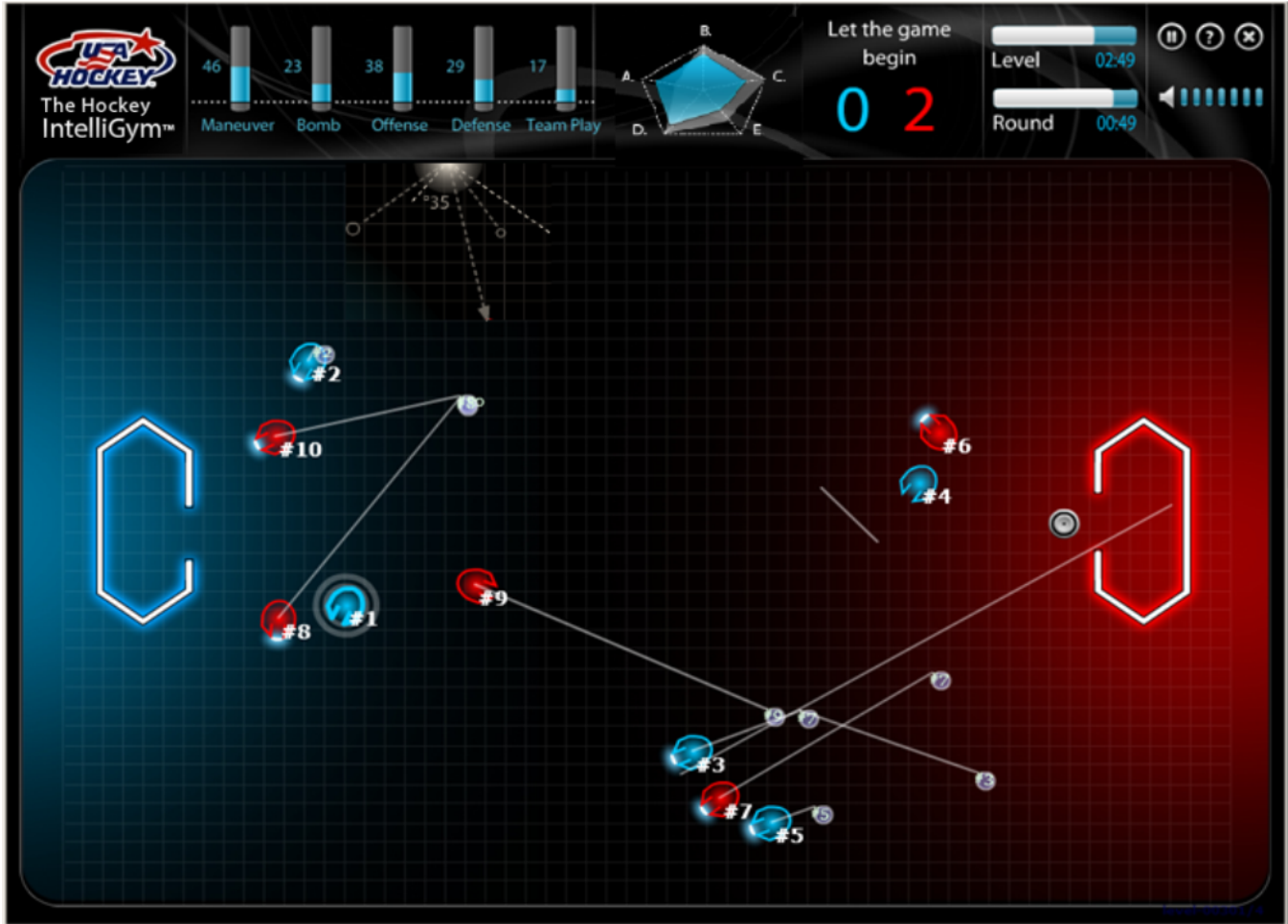


Figure 1. Exemplar screenshot of the IntelliGym program. The participant is identified as “#1” in the screenshot.

Head impact kinematics were measured utilizing the Smart Impact Monitor-G (SIM-G, Triax Technologies Inc., Norwalk, CT, USA) accelerometers. The SIM-G utilizes a high-g and low-g triaxial accelerometer to measure linear acceleration levels within a 3–150 g range and a triaxial gyro to measure angular head motion. In laboratory investigations, SIM-G was highly accurate for identifying the number of impacts (99.29 – 100%) and had average acceleration errors range from 7.9 – 20.6% which are comparable to other head impact measurement accelerometers systems (e.g., HITS: 14.1 – 29.5%, XPatch: 17.3 – 22.0%) (15). The SIM-G has been successfully utilized in clinical settings to capture real-time head impact kinematics (12). The threshold was set at 10 g’s and if an impact exceeded the threshold then data from 10-ms before and 52-ms after the impact were recorded and transmitted in real-time to an access point connected via USB to a laptop computer.

