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Altered balance control following concussion is better detected with an attention test during gait

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Abstract

The purpose of this study was to examine the effects of concussion on gait stability when either a cognitive or motor perturbation is imposed. Fourteen individuals suffering from a grade II concussion and 14 matched controls performed a single task of level walking, a continuous sequential question and answer task while walking, and an obstacle-crossing task. Common gait spatial/temporal measurements, whole-body center of mass motion, and center of pressure trajectory were assessed. Concussed individuals adopted a more conservative strategy to maintain gait stability. Some measurements indicating conservative gait were seen during obstacle crossing, but this was most evident during the Q&A task. Concussed individuals also displayed signs of possible instability during the Q&A task. The question and answer task was most sensitive to distinguishing concussed individuals from healthy individuals, supporting the use of a similar dual-task modality in future testing after concussion to determine a proper time for return to activity.

Keywords: Concussion; Cognition; Secondary task; Attention; Gait

1. Introduction

Each individual case of concussion is susceptible to a wide range of immediate mental deterioration: from brief wooziness to loss of consciousness. The first concussive incident is the source of many cognitive and motor deficits, but multiple concussions have been determined to be a greater source of more permanent damage, with the degree of damage based on a temporal relationship to the first concussion [1].

The concussive pathway (Fig. 1) begins with a primary insult that causes the first concussion, leading to increased neurological susceptibility to a second concussion [2]. Motor deficits reported after a concussion include reduced strength, uncoordinated movement and imbalance [3]. Imbalance particularly, can lead directly to another concussive incident. Cognitive deficits following concussion include an inability to concentrate, reduced memory, and poor judgment [3]. If a component of a multi-task situation happens to rely on stability, then attentional deficits have a greater possibility of leading to subsequent concussions. This proposed model suggests that permanent brain damage resulting from multiple concussions may be more likely to occur due to the combination of each of these pathways. Guskiewicz et al. [4], have found that a person is about three times more likely to sustain a second concussion, as compared to a primary concussion, within a 3-month period. Rest from activity for as long as 2 weeks is currently the most common treatment after a concussion [5]. During this time, measurements of balance and cognitive recovery are occasionally performed (the latter more so than the former), however separately; so task interactions are essentially ignored.

Recently, measurements of center of mass (CoM) trajectory have been found to provide better insight into dynamic balance control mechanisms [6]. Studies on patient populations [7] have demonstrated that measurements derived from CoM and center of pressure (CoP) motion during obstructed gait were able to identify conservative gait adaptations [8] and gait instability [7]. Furthermore, cognitive tests have been incorporated with gait to provide

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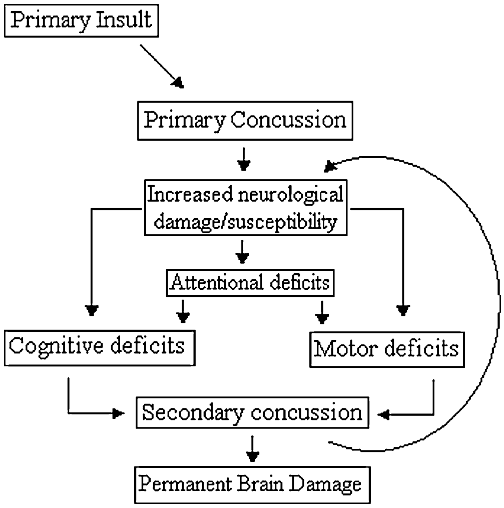

Fig. 1. An outline of the concussive pathway from initial injury to permanent brain damage. One-directional arrows indicate a sequential order of events.

dynamic attentional tests in a dual-task setting for healthy individuals [9]. These tests have been described as most similar to real life scenarios [9].

Researchers have yet to compare gait stability control during a cognitive secondary task and obstacle crossing in a concussed population. The purpose of this study was to compare two previously utilized methods for differentiating concussed from healthy individuals using gait stability measurements. Information acquired from this study will enhance the development of a more sensitive detection of concussion deficits for determining a proper time to return to activity.

2. Methods and materials

2.1. Subjects

Twenty-eight young adults from the University of Oregon participated in this study. Subjects were divided into two groups: 14 subjects suffering from concussion (CONCs) and 14 controls without injury (NORMs). The experimental protocol was approved by the Institutional Review Board. Written and verbal instructions of testing procedures were provided, and written consent was obtained from each subject prior to testing.

