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Short communication

Initial contact and toe off event identification for rearfoot and non-rearfoot strike pattern treadmill running at different speeds

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ABSTRACT

The purpose of this study was to determine the validity of kinematic based initial contact (IC) and toe-off (TO) identification algorithms for rearfoot and non-rearfoot runners across a broad range of treadmill running speeds. 14 healthy active participants completed six 20–60 s treadmill running trials at 6 speeds: 2.24, 2.68, 3.13, 3.58, 4.02, and 4.48 ms^{-1}. 3D kinematic data were collected for the last 20 s of each trial. Force plates (FP) were used as the gold standard to determine ICFP and TOFP for each step. Three algorithms for finding IC, IC_{Milner}, IC_{Alvim}, $IC_{Alvim\text{-}mod}$, and one algorithm for finding toe off, TO_{Fellin}, were chosen for analysis. Root mean square errors (RMSE) and difference scores with 95% confidence intervals were computed for IC, TO and stance time (ST). IC_{Alvim} RMSE ranged from 0.175 to 0.219 s. ST_{Alvim} RMSE ranged from 0.168 to 0.216 s. $IC_{Alvim\text{-}mod}$ RMSE ranged from 0.105 to 0.131 s. $ST_{Alvim\text{-}mod}$ RMSE ranged from 0.108 to 0.129 s. IC_{Milner} RMSE ranged 0.012 to 0.015 s. ST_{Milner} RMSE ranged 0.019 to 0.024 s. IC_{Milner} accuracy was inversely related to speed. IC_{Milner} corrected with a linear regression equation reduced differences to-0.006 ± 0.012 s with 86% of foot strikes identified within 20 ms and 58% with 10 ms. TO_{Fellin} RMSE ranged from 0.012 to 0.016 s. IC_{Milner} adjusted for speed and TO_{Fellin} can be used to predict IC and TO within a broad range of treadmill running speeds (2.24–4.48 ms^{-1}) and for rearfoot and non-rearfoot strikers.

1. Introduction

Stride rate (SR) and foot strike pattern (FSP), among other variables, are common parameters examined as a profile of a runner's biomechanics. Accurately measuring SR and FSP requires determination of initial contact (IC) and toe-off (TO). Ideally, these variables are determined from a force plate during over ground running or from a force-instrumented treadmill during treadmill running. However, kinematic studies performed in the field or on a standard treadmill rely on identification of IC and TO from kinematic variables.

Many kinematic algorithms for determining IC and TO are available (Alvim et al., 2015; Fellin et al., 2010; Leitch et al., 2011; Milner and Paquette, 2015; Osis et al., 2014). However, most algorithms are specific to a runner's FSP (Alvim et al., 2015; Leitch et al., 2011; Milner and Paquette, 2015; Osis et al., 2014) or have been validated over a limited range of speeds (Fellin et al., 2010; Osis et al., 2014; Leitch et al. 2011; Milner and Paquette, 2015). While the majority of runners run with a rearfoot strike pattern, between 20 and 25 percent mid and forefoot strike (de Almeida et al., 2015; Hasegawa et al., 2007). As running speed increases, runners who rearfoot strike can shift to a midfoot or forefoot strike pattern (Breine et al., 2014; Keller et al., 1996; Novacheck, 1998).

In the absence of force plates, foot strike pattern can be determined using 2D video synchronized with a 3D system (Damsted et al., 2015), though extra acquisition & processing steps are required. A reliable method of identifying IC and TO for all foot strike patterns over a large range of speeds is needed for running analyses where force plates or footswitches are unavailable. The purpose of this study was to determine if previously published algorithms for determining IC and TO are valid when applied to different foot strike patterns over a large range of running speeds during treadmill running.

2. Methods

Fourteen healthy active adults accustomed to treadmill running, 5 males and 9 females, 7 self-reported forefoot/midfoot strikers and 7 self-reported rearfoot strikers (RFS), between the ages of 20 and 55 (age 28 ± 11 y; 168 ± 8.10 cm; 67.8 ± 10.51 kg), had their

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running kinematics analyzed across a range of speeds. Midfoot and forefoot strikers were classified as non-rearfoot strikers (nRFS). All participants gave their written informed consent prior to participation (Ithaca College IRB).

