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Evaluation of Kinematic Methods of Identifying Gait Events during Running

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Abstract. Gait analysis necessitates the identification of foot-strike and toe-off events. This is characteristically achieved using force-platforms. However, when force data is unavailable, alternative methods are necessary. Several kinematic algorithms have emerged, but their effectiveness has yet to be validated for running gait. The rationale for this investigation is to contrast the timing of kinematically predicted events to those detected using force data.

Synchronized vertical ground reaction force recordings and lower extremity kinematics of five trials from eleven participants running at 4.0ms^{-1}±5% were recorded. From these eight kinematic algorithms, heel-strike and toe-off events were defined and compared using repeated-measures ANOVA’s.

Heel-strike was most accurately determined using the Alton *et al.* (1998) O’Connor *et al.* (2007) and Dingwell *et al.* (2001) methods. Toe-off was most accurately determined using the methods described by Dingwell *et al.* (2001) and Schace *et al.* (2003). Thus, an argument is presented for the utilization of these algorithms during running analysis when force data is unavailable.

Keywords: Gait events, Heel-strike, Toe-off, Algorithm, Kinematics.

1. Introduction

Gait analysis necessitates identification of both heel-strike and toe-off to define key components of the gait cycle. This is most accurately quantified using force platforms where a threshold is defined to determine heel-strike and toe-off (Hansen *et al*. 2002). However, this method is restricted to specific gait laboratories and relies on the ability of the participants to consistently make contact with the platform without altering their natural gait pattern (O’Connor *et al*. 2007). Additional methods such as footswitches, pressure sensors and accelerometers are also often utilized (Auvinet *et al*. 2002, Nillsson *et al,* 1985 and Hausdroff *et al*. 1995). However these methods may complicate the experimental procedure and introduce an extra source of error to the data as they need to be accompanied by additional devices and may reduce the number of available analogue channels (Mickelborough *et al.* 2001). It is therefore necessary to identify alternative methods of quantifying foot strike and toe-off during running analyses. Several kinematic methods are available for gait event determination, yet comparisons of their accuracy in defining stance phase events have, yet to be reported.

Mickelborough *et al*. (2001) developed a method of determining gait events during walking. Heel-strike was associated with the second of the W shaped minima of the foot vertical velocity curve in the Z (vertical) axis whilst toe-off was determined as the minimum position of the toe-markers in the Z axis. O’Connor *et al*. (2007) developed the foot velocity algorithm, whereby heel-strike was associated with the first trough of the foot segment velocity in the Z (vertical) axis and toe-off was associated with the peak foot segment velocity in the Z (vertical axis). Alton *et al*. (1998) used the minimum position of the lateral malleolus in the Z axis in order to determine footstrike. Toe-off was defined using the same method as Mickelborough *et al.* (2001) via the position of the metatarsal markers in the Z axis. Similarly, Zeni *et al*. (2008) proposed two methods of identifying gait events. The first used the difference in displacement of the peaks and troughs of sacral and foot markers in the sagittal plane. The second method is a velocity based technique. The velocity of the heel marker in the sagittal plane changes from positive to a negative direction at each heel strike. The frame at which backward movement of the foot is initiated is termed heel-strike. At the initiation of swing phase the velocity of the heel or toe markers alters from negative to positive and is thus labelled toe-off.

Hreljac and Stergiou (2000) utilized shank and foot motion in the sagittal plane. They determined foot strike as the time that coincided with the minimum sagittal plane foot angular velocity, and toe-off as the local minimum of the shank angular velocity. Schace *et al.* (2001) utilized the vertical velocity and displacement of the foot markers to identify gait events for overground and treadmill running. Heel strike was deemed to be the time of the downward spike of the vertical velocity of the 1st metatarsal and the plateau in the displacement of the lateral malleoli marker in the Z axes. Toe-off was deemed to be the onset of the rise in vertical displacement and velocity of the 1st metatarsal marker. Finally, Dingwell *et al.* (2001) provided a kinematic method designed specifically for treadmill running. Foot strike was deemed to be the first time when peak knee extension occurred and toe-off was determined as the second occurrence of peak knee extension.

Of the eight computational algorithms presented Zeni *et al.* (2008) were the only authors that validated their technique against force platform information. As such the overall objective of this investigation was to illustrate the most accurate means of predicting heel strike and toe-off during running, by contrasting the computationally predicted events to those detected using force data.

2. Methods

2.1. Participants

Eleven male participants volunteered to take part in this investigation (age 19 ± 1 years; Height 1.77 ± 0.52 m; Mass 78.4 ± 9.0 kg). A statistical power analysis was conducted in order to reduce the likelihood of a type II error and determine the minimum number of participants needed for this investigation. It was found that the sample size was sufficient to provide more that 80% statistical power in the experimental measure. Ethical approval for this project was obtained from the School of Psychology ethics committee, and each participant provided written consent in accordance with the declaration of Helsinki.

