Vestibular Rehabilitation Is Associated With Visuovestibular Improvement in Pediatric Concussion

Eileen P. Storey, BA, Douglas J. Wiebe, PhD, Bernadette A. D'Alonzo, MPH, Kim Nixon-Cave, PT, PhD, PCS, Janet Jackson-Coty, PT, DPT, PCS, Arlene M. Goodman, MD, Matthew F. Grady, MD, CAQSM, and Christina L. Master, MD, CAQSM

Background and Purpose: Vision and vestibular-related deficits are common after concussion and are associated with prolonged recovery times, substantially impacting the quality of life for children. The utility of targeted vestibular rehabilitation for these deficits in children after concussion is unknown. The purpose of this study was to determine whether active vestibular rehabilitation is associated with an improvement in visuovestibular signs and symptoms in children with concussion.

Methods: A retrospective cohort study of children diagnosed with concussion and referred to vestibular rehabilitation between 2012 and 2014 was conducted. Patient-reported symptoms and visuovestibular performance measures were assessed in the medical practice and physical therapy settings.

Results: One hundred nine children were included in the study with a mean age of 11.8 (3.4) years. Among this group, 59 (54%) were male and 48 (44%) had a sports-related concussion. Children presented to a pediatric sports medicine office and physical therapy a median of 24 (interquartile range [IQR], 14-42) and 55 (IQR, 39-94) days after injury, respectively. Concussion symptoms decreased from a median of 9 (IQR, 5-13) symptoms at initial evaluation to a median of 0 (IQR, 0-2) symptoms at final assessment. Performance on all visuovestibular tasks improved significantly over the course of therapy except for near point of convergence. For the 45 children who completed the Balance Error Scoring System at both initial and final therapy visits, there was a significant improvement in mean level of performance ($P < 0.0001$). Characteristics between those who completed a full versus partial course of physical therapy were similar.

Discussion and Conclusions: Vestibular rehabilitation in children with concussion is associated with improvement in symptoms as well as visuovestibular performance. This active intervention may benefit children with persistent symptoms after concussion. Future prospective studies are needed to determine the efficacy and optimal postinjury timing of vestibular rehabilitation.

Video Abstract available for more insights from the authors (see Supplemental Digital Content 1, available at: http://links.lww.com/JNPT/A208).

Key words: *concussion, children, human movement system, vestibular rehabilitation, visuovestibular system*

(*JNPT* 2018;42: 134–141)

INTRODUCTION

Of the estimated 3.8 million cases of concussion each year in the United States, 65% occur in children and adolescents.[1–3] The proportion of youth concussions has increased dramatically in the past 15 years with the rise in concussion awareness and youth participation in sports.[4] Although most individuals with concussion report symptom resolution within 7 to 10 days, approximately 30% experience symptoms that do not resolve within 2 weeks.[5–8] For this substantial group, visuovestibular deficits are often contributors to persistent symptoms.[9–11] Given the prevalence of vestibular-related deficits after concussion and their association with prolonged recovery, active vestibular rehabilitation is a therapeutic intervention of interest in concussion management.[12]

Vestibular rehabilitation involves the use of specific exercises designed to reduce dizziness and improve gaze stability and balance function. Previous studies have shown that vestibular rehabilitation improves outcomes for adults and children with vestibular dysfunction unrelated to concussion, such as vertigo and motion sensitivity.[13–18] Since postconcussive symptoms and deficits may relate to vestibular dysfunction,[9,10,19] vestibular rehabilitation has been described in the literature as a promising therapeutic intervention for adults and adolescents with prolonged dizziness and balance deficits after concussion.[20–25]

Active vestibular rehabilitation has also recently received attention as a potential tool in the acute management

The Children's Hospital of Philadelphia, Division of Orthopaedics, Sports Medicine and Performance Center, Philadelphia, Pennsylvania (E.P.S., K.N-C., J.J-C., M.F.G., C.L.M.); Perelman School of Medicine, University of Pennsylvania, Philadelphia (M.F.G., C.L.M.); Saint Peter's Sports Medicine Institute, Somerset, New Jersey (A.M.G.); and Center for Clinical Epidemiology and Biostatistics, University of Pennsylvania, Philadelphia (D.J.W., B.D.).

The study was performed at The Children's Hospital of Philadelphia under the approval of CHOP's Institutional Review Board. Part of this work was presented at the Pediatric Research in Sports Medicine Annual Meeting in San Diego, California, in January 2015.

The authors declare no conflict of interest.

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

Correspondence: Christina L. Master, MD, CAQSM, The Children's Hospital of Philadelphia, Division of Orthopaedics, Sports Medicine and Performance Center 34th and Civic Center Blvd, Wood Bldg, 2nd Floor, Philadelphia, PA 19104 (masterc@email.chop.edu).