Anthropometric measurements were taken and 16 reflective markers were placed on the lower extremities and pelvis following the Plug-In-Gait marker setup (Vicon, Centennial CO, USA). Participants wore their own running shoes and completed a three-minute light jogging warm-up before beginning the running trials. Participants ran for 20–60 s, depending on speed, at 2.24, 2.68, 3.13, 3.58, 4.02 and 4.48 ms^{-1} in self-selected orders on a standard treadmill (Precor, C954, WA, USA). Data were collected for the last 20 s of each trial using a Vicon Nexus 2.5 (Vicon, Centennial, CO, USA) nine-camera motion capture system (200 Hz). Two AMTI force plates (model OR6, Watertown, MA, USA) sampling at 1000 Hz were placed under the back of the treadmill for identification of IC and TO. Data were exported to Visual 3D (C-motion, Baltimore, MD, USA) for analysis.

Three algorithms for finding IC (IC_{Alvim}, $IC_{Alvim\text{-}mod}$, IC_{Milner}), and one algorithm for finding TO (TO_{Fellin}) were chosen for analysis (Alvim et al., 2015; Fellin et al., 2010; Milner and Paquette, 2015). The selected algorithms showed promise for minimal IC and TO detection error across running speeds and foot strike patterns during pilot testing. $IC_{Alvim\text{-}mod}$ used the first local minimum of the first derivative of the product of vertical and horizontal heel positions as opposed to the absolute local minimum (IC_{Alvim}). Details of each algorithm are in the Appendix. IC, TO and stance time (ST) from the algorithms (IC_{Alvim}, $IC_{Alvim\text{-}mod}$, IC_{Milner}, TO_{Fellin}, ST_{Alvim}, $ST_{Alvim\text{-}mod}$, ST_{Milner}) were compared to IC, TO, and ST as determined from the force plates (IC_{FP}, TO_{FP}, ST_{FP}) using a 20 N threshold (Fellin et al., 2010; Milner and Paquette, 2015). ST was calculated between the three IC algorithms and TO_{Fellin}. Foot strike pattern, RFS versus nRFS, was determined from foot angle at initial contact (Altman and Davis, 2012).

Difference scores were calculated between each algorithm and the FP and 95% confidence intervals were determined and plotted. Root mean square errors (RMSE) were calculated for each speed for all subjects $\sqrt{\frac{1}{n}\sum_{ij}(AL_{i,j}-FP_{ij})^2}$ where AL = algorithm (i.e. IC_{Alvim}, TO_{Fellin}, ST_{MIlner}), FP = IC_{FP}, TO_{FP}, or ST_{FP}, i = subject, and j = IC or TO count within each speed for each subject. For IC and ST, RMSEs were also calculated for nRFS and RFS separately.

3. Results

There were 4491 foot contacts (1952 RFS and 2539 nRFS). Ten participants had mixed strike patterns. Seven participants were less than 90% consistent in strike pattern for at least one speed. Three participants had less than 90% consistency in strike pattern averaged across all 6 speeds. Results for RFS and nRFS are reported for observed strike pattern of each step based on foot angle (Altman and Davis, 2012) as opposed to self-reported strike pattern.

IC_{Alvim} was identified on average 0.081 ± 0.182 s after IC_{FP} and $IC_{Alvim\text{-}mod}$ was identified on average 0.103 ± 0.061 s before IC_{FP}. RMSEs are in Table 1. Difference scores for IC_{Alvim} and $IC_{Alvim\text{-}mod}$ with 95% confidence intervals are in Fig. 1a and b, respectively. IC_{Milner} was identified on average 0.004 ± 0.013 s before IC_{FP}. Difference scores were inversely related to speed (R^2 = 0.960) with IC_{Milner} identifying IC after IC_{FP} at slower speeds and before IC_{FP} and faster speeds (Fig. 1c). At all speeds, $\Delta_{M\text{-}FP}$ was greater for RFS than nRFS; though differences were within the 95% confidence intervals (Fig. 1c). TO_{Fellin} was identified on average 0.002 ± 0.013 s after TO_{FP}. At 2.24 ms^{-1}, TO_{Fellin} identified TO −0.006 ± 0.014 s before TO_{FP}. At all other speeds TO_{Fellin} identified TO after TO_{FP} (Fig. 2).

