EXAMINATION OF A METHOD FOR DETECTION OF WALKING HEEL STRIKE AND TOE-OFF OVER A WIDE RANGE OF SPEEDS

Takuya Sugimoto[1] and Hidetaka Okada[1]

Department of Mechanical Engineering and Intelligent System,

The University of Electro-Communications, Tokyo, Japan [1]

This study examines a simple method to accurately detect heel strike (HS) and toe off (TO) timing over a wide range of walking speeds. HS was the moment when the heel passed a threshold in the downward direction. TO was the moment when the fifth metatarsal passed the threshold in the upward direction. The accuracies of these measurements were evaluated by comparing the moment acquired using a force platform. The root mean square (RMS) errors were 6.10 ms for HS and 15.6 ms for TO. These errors were smaller than those of previous studies. Furthermore, walking speed did not affect the detection precision in this method. Therefore, the detection method proposed in this study can detect HS and TO timing with better accuracy over a wide range of walking speed than previous methods.

KEY WORDS: kinematic data, inductive method, cross validation.

INTRODUCTION: In gait motion analysis, it is very important to detect heel strike (HS) and toe off (TO) in order to define the gait cycle and gait phases such as stance or swing. Foot switches or force platforms are often used to detect these event points. However, these apparatuses have problems such as (1) increased load of measurement, (2) limitations in experimental locations and conditions, and (3) apparatus costs. It is particularly difficult to use force platforms in experiments involving treadmills.
O'Connor et al. (2007) developed methods for detecting HS and TO based on the vertical velocity of the midpoint of the heel and fifth metatarsal, and Hreljac and Marshall (2000) developed methods for determining HS and TO based on the jerk (the derivative of acceleration) of the heel and fifth metatarsal. However, these studies did not consider walking speed despite its potential effect on the accuracy of the measurement.
This study proposed a method that could detect HS and TO from simple foot kinematic data and examined the accuracy of the detection over a wide range of speeds.

METHODS: A total of 266 healthy men and women (age: 21–86 yrs., height: 156.1 ± 9.0 cm, body mass: 59.0 ± 9.0 kg) walked at four different speeds (SW: slow walk, NW: normal walk, FW: fast walk, and MW: maximum-speed walk) on a walkway of approximately 8 m in length. The Subjects walked with their own shoes. Ground reaction force (GRF) was measured using a force platform embedded in the walkway. In this study, the points of timing for HS and TO acquired from the force platform were treated as true timings. Lower limb motion was measured using a video tape recorder (VTR) camera at 60 fps. Retro-reflective markers were placed on the head of fifth metatarsal and heel of the right leg of each subject. To detect HS and TO timing, thresholds were set in the vertical direction. HS was point of time when the heel passed the threshold in the downward direction. TO was point of time when the head of fifth metatarsal passed the threshold in the upward direction.
The vertical position of the heel at the true HS of each step was described by equation (1).

$$Y_{trueHS\_i} = Y_{heel\_\min\_i} + \Delta_{on\_i} \quad [m] \qquad (1)$$

Where Y_{trueHS_i} was the vertical position of the heel at the true HS for step i, $Y_{heel\_\min\_i}$ was the minimum vertical position of the heel during the step, and Δ_{on_i} was the difference between Y_{trueHS_i} and $Y_{heel\_\min\_i}$. Figure 1 shows the relationship between Δ_{on_i} and the walking speed. Because Δ_{on_i} was not significantly correlated with walking speed, the mean of Δ_{on_i} for all steps of all subjects was used to obtain the threshold. The threshold to detect HS was determined by equation (2).

$$Th_{on\_i} = Y_{heel\_\min\_i} + \Delta_{on\_mean} \quad [m] \quad (2)$$

Where Th_{on_i} was the threshold of HS for the step i. Δ_{on_mean} was $6.95 \cdot 10^{-4}[m]$.

The vertical position of the head of fifth metatarsal at the true TO of each step was described by equation (3).

$$Y_{trueTO\_i} = Y_{meta\_\min\_i} + \Delta_{off\_i} \quad [m] \quad (3)$$

Where Y_{trueTO_i} was the vertical position of the head of fifth metatarsal at the true TO for step i, $Y_{meta\_\min\_i}$ was the minimum vertical position of the head of fifth metatarsal during the step, and Δ_{off_i} was the difference between Y_{trueTO_i} and $Y_{meta\_\min\_i}$. Because Δ_{off_i} was significantly correlated (r=0.324, p<0.01) with walking speed (see Figure 1), $\Delta_{off\_regression\_i}$ was calculated by equation (4).

$$\Delta_{off\_regression\_i} = 1.40 \cdot 10^{-2} \cdot V_i + 4.67 \cdot 10^{-2} \quad [m] \quad (4)$$

Where V_i was walking speed [m/s].

The threshold to detect TO was calculated by equation (5).

$$Th_{off\_i} = Y_{meta\_\min\_i} + \Delta_{off\_regression\_i} \quad [m] \quad (5)$$

Where Th_{off_i} was the threshold of TO for step i.