Participants were randomly assigned to one of two groups: a cognitive training (CT) or a control group with similar time requirements. The CT group were instructed to perform two 30-minute training sessions per week for the 20-week long season. Participants in the control group were instructed to review two 30-minute sessions of hockey videos per week, provided by the research team, and report on specific player performance (e.g., number of shots on goal, number

of passes successfully completed). All participants denied utilizing the cognitive training program outside of the study and program compliance was not tracked.

All participants wore the SIM-G accelerometers for all practices and home games. The SIM-Gs were secured to the participants head using either a headband or skullcap and positioned on the nuchal line by a certified athletic trainer prior to each event and then collected following the event (12, 35). All head impact kinematics were monitored in real time by a research team member who addressed any issues which arose during the session (e.g., player took the headband off). All practices and home game were video recorded to allow the research team to review and confirm recorded head impact, consistent with current recommendations for head impact telemetry data (49). The SIM-G system was enabled at the start of the event and terminated at the conclusion to ensure only session related impacts were recorded. Participant injuries were not tracked during the course of the season as this was not the aim of the study.

Statistical Analysis

Descriptive analysis (mean and standard deviations) of the head impacts were calculated, but analysis by position was not conducted due to limited sample size per position. Prior CT studies have suggested ten hours across 20 sessions of training are needed to demonstrate improvements (23, 26). Therefore, the season was divided into two halves (week 1 - 10 and weeks 11 - 20), which served as the independent variable. The five dependent variables of interest were: 1) number of head impacts, 2) cumulative linear acceleration (CLA), 3) mean peak linear acceleration, 4) cumulative rotational acceleration (CRA), and 5) mean peak rotational acceleration. The dependent variables of interest were compared with a 2 (group) x 2 (time) mixed design analysis of variance (ANOVA). Significant interactions were followed up with a pairwise comparison, using Tukey's procedure to examine the simple main effect of time for each group and effect sizes were reported using standard partial eta classifications.

RESULTS

There were no concussions reported by any participants during the season. Participants completed an average of 28.6 ± 6.8 practice and games over the course of the season and there was no difference between groups for sessions (CT: 29.9 ± 7.2 sessions and Control: 27.3 ± 6.4 sessions, $F = 0.725$, $p = 0.406$) completed. There was no significant interaction between group and number of sessions ($F = 1.589$, $p = 0.224$) per time period. Impact kinematics by position are provided in Table 1.

Table 1. Head Impact Kinematics by Position.

	Linear Acceleration (Mean \pm SD)	Rotational Acceleration (Mean \pm SD)
Defenseman (N=8)	39.8 ± 18.5 g's	$4,147.4 \pm 2,947.3$ rad/s ²
Winger (N=7)	36.3 ± 17.5 g's	$4,078.3 \pm 2,808.3$ rad/s ²
Center (N=3)	29.6 ± 12.6 g's	$2,593.9 \pm 1,325.6$ rad/s ²
Goalie (N=2)	31.6 ± 14.7 g's	$3,365.4 \pm 2,670.7$ rad/s ²
Total Participants (N=20)	36.7 ± 17.6 g's	$3,985.6 \pm 2,807.2$ rad/s ²

The position was determined by the participant's self-reported "primary" position during the season. Statistical analysis by position was not performed as the sample was underpowered.

A significant interaction was identified for number of head impacts ($F = 7.494$, $p = 0.014$, $\eta_p^2 = 0.294$). Post-hoc testing identified a significant difference between Weeks 1 - 10 and 11 - 20 for number of impacts per player in the CT group (21.8 ± 9.9 and 8.0 ± 4.2 respectively; $p < 0.001$), but not for the Control group (16.1 ± 6.6 and 13.8 ± 8.4 respectively; $p = 0.451$). There was no significant interaction between CT (Weeks 1 - 10: 33.4 ± 5.7 g's and Weeks 11 - 20: 38.3 ± 5.5 g's) and Control (Weeks 1 - 10: 35.1 ± 6.8 g's and Weeks 11 - 20: 39.0 ± 10.1 g's) for mean peak linear acceleration ($F = 0.062$, $p = 0.806$, $\eta_p^2 = 0.003$). A significant interaction for CLA was identified ($F = 4.725$, $p = 0.043$, $\eta_p^2 = 0.208$). Post-hoc testing revealed a significant difference between Weeks 1 - 10 and 11 - 20 for CLA in the CT group (408.2 ± 334.6 g's and: 169.1 ± 178.3 g's respectively; $p = 0.007$), but not for the Control group (333.3 ± 174.9 g's and 337.4 ± 194.5 g's respectively; $p = 0.959$) (Figure 2). A significant reduction in the CT group (58.6%) in the second half (weeks 11 - 20) of the season was determined, but no significant change during the same time period was noted in the Control group ($\uparrow 1.2\%$).

