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What is This?
Adolescents Demonstrate Greater Gait Balance Control Deficits After Concussion Than Young Adults

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Investigation performed at the University of Oregon, Eugene, Oregon, USA

Background: Age has been described as a factor that affects recovery after concussion. The recommended management protocol is to treat adolescents in a more cautious manner than adults. However, few studies have prospectively and longitudinally assessed the way these age groups perform on motor tasks after concussion.

Purpose: To examine dual-task gait balance control deficits after concussion in a group of adolescents and young adults in reference to matched control subjects within 72 hours of injury and throughout 2 months after injury.

Study Design: Cohort study; Level of evidence, 2.

Methods: Adolescents and young adults who sustained a concussion and individually matched controls completed a whole-body motion gait analysis while simultaneously performing a cognitive task. Subjects with concussion reported to the laboratory within 72 hours after injury and at the following time points: 1 week, 2 weeks, 1 month, and 2 months after injury. Control subjects completed the same protocol at similar time points. Gait balance control measurements included whole-body center-of-mass (COM) medial-lateral displacement/velocity and anterior velocity.

Results: A total of 38 subjects with concussion, 19 young adults (mean ± SD age, 20.3 ± 2.4 years) and 19 adolescents (mean ± SD age, 15.1 ± 1.1 years), and 38 individually matched control subjects were tested. Within 72 hours of injury, adolescents displayed significantly greater COM medial-lateral displacement \((P = .001)\) and peak velocity \((P = .001)\) relative to their control group, and the young adult concussion group displayed significantly less peak COM anterior velocity than their control group \((P = .01)\). Across the 2 months of testing, adolescents with concussion displayed significantly greater total COM medial-lateral displacement than did adolescent controls \((P = .001)\), while young adults with concussion did not significantly differ from their matched controls \((P = .07)\).

Conclusion: An examination of gait balance control during dual-task walking revealed that after concussion, in reference to matched controls, adolescents demonstrated greater gait balance control deficits than did young adults initially and throughout the 2-month postinjury period, supporting the recommendation of conservative management for adolescents after concussion.

Keywords: cerebral concussion; postural balance; development; adolescence

The management of concussion has evolved considerably over the past several years. Although concussion severity grading scales were traditionally used to guide management decisions, they have now been abandoned in favor of an individualized approach to concussion management based on a multifaceted evaluation of function. Traumatic brain injury has been reported to affect a developing brain differently than one that is fully developed, suggesting that adolescents may have a more complicated recovery than adults. Thus, best-practice treatment statements have identified age as a treatment modifier, recommending that younger populations who sustain a concussion be managed more conservatively and cautiously than adults to allow more time to heal before resumption of preinjury physical or cognitive activities.

Adolescence is a critical time of brain development, and brain injury during this stage of life may result in a greater degree of injury than for an adult. In addition to developmental differences, anatomic and physiological differences such as brain water content, degree of myelination, skull shape, cerebral metabolic rate of glucose, and total number of synapses have been identified as possible factors that may explain adolescent vulnerability to concussion-related effects. The mechanics of the concussive event may
also affect injury-related outcomes. High school and collegiate football players appear to undergo similar levels of head acceleration during impact, but due to the immaturity of the musculoskeletal system, younger athletes may possess a diminished ability to control the head and reduce head acceleration after impact, potentially leading to increased stress of brain tissue.

Previous concussion-related research has revealed post-injury deficits to brain function through neuropsychological testing, attentional testing, static balance testing, and dynamic balance testing. Dual-task balance assessments in particular have been reported to provide a sensitive detection of persistent neurological deficits and may help to identify compromised processes that may require more healing after concussion. The Stroop test has been documented as a secondary task in a dual-task paradigm that engages conflict-resolution function, previously shown to be affected by concussion. Thus, an examination of dual-task gait balance control may provide information about the ability to multitask in daily activities after concussion.

