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Subtle Motor Findings During Recovery from Pediatric Traumatic Brain Injury: A Preliminary Report

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Abstract

Pediatric traumatic brain injury (TBI) is a heterogeneous condition, varying in both severity and sequelae. The long-term motor deficits following severe TBI requiring inpatient rehabilitation are better established than those following milder forms of TBI. The authors examined motor performance 2 and 12 months postinjury in children without overt motor impairment using standard measures of upper limb function and the Physical and Neurological Examination for Subtle Signs (PANESS). The PANESS was sensitive to differences between children with TBI and uninjured children as well as to changes in children with TBI over time. These data suggest that subtle motor deficits are present after milder forms of TBI and, particularly those related to balance and gait, may persist even 12 months postinjury.

Keywords

motor; pediatric; rehabilitation; traumatic brain injury

Traumatic brain injury (TBI) is a leading cause of death and disability in the United States (Faul & Coronado, 2010). TBI is a highly heterogeneous condition, varying in both severity and sequelae. With regard to motor sequelae, children with more severe injuries who require inpatient rehabilitation often experience marked motor deficits in fine motor control and strength and gross motor skills (e.g., balance and gait) which persist throughout and beyond the first year postinjury (Ahlander, Persson, & Emanuelson, 2013; Katz-Leurer, Rotem, Keren, & Meyer, 2010; Kuhtz-Buschbeck, Hoppe, et al., 2003). Conversely, in mild TBI literature behavior problems (Taylor et al., 2015) and cognitive issues (Loher, Fatzer, & Roebbers, 2014) are typically studied, but motor deficits are also examined (Babikian et al., 2011; Gagnon, Swaine, Friedman, & Forget, 2004a, 2004b; Howell, Osternig, Koester, & Chou, 2014; Rhine, Quatman-Yates, & Clark, 2015; Wallen, Mackay, Duff, McCartney, & O'Flaherty, 2001).

The same types of motor behaviors examined in severe TBI (i.e., fine motor control and gross motor ability) have also been evaluated in children with mild TBI, though, unsurprisingly, the type and duration of deficits vary. Measures of fine motor control fail to identify deficits in children with mild TBI, even when participants are tested within the first 10 days postinjury (Wallen et al., 2001). Babikian et al. (2011) also found no deficits on pure motor speeded measures but when collapsing data collected one, six, and 12 months postinjury did observe small differences between children with mild TBI and uninjured controls on motor tasks with cognitive components (e.g., Color Trails). In subacute stages (i.e., 1–3 months postinjury) of mild TBI, multiple authors have identified gross motor deficits including postural instability (Rhine et al., 2015) and impaired dynamic balance (Gagnon et al., 2004a; Howell et al., 2014); longer term follow-up of these findings has not been reported, though in adults, motor findings have been identified years after mild TBI (Martini et al., 2011). In summary, following mild pediatric TBI, subtle motor deficits may be observed in the months postinjury, but less is known about the longitudinal course of these findings. Furthermore, little is known about the motor function of children with injuries who fall in intermediate categories of severity—children with injuries that are more severe than typical concussion but who do not have overt motor impairments.

Our objective was to examine longitudinal motor function in a pilot cohort of children with TBI of mixed severity of injury but without overt motor impairment. We elected to include measures of fine motor control, which are sensitive to deficits in severe TBI, in order to determine their role in evaluating a mixed severity cohort. Additionally, we included a measure of subtle motor signs that provides a quantitative and qualitative report of gait and balance, as well as fine motor coordination and speed. We sought to identify which of these measures were sensitive to motor performance differences between children with TBI and uninjured peers at two and 12 months postinjury. We also sought to establish which measures were sensitive to improvement or persistence of motor deficits over time within children with TBI. Finally, we examined which specific motor deficits, if any, accounted for performance differences between children with TBI and uninjured peers.