ST_{Alvim} was on average 0.079 ± 0.179 s shorter than ST_{FP}. RMSEs are in Table 2. $ST_{Alvim\text{-}mod}$ was identified on average 0.105 ± 0.059 s longer than ST_{FP}. Difference scores for ST_{Alvim} and $ST_{Alvim\text{-}mod}$ with 95% confidence intervals are in Fig. 3a and b, respectively. IC_{Milner} was identified on average 0.007 ± 0.019 s longer than ST_{FP}. Difference scores were related to speed (R^2 = 0.876) with ST_{Milner} shorter than ST_{FP} at slower speeds and longer than ST_{FP} faster speeds (Fig. 3c).

Linear regression analyses were performed on IC_{Milner} across speed to determine prediction algorithms for correcting IC_{Milner} based on running speed for all subjects combined ($\Delta_{M2\text{-}FP}$ = −0.0065 * speed + 0.0355, R^2 = 0.94), RFS ($\Delta_{M2\text{-}FP,RFS}$ = −0.0081 * speed + 0.0454, R^2 = 0.908), and nRFS ($\Delta_{M2\text{-}FP,nRFS}$ = −0.0064 * speed + 0.0323, R^2 = 0.89) where $\Delta_{M2\text{-}FP} = IC_{Milner2} - IC_{FP}$ and $IC_{Milner2} = IC_{Milner}$ + 0.015 s (Appendix). 86% of ICs were identified within 20 ms, 4 frames at 200 fps, of IC_{FP} and 58% of ICs identified within 10 ms, 2 frames at 200 fps, of IC_{FP} (Table 3). 59% of STs were within 20 ms of ST_{FP} and 27% of STs were within 10 ms of ST_{FP} (Table4). For RFS, 99% of IC were within 20 ms of IC_{FP} and 56% of ICs were within 10 ms of ICFP. 46% of STs were within 20 ms of ST_{FP} and 16% of STs within 10 ms of ST_{FP}. For nRFS, 76% of ICs were within 20 ms of IC_{FP} and 41% of IC were within 10 ms of $IC_{FP;}$ 62% of STs were within 20 ms of ST_{FP} and 32% were within 10 ms of ST_{FP}.

4. Discussion

Root mean square errors for IC_{Alvim} were larger than previously reported (Alvim et al., 2015). The current study used a larger range of running speeds (2.24 ms^{-1} to 4.48 ms^{-1}) as compared to Alvim et al. (2015). However, the errors in the current study, at speeds comparable to Alvim et al. (2015), were more than 10 times greater than the errors reported by Alvim et al. (2015). Inclusion of nRFS likely affected the large variability observed. RMSEs were smaller for nRFS as compared to RFS. In both the current study and the original work by Alvim et al. (2015), running speed did not affect IC identification accuracy. Alvim et al. (2015) used footswitches as opposed to a force plate during the treadmill running to identify initial contact; over-ground running footswitch accuracy is ±5.7 ms as compared to a force plate (Alvim et al., 2015). To our knowledge foot switch accuracy during treadmill running has not been documented. Inspection of data used to calculate IC_{Alvim} revealed inconsistency in position of the local minimum used for IC identification based on running biomechanics. Modifying the algorithm to use the first local minimum decreased errors on average 40% but only

Table 1
RMSE between gold standard force plate and kinematic algorithms for determining IC and TO across all subjects for all speeds.