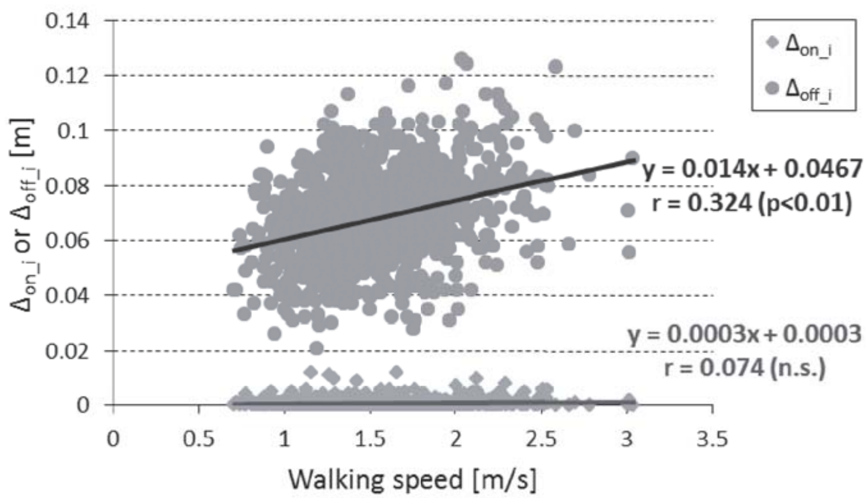

Figure 1: Relationships between Δ_{on_i}, Δ_{off_i} and walking speed

A similar experiment was conducted in a different subject group (n=25, age: 21–77 yrs, height: 158.2 ± 8.4 cm, body mass: 53.1 ± 8.6 kg) for examining the cross validation of this detection method. In this additional experiment, lower limb motion was measured by an optical motion capture system (Optitrack S250e, Natural Point Inc., USA) at 200 Hz.

RESULTS: Figure 2 shows the detection error of HS and TO for this study method and two previous studies method. These detection error were conducted from the experiment for the cross validation.

In this study, the estimation errors for HS and TO were 1.45 ± 5.92 and 1.45 ± 15.5 ms, respectively. The probability of HS and TO being detected with an estimation error of less than 15 ms among all trials was 97% and 80%, respectively. The root mean square (RMS) errors in this study were 6.10 ms for HS and 15.6 ms for TO. These errors were 21.9 and 23.7 ms using O'Connor's method, and 24.8 and 19.8 ms using Hreljac's method, respectively.

Our method had a smaller error than previous studies. Furthermore, the detection precision of this study was acquired over a wide range of speeds (0.75–2.41 [m/s]).

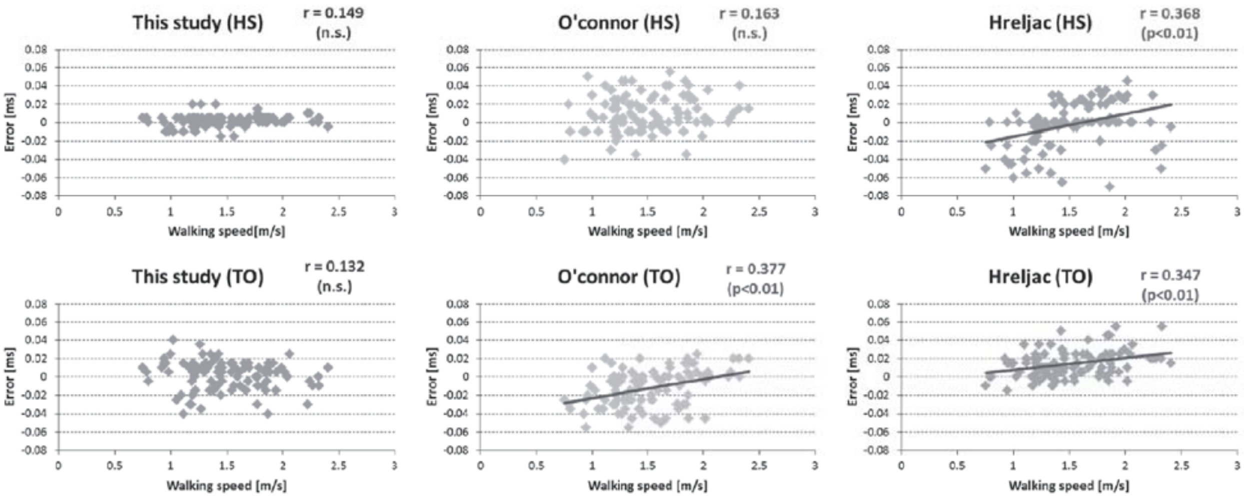

Figure 2: Relationships between detection error and walking speed for this study, O'Connor et al.(2007), and Hreljac and Marshall (2000)

DISCUSSION: This study did not demonstrate a correlation between walking speed and estimation error of HS similar to that of O'Connor's method, but Hreljac's method had an tendency in error plot in which the detection was later with increasing walking speed (see Figure 2). Thus, walking speed did not influence the detection error in this study method and in O'Connor's method, unlike in Hreljac's method. There was no correlation between the walking speed and estimation error of TO for this study method, but O'Connor's and Hreljac's methods had error tendencies towards early and late detection with changing walking speeds. Therefore, based on these results, the detection error in this study method was not influenced by the walking speed, unlike in O'Connor's and Hreljac's methods. In addition, these results seem to show a high cross validation of this method.
These findings suggest that the HS and TO detection method described in this study may be better than those described in previous studies and is more applicable over a wide range of walking speeds.

CONCLUSION: We proposed an inductive method that uses simple foot kinematic data to detect the timing of HS and TO. Our results suggest that this method can detect these timings with smaller errors than those of previous studies and is applicable over a wide range of walking speeds.

REFERENCES:

O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. (2007). Automatic detection of gait events using kinematic data, Gait & Posture, 25(3), 469-474.

Hreljac A, Marshall RN. (2000). Algorithms to determine event timing during normal walking using kinematic data, Journal of Biomechanics, 33(6), 783-786.