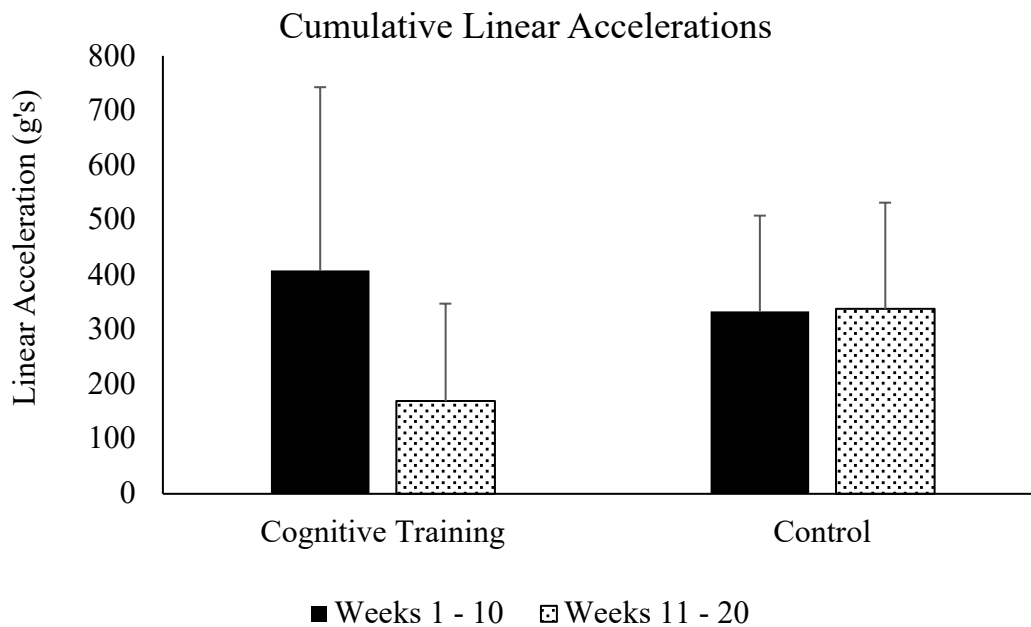


Figure 2. Cumulative Linear Acceleration.

There was no significant interaction between CT (Weeks 1 - 10: 3.9 ± 1.1 krad/s² and Weeks 11 - 20: 2.0 ± 0.8 krad/s²) and Control (Weeks 1- 10: 4.6 ± 1.7 krad/s² and Weeks 11 - 20: 1.5 ± 0.7 krad/s²) for mean peak rotational acceleration ($F = 3.375$, $p = 0.083$, $\eta_p^2 = 0.158$). Additionally, there was no significant interaction between CT (Weeks 1 - 10: 56.4 ± 59.7 krad/s² and Weeks 11 - 20: 22.9 ± 20.5 krad/s²) and Control (Weeks 1- 10: 50.2 ± 32.5 krad/s² and Weeks 11 - 20: 51.2 ± 42.4 krad/s²) for CRA ($F = 3.127$, $p = 0.094$, $\eta_p^2 = 0.148$).

DISCUSSION

This preliminary study evaluated the effectiveness of a commercially available computerized CT program on head impact kinematics in youth ice hockey players. The primary finding of this preliminary study was a reduction in the number and CLA of ice hockey head impacts, with moderate to large effect sizes, in the second half of the season following the utilization of a CT program. As there were no interactions for mean linear and rotational peak acceleration, the reduction in CLA is likely the result of the reduced number of head impacts which occurred in the second half of the season. While these results must be replicated in larger studies, this preliminary finding suggests CT could be a primary prevention method to reduce head impacts and the potential subsequent neurological burden of RHI in hockey.