CONCs (six females/eight males; age = 22.3 ± 4.5 years; mass = 75.2 ± 15.4 kg; height = 173.4 ± 8.5 cm) were diagnosed with grade II concussions defined by the American Academy of Neurology [10]. A grade II concussion entails transient confusion, and symptoms lasting longer than 15 min, but no loss of consciousness. Exclusion criteria included a prior concussion within the previous year and preexisting injury or surgery that affects normal gait patterns and/or cognitive abilities. NORMs were matched by gender, age (22.3 ± 3.1 years), mass (75.1 ± 16.9 kg), height (172.8 ± 8.5 cm) and level of education. Exclusion criteria of NORMs were the same as exclusion criteria for CONCs, with the additional exclusion criterion of symptoms common after a concussion (e.g. vision problems, nausea, headaches, etc.) [11].

2.2. Experimental apparatus

Three-dimensional marker trajectories were collected with an eight-camera motion system (MotionAnalysis, Santa Rosa, CA). Twenty-nine retroreflective markers were placed bilaterally on bony landmarks of the body [8,12]. Ground reaction forces and moments were collected by two sequential (separated by 25.9 cm) force plates (Advanced Mechanical Technologies Inc., Watertown, MA) located in the center of the walkway.

A PVC pipe crossbar (1/2 in. diameter, 1.3 m long) between the two force plates served as an obstacle during obstacle-crossing trials. It sat atop two adjustable upright standards in such a way that it could easily be dislodged if struck by the subject. The height of the obstacle was set to 10% of each subject's height. The global position of the crossbar was tracked during obstacle trials.

2.3. Experimental protocol

Subjects were asked to perform walking at a comfortable self-selected pace along an 8-m walkway. Several practice trials were allowed so that subjects could become comfortable walking with the markers and the starting location could be adjusted by the proctor to insure that the subjects contact each force plate with the entire foot. This was done without informing subjects of the reason to avoid a conscious effort to contact the force plates.

Data collection began with single-task level walking (LEVEL). Walking with an obstacle-crossing task (OB) was then performed. Finally, a continuous question and answer dual-task situation (Q&A) was performed. Q&A required continuous answers from the beginning throughout the walkway. The cognitive questions included common tests from a clinical mental status examination: spelling a common five-letter word in reverse, continuous subtraction, and reciting the months of the year in reverse [13]. Order and specifics of each task were not shared with subjects prior to testing. Only at the beginning of each trial was a subject given the specific task for that trial.

2.4. Data processing

Data from the force plates were collected at 960 Hz for 4 s. Marker trajectories were sampled at 60 Hz for 4 s and were then filtered with a low-pass, fourth order Butterworth filter at a cutoff frequency of 8 Hz. Virtual markers were created at joint centers and combined with anthropometric data to determine center of mass (CoM) location for each of 13 body segments [14]. Motion data were calculated for one complete stride; heel strike on to the first force plate to heel strike of the same foot after the second force plate. The whole-body CoM was calculated from each segment CoM using a weighted sum method [14]. Velocities were calculated using Woltring's generalized cross-validated spline algorithm [15]. The center of pressure (CoP) was calculated using the measured ground reaction forces and moments.

CoM displacement in the anterior (APdisp) and medial/lateral (MLdisp) directions, and peak velocity in the anterior (APv) and M/L directions (MLv) were examined. CoM data were time synchronized with CoP data to find the maximum horizontal separation distance between the CoM and CoP in both the anterior (APmax) and M/L (MLmax) directions. Instantaneous velocities at the time of maximum CoM–CoP separation were also identified (APVmax and MLVmax, respectively).

Gait velocity, stride length, step width, and stride time were also calculated. Stride length and stride time were determined from the position change of the heel marker and respective time change. Step width was calculated from left to right ankle joint centers at heel strikes. Gait velocity was calculated from the position change of the body CoM and time change during a complete stride.

The number of answers attempted, the number of answers correct and the correct percentage (answer percentage) were all calculated to measure Q&A secondary task performance. Vertical toe-obstacle clearance (TOC) for both of the limbs, the horizontal toe-obstacle distance of the trailing foot (HTO) and the heel-obstacle distance of the leading foot (HHO) were calculated for obstacle-crossing trials. These measurements were determined from the displacement between the markers rather than actual anatomical locations.

