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Monitoring recovery of gait balance control following concussion using an accelerometer

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ABSTRACT

Despite medical best-practice recommendations, no consistent standard exists to systematically monitor recovery from concussion. Studies utilizing camera-based systems have reported center-of-mass (COM) motion control deficits persisting in individuals with concussion up to two months post-injury. The use of an accelerometer may provide an efficient and sensitive method to monitor COM alterations following concussion that can be employed in clinical settings. This study examined: (1) frontal/sagittal plane acceleration characteristics during dual-task walking for individuals with concussion and healthy controls; and (2) the effectiveness of utilizing acceleration characteristics to classify concussed and healthy individuals via receiver operating characteristic (ROC) curve analyses. Individuals with concussion completed testing within 72 h as well as 1 week, 2 weeks, 1 month, and 2 months post-injury. Control subjects completed the same protocol in similar time increments. Participants walked and simultaneously completed a cognitive task while wearing an accelerometer attached to L5. Participants with concussion walked with significantly less peak medial–lateral acceleration during 55–75% gait cycle ($p=0.04$) throughout the testing period compared with controls. Moderate levels of sensitivity and specificity were found at the 72 h and 1 week testing times (sensitivity$=0.70$, specificity$=0.71$). ROC analysis revealed significant AUC values at the 72 h (AUC$=0.889$) and two week (AUC$=0.810$) time points. Accelerometer-derived measurements may assist in detecting frontal plane control deficits during dual-task walking post-concussion, consistent with camera-based studies. These initial findings demonstrate potential for using accelerometry as a tool for clinicians to monitor gait balance control following concussion.

1. Introduction

Gait balance disturbances have been identified in individuals following concussion. Individuals with concussion exhibit greater displacement and velocity of the whole body center-of-mass (COM) in the frontal plane and smaller peak COM velocity in the sagittal plane during dual-task walking than individually matched and uninjured controls (Howell et al., 2015a, 2015b, 2014, 2013; Parker et al., 2006). Such COM position or velocity differences could be due to poor momentum control resulting from difficulties in regulating COM acceleration. As the examination of COM acceleration during a sit-to-stand task has been shown to differentiate individuals with functional limitations from healthy individuals (Fujimoto and Chou, 2014, 2012), the measurement of COM acceleration may help to identify how individuals control balance during daily activities. Recent studies have utilized accelerometers placed at L5 (King et al., 2014), the anterior midline of the pelvis (Furman et al., 2013), and the forehead (Brown et al., 2014) to increase the objectivity in measuring static balance post-concussion. However, no studies have examined acceleration during gait following concussion.

Best-practice statements have recommended that balance testing is a critical component in the clinical examination of concussion (Harmon et al., 2013; McCrory et al., 2013). Laboratory-based studies have identified gait balance control deficits following concussion, particularly in whole body COM displacement and velocity (Howell et al., 2014, 2013). However, analysis of COM displacement and velocity may require substantial motion capture equipment not often available in clinical settings where post-concussion assessments are conducted. Hence, a need exists to develop protocols utilizing inexpensive, easily implemented

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alternatives that provide accuracy and sensitivity comparable to camera-based systems for measuring gait balance control in a wide spectrum of clinical sites. As COM displacement and velocity are directly connected to COM acceleration, the use of accelerometers may offer a cost-effective, readily available alternative for measuring longitudinal alterations in the magnitude or pattern of COM motion during gait following concussion.

Through the use of dual-task paradigms, previous investigations have observed that the completion of simultaneous motor and cognitive tasks are affected by concussion (Fait et al., 2013; Howell et al., 2013; Martini et al., 2011). As such, dual-task testing has been identified as a useful component in the management of concussion (Register-Mihalik et al., 2013b) and as method which may detect subtle neurological impairments following injury (Lee et al., 2013). Dual-task testing in concussion assessments may provide information about the ability to multitask in everyday activities (Howell et al., 2013) and allow for a greater ability to detect impairments following concussion than single-tasks focusing solely on motor or cognitive task completion.

The objective of this study was to examine peak sagittal and frontal plane accelerations, measured with an accelerometer during dual-task walking, in a cohort of participants with concussion within 72 h of injury and regularly over the subsequent 2-month post-injury period and similarly in uninjured controls. The effectiveness of utilizing acceleration characteristics to classify subjects was also assessed. It was hypothesized that differences between groups (concussion and control) in forward and side-to-side movements would be detectable with a single accelerometer placed at L5, and that protocol measurements would demonstrate moderate to high sensitivity and specificity in discriminating between participants with and without concussion.

2. Methods

2.1. Participants

Seventeen subjects were identified and recruited for testing. Ten subjects were diagnosed with a concussion by a healthcare professional (physician/athletic trainer) and seven uninjured subjects served as controls (Table 1). The definition of concussion was consistent with the latest best-practice statement (McCrory et al., 2013) as an injury caused by a direct blow to the head, face, neck, or elsewhere in the body resulting in impaired neurologic function and clinical symptoms. Prior to data collection, the institutional review board reviewed and approved the study protocol. All subjects and parents/guardians (if under the age of 18) provided written consent to participate in the study.