Althought the developing brain may react to an injurious event differently than an adult brain, comparisons of motor function deficits between adolescent and adult age groups after concussion have yet to be reported. Therefore, the purpose of this study was to prospectively and longitudinally examine how adolescents and young adults with concussion perform on measures of gait stability during dual-task walking in comparison with matched control subjects within 72 hours after injury and systematically throughout a 2-month postinjury period. It was hypothesized that adolescents with concussion would display greater gait balance control deficits than young adults with concussion in relation to matched control subjects 72 hours after injury and that such deficits would require a longer duration of time to reach a level similar to control subjects for adolescents than young adults.

MATERIALS AND METHODS

Subject Identification

High school and college students who sustained a concussion were diagnosed and identified for potential inclusion in the study by a certified athletic trainer or physician. The definition of concussion was consistent with that described by McCrory et al: an injury caused by a direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head, resulting in a graded set of clinical symptoms. The high school subjects who sustained a head injury were evaluated at the site of the injury or at a high school athletic training facility. The college subjects who sustained a head injury were evaluated at a college student health center. After the evaluation and confirmation of concussion diagnosis by a physician or certified athletic trainer, prospective subjects were informed about the study and, if interested, provided written permission (prospective subject and parent/guardian permission if younger than 18 years) for study investigators to contact them for detailed study information and subsequent informed consent. Each subject with concussion enrolled in the study was matched with a healthy control subject by sex, height, mass, age, and activity participation. Prospective control subjects (prospective subject and parent/guardian if younger than 18 years) were informed about the study via referral by enrolled subjects, student health center physicians, or certified athletic trainers; were interviewed; and, if meeting inclusion and exclusion criteria, could be considered eligible for enrollment through a similar process as concussion participants.

Before data collection, the institutional review board reviewed and approved the study protocol. All subjects and parents/guardians (if a subject was younger than 18 years) provided written consent to participate in the study. Permission was also granted by the respective high school districts and colleges or universities to conduct testing with student participants. Exclusion criteria for all prospective subjects included the following: (1) lower extremity deficiency or injury that may affect normal gait patterns; (2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities; (3) history of 3 or more previous concussions; (4) loss of consciousness from the concussion lasting longer than 1 minute; (5) history of attention-deficit hyperactivity disorder; or (6) a previously documented concussion within the past year. Consistent with previous work, potential subjects with 3 or more previous concussions were not included in the study to ensure, to the extent possible, that those with chronic mild traumatic brain injury were not a part of the study. Additionally, those who experienced a loss of consciousness for greater than 1 minute were excluded because of the role that this sign plays in concussion management modification. For each subject, a verbal medical history was taken by a certified athletic trainer upon the subject’s first laboratory visit to confirm that all criteria were met for inclusion in the study. Concussion management decisions for all subjects in the study were made independently from the study by attending physicians.

Testing Timeline

A prospective, repeated-measures design was used whereby subjects with concussion reported to the laboratory within 72 hours after injury as well as approximately 1 week, 2 weeks, 1 month, and 2 months after injury. Control subjects were initially assessed and then tested similarly according to the same testing schedule as concussion subjects.

Protocol

All subjects were evaluated on measures of balance control during dual-task walking. During the assessment, subjects walked barefoot at a self-selected speed along a walkway while completing an auditory Stroop test. The Stroop test consisted of the subject listening to 4 auditory stimuli: the recorded words “high” or “low” spoken in either a high or low pitch. Subjects were instructed to identify the pitch of the word, regardless of whether the pitch...
was congruent with the word. Each of the 4 stimuli was presented in random order at a specific time while subjects were walking. The first stimulus, presented once the subject had achieved steady-state gait, was triggered by a photocell located several steps after gait initiation. Each of the 3 subsequent stimuli was presented 1 second after the previous response while the subject continued to walk. Subjects were not instructed to focus attention specifically on either the walking task or the Stroop test but were told to continue walking while correctly responding to each stimulus. Eight to 10 consecutive trials were completed at each testing session.