Although causation has not been demonstrated, RHI is speculated to be a primary or contributing cause of later life neuropathology (38, 44, 60). Therefore, a reduction in the number and cumulative magnitude of ice hockey head impacts may potentially help mitigate the neuropathological risks. While no dose response or threshold for RHI is currently well accepted in the scientific literature, Montenigro has proposed a cumulative head impact index and suggested RHIs exceeding this threshold elevates the risk of cognitive and behavioral impairments in later life, but this was specific to football impacts (44). The ~62% reduction in head impacts during the second half of the season as well as reduction in cumulative linear acceleration herein is suggestive that CT could be beneficial in reducing the likelihood of exceeding the proposed threshold. Future studies need to investigate if these head impact kinematic reductions plateau or grow exponentially over time in order to more fully understand the potential benefits of CT.

This study was not designed to identify potential mechanisms underlying the reduction in head impact kinematics although several mechanisms can be extrapolated from the literature (26, 27, 30, 39, 46). Complex computerized CT, like the program used herein, employs a broad transfer approach which refers to transferring the effects of training tasks to other tasks which are significantly different from those that were trained (26). Indeed, programs like Space Fortress, which incorporate complex integrative CT, as opposed to isolated domain training, have demonstrated speed improvements associated with broad style transfer effects (27, 46). Furthermore, this approach focusing on attentional control has demonstrated improvements in both performance outcomes (e.g., flight performance) and underlying neurological adaptations (e.g., training induced plasticity) (26, 46). During flight performance, Gopher noted improved positive transfer of attentional strategies with pilots better able to adjust to dual-task demands and maintain performance despite elevated cognitive load (26). While the extrapolation to sports performance is not direct, Mihalik suggested that ice hockey players with increased awareness of their surroundings are better able to anticipate and prepare for an impact potentially mitigating the impact's severity (39). Herein, although there were no differences in the peak linear or rotational acceleration between groups, the CT group did have a reduced number of head impacts suggesting the possibility they were able to avoid the impact altogether. Future studies should investigate the neurological and behavioral mechanisms underlying with these improvements identified in this preliminary study.

The participants herein sustained relatively few head impacts compared to other hockey (~200) and football (500 - 700 impacts) adolescence studies (7, 42). There are several potential explanations for this lower number of impacts. First, impacts occur far more frequently in games compared to practices and herein only home games were recorded (41, 42). Secondly, the influence of media coverage of concussions and RHI may have played a role as the research team noted numerous instances of coaches instructing players on reducing or eliminating head impacts during practice. While the number of impacts was low, the mean peak linear ($36.7 + 17.6$ g's) and rotational ($4.0 + 2.8$ krad/s²) accelerations were higher than previously reported in ice hockey (linear: $17.5 - 35.0$ g's and rotational: $1.4 - 1.6$ krad/s²) (14, 39, 43). Previous hockey investigations have primarily utilized the Head Impact Telemetry System (HITS) whereas herein the SIM-G tri-axial accelerometer was utilized which has demonstrated lower acceleration related mean absolute error, root mean square errors, and a higher impact reporting accuracy than HITS (15). Furthermore, the relatively high linear peak acceleration per impact but low number of impacts identified herein could therefore be a result of reducing the "minor" head impacts thereby skewing the mean peak linear acceleration higher. Nonetheless, the overall outcome of fewer head impacts and the resulting lower cumulative acceleration in the CT group may be a positive development to improve player safety.

This finding may be particularly important as many other prevention strategies have largely been ineffective at reducing head impact kinematics (4, 39, 43). While strength training is feasible and has shown reductions in resultant accelerations in laboratory testing, cervical strength was not effective at reducing linear or rotational head impact severity in youth ice hockey players (17, 43). Rules adjustments have been attempted with inconsistent results. Eliminating body checking in younger leagues appears to reduce both overall injury and concussion risks; however, this does not benefit older players, like the U16 and U18 teams herein, in leagues which allow checking (4, 18, 19, 28). Improved rule enforcement may be beneficial strategy as illegal contact have high linear accelerations and resulting injuries, but rule enforcement cannot be controlled by the individual player (39, 40). Behavioral modification programs such as "Fair Play" (teams are awarded/penalized points based on penalty minutes) have generally been effective at reducing injury, but not concussion, risk (54, 59). While the incidence was very low, "Fair Play" has reduced the number of non-concussion head impacts (59). Finally, the inclusion of a "look-up line" (warning track near the boards) has not been assessed on concussion risk, but was not effective at improving player's head kinematics when skating near the boards (66). Thus, given the limited options for primary injury prevention, the use of CT, along with delayed body checking rules, could be an effective low-risk intervention to help reduce RHI.