ISSN: 1557-0576/18/4203-0134

DOI: 10.1097/NPT.0000000000000228

of pediatric concussion. One randomized controlled trial in subjects 12 to 30 years of age (median: 15 years of age) found that those who received vestibular and physical therapy had reduced time until medical clearance to return to sport than an age- and sex-matched control group.[24] More recently, a retrospective cohort study of 25 subjects, 12 to 20 years of age (median: 15 years of age), demonstrated that a multimodal course of therapy is safe and associated with reduced symptoms.[26] While these studies offer preliminary evidence for the safety and potential efficacy of physical therapy in adolescent populations, our study extends this line of investigation by examining the clinical presentation and outcomes of a larger and younger cohort of children with both sports- and non-sports-related concussion to address persistent symptoms and visuovestibular deficits. We describe changes in patient-reported symptoms and performance on visuovestibular tasks following vestibular rehabilitation.

METHODS

Research Design and Participants

We conducted a retrospective cohort study of 109 children diagnosed with concussion who were referred for physical therapy services within a large pediatric tertiary care network for vestibular rehabilitation between April 24, 2012, and March 31, 2014. Study eligibility criteria were (1) 18 years of age or younger, (2) diagnosis of concussion and referral to therapy from a physician inside the care network within 1 year of injury, (3) absence of intracranial hemorrhage or other traumatic abnormalities on neuroimaging, and (4) no subsequent concussions during the treatment period. Although the cohort included children with both sports-related and non-sports, trauma-related injuries, including assaults, motor vehicle crashes, and falls, all children had comparable injuries.[9] Study data were collected via a query of the electronic health record (EPIC) and abstracted electronically into the Research Electronic Data Capture (REDCap) tool hosted at the same hospital network for analysis.[27] The study was approved by the institutional review board at The Children's Hospital of Philadelphia.

Clinical Assessments and Management

Four physicians with experience caring for concussion within the same care network confirmed the diagnosis using the definition specified by the International Consensus on Concussion in Sport as an injury caused by transmission of biomechanical forces to the brain leading to clinical symptoms affecting multiple domains of physical, cognitive, sleep, and neurobehavioral functioning.[28]

At the time of presentation to clinic, demographic data, past medical and concussion history, family history, and injury details were recorded in the electronic medical record. Children also reported if they had any of the 22 concussion-related symptoms listed on the Post-Concussion Symptom Scale.[29] All children underwent a standardized examination performed and documented in the electronic medical record by 1 of the 4 physicians. A standardized template was created within the electronic medical record to ensure consistent documentation across providers. The clinical examination included a standardized visuovestibular assessment that evaluated smooth pursuits, horizontal and vertical saccades, horizontal and vertical gaze stability, tandem gait, near point of convergence (NPC), and accommodation.[9,30]

Ocular smooth pursuits were assessed by having the child follow the clinician's finger as it moved progressively more rapidly from one side of the child's visual field to the other. If children showed evidence of nystagmus or reported symptom provocation, the test was documented as abnormal. Horizontal and vertical saccades were tested by having a child look back and forth as rapidly as they could between 2 targets held shoulder-width and forehead-chin distance apart, respectively, without moving their head. If a child reported symptom provocation or exhibited signs of eyes slowing, watering, or reddening as observed by the physician, the examination was documented as abnormal. Children were assessed up to 30 repetitions to address potential ceiling effects with saccadic assessment unless they were limited by symptom provocation. Gaze stability was assessed by having a child shake his or her head in both the pitch (vertical) and yaw (horizontal) directions while keeping his or her eyes fixed on a stationary target. If a child reported symptom provocation, the examination was documented as abnormal. Near point of convergence and accommodation were measured using a standard Astron accommodative rule (Gulden Ophthalmics, Elkins Park, PA) with a single-column 20/30 card. Abnormal NPC was defined as a break at greater than 6 cm and accommodation was defined as abnormal at a distance greater than the age-adjusted standard.[31,32] As part of the visuovestibular examination, children also completed a dynamic tandem gait task in which the child walked heel-toe in a straight line both forward and backward with eyes open and closed to assess balance. The clinician documented each condition (forward eyes open, forward eyes closed, backward eyes open, backward eyes closed) separately and noted the condition as abnormal if the child raised arms for stability, widened his or her gait, had significant truncal sway, or stepped off the line. Details of the examination have been previously published[9] and are further described in Supplemental Digital Content 2 Appendix, available at: http://links.lww.com/JNPT/A209. Referrals for vestibular rehabilitation were based on clinical findings on the visuovestibular examination. In general, children who had deficits that persisted more than 3 weeks after injury were referred to physical therapy for vestibular rehabilitation.

The visuovestibular examination was administered at every medical office visit. The standardization across visits allowed for the comparison of patient-reported symptoms and performance on the visuovestibular examination. Findings of the following variables were compared between initial and final clinical visits: number of patient-reported symptoms, symptoms provoked by smooth pursuits, and saccades and gaze stability testing, as well as performance on the NPC, accommodation, and tandem gait tasks.

Vestibular Rehabilitation Exposure

Vestibular rehabilitation was performed by physical therapists at 4 sites within the same pediatric care network and consisted of a customized program to target each child's impairments and functional limitations related to dizziness,

balance, and visual deficits. Vestibular rehabilitation in this pediatric care network is similar to other programs described in the literature with modifications to accommodate the younger pediatric population.[33–37] All children underwent a thorough multimodal evaluation by a licensed physical therapist trained in managing pediatric concussion to identify specific deficits to target with therapy.

