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The effect of divided attention on gait stability following concussion

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Abstract

Background. The need to identify functional impairment following a brain injury is critical to prevent re-injury during the period of recovery. While many neuropsychological tests have been developed to assess cognitive performance, relatively little information on gait and dynamic stability is available on motor task performance for young adults following concussion. This study was performed to investigate the effect of divided attention following concussion on various gait variables. It was hypothesized that, when compared to uninjured controls, concussed subjects would demonstrate deficits in maintenance of dynamic stability.

Methods. Ten subjects with Grade 2 concussion completed testing within 48 h of injury as well as 10 age-, height-, weight-, and activity-matched controls. The gait protocol consisted of level walking under two conditions: (1) undivided attention (single-task) and (2) while simultaneously completing simple mental tasks (dual-task). Whole-body motion data were collected using a six-camera motion analysis system. A 13-segment biomechanical model was used to compute whole body center of mass motion and velocity.

Findings. Walking with a concurrent cognitive task resulted in significant changes in gait and center of mass measurements for both groups. Concussed subjects were found to be able to conservatively adjust their whole body center of mass motion to maintain dynamic stability while walking without divided attention. However, while walking with divided attention, subjects with concussion demonstrated a significantly greater medio-lateral center of mass sway.

Interpretation. These data suggest that the ability to control and maintain stability in the frontal plane during walking is diminished under divided attention in individuals following a concussion.

Keywords: Traumatic brain injury; Center of mass; Gait; Balance

1. Introduction

The brain is a highly complex organ that coordinates all functions of the body from intelligence and consciousness to automatic responses such as breathing and circulation. Injuries to the brain, such as concussion, and the resulting symptoms have been recognized since the 16th century (Maroon et al., 2000). Difficulties in definition, recognition, and assessment of concussion have made epidemiological study difficult. However, the yearly incidence of football-related concussions was estimated at 40,000 in 1.1 million high school football players, or 3.6% (Powell and Barber-Foss, 1999). In a study of 141 high school and college football players followed for two years (McCrea et al., 1997), 4.3% experienced mild traumatic brain injury (MTBI). While the high impact nature of football lends itself to high incidences of concussion, the potential for injury to the brain is present in all sports.

According to the Centers for Disease Control and Prevention (1999) it is estimated that 5.3 million Americans live with disabilities associated with traumatic brain injury (TBI) at a cost of $56.3 billion annually. Many of these injuries fall under the category of MTBI (Bailes and Hudson, 2001). While no injury to the brain should be considered minor (Cantu, 1997) there is a

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prevailing notion that one concussion results in little permanent neurological damage (Maroon et al., 2000). However, rate of recovery, even from a single concussion, is highly individual, and standardized recovery curves are not readily available to physicians and certified athletic trainers to make objective return-to-play decisions (McCrory et al., 2000). Given the potentially serious consequences of concussions, the need to identify functional impairment following a brain injury is critical to prevent re-injury during the period of recovery. While many neuropsychological tests have been developed to assess cognitive performance (Wojtys et al., 1999), relatively little information is available on dynamic motor task performance following concussion. Some patients report symptoms long after the injury even though their cognitive deficits are small (Alves et al., 1986).

Most biomechanical studies on MTBI to date have largely been limited to postural sway during quiet standing or during standing with altered sensory inputs (Geurts et al., 1996; Geurts et al., 1999; Guskiewicz et al., 1996; Ingersoll and Armstrong, 1992; Lahat et al., 1996; Lehmann et al., 1990; Rubin et al., 1995; Wade et al., 1997; Wober et al., 1993). Guskiewicz et al. (1996) concluded that participants with MTBI demonstrated impaired postural stability for one to three days following injury. Guskiewicz et al. (2001) also reported no relationship between symptoms, performance on tests of cognitive function, and static postural stability. The data suggested that recovery of motor function, as demonstrated by static postural control following MTBI, might be independent of cognitive recovery.

Recent studies have reported effects of moderate to severe TBI on gait and dynamic stability (Basford et al., 2003; McFadyen et al., 2003; Chou et al., 2004). Such post-TBI individuals, even with a normal neurological and musculoskeletal examination, were found to walk with increased caution, demonstrating a significantly slower walking speed and shorter stride length. Compared to matched controls, patients with TBI also displayed a significantly greater and faster medio-lateral center of mass (CoM) motion, which has been demonstrated to be a sensitive measure of dynamic stability (Basford et al., 2003; Chou et al., 2004). However, most of the participants included in these studies suffered a moderate to severe TBI (initial Glasgow Coma Scale $\leqslant$ 12) and complained of instability during gait at the time of testing (duration of injury: 2–22 months). Similar information on gait and dynamic stability is currently not available for young adults following a concussion.

