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Detection of swing heel-off event in gait initiation using force-plate data

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Abstract

This study investigated the accuracy and reliability of four methods using force-plate data for detecting the swing heel-off (HO) time in gait initiation. Results of these methods were compared to those obtained by means of a reference method using a footswitch. Ten young healthy adults performed 18 forward gait initiation trials at self-selected speed and at maximal speed. Results showed that the method based on vertical impulse was the most accurate and reliable in determining HO in both speed conditions. The mean error obtained with this method was -8 ± 10 ms in the self-selected speed condition (-7 ± 10 ms in the maximal speed condition), with no significant effect of gait speed ($P > 0.05$). These findings suggest that this method based on force-plate data is valid and reliable for detecting HO in forward gait initiation in the absence of additional hardware.

Keywords: Heel-off detection; Force-plate; Anticipatory Postural Adjustments; Gait initiation; Ground reaction force.

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1. Introduction

Gait initiation, which is the transition between the upright stance and the steady-state gait, is a classical paradigm to investigate the coordination between posture and movement. In this process, the swing heel-off (HO) time delineates the postural phase (the so-called “anticipatory postural adjustments” (APA)) with the execution phase [1]. The exact detection of the HO event is crucial for quantifying APA features, i.e. duration and amplitude.

In most studies, force-plates are used for biomechanical analysis of gait initiation, e.g. to determine the dynamics of the centre of pressure (CP) [1, 2] and the centre of gravity (CG) [1]. Furthermore, additional hardwares such pressure sensors or footswitches are usually used to detect the HO event [1, 3]. Although these devices are effective, they may hinder natural gait development [4]. They also reduce the number of channels available for the simultaneous collection of analogue data (e.g., electromyography) [5]. An alternative method using kinematic data has been proposed [5], but the cost and the complexity of collecting measurements of motion capture systems limit its use [6].

To avoid these limitations, many studies use only force-plate data to detect HO. Several methods based on CP displacement [2, 7, 8] or CG vertical dynamics [9] have been described in the literature. Nevertheless, it appears from these studies that there is no clear consensus on the method to be used to detect this instant. The questions of whether the accuracy and reliability of these methods are equivalent and how they compare with the footswitch, the hardware regularly used, remain open.

The aim of this study was to assess the accuracy and reliability of four force-plate methods (three methods previously reported in the literature and a novel method) to detect HO and to compare their performance with a reference method using a footswitch.

2. Methods

Ten healthy subjects (eight males and two females, age 23 ± 2 years (mean \pm standard deviation [SD]), height 173 ± 9 cm, weight 72 ± 11 kg) were recruited for this study after being fully informed of the experimental procedure approved by the local ethics committee.

Each subject initially stood upright, barefoot and motionless on a force-plate (40×60 cm, AMTI, USA). Beforehand, a footswitch (25 mm, Biometrics, France) was secured to the force-plate under the heel of the swing foot. To ensure that subjects returned to the same initial position after each trial, the foot positions were outlined on the force-plate. A second force-plate was positioned in front of the subject at a distance appropriate for the swing foot

to step onto it. At the experimenter's signal, subjects initiated gait and continued walking straight ahead along a 5-metre walkway. The swing leg was self-selected and remained the same throughout the experiment. Each subject performed series of 18 trials in two gait speed conditions: a self-selected speed and a maximal speed. Three practice trials were performed in each condition before the recordings. The order of the speed conditions was randomized across subjects.

The first force-plate was used to detect the HO time; the second force-plate was simply used to obtain all reaction forces during the entire gait initiation time-window (Fig. 1). The force-plate and footswitch signals, sampled to 1 000 Hz, were transmitted to an acquisition system and synchronized. Before analysis, the force-plate data were low-pass filtered at 10 Hz [3] with a fourth-order zero-lag Butterworth filter. The mediolateral CP coordinate (y_P) was calculated from force-plate data and was corrected by the 250 ms baseline preceding the start signal [3]. Vertical impulse (I_z) was calculated by integrating (trapezoidal rule) the vertical ground-reaction force (F_z), after weight correction (Fig. 1). Calculation was performed with integration constant equal to zero, i.e. initial impulse null [1].

