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Original Research

Sensorimotor training for injury prevention in collegiate soccer players: An experimental study

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ABSTRACT

Objectives: Deliver a sensorimotor training intervention; quantify the change in clinical measurements of sensorimotor control; and compare injury rate to a historical control.
Design: One-arm experimental pilot; Level 3.
Setting: NCAA Division II university athletic facilities.
Participants: 75 collegiate soccer players (38 males; 37 females) were enrolled, including 30 (40%) with history of concussion, and participated in eight training sessions.
Outcomes: Change in pre-to post-intervention for: static balance on the Sway app, near-point convergence, self-reported symptoms on the Post-Concussion Symptom Scale, cervical flexor neuromotor control/endurance, measured by the Cranial-Cervical Flexion Test and Joint Position Error test, and gaze stability on the Dynamic Visual Acuity Test. Injury incidence rate in 2018 was calculated using the number of traumatic injuries across the season and athlete exposure counts, as compared to a historical control.
Results: Significant improvements were obtained in static balance, cervical flexor neuromotor control/endurance, and near-point convergence (p-values<0.01–0.03). Increases in symptom report ($p = 0.02$) and a decline in dynamic gaze stability ($p < 0.01$) were observed. There were 11.8 injuries/1000 athlete exposures in 2017 and 8.9 injuries/1000 athlete exposures in 2018 after the treatment ($p = 0.18$).
Conclusion: This intervention holds promise as a preventive strategy for sports-injury as a comprehensive population-based intervention.

1. Introduction

Prevention of injury is a population health priority for athletes on sports teams, from youth leagues to the professional level. According to the National Collegiate Athletic Association Injury Surveillance Program (NCAA-ISP), injury incidence rates range between 4.3 (women's softball) and 35.9 (men's football) per 1000 athlete-exposures in a game environment (Hootman, Dick, & Agel, 2007). Musculoskeletal injuries are common, but within the past 15 years concussion has risen to the top as a critically concerning injury associated with sports (Hootman et al., 2007; Langlois, 2006). Despite the risks associated with contact sport participation, it is generally accepted that the benefits of participation on social development, leadership, and overall health and well-being outweigh the risks (Downward, Hallmann, & Rasciute, 2018; Eime, Young, Harvey, Charity, & Payne, 2013). Short of banning contact sports, it is impossible to prevent all bodily harm associated with participation. Therefore, effective prevention strategies are necessary to ensure that risks are mitigated to the extent possible.

Contact sports require integration of high levels of speed, balance, and agility, while navigating the trajectory of other players and a ball. These abilities are only possible through precise subconscious integration of disparate sensory information to permit appropriate motor output from the central nervous system (Wallace & Lifshitz, 2016). This process is known collectively as sensorimotor control with contributions from multiple subsystems. On the afferent side of sensorimotor control, the vestibular system senses angular and linear acceleration, providing feedback and eliciting ocular and postural reflexes; the visual system is used to plan movements in a feed-forward manner; and the proprioceptive system provides information across the joints and

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muscles in the body to permit kinesthetic awareness. This information directs the efferent output necessary to complete the intended action through precise motor control (Peterka, 2002). Any deficiency in the system can result in perceptual and motoric errors (Treleaven, 2017), which, in a fast-paced sports environment, may contribute to decreased performance and injury.

Concussion frequently results in functional disturbances of sensorimotor control (Alsalaheen et al., 2010; Hides et al., 2017a; Schneider et al., 2014). Deficits in vestibular, visual, and proprioceptive senses as well as dysfunction of postural and oculomotor control systems after a concussion have been reported (Doherty et al., 2017; Leddy et al., 2015; Yorke, Smith, Babcock, & Alsalaheen, 2017). It is widely agreed that athletes should refrain from sports after a concussion until recovery has been attained, as determined by a medical professional (McCrory et al., 2017). However, research findings have reported that sub-clinical deficits in sensorimotor function linger (Galea, Cottrell, Treleaven, & O'Leary, 2018), despite clearance for return-to-sport (Cavanaugh et al., 2005; Fino, 2016; Meier, Lancaster, Mayer, Teague, & Savitz, 2017). A recent meta-analysis including athlete participants ranging from high school to professional levels revealed that athletes with a history of concussion are more likely to sustain a subsequent concussion (OR = 4.44; 95%CI 2.90,6.79) at higher rate per athlete exposure (RR = 1.97; 95%CI 1.47,2.63) (Reneker, Babl, & Flowers, 2019). Athletes with a history of concussion are also at greater risk of sustaining lower extremity injuries (OR = 1.82; 95%CI 1.34,2.47), incurred at a higher rate per athlete exposure (RR = 1.74; 95%CI 1.16,2.62) than non-previously concussed athletes (Reneker et al., 2019). While the underlying causes for increased risk of injury among previously concussed athletes are unknown, it is possible that persistent alterations in sensorimotor control are to blame (Hides et al., 2017b).

