Gait & Posture 42 (2015) 101–103

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Short Communication

Using horizontal heel displacement to identify heel strike instants in normal gait

Jacob J. Banks [a,*], Wen-Ruey Chang [a], Xu Xu [a], Chien-Chi Chang [b]

[a] Liberty Mutual Research Institute for Safety, Center for Physical Ergonomics, 71 Frankland Road, Hopkinton, MA 01748, USA
[b] Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC

ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form 19 March 2015
Accepted 23 March 2015

Keywords:
Gait events
Comparison
Walking speed
Overground
Stance

ABSTRACT

Heel strike instants are an important component of gait analyses, yet accurate detection can be difficult without a force plate. This paper presents two novel techniques for kinematic heel strike instant (kHSI) detection which examined maximal resultant horizontal heel displacement (HHD). Each of these HHD techniques calculates HHD from a selected reference location of either the stance ankle or stance heel to the swing heel. The proposed techniques, along with other previously established techniques, were validated against a 10 N force plate threshold. Fifty-four healthy adults walked overground at both normal and fast speeds while wearing athletic shoes. The reported true and absolute errors were as low as 3.2 (4.4) and 5.7 (3.4) ms, respectively, across 8678 kHSI when using the stance ankle as a reference, which significantly outperformed ($p < 0.0001$) the established techniques. Gait speed was shown to have a significant effect ($p < 0.0001$) on HHD-determined kHSI, as well as the three other techniques evaluated, highlighting the need for condition-specific identification of kHSI.

1. Introduction

Proper detection of heel strike instants is critical in studying human gait. A force plate is conventionally used to identify heel strike instants (fHSI) by detecting a minimum vertical ground reaction force threshold of 5, 10, or 20 N [1–9]. Without a force plate, researchers can develop techniques based on kinematics to determine heel strike instants (kHSI) for overground gait. Notable techniques are those focusing on changes in foot marker variables like heel height, heel velocity, heel vertical acceleration, swing foot horizontal displacement, filtered displacement of two foot markers, hip extension, or a heel velocity threshold [1–9]. These techniques have demonstrated varying degrees of accuracy, with average errors of 0.6–27.0 ms when compared with fHSI [7,8]. Most of these studies were validated with relatively small sample sizes [5–7] or at only one gait speed [1–4 and 6–8]. This could be problematic because of observed participant variability [10] and gait speed effects on kinematics [11,12], both of which could affect kHSI accuracy. Due to the inherent variation within and across participants, as well as emerging technologies in data collection, the search for alternative techniques remains.

In normal gait, heel strikes occur at roughly the same instant as the horizontal heel displacement (HHD) reaches a maximum. In the current study, it was hypothesized that using a location on the stance foot's ankle or heel, rather than the sacrum or ASIS [6,13], may improve the identification of kHSI. A second hypothesis is that gait speed, via its recognized effect on gait parameters [11,12], would affect the technique's ability to identify kHSI. The proposed techniques were validated with a large dataset of healthy adults wearing athletic shoes walking overground. The subsequent kHSIs were compared, along with three other techniques [5–7], with fHSI.

2. Methods

2.1. Participants, setup and procedure

The dataset used was from a previous study [14]. Fifty-four healthy adults (28 females, 26 males, 44.7 ± 13.2 years, 166.5 ± 10.1 cm, and 73.2 ± 14.2 kg) gave their informed consent to a protocol approved by an institutional review board. Participants walked back and forth on a 12.2 m long, dry quarry-tiled walkway incorporating three Kistler force plates (Amherst, New York) while wearing athletic shoes. A motion tracking system (Motion Analysis

* Corresponding author. Tel.: +1 5084970214.
E-mail addresses: jacob.banks@libertymutual.com (J.J. Banks), wen.chang@libertymutual.com (W.-R. Chang), xu.xu@libertymutual.com (X. Xu), max.chang@ie.nthu.edu.tw (C.-C. Chang).

