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Short Communication

Heel strike detection using split force-plate treadmill

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ABSTRACT

A common source of error when detecting heel-strike moments utilizing split force-plate treadmills is unwillingly stepping on contra-lateral force-plate. In this study, we quantified this error when heel-strike was detected based on such erroneous data and compared three methods to investigate how well the heel-strikes and stride-intervals were detected with erroneous data. Eleven subjects walked on a split force-plate treadmill for more than 20 min. We used 20 N and 50% body-weight thresholds to detect the heel-strike moments (HS_{20N} and $HS_{50\%}$, respectively). Besides, we used linear approximation to estimate the unaffected force profile from affected force-plate data, and subsequently to detect the heel-strike moments (HS_{est}). We used heel-strike moments detected by a foot-switch as a reference to compare accuracy of HS_{20N}, $HS_{50\%}$ and HS_{est}. HS_{20N} and HS_{est} detected heel-strike moments accurately for unaffected force-plate data (median(max) errors for all subjects: 9(23) and 9(37) ms) but $HS_{50\%}$ showed significantly larger errors (52(74) ms). Unlike $HS_{50\%}$ and HS_{est}, HS_{20N} was considerably affected by the affected force-plate data (23(68) ms). The error in stride-interval measurement was relatively small using any methods for unaffected force-plate data (3(7), 6(8), and 6(12) ms), while stride-interval errors were large for some subjects when using HS_{20N} for affected data (6(175) ms).

We concluded that unwillingly stepping on contra-lateral force-plate occurred a few percent and up to 37.7% of all strides (median: 12.9%). Our proposed method (HS_{est}) robustly showed small errors for heel-strike detection and stride-interval calculation consistently among subjects, while $HS_{50\%}$ and HS_{20N} showed large errors depending on subjects.

1. Introduction

Treadmills mounted on three-dimensional (3D) force-plates (instrumented treadmills) are recently getting more popular in human biomechanics assessments, such as investigating the mechanism of gait variability [1–3]. An instrumented treadmill can be used to detect heel strikes (HS) during walking on the treadmill, with which stride interval (SI: temporal interval between two consecutive heel strikes of the same leg) can be measured [3]. That is, when a heel is striking a force-plate mounted on the treadmill, non-zero values detected with a threshold represent the moment of HS with the treadmill. As the threshold detecting HS using an instrumented treadmill, various values were used such as a fixed vertical force value of 20 N [3,4] and 10 N [5], or 10 percent of body weight [6] or of the maximum vertical force [7].

Using treadmills with two force-plates, it is possible to consecutively detect each HS. There are a few variations in the arrangement of the force-plates, such as front–rear [3] and left–right [5–8] configurations. In case of instrumented treadmills with left–right configuration, unwilling stepping on the contra-lateral force-plate causes a problem in detecting HS. This unwilling event affects the accuracy of HS detection for each foot, since a force profile due to a HS is contaminated by the contact of the contra-lateral foot with a force-plate.

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In this study, we aimed to quantify this unwilling contra-lateral foot contact in normal gait on an instrumented treadmill, and compared three methods for HS and SI detection and evaluated their ability to detect HS and SI accurately despite unwilling stepping on the contra-lateral force-plate. We hypothesized that linear approximation of the vertical force measured by force-plate after HS and applying threshold on this line is robust against these errors.

2. Methods

2.1. Experiments

Eleven healthy men (26 ± 4 years, 175 ± 6 cm, 66.6 ± 6.4 kg) participated in this study and walked on a treadmill instrumented with two (left–right) force-plates (ADAL3D, Techmachine, France) with speed of 1.1 m/s for more than 20 min. A foot-switch was affixed to the posterior region of each subject's right heel. The subjects were instructed to walk naturally without considering the force-plates alignment by looking forward and without seeing the treadmill belt. All data were recorded at 1000 Hz. The force signal measured using an instrumented treadmill tends to be noisier than a ground-fixed one, and the piezo-sensors used in the applied system tends to have drifting property. Therefore, the measured force signals were low-pass filtered (median filter with 7-sample windows), and de-drifted (setting minimum of every 5-s window to zero). All subjects gave written informed consent to participate in the experiment, and the local ethics committee approved the experimental procedures.

