Consistency and cost of dual-task gait balance measure in healthy adolescents and young adults

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Abstract

Matched control data are commonly used to examine recovery from concussion. Limited data exist, however, examining dual-task gait data consistency collected over time in healthy individuals. The study purposes were to: 1) assess the consistency of single-task and dual-task gait balance control measures, 2) determine the minimal detectable change (MDC) of gait balance control measures, and 3) examine the extent to which age and task complexity affect dual-task walking costs in healthy adolescents and young adults. Twenty-four adolescent (mean age= 15.5±1.1 years) and 21 young adult (mean age= 21.2±4.5 years) healthy participants completed 5 testing sessions across a two-month period, which involved analyses of gait balance control and temporal-distance variables during single-task and dual-task walking conditions in a motion analysis laboratory. Cronbach's α and MDCs were used to determine the consistency of the gait balance control variables and the smallest amount of change required to distinguish true performance from change due to the performance/measurement variability, respectively. Dual-task costs were evaluated to determine the effect of task complexity and age across time using 3-way ANOVAs. Good to excellent test-retest consistency was found for all single-task and dual-task walking (Cronbach's α range: .764 – .970), with a center-of-mass medial-lateral displacement MDC range of 0.835-0.948 cm. Greater frontal plane dual-task costs were observed during more complex secondary tasks ($p < .001$). The results revealed good-excellent consistency across testing sessions for all variables and indicated dual-task costs are affected by task complexity. Thus, healthy controls can be effective comparators when assessing injured subjects.

1. Introduction

Dual-task gait assessments provide a method to monitor simultaneous completion of a motor and cognitive task and have been used to monitor balance control recovery after concussion [1,2]. While recent studies support the use of dual-task gait balance assessments to detect persistent and lingering neurological deficits following concussion [2–4], no studies have identified the consistency of dual-task gait balance measurements collected repeatedly across time in uninjured control subjects to which injured population data are compared to assess recovery. Determining the amount of expected change occurring in dual-task walking conditions of varying complexity over repeated test sessions in healthy, matched control subjects can help to better delineate the effects of learning from actual recovery following concussion.

To assess recovery from concussion, minimal detectable change (MDC) scores have been calculated to assist clinicians with the interpretation of performance [5,6]. For example, a 10 point change on the post-concussion symptom scale has been considered the MDC from baseline to post-injury assessments [5] and the MDC for the Balance Error Scoring System (BESS) test has been reported to range from 7-9 errors [6]. While self-reported symptom assessments and clinician-rated tests of static postural control can be easily administered and have clinical utility, objective evaluations of dual-task dynamic gait balance control have been shown to detect subtle impairments after concussion beyond symptom resolution after concussion [2,3]. Although the effects of learning for dual-task walking have been reported [2,7], analyses of test-retest consistency and MDC for dual-task gait balance control across a series of testing periods in uninjured matched control subjects have yet to be conducted. The information derived from such analyses is important to differentiate between the effects of learning and concussion over time, and thereby improve the analysis of the recovery process.

Previous studies have used kinematic measurements of whole body center-of-mass (COM) motion during walking to examine recovery of gait balance control following concussion [2,3,8,9]. However, no research has directly examined the reliability or consistency of these measures in a group of uninjured participants. Thus, the purposes of this study were: 1) to assess the consistency of single-task and dual-task gait balance control and walking performance measurements in uninjured adolescents and young adults, 2) to calculate the MDC scores for each gait balance control measure, and 3) to examine the extent to which the cost of dual-task walking is affected by age and task complexity.

2. Methods

2.1 Participants

The participants in the current study had served as matched, uninjured control subjects as a part of a longitudinal assessment of individuals with concussion [2,3,7,8]. They reported to the laboratory for an initial assessment, and then returned for repeat testing at the following approximate time points: 1 week, 2 weeks, 1 month, and 2 months post-initial assessment. Exclusion criteria included: 1) lower extremity deficiency or injury, which may affect normal gait patterns; 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities; 3) history of attention deficit hyperactivity disorder; 4) history of three or more previous concussions; or 5) a documented concussion within the past year. A certified athletic trainer administered a verbal medical history inventory for all participants upon their first laboratory visit to confirm all criteria were met for inclusion in the study. Prior to data collection, the institutional review board reviewed and approved the study. All participants and parent/guardian (if under the age of 18) provided informed consent to participate in the study.