Exclusion criteria for prospective subjects 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 three or more previous concussions; (4) loss of consciousness from the concussion lasting greater than one minute (for participants with concussion); (5) history of attention deficit hyperactivity disorder; or (6) a previously documented concussion within the past year.

A prospective, repeated-measures design was employed where subjects with concussion reported to the laboratory for testing within 72 h post-injury as well as time points approximately 1 week, 2 weeks, 1 month, and 2 months post-injury.

Table 1
Subject demographics: mean (SD) for each group of participants.

Group	Concussion	Control
Sex	7M/3F	3M/4F
Age (years)	19.0 (5.5)	20.0 (4.5)
Height (cm)	170.9 (6.7)	168.6 (8.4)
Mass (kg)	67.1 (10.7)	65.1 (10.5)
Mechanism of injury (*n*)	Head – head contact: 3	N/A
	Head – opponent body contact: 2	
	Head – ground contact: 2	
	Bike accident: 2	
	Activities of daily living: 1	

Control subjects were initially assessed and then tested according to the same testing schedule as subjects with concussion.

2.2. Experimental protocol

All study participants walked barefoot at a self-selected speed along a walkway while simultaneously completing an auditory Stroop test (dual-task). Gait balance control, under the Stroop test condition, has been shown previously to be affected in subjects with concussion for an extended post-injury period (Howell et al., 2014, 2013). The Stroop test consisted of the subject listening to four 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 four stimuli was presented in random order at a specific time while walking. The first stimulus was presented once the subject had achieved steady state gait and was triggered by a photocell located several steps after gait initiation. Each of the three subsequent stimuli was presented one second following the previous response while the subject continued to walk. Prior to test administration, subjects were provided verbal instructions by a study investigator, along with examples of the auditory stimulus. Following confirmation that the subject understood and could adequately hear each auditory stimulus, a practice trial was completed with verbal accuracy feedback. After successful completion of the practice trial, experimental trials began.

While walking, participants wore an accelerometer (Opal Sensor, APDM Inc., Portland, OR) attached with an elastic belt at L5, and linear acceleration was measured along three orthogonal axes so that the reference coordinate system x-axis was oriented vertically downward, the y-axis was oriented to the right, and the z-axis was oriented orthogonal to the x- and y-axes, toward the front. Accelerometer data were used to identify linear accelerations in the anterior–posterior and medial–lateral directions, obtained at a sampling frequency of 128 Hz and saved via data-logger for offline post-processing.

In addition to the accelerometer, retro-reflective markers were placed on bony landmarks (Hahn and Chou, 2004) of the subject, and marker trajectory data were collected using a 10-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60 Hz. Gait velocity was calculated as the mean forward velocity of the sacral marker during a gait cycle.

2.3. Data analysis

For analysis of accelerometer signals, four trials were identified for each subject at each testing time point. Relevant raw data were filtered with a zero-lag, fourth-order Butterworth low pass filter with a cutoff frequency of 12 Hz. To remove the gravitational component from the accelerometer, participants also completed a 30-second quiet standing trial. The RMS value in anterior and medial–lateral directions was subtracted from respective data. Heel strikes were used to identify the beginning and the end of the gait cycle, as previously demonstrated (Bugané et al., 2012; Zijlstra and Hof, 2003). Each trial was normalized to 100% gait cycle.

The peak forward acceleration was identified at approximately 50% of the gait cycle (Fig. 1A). Three distinct peak medial–lateral accelerations were identified: (1) during 25–45% of the gait cycle, (2) during 45–55% of the gait cycle, and (3) during 55–75% of the gait cycle (Fig. 1B). Absolute values were used in further analysis to normalize between right and left directions.

2.4. Statistical analysis

Peak accelerations were analyzed by two-way mixed effects analyses of covariance, with average gait velocity as a covariate, in order to determine the effect of group (concussion and control), time (72 h, 1 week, 2 weeks, 1 month, and 2 months post-injury) and the interaction between these two independent variables. For all omnibus tests, significance was set at $p < 0.05$. Follow-up pairwise comparisons were examined using the Bonferroni procedure to control family wise type I error. Effect size estimations for mean differences are reported as partial eta squared ($\eta_p{}^2$) values.

In order to evaluate the sensitivity and specificity of acceleration data to classify participants, and to evaluate the effectiveness of acceleration characteristics to discriminate between participants with concussion and healthy controls, further analyses were conducted on those variables which demonstrated a significant effect when tested using analysis of covariance. To determine sensitivity and specificity, predictive cutoff values which would indicate abnormal performance were determined using the lower limit of the 95% confidence interval (CI) of the control group mean at each testing time point (Register-Mihalik et al., 2013a). Sensitivity indicates the probability that a participant with concussion will be identified as abnormal using an established peak acceleration cutoff threshold. Specificity indicates the probability that a control participant would be correctly classified healthy using the same method (Register-Mihalik et al., 2013a).

Furthermore, how well acceleration values accurately identify participants with a concussion was estimated using a receiver operating characteristic (ROC) curve analysis. The area under an ROC curve (AUC) was used as a measure of the ability of acceleration data to distinguish between the two participant groups, independent