2.2. Procedures

Participants completed five trials, running at 4.0 $m.s^{-1}$ along a 20 m runway striking the centre of a force platform (Kistler, Kistler Instruments Ltd; Model 9281CA), sampling at 1000 Hz. Timing gates Newtest 300 (Newtest, Oy Koulukatu 31 B 11 90100 Oulu Finland) were used to monitor running velocity, a maximum deviation of ±5% from the specified velocity was allowed. Kinematic data were obtained via an eight camera infra red motion analysis system (Qualisys 300 Medical AB, Goteburg, Sweden) operating at 350Hz. Dynamic calibration of the system was performed prior to each data collection session. Calibrations which produced residuals of less than 0.85 mm and points above 4000 for each camera from a 750.5mm wand length were accepted prior to data collection.

The marker set used for the study was based on the CAST technique (Cappozo *et al.* 1995). Retro-reflective markers were attached to the 1st and 5th metatarsal heads, medial and lateral maleoli, medial and lateral epicondyle of the femur, greater trochanter, iliac crest, anterior superior iliac spines and posterior superior iliac spines in order to define the pelvis, thigh, foot and tibial segments. Tracking clusters were also positioned on the shank and thigh of left and right legs. A static trial was conducted with the participant in the anatomical position in order for the positions of the anatomical markers in relation to the tracking clusters to be recorded, following which markers not used for tracking the segments during motion were removed.

Kinematic parameters were quantified using Visual 3-D (C-Motion Inc, Gaithersburg, USA) after being filtered at 10 Hz using a low pass Butterworth 4th order zero-lag filter. Angles were created using an XYZ rotation cardan sequence referenced to coordinate systems about the proximal end of the segment, where X is flexion-extension; Y is ab-adduction and is Z is internal-external rotation. Plots of vertical force were produced from which heel strike and toe-off events were identified, specifically heel strike was quantified as the first instance at which the vertical component of the GRF was greater than 20N; toe-off was determined to be the first instance in which the vertical GRF fell below 20N.

Both average and absolute errors were quantified for each of the event detection methods as either the net or absolute discrepancy between kinematic and force event times. These errors were averaged across the five trials for each runner and across all runners. A positive value represented an event defined after the event established from the force data and a negative value represented an event defined prior to the force plate event. The difference in the time of occurrence in milliseconds was then tabulated in Excel (Microsoft Corp., Redmond, WA, USA).

2.3. Statistical Analysis

The statistical differences of both average and absolute errors between the kinematic methods were examined using a repeated measures analysis of variance with significance accepted at the ($p \leq 0.05$) level. Post hoc analyses were conducted using a Bonferoni correction to control for type I error. The Shapiro-Wilk statistic for each condition confirmed that the data were normally distributed and the sphericity assumption was met in all cases. All statistical procedures were conducted using SPSS 17.0.

3. Results

Tables 1 and 2 present average and absolute errors relative to force data for heel-strike and toe-off with respect to the methods studied. For heel-strike a significant main effect was found for both absolute $F_{(7, 63)} = 33.72$, $p \leq 0.01$, $eta^2 = 0.79$ and average error $F_{(7, 63)} = 42.20$, $p \leq 0.01$, $eta^2 = 0.82$. Post-hoc analysis revealed that the Alton et al. (1998), O'Connor et al. (2007) and Dingwell et al. (2001) algorithms were associated with significantly $p \leq 0.05$ lower average and absolute errors. For toe-off a significant main effect for both absolute $F_{(7, 63)} = 4.51$, $p \leq 0.05$, $eta^2 = 0.33$ and average error $F_{(7, 63)} = 4.35$, $p \leq 0.05$, $eta^2 = 0.33$ was found. Post-hoc analysis indicated that the Dingwell et al. (2001) and Schace et al. (2001) algorithms were associated with significantly $p \leq 0.05$ lower average and absolute errors.

4. Discussion

The aim of this investigation was to identify the most appropriate algorithms for the determination of heel-strike and toe-off using kinematic techniques during overground running. A reliable algorithm must be both reliable and accurate allowing the gait cycle to be separated into phases of stance and swing.