The initial physical therapy evaluation followed a standardized protocol designed to identify individual deficits and develop a customized, targeted therapeutic plan. The evaluation included a concussion history and an examination of the visuovestibular systems. The visuovestibular examination included tasks that matched those administered on the clinical examination, including smooth pursuits, saccades, gaze stability, and convergence. Rehabilitation interventions were designed to promote habituation and adaptation in order to improve gaze stability and eye-head coordination. Balance was assessed using the Balance Error Scoring System (BESS), a validated tool for repeated measures of postural stability at visits until static balance plateaued.[38] The test consisted of 3 stances performed with eyes closed on both firm and foam surfaces for a total of 6 conditions. The physical therapist administering the session used the standardized BESS scoring system and noted errors, or deviations from the proper stance, accumulated by the subject. Errors included moving hands off iliac crest, opening eyes, stepping, stumbling or falling, abduction or flexion of the hip beyond 30°, lifting the forefoot or heel off of the testing surface, and remaining out of the proper testing position for more than 5 seconds. All errors were summed to produce total scores for the firm and foam surfaces and those scores were combined to yield an overall BESS score. Because of ceiling effects reported with BESS testing,[38] additional examination of dynamic tandem gait as described previously was also used longitudinally.

All children in physical therapy received a comprehensive daily exercise program with visuovestibular objectives to complete between each therapy session as part of their active rehabilitation (see Supplemental Digital Content 2 Appendix, available at: http://links.lww.com/JNPT/A209). Each course of physical therapy followed a similar framework, prescribing specific visual oculomotor and balance exercises to target impairments and gradually increasing the difficulty of those exercises to help children return to preinjury functional levels, with the progression of difficulty tailored to each child. Results were compared between initial and final therapy visits.

Statistical Analysis

Descriptive statistics, including means, medians, ranges, and interquartile ranges (IQRs), were used to describe demographics and characteristics upon initial presentation. Continuous variables were evaluated with histograms, Q-Q plots, and the Kolmogorov-Smirnov test to assess normality to inform the approach to analysis. When comparing those who completed therapy and those who did not, paired and unpaired *t* tests and nonparametric tests were used to assess for differences in continuous variables, and χ^2 tests and Fisher exact test were used to assess for differences in categorical variables. In addition, we also tested each continuous variable with nonparametric tests of medians. Results were similar and thus not reported for the sake of brevity. Multivariate logistic regression was used to assess for changes in performance between initial and final visits based on demographics and clinical characteristics. A P value of 0.05 was used as a cutoff for significance. All statistical analyses were performed using Stata (version 14.2, Stata Corp).

RESULTS

Participants

Of the 123 children referred to physical therapy for vestibular rehabilitation during the study period, 109 (88%) met the study eligibility criteria. Nine children were excluded because they were referred from outside sports medicine and trauma clinics and so they did not have medical office assessments, 1 child suffered a second concussion during the treatment period, and 4 children presented to therapy more than 365 days after injury (Figure 1). The remaining group of children (59 males, 50 females) had a median age of 12 years (range, 5-18 years), with 39 (36%) aged 10 years or younger. More than half of the children (56%) sustained a concussion outside of the sports setting. Of the 48 (44%) with a sports-related concussion, 18 (37%) continued to play after injury. Thirty-four (31%) had a prior history of concussion and 13 (12%) had loss of consciousness at the time of injury (Table 1).

Presentation

Children presented to clinic a median of 24 days (IQR, 14-42) after injury. All 109 children presented with signs of visuovestibular dysfunction on the initial medical office examination (Table 1). Approximately 8 of every 10 children had symptom provocation with horizontal (79.6%) and vertical (83.3%) saccades. Of the 105 children who had gaze stability assessed at their initial examination, 56 (53.9%) became symptomatic in the yaw (horizontal) direction while 53 (51.0%) became symptomatic in the pitch (vertical) direction. Of the 108 children who completed the tandem gait task, 83 (77.6%) were abnormal. On vision-specific testing, 26.0% had abnormal convergence and 34.7% had abnormal accommodation. At presentation to physical therapy, 102 children completed the BESS and scored a median of 33 errors (range, 8-60).

Although all children had signs of visuovestibular dysfunction on physical examination upon presentation, 77 (70.1%) reported at least 1 visuovestibular symptom at their initial clinical visit, as 61 (56.0%) presented with dizziness, 61 (56.0%) with balance problems, and 46 (42.2%) with vision problems. Those who had abnormal findings on NPC and accommodation were not significantly more likely to endorse visual symptoms at presentation ($P = 0.624$ and $P = 0.234$, respectively). Notably, 59 (54.1%) children described more than 1 vestibular symptom at their initial clinical visit: 79% of children with dizziness also reported balance problems, while 67.7% with dizziness also reported vision problems (Figure 2). Headache was the most common presenting symptom, described by 91 (83.5%) children.