Given concussion incidence associated with participation in contact sports and the number of exposures to potential concussions accumulated across years of play, it is likely that many collegiate athletes have suffered one or more concussions prior to beginning college (Kawata, Tierney, Phillips, & Jeka, 2016; Merchant-Borna et al., 2016). In the absence of concussion, rehabilitation interventions provided by physical therapist (PT) are routinely utilized to ameliorate functional sensorimotor disturbances and neuromotor control (Herdman & Clendaniel, 2014; Kristjansson & Treleaven, 2009; Treleaven, 2008, 2017). Rehabilitation, in this context, drives adaptive experience-dependent neuroplasticity to recalibrate the reflexive components of the systems, fine-tune cortical sensory integration of the disparate information, and direct appropriate motor responses (Kristjansson & Treleaven, 2009; Treleaven, 2008, 2017; Wallace & Lifshitz, 2016). In addition to use of these interventions for sensorimotor disturbances and neuromotor control, many publications have reported on the benefit of these types of interventions after concussion during the acute as well as the chronic phases of recovery (Alsalaheen et al., 2010; Murray, Meldrum, & Lennon, 2017; Reneker et al., 2017; Schneider et al., 2013, 2014). Therefore, it was believed that these types of training exercises would be beneficial to athletes as a method of restoration and fine-tuning for the purpose of injury prevention. Because evidence only recently emerged supporting the use of sensorimotor rehabilitation after concussion (Reneker et al., 2017; Schneider et al., 2014), it is likely that a majority of current collegiate athletes did not have adjunctive rehabilitation therapies to restore sensorimotor function after a concussion.

At this time, it is not known whether a sensorimotor control intervention, involving training the sub-system components of this system, is effective to prevent sports injury. Because concussion remains a vastly underreported injury among athletes, either through voluntary non-reporting or lack of recognition (Kroshus, Baugh, Daneshvar, & Viswanath, 2014; McDonald, Burghart, & Nazir, 2016), it is difficult to know which athletes may be at the greatest risk for subsequent injury. In addition, it is unreasonable to attempt to individually examine, assess, and treat all collegiate athletes pre-season for potential, enduring sensorimotor control deficits. Therefore, a population-based intervention is an excellent strategy to control incidence of injury (McClure et al., 2005; Rose, 1985). Sensorimotor control training activities can be delivered in a group environment and have no inherent risks for individuals with normal sensorimotor control (Cone, Levy, & Goble, 2015). In this case, there is potential to improve upon an already stable system.

Therefore, the purpose of this investigation was to determine the effects of a population-based sensorimotor training intervention by quantifying 1) the change in clinical measures of functional sensorimotor control, and 2) the injury incidence rate of the participants in comparison to a historical control. The hypothesis was that functional measures of sensorimotor control would improve, regardless of whether the athlete had a history of concussion, and injury incidence rate would decrease after participation in the intervention.

2. Methods

Trial design: This study was conducted as a pilot, one-arm intervention using, 1) pre- and post-participation measures and 2) injury incidence rate over the 2018 sports season compared to a historical control, identified as the 2017 season of the same teams. This research protocol was registered prospectively on clinicaltrials.gov and there were no changes to the methods after trial commencement. The study was approved by the University of Mississippi Medical Center Institutional Review Board (IRB) and the Mississippi College IRB prior to initiation. Informed written consent was received prospectively and the rights of each participant were protected. The 2010 CONSORT checklist was adapted for reporting and the Template for Intervention Description and Replication (TIDieR) checklist was utilized to describe the intervention (Hoffmann et al., 2014; Schulz, Altman, & Moher, 2010).

Participants: Participants were recruited from the men's and women's soccer teams at Mississippi College in Clinton, Mississippi, USA, a Division II member of the NCAA, upon reporting to campus for the 2018 season on August 11, 2018. Soccer was chosen as the sport of interest because of dual representation of both sexes and because of equivalent rates of injury (8.07 and 8.44 per 1000 exposures) (Hootman et al., 2007). Athletes eligible to play in the 2018 soccer season, aged 18 or over, were eligible for inclusion. Athletes with a current diagnosis of concussion (i.e. non-medically cleared), lower-extremity musculoskeletal injury, or other diagnosis that would prevent the athlete from participating in the intervention were excluded. In addition, an athlete sustaining a concussion during the timeframe for the intervention delivery would be withdrawn.

2.1. Multi-modal sensorimotor training intervention

Under the premises of this study, this is considered tertiary prevention (i.e. efforts to reduce risk of secondary injury) for the athletes who have altered sensorimotor control., For those who do not have altered sensorimotor control, this is considered primary prevention (i.e. efforts to prevent injury in the first place). (Gopfert, Van Hove, Emond, & Mytton, 2018).

The intervention was 4-weeks long, consisting of 2 face-to-face sessions per week for each athlete in addition to a home exercise program (HEP) delivered via each athlete's personally owned smart phone. Within the intervention, participants completed an array of training activities, aiming at the various sub-systems which contribute to overall sensorimotor control. These training activities included vestibular, visual and oculomotor activities, cervical neuromotor control and strength training, and postural/balance exercises. The equipment utilized, a basic description of each function of sensorimotor control, and the specific abilities addressed during the training sessions are in Table 1. Supplemental materials with a detailed description of the exercises are available online. Part of the intervention included four novel activities/games in virtual reality (VR) to train several components of oculomotor control and visual acuity. These were delivered via headset VR (Oculus Go).