Permission was also obtained from the representative school districts and college student health centers to conduct testing with student participants.

2.2 Experimental Protocol

Participants walked barefoot at a self-selected speed along a 12m walkway under three conditions of increasing complexity: 1) walking with undivided attention (single-task walking), 2) dual-task Stroop walking (walking while simultaneously completing an auditory Stroop test), and 3) dual-task question and answer (Q&A) walking (walking while simultaneously completing a mental task). The auditory Stroop test, described previously [7], consisted of the subject listening to four auditory stimuli: the recorded words “high” or “low” each spoken in either a high pitch or low pitch. Participants were instructed to correctly identify the pitch of the word, regardless of whether the pitch was congruent with the meaning of the word. The initial auditory stimulus was presented once subjects had reached steady-state gait, which occurred several steps after gait initiation, and triggered by a photocell. Each subsequent stimulus was then played one second after the previous response. The Q&A test, described previously [7], consisted of 3 verbal test forms: 1) spelling a five-letter word backwards, 2) subtracting continually from a given numeral by 6s or 7s, or 3) reciting the months in reverse order, starting with a random month. Subjects completed one of these test forms per walking trial. The specific Q&A test form to be completed was randomly selected for each trial to avoid learning effects from one trial to the next. The instructions for the Q&A task were given to the subjects prior to gait initiation after which they were instructed to begin walking and respond to the task once an auditory beep was played, triggered by a photocell located several steps after gait initiation. **Cognitive performance was analyzed from objective measurements of the accuracy of subject responses to the Q&A and Stroop cognitive tasks.**

For all dual-task trials, participants were not instructed to focus specifically on the walking or the cognitive task, but to continue walking while correctly responding to the task. Participants completed 8-10 trials in each condition. Consistent with prior literature [2,7,10–12], data from a gait cycle occurring **during the** auditory stimulus presentation across trials in each testing condition on each testing day were used in further analyses. This approach provided trial to trial consistency in gait cycle analysis for the 3 walking conditions.

2.3 Outcome Variables

In this study, test-retest consistency in healthy participants was assessed for gait balance control variables which have been associated with impairments after concussion [1,2,7,9]. After concussion, injured individuals exhibit decreased gait balance control, as defined as greater and faster COM motion in the frontal plane and less sagittal plane velocity compared with matched controls [2,7–9]. Therefore, the dependent variables measured in each condition included the total medial-lateral COM displacement and peak linear medial-lateral and anterior COM velocities during one gait cycle as well as the temporal-distance parameters: average gait velocity, step length, and step width. For each trial, data were analyzed for one gait cycle, defined as heel strike to heel strike of the same limb.

To quantify gait balance control, a set of 29 retro-reflective markers were placed on bony landmarks of the participant [13], and whole body motion analysis was performed using a 10-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60Hz to capture and reconstruct the three-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8Hz. External markers and estimated joint centers were used to calculate the COM of each individual body segment and whole body COM position data were calculated as

the weighted sum of all body segments, using the body mass distribution data from Winter [14], with 13 segments representing the whole body [2]. The total amount of COM medial-lateral displacement during one gait cycle was calculated. Linear COM velocities in the anterior and medial-lateral directions of movement were calculated using the cross-validated spline algorithm from the COM position [15], and peak velocities during the gait cycle were identified. Average walking speed was calculated as the mean forward velocity throughout the gait cycle. Step length and width were calculated as the distances between right and left heel markers at each heel strike in the anterior/posterior and medial/lateral directions, respectively

Dual-task costs were also calculated for all gait variables. Previously, dual-task costs have been used to identify the amount of change during a dual-task trial relative to a single task trial [2], thus providing a measure of the relative change between conditions. The dual-task cost was calculated as: $(\text{Dual task value} - \text{Single task value}) / (\text{Single task value})$. Finally, cognitive task accuracy was calculated as the number of correct responses divided by the total number of cognitive tasks the participant attempted during the testing session.