2.2. HS detection

We compared three methods for HS detection using the foot-switch as the reference:

1. Detecting HS based on 20 N that was 3.1 ± 0.3% of body weight for our subjects (HS_{20N}).
2. Detecting HS based on 50% of body weight ($HS_{50\%}$).
3. Detecting HS based on 20 N under an assumption that the vertical ground reaction force (F_v) develops linearly at middle sections of ascending period (Fig. 1) (HS_{est}). This assumption was based on our preliminary observation.

The threshold of 20 N was selected as the value sufficiently low and without being affected by noise on the force signal based on our preliminary observation and according to previous studies [3,4]. Thus, HS_{20N} was supposed to be close to ones from the foot-switch method. However, it could be contaminated by the contralateral foot contact in case of instrumented treadmills with left–right configuration. $HS_{50\%}$ was supposed to be robust to the contamination but could induce erroneous HS detection. HS_{est} was developed to compensate the contamination with keeping the accuracy of HS detection.

2.3. Analysis

All strides were categorized into three groups.

Group 1 – unaffected strides: Strides where F_v during 60% of swing phase (based on 50% of body weight threshold) was smaller than 20 N.

Group 2 – moderately affected strides: Strides where F_v was smaller than 20 N during less than 60% of swing phase but more than 0%.

Group 3 – severely affected strides: Strides where F_v was larger than 20 N during the entire swing phase.

We counted the number of strides in each group, to describe how much a force profile was contaminated by unwilling contacts of the contralateral foot, in healthy young group of subjects. Then for Group 1 and Group 2 data, we compared HS detected by each method with HS detected by the foot-switch (HS_{fs}) to quantify the error. Further, we also compared SI calculated by each method to SI calculated using the foot-switch. The errors were statistically compared among the three methods using Wilcoxon Signed Rank tests with Bonferroni correction (Matlab, Mathworks, USA), with a significant level of 5/3 = 1.67%.

3. Results

Subject 11 frequently moved laterally during walking over treadmill, his strides measurements were affected to a large extent, and thus his data were completely excluded from the analysis. Additionally, the foot-switch beneath another subject's foot did not record HS events properly and thus his data (Subject 3) were also excluded only from the analyses comparing with the foot-switch.

There was a tendency among all subjects that the left foot unwillingly stepped on the right force-plate more than the opposite case (Table 1). This might be related to dominance, but there was no evidence as we did not record subjects' dominance. As the result, overall, 12.9(37.7)% (median(max) for all subjects) of all the strides on the right force-plate were affected more than moderately.

Fig. 2A and B shows the absolute error amount of HS detection for each method. $HS_{50\%}$ showed larger errors (median(max) of absolute values of error for all subjects: 52(74) ms) compared to HS_{20N} (p = 0.004) and HS_{est} (p = 0.004) for strides in Group 1 (Fig. 2A). For strides in Group 2, there was no statistical difference