Maintenance of balance and limb coordination during locomotion or sport activities requires a complex interaction of sensory input and motor output. Sensory systems monitor the location of the whole body CoM relative to the foot-ground center of pressure (CoP), provide orientation in space, and monitor the environment. Motor systems provide appropriate coordinated muscular activation and force generation. When the brain is engaged the effect is synchronized movement. This dynamic interaction is vividly portrayed in athletics. But when a person is required to perform synchronized movement with divided attention, the effect is not as well understood. Previous studies have found that attentional demands increase as physical requirements increase. Lajoie et al. (1993) found that response time to an auditory stimulus were shortest when physical demands were less (sitting) and increased as the task demands increased (standing and walking). They also found that the response times were greater in the more unstable single-stance phase of gait compared to double-stance. It has been reported further that divided attention reduced obstacle avoidance performance while walking (Weerdesteyn et al., 2003). Ebersbach et al. (1995) also demonstrated that mean digit recall was greater during quiet stance than during walking. However, to date little is known about the effect of divided attention on gait in persons with recent brain injury.

A functionally challenging dual task, such as varying conditions of mental concentration while walking, may prove to be related to post-concussion status and provide more pertinent information regarding the optimal time for return to play. The overall goal of this study was to determine the effect of divided attention on balance control during gait in persons who have recently suffered a concussion. It was hypothesized that, when compared to uninjured controls, concussed subjects would demonstrate deficits in maintenance of dynamic stability, as indicated by an increased frontal plane CoM motion, while performing a concurrent cognitive task during walking.

2. Methods

Twenty college-aged volunteers served as subjects for this study. The subject groups consisted of ten college-aged men and women who had sustained a concussion (CONC) and ten uninjured controls (NORM). Each CONC subject was matched to a NORM subject by age, height, weight, and physical activity profile. All participants were involved in intercollegiate, club, intramural sports, or recreational activities. All CONCs sustained a Grade 2 concussion as defined by the American Academy of Neurology Practice Parameter (American Academy of Neurology, 1997; Table 1). CONC participants were initially identified by Certified Athletic Trainers and attending medical doctors in the university intercollegiate athletic program and the student health center, and were referred for testing as soon as possible following the concussion. None of the NORM subjects had a history of neurological diseases, visual impairment

Table 1
American academy of neurology practice parameter (1997)

Grade	Description
1	Transient confusion No loss of consciousness Concussion symptoms or mental status changes resolve within 1 min
2	Transient confusion No loss of consciousness Concussion symptoms or mental status changes last longer than 15 min
3	Loss of consciousness either brief or prolonged

not correctable with lenses, musculoskeletal impairments, or persistent symptoms of vertigo, lightheadedness, unsteadiness, or falling. Nine of the ten NORM subjects had no history of traumatic brain injury. One NORM subject suffered a grade 1 or grade 2 concussion more than 3.5 yr prior to testing but with no lasting effects. The experimental protocol was approved by the Institutional Review Board of the University. The experimental procedures were explained to all subjects prior to testing and verbal and written consents were obtained.

The gait protocol consisted of level walking with no obstructions and was performed by each subject under two conditions: (1) with undivided attention (single-task) and (2) while simultaneously completing simple mental tasks (dual-task). These tasks consisted of spelling 5-letter words in reverse, subtraction by sevens, and reciting the months of the year in reverse order (Bell and Hall, 1977). These tasks are frequently used in mental status examinations to assess attention and concentration. The type of dual-task was randomly selected for each walking trial to avoid any learning effects, and each type of dual-task was completed by each subject. All dual-task walking trials were conducted in the same manner with verbal instructions given just prior to the command to begin walking. The subject then responded to the task throughout the walking trial. Each testing session began with five trials of single-task walking followed by the dual-task condition. The participants were instructed to walk down a 10 m walkway at a comfortable self-selected walking speed. In order to avoid any shoe type differences, all subjects were tested while barefoot.