The Stroop test has been previously reported to provide information about conflict-resolution abilities by requiring a response to congruent and incongruent configurations, thereby probing executive functions, previously documented to be affected by concussion.6,11,13 Previous studies that have used the auditory Stroop task in dual-task experiments to assess cognitive function while walking have reported significant deficits in accuracy from the time of injury and throughout the 2-month postinjury period.14,16

A set of 29 retroreflective markers were placed on bony landmarks of the subject,10 and whole-body motion analysis was performed by use of a 10-camera motion analysis system (Motion Analysis Corp) at a sampling rate of 60 Hz to capture and reconstruct the 3-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8 Hz. Whole body center-of-mass (COM) position data were then calculated as the weighted sum of all body segments, with 13 segments representing the whole body.

**Dependent Variables**

The dependent variables for this study were derived from previous research, which identified dynamic balance control indicators from COM movement during walking in elderly individuals,10 those suffering from traumatic brain injury,2 young adults with concussion,20 and adolescents with concussion.24,16,14 For each trial, motion data were analyzed for 1 gait cycle, defined as heel strike to heel strike of the same limb. The balance control variables included total medial-lateral COM displacement and the peak instantaneous COM velocity in the medial-lateral and anterior directions. The medial-lateral and anterior linear COM velocities were calculated by use of the cross-validated spline algorithm from COM positions,29 and the peak velocities in both directions were identified.

Correct and incorrect responses on the Stroop test were also obtained during data collection. Accuracy was then calculated as the total number of correct responses by the total trials completed during each testing session for each subject.

Clinical symptoms were assessed at each laboratory visit by use of a 22-symptom inventory adapted from the Standardized Concussion Assessment Tool (version 2).23 Subjects ranked each symptom on a Likert scale from 0 to 6, resulting in a range of scores from 0 (not experiencing any symptoms) to 132 (maximum severity on all symptoms).

**Statistical Analysis**

Demographic data were analyzed by 1-way analyses of variance. Each dependent variable (total medial-lateral COM displacement, peak medial-lateral COM velocity, peak anterior COM velocity, and clinical symptom severity) was evaluated (1) to determine whether differences existed between groups within 72 hours after injury and (2) to examine how each group performed across the 2 months after injury. Within 72 hours after injury, data were analyzed via 1-way analyses of variance to determine differences between adolescent and young adult groups. Data related to performance across the 2 months after injury were analyzed via 2-way mixed-effects analyses of variance to determine the effect of group, time, and the interactions between these independent variables. For all omnibus tests, significance was set at \( P < .05 \). Follow-up pairwise comparisons, performed with the Bonferroni procedure to control family-wise type I error, were conducted to compare groups of the same age (young adult concussion vs young adult control; adolescent concussion vs adolescent control) and concussion and healthy groups (young adult concussion vs adolescent concussion; young adult control vs adolescent control). Effect size estimations for mean differences are reported as eta-squared (\( \eta^2 \)) or partial eta-squared (\( \eta_p^2 \)) values. All statistical analyses were performed with SPSS version 20 (SPSS Inc).

**RESULTS**

**Subjects**

Thirty-eight individuals who sustained a concussion and 38 individually matched control subjects completed the study protocol. Of the 38 subjects in the concussion group, 19 were young adults (age range, 18-27 years) and 19 were adolescents (age range, 14-17 years) (Table 1). All adolescents were injured during sport participation (15 football, 3 soccer, 1 volleyball), whereas not all young adults were injured as a result of sport participation (4 rugby, 2 soccer, 1 basketball, 1 wrestling, 1 snowboarding) (Table 1). No significant differences were detected for body height or mass. Concussion subjects were assessed at a mean \( \pm \) SD of 2 \( \pm \) 0.7, 8 \( \pm \) 1.8, 17 \( \pm \) 3.1, 30 \( \pm \) 3.6, and 58 \( \pm \) 4.3 days after injury. Control subjects underwent an initial assessment and then were assessed at 8 \( \pm \) 1.7, 16 \( \pm \) 3.6, 30 \( \pm \) 3.4, and 58 \( \pm \) 6.7 days after initial assessment. No subject reported sustaining a concussion during the testing period. No attrition occurred among the 76 subjects in the study.

