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Short communication

A comparison of kinematic-based gait event detection methods in a self-paced treadmill application

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ABSTRACT

Kinematic-based algorithms for detecting gait events are efficient and useful in the absence of (reliable) kinetic data. However, the validity of these kinematic-based algorithms for self-paced treadmill walking is unknown, particularly given the influence of walking speed on such data. We quantified offsets in event detection of four foot kinematics-based algorithms (horizontal position, horizontal velocity, vertical velocity, and sagittal resultant velocity) relative to events determined by a threshold in vertical ground reaction force among seven uninjured individuals – and nine with unilateral transtibial amputation – walking on a self-paced treadmill. Across walking speeds from 0.48–1.64 m/s (0.5–31.7% CV), offsets ranged from -7 to $+3$ frames (≈ 83.3 ms) in heel strike, and -3 to $+5$ frames (≈ 66.6 ms) in toe off. Regardless of method, offsets in heel strike were not influenced ($-0.01 < r < 0.01$, all $P > 0.61$) by variability in walking speed. However, offsets in toe-off were positively correlated with variability in walking speed for the horizontal position ($r=0.539$; $P<0.001$) and velocity ($r=0.463$; $P<0.001$) algorithms, and negatively correlated ($r=-0.317$; $P<0.001$) for the vertical velocity algorithm; offsets from the sagittal resultant velocity algorithm, with thresholds adjusted for walking speed, were not strongly associated ($r=0.126$; $P=0.27$). Although relatively minimal offsets support the applicability of these algorithms to self-paced walking, for individuals with asymptomatic and pathological gait patterns, sagittal resultant velocity of the foot produces the most consistent event detection over the widest range of (and variability in) walking speeds.

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1. Introduction

Many biomechanical evaluations of gait are initially dependent on accurate and reliable detection of gait events (i.e., heel strike and toe off). Typically, such identification is defined by an ascending/descending threshold in the vertical component of the ground reaction force (GRF). Although reliable, additional methods have been developed which utilize kinematic (marker) data exclusively (e.g., Ghoussayni et al., 2004; O'Connor et al., 2007; Zeni et al., 2008). These kinematic-based methods have been specifically highlighted for their ease of use and efficiency when analyzing large amounts of data obtained during extended treadmill collections, particularly when noise in (absence of) force signals or cross-over steps between split belts preclude the application of GRF-based methods (Kiss, 2010). Recently, the use of self-paced algorithms – in which the speed of the treadmill belt (s) is controlled by the relative positioning of the participant – has increased in both clinical and research settings (Choi et al., 2015; Sinitski et al., 2015; Sloot et al., 2014). Self-selected walking speed is an important and easily discernable biomechanical measure, and allowing individuals to modulate walking speed likely improves ecological and/or construct validity of an evaluation (when controlling speed is not a requirement for a given analysis). While previous efforts have developed and/or compared kinematic- and GRF-based methodologies for gait event detection (Alton et al., 1998; Ghoussayni et al., 2004; O'Connor et al., 2007; Zeni et al., 2008), both overground and on treadmills, none have explicitly analyzed these methods during self-paced treadmill walking. This evaluation is of particular importance given the sensitivity of kinematic data to changes in walking speed, as fluctuations in walking speed throughout a self-paced trial may differentially influence the relative timing of kinematic-based gait event detection. The primary aim of this study was to evaluate and

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compare kinematic- and GRF-based gait event detection in self-paced treadmill walking. As a secondary aim, we also compared such methods in a population with lower-extremity amputation, in an effort to evaluate its applicability and robustness in populations who may walk with pathologic gait patterns. Results are intended to facilitate the selection of the most appropriate/robust gait event detection method for future studies utilizing self-paced treadmill walking.

2. Methods

2.1. Participants

Seven uninjured males – and nine males with unilateral transtibial (TTA) amputation – participated in this study. Mean (standard deviation) age, stature, and body mass for the uninjured males were 28.9 (4.2) yrs, 178.1 (8.5) cm, and 81.9 (6.0) kg; corresponding values for the males with TTA were 31.6 (6.5) yrs, 180.6 (4.5) cm, and 87.2 (7.5) kg. All participants provided written consent, and all procedures were approved by the local Institutional Review Board. Uninjured participants reported being free of current or recent injuries, illnesses, musculoskeletal disorders, or other health-related aspects that may have influenced their gait. Participants with TTA sustained their amputation through a traumatic event, were at least 1-year post injury (mean=2.2 yrs, range = 1.0–5.5 yrs), and all independent ambulators without the use of assistive devices. Persons with and without TTA were excluded based on the presence of traumatic brain injuries and/or dizziness, as these may affect gait or balance. All participants reported being comfortable walking on a treadmill.

2.2. Procedures

Participants walked on an instrumented treadmill within a Computer Assisted Rehabilitation Environment (CAREN; Motekforce Link, The Netherlands). Retro-reflective markers (diameter=8 mm) were placed on the heel, toe, and lateral border of each foot, and bilaterally on the malleoli, shank, knee, thigh, and anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). Marker data were tracked at 120 Hz with a 12-camera motion capture system (Vicon, Oxford, UK), and bilateral GRFs were simultaneously sampled at 1200 Hz from the two force platforms within the split-belt treadmill system (Bertec, Columbus, OH, USA). A self-paced treadmill speed algorithm was used (Sloot et al., 2014), which controls belt speed based on mean anterior-posterior position, velocity, and acceleration of the bilateral ASIS and PSIS markers (self-paced sensitivity scaling was set at 1.0 and maximum treadmill acceleration set at 0.3 m/s^2). Participants were initially given instruction on operation and control of the self-paced treadmill, including start, stop, and acceleration/deceleration, and subsequently completed a 4-min acclimation trial. Following the acclimation trial, participants completed a 2-min walking trial, with verbal instructions to simply "walk at a comfortable pace." No optical flow was provided within the CAREN system; however, a stationary object was displayed for purposes of providing a point of reference.