2.4 Statistical Analysis

The data were examined in 3 ways: 1) to determine the consistency of single-task and dual-task walking measurements across 5 different testing times; 2) to describe the minimal detectable change for each gait balance control variable; and 3) to examine dual-task cost differences among the age groups and different walking conditions. Cronbach's α was used to determine test consistency across the 5 testing sessions for COM, temporal-distance gait, and cognitive task accuracy measures in all subjects and grouped according to age. Values that were greater than 0.9 were considered excellent, between 0.7 – 0.9 good, and lower than 0.7 poor [16]. A Fisher-Bonnett test was used to determine if the consistency of the measurement was similar between

age groups [17]. For COM measurements, the minimal detectable change (MDC) was calculated to determine the smallest amount of change that can be detected by a measure that corresponds to a noticeable change in ability [18,19]. The MDC was based on a 90% confidence interval, and was calculated as $(1.65) \times (\text{the standard error of the measurement}) \times (\sqrt{2})$ [19]. To determine if the cost of dual-task walking was affected by age and task complexity, three-way mixed effects analyses of variance were used to identify main effects and interactions among the independent variables (age group x task x time) on gait balance control COM outcome measures. All statistical analyses were two-sided, evaluated with a significance level of $p < .05$, and were adjusted using the Bonferroni procedure when necessary. Analyses were performed using SPSS (IBM SPSS Statistics for Windows, Version 23.0.Armonk, NY: IBM Corp.)

3. Results

A total of 45 uninjured participants completed the study protocol and reported to the laboratory for 5 testing sessions; they were tested at the following mean (SD) time increments: 7(2), 15(3), 29(3), and 57(5) days after the initial exam. Twenty-four of the participants were adolescents (between 14-17 years of age) and 21 participants were young adults (between 18-26 years of age). Eleven participants reported a history of a concussion (24%), and only 2 participants reported sustaining more than one lifetime concussion. Of those who reported sustaining a prior concussion, the most recent concussive event occurred at a mean of 2.4 ± 0.8 years prior to the initial testing date. No participant attrition occurred during the course of the study period.

Results from Cronbach's α indicated good internal consistency across the 5 testing sessions for the total medial-lateral COM displacement variable (Table 2) and peak medial-lateral COM

velocity (Table 2). Peak anterior COM velocity, average gait velocity, step length, and step width variables all demonstrated excellent internal consistency across the 5 testing sessions (Table 2). Adolescents and young adults demonstrated similar consistency across time on all measurements, with the exception of step length **consistency** (Table 2). Among the 3 walking conditions, MDCs ranged from 0.835-0.948 cm for total COM medial-lateral displacement, 2.21-2.65 cm/s for peak COM medial-lateral velocity, and 5.98-7.42 cm/s for peak COM anterior velocity (Table 3).

Dual-task costs were not significantly different between adolescents and young adults on any gait balance control measurement (Table 4). Task complexity, however, influenced gait balance control. There was a significantly greater dual-task cost during the Q&A condition compared to the Stroop condition across the testing timeline for total M-L displacement, peak M-L COM velocity, and at the first 4 time points for peak COM anterior velocity (Table 4). The cognitive task accuracy rates among participants across the 5 testing time points were $99.4 \pm 1.6\%$ for dual-task Stroop walking and $87.3 \pm 13.7\%$ during dual-task Q&A walking. Young adults were significantly more accurate during Q&A dual-task walking than adolescents ($90.3 \pm 11.7\%$ vs. $84.9 \pm 14.8\%$, respectively; $p = 0.003$), while no significant Stroop dual-task cognitive task accuracy rate differences were found ($99.3 \pm 1.5\%$ vs. $99.4 \pm 1.7\%$, respectively). Similar to the dual-task cost gait, participants were significantly less accurate during dual-task Q&A than during dual-task Stroop walking ($p < .001$). Q&A accuracy while walking was consistent across time (Cronbach's $\alpha = .873$). Stroop accuracy consistency could not be computed due to assumption violations (covariance matrix determinant = 0).

4. Discussion

This investigation examined the dual-task gait balance control of healthy young adults and adolescents who completed 5 testing sessions across a 2 month period of time. For both age groups, the results indicate good levels of test consistency across time for frontal plane gait balance control variables and excellent test consistency measurements for sagittal plane movement and gait temporal-distance parameters, and that gait variable consistency was similar between adolescents and young adults. Additionally, task complexity appeared to influence balance control as the dual-task cost during Q&A gait was significantly greater than the dual-task cost during Stroop gait for COM displacement and velocity variables.