The reference HO time (HO_{ref}) was determined from the footswitch signal, as shown in Fig. 1(a). Four methods based on force-plate data were used to estimate the HO time. For each method, the HO event was detected manually by two experimented raters as illustrated in Fig. 1:

- *Method 1* detected HO when y_P first peaked towards the swing limb [2, 8] (b).
- *Method 2* identified HO when y_P changed sign [7] (c).
- *Method 3* predicted HO when F_z peaked downwards (based on [9]) (d).
- *Method 4* was custom-designed and detected HO when I_z peaked downwards (e).

The mean and standard deviation of the differences (errors) between the HO instant estimated by each of the four force-plate methods and that obtained by the footswitch method were calculated to assess the accuracy and reliability of these methods [10]. A positive value indicated that the HO time was delayed compared with the reference method while a negative value indicated it was early. The differences were expressed in milliseconds and as a percentage of APA duration (dAPA). APA duration was defined as the delay between the first dynamic phenomena (t_0) and HO time [1]. After checking for data normality with Kolmogorov-Smirnov test, Student's t -tests for paired samples were used to assess the effect of gait speed on the error made with each method. Threshold for significant difference was $P < 0.05$.

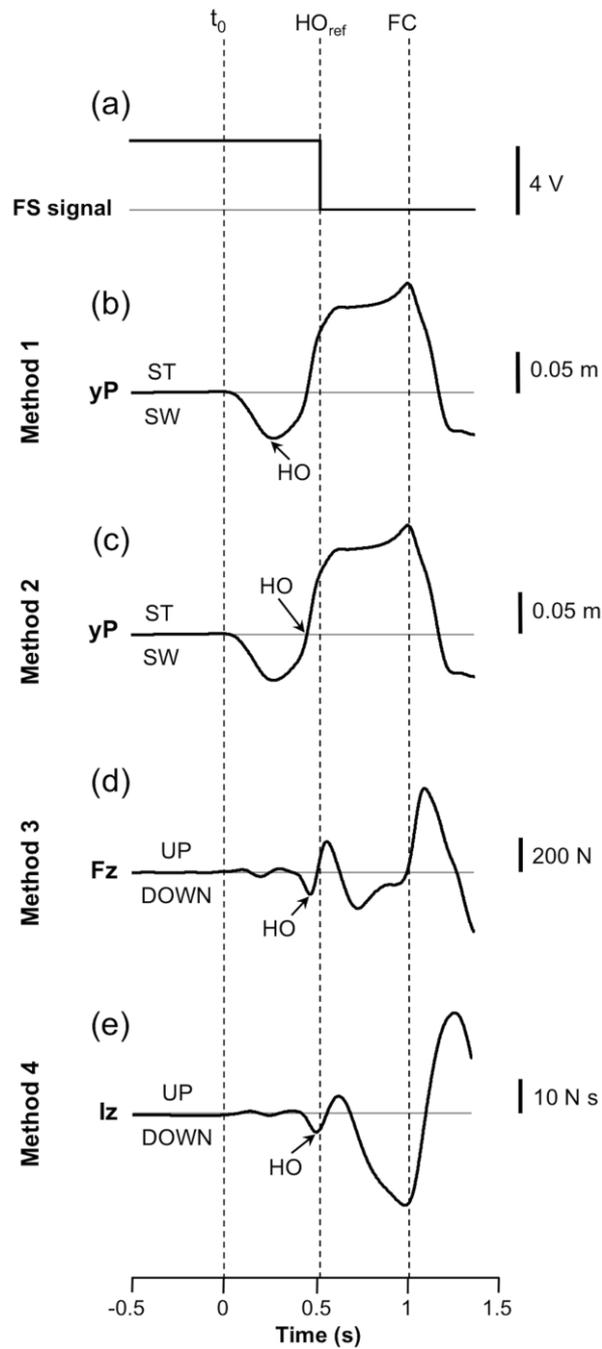


Fig. 1: Illustration of the various methods to detect the swing heel-off (HO) event. Traces are shown for one representative subject initiating gait at self-selected speed with the right leg. FS signal, y_P , F_z , I_z : footswitch sensor signal, mediolateral displacement of centre of pressure, vertical ground reaction force, vertical impulse, respectively. These traces were corrected by the 250ms baseline preceding the start signal. t_0 , HO_{ref} , FC were the onset variation of the y_P trace from the baseline, reference swing heel-off instant, and swing foot-contact, respectively. F, B, ST, SW, UP, DOWN indicate forward, backward, stance limb, swing limb, upward and downward respectively. The footswitch sensor signal was used to identify the reference HO time (HO_{ref}) (a). *Method 1* predicted HO when y_P reached its maximal value towards the swing limb (b). *Method 2* predicted HO when y_P changed sign (the first frame was considered) (c). *Method 3* identified HO when F_z peaked downwards (peak preceding the last downward peak) (d). And *Method 4* identified HO when I_z peaked downwards before the last (usually maximal) downward peak (e).