2.5. Statistical analysis

Statistical analyses were performed with SPSS 12.0 (SPSS Inc., Chicago, IL). A two-way (two groups, three tasks) ANOVA with repeated measures was used to determine group-by-task interactions for primary (gait) task variables ($p < 0.05$). Group-by-task interactions, main effects between groups and between tasks were examined. Significance between group means ($p < 0.05$) were further analyzed with Tukey's honestly significant difference post hoc analyses to determine within-task differences. Significance between task means ($p < 0.05$) were further analyzed with Bonferroni pairwise comparisons to determine within group differences in tasks. Secondary task variables were examined for group differences with independent sample *t*-tests ($p < 0.05$).

3. Results

3.1. Spatial/temporal gait parameters

No group-by-task interactions were detected for any of the four spatial/temporal gait parameters (Table 1). Gait velocities during all tasks were significantly slower in CONCs compared to NORMs ($p = 0.003$). Both Q&A and OB scenarios elicited slower gait velocities than single-task level walking ($p < 0.001$). CONCs took longer to complete a stride than NORMs during the Q&A task and the OB task ($p = 0.006$). All subjects took longer to complete a stride during obstacle crossing as compared to Q&A ($p < 0.001$) and LEVEL ($p < 0.001$). Stride lengths were approximately 10 cm greater during obstacle crossing compared both other tasks ($p < 0.001$), but there were no group differences. CONCs had a wider step width for the obstacle-crossing task as compared to NORMs ($p = 0.040$), but both groups had similar step widths between tasks.

3.2. Sagittal plane CoM motion

There were no significant group-by-task interactions for CoM motion variables in the sagittal plane (Table 2). APdisp showed no significant group differences. All subjects had a significantly greater APdisp during obstacle crossing compared to LEVEL ($p < 0.001$) and Q&A ($p < 0.001$) and a significantly decreased APdisp during Q&A compared to LEVEL ($p = 0.019$). CONCs displayed significantly slower peak anterior velocities than NORMs for each task ($p = 0.007$). All subjects significantly decreased their APv during the Q&A task compared to LEVEL ($p < 0.001$) and OB ($p < 0.001$). CONCs demonstrated a significantly smaller maximum CoM–CoP separation distance in the anterior direction compared to NORMs during the Q&A task ($p = 0.038$). When compared among tasks, APmax showed

Table 1
Mean values and standard deviations of gait spatial/temporal variables

	CONC			NORM		
	LEVEL	Q&A	OB	LEVEL	Q&A	OB
Gait velocity (m/s)	1.219 (0.137)[a,b]	1.097 (0.166)[b]	1.083 (0.120)[b]	1.361 (0.136)[a]	1.276 (0.133)	1.219 (0.121)
Stride time (s)	1.111 (0.139)	1.189 (0.148)[c]	1.302 (0.099)[c,d]	1.036 (0.062)	1.060 (0.075)	1.208 (0.095)[d]
Stride length (m)	1.312 (0.128)	1.285 (0.125)	1.404 (0.100)[d]	1.404 (0.100)	1.346 (0.109)	1.464 (0.101)[d]
Step width (m)	0.112 (0.028)	0.113 (0.021)	0.121 (0.020)[c]	0.094 (0.035)	0.093 (0.032)	0.096 (0.034)

[a] >Q&A and OB.
[b] <NORM.
[c] >NORM.
[d] >LEVEL and Q&A.

Table 2
Mean values and standard deviations of sagittal plane CoM variables

	CONC			NORM		
	LEVEL	Q&A	OB	LEVEL	Q&A	OB
APdisp (m)	1.322 (0.130)	1.288 (0.126)[a]	1.456 (0.101)[b]	1.409 (0.100)	1.348 (0.105)[a]	1.511 (0.102)[b]
APv (m/s)	1.373 (0.165)[c]	1.234 (0.168)[a,c]	1.352 (0.144)[c]	1.524 (0.157)	1.427 (0.154)[a]	1.499 (0.143)
APmax (m)	0.204 (0.036)	0.189 (0.041)[a,c]	0.258 (0.041)[b]	0.225 (0.022)	0.214 (0.028)[a]	0.279 (0.031)[b]
APVmax (m/s)	1.210 (0.152)[d]	1.070 (0.181)[c]	1.026 (0.125)[c,e]	1.328 (0.142)[d]	1.246 (0.138)	1.167 (0.150)[e]

[a] <LEVEL and OB.
[b] >LEVEL and Q&A.
[c] <NORM.
[d] >Q&A and OB.
[e] <LEVEL and Q&A.