The results suggest that heel-strike and toe-off during running are most accurately determined using algorithms from different manuscripts. Heel-strike was most accurately determined using the Alton *et al.* (1998), O'Connor *et al.* (200)7 and Dingwell *et al.* (2001) algorithms, which use the position of the lateral malleolus marker, foot velocity algorithm and the first incidence of peak knee extension. Toe-off was most appropriately determined via the Dingwell *et al.* (2001) and Schace *et al.* (2001) knee extension and 1st metatarsal velocity method. The mean errors for event detection appear to correspond to those reported by other studies, with the exception of the Mickelborough *et al.* (2000) method which was confounded by repeatability issues. That is, the vertical velocity of the foot markers often exhibited multiple maxima and/or minima causing gait events to be located incorrectly. This is common when applying algorithms designed for walking to running data.

In conclusion the Alton *et al.* (1998), Dingwell *et al.* (2001), O'Connor *et al.* (2007) and Schace *et al.* (2001) event detection methods represent simple and robust methods for determining heelstrike and toe-off events during running that do not require 3-D analysis to employ. An argument is therefore presented for the utilization of these algorithms when force data is unavailable. Additional work is required to determine the applicability of these algorithms to treadmill and pathological locomotion.

Conflict of Interest Statement

No conflict of interest.

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Table 1: Average and absolute Error (ms) of heel-strike determination methods (means, standard deviation, minimum maximum and 95% confidence intervals).

		Schace	***Alton***	***Dingwell***	***Mickelborough***	***Hreljac***	***Zeni A***	***Zeni B***	***O'Connor***
True error (ms)	*mean*	*-40.17*	*15.84*	*-28.43*	*295.02*	*-57.34*	*-47.87*	*2.82*	*12.82*
	std.dev	*47.38*	*11.36*	*17.35*	*126.63*	*42.71*	*21.90*	*72.82*	*15.55*
	max	*21.66*	*40.00*	*17.30*	*472.30*	*16.70*	*-11.00*	*176.90*	*50.00*
	min	*-104.29*	*3.00*	*-45.00*	*66.40*	*-113.20*	*-92.00*	*-58.30*	*-1.40*
	95% C.I	*-74.0/-6.27*	*7.72/23.96*	*-40.8/-16.02*	*204.43/385.61*	*-87.89/-26.79*	*-63.54/-32.20*	*-49.27/-54.91*	*1.63/23.95*
Absolute error (ms)	*mean*	*45.83*	*15.84*	*31.89*	*295.02*	*62.82*	*47.87*	*53.40*	*14.22*
	std.dev	*41.28*	*11.36*	*8.31*	*126.63*	*33.05*	*21.90*	*46.29*	*18.83*
	max	*104.29*	*40.00*	*45.00*	*472.30*	*113.20*	*92.00*	*176.90*	*62.50*
	min	*3.33*	*3.00*	*17.30*	*66.40*	*10.70*	*11.00*	*10.20*	*1.40*
	95% C.I	*16.30/75.36*	*7.72/23.96*	*25.95/37.83*	*204.43/385.61*	*39.18/86.46*	*32.30/63.54*	*20.29/86.51*	*0.75/27.69*

Table 2: Average and absolute Error (ms) of toe-off determination methods (means, standard deviation, minimum maximum and 95% confidence intervals).

		Schace	***Alton***	***Dingwell***	***Mickelborough***	***Hreljac***	***Zeni A***	***Zeni B***	***O'Connor***
True error (ms)	*mean*	*-45.77*	*-80.59*	*10.99*	*-80.59*	*-97.32*	*2.23*	*45.46*	*-123.47*
	std.dev	*25.48*	*71.86*	*14.19*	*71.86*	*82.62*	*118.55*	*146.46*	*124.66*
	max	*20*	*87.1*	*43.5*	*87.1*	*10.0*	*112.4*	*153.3*	*46.7*
	min	*-80.70*	*-170.2*	*-8.3*	*-170.2*	*-260*	*-265.0*	*-332.0*	*-276.3*
	95% C.I	*-63.99/-27.54*	*-131.99/-29.19*	*0.84/21.14*	*-131.99/-29.19*	*-156.42/-38.22*	*-82.57/87.03*	*-59.31/150.23*	*-212.65/-34.29*
Absolute error (ms)	*mean*	*49.77*	*98.01*	*13.27*	*98.01*	*100.74*	*89.93*	*123.98*	*135.90*
	std.dev	*14.99*	*41.31*	*11.82*	*41.31*	*77.93*	*71.22*	*81.66*	*109.37*
	max	*80.7*	*170.2*	*43.5*	*170.2*	*260.0*	*265.0*	*332.0*	*280.12*
	min	*20.0*	*43.3*	*3.1*	*43.3*	*7.1*	*3.30*	*39.01*	*0.40*
	95% C.I	*39.05/60.49*	*68.46/127.56*	*4.81/21.79*	*68.46/127.56*	*44.99/156.48*	*38.98/140.88*	*65.56/182.40*	*57.65/214.13*