**Center-of-Mass Movement**

The 72-hour postinjury results for total COM medial-lateral displacement indicated a significant main effect of group (\( F_{3,70} = 4.77 \), \( P = .004 \), \( \eta^2 = .125 \)) (Figure 1A). Follow-up comparisons revealed that adolescent concussion subjects walked with significantly greater total COM medial-lateral displacement than did adolescent controls (\( P = .001 \)), while no significant difference was observed...
between the young adult groups \( (P = .149) \). The results across the 2 months after injury revealed a significant main effect of group for total COM medial-lateral displacement during dual-task walking \( (F_{3,75} = 5.26, P = .002, \eta_p^2 = .182) \) (Figure 1). The adolescent concussion group demonstrated significantly more total COM medial-lateral displacement than did the adolescent control group throughout the 2 months of testing \( (P = .001) \), while the difference between young adult concussion and control groups approached but did not achieve significance throughout the same time period \( (P = .07) \). No differences were detected between concussion groups or between control groups.

At 72 hours after injury, peak COM medial-lateral velocity analysis revealed a main effect of group \( (F_{3,75} = 8.36, P = .001, \eta^2 = .221) \) (Figure 2A). The adolescent concussion group walked with significantly greater peak COM medial-lateral velocity than did adolescent controls \( (P < .001) \), while young adult concussion and control groups were not significantly different. Analysis for peak COM medial-lateral velocity across the 2 months of testing revealed a significant time \( \times \) group interaction \( (F_{12,284} = 2.20, P = .012, \eta_p^2 = .085) \) (Figure 2). The adolescent concussion group displayed greater peak COM medial-lateral velocity than did adolescent controls at the 2-month testing time point only \( (P = .004) \). Significant differences were not detected between young adult concussion and control groups, between concussion groups, or between control groups.

Peak COM anterior velocity analysis revealed a main effect of group at 72 hours after injury \( (F_{3,75} = 8.36, P = .001, \eta^2 = .220) \) (Figure 3A). The young adult concussion group walked with significantly less peak COM anterior velocity than did its corresponding control group \( (P = .01) \), while the adolescent concussion group did not significantly

### TABLE 1

Demographic Data for Each Subject Group

<table>
<thead>
<tr>
<th>Group</th>
<th>Sex, n</th>
<th>Age, y, Mean ± SD (Range)</th>
<th>Height, cm, Mean ± SD</th>
<th>Mass, kg, Mean ± SD</th>
<th>Mechanism of Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young adult concussion</td>
<td>10 F, 9 M</td>
<td>20.3 ± 2.4 (18-27)</td>
<td>171.5 ± 9.5</td>
<td>71.8 ± 15.4</td>
<td>Activities of daily living: 5 Bike accident: 4 Sport (head–opponent): 4 Sport (ball–head): 3 Sport (head–ground): 2 Motor vehicle accident: 1</td>
</tr>
<tr>
<td>Young adult control</td>
<td>10 F, 9 M</td>
<td>20.4 ± 2.1 (18-26)</td>
<td>171.4 ± 9.7</td>
<td>71.1 ± 11.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Adolescent concussion</td>
<td>2 F, 17 M</td>
<td>15.1 ± 1.1 (14-17)</td>
<td>173.9 ± 6.5</td>
<td>74.2 ± 16.9</td>
<td>Sport (head–head): 14 Sport (head–ground): 3 Sport (head–opponent): 2</td>
</tr>
<tr>
<td>Adolescent control</td>
<td>2 F, 17 M</td>
<td>15.6 ± 1.1 (14-17)</td>
<td>172.9 ± 8.1</td>
<td>68.8 ± 11.1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\( ^a \)Values are presented as mean ± SD unless otherwise indicated. F, females; M, males; N/A, not applicable.

**Figure 1.** Mean ± SE total center-of-mass (COM) medial-lateral displacement for (A) the initial assessment within 72 hours of injury for the 4 groups of subjects and (B) performance by all 4 groups examined across 2 months of postinjury testing. *Significant difference between adolescent concussion and control groups.
differ from its corresponding control group ($P = .03$). The results for peak COM anterior velocity across the 2 months of testing indicated a significant time $\times$ group interaction ($F_{12,284} = 2.05, P = .038, \eta^2_p = .080$) (Figure 3). However, no significant follow-up comparisons were detected between groups or across time.