In order to assess gait variables a set of 25 reflective markers were placed on bony landmarks of the participant. Fifteen markers were used to define the foot, leg, and thigh segments of both lower extremities. These markers were placed on the following anatomic landmarks: between the 2nd and 3rd metatarsals (dorsal), the posterior calcaneus, the lateral malleoli, the lateral femoral epicondyles, the lateral distal tibia and thigh, and both anterior superior iliac spines, and the sacrum. Nine markers defined the head, arm, and trunk segments. These markers were placed on the wrists, lateral epicondyles of the humerus, acromioclavicular joints of the shoulder, just anterior to each ear, and the top of the head. One additional marker was placed on the right scapula for tracking purpose. A six-camera Expert-Vision^{TM} HIRES system (Motion Analysis Corporation, Santa Rosa, CA, USA) was used to capture and reconstruct the 3-dimensional trajectory of the surface markers. Three-dimensional marker trajectory data were collected at 60 Hz and low-pass filtered using a fourth-order Butterworth filter with the cutoff frequency set at 8 Hz. Virtual marker positions were estimated using EVa software (Version 6.0, Motion Analysis Corporation) to represent internal segment endpoints from the external markers, and the relative positions of the segmental CoM. External markers and estimated joint centers were used to calculate the three-dimensional motion for individual body segments and locations of segmental CoM. Anthropometric reference data were adapted from Dempster (Winter, 1990) for both age groups and genders. Whole body CoM position data were calculated as the weighted sum of each body segment, with 13 segments representing the whole body (head–neck, trunk, pelvis, upper and lower arms, upper and lower legs, feet). Velocities and accelerations of the CoM were estimated using the generalized cross-validated spline algorithm (Woltring, 1986). The motion analysis system was calibrated before each session [volume = 4 m long, 1.5 m wide, 2 m high]. In order to compute the CoP, ground reaction forces were collected by two force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) positioned in series along the gait path and sampled at a frequency of 960 Hz. Motion data were analyzed from heel strike of the trailing limb as it struck the first force plate to the next heel strike of that same limb. OrthoTrak 4.0 (Motion Analysis Corporation) was used in the calculation of temporal–distance parameters.

Temporal–distance parameters included gait velocity, stride length, stride time, and step width. Three-dimensional ranges-of-motion (RoM) of the CoM were monitored in the anterior–posterior (APRoM) and medio-lateral (MLRoM) directions. Other variables included maximum instantaneous linear velocities of the CoM in the anterior–posterior (APVEL) and medio-lateral (MLVEL) directions, and maximum separation between the CoM and CoP of the supporting foot in the anterior–posterior (APMAX) and medio-lateral (MLMAX) directions (Chou et al., 2003, 2004). The effects of group (CONC vs. NORM) and task (single vs. dual) on these variables were examined. Repeated measures (2×2) mixed design analyses of variance (ANOVAs) and Tukey *post hoc* tests, where appropriate, were computed to determine whether differences ($P < 0.05$) existed between groups and tasks for each variable.

Table 2
Subject demographics; group mean (standard deviation)

Characteristic	CONC	NORM	*t*-test
Age (*y*)	20.20 (1.70)	19.90 (1.90)	$P = 0.83$
Height (m)	1.85 (0.12)	1.78 (0.09)	$P = 0.96$
Weight (kg)	84.20 (20.10)	83.40 (25.30)	$P = 0.44$
Gender (men/women)	4/6	4/6	
Mean time from injury to testing (h)	37.60 (12.80)	NA	

3. Results

No significant differences in anthropometric data were observed between the two subject groups (independent-samples *t*-test: Age $P = 0.83$; height $P = 0.96$; weight $P = 0.44$; Table 2). Testing commenced within 48 h after injury for all subjects with concussion with the exception of one subject who began testing at 50 h post-concussion.

During the dual-task condition both groups displayed a gait pattern with a significantly slower gait velocity (GV; $P < 0.001$), shorter stride length (SL; $P < 0.001$), and longer stride time ($P = 0.001$) than during the single-task condition (Table 3). The concussion group adopted a significantly shorter stride length ($P = 0.042$) and demonstrated a slower, but not significant, gait velocity ($P = 0.066$) than the matched controls. There were no significant group or task effects for step width.

The RoM of the CoM in the anterior-posterior direction (APRoM) was significantly smaller ($P < 0.001$) during the dual-task when compared to the single-task condition for both subject groups (Table 4). Similar to the gait velocity, subjects in the CONC group demonstrated a smaller, but not significant, APRoM ($P = 0.078$) than their matched controls. The instantaneous anterior velocity of the CoM reached its peak during the double stance phase. This peak anterior velocity of the CoM (APVEL) was found to be significantly smaller in the dual when compared to single-task condition ($P < 0.001$) for both subject groups (Table 4). Furthermore, when compared to controls, the APVEL was significantly slower in the concussion group ($P = 0.041$). The maximum AP separation distance between the CoM and CoP (APMAX) occurred at heel contact. Both groups maintained a significantly smaller APMAX during the dual-task when compared to the single-task condition ($P = 0.003$; Table 4).