The exercises delivered face to face were completed in a group format, using a standardized circuit of exercises that each athlete completed. A typical session included 2–3 rounds of 5–6 exercise stations for 2.5–3.5 min at each station. Each session lasted approximately 45 min. All sessions occurred in the meeting room at the soccer fieldhouse at Mississippi College. The sessions began in August, during the first week of conditioning and prior to the start of the official soccer season. The sessions continued for 4 weeks, into the start of the official season. Subsequent sessions built upon previous sessions to work the sensorimotor control system in progressively more challenging and sport-specific scenarios.

Although the standardized exercises were delivered in a group format, the monitors at each station provided tailoring to ensure an appropriate challenge for each individual. Generally, this involved changing the stance position (e.g. double leg to single leg stance) and/or the standing surface (e.g. firm ground to foam or BOSU surface).

The HEP was provided through a group messaging application (WhatsApp). The HEP was delivered through video web-links to a secure YouTube channel, which presented instructions for: horizontal gaze stability, near-point convergence, and horizontal eye-head coordination. Each exercise used the participant's smart phone to display the visual stimulus for the prescribed time (ranging from 30 s–2 min) and did not display the visual stimulus for the 15-s rest in between each repetition. To make the exercises more challenging, the visual stimulus was presented on progressively challenging backgrounds. Two additional cervical exercises did not use the participant's phone for completion, but videos with instructions were delivered through the messaging application. A PT taught the HEP to each athlete and ensured completion with the participants at the face-to-face sessions as one of the stations in the circuit. The participants had access to this HEP throughout the week if they wanted to complete it on off days although this was not tracked across the study period. The basic instructions for the HEP can be located in the supplemental materials.

All interventions were developed by three licensed PTs. One is board certified as a neurological clinical specialist, holds a vestibular competency, and has numerous publications in the area of sports-concussion (JCR). The second is board certified as an orthopedic clinical specialist and is a certified strength and conditioning specialist (RB). The third completed a residency program in sports physical therapy and is a candidate for board certification as a sports clinical specialist (WCP). The basic plan for the intervention sessions was developed prior to the initiation of the study to ensure that each core component of sensorimotor control was represented multiple times with progression across time. This was done with an intention to modify the activities as needed to reflect participant response to the level of difficulty. One or more of the intervention developers was present at each session with the participants. In addition across the intervention delivery, 8 licensed PTs and 24 Doctor of Physical Therapy students served as trained monitors at each session.

2.2. Outcomes

Prior to study initiation, the PTs who completed the baseline and post-participation examination of the participants attended training with competency assessments to standardize the

Table 1
Overview of training and equipment utilized for the intervention delivery.

Functional Category	Specific Abilities Trained	Equipment Used
Oculomotor control	Smooth Pursuit	Headset Virtual Reality
	Saccades	Headset Virtual Reality Eye charts/letter boards
	Convergence	Dice on a table Visual stimulus presented on a smart phone
Visual Acuity	Peripheral Perception	Headset Virtual Reality
	Dynamic Gaze Stability	Visual stimulus presented on a smart phone Eye charts
	Figure Ground Discrimination	Headset Virtual Reality
Cervical Neuromotor Control	Proprioceptive accuracy	Bulls-eye Targets (Tracker Laser) Head-mounted LED lights
	Kinesthetic Awareness	Maze and Target Posters (SenMoCor System) Head-mounted LED lights
	Deep Flexor Activation	Stabilizer Pressure Biofeedback (Chattanooga) Towel rolls Portable Mat tables Airex Yoga Mats
	Deep Extensor Activation	Towel rolls Portable Mat tables Airex Yoga Mats
	Functional Cervical Control/Strength	IronNeck with appropriate resistance (5 lb. – 40 lb.)
Coordination	Head-Eye Coordination	Visual stimulus presented on a smart phone or on a wall
	Sport-Specific Coordination	Soccer ball Visual stimulus on each player
Postural Control	Standing Balance (completed during performance of the above activities)	BOSU Elite Airex foam pads

completion of the clinical tests and to decrease measurement bias.

A description of the clinical measures of sensorimotor control used in this project can be found in Table 2. These outcomes were chosen because they have been extensively used in research related to concussion to measure various domains of sensorimotor control and have demonstrated clinical usefulness and psychomotor soundness (Herdman & Clendaniel, 2014; Kaufman et al., 2014; Kawata et al., 2016; Kristjansson & Treleaven, 2009; Lovell et al., 2006; Moral-Munoz, Esteban-Moreno, Herrera-Viedma, Cobo, & Perez, 2018; Scheiman et al., 2003; Schneider, Meeuwisse, Palacios-Derflingher, & Emery, 2018).