http://dx.doi.org/10.1016/j.gaitpost.2015.03.015
0966-6362/

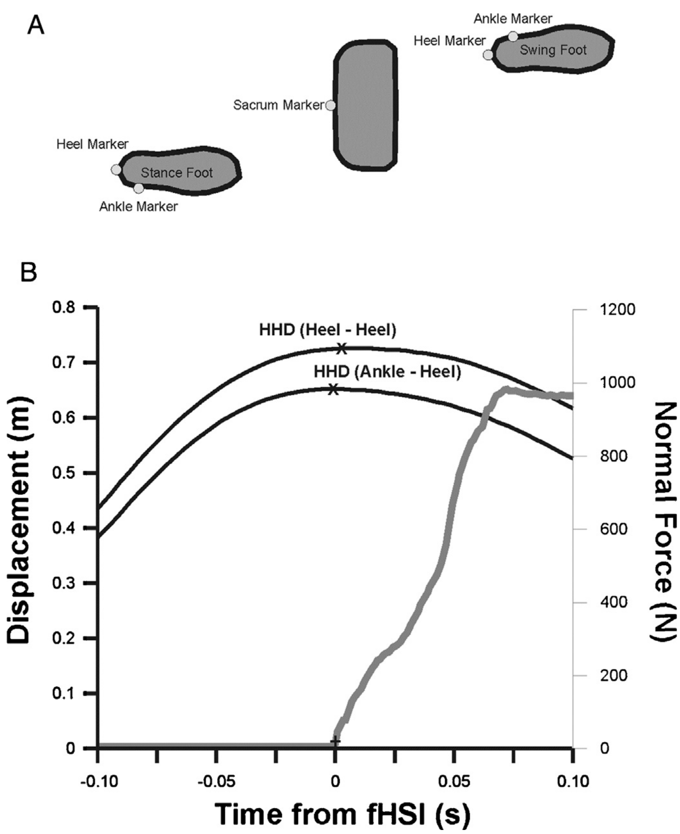

Fig. 1. (A) Illustration of markers used and their placement. (B) Experimental data from a select trial comparing the two different horizontal heel displacement (HHD) technique peaks (X) along with their corresponding force plate-determined heel strike instants (+).

Corporation, Santa Rosa, CA) recorded markers positioned on the sacrum, both lateral malleoli, and each shoe heel (Fig. 1). Synchronized force plate and motion data were sampled at 1000 and 250 Hz, respectively. Each participant walked under two conditions: self-selected fast and normal gait speeds.

2.2. Techniques for identifying kHSI

kHSIs were determined via two proposed HHD techniques which identified the instant the resultant horizontal distance between the heel marker of the swing foot and a reference marker located on the stance limb reached a maximum during a gait cycle (Fig. 1). Two reference locations on the stance limb were investigated: the heel ("Heel–Heel") and lateral ankle ("Ankle–Heel"). The motion data were processed with a zero-lag fourth order low pass Butterworth filter at 12 Hz. Each maximum was refined by a linear interpolation at the zero-crossing of the respective derivative. In addition, three other established techniques incorporating the swinging heel, calculated with original specifications, were applied to the current dataset. These techniques identified kHSI via heel vertical acceleration [5], peak distance between the heel and sacrum [6], or a filtered heel displacement [7].

2.3. Data analysis

Matlab (Mathworks, Natick, MA) was used to analyze the kinematic data. Gait speed was the instantaneous sacral marker horizontal velocity. The aforementioned procedures were applied to the data to determine kHSIs for each technique. The resulting kHSIs were then compared with corresponding fHSIs to determine the error. A successful fHSI occurred when the normal force exceeded 10 N and the participant's heel was within the bounds of a force plate. The true error (TE) was defined as kHSI minus fHSI, while the absolute error (AE) was the TE magnitude. Average error and standard deviations were calculated from the subject averages. A mixed linear model with fixed and random effects was applied to the TE using the *proc mixed* procedure in SAS 9.3 (SAS Institute Inc., Cary, NC). A three-way ANOVA with repeated measures and interaction was used. The technique and speed were considered as fixed effects and participants as a random effect, interaction technique*speed was included in the analysis ($p \leq 0.05$, for significance). A post hoc analysis with a Bonferroni adjustment for multiple comparisons was done for the technique variable.