METHOD

Participants

Data from participants with TBI were obtained as part of a longitudinal study of inhibitory control after TBI. Inclusion criteria for the larger study included children 10–17 years old with an isolated event of trauma resulting in TBI characterized by at least one of the following: posttraumatic amnesia lasting at least 1 hr, loss of consciousness lasting greater than 15 min, or presence of injury-related intracranial findings on clinical imaging. Additionally, children had to be out of posttraumatic amnesia (PTA) and without overt motor impairment that would limit their ability to participate in cognitive and motor tasks. All 14 participants with TBI from the larger study who underwent behavioral testing at two months ($M = 66$ days) and 12 months ($M = 385$ days) postinjury were included in the current analyses. Glasgow Coma Scale scores from the day of injury were not available for many participants. Using American Congress of Rehabilitation Medicine criteria for description purposes, severity of injury was described based on duration of PTA (<24 hr = mild, 24 hr to

7 days = moderate, >7 days = severe) and presence of injury-related intracranial findings on clinical computed tomography (CT) findings (no findings = mild TBI, findings = moderate or severe TBI; American Congress of Rehabilitation Medicine, 1993). In the TBI group, one child had a premorbid diagnosis of attention-deficit/hyperactivity disorder (ADHD), another child had preinjury executive functioning deficits without a diagnosis of ADHD, and one child had obsessive-compulsive symptoms prior to injury but did not meet diagnostic criteria for obsessive-compulsive disorder or other anxiety disorder.

Comparison data from a single time point of testing were obtained for a single control group with 19 age- and sex-matched typically developing, uninjured children. None of the participants in the control group had learning, behavioral, or psychiatric concerns.

The Johns Hopkins Medicine Institutional Research Board approved this study. Written informed consent and assent were obtained from a parent or legal guardian and child participants, respectively.

Measures

The Physical and Neurological Examination of Subtle Signs (PANESS; Denckla, 1985) examines subtle signs of motor impairment during gait, balance, and timed basic motor functions. In the PANESS, higher values represent poorer motor performance, specifically the presence of balance or walking disturbances, excessive motor movements, irregular posture or muscle tone, irregular rhythm, or speed/accuracy deficits during repetitive motor tasks. The PANESS has two subscores (gaits and stations and total timed) which are summed to determine the PANESS total score; see Table 1 for a description of the component tasks from each subscore. PANESS scoring accounts for developmental expectations. Speeded tasks are age-normed and other component scores consider the age of the participant when scoring errors—in younger children, for example, disrupted balance or excessive motor movements are expected and not scored as errors. The PANESS has also been shown to have good re-test reliability (Vitiello, Ricciuti, Stoff, Behar, & Denckla, 1989). PANESS total score, gaits and stations subscore, and total timed subscore were the primary outcomes of interest. PANESS data were collected by psychological associates who were independent from the research team and blind to the study hypotheses. These psychological associates received training on the PANESS and demonstrated interrater reliability of at least 0.90 with one of two senior faculty members with expertise in the PANESS (including M. Denckla) prior to independently administering and scoring the PANESS. PANESS data were available for all participants.

The motor speed task from the Delis-Kaplan Executive Function System (D-KEFS) Trails (Delis, Kaplan, & Kramer, 2001) was used. Scaled scores were used for analyses. Data for this task were available for 13 participants with TBI; data from one participant was eliminated due to error in task administration. Data were collected for 12 of the 19 control participants who were age and sex matched to the participants with TBI.

The Lafayette Grooved Pegboard (LGP) evaluates for fine motor coordination and speed (Lafayette Instrument Company, Inc., Lafayette, IN, USA). Z scores for motor speed from dominant and nondominant hand were analyzed separately. Data were available for all

participants with TBI and the same subset of control participants from whom D-KEFS Trails data were available.