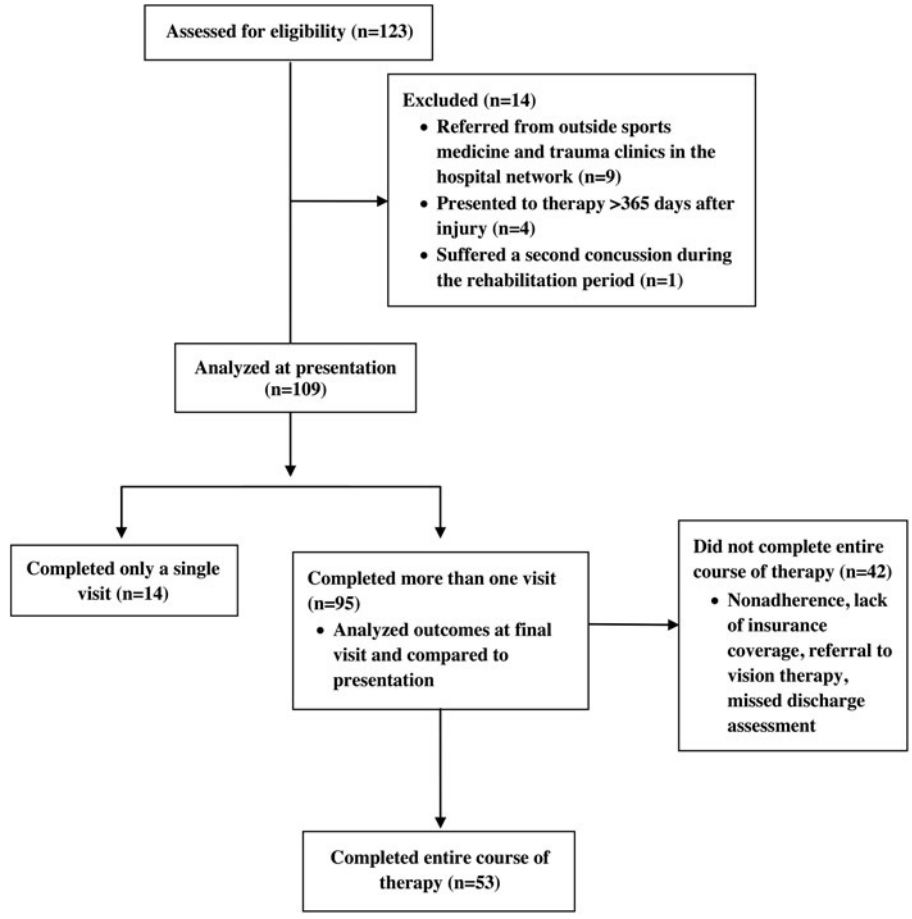

Figure 1. Flow diagram of patients included in the study.

Clinical Outcomes

Of the 109 children who presented to physical therapy for vestibular rehabilitation, 14 (13%) completed an initial evaluation but did not return for a second visit. The 95 children who completed at least 2 visits of vestibular rehabilitation showed improvements in postconcussion symptoms and performance on visuovestibular tasks by their final visit to therapy. Concussion symptoms decreased from a median of 9 (IQR, 5-13) symptoms at initial evaluation to a median of 0 (IQR, 0-2) symptoms at final assessment. Twenty percent of children still reported at least 1 vestibular-related symptom (dizziness, balance problems, vision problems) at their final visit compared with 70.1% initially. Headaches remained the most common symptom at the final evaluation but were reported by 24% of children after the intervention compared with 83.5% initially.

Performance on all visuovestibular tasks improved substantially over the course of therapy (Table 2). At final evaluation, 19 of the 72 children (26%) who completed the visuovestibular examination continued to have deficits compared with all 95 children with deficits at initial evaluation. Balance also improved substantially in both the clinical and physical therapy settings. Of those who completed the tandem gait task at final evaluation, 14.1% still had balance deficits, which was a decrease of 63% from clinical presentation. Of the 83 children who completed the BESS at their initial therapy visit, the average total score was 33.8 (10.85). Fifty children completed the BESS at final evaluation and had an average total score of 21.7 (8.8). For the 45 children who completed the BESS at both initial and final therapy visits, there was a significant improvement in mean level of performance ($P < 0.0001$).

Fifty-three children (49%) completed an entire course of vestibular rehabilitation, as indicated by a discharge assessment documenting achievement of recovery goals. Children who completed therapy did so in a median of 7 visits (IQR, 5-9) occurring over a median duration of 56 days (IQR, 42-79). Reasons for not completing therapy included nonadherence, lack of insurance coverage, referral to vision therapy, or missed discharge assessment. There were no significant visuovestibular differences between those who completed an entire or partial course of vestibular rehabilitation at presentation except for performance on the BESS ($P = 0.037$) and tandem gait backward with eyes closed ($P = 0.023$), which was worse in those not completing vestibular physical therapy (PT) (Table 3). Those who completed vestibular PT had a significantly lower overall symptom burden at presentation than those who did not complete ($P = 0.006$).