3. Results

In all, 8678 successful heel strikes were analyzed. The means and standard deviations of the normal (4190 trials) and fast (4488 trials) speeds were 1.4 (0.16) and 1.9 (0.22) m/s, respectively. Averages and standard deviations of TE and AE from all the techniques are shown in Table 1. The three-way ANOVA indicated that technique had a significant effect ($p < 0.0001$). Effects of gait speed and its interaction with a technique were statistically significant ($p < 0.0001$). The post hoc analysis demonstrated statistically significant differences among all five techniques ($p < 0.0001$). The two proposed HHD techniques outperformed all other algorithms with the HHD Ankle–Heel technique demonstrating the least TE and AE. Histograms of the TE from all technique and speed conditions are shown in Fig. 2.

4. Discussion

Our two HHD techniques outperformed three other established techniques [5–7] in determining kHSI when compared with fHSI. The HHD Ankle–Heel technique achieved a mean TE and AE of 3.2 and 5.7 ms, respectively. While kHSI from the Heel–Heel technique also improved upon existing techniques, the heel's upward rotation about the ankle seems to delay the timing of the horizontal maximum. The stance ankle demonstrated added accuracy by focusing on more of the translational motion in the stance limb prior to heel strike.

The results demonstrated, in four of the five techniques, a reduced error in the faster speed condition. The association between speed and kHSI detection agrees with that found by Kiss

Table 1
Mean and standard deviation of true and absolute error for all techniques against force plate-determined values across both fast and normal gait speeds.

Algorithm type	True error (ms)			Absolute error (ms)		
	All	Fast	Normal	All	Fast	Normal
HHD (Heel–Heel)	8.6 (4.4)	7.1 (4.1)	10.1 (4.7)	9.5 (4.0)	8.2 (3.6)	10.7 (4.3)
HHD (Ankle–Heel)	3.2 (4.4)	2.9 (4.2)	3.5 (4.6)	5.7 (3.4)	5.4 (3.2)	6.0 (3.5)
Heel vertical acceleration [5]	11.5 (5.3)	12.2 (5.9)	10.8 (4.8)	12.0 (4.8)	12.7 (5.2)	11.3 (4.4)
Sacrum–heel [8]	−20.6 (5.3)	−19.5 (5.1)	−21.7 (5.5)	20.6 (5.3)	19.5 (5.1)	21.7 (5.5)
Filtered heel displacement [9]	−46.9 (12.9)	−45.4 (15.5)	−48.5 (10.2)	47.8 (11.0)	47.1 (11.9)	48.6 (10.1)

Note: A positive true error value indicates the kHSI detection occurred after fHSI.