STATISTICAL ANALYSES

Due to a relatively small sample size and nonnormally distributed behavioral tasks, all data were subjected to nonparametric analyses. Two sets of Mann-Whitney *U* tests were used to evaluate differences between the control group and the participants with TBI at the two time points (two and 12 months postinjury). Wilcoxon signed-rank tests were used to evaluate change between two and 12 months within the TBI group. As an exploratory analysis, between-group and within-group analyses were repeated for component task scores from the PANESS to identify which, if any, component tasks were driving observed performance differences. Finally, as only one child had a severe TBI and another participant in the TBI group had a premorbid ADHD diagnosis which has been associated with motor problems in previous research (e.g., (Gaddis et al., 2015), all aforementioned analyses were repeated with each participant's data removed to assess whether either participant was driving findings. Findings were not significantly altered, unless otherwise stated. Alpha was set at .05, and *p* values between .05 and .10 were considered trend level findings.

RESULTS

Participant Characteristics

The TBI group included nine participants with mild, four participants with moderate, and one participant with severe TBI. Three children had abnormal findings on initial CT scans (punctate hemorrhage, hemorrhagic contusion, and 1 mm subdural hematoma). Additionally, three children with normal CT scans had abnormal findings on magnetic resonance imaging acquired at the first study visit (two with single punctate abnormalities and one with multiple punctate abnormalities, none of which were clearly trauma related) that may have been premorbid). Two children had PTA for longer than 24 hr (two and 27 days). No significant differences existed between the single control group and TBI participants in sex ($p = .37$) or age at the two-month ($p = .31$) or 12-month ($p = .88$) time points (Table 2).

Sensitivity of Measures—Identifying Differences Between Groups

PANESS—On the PANESS total score, the between group analysis revealed that at two months postinjury, the TBI group performed significantly poorer than controls, $U(1, 31) = 199.00$, $p = .02$. This difference was no longer significant when the TBI group was 12 months postinjury, $U(1, 31) = 179.50$, $p = .13$ (Figure 1A). On the gaits and stations subscore, at two months postinjury, there was a trend toward poorer performance in the TBI group, $U(1, 31) = 183.5$, $p = .07$, and this trend remained at 12 months postinjury, $U(1, 31) = -185.5$, $p = .06$ (Figure 1B). When data were removed from either the child with a severe TBI or the child with premorbid ADHD, the difference between controls and the TBI group two months postinjury shifted just beyond the upper limit of trending, (p values = .11 and .12, respectively). On the total timed subscore, at two months postinjury, the TBI group performed significantly poorer than did controls, $U(1, 31) = 187.5$, $p = .05$, but no significant differences existed when the TBI group was 12 months postinjury, $U(1, 31) =$

157.00, $p = .40$ (Figure 1C). When the child with severe TBI was removed from analysis, the difference between controls and the TBI group at two months postinjury shifted from significant to trending ($p = .08$).

Other Behavioral Measures—No significant between group differences were identified on the D-KEFS Trails motor speed or LGP for dominant or nondominant hand at two or 12 months postinjury (p values between .14 and .93).

Change in Motor Performance Over Time—Identifying Differences Within the TBI Group

PANESS—In within group analysis, the TBI group had a significantly poorer PANESS total score at 2 months postinjury compared to 12 months postinjury, $Z(1, 13) = 16.00$, $p = .02$ (Figure 1A). No significant differences existed within the group on the gaits & stations subscore, $Z(1, 13) = 35.50$, $p = .48$ (Figure 1B). In contrast, the TBI group at 2 months postinjury performed significantly poorer on the total timed subscore than at 12 months post-injury, $Z(1, 13) = 10.50$, $p = .03$ (Figure 1C).

Other Behavioral Measures—No significant within-group differences were identified on the other motor measures (p values between .21 and .59).

Component Tasks of PANESS

Gaits and stations—At 2 months postinjury, there was a trend toward poorer performance in the TBI group on the total axial component task $U(1, 31) = 184.50$, $p = .06$ (Figure 2). When data were removed from either the child with a severe TBI or the child with premorbid ADHD, the difference between controls and the TBI group two months postinjury shifted just beyond the upper limit of trending, (p values = .11). There were no significant differences between groups on the overflow component task, $U(1, 31) = 150.50$, $p = .53$ or the total miscellaneous/involuntary component task, $U(1, 31) = 148.50$, $p = .58$. Again, at 12 months postinjury, there was a trend toward poorer performance in the TBI group on the total axial component task, $U(1, 31) = 179.50$, $p = .09$. No significant differences emerged on the total overflow component task, $U(1, 31) = 132.00$, $p = .99$, or on the total miscellaneous/involuntary component task, $U(1, 31) = 178.00$, $p = .11$. When the child with premorbid ADHD was removed from analysis, the difference between controls and the TBI group at 12 months postinjury shifted from nonsignificant to trending ($p = .08$).