Table 1. Demographics and Clinical Characteristics of 109 Pediatric Patients Referred to Vestibular Rehabilitation After Concussion

Variable	Total Sample (n = 109)
Sex	
Males	54.1%
Females	45.9%
Age, y	
≤10	35.8%
11-14	36.7%
15-18	27.5%
Loss of consciousness	11.9%
Sports related	44%
Prior concussion	31.2%
Symptoms at presentation	
Headache	83.5%
Dizziness	56.0%
Balance problems	56.0%
Visual problems	42.2%
Symptom provocation on visuovestibular examination	
Horizontal saccades	79.6
Vertical saccades	83.3
Horizontal gaze stability	53.9
Vertical gaze stability	51
Performance on physical examination	**Mean (SD)**
Horizontal saccades	15.6 (9.5) repetitions
Vertical saccades	14.1 (9.1) repetitions
BESS	32.7 (11.2) errors
	% Abnormal
Convergence	26.0
Accommodation	34.7
Tandem gait	
Eyes open backward	44.9
Eyes closed backward	77.6

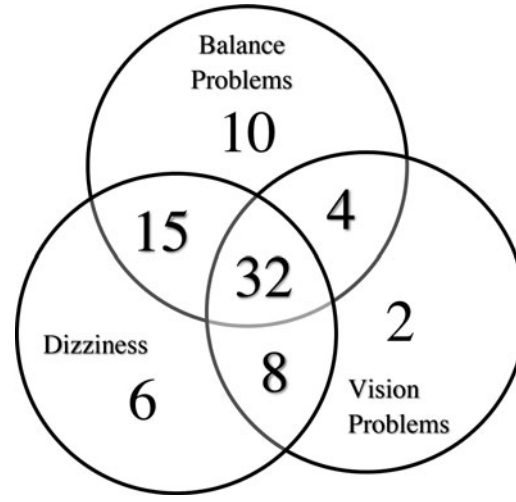

Figure 2. Visuovestibular symptoms at clinical presentation in a cohort of pediatric patients referred to vestibular rehabilitation after concussion.

DISCUSSION

The goal of this study was to identify any association between vestibular rehabilitation after concussion and improvement in concussion symptoms and visuovestibular performance. The prevalence of vestibular deficits and their association with prolonged recovery after concussion have been well established.[9,39–42] In addition, many authors have described the use of vestibular rehabilitation to manage adult and adolescent concussions.[20–25] Overall, the results in this study confirm these previously published studies, indicating that even young children with persistent dizziness and balance deficits after concussion can tolerate and potentially benefit from a course of vestibular rehabilitation. In particular, this study is the first to indicate that younger preadolescent children with concussion demonstrate a reduction in symptoms and improvement in visuovestibular performance associated with vestibular therapy.

Table 2. Mean Change in Oculomotor and Balance Performance Before and After Therapy Among Those Who Had More Than 1 Visit of Vestibular Therapy (n = 95)

Variable	Before Therapy Repetitions, Mean	After Therapy Repetitions, Mean	P^a	Before Therapy Provoked Symptoms, %	After Therapy Provoked Symptoms, %	P^b
Saccades						
Horizontal	16.1	28.4	<**0.0001**	78.1	20.0	<**0.0001**
Vertical	15.0	28.3	<**0.0001**	82.3	20	<**0.0001**
Gaze stability						
Horizontal	. . .	. . .	. . .	52.7	6.7	<**0.0001**
Vertical	. . .	. . .	. . .	51.6	7.9	<**0.0001**
				Abnormal, %	**Abnormal, %**	
Tandem gait						
Backward open	. . .	. . .	. . .	47.4	6.3	<**0.0001**
Backward closed	. . .	. . .	. . .	76.8	14.1	<**0.0001**
Convergence	. . .	. . .	. . .	22.7	15.4	0.397
Accommodation	. . .	. . .	. . .	34.1	5.0	**0.0009**
	Errors, Mean	**Errors, Mean**				
BESS	33.8	21.7	<**0.0001**	. . .	. . .	. . .

Abbreviation: BESS, Balance Error Scoring System.
[a] *P*-value based on paired *t* test. 0.05 was used as a cutoff for significance.
[b] *P*-value based on difference of proportions test. 0.05 was used as a cutoff for significance.

Table 3. Comparing Presentation of Those Who Completed (n = 53) and Those Who Did Not Complete (n = 42) an Entire Course of Vestibular Therapy

Variable	Completed Therapy Repetitions, Mean (SD)	Did Not Complete Therapy Repetitions, Mean (SD)	P^a	Completed Therapy Provoked Symptoms, %	Did Not Complete Therapy Provoked Symptoms, %	P^b
Saccades						
Horizontal	15.8 (1.7)	15.5 (1.6)	0.909	73.6	84.9	0.151
Vertical	14.5 (1.6)	13.7 (1.5)	0.691	83.0	83.0	1.000
Gaze stability						
Horizontal	...	...	...	52.8	53.1	0.981
Vertical	...	...	...	49.1	51.0	0.843
				Abnormal, %	**Abnormal, %**	
Tandem gait						
Backward open	...	...	...	37.7	51.9	0.144
Backward closed	...	...	...	67.9	86.5	0.023
Convergence	...	...	...	22.2	31.8	0.449
Accommodation	...	...	...	29.6	42.9	0.342
	Errors, Mean (SD)	**Errors, Mean (SD)**				
BESS	35 (1.7)	31 (1.5)	**0.037**	...	...	...