This study involved 20 participants from two youth ice hockey teams and the results should be viewed as preliminary until they are confirmed in larger and more diverse studies. This study did not assess concussions and no extrapolation to concussion risk should be implied from these results. The head impact data was delimited to practices and home games due to travel logistics for the research team, thus it is unknown how head impacts during road games would have affected these results; however home games have been utilized previously in hockey analysis (52). While the SIM-G tri-axial accelerometer has been validated in laboratory settings with comparable results to other commonly utilized head impact accelerometer systems and utilized

in soccer studies; there is ongoing discussion regarding accuracy and other limitations (e.g., accelerometer placement, movement, etc.) inherent across accelerometer systems (15, 47, 49). However, it is important to note that both groups herein used the same system and all events were video recorded and impacts confirmed by a member of the research team. Finally, we were not able to accurately track ice time due to camera positioning, therefore the exposure could have fluctuated over the course of the season.

The results of this preliminary study suggest that computerized CT may be an effective primary prevention strategy to reduce head impacts and cumulative linear acceleration in youth ice hockey players. Specifically, these reductions hold potential promise to reduce the long-term risks associated with repetitive head impacts. As concerns over RHI in collision sports remains high, the implementation of CT, continued rule modifications such as delayed body checking, and proper rule enforcement may serve to reduce the risk of RHI in ice hockey.

REFERENCES

1. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury: A review. *J Neurosurg* 119(5): 1235-1245, 2013.
2. Baugh CM, Kroshus E, Daneshvar DH, Stern RA. Perceived coach support and concussion symptom-reporting: differences between freshmen and non-freshmen college football players. *J Law Med Ethics* 42(3): 314-322, 2014.
3. Belanger HG, Vanderploeg RD, McAllister T. Subconcussive blows to the head: A formative review of short-term clinical outcomes. *J Head Trauma Rehabil* 31(3): 159-166, 2016.
4. Black AM, Hagel BE, Palacios-Derflinger L, Schneider KJ, Emery CA. The risk of injury associated with body checking among pee wee ice hockey players: An evaluation of Hockey Canada's national body checking policy change. *Br J Sports Med* 51(24): 1767-1772, 2017.
5. Blumen HM, Gopher D, Steinerman JR, Stern Y. Training cognitive control in older adults with the Space Fortress game: The role of training instructions and basic motor ability. *Front Aging Neurosci* 2: 145, 2010.
6. Breedlove KM, Breedlove EL, Robinson M, Poole VN, King JR, Rosenberger P, Rasmussen M, Talavage TM, Leverenz LJ, Nauman EA. Detecting neurocognitive and neurophysiological changes as a result of subconcussive blows in high school football athletes. *Athl Train Sports Health Care* 6(3): 119-127, 2014.
7. Broglio SP, Williams R, Rettmann A, Moore B, Eckner JT, Meehan S. No seasonal changes in cognitive functioning among high school football athletes: implementation of a novel electrophysiological measure and standard clinical measures. *Clin J Sport Med* 28(2): 130-138, 2018.
8. Broglio SP, Williams RM, O'Connor KL, Goldstick J. Football Players' head-impact exposure after limiting of full-contact practices. *J Athl Train* 51(7): 511-518, 2016.
9. Buckley T, Baugh C, Meehan W, DiFabio M. Concussion management plan compliance: A study of NCAA power 5 schools. *Ortho J Sports Med* 5(4): 2325967117702606, 2017.
10. Caccese J, Iverson GL, Cameron K, Houston MN, McGinty Gt, Jackson JC, O'Donnell P, Pasquina PF, Broglio SP, McCrea M, McAllister A, Buckley TA. Estimated age of first exposure to contact sports is not associated with greater symptoms or worse cognitive functioning in U.S. service academy athletes. *J Neurotrauma* 37(2): 334-339, 2020.