Within the TBI group, on the total overflow component task, there was a trend toward poorer performance in the TBI group at two months postinjury, $Z(1, 13) = 4.00$, $p = .09$. On the total Miscellaneous/Involuntary component task, there was an unexpected trend toward better performance in the TBI group at two months postinjury $Z(1, 13) = 18.5$, $p = .08$. When the child with severe TBI was removed from analysis, this trend was no longer significant ($p = .16$). No significant differences emerged within the TBI group on the total axial component task, $Z(1, 13) 30.5$, $p = .50$.

Total timed—No participants in either group had choreoathetosis or hemiparesis, so this component score was not further evaluated. No significant between- or within-group

differences existed for the other three component tasks (p values between .12 and .93; Figure 3).

DISCUSSION

Summary of Findings

Our study was designed to evaluate the sensitivity of a motor battery to deficits two and 12 months after pediatric TBI. In addition to evaluation of standardized assessments of fine motor control that are commonly used in clinical settings (i.e., the D-KEFS Trails and LGP), we also included the PANESS to examine more subtle motor deficits. The PANESS has been used in other pediatric neurodevelopmental populations to identify subtle motor dysfunction, such as ADHD (Gaddis et al., 2015) and autism (MacNeil & Mostofsky, 2012), but the PANESS has not previously been used after TBI.

We compared age- and sex-matched uninjured children to a population of children with TBI at two and 12 months postinjury. The TBI cohort was heterogeneous. Although largely comprising children with mild to moderate injuries, the inclusion criteria excluded children with the mildest concussions. In addition, while one child met criteria for a severe injury, in general that child did not appear to drive the findings, suggesting that the findings can be conceptualized as representing performance in a cohort of children with mild-complicated to moderate TBI. Additionally, after excluding data from the child with premorbid ADHD, we did not observe notable differences in our results, suggesting that this child's preinjury diagnosis did not drive the reported findings.

We found that while at two months postinjury children with TBI had significantly poorer PANESS total scores compared to uninjured children; at 12 months postinjury this was no longer true. The same pattern was seen for the PANESS total timed subscore, although, on the gaits and stations subscore the children with TBI performed worse than controls at both time points. In contrast to findings from PANESS, TBI participant performance at two and 12 months postinjury was not significantly poorer than controls on the motor speed task from the D-KEFS and the LGP task.

To complement these between group findings, we examined changes in scores within the children with TBI over time to understand whether scores changed significantly over the course of recovery. We found significant improvements over time for PANESS total and total timed scores, which is consistent with our between group findings that while between-group differences in these scores were identified at two months, they were no longer present at 12 months postinjury. We did not observe significant differences within the TBI group over time for the gaits and stations subscore nor the D-KEFS Trails or LGP tasks. This is also concordant with between-group findings, though for the gaits and stations tasks this reflects continued between-group differences over time, while for the other tasks this reflects lack of between-group differences at either time point.

Finally, we investigated which specific motor deficits, if any, were driving performance differences between uninjured and injured children on the PANESS by examining component tasks of the PANESS gaits and stations and total timed subscores. We found that