Abbreviation: BESS, Balance Error Scoring System.
[a] *P*-value based on paired *t* test. 0.05 was used as a cutoff for significance.
[b] *P*-value based on difference of proportions test. 0.05 was used as a cutoff for significance.

A vestibular cluster of signs and symptoms that include oculomotor and balance function has been previously defined,[43] and our data indicate that both symptom provocation and performance on oculomotor and balance tasks improved in our cohort receiving vestibular therapy. This reinforces the importance of assessing oculomotor function even in the absence of balance dysfunction. While all clinical measures of visuovestibular function improved after therapy, including accommodation, NPC did not. Accommodation is related to convergence in a visual cluster of physical examination signs[43] and, while accommodation may contribute to NPC deficits in many children with concussion, our data indicate that there is a subset of children who have NPC deficits that are not primarily driven by accommodation deficits and do not improve after vestibular therapy despite resolution of their accommodation deficits. This indicates an important potential role for targeted vision rehabilitation to address these deficits that persist after vestibular PT. These persisting visual deficits may also partially account for the subset of children (24%) with lingering symptoms following vestibular PT. These persistent symptoms after vestibular PT may also be explained by the underlying presence of nonspecific symptoms in adolescents as base rates of concussion symptoms have been reported as high as 28% in uninjured teens.[44] Identification of visuovestibular deficits in children is important since these deficits have important implications for return-to-learn and return-to-play decisions. Since impairment in saccadic eye movements can cause significant symptoms related to school activities, such as reading and note-taking, it is critical to find ways to facilitate recovery for children with ongoing vestibular- and vision-related symptoms after concussion. In addition, since children often do not recognize visual symptoms even when they have underlying visual deficits on their physical examination,[45] it is especially important for clinicians to proactively detect and treat these deficits that can substantially affect school performance.[46] Thus, clinicians caring for children recovering from concussion should consider vestibular rehabilitation for children who have ongoing visuovestibular symptoms and deficits.

In addition to considering vestibular rehabilitation as a treatment option for children after concussion, it is important for clinicians to recognize some of the barriers to completing this active intervention. Reasons for nonadherence to recommended physical therapy are wide and varied in scope, including insurance reasons, referral to vision therapy, or missed discharge assessment. This area represents an important line of future investigation in order to identify barriers to treatment or disparities in access to treatment that may need to be addressed in order to realize the full rehabilitative potential of such an active intervention. However, in this study, there were no significant differences between those who adhered to an entire course of vestibular rehabilitation and those who did not, suggesting that those who did not complete therapy still had a sufficient dose of therapy to improve. This indicates that children may vary in the amount of therapy they need to recover from a concussion. Further research is needed to determine individual factors that could influence responsiveness to active therapeutic interventions after concussion.

This study has several methodological limitations. The findings cannot be generalized to concussion in all populations since children in our study came from a pediatric subspecialty referral population. Those with less severe injuries that resolved within 1 to 2 weeks likely would not have been referred to physical therapy for vestibular rehabilitation to recover from concussion. In addition, since this was a retrospective study without a control group, we cannot attribute improvements to therapy. Children typically were not seen in the medical practice until more than 3 weeks postinjury and did not begin vestibular rehabilitation until more than 7 weeks

postinjury; therefore, improved outcomes could be attributed to spontaneous recovery with time. Since preinjury physical characteristics and performance on the visuovestibular clinical examination prior to injury were unknown, the visuovestibular symptoms and deficits may have been preexisting and unrelated to the injury. However, as the prevalence of vestibular disorders among children in the general population is significantly lower than what we found in this study,[47,48] it is likely that most of these vestibular symptoms and deficits were related to the concussion.

Our outcome measures were limited to subjective assessments that depend on clinician judgment and patient effort and are influenced by learning effects. This study would be improved if additional clinical tests, such as the Head Impulse Test and Dynamic Visual Acuity Test, were included to further characterize the vestibular function of children after concussion and during a course of rehabilitation. In addition, the visuovestibular examination is a clinical examination and BESS was designed as a sideline measure to acutely evaluate concussion, so their reliability in the chronic concussion population is not firmly established; however, recent studies have demonstrated the potential reliability of these assessments in this setting.[49−51] Additional research is needed to demonstrate the reliability of these assessments for concussion and to incorporate objective balance measurements with force plates and accelerometers and objective vision measurements with advanced eye tracking technology. Despite these limitations and the small sample size, statistically significant improvements in the resolution of symptoms and visuovestibular deficits were noted.