Injury incidence rate: The second primary outcome was injury incidence rate during the 2018 soccer season compared to a historical control (2017 season). For both years of interest, injury was defined using the same criteria, according to the NCAA-ISP, and included concussions and traumatic lower extremity musculoskeletal injuries (Dick, Agel, & Marshall, 2007). In this study, a reportable injury was one that (1) occurred during participation in a NCAA-sanctioned practice or competition and (2) required attention from an athletic trainer and/or physician. Contusions and non-traumatic (i.e. overuse) injuries were not included. The rate of injury was based on athlete exposures (AE). Each AE was defined as one student-athlete participating in one NCAA-sanctioned practice or competition which exposed the athlete to the possibility of injury, regardless of the time associated with that participation (Dick et al., 2007). Athlete exposures were counted as reported in the Countable Athletic Related Activities (CARA) logs utilized by NCAA sanctioned schools. The participating university collected athlete injuries and tracked CARA activities per their standard of practice. The systems used to collect and report these data were the same in 2017 and 2018.

2.3. Statistical methods

Sample size and sampling: Because this was a pilot study, conducted to provide preliminary results for a larger multi-site trial, the sample was not intended to power a full-scale study.

Means with standard deviations and counts with percentages were used as descriptive statistics for baseline characteristics. Right skewed outcomes (PCSS, NPC, DVA, JPE) were modeled with log-gamma mixed effect random intercept models with variance component covariance structures. Normal outcomes (static balance) were modeled with Gaussian random intercept models. Finally, count outcomes (PCSS, CCFT) were modeled with Poisson generalized estimating equations or mixed models. Injury rates were modeled using Poisson models, as well. Two models for each outcome were constructed: one interacting pre/post intervention with previous concussion status and one pooling across and

Table 2
Clinical outcome measures of sensorimotor control.

Outcome	Description of method of measurement
Post-Concussion Symptom Scale (PCSS)	The PCSS was utilized as a self-report symptom scale including 22 items commonly associated with concussion. (Lovell et al., 2006) Participants were asked to rate each symptom according to the following statement: “Considering how you have felt in the past 24 h, indicate the severity of each symptom below.” Athletes ranked each item in severity from 0 to 6 on a Likert scale, with 0 as “no symptom” and 6 as “severe” symptom. The total score was summed across the 22 symptoms and recorded. It was anticipated that the score on the PCSS would remain in the range of normative values of 5 total for men and 9 total for women throughout the study. Symptom measurement was included as an outcome to ensure that there were no symptom spikes, potentially indicating an active concussion at baseline or post-testing. (Lovell et al., 2006)
Static Balance measured by the Sway Balance App (static balance)	The Sway Balance App is a Food and Drug Administration approved medical device with research literature supporting its use as a valid and reliable baseline assessment of static balance in athletes. (Brett, Zuckerman, Terry, Solomon, & Iverson, 2018; Moral-Munoz et al., 2018) Sway uses the triaxial accelerometer in a smartphone and a proprietary algorithm to calculate postural sway on a 0–100 point scale, where 100 is perfect. Participants completed this test by logging in to the Sway App on their phone. The total balance score, calculated across three separate trials, was recorded.
Near Point Convergence (NPC)	NPC was tested by asking each participant to follow the path of a bead threaded on a string and marked with an 11-point font “x”, with both eyes as it moved horizontally towards his/her nose. The participant was instructed to stop the bead along the string where either: 1) diplopia of the “x” was reported or, 2) the examiner observed one eye moving laterally away from midline. The test was completed 3 times and the mean distance of NPC was calculated and recorded in centimeters. (Scheiman et al., 2003)
Dynamic Visual Acuity (DVA) – Non-instrumented	This was used as a clinical test of gaze stability, mediated by the vestibular system. (Kaufman et al., 2014) Visual acuity was measured in two conditions using an ETDRS eye chart, mounted on a wall at eye-height with the subject seated 20′ away. In the first condition, the participant's head was still, while in the second condition, an examiner assisted head rotation, timed with a metronome set at 2 Hz. A line of the eye chart was considered correct if less than 2 errors in recitation of letters occurred. The lowest line read correctly with a static head position and the lowest line read correctly with dynamic head movement was determined. The difference between the number of lines in the static and dynamic testing condition was recorded.
Cranial Cervical Flexion Test (CCFT3 and CCFT10)	This was used as a test of cervical flexor control and endurance by having the participant recruit the deep neck flexors in a precise manner according to the Stabilizer biofeedback device (Chattanooga). As described by Jull, (Jull, O'Leary, & Falla, 2008) this test had 2 stages. Stage 1 (CCFT3): was used to measure the ability to recruit and control the deep cervical flexors. (Jull et al., 2008) The highest level (22, 24, 26, 28 or 30 mmHg) that the participant could achieve and hold for 3 s with the correct muscle action, without palpable activity of the superficial flexors was recorded. Stage 2 (CCFT10): was used as a test of isometric endurance of the DCF. This stage was initiated with every participant that completed the correct movement of craniocervical flexion in stage 1, even if all pressures were not reached. At each step, the test was progressed to the next pressure target if the participant performed 3 repetitions of 10-s holds without substitution strategies. The highest level (22, 24, 26, 28 or 30 mmHg) that the participant could achieve and hold for three, 10-s counts with the correct muscle action was recorded.
Joint Position Error Test (JPE)	The JPE was utilized as a test of cervical proprioception and motor control. (Treleaven, Jull, & Sterling, 2003) The subject's ability to relocate the natural head posture following active cervical movements (left rotation, right rotation and extension) was tested without the use of vision. With the participant wearing a blindfold and a laser light attached to a headband, an examiner guided the participant to the center of the target using the light. Each direction was tested 3 times, in series with the examiner passively repositioning the participant's head to the center of the target in between each repetition. Using a calibrated target with numbered lines (Tracker Target), performance was recorded to the nearest .5, with the examiner rounding up when in question. The mean absolute error across all 9 trials was calculated and reported in centimeters.