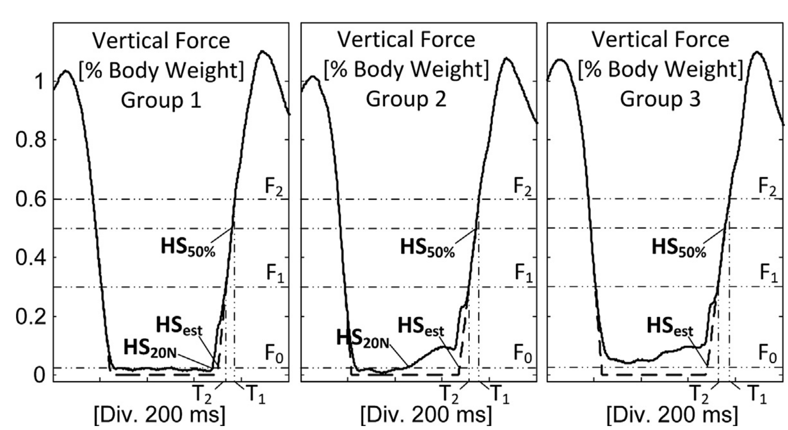

Fig. 1. Schematic representation of the new algorithm proposed in this study for strides in Groups 1, 2, and 3. Vertical ground reaction force (F_v) was normalized to the body weight. We assumed that F_v ascended linearly from T_1 to T_2 after the actual HS. T_1 and T_2 were identified using thresholds, F_1 and F_2, respectively. HS estimated by this algorithm (HS_{est}) was defined the time when the linear regression line calculated between T_1 and T_2 crossed a threshold (F_0). In this study, F_0, F_1, and F_2 were chosen as 20 N and 30% and 60% of body weight. F_1 should be high enough to minimize the effect of potential contact of the contra-lateral foot on the force-plate. F_2 should be low enough to ensure accuracy of linear approximations of F_v from F_1 to F_2. In addition, HS obtained by HS_{20N} and $HS_{50\%}$ are shown.

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Table 1
Total number of analyzed strides and the percentage of strides corresponding to Group 1, Group 2, and Group 3 for each subject. The total number of analyzed strides may differ as one between left and right sides because time-series were cut independently at their two ends.

Subject	Number of Stride		Group 1		Group 2		Group 3	
	Right	Left	Right	Left	Right	Left	Right	Left
1	1483	1482	85	95.4	11.1	4.6	3.9	0
2	1241	1241	88.6	100	9.8	0	1.6	0
3	1239	1239	93.9	92.5	4.1	7.5	1.9	0
4	1293	1294	84.1	100	15.9	0	0	0
5	1197	1196	79.6	94	16.2	4.8	4.2	1.3
6	1076	1076	62.3	99.3	21.5	0.7	16.3	0
7	1261	1262	100	100	0	0	0	0
8	1240	1241	85.6	100	14.4	0	0	0
9	1273	1274	92.5	99.7	5.5	0.3	2	0
10	1291	1291	100	100	0	0	0	0
Minimum	1076	1076	62.3	92.5	0	0	0	0
Median	1251	1251.5	87.1	99.85	10.45	0.15	1.75	0
Maximum	1483	1482	100	100	21.5	7.5	16.3	1.3

between HS_{20N} and $HS_{50\%}$. Only HS_{est} showed small errors consistently among subjects (Fig. 2B), still significantly smaller than $HS_{50\%}$ ($p = 0.016$).

Fig. 2C and D shows the absolute error amount for calculated SIs using each method. In Fig. 2C, it is shown that the absolute error amount was 3(7), 6(8) and 6(12) ms in HS_{20N}, $HS_{50\%}$ and HS_{est} respectively, while errors of SIs calculation using HS_{20N} showed statistically smaller errors than HS_{est} ($p = 0.016$) in Group 1. For strides in Group 2 (Fig. 2D), there was no statistical difference among the three methods while errors of SIs calculation using $HS_{50\%}$ and HS_{est} showed small values consistently among subjects (7(9) and 10(13) ms).

4. Discussion

Up to 12.9(37.7)% (median(max) for all subjects) of our stride recordings were affected by unwillingly stepping on contra-lateral force-plate. A method robust to this error or compensating this error is required.

HS was detected equally accurately (compared to HS_{fs} as a reference) by HS_{20N} and HS_{est} for unaffected force data (Fig. 2A). For affected force data, although there was no statistical difference between HS_{20N} and HS_{est}, it is obvious that only $HS_{50\%}$ and HS_{est} showed similar errors to ones in Group 1 (Fig. 2B). Nevertheless, the small sample size (nine and seven samples) was a limitation and larger sample sizes might show more significant differences. In contrast, as HS_{20N} was easily affected by the contaminated force data, HS_{20N} showed relatively large errors for some subjects in Group 2 (23(68) ms) unlike its results in Group 1 (9(23) ms). $HS_{50\%}$ was not affected by the contaminated force data, but its error was inevitably large (48(73) ms) (Fig. 2B). However, HS_{est} could detect actual HS (error: 8(23) ms) consistently regardless of the force contamination (Fig. 2A and B). Thus, HS_{est} may have a benefit in detecting HS using an instrumented treadmill with left–right configuration.