CONCLUSIONS

The results of our retrospective cohort study indicate that children with prolonged deficits after concussion tolerate vestibular rehabilitation and show improvement in symptoms and visuovestibular deficits, warranting future prospective investigations to evaluate the efficacy and optimal timing postinjury of vestibular rehabilitation for this population. Further research is needed to determine whether children with certain comorbidities or presenting symptoms are more likely to make gains with a course of vestibular rehabilitation.

ACKNOWLEDGMENT

We would like to acknowledge Luke Basta for his help with this project.

REFERENCES

1. Faul M, Likang X, Wald MM, Coronado VG. *Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations, and Deaths 2002-2006*. Atlanta, GA: US Department of Health & Human Services, Centers for Disease Control and Prevention, National Center for Injury Prevention and Control; 2010.
2. Gilchrist J, Thomas KE, Xu L, McGuire LC, Coronado V. *Nonfatal Traumatic Brain Injuries Related to Sports and Recreation Activities Among Persons Aged <19 Years—United States 2001-2009*. MMWR Morb Mortal Wkly Rep. 201;60(39):1337-42.
3. Centers for Disease Control and Prevention. *Nonfatal Traumatic Brain Injury From Sports and Recreation Activities—United States 2001-2005*. MMWR Morb Mortal Wkly Rep. 2007;56(29):733-7.
4. Bakhos LL, Lockhart GR, Myers R, Linakis JG. Emergency department visits for concussion in young child athletes. *Pediatrics*. 2010; 126(3):e550-e556.
5. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2556-2563.
6. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *J Int Neuropsychol Soc*. 2013;19(1):22-33.
7. Field M, Collins MW, Lovell MR, Maroon J. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr*. 2003;142(5):546-553.
8. Zemek R, Barrowman N, Freedman SB, et al. Clinical risk score for persistent postconcussion symptoms among children with acute concussion in the ED. *JAMA*. 2016;315(10):1014-1025.
9. Corwin DJ, Wiebe DJ, Zonfrillo MR, et al. Vestibular deficits following youth concussion. *J Pediatr*. 2015;166(5):1221-1225.
10. Ellis MJ, Cordingley DM, Vis S, Reimer KM, Leiter J, Russell K. Clinical predictors of vestibulo-ocular dysfunction in pediatric sports-related concussion. *J Neurosurg Pediatr*. 2017;19(1):38-45.
11. Henry LC, Elbin RJ, Collins MW, Marchetti G, Kontos AP. Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*. 2016;78(2): 232-241.
12. McCrory P, Meeuwisse W, Dvorak J, et al. Consensus statement on concussion in sport-the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*. 2017;51(11):838-847.
13. Badke MB, Shea TA, Miedaner JA, Grove CR. Outcomes after rehabilitation for adults with balance dysfunction. *Arch Phys Med Rehabil*. 2004;85(2):227-233.
14. Gaikwad SB, Johnson EG, Nelson TC, Ambode OI, Albalwi AA, Alharbi AA, Daher NS. Effect of gaze stability exercises on chronic motion sensitivity: a randomized controlled trial. *J Neurol Phys Ther*. 2018 Apr;42(2):72-79.
15. Brown KE, Whitney SL, Marchetti GF, Wrisley DM, Furman JM. Physical therapy for central vestibular dysfunction. *Arch Phys Med Rehabil*. 2006;87(1):76-81.
16. Hall CD, Cox LC. The role of vestibular rehabilitation in the balance disorder patient. *Otolaryngol Clin North Am*. 2009;42(1):161-169, xi.
17. Medeiros IR, Bittar RS, Pedalini ME, Lorenzi MC, Formigoni LG, Bento RF. Vestibular rehabilitation therapy in children. *Otol Neurotol*. 2005;26(4):699-703.
18. Rine RM, Wiener-Vacher S. Evaluation and treatment of vestibular dysfunction in children. *Neurorehabilitation*. 2013;32(3):507-518.
19. Lau BC, Kontos AP, Collins MW, Mucha A, Lovell MR. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? *Am J Sports Med*. 2011;39(11):2311-2318.
20. Aligene K, Lin E. Vestibular and balance treatment of the concussed athlete. *Neurorehabilitation*. 2013;32(3):543-553.
21. Alsalaheen BA, Mucha A, Morris LO, et al. Vestibular rehabilitation for dizziness and balance disorders after concussion. *J Neurol Phys Ther*. 2010;34(2):87-93.
22. Gottshall K. Vestibular rehabilitation after mild traumatic brain injury with vestibular pathology. *Neurorehabilitation*. 2011;29(2):167-171.
23. Gurley JM, Hujsak BD, Kelly JL. Vestibular rehabilitation following mild traumatic brain injury. *Neurorehabilitation*. 2013;32(3):519-528.
24. Schneider KJ, Meeuwisse WH, Nettel-Aguirre A, et al. Cervicovestibular rehabilitation in sport-related concussion: a randomised controlled trial. *Br J Sports Med*. 2014;48(17):1294-1298.
25. Gagnon I, Grilli L, Friedman D, Iverson GL. A pilot study of active rehabilitation for adolescents who are slow to recover from sport-related concussion [published online ahead of print March 3, 2015]. *Scand J Med Sci Sports*. 2016;26(3):299-306.
26. Grabowski P, Wilson J, Walker A, Enz D, Wang S. Multimodal impairment-based physical therapy for the treatment of patients with postconcussion syndrome: a retrospective analysis on safety and feasibility. *Phys Ther Sport*. 2016;23:22-30.
27. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap)—a metadata-driven methodology and