A significant group by task interaction ($P = 0.021$) was detected for the RoM of the CoM in the medio-lateral direction (MLRoM; Fig. 1). Tukey's multiple comparisons revealed that only the CONC group was significantly affected by the task condition. The MLRoM of the CONC group was found to be signifi-

Table 3
Means and standard deviations for NORM and CONC groups in single and dual-task conditions for gait variables

Variable	NORM		CONC	
	Single	Dual	Single	Dual
Gait velocity (m/s)	1.324 (0.131)	1.219 (0.111)*	1.250 (0.122)	1.097 (0.113)*
Step width (m)	0.103 (0.029)	0.113 (0.018)	0.091 (0.037)	0.097 (0.047)
Stride length (m)	1.389 (0.088)	1.332 (0.078)*	1.335 (0.098)†	1.228 (0.083)*,†
Stride time (s)	1.054 (0.072)	1.100 (0.081)**	1.072 (0.069)	1.133 (0.117)**

* Significantly less than single-task.
** Significantly greater than single-task.
† Significantly less than NORM group.

Table 4
Means and standard deviations for NORM and CONC groups in single and dual-task conditions for CoM and CoP variables

Variable	NORM		CONC	
	Single	Dual	Single	Dual
APRoM (m)	1.396 (0.087)	1.338 (0.080)*	1.339 (0.097)	1.248 (0.112)*
APVEL (m/s)	1.455 (0.147)	1.352 (0.130)*	1.361 (0.112)†	1.207 (0.136)*,†
APMAX (m)	0.234 (0.028)	0.220 (0.023)*	0.219 (0.023)	0.203 (0.026)*
MLRoM (m)	0.037 (0.004)	0.037 (0.008)	0.031 (0.006)†	0.043 (0.012)**,‡
MLVEL (m/s)	0.122 (0.011)	0.140 (0.020)**	0.110 (0.020)	0.133 (0.028)**
MLMAX (m)	0.070 (0.021)	0.079 (0.028)	0.062 (0.014)	0.067 (0.016)

* Significantly less than single-task.
** Significantly greater than single-task.
‡ Significantly greater than NORM group.
† Significantly less than NORM group.

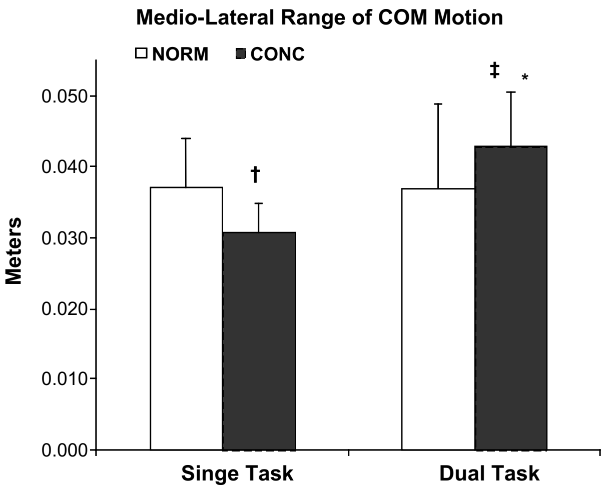

Fig. 1. Group means for the CoM range of motion in the medio-lateral direction measured during a gait cycle in both single and dual conditions for normal (NORM) and concussion (CONC) subjects. *Dual > Single, †CONC < NORM, ‡CONC > NORM.

cantly smaller during the single-task but significantly greater during the dual-task condition when compared to the NORM group. Compared to the single-task condition, subjects in both groups walked with a significantly greater medio-lateral CoM sway velocity (MLVEL) than in the dual-task condition ($P < 0.001$; Table 4). No significant group effects were detected for the MLVEL. Neither subject group nor task condition had a significant effect on the maximum medio-lateral separation distance between the CoM and CoP (Table 4).

4. Discussion

The purpose of this study was to determine how a concussion affects dynamic balance under conditions of divided and undivided attention soon after the occurrence of injury. It was hypothesized that concussed individuals would demonstrate less stability while performing a concurrent cognitive task during walking than uninjured normal controls. Results from this study revealed that concussed subjects had to conservatively adjust their whole body CoM motion to maintain dynamic stability when walking without divided attention. They accomplished this with a significantly slower instantaneous forward velocity and a significantly smaller medio-lateral sway. While walking with a concurrent cognitive task resulted in significant changes in gait and CoM measurements for both groups, subjects with concussion demonstrated a significantly greater medio-lateral CoM sway, which may reflect deficits in their management of dual tasks resulting from brain injury.

