DETECTION OF FOOT CONTACT AND TOE-OFF USING KINEMATIC DATA FOR TREADMILL RUNNING OVER A WIDE RANGE OF SPEEDS

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The purposes of this study were to propose a method for simply and accurately detecting the foot contact and toe-off events during treadmill running over a wide range of speeds and to examine the validity and accuracy of the method. Three patterns of foot-strike were distinguished from the foot kinematic data. The thresholds for foot contact and toe-off were determined inductively based on the minimum height of the heel or metatarsal for each foot-strike pattern with regard to running speed. The estimate for foot contact and toe-off indicates that this method can apply over a wide range of speeds with high accuracy.

KEYWORDS: event determination, inductive method, foot-strike pattern

INTRODUCTION: It is very important to detect accurately the instant of foot contact and toe-off when analyzing locomotion. Foot switches, force platforms, photocells, and video cameras are usually used for the detection. However, using these devices means additional labor for measuring. Furthermore, some of these devices are expensive and sometimes their usage may be limited to specific situations and locations. For example, force platforms usually cannot be used in treadmill running. Some previous studies proposed determining them from kinematic data (Hreljac and Stergiou, 2000; De Witt, 2010). However, these methods are easily affected by error because they use the jerk or angular jerk for determination. Furthermore, they can be used only for a small range of speeds. The purposes of this study were to propose a method for simply and accurately detecting the foot contact and toe-off events during treadmill running over a wide range of speeds and to examine the validity and accuracy of the method.

METHODS: Subjects were 16 young males (22.3±1.6 yrs; 171.3±3.0 cm; 65.3±7.9 kg). Eight participants trained as sprinters or long-distance runners while the remained eight were untrained. They wore 10 retro-reflective markers on the head of the fifth metatarsal, heel, lateral malleolus, lateral epicondyle, and greater trochanter of both sides. They ran for 1 minute at 6 different constant speeds (150, 200, 250, 300, 350 and 400 m/min) on a level treadmill. Sufficient rest was taken between each set. Three dimensional coordinates of markers were recorded at 250 Hz with 10 cameras of an optical motion capture system (Optitrack S250e, NaturalPoint Inc., USA). A high-speed video camera (HAS-220, DITECT Inc., Japan) was used to record the foot motion at 200 fps. Foot contact and toe-off timing were visually determined from the recorded image. In this study, these are treated as true points of time for foot contact and toe-off. We adopted a simple inductive method to automatically detect the events. First, we distinguished the pattern of foot-strike (HS: Heel Strike; MS: Mid-foot Strike; FS: Forefoot Strike) for each step of each subject at each running speed. Next, we acquired the vertical displacement of the heel and metatarsal at true foot contact and true toe-off. Three foot-strike patterns were distinguished from combinations of the following conditions.

Condition 1. The first local maximum of foot angle was

(1) equal to or greater than 7 ° or (2) less than 7 ° .

Condition 2. The pattern of change in foot angle near the local maximum was

(1) monophasic. or (2) diphasic, and the local minimum was equal to or greater than -7 ° or (3) diphasic, and the local minimum was less than -7 ° .

Here, foot angle was defined as the angle of the line joining the head of fifth metatarsal and ankle joint, and zero degrees was set as the angle in the standing position.

It is difficult to define the ground plane in treadmill running because the plane of the belt fluctuates vertically. Therefore, we set the minimum vertical displacement of heel or head of fifth metatarsal during one step as a reference height. The vertical displacement of the heel at the true foot contact of each step for HS was described by equation (1).

$$Z_{HS\_true\_on\_i} = Z_{heel\_min\_i} + \Delta_{HS\_on\_i} \quad (1)$$

Where $Z_{HS\_true\_on\_i}$ was the vertical displacement of the heel at the true foot contact of step i for HS, $Z_{heel\_min\_i}$ was the minimum vertical displacement of the heel (reference heights) during the step, and $\Delta_{HS\_on\_i}$ was the difference between $Z_{HS\_true\_on\_i}$ and $Z_{heel\_min\_i}$. The vertical displacements of the head of fifth metatarsal at the true foot contact of each step for MS and FS were described by equation (2) and (3), respectively.

$$Z_{MS\_true\_on\_i} = Z_{meta\_min\_i} + \Delta_{MS\_on\_i} \quad (2)$$

$$Z_{FS\_true\_on\_i} = Z_{meta\_min\_i} + \Delta_{FS\_on\_i} \quad (3)$$

Where $Z_{MS\_true\_on\_i}$ and $Z_{FS\_true\_on\_i}$ were the vertical displacement of the head of fifth metatarsal at the true foot contact of step i for MS and FS, respectively, $Z_{meta\_\min\_i}$ was the minimum vertical displacement of the head of fifth metatarsal (reference heights) during the step, and $\Delta_{MS\_on\_i}$ and $\Delta_{FS\_on\_i}$ were the difference between $Z_{MS\_true\_on\_i}$ and $Z_{meta\_min\_i}$, $Z_{FS\_true\_on\_i}$ and $Z_{meta\_\min\_i}$., respectively. Because Δ_{HS_on} was significantly correlated with running speed (r=0.96, p<0.01), $\Delta_{HS\_on\_i\_reg}$ from the regression equation (4) was used to determine the threshold.

$$\Delta_{HS\_on\_i\_reg} = 1.77 \times 10^{-5} \times \mathrm{V_i} + 1.10 \times 10^{-4} \quad [m] \quad (4)$$

Where $\mathrm{V_i}$ was the running speed [m/s] during the step i.