adjusting for previous concussion status. Models were translated to expected marginal outcomes and differences in expected marginal outcomes for ease of interpretability. All models were adjusted for sex, age, race, and lifetime number of years of soccer played. All analyses were conducted in Stata v15.1 *(StataCorp, College Station, TX).*

3. Results

All of the eligible athletes (n = 75; 38 males and 37 females), including 30 athletes with a history of concussion, enrolled in the research study. Of these, 72 received the intended treatment and were included in the analyses. Three participants dropped out of the study concurrent to their decision to stop playing soccer and no outcome data could be obtained. Baseline testing was completed on August 12, 2018. The training intervention began on August 13, 2018, concluded on September 7, 2018, with post-intervention testing completed on September 10 and 12, 2018. Baseline characteristics can be found in Table 3. The mean age of the participants was 20.2 (SD = 1.46). Thirty-five (49%) of the final cohort were females, and 16 (22%) were non-Caucasian. Twenty-eight (39%) had experienced a prior concussion, and the mean number of years of soccer played was 13.9 (SD = 2.31).

Treatment delivery: Of the 72 participants who completed baseline and post-participation outcome assessments, 64 (88.9%) completed all 8 intervention sessions as scheduled; 8 (11.1%) completed seven intervention sessions as scheduled, missing one training session.

According to the statistical analyses, the intervention was effective in improving static balance, NPC, and CCFT3 and CCFT10 values with similar improvement in both groups. As measured by the Sway Balance App, there was an increase of 3.8 points on average in static balance between baseline and post-testing (88.4 vs. 92.2; $p < 0.01$). The distance of NPC decreased by 0.63 cm (1.69 vs. 1.06; $p < 0.01$). There was also an improvement in motor control and endurance of the deep-cervical flexors, as measured by the CCFT3 and CCFT10 by averages of 2.6 and 4.3 mmHg, respectively (25.9 vs. 28.5; $p < 0.01$ and 23.5 vs. 27.8; $p < 0.01$).

For absolute error on the JPE, there was an interaction effect, with the training significantly benefitting the previously concussed group (4.54 vs. 3.54; $p < 0.01$) and no change in the non-previously concussed group ($p = 0.93$). There was also an interaction effect on the PCSS, demonstrating a significant increase in symptom report for the non-previously concussed group (2.96 vs. 4.93 points; $p < 0.01$). This was not viewed as a meaningful increase because all means remained within the normative range. There was a significant decline in performance on the DVA post-treatment with an average of 1.1 lines increase between static and dynamic gaze stability (1.0 vs. 2.1; $p < 0.01$). Finally, we did observe a 27% total reduction in injury rates after treatment (11.8 per 1000 athlete exposures in 2017 vs. 8.94 per 1000 athlete exposures in 2018), but this did not reach statistical significance ($p = 0.18$). All supporting underlying data and confidence intervals can be seen in Figs. 1 and 2 and Table 4.

Table 3
Baseline participant characteristics.

Age	20.2 (1.46) 19.1 [20.2] 21.1
Female	37 (49%)
Nonwhite	17 (23%)
Previous Concussion	30 (40%)
Years Played of Soccer	13.88 (2.39) 12 [14]15
PCSS	3.73 (5.72) 0 [2] 5
Static Balance	88.1 (8.10) 85.0 [88.8] 94.2
NPC	1.96 (3.27) 0 [0.5] 3
DVA	1 (1.09) 0 [1] 2
CFFT3	25.9 (2.57) 24 [26]28
CFFT10	23.6 (2.59) 22 [24] 26
JPE	4.21 (1.38) 3.18 [4.03] 4.87

Continuous variables are represented as: mean (SD) Q1[median]Q3. PCSS = total symptom score; Static Balance = Sway score from 1 to 100; NPC measured in centimeters; DVA measured in number of lines difference between static and dynamic visual acuity; CCFT3 and CCFT 10 measured in mmHg on the biofeedback pressure gauge; JPE measured in degrees from center of target (absolute error).