11. Caccese JB, DeWolf RM, Kaminski TW, Broglio SP, McAllister TW, McCrea M, Buckley TA, CARE Consortium Investigators. Estimated age of first exposure to american football and neurocognitive performance amongst NCAA male student-athletes: a cohort study. *Sports Med* 49(3): 477-487, 2019.
12. Caccese JB, Lamond LC, Buckley TA, Kaminski TW. Reducing purposeful headers from goal kicks and punts may reduce cumulative exposure to head acceleration. *Res Sports Med* 24(4): 407-415, 2016.
13. Cobb BR, Urban JE, Davenport EM, Rowson S, Duma SM, Maldjian JA, Whitlow CT, Powers AK, Stitzel JD. Head impact exposure in youth football: Elementary school ages 9-12 years and the effect of practice structure. *Ann Biomed Eng* 41(12): 2463-2473, 2013.
14. Cubos J, Baker J, Faught B, McAuliffe J, Keightley ML, McPherson M. Relationships among risk factors for concussion in minor ice hockey. *J ASTM International* 6(6): 1 - 10, 2009.
15. Cummiskey B, Schiffmiller D, Talavage TM, Leverenz L, Meyer JJ, Adams D, Nauman EA. Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *Proceedings of the Institution of Mechanical Engineers Part P-J Sports Engin Tech* 231(2): 144-153, 2017.
16. Donchin E. Video Games as research tools - the Space Fortress game. *Behav Res Methods Instrum Comput* 27(2): 217-223, 1995.
17. Eckner JT, Goshtasbi A, Curtis K, Kapshai A, Myyra E, Franco LM, Favre M, Jacobson JA, Ashton-Miller JA. Feasibility and effect of cervical resistance training on head kinematics in youth athletes: A pilot study. *Am J Phys Med Rehabil* 97(4): 292-297, 2018.
18. Emery CA, Black AM, Kolstad A, Martinez G, Nettel-Aguirre A, Engebretsen L, Johnston K, Kissick J, Maddocks D, Tator C, Aubry M, Dvořák J, Nagahiro S, Schneider K. What strategies can be used to effectively reduce the risk of concussion in sport? A systematic review. *Br J Sports Med* 51(12): 978 - 984, 2017.
19. Emery CA, Kang J, Shrier I, Goulet C, Hagel BE, Benson BW, Nettel-Aguirre A, McAllister JR, Hamilton GM, Meeuwisse WH. Risk of injury associated with body checking among youth ice hockey players. *JAMA* 303(22): 2265-2272, 2010.
20. Emery CA, Meeuwisse WH. Injury rates, risk factors, and mechanisms of injury in minor hockey. *Am J Sports Med* 34(12): 1960-1969, 2006.
21. Forward KE, Seabrook JA, Lynch T, Lim R, Poonai N, Sangha GS. A comparison of the epidemiology of ice hockey injuries between male and female youth in Canada. *Paediatr Child Health* 19(8): 418-422, 2014.
22. Frias FJ, McNamee M. Ethics, brain injuries, and sports: Prohibition, reform, and prudence. *Sport Ethics Phil* 11(3): 264-280, 2017.
23. Gajewski PD, Freude G, Falkenstein M. Cognitive training sustainably improves executive functioning in middle-aged industry workers assessed by task switching: A randomized controlled ERP study. *Front Human Neurosci* 11: 15, 2017.
24. Gilbert FC, Burdette GT, Joyner AB, Llewellyn TA, Buckley TA. Association between concussion and lower extremity injuries in collegiate athletes. *Sports Health* 8(6): 561-567, 2016.
25. Gopher D. Development of cognitive trainers for sport. In PACT 2016 International Psychological Applications Conference and Trends. Lisbon, Portugal, 2016.