children with TBI performed worse on the total axial component task of the gaits and stations subscore at both two and 12 months postinjury. The total axial component task assesses disturbances of standing balance and gait. At both two and 12 months postinjury, children with TBI had difficulty with tandem walking and with standing or hopping on one foot. These observed deficits converge well with the pediatric literature demonstrating that gait and balance disturbances are observed over time and by varying methods after mild pediatric TBI, including in the acute stages as measured by computerized posturography (Lahat et al., 1996) and in subacute stages as measured by standardized assessments of balance and posture, such as balance subtest of the Bruininks-Oseretsky Test of Motor Proficiency, the Pediatric Clinical Test of Sensory Interaction for Balance, and the Postural Stress Test (Gagnon et al., 2004a); center of mass measurements during dual task performance (Howell et al., 2014); and with use of the Nintendo Wii Balance Board (Rhine et al., 2015). Our findings are also coherent with adult data suggesting that gait and balance deficits are identified using an electronic walkway assessment tool even years after mild TBI (Martini et al., 2011). It is also possible that the balance deficits preceded brain injury, as children with worse balance may be more likely to get injured; whether the balance deficits predate or result from injury, rehabilitation efforts to improve performance may decrease risk of reinjury. Children with TBI also had poorer performance on the overflow component task, although this was only observed at two months postinjury and did not persist 12 months postinjury. Overflow in hands was generally evenly distributed during each of the gait tasks (walking on heels of the feet, toes, and sides of the feet), although slightly more overflow was observed while children were walking on the sides of their feet. While overflow movements can be age appropriate at younger ages (<9 years old), at enrollment, the age of the current cohort was such that they had already aged out of the developmental cutoffs for overflow in the gaits and stations tasks. Thus, the resolution of between-group difference in overflow is more likely due to recovery from injury rather than developmental maturation.

On the total miscellaneous/involuntary component task, we discovered an unexpected trend within the TBI, where better performance was observed at two months postinjury than at 12 months postinjury. The total miscellaneous/ involuntary component task assesses motor precision, posture, and eye movements. Upon closer examination, we found that, at 12 months postinjury, nearly all children maintained (scored within ± 1 point) their initial performance. The child with severe TBI, however, showed an increase in 3 points between the visits, due to new overshooting on a finger to nose task. When examining this child's performance on speeded tasks over time, we found that he was very slow on speeded tasks at two months postinjury and showed a significant improvement in speed at 12 months postinjury. We hypothesize that for this child, the early effects of injury on speeded performance provided a benefit for accuracy at two months, and once his speed improved, it resulted in a trade-off with less accurate performance at 12 months. The behavioral pattern of reduced motor speed acutely in the one child with severe pediatric TBI is coherent with other research (Kuhtz-Buschbeck, Stolze, Golge, & Ritz, 2003). Larger studies may be useful for determining whether this evolution in speed/accuracy trade-off is a common pattern of performance in children with severe TBI; if so, this may also drive changing rehabilitation goals across recovery.

In contrast to findings on the PANESS, the standard measures of fine motor control from our battery did not identify deficits in this cohort. This is compatible with previous research where deficits were not observed using similar measures in children with mild TBI (Babikian et al., 2011). Collectively, our findings and previous work suggests that these measures are less sensitive to motor deficits in mild to moderate severity injuries. Best rehabilitation practice may include their use in conjunction with more sensitive motor assessments.

Implications for Rehabilitation Professionals

Our findings suggest that the PANESS may be a sensitive tool for assessing subtle motor deficits after childhood TBI compared to commonly used measures of fine motor control. Rehabilitation professionals must have sensitive assessment tools order to readily identify subtle gross motor deficits, like balance and gait, that would benefit from intervention and to use as outcome measures. Tools like the PANESS could serve as indicators of functional improvements and, as discussed with regard to speed–accuracy trade-offs, may also identify changing areas for intervention over time. Furthermore, these results underscore that recovery after pediatric TBI can be a lengthy process, and it is important to consider both clinically and in future research how subtle, ongoing motor deficits might impact occupational performance in academic, athletic, and social engagement.