workflow process for providing translational research informatics support. *J Biomed Inform*. 2009;42(2):377-381.
28. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med*. 2013;47(5):250-258.
29. Lovell MR, Iverson GL, Collins MW, et al. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Appl Neuropsychol*. 2006;13(3):166-174.
30. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate concussions: preliminary findings. *Am J Sports Med*. 2014;42(10):2479-2486.
31. Hayes GJ, Cohen BE, Rouse MW, De Land PN. Normative values for the nearpoint of convergence of elementary schoolchildren. *Optom Vis Sci*. 1998;75(7):506-512.
32. Scheiman M, Gallaway M, Frantz KA, et al. Nearpoint of convergence: test procedure, target selection, and normative data. *Optom Vis Sci*. 2003;80(3):214-225.
33. Alsalaheen BA, Whitney SL, Mucha A, Morris LO, Furman JM, Sparto PJ. Exercise prescription patterns in patients treated with vestibular rehabilitation after concussion. *Physiother Res Int*. 2013;18(2):100-108.
34. Whitney SL, Sparto PJ. Principles of vestibular physical therapy rehabilitation. *Neurorehabilitation*. 2011;29(2):157-166.
35. Han BI, Song HS, Kim JS. Vestibular rehabilitation therapy: review of indications, mechanisms, and key exercises. *J Clin Neurol*. 2011;7(4):184-196.
36. Kaufman DR, Puckett MJ, Smith MJ, Wilson KS, Cheema R, Landers MR. Test-retest reliability and responsiveness of gaze stability and dynamic visual acuity in high school and college football players. *Phys Ther Sport*. 2014;15(3):181-188.
37. Kirkwood MW, Yeates KO, Wilson PE. Pediatric sport-related concussion: a review of the clinical management of an oft-neglected population. *Pediatrics*. 2006;117(4):1359-1371.
38. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic review of the Balance Error Scoring System. *Sports Health*. 2011;3(3):287-295.
39. Corwin DJ, Zonfrillo MR, Master CL, et al. Characteristics of prolonged concussion recovery in a pediatric subspecialty referral population. *J Pediatr*. 2014;165(6):1207-1215.
40. Sosnoff JJ, Broglio SP, Shin S, Ferrara MS. Previous mild traumatic brain injury and postural-control dynamics. *J Athl Train*. 2011;46(1):85-91.
41. Greenwald BD, Gurley JM. Balance and vestibular function. *Neurorehabilitation*. 2013;32(3):433-435.
42. Boake C, McCauley SR, Levin HS, et al. Diagnostic criteria for postconcussional syndrome after mild to moderate traumatic brain injury. *J Neuropsychiatry Clin Neurosci*. 2005;17(3):350-356.
43. Master CL, Master SR, Wiebe DJ, et al. Vision and vestibular system dysfunction predicts prolonged concussion recovery in children. *Clin J Sport Med*. 2018;28(2):139-145.
44. Iverson GL, Silverberg ND, Mannix R, et al. Factors associated with concussion-like symptom reporting in high school athletes. *JAMA Pediatr*. 2015;169(12):1132-1140.
45. Storey EP, Master SR, Lockyer JE, Podolak OE, Grady MF, Master CL. Near point of convergence after concussion in children. *Optom Vis Sci*. 2017;94(1):96-100.
46. Master CL, Scheiman M, Gallaway M, et al. Vision diagnoses are common after concussion in adolescents. *Clin Pediatr (Phila)*. 2016;55(3):260-267.
47. O'Reilly RC, Morlet T, Nicholas BD, et al. Prevalence of vestibular and balance disorders in children. *Otol Neurotol*. 2010;31(9):1441-1444.
48. Corwin DJ, Zonfrillo MR, Wiebe DJ, Master CL, Grady MF, Arbogast KB. Vestibular and oculomotor findings in neurologically-normal, nonconcussed children. *Brain Inj*. 2018;32(6):794-799.
49. Yorke AM, Smith L, Babcock M, Alsalaheen B. Validity and reliability of the vestibular/ocular motor screening and associations with common concussion screening tools. *Sports Health*. 2017;9(2):174-180.
50. Moran RN, Covassin T, Elbin RJ, Gould D, Nogle S. Reliability and normative reference values for the vestibular/ocular motor screening (VOMS) tool in youth athletes. *Am J Sports Med*. 2018;46(6):1475-1480.
51. Cushman D, Hendrick J, Teramoto M, Fogg B, Bradley S, Hansen C. Reliability of the balance error scoring system in a population with protracted recovery from mild traumatic brain injury. *Brain Inj*. 2018;32(5):569-574.