3. Results

Table 1 shows the differences (mean \pm SD) between the instants of HO predicted by each force-plate method and the reference timing identified from the footswitch sensor. The errors distribution for each method is illustrated as histogram in Fig. 2. On average, the methods detected HO earlier than the reference method (Table 1). In both gait speed conditions, *Method 4* provided the smallest mean error and SD among the tested methods (Table 1). The mean error on HO detection obtained with this method was -8 ± 10 ms in the self-selected speed condition and -7 ± 10 ms in the maximal speed condition, with no significant difference across conditions ($P > 0.05$). Note that this error corresponded to solely -1 ± 2 % of APA duration. In absolute terms, the errors of this method were less than 30 ms in 96% of trials in the self-selected speed condition (97% in the maximal speed condition; Fig. 2g and h).

In contrast to *Method 4*, statistical analysis revealed that the mean error (expressed in percentage of APA duration) significantly decreased with gait speed for *Method 1* ($t = -4.562$, $P < 0.01$), *Method 2* ($t = -2.762$, $P < 0.05$) and *Method 3* ($t = -3.250$, $P < 0.05$). When expressed in milliseconds, it significantly decreased with gait speed only for *Method 1* ($t = -2.974$, $P < 0.05$).

Table 1: The means and standard deviations (SD) of the differences between the instants of swing heel-off (HO) predicted by the various methods and the reference timing identified from the footswitch sensor, expressed in milliseconds (ms) and as a percentage of APA duration (%dAPA).

	Method 1	Method 2	Method 3	Method 4
<i>Self-selected Speed</i>				
Mean error \pm SD (ms)	-243 ± 86^a	-77 ± 42	-43 ± 15	-8 ± 10
Mean error \pm SD (%dAPA)	-40 ± 13^b	-13 ± 7^a	-7 ± 3^a	-1 ± 2
<i>Maximal Speed</i>				
Mean error \pm SD (ms)	-215 ± 83	-70 ± 37	-41 ± 13	-7 ± 10
Mean error \pm SD (%dAPA)	-34 ± 13	-11 ± 6	-6 ± 2	-1 ± 2

Method 1: algorithm identifying HO when the mediolateral displacement of the CP first peaked towards the swing limb. *Method 2:* algorithm identifying HO when the mediolateral displacement of the CP changed sign. *Method 3:* algorithm using the vertical ground reaction force. *Method 4:* algorithm using the vertical impulse.