2.3. Analyses

Heel-strike and toe-off events were determined using four kinematic-based algorithms: (1) horizontal heel and toe position relative to the pelvis (Zeni et al., 2008); (2) absolute horizontal heel and toe velocity (Zeni et al., 2008); (3) vertical velocity of the foot center-of-mass (O'Connor et al., 2007); and (4) sagittal resultant velocity of the heel and toe markers (Ghoussayni et al., 2004) using automated detection thresholds adjusted for walking speed (Bruening and Ridge, 2014). These algorithms were chosen based on existing evidence of good reliability for treadmill walking, and to an extent, their robustness in potential applicability to pathological gait (Bruening and Ridge, 2014). For purposes of comparing the aforementioned kinematic-based methods to a "gold standard", GRF-based events were also determined using a 20 N ascending and descending threshold in vertical force component, adjusted upward slightly from previous thresholds (10 N) to account for additional noise from the treadmill belts/platform (Tirosh and Sparrow, 2003; Zeni et al., 2008). GRFs were filtered with a zero-lag, 4th order Butterworth filter at a cut-off frequency of 20 Hz, while marker trajectories were filtered at 6 Hz (note, analog data were first downsampled). Subsequently, the relative difference in event timing ("offset"; in frames) between each kinematic method and the GRF method were computed; positive/negative differences=late/early events, respectively. Offsets calculated for the right and left limbs of uninjured participants were pooled given similar values between limbs within each method (all $P > 0.14$). In contrast, offsets calculated for the intact and prosthetic limbs among participants with TTA were analyzed separately given differing values between limbs within each method (all $P < 0.03$). Finally, to evaluate influences of variations in walking speed (from measured belt speed at 1200 Hz) on the offset in event detection, bivariate correlation analyses (Pearson) were used to compare absolute offsets with the variability in walking speed, independently for each method and event type (i.e., heel strike and toe off). For this evaluation, coefficients of variation (CV=100*standard deviation/mean) in walking speed were computed throughout the 2-minute walking trial (in 20 s windows, to capture changes in speed across multiple strides), and compared to the calculated offsets within each respective 20 s window. All data were processed within Visual3D (C-Motion, Germantown, MD, USA). Values below are reported as means (standard deviations).

3. Results

Uninjured participants walked at 1.27 (0.18) m/s with a CV of 2.6 (1.3) %. There were 1183 unique heel strike and 1162 unique toe-off events, of which 113 and 137, respectively, were discarded due to belt cross-over (i.e., lacked reliable kinetic information for method comparisons). Heel strike events preceded GRF-based estimates when using horizontal foot position, horizontal foot velocity, and sagittal resultant foot velocity, while those detected from the vertical foot velocity method were more consistent with GRF-based estimates (Table 1). Toe-off events were more consistent with GRF-based estimates when using horizontal foot position and velocity, while toe-off events preceded GRF-based estimates using vertical foot velocity and sagittal resultant foot velocity (Table 1).

Participants with TTA walked at 1.11 (0.33) m/s with a CV of 11.9 (7.3) %. There were 1371 unique heel strike and 1382 unique toe-off events, of which 141 and 311, respectively, were discarded due to belt cross-over. Similar to uninjured participants, prosthetic/intact heel strike events preceded GRF-based estimates when using horizontal foot position, horizontal velocity, and sagittal

Table 1
Overall mean (SD) offset, in frames, for heel strike and toe off events between each kinematic method relative to vertical ground reaction force (negative/positive values indicate events determined before/after, respectively). Methods: (1) Horizontal foot position (Zeni et al., 2008); (2) absolute horizontal foot velocity (Zeni et al., 2008); (3) vertical foot velocity (O'Connor et al., 2007); and (4) sagittal resultant foot velocity (Ghoussayni et al., 2004), using detection thresholds adjusted for walking speed (Bruening and Ridge, 2014). Values with dissimilar superscripted letters indicate significant differences in offsets between methods (within a particular limb and event type).

Offset (frames)		Method 1	Method 2	Method 3	Method 4
Heel Strike					
	Uninjured	−4.9 (1.6)[a]	−4.0 (1.7)[a]	0.2 (1.1)[b]	−2.7 (1.4)[a]
	Prosthetic	−5.0 (1.0)[a]	−4.4 (0.8)[a]	−0.5 (1.1)[b]	−2.9 (1.3)[c]
	Intact	−4.2 (1.2)[a]	−3.7 (1.0)[a]	0.4 (1.4)[b]	−2.3 (1.0)[bc]
Toe Off					
	Uninjured	−0.5 (1.3)[a]	−0.3 (1.4)[a]	−3.1 (1.9)[b]	−0.7 (1.0)[a]
	Prosthetic	0.6 (0.8)[a]	1.0 (1.5)[a]	−2.5 (1.6)[b]	−1.5 (0.9)[b]
	Intact	−0.1 (1.1)[a]	0.5 (1.0)[a]	−4.5 (0.6)[b]	−1.8 (0.6)[c]