4. Discussion

The purpose of this investigation was to determine the effects of a population-based multi-modal sensorimotor training intervention on injury prevention in collegiate soccer players. The hypothesis was that functional measures of sensorimotor control would improve and injury incidence would decrease. The results indicate that an intervention, such as the one described here, improved clinical measures of sensorimotor control, potentially decreasing the risk of sports-injury for individuals with and without a history of concussion. To our knowledge, this study is the first description of training activities developed to target each subsystem component of sensorimotor control as a comprehensive population-based intervention to target primary and tertiary injury prevention in athletes. Additionally, this is the first description of the use of VR for the purposes of sensorimotor training.

As a method of sports-injury prevention, this project sought to adapt the neurological system through a new application of existing therapeutic techniques. The field of sports-performance training uses various methods to improve upon reaction time, balance, speed and other abilities in healthy athletes (Bachero-Mena, Pareja-Blanco, & Gonzalez-Badillo, 2019; Bourgeois, Gamble, Gill, & McGuigan, 2017; Yoo, Park, Yoon, Lim, & Ryu, 2018). As an extension of sports-performance and as a form of primary injury prevention for those with no history of concussion, the intervention was presumed to fine-tune a stable system. On the other hand, because deficits in sensorimotor and neuromotor control are potential contributors to the increase risk of secondary injury after an initial concussion (Kardouni, Shing, McKinnon, Scofield, & Proctor, 2018; Reneker et al., 2019), the intervention was used to rehabilitate latent and subtle deficits (tertiary injury prevention). Regardless of history of previous concussion, it was believed that the neural adaptation from deliberate specific sports-performance training would, in turn, increase precision in central sensory integration and resultant motor output to prevent injury.

In addition to the significant improvements demonstrated in the clinical measures of sensorimotor control, the results demonstrate a non-significant reduction in rate of injury between the 2018 and 2017 season and a 27% reduction in total injury incidence. As a pilot study of a population intervention with a small sample, it was very unlikely that significance would be attained. However, this downward trend promotes optimism in the ability of the intervention to control an underlying neural mechanism contributing to injury risk, thereby decreasing incidence. Larger samples across time will be required to determine whether there is a significant shift in injury rate.

This research provides strong evidence for additional investigation on the use of sensorimotor training for injury prevention in athletes. Recent research has demonstrated that targeted neuromotor and balance training can decrease risk for injury in sports contexts (Emery, Roy, Whittaker, Nettel-Aguirre, & van Mechelen, 2015; Hislop et al., 2017; Huebner, Plisky, Kiesel, & Schwartzkopf-Phifer, 2019). Similarly, visual training for performance athletes has been described as an effective method for performance enhancement as well as injury prevention (Clark et al., 2015). The approach described here adds to these findings and could exert a

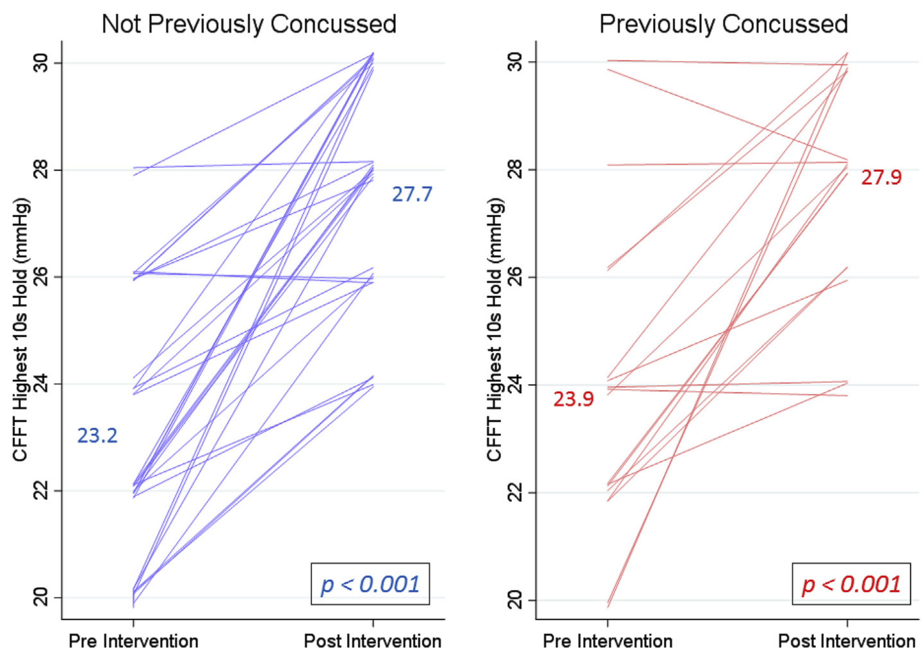

Fig. 1. Trajectories for Cranial Cervical Flexion Test (CCFT10) 10 s hold.
Shown are marginal expected values for CCFT10 modeled using generalized estimating equations with Poisson families, adjusted for sex, age, race, and number of years of soccer played. The p-value for interaction between pre/post and concussion status was $p = 0.373$, and pooling across concussion status yielded expected marginal CCFT10s of 23.5 and 27.8, pre and post, respectively ($p < 0.001$).