Table 3
Mean values and standard deviations of coronal plane CoM variables

	CONC			NORM		
	LEVEL	Q&A	OB	LEVEL	Q&A	OB
MLdisp (m)	0.038 (0.006)	0.043 (0.010)[a]	0.051 (0.010)[b]	0.033 (0.009)	0.034 (0.010)	0.045 (0.017)[b]
MLv (m/s)	0.142 (0.016)[a]	0.149 (0.020)[a]	0.163 (0.018)[a,c]	0.119 (0.037)	0.122 (0.039)	0.136 (0.053)[c]
MLVmax (m/s)	0.064 (0.032)	0.055 (0.039)	0.072 (0.027)[c]	0.033 (0.022)	0.050 (0.035)	0.069 (0.034)[c]

[a] >NORM.
[b] >LEVEL and Q&A.
[c] >LEVEL.

similar task results to APdisp. Along with a decreased separation distance, the instantaneous forward velocity of the CoM at the time of maximum separation was also significantly slower in the CONC group during the Q&A and OB task ($p = 0.010$). Obstacle crossing resulted in a significantly slower APVmax compared to both LEVEL ($p < 0.001$) and Q&A ($p = 0.026$). APVmax was also significantly slower during Q&A than LEVEL ($p < 0.001$).

3.3. Coronal plane CoM motion

There were no significant group-by-task interactions for CoM motion variables in the coronal plane (Table 3). CONCs swayed significantly greater than NORMs only during the Q&A task ($p = 0.045$). Obstacle crossing caused a significantly greater sway than LEVEL ($p < 0.001$) and Q&A ($p = 0.006$). CONCs also swayed significantly faster than NORMs ($p = 0.034$). CoM peak M/L velocity was significantly faster for obstacle crossing compared to LEVEL ($p = 0.002$). MLmax showed neither group nor task differences. The instantaneous CoM M/L velocity at maximum separation also displayed no significant group differences, but obstacle crossing resulted in significantly faster instantaneous velocities than LEVEL ($p = 0.012$).

3.4. Secondary tasks

There were no group differences in Q&A secondary task performance, though CONCs showed a trend of attempting fewer answers ($p = 0.085$). Only obstacle-crossing performance showed a group difference. CONCs demonstrated a significantly greater trailing toe clearance over the obstacle ($p = 0.034$).

4. Discussion

Our goal was to compare the sensitivity of two previously utilized dynamic tests to distinguish concussed individuals from their healthy peers. Identification of an appropriate test will enhance the ability of detecting deficits and recovery following concussion.

4.1. Task differences

Identifying a sensitive protocol first required a comparative analysis of gait attributes during each task. Conceptually and experimentally, the continuous question and answer task and obstacle crossing are both more difficult than single-task level walking, however in comparison to each other, little information has previously been available. Crossing over an obstacle has previously been shown to be mentally processed several steps prior [16]. However, increased attentional demands have continued through the gait cycle as elderly subjects completed the crossing of an obstacle [16,17]. The physical and mental demands of getting over the obstacle show that it requires changes in gait and attentional resources leading up to the obstacle.

Both the question and continuous answer secondary task (Q&A) and obstacle crossing (OB) affected spatial/temporal and sagittal plane CoM variables. The Q&A task resulted in slower velocities, perhaps due to decreased range of the

CoM in the sagittal plane. Obstacle crossing resulted in slower gait velocities, not as a result of decreased range of motion as during Q&A, but rather possibly due to increased stride time. Obstacle crossing actually resulted in greater displacement of the CoM in the sagittal plane. Adjustments to sagittal plane motion due to obstacle crossing are expected based on the physical constraints the obstacle imposes. To maintain a safe distance from contacting the obstacle, the feet must be spaced further apart in the sagittal plane [17], increasing stride length. Stride length increases during OB coincided with increased anterior CoM displacement and increased anterior separation between the CoM and CoP. These increases are in agreement with previous results of obstacle crossing [14].