Symptom Severity Inventory

Within 72 hours of injury, a main effect of group was found for self-reported symptom severity ($F_{3,75} = 26.11, P < .001, \eta^2_p = .521$) (Figure 4A). Young adult and adolescent concussion subjects reported significantly more symptoms than did their respective controls ($P < .001$). Symptom severity analysis across the 2 months of testing indicated a significant time $\times$ group interaction ($F_{12,284} = 8.59, P < .001, \eta^2_p = .266$) (Figure 4), as the adolescent concussion group reported significantly greater symptom severity than did adolescent controls at the 1-week ($P < .001$) and 2-week ($P = .002$) time points, but significant differences were no longer observed at the 1-month or 2-month time points. The young adult concussion group reported significantly greater symptom severity than did the young adult control group at 1 week after injury ($P < .001$), but differences were no longer significant throughout the rest of the testing period. No differences were detected between concussion groups or between control groups.

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**Figure 2.** Mean ± SE peak center-of-mass (COM) medial-lateral velocity for (A) the initial assessment within 72 hours of injury for the 4 groups of subjects and (B) performance by all 4 groups examined across 2 months of postinjury testing. *Significant difference between adolescent concussion and control groups.

**Figure 3.** Mean ± SE peak center-of-mass (COM) anterior velocity for (A) the initial assessment within 72 hours of injury for the 4 groups of subjects and (B) performance by all 4 groups examined across 2 months of postinjury testing. †Significant difference between young adult concussion and control groups.
Stroop Test Accuracy

Stroop test accuracy data indicated no main effect of group within 72 hours of injury ($P = .069$) (Table 2). Across the subsequent 2 months of testing, Stroop test accuracy data revealed a main effect of group ($F_{3,75} = 4.73, P = .005, \eta^2 = .168$) (Table 2). Follow-up comparisons revealed that the adolescent concussion group displayed less Stroop test accuracy than did adolescent controls ($P = .005$) throughout the 2 months of testing. Significant differences were not detected between young adult concussion and control groups or between control groups.

DISCUSSION

The study data revealed that initially after injury and throughout the 2-month postinjury period, adolescents with concussion displayed greater total COM medial-lateral displacement during dual-task walking compared with their controls than did the young adults with concussion compared with their controls. As no previous work has directly compared age-related gait balance control deficits after concussion, the results suggest that adolescents with concussion may have greater difficulty controlling medial-lateral COM movement during divided attention walking than do young adults with concussion, supporting the recommendation that adolescents require a more cautious management plan than adults following a concussion.\textsuperscript{12,22,25}

Rather than the younger brain being more “plastic” and thus better able to recover from injury than an adult brain,\textsuperscript{1} younger individuals who sustain head trauma may actually be more vulnerable than adults to the effects of head injury.\textsuperscript{1,25} Previous age group recovery time differences after concussion have been documented through neuropsychological testing outcomes, suggesting that high school athletes required a longer recovery than do college athletes.\textsuperscript{8} Memory impairments for high school athletes have also been reported to last longer than for collegiate athletes after concussion,\textsuperscript{7} and adolescents have previously been shown to display electrophysiological impairments for a longer duration of time than do pediatric or young adult age groups after a concussion.\textsuperscript{9}

TABLE 2

<table>
<thead>
<tr>
<th>Group</th>
<th>Time After Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>72 Hours</td>
</tr>
<tr>
<td>Young adult concussion</td>
<td>94.1 ± 13.0</td>
</tr>
<tr>
<td>Young adult control</td>
<td>99.2 ± 1.7</td>
</tr>
<tr>
<td>Adolescent concussion</td>
<td>97.6 ± 2.8</td>
</tr>
<tr>
<td>Adolescent control</td>
<td>99.2 ± 1.3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Values are presented as mean ± SD percentages.