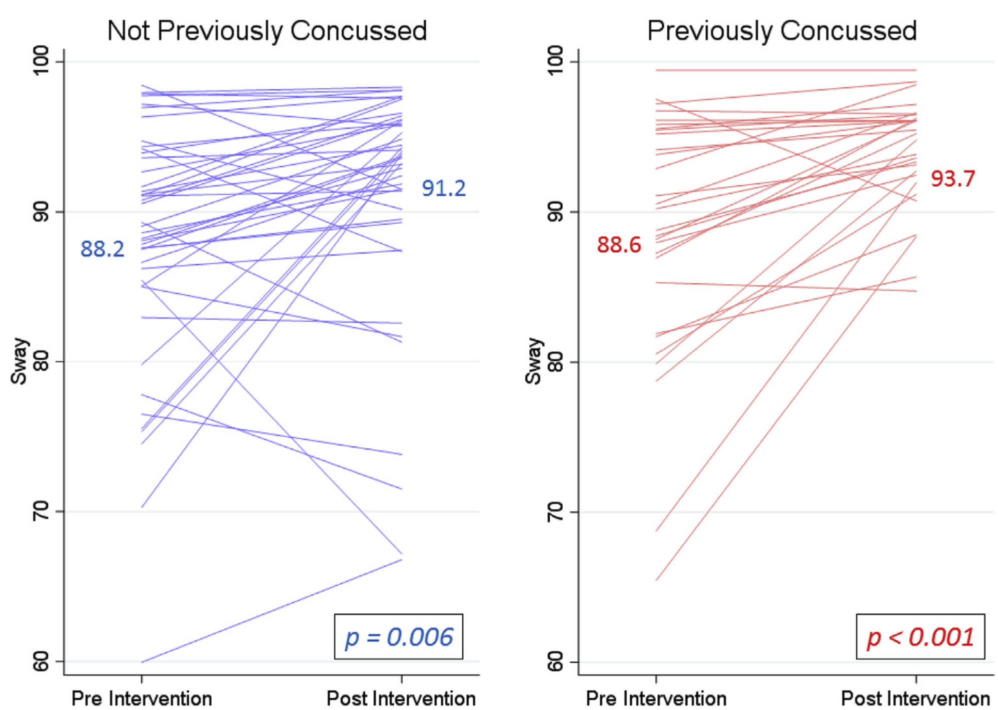

Fig. 2. Trajectories for Sway Score (static balance).
Shown are marginal expected values for static balance as measured by the Sway balance app modeled using multilevel mixed models with Gaussian families, adjusted for sex, age, race, and number of years of soccer played. The p-value for interaction between pre/post and concussion status was $p = 0.232$, and pooling across concussion status yielded expected marginal Sway score of 88.4 and 92.2, pre and post, respectively ($p < 0.001$).

substantial shift in current practices by promoting a more contemporary model of sports-performance training and conditioning to include fine-tuning of the sensorimotor control system.

One unexpected finding is that gaze stability (mediated by the vestibular system) appears to have declined based on the DVA performance. At the pre-intervention testing, the participants did not know the therapists completing the examination. The DVA test was stopped at the point of failure (i.e. missing 2 or greater optotypes in one line) (Kaufman et al., 2014). At post-intervention testing however, the examiners were well-known to the

Table 4
Modeling results.

	Pooled			Not Previously Concussed			Previously Concussed			Interaction p-value
	Pre-Int	Post-Int	Difference	Pre-Int	Post-Int	Difference	Pre-Int	Post-Int	Difference	
PCSS	4.27 (2.19, 6.35)	5.38 (2.79, 7.96)	1.11 p = 0.019 (0.18, 2.03)	2.96 (1.32, 4.60)	4.93 (2.27, 7.60)	1.97 p = 0.004 (0.63, 3.32)	6.15 (2.29, 10.0)	5.81 (2.16, 9.46)	−0.35 p = 0.624 (-1.74, 1.04)	0.001
Static Balance	88.4 (86.8, 90.0)	92.2 (90.6, 93.8)	3.79 p < 0.001 (2.11, 5.48)	88.2 (86.2, 90.2)	91.2 (89.1, 93.2)	2.97 p = 0.006 (0.83, 5.11)	88.6 (86.1, 91.2)	93.7 (91.1, 96.3)	5.06 p < 0.001 (2.39, 7.72)	0.232
NPC	1.69 (1.22, 2.16)	1.06 (0.70, 1.43)	−0.63 p = 0.002 (-1.02, −0.24)	1.78 (1.16, 2.39)	1.20 (0.71, 1.70)	−0.57 p = 0.031 (-1.10, −0.05)	1.56 (0.88, 2.24)	0.86 (0.36, 1.36)	−0.70 p = 0.019 (-1.28, −0.11)	0.603
DVA	1.00 (0.74, 1.26)	2.10 (1.75, 2.46)	1.10 p < 0.001 (0.74, 1.47)	0.96 (0.63, 1.29)	2.06 (1.61, 2.51)	1.10 p < 0.001 (0.64, 1.56)	1.07 (0.65, 1.49)	2.17 (1.60, 2.74)	1.11 p < 0.001 (0.52, 1.70)	0.942
CFFT 3	25.9 (25.1, 26.6)	28.5 (27.5, 29.4)	2.62 p < 0.001 (1.41, 3.83)	25.6 (24.6, 26.6)	28.4 (27.2, 29.6)	2.82 p < 0.001 (1.29, 4.34)	26.3 (25.0, 27.6)	28.6 (27.1, 30.2)	2.31 p = 0.022 (0.33, 4.28)	0.579
CFFT 10	23.5 (22.9, 24.1)	27.8 (26.9, 28.7)	4.32 p < 0.001 (3.27, 5.36)	23.2 (22.5, 23.9)	27.7 (26.6, 28.9)	4.54 p < 0.001 (3.23, 5.85)	23.9 (22.9, 25.0)	27.9 (26.4, 29.4)	3.96 p < 0.001 (2.26, 5.67)	0.373
JPE	4.27 (3.96, 4.58)	3.86 (3.58, 4.14)	−0.40 p = 0.027 (-0.76, −0.05)	4.09 (3.72, 4.47)	4.07 (3.70, 4.45)	−0.02 p = 0.933 (-0.46, 0.42)	4.54 (4.02, 5.06)	3.54 (3.13, 3.95)	−1.00 p < 0.001 (-1.55, −0.45)	0.005