On the other hand, $\Delta_{MS\_on\_i}$ and $\Delta_{FS\_on\_i}$ were not significantly correlated with running speed, therefore mean values of them ($\Delta_{MS\_on\_mean}$ and $\Delta_{FS\_on\_mean}$) were used to determine the threshold. $\Delta_{MS\_on\_mean}$ was 0.01 [m]. $\Delta_{FS\_on\_mean}$ was also 0.01 [m].

The threshold for detecting foot contact for each foot-strike pattern was determined as follows.

$$Th_{HS\_on\_i} = Z_{heel\_\min\_i} + \Delta_{HS\_on\_i\_reg} \quad [m] \quad (5)$$

$$Th_{MS\_on\_i} = Z_{meta\_\min\_i} + \Delta_{MS\_on\_mean} \quad [m] \quad (6)$$

$$Th_{FS\_on\_i} = Z_{meta\_\min\_i} + \Delta_{FS\_on\_mean} \quad [m] \quad (7)$$

Where $Th_{HS\_on\_i}$, $Th_{MS\_on\_i}$, and $Th_{FS\_on\_i}$ were the thresholds for detecting foot contact for HS, MS, and FS, respectively.

In the same way, the vertical displacement of the head of fifth metatarsal at the true toe-off of each step was described by equation (8).

$$Z_{true\_off\_i} = Z_{meta\_\min\_i} + \Delta_{off\_i} \quad (8)$$

Where $Z_{true\_off\_i}$ was the vertical displacement of the head of fifth metatarsal at the true toe-off of step i, $Z_{meta\_min\_i}$ was the minimum vertical displacement of the head of fifth metatarsal (reference heights) during the step, and Δ_{off_i} was the difference between $Z_{true\_off\_i}$ and $Z_{meta\_\min\_i}$. Unlike foot contact, the threshold for detecting toe-off was determined by using the vertical displacement of the head of fifth metatarsal, regardless of the foot-strike pattern. Because Δ_{off} was significantly correlated with running speed (r=0.99, p<0.01), $\Delta_{off\_i\_reg}$ from the regression equation (9) was used to determine the threshold.

$$\Delta_{off\_i\_reg} = 1.02 \times 10^{-4} \times \mathrm{V_i} + 4.16 \times 10^{-2} \quad [m] \quad (9)$$

Where $\mathrm{V_i}$ was the running speed [m/s] during the step i.

The threshold for detecting toe-off was determined as follow.

$$Th_{off\_i} = Z_{meta\_\min\_i} + \Delta_{off\_i\_reg} \quad [m] \quad (10)$$

Where Th_{off_i} was the threshold for detecting toe-off.

The instant that the heel (for HS) or the head of fifth metatarsal (for MS and FS) was below $Th_{HS\_on\_i}$ or $Th_{MS\_on\_i}$ or $Th_{FS\_on\_i}$ was regarded as an estimated foot contact, and the instant that the head of fifth metatarsal passed Th_{off_i} in the upward direction was regarded as an estimated toe-off.

RESULTS AND DISCUSSION: Figure 1 presents the RMS error of the estimated foot contact and toe-off. RMS errors were 4.5 to 7.8 ms for foot contact and 4.9 to 8.8 ms for toe-off. In both of foot contact and toe-off, estimation error tended to decrease with increase in running speed. These values are small enough compared with one frame time of a normal video

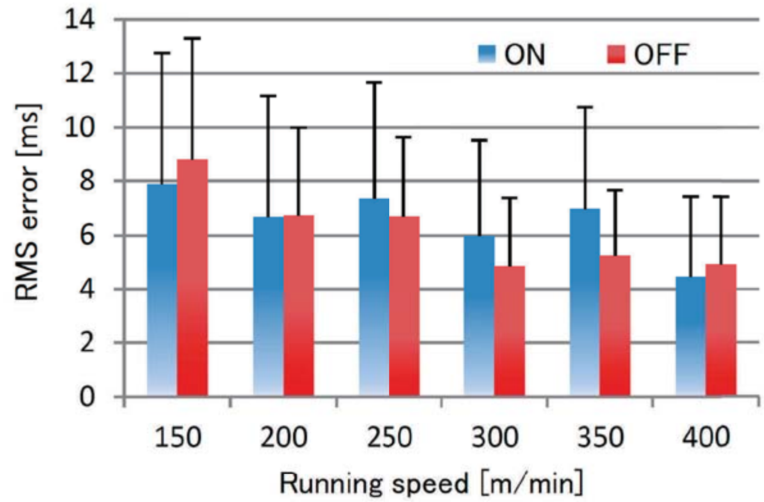

Figure 1: RMS errors for estimated foot contact (ON) and toe-off (OFF)

camera (16.7 ms) and the errors by using the methods of previous studies. The percentage that the error was less than one frame time of a normal video camera was 94.9% (3379 of 3560 steps) for foot contact and 95.0% (3383 of 3560 steps) for toe-off. Highly precise detection could be done in all speed, however, in 150 m/min and 200 m/min, maximum error for foot contact was beyond the two frame time (33.3ms). The distinction error of the foot-strike pattern might occur in these slow speeds, and it was regarded as the cause of the relative high maximum error. However, the estimate errors of the timing detection were smaller than those of previous studies even at the slower speeds.
From these results, the detection method for foot contact and toe-off in this study seems to be better than previous studies and applicable over a wide range of running speeds with a small error.

CONCLUSION: This study proposed an inductive method for simply and accurately detecting the foot contact and toe-off events from the foot kinematics during treadmill running. It was indicated that this method could be applied to a wide range of speeds with a small error.

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