The error in SI was relatively small using any methods for strides in Group 1 (Fig. 2C). However, for strides in Group 2, irregular large errors in HS_{20N} caused large errors for some subjects (6(175) ms) in the calculated SIs (Fig. 2D). Although there was no statistical difference due to the small sample size, $HS_{50\%}$ and HS_{est} constantly showed relatively small error (7(9) and 10(13) ms) that was similar to the ones for SI calculation in Group 1 (Fig. 2C and D). This result also implies the advantage of HS_{est} in calculating the SI using an instrumented treadmill with left–right configuration. Even in $HS_{50\%}$ that showed a large error in HS detection, the error of

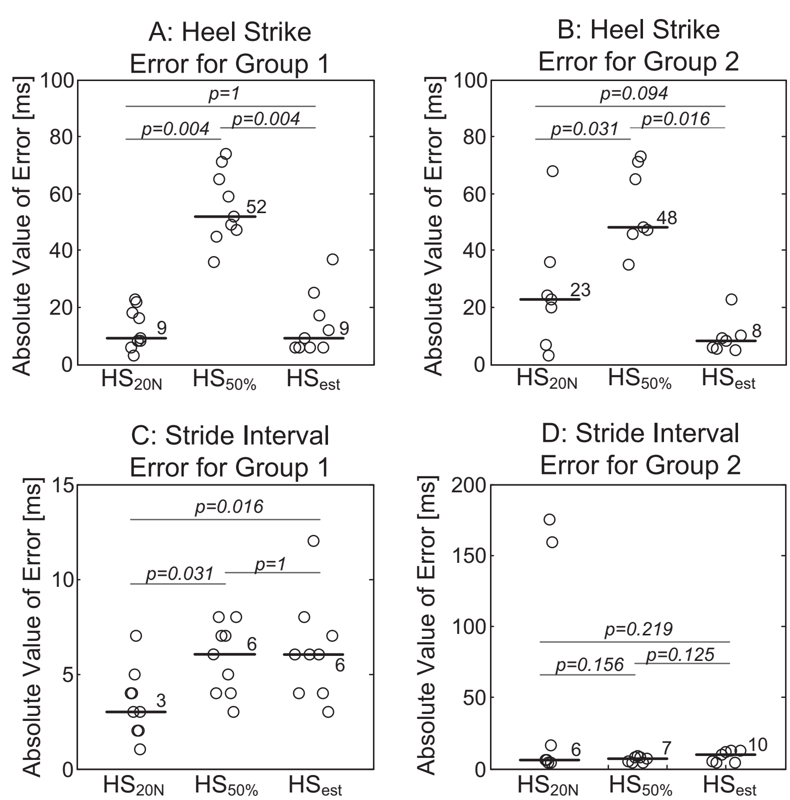

Fig. 2. Errors of the detected HS using each method (HS_{20N}, $HS_{50\%}$ and HS_{est}) for strides in Group 1 (A) and Group 2 (B), and errors the calculated stride interval using each method for Group 1 (C) and Group 2 (D). Each dot indicates the median of absolute error among all strides for each subject. The horizontal lines in each plot indicate the median among subjects' values. *p*-values are shown for each statistical comparison. Note that only seven subjects out of nine had affected strides, and thus Group 2 presented the data of seven subjects. Figures are plotted with different scales to show errors for each subject.

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the calculated SI was similar to HS_{est} that showed a smaller error in HS detection than $HS_{50\%}$ (Fig. 2C and D). This was because the actual error (not absolute error) in SI was evenly distributed around zero in any methods (not shown here). Due to this, when one only considers the average value of stride interval, the problem caused by force contamination may become minor.

The assumption of linear force development in determining HS_{est} and the force threshold values depended on our preliminary observation with young healthy subjects. We also tested other threshold values, but they did not essentially change our conclusion. Thus, we think that the present conclusions about efficiency of our proposed method (HS_{est}) are robust to the threshold values. However, in case of neurological patients who could have unusual force development, the assumption or threshold values may be reconsidered.

We conclude that unwillingly stepping on contra-lateral force-plate occurred a few percent and up to 37.7% of all strides (median: 12.9%), and that our proposed method (HS_{est}) robustly showed small errors for HS detection and SI calculation consistently among subjects, while $HS_{50\%}$ and HS_{20N} showed large error depending on subjects in HS detection and SI calculation, respectively.

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Conflict of interest

None.

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