26. Gopher D, Weil M, Bareket T. Transfer of skills from a computer game trainer to flight. *Hum Factors* 36(3): 387-405, 1994.
27. Green CS, Pouget A, Bavelier D. Improved probabilistic inference as a general learning mechanism with action video games. *Cur Bio* 20(17): 1573-1579, 2010.
28. Hagel BE, Marko J, Dryden D, Couperthwaite AB, Sommerfeldt J, Rowe BH. Effect of bodychecking on injury rates among minor ice hockey players. *CMAJ* 175(2): 155-160, 2006.
29. Huber BR, Alosco ML, Stein TD, McKee AC. Potential Long-term consequences of concussive and subconcussive injury. *Phys Med Rehabil Clin N Am* 27(2): 503-511, 2016.
30. Janssen A, Boster A, Lee H, Patterson B, Prakash RS. The effects of video-game training on broad cognitive transfer in multiple sclerosis: A pilot randomized controlled trial. *J Clin Exp Neuropsychol* 37(3): 285-302, 2015.
31. Kerr ZY, Collins CL, Fields SK, Comstock RD. Epidemiology of player-player contact injuries among us high school athletes, 2005-2009. *Clin Pediatr* 50(7): 594-603, 2011.
32. Kerr ZY, Dalton SL, Roos KG, Djoko A, Phelps J, Dompier TP. Comparison of Indiana high school football injury rates by inclusion of the USA football "Heads Up Football" player safety coach. *Orthop J Sports Med* 19(4): 5, 2016.
33. Koerte IK, Kaufmann D, Hartl E, Bouix S, Pasternak O, Kubicki M, Rauscher A, Li DK, Dadachanji SB, Taunton JA, Forwell LA, Johnson AM, Echlin PS, Shenton ME. A prospective study of physician-observed concussion during a varsity university hockey season: white matter integrity in ice hockey players. Part 3 of 4. *Neurosurg Focus* 33(6): 1-7, 2012. doi: 10.3171/2012.10.FOCUS12303
34. Krolikowski MP, Black AM, Palacios-Derflingher L, Blake TA, Schneider KJ, Emery CA. The effect of the "zero tolerance for head contact" rule change on the risk of concussions in youth ice hockey players. *Am J Sports Med* 45(2): 468-473, 2017.
35. Lamond LC, Caccese JB, Buckley TA, Glutting JJ, Kaminski TW. Linear acceleration in direct head contact across impact type, player position, and playing scenario in collegiate women's soccer. *J Athl Train* 53(2): 115-121, 2018.
36. Llewellyn T, Burdette GT, Joyner AB, Buckley TA. Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clin J Sport Med* 24(1): 76-79, 2014.
37. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med* 14(1): 13-17, 2004.
38. McKee AC, Alosco ML, Huber BR. Repetitive head impacts and Chronic Traumatic Encephalopathy. *Neurosurg Clin N Am* 27(4): 529-535, 2016.
39. Mihalik JP, Blackburn JT, Greenwald RM, Cantu RC, Marshall SW, Guskiewicz KM. Collision Type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics* 125(6): E1394-E1401, 2010.
40. Mihalik JP, Greenwald RM, Blackburn JT, Cantu RC, Marshall SW, Guskiewicz KM. Effect of infraction type on head impact severity in youth ice hockey. *Med Sci Sports Exerc* 42(8): 1431-1438, 2010.
41. Mihalik JP, Guskiewicz KM, Jeffries JA, Greenwald RM, Marshall SW. Characteristics of head impacts sustained by youth ice hockey players. *J Sports Eng Techn* 222(P1): 45-52, 2008.

42. Mihalik JP, Guskiewicz KM, Marshall SW, Blackburn JT, Cantu RC, Greenwald RM. Head impact biomechanics in youth hockey: Comparisons across playing position, event types, and impact locations. *Ann Biomed Eng* 40(1): 141-149, 2012.
43. Mihalik JP, Guskiewicz KM, Marshall SW, Greenwald RM, Blackburn JT, Cantu RC. Does cervical muscle strength in youth ice hockey players affect head impact biomechanics? *Clin J Sport Med* 21(5): 416-421, 2011.
44. Montenigro PH, Alosco ML, Martin BM, Daneshvar DH, Mez J, Chaisson CE, Nowinski CJ, Au R, McKee AC, Cantu RC, McClean MD, Stern RA, Tripodis Y. Cumulative head impact exposure predicts later-life depression, apathy, executive dysfunction, and cognitive impairment in former high school and college football players. *J Neurotrauma* 34(2): 328-340, 2017.
45. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. *Int J Exerc Sci* 12(1): 1-8, 2019.
46. Nikolaidis A, Voss MW, Lee H, Vo LTK, Kramer AF. Parietal plasticity after training with a complex video game is associated with individual differences in improvements in an untrained working memory task. *Front Hum Neurosci* 8: 169, 2014.
47. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-impact-measurement devices: a systematic review. *J Athl Train* 52(3): 206-227, 2017.
48. Panchal H, Sollmann N, Pasternak O, Alosco ML, Kinzel P, Kaufmann D, Hartl E, Forwell LA, Johnson AM, Skopelja EN, Shenton ME, Koerte IK, Echlin PS, Lin AP. Neuro-metabolite changes in a single season of university ice hockey using magnetic resonance spectroscopy. *Front Neurol* 9: 616, 2018.
49. Patton D, Huber C, McDonald C, Margulies SS, Master CL, Arbogast KB. Video confirmation of head impact sensor data from high school soccer players. *Am J Sports Med* 48(5): 1246-1253, 2020.
50. Poole VN, Breedlove EL, Shenk TE, Abbas K, Robinson ME, Leverenz LJ, Nauman EA, Dydak U, Talavage TM. Sub-concussive hit characteristics predict deviant brain metabolism in football athletes. *Dev Neuropsychol* 40(1): 12-17, 2015.
51. Purcell L, Harvey J, Seabrook JA. Patterns of recovery following sport-related concussion in children and adolescents. *Clin Pediatr* 55(5): 452-458, 2016.
52. Reed N, Taha T, Keightley M, Duggan C, McAuliffe J, Cubos J, Baker J, Faught B, McPherson M, Montelpare W. Measurement of head impacts in youth ice hockey players. *Int J Sports Med* 31(11): 826-833, 2010.
53. Register-Mihalik J, Baugh C, Kroshus E, Kerr ZY, McLeod TC. A multifactorial approach to sport-related concussion prevention and education: Application of the socioecological framework. *J Athl Train* 52(3): 195-205, 2017.
54. Roberts WO, Brust JD, Leonard B, Hebert BJ. Fair-play rules and injury reduction in ice hockey. *Arch Pediatr Adolesc Med* 150(2): 140-145, 1996.
55. Shultz SR, MacFabe DF, Foley KA, Taylor R, Cain DP. Sub-concussive brain injury in the Long-Evans rat induces acute neuroinflammation in the absence of behavioral impairments. *Behav Brain Res* 229(1): 145-152, 2012.
56. Simons DJ, Boot WR, Charness N, Gathercole SE, Chabris CF, Hambrick DZ, Stine-Morrow EA. Do "brain-training" programs work? *Psychol Sci Public Interest* 17(3): 103-186, 2016.