Prior studies have reported greater dual-task frontal plane COM motion during dual-task walking in subjects with concussion when compared to their own single-task measurements, and that of matched controls across time [2,7,9]. This suggests that the control of body movement while walking and completing a mental task may be particularly affected by concussion, as these deficits tend to persist beyond self-reported symptom resolution [2,20]. The Cronbach's α coefficients in this study indicated good to excellent COM frontal plane movement consistency across testing sessions during gait in a cohort of healthy subjects. This indicates that using these measures for monitoring recovery across time is appropriate, as improved dynamic balance control after a concussion may reflect motor system recovery rather than a learning effect, often present in other forms of balance testing [18,21,22].

Previously, researchers have examined the repeatability of postural control in cohorts of subjects completing the BESS test, a commonly utilized static clinical exam [23]. The BESS is a novel task which requires some learning and results in improvements due to practice [21,22]. The data from the current study indicate that the dynamic walking characteristics do not fluctuate greatly across repeat testing assessments. In particular, the sagittal plane movement

characteristics were highly consistent across the testing period suggesting that forward walking is an automated process [24]. Such automation, particularly during single-task walking, may be an underlying mechanism for an individualized walking pattern which produces a high level of consistency across repeated days of testing in healthy subjects. This suggests that the examination of multiple gait characteristics, including single-task and dual-task variables, can be a useful and valid method to measure gait balance control across time with minimal changes occurring due to practice effects. The MDCs calculated thus indicate the amount of change necessary to be confident that a change in gait balance control is not due to normal test variability, which may be helpful in both clinical and research settings [19].

Age group comparisons revealed similar consistency for all COM movement measures between young adults and adolescents. Gait patterns mature throughout development and may be fully automated by the time an individual reaches adolescence [25], which could result in consistent performance values when measured across time. While age is a modifying factor in concussion management [26], the finding of comparable consistency in performance and the lack of dual-task cost differences between age groups suggests that dual-task walking assessments may be appropriate for use as in monitoring recovery from concussion in for those between the age of 14 and 26.

The utility of dual-task assessments in clinical settings has been documented previously. The addition of a cognitive task has been described as a method to increase the reliability of post-concussion postural control exams [27]. A systematic review has reported that return-to-play decisions may be augmented with the use of more complex assessments of function, such as dual-tasks, but that few studies have transferred such assessments to testing batteries which are feasible to conduct in a traditional clinic setting [1]. Further, a recent study has suggested that

body-worn accelerometers may be one method to monitor dual-task gait balance control recovery in a portable fashion [4]. As our findings indicate that gait measurements obtained in a motion analysis laboratory are consistent across time, future work should assess the consistency of accelerometer-based measurements of dual-task gait balance control in order to provide a more ubiquitous paradigm with potential for widespread clinical applicability.

Data obtained in this investigation were from a single laboratory where reasonably healthy individuals came as a part of an ongoing study investigating how concussion affects gait. As such, the generalizability of our results may be limited. Additionally, the individual learning and attentional abilities of participants in this study may have affected their dual-task performance, as they ranged in age from 14 to 26 years. **Finally, although the subjects were instructed to not focus specifically on the walking or the cognitive task, the degree to which participant prioritization occurred between the gait and cognitive task cannot be unequivocally identified, and may have affected the study results.**

Injury management decisions are typically based on the functional capacity of an individual to successfully complete the demands required by the activities in which they wish to return [27]. Concussion management decisions based on a reliable test of dual-task function may provide a method to accurately assess such functional capacities prior to returning to sport or other physical activities. The data from this investigation suggest that minimal changes occur in relatively complex dual-task gait activities when tested repeatedly across time in healthy individuals, and that healthy, matched controls can be effective comparators when assessing injured subjects. Future research should look to examine the sensitivity and specificity of dual-task gait balance control measures across time to better identify objective markers of recovery from concussion, which can better inform injury management decisions.

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Table 1: Participant characteristics. Mean (SD) are presented for continuous variables, percentages are expressed for categorical variables.

Variable	Adolescents (n = 24)	Young Adults (n = 21)
Age (years)	15.5 (1.1)	21.2 (4.5)
Height (cm)	173 (7.6)	172 (9.6)
Mass (kg)	70.1 (12.4)	71.0 (10.1)
Sex (females)	4 (17%)	10 (48%)

Table 2: Gait balance control and temporal-distance variables for test consistency across all 5 testing sessions for all participants and between age groups.