^a: Significant difference self-selected versus maximal speed, $P < 0.05$

^b: Significant difference self-selected versus maximal speed, $P < 0.01$

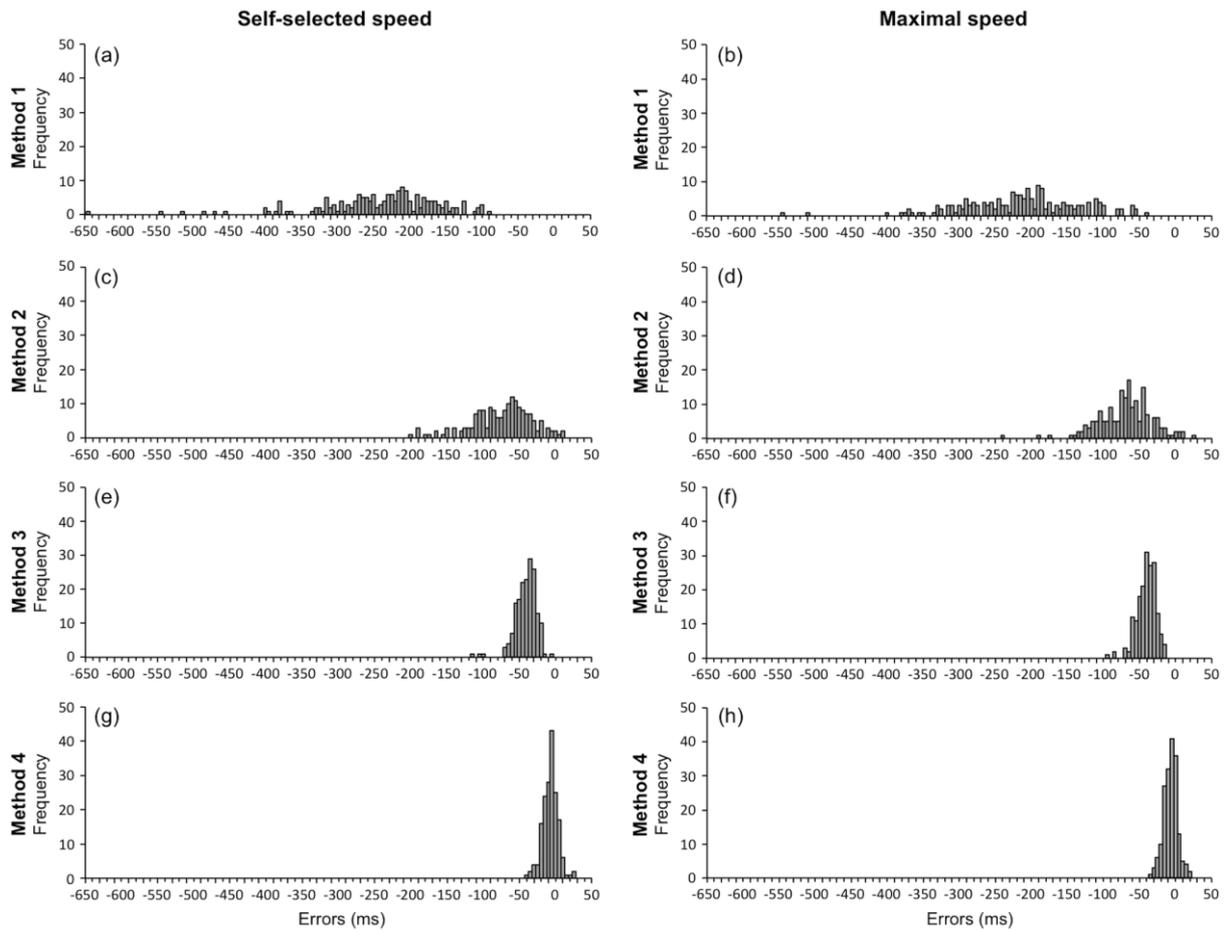


Fig. 2: Frequency distribution of errors for each method in the conditions of self-selected speed (left column) and maximal speed (right column).

4. Discussion

Globally, the methods detected HO earlier than the reference method. Some authors [6] had already reported this trend for *Method 2*. In the current study, *Method 4* presented the smallest error and SD whatever the gait speed, indicating that this method was the most accurate and reliable method to detect HO in those tested. The errors of this method were smaller than 30 ms in 96% of trials in the self-selected speed condition (97% in the maximal speed condition). It is noteworthy that these results are slightly better than those found using a kinematic method where errors are less than 30 ms in over 92.5% of the cases [5].

The high reliability and accuracy of *Method 4* might be ascribed to a causal link between the HO time and the marker used to detect this time (peak of downward I_z). HO is indeed associated with swing leg rise, which could act to attenuate the fall of the CG (classically described using the CG vertical velocity [11]) during the subsequent execution phase. In other words, it could be that the reversal of the negative vertical impulse might be ascribed to an

effect of the swing leg rise associated with HO. The fact that the accuracy and reliability of *Method 4* are speed-independent (in contrast to the other methods) is in agreement with this hypothesis.

Results further showed that SD values ranged from 10 ms (i.e. 2% of APA duration) with *Method 4* to 86 ms (13% of APA duration) with *Method 1* (Table 1). This range of SD values suggests that the reliability of the HO time measure (and therefore the reliability of APA spatio-temporal features) may strongly depend on the method used. Future studies on APA in gait initiation should therefore be cautious with regard to the method used to detect HO. Further investigation is also required to determine whether the present results apply to populations with gait disorders.

5. Conclusion

The results showed that the method based on vertical impulse was the most accurate and reliable for detecting HO time from force-plate data. In the absence of additional hardware, this method constitutes an attractive alternative to detect the swing heel-off time in forward gait initiation.

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