57. Slemmer JE, Weber JT. The extent of damage following repeated injury to cultured hippocampal cells is dependent on the severity of insult and inter-injury interval. *Neurobiol Dis* 18(3): 421-431, 2005.
58. Slobounov SM, Walter A, Breiter HC, Zhu DC, Bai X, Bream T, Seidenberg P, Mao X, Johnson B, Talavage TM. The effect of repetitive subconcussive collisions on brain integrity in collegiate football players over a single football season: A multi-modal neuroimaging study. *Neuroimage Clin* 14: 708-718, 2017.
59. Smith AM, Gaz DV, Larson D, Jorgensen JK, Eickhoff C, Krause DA, Fenske BM, Aney K, Hansen AA, Nanos SM, Stuart MJ. Does fair play reduce concussions? A prospective, comparative analysis of competitive youth hockey tournaments. *BMJ Open Sport Exerc Med* 2(1): e000074, 2016.
60. Stamm JM, Bourlas AP, Baugh CM, Fritts NG, Daneshvar DH, Martin BM, McClean MD, Tripodis Y, Stern RA. Age of first exposure to football and later-life cognitive impairment in former NFL players. *Neurology* 84(11): 1114-1120, 2015.
61. Stamm JM, Koerte IK, Muehlmann M, Pasternak O, Bourlas AP, Baugh CM, Giwerc MY, Zhu A, Coleman MJ, Bouix S, Fritts NG, Martin BM, Chaisson C, McClean MD, Lin AP, Cantu RC, Tripodis Y, Stern RA, Shenton ME. Age at first exposure to football is associated with altered corpus callosum white matter microstructure in former professional football players. *J Neurotrauma* 32(22): 1768-1776, 2015.
62. Stemper BD, Shah AS, Harezlak J, Rowson S, Duma S, Mihalik JP, Riggen LD, Brooks A, Cameron KL, Giza CC, Houston MN, Jackson J, Posner MA, McGinty G, DiFiori J, Broglio SP, McAllister TW, McCreary M, CARE Consortium Investigators. Repetitive head impact exposure in college football following an ncaa rule change to eliminate two-a-day preseason practices: A study from the NCAA-DoD CARE Consortium. *Ann Biomed Eng* 47(10): 2073-2085, 2019.
63. Stuart MJ, Smith AM, Nieva JJ, Rock MG. Injuries in youth ice hockey - a pilot surveillance strategy. *Mayo Clin Proc* 70(4): 350-356, 1995.
64. Talavage TM, Nauman EA, Breedlove EL, Yoruk U, Dye AE, Morigaki KE, Feuer H, Leverenz LJ. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotrauma* 31(4): 327-338, 2014.
65. Talavage TM, Nauman EA, Leverenz LJ. The role of medical imaging in the recharacterization of mild traumatic brain injury using youth sports as a laboratory. *Front Neurol* 6: 273, 2016.
66. Vickers JN, Causer J, Stuart M, Little E, Dukelow S, Lavangie M, Nigg S, Arsenault G, Morton B, Scott M, Emery C. Effect of the look-up line on the gaze and head orientation of elite ice hockey players. *Eur J Sport Sci* 17(1): 109-117, 2017.