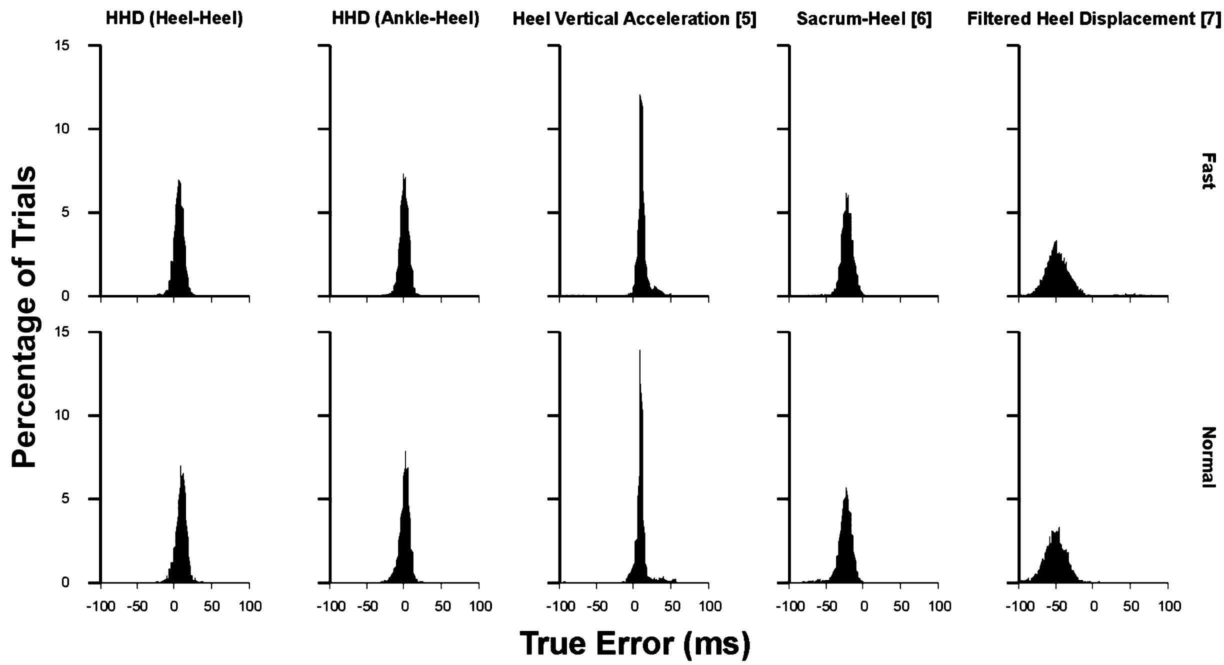

Fig. 2. Histograms depicting true error (ms) vs. percentage of trials (%) for all techniques across both fast and normal gait speed conditions.

[13], but differs from others [5,9] whom found no such impact. These conflicting effects of gait speed on kHSI detection could be attributed to inter- and intra-participant variability, the kHSI technique, and/or sample sizes differences.

Ideally, prior to data analysis, a comparison should be performed to evaluate which of the numerous techniques [1–9], along with the two proposed here, perform the best with a given dataset. Such specificity may become even more important when evaluating clinical patients, treadmill trials, or emerging tracking technologies. One can hypothesize that in cases using accelerometers or focusing on clinical data, where precise segment locations or a predictable gait pattern are typically absent, the proposed techniques may not be applicable. As techniques mature, some of these concerns could be diminished. We examined a healthy population walking overground in a controlled motion tracking laboratory; therefore, the efficacy in alternative circumstances remains unknown. Also, the impact of these kHSI detection errors on specific gait parameters and their practical significance ought to be determined in future research.

In this study, we demonstrated the capability of novel HHD techniques to identify kHSI in healthy adults walking overground. A technique which references the swinging heel to the stance ankle revealed the lowest error with respect to the fHSI when compared with previous techniques [5–7]. Walking faster improved the accuracy of the technique.

Conflict of interest

None.

References

[1] Alton F, Baldey L, Caplan S, Morrissey MC. A kinematic comparison of overground and treadmill walking. Clin Biochem 1998;13(6):434–40.
[2] O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. Automatic detection of gait events using kinematic data. Gait Posture 2007;25(3):469–74.
[3] Mickelborough J, van der Linden ML, Richards J, Ennos AR. Validity and reliability of a kinematic protocol for determining foot contact events. Gait Posture 2000;11:32–7.
[4] Salazar-Torres JJ. Validity of an automated gait event detection algorithm in children with cerebral palsy and non-impaired children. Gait Posture 2006;24S:S130.
[5] Hreljac A, Marshall RN. Algorithms to determine event timing during normal walking using kinematic data. J Biomech 2000;33(6):783–6.
[6] Zeni Jr JA, Richards JG, Higginson JS. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait Posture 2008;27(4):710–4.
[7] Desailly E, Daniel Y, Sardain P, Lacouture P. Foot contact event detection using kinematic data in cerebral palsy children and normal adults gait. Gait Posture 2009;29(1):76–80.
[8] De Asha AR, Robinson MA, Barton GJ. A marker based kinematic method of identifying initial contact during gait suitable for use in a real-time visual feedback application. Gait Posture 2012;36:650–2.
[9] Ghoussayni S, Stevens C, Durham S, Ewins D. Assessment and validation of a simple automated method for the detection of gait events and intervals. Gait Posture 2004;20:266–72.
[10] Owings TM, Grabiner MD. Measuring step kinematic variability on an instrumented treadmill: how many steps are enough? J Biomech 2003;36(8):1215–8.
[11] Chung MJ, Wang MJ. The change of gait parameters during walking at different percentage of preferred walking speed for healthy adults aged 20–60 years. Gait Posture 2010;31(1):131–5.
[12] Novacheck TF. Walking, running, and sprinting: a three-dimensional analysis of kinematics and kinetics. AAOS Instr Course Lect 1995;44:497–550.
[13] Kiss RM. Comparison between kinematic and ground reaction force techniques for determining gait events during treadmill walking at different speeds. Med Eng Phys 2010;32:662–7.
[14] Chang WR, Matz S, Chang CC. Stochastic distribution of the required coefficient of friction for level walking-an in-depth study. Ergonomics 2012;55(8):937–45.