Similarly, compared to LEVEL and Q&A tasks, obstacle crossing resulted in a greater CoM side-to-side sway, increased sway velocity and increased velocity at the maximum separation of the CoM and the CoP in both subject groups. Medial/lateral sway of the CoM of healthy subjects has previously been unaffected by obstacle crossing [14], however our results found that when the groups were combined in our statistical model, obstacle crossing did result in more medial lateral sway and faster peak sway velocities when compared to level walking. These results suggest that obstacle crossing might perturb an individual's gait up to a level that is unable to detect differences in concussed patients from their matched controls.

4.2. Group differences

Secondly, we sought to identify changes in gait due purely to concussion by identifying group differences in all three tasks. Gait velocity and peak forward CoM velocity were slower for all tasks as a result of a concussion as has been shown previously [4]. Peak medial/lateral CoM velocity has previously been reported to increase in both level walking and obstacle crossing due to a more severe traumatic brain injury [7] and this was extended to milder concussions in the current study. During obstacle crossing, concussed individuals were also found to increase their trailing toe clearance compared to controls. This could be a safety mechanism for traveling over the obstacle, but increasing toe height could also result in increased instability [18].

4.3. Attentional deficits

Increased step width was the only gait parameter that showed group differences during obstacle crossing, and not any other task. Interestingly, these findings did not correspond with a difference between groups in horizontal separation of the CoM and CoP in the medial/lateral direction during obstacle crossing. Increased trailing toe-obstacle clearance is the only other difference that concussed individuals had during obstacle crossing. Both of these differences suggest that concussed individuals attempted to adopt a safer crossing strategy. The absence of differences in CoM control suggests that concussed individuals did so without compromising balance. Gage et al. [17] suggested that fear of falling in an elderly population is correlated with increased attentional demands at the moment of crossing over an obstacle. However, no subjects in our study expressed concern for completing this task, and no formal information was gathered about increased fear of falling due to concussion. Without an obvious fear of falling or indication of imbalance, we cannot suggest that obstacle crossing demanded more attention for concussed individuals. A probe reaction time test would help to confirm these findings. Our findings do not account for possible attention deficits from concussion during the pre-obstacle phase, which others have identified as a crucial time for mental preparation of obstacle crossing [16]. Further testing during this portion of obstacle crossing is also recommended for the discovery of attention deficits in this task.

Only the Q&A task was able to differentiate the two groups based on common measurements of conservative adaptations and a measurement of gait stability. Besides the previously mentioned variables that indicate a conservative adaptive gait after a concussion in the Q&A task, only the Q&A task elicited group differences in the maximum anterior separation of the CoM and CoP and the medial/lateral sway of the CoM. Concussed individuals once again showed a conservative gait adaptation, but also signs of instability with increased side-to-side sway. These results support previous research indicating attentional deficits during a Q&A task performed while walking [12]. As for the secondary task, both groups performed statistically similar, indicating a bottle-neck model of attentional deficits [19].

4.4. Identification of a dynamic test sensitive to concussion

Obstacle crossing at the implemented height was not concluded to be a sensitive test to distinguish concussed from healthy individuals compared to LEVEL and Q&A. This task was only able to distinguish the two groups based on variables previously used to indicate more conservative gait. If just compared to LEVEL during a statistical analysis, the OB task might be sensitive enough to distinguish the two groups, so rather than suggesting OB is not a sensitive task, we are suggesting that Q&A was a more sensitive task. The Q&A task showed it was able to distinguish the two groups using the same conservative gait indicators as the OB task, as well as in a measurement previously shown to be sensitive to subjects with known instability. It should be noted that both groups produced their greatest MLdisp during obstacle crossing, so rather than suggesting that concussed individuals were most unstable during Q&A, or unstable at any time, we are merely showing that concussed individuals show signs of being more unstable than healthy individuals during the Q&A task.

5. Conclusions

Findings of this study demonstrate that concussed individuals adopted a more conservative gait strategy to maintain gait stability, but still showed signs of possible instability. Attention deficits after concussion were evident from measurements of gait stability during the Q&A task. Compared to level walking or obstacle crossing, a dynamic attentional test is more sensitive to the gait/balance deficits that inflict the concussed population, suggesting that it might serve as a better assessment following concussion to determine a proper time to return to activity.

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