\textsuperscript{b}Main effect of this group was significantly less than that of the adolescent control group across the 2 months of testing ($P = .005$).
The current study data revealed that medial-lateral COM motion control during dual-task walking was affected by concussion throughout the 2 months of testing for adolescents, suggesting a decreased ability to control balance while walking. These medial-lateral COM displacement data suggest that a postinjury period longer than 2 months may be necessary for some adolescents to recover dual-task gait balance control. While total COM medial-lateral displacement differences between young adult concussion and control groups did not achieve significance in the current study, dual-task gait stability impairments for up to 4 weeks after injury have previously been reported in a cohort of collegiate athletes after concussion while subjects walked and simultaneously completed a mental status examination rather than a continuous auditory Stroop task. This is an important methodological difference, as recent evidence suggests that cognitive task complexity during dual-task walking differentially affects gait stability after concussion. Since the secondary task used in the current study has been identified as a less complex task than a mental status examination, it may not have provided the necessary complexity to detect deficits between healthy and injured young adult groups.

Consistent with previous work, current study data identified that young adults with concussion displayed significantly smaller peak COM anterior velocity compared with control subjects within 72 hours of injury. Smaller peak forward velocity may be indicative of a reduction of attentional resources due to concussion, potentially resulting in a reduced ability to control forward momentum to accommodate the increased attentional demand imposed by the dual-task condition.

Prior work reported that adolescents with concussion display memory deficit variability during the week after injury, suggesting that recovery may not always occur linearly across time. In the current study, adolescents with concussion displayed a significantly greater medial-lateral peak velocity compared with controls within 72 hours after injury and again 2 months after injury. A regression of gait stability recovery has been identified in young adults after the return to preinjury physical activities after concussion, supporting the observation of a nonlinear recovery phenomenon. Further, a recent study reported that after clearance to return to physical activities following a concussion, adolescents displayed an increased medial-lateral COM displacement and velocity relative to before clearance, suggesting a recovery regression after returning to physical activities. In the current study, the mean return-to-activity timeframe for the adolescents, who returned within 2 months after injury, was 24 ± 14 days after injury. Hence, returning to physical activities may have influenced recovery and possibly may have contributed to the significant difference observed between adolescent concussion and control groups at 2 months after injury.

A recent comparison between adolescent and young adult age groups revealed no age-related differences on postconcussion symptom severity scores. In contrast, the current study data indicate that adolescents with concussion had significantly greater symptom severity than matched controls for up to 1 month after injury, while young adults with concussion displayed differences from controls only up to 2 weeks after injury. This finding may be explained, in part, by prior work suggesting that a protracted state of physiologic abnormalities that lead to symptom generation after concussion may exist for a longer duration of time in adolescent-aged individuals than in adults and may result in a longer time duration required for symptom resolution.

A greater variability in Stroop test accuracy observed within the young adult concussion group may have contributed to the lack of a significant difference between groups at 72 hours after injury. Two young adult participants with concussion performed at an accuracy rate of 57% and 58%, respectively, during this initial testing session but performed at a rate more closely approximated to the group mean at each point thereafter. The adolescent concussion group performed significantly less accurately on the Stroop test while walking in comparison with matched controls across the 2 months of testing, potentially further indicating deficits for the adolescent concussion group across both motor and cognitive domains, particularly when performed simultaneously.

While each study participant with concussion was diagnosed by a health care professional, the management recommendations may have varied between health care providers. While the role that management recommendations may play in concussion recovery is unknown, a consistent definition of concussion was used in the prospective identification of all subjects in this study. Future studies should measure dual-task gait balance control recovery beyond 2 months after injury to further identify the extent to which these deficits are present.

In conclusion, by assessing dynamic balance control during dual-task walking, we observed that adolescents demonstrated greater difficulty controlling their frontal plane COM movement throughout the 2 months after injury compared with their age-matched controls than did young adults who completed the same testing protocol. These data support the view that adolescents may be particularly sensitive to the balance control effects of concussion and may require a more cautious postinjury management approach.

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REFERENCES