Gait temporal–distance parameters of this study are consistent, in part, with previous investigations (Basford et al., 2003; McFadyen et al., 2003; Chou et al., 2004) reporting significantly smaller stride lengths in individuals who had suffered major traumatic brain injury. Differences in the severity of injury between subjects included in this study (classified as mild TBI) and others (classified as moderate to severe TBI) might explain our detection of a slower but not significant gait velocity. However, the current findings suggest a similarity in some gait variables among individuals who sustained major head trauma with unresolved symptoms, and individuals with less severe, acute head injuries. Wade et al. (1997) found that individuals with a severe brain injury undergoing rehabilitation walked with a mean gait velocity of 1.17 m/s and a stride length of 1.32 m. In the present study, concussion subjects walked faster (1.25 m/s) and with a longer stride length (1.34 m) during the single-task condition. However, during the more challenging dual-task condition the concussion subjects' gait velocity and stride length decreased to 1.10 m/s and 1.23 m respectively, below those reported by Wade et al. (1997) for severely brain injured subjects. This suggests that the addition of a secondary task may compromise gait performance in subjects with a less than severe brain injury.

The observed significant reductions in the sagittal plane CoM motion suggest an adoption of a conservative approach when walking with divided attention. Pai and Patton (1997) defined the concept of a "feasible stability region" as the range of the CoM instantaneous velocity and its allowable distance from the base of support within which dynamic balance could be properly maintained. Reducing the peak instantaneous anterior velocity and CoM–CoP separation distance might reflect decreases in this feasible stability region. Even during the single-task condition, subjects with concussion were found to walk with a significantly slower peak instantaneous anterior velocity than their matched controls. It is possible that recently concussed individuals might have a reduced ability to properly control their forward motion. As a result, the forward velocity and motion are decreased to maintain steadiness within the feasible stability region.

It is interesting to note that during the single-task condition, the CONC group was found to walk with a significantly smaller CoM medio-lateral sway. This could be explained that after suffering a concussion individuals have a reduction in their allowable range of medio-lateral CoM sway within which the balance control system would be least perturbed. While walking without a divided attention, concussed individuals were found to be able to conservatively confine their frontal plane CoM motion to avoid imbalance. However, they were unable to maintain this strategy when their attention was divided. The NORM group displayed no between-task differences for this variable while the CONC group averaged 42% more medio-lateral sway in the dual-task condition. Given that a significantly greater medio-lateral CoM sway was observed in individuals having complaints of imbalance during walking (Hahn and Chou, 2003; Basford et al., 2003; Chou et al., 2004), the current data could suggest that the ability to control and maintain stability in the frontal plane during walking is diminished in the CONC group under divided attention.

For the CONC group in the present study, the demand on attention during walking was significant enough to be discernable during the single-task condition. This demand was even more evident during the dual-task condition. One possible explanation for this finding may be derived from theories of attention and capacity interference. Attention is a finite commodity and any tasks that require attention compete for this limited capacity (Weerdesteyn et al., 2003). If capacity is exceeded, performance on one or more of the tasks will be diminished. A mild brain injury may decrease attentional capacity (Ebersbach et al., 1995). The dual-task condition possibly required more than the available capacity and, as a result, gait stability was compromised. The control group also showed a decrease in gait performance during the dual-task, but the concussion group was affected to a greater degree. This further suggests that brain injury may have an effect on attentional capacity.

The decision of when to return an athlete to competition can be difficult and complex. The demands of sport require athletes to be able to "think on their feet" in order to be successful and avoid injury. The demands of performing a dynamic motor task combined with a mental activity that divides attention may effectively approximate the demands to an athlete in competition. However, if the concussed individuals have difficulty maintaining medio-lateral stability in a controlled environment they may well have difficulty adjusting to the multiple input environment of the athletic arena within 48 h of injury. In conclusion, the findings of this study demonstrate that concussion has an observable and measurable effect on the body's ability to maintain and control dynamic stability. However, this study does not resolve the issue of how long the pattern of altered gait dynamics continues among victims of concussion. Further research is needed to address this question and to determine how concussion affects more complex gait maneuvers, such as negotiating obstacles, under varying external demands.

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