Study Limitations and Future Directions

Limitations of this current study lend themselves to future work. First, we only had data from our control group at one time point; future work should consider a longitudinal study design with both the clinical and control population, potentially with additional time points to more clearly understand trajectories of recovery. Additionally, to further minimize potential bias in PANESS scoring, future use may include a blinded rater scoring the PANESS from videotape. Also, the longitudinal PANESS data need to be considered with respect to any developmental effects over the 10 months between assessments in the TBI group. The improvement, or resolution of deficits, observed from two to 12 months in PANESS total and total timed scores could be in part attributable to developmental maturation or familiarity with the measure, although the scoring for the timed tasks incorporates age-based norms, so the children with TBI did not merely improve numerically between the visits, but did catch up to their uninjured peers by 12 months postinjury, likely indicating recovered function. Furthermore, typically developing children up to 14 years old have been shown to display improvement with age on the gaits and stations subscore of the PANESS (Larson et al., 2007); therefore, the lack of improvement in the TBI group over time on the gaits and stations subscore, driven by deficits in balance and gaits as measured by the total axial component task, is even more compelling. Last, future researchers might combine use of the PANESS with instrumentation for evaluation of balance in order to further examine potential deficits after TBI in children.

These data, however, are from a small sample size of children with mixed TBI severity. The sample was likely underpowered to identify more modest between-group findings. Replication in future studies with larger populations of children with TBI—including children with the mildest injuries—will be important to better understand for which groups

of children the PANESS may be most useful. Given prior work suggesting an association between atypical cortical connectivity at two months postinjury and performance on the PANESS (Risen, Barber, Mostofsky, & Suskauer, 2015) examining longitudinal cortical activity associated with subtle motor deficits could help us better understand the neural basis of motor recovery and persistence of motor deficits after pediatric TBI.

CONCLUSION

In summary, in this preliminary cohort we found that the PANESS was more sensitive than other typically used motor tasks for detecting differences between children with TBI and uninjured children, as well as changes among children with TBI over time. Moreover, this study provides additional support that motor deficits related to balance and gait may persist even 12 months after injury. These preliminary findings indicate that the PANESS may be a useful tool for health care professionals, including occupational therapists, in the comprehensive and longitudinal assessment of motor function in pediatric TBI.

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FIGURE 1.

Physical and Neurological Examination for Subtle Signs (PANESS) performance: between- and within-group differences. Mean scores for PANESS total and subscores are depicted; higher scores indicate poorer performance. Significant between-group and within-group differences were observed on the PANESS total score. On the gaits and stations subscore, a trend was observed between the control group and the traumatic brain injury group at both two and 12 months postinjury. Significant between- and within-group differences were also observed on the total timed subscore. Error bars represent *SEM*. * $p < .05$. ^ $p = .06-.10$

FIGURE 2.

Gaits and stations component scores: between-and within-group differences. Mean scores for component tasks are depicted; higher scores indicate poorer performance. On the total axial component task, a trend was observed between the control group and the traumatic brain injury (TBI) group at both two and 12 months postinjury. On the total miscellaneous/involuntary and total overflow component tasks, trends were observed within the TBI group. Error bars represent *SEM*. * $p < .05$. ^ $p = .06-.10$

FIGURE 3.

Total timed component scores: between- and within-group differences. Mean scores for component tasks are depicted; higher scores indicate poorer performance. No significant differences were observed between or within groups on any component task. Error bars represent *SEM*. * $p < .05$. $^{\wedge}p = .06-.10$

TABLE 1

PANESS subscore components

PANESS total score	Assesses presence of
Gaits and stations	
Total axial	• Disruptions in standing balance and/or gait
Total overflow	• Excessive motor movements during gait
Total miscellaneous/ involuntary	• Choreiform, tremors, abnormal posture, or eye movements
Total timed	
Total timed overflow	• Excessive motor movements during timed motor tasks
Total dysrhythmia	• Irregularity in rhythm of timed motor tasks
Total timed miscellaneous	• Choreoathetosis and/or hemiparesis during timed motor tasks
Total SFA	• Standard deviation from age-based normative mean in speed of motor tasks

Note. Gaits and stations and total timed collectively represent the Physical and Neurological Examination for Subtle Signs (PANESS) total score.

TABLE 2

Study group characteristics

Study group	Total	Women	<i>M</i> age (years)
Uninjured control group	19	4	15.43
TBI group two months post injury	14	5	14.55
TBI group 12 months post injury	14	5	15.32