All models adjusted for sex, age, race, and years of soccer; PCSS = total symptom score; Static Balance = Sway score from 1 to 100; NPC measured in centimeters; DVA measured in number of lines difference between static and dynamic visual acuity; CCFT3 and CCFT 10 measured in mmHg on the biofeedback pressure gauge; JPE measured in degrees from center of target (absolute error); measurements presented as mean difference and 95% confidence interval; p-value for within group change.

participants. Frequently during the dynamic portion, the participants verbally expressed that they could no longer read the eye chart and requested to stop the test. In these cases, the test was ceased prior to an actual failure in optotype recitation. For those who agreed to continue trying, this often resulted in better performance than what would have been recorded if the test was ceased when difficulty was initially reported. Differentiation between those who requested to stop the test and those who actually failed was not captured in the data. While it is possible that there was a decline in actual visual stability pre-to post-intervention, this is unlikely. Recent research has demonstrated that even acutely post-concussion in the presence of reported dizziness, DVA performance does not routinely decline when compared to an individual's pre-concussion performance (Schneider et al., 2018). Therefore, the investigators believe this finding was a reflection of discontinuing the test prematurely.

Limitations: This study was limited by the small sample size (for a population health type of study) and utilization of a pre-post-intervention design. Because there was no concurrent control group, it is not known if the results demonstrated here can be attributed solely to the intervention or if the other training activities associated with collegiate soccer participation could contribute to improvements on the outcomes. In addition, only one historical season of injury data and athlete exposures was utilized as the comparator. Additional seasons of data, had they been available and comparable to the 2018 season, would have been helpful to more completely see any trend in injury incidence. Despite this, the present study does provide good preliminary data on an active preventive intervention. Comparative effectiveness studies are needed to fully vet the value of this type of training in various contact sports, in different ages, and across those with and without history of concussion. A second limitation is that the assessors at baseline and post-intervention delivered the intervention. This creates the potential for measurement biases. To help attenuate this, baseline measures were not available to any of the assessors during post-testing and the participants did not know their prior performance score on any of the measures. Additionally, 2 assessors were used for the DVA and JPE tests, lessening opportunities for measurement error. The Sway balance test was also scored on the app, without any input from an assessor. Finally, all statistics were completed by a biostatistician who was independent from the data collection and study completion.

On a final note, it is important to emphasize that the participants were healthy athletes at the time the study began. This point is important because the outcomes utilized are typically used to identify impairment of the visual, vestibular, neuromotor, and postural control systems. Most of the athletes performed within normal ranges or at the ceiling at baseline, leaving little room for improvement. Additionally, the clinical outcomes utilized in this study have not been described for the purpose of demonstrating improvement in a healthy sample. Therefore, their sensitivity to detect change was hampered. Despite this, the results demonstrate improvement in static balance, NPC, and cervical neuromotor control and endurance (CCFT 3 and CCFT10), which we believe should be further explored with more sensitive measurement devices.

5. Conclusion

Participation in contact sports confers risk for injury and athletes with a history of concussion have greater risk than athletes without a history of concussion. The population-based sensorimotor intervention described here holds promise as an injury prevention strategy and may be beneficial to consider as a component of routine sports training and conditioning.

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Ethics approval

This research protocol was approved by the Institutional Review Board at UMMC and Mississippi College prior to initiation. Prospective written consent was obtained from all participants.

Registration

This protocol was registered prospectively, prior to any participant enrollment at www.clinicaltrials.gov, ID NCT03594669.

Declaration of competing interest

The Principal Investigator reports non-financial support from Lenovo, Inc., outside the submitted work during the conduct of the study. In addition, the PI has a patent pending related to this work. No other investigators report a conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.09.012.

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