Variable	<u>Cronbach's α</u>		
	All Subjects	Adolescents	Young Adults
<u>Total COM M-L Displacement</u>			
Single-task	0.764	0.662	0.855
Dual-task Stroop	0.786	0.780	0.819
Dual-task Q&A	0.792	0.762	0.839
<u>Peak COM M-L Velocity</u>			
Single-task	0.861	0.840	0.873
Dual-task Stroop	0.886	0.892	0.892
Dual-task Q&A	0.848	0.841	0.846
<u>Peak COM Anterior Velocity</u>			
Single-task	0.933	0.943	0.902
Dual-task Stroop	0.961	0.967	0.949
Dual-task Q&A	0.938	0.936	0.931
<u>Average Walking Speed</u>			
Single-task	0.936	0.945	0.910
Dual-task Stroop	0.964	0.968	0.957
Dual-task Q&A	0.944	0.936	0.944
<u>Step Length</u>			
Single-task	0.904	0.952	0.859 ^a
Dual-task Stroop	0.927	0.961	0.899 ^a
Dual-task Q&A	0.897	0.939	0.855 ^a
<u>Step Width</u>			
Single-task	0.967	0.964	0.975
Dual-task Stroop	0.961	0.957	0.969
Dual-task Q&A	0.970	0.968	0.976

^a Fisher-Bonett tests revealed that Cronbach's α coefficients for step length were significantly higher for adolescents compared to young adults during single-task ($p = .02$), dual-task Stroop ($p = .03$), and dual-task Q&A ($p = .04$) conditions.

Table 3: Mean (SD) and minimal detectable change (MDC) values for COM gait balance control measurements calculated from all study participants.

Variable	Mean (SD)	MDC
<i><u>Total COM M-L Displacement (cm)</u></i>		
Single-task	3.594 (0.772)	0.875
Dual-task Stroop	3.645 (0.774)	0.835
Dual-task Q&A	3.936 (0.891)	0.948
<i><u>Peak COM M-L Velocity (cm/s)</u></i>		
Single-task	11.55 (2.909)	2.53
Dual-task Stroop	11.72 (2.807)	2.21
Dual-task Q&A	12.62 (2.912)	2.65
<i><u>Peak COM Anterior Velocity (cm/s)</u></i>		
Single-task	142.2 (12.28)	7.42
Dual-task Stroop	137.1 (12.99)	5.98
Dual-task Q&A	132.8 (11.63)	6.76

Table 4: Dual-task cost means (lower, upper 95% CI) for the Stroop and Q&A walking conditions among adolescent and young adult participants. Values are expressed as a percentage and represent the amount of change during dual-task walking compared with single-task walking. Positive values indicate increased values for the dual-task relative to the single-task condition.

Variable	Adolescent (n=24)	Young Adult (n=21)
<i>Total COM M-L Displacement (% change)</i>		
Stroop	5.41% (1.40, 9.42)	2.18% (-2.02, 6.37)
Q&A ^a	12.9% (7.09, 18.6)	11.4% (5.36, 17.4)
<i>Peak COM M-L Velocity (% change)</i>		
Stroop	6.20% (1.72, 10.7)	1.29% (-3.40, 5.99)
Q&A ^a	16.0% (9.89, 22.2)	9.92% (3.50, 16.3)
<i>Peak COM Anterior Velocity (% change)</i>		
Stroop	-3.91% (-5.31, -2.51)	-2.90% (-4.37, -1.43)
Q&A ^b	-6.69% (-8.59, -4.79)	-5.86% (-7.85, -3.87)

^a Participants exhibited a greater dual-task cost in the Q&A condition compared to the Stroop condition for total COM M-L displacement (main effect of task; $F_{1,42} = 17.5$; $p < .001$; $\eta_p^2 = .294$) and peak COM M-L velocity variables (main effect of task; $F_{1,42} = 25.6$; $p < .001$; $\eta_p^2 = .379$).

^b Participants exhibited a greater dual-task cost in the Q&A condition compared to the Stroop condition for peak COM anterior velocity at the first four testing assessments (task x time interaction; $F_{4,168} = 3.74$; $p = .006$; $\eta_p^2 = .082$).