Speed (ms^{-1})	N	IC_{Milner}	IC_{Alvim^*}	$IC_{Alvim\text{-}mod}$	TO_{Fellin}
2.24	687	0.013	0.203	0.131	0.016
2.68	702	0.012	0.219	0.129	0.013
3.13	734	0.012	0.213	0.123	0.014
3.58	766	0.013	0.195	0.120	0.012
4.02	773	0.014	0.191	0.111	0.012
4.48	829	0.015	0.175	0.106	0.012

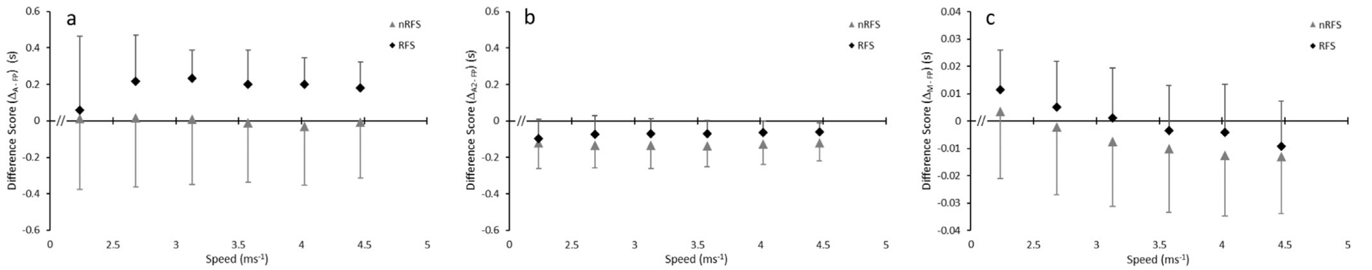

Fig. 1. IC_{Alvim} (a), $IC_{Alvim\text{-}mod}$ (b), and IC_{MIlner} (c) differences with 95% confidence interval displayed for all 6 running speeds for RFS and nRFS runners showing a linear decrease in $\Delta_{M\text{-}FP}$ with speed for both foot strike patterns. Values are mean differences (±95% CI) calculated across subjects.

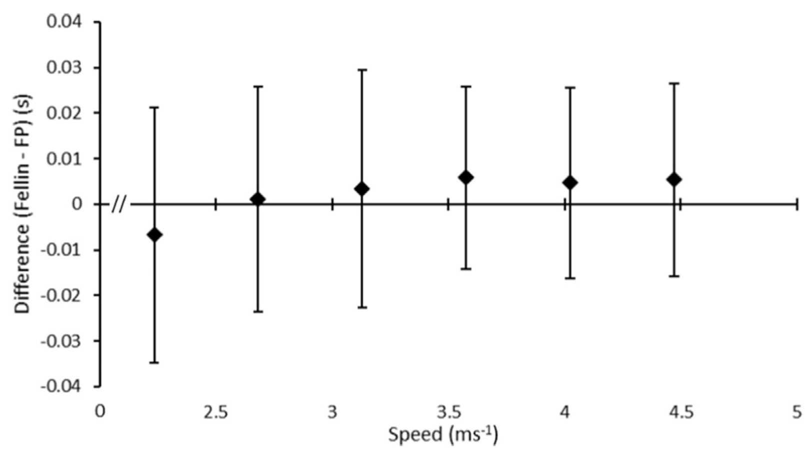

Fig. 2. TO_{Fellin} differences to TO_{FP} with 95% confidence intervals displayed for all 6 running speeds Values are means (±95% CI) calculated across subjects.

Table 2
RMSE between gold standard force plate and kinematic algorithms for determining ST across all subjects for all speeds.

Speed (ms^{-1})	N	ST_{Milner}	ST_{Alvim^*}	$ST_{Alvim\text{-}mod}$
2.24	687	0.024	0.203	0.124
2.68	702	0.019	0.216	0.129
3.13	734	0.020	0.210	0.126
3.58	766	0.019	0.190	0.125
4.02	773	0.020	0.187	0.115
4.48	829	0.022	0.168	0.108

moderately decreased variability. The majority of ICs were still identified more than 20 ms from IC_{FP} (even after accounting for a 103 ms offset, Appendix). A 20 ms IC identification threshold was recommended for walking (Mickelborough et al., 2000) and has been used in running (Alvim et al., 2015; Osis et al., 2014). For the runners in this study, IC_{Alvim} and $IC_{Alvim\text{-}mod2}$ did not meet that criterion.

Root mean square errors for IC_{Milner} were between 12 and 25 ms with accuracy linearly related to running speed. The dependence of IC_{Milner} on running speed is a novel finding of this study. IC_{Milner} was developed for RFS and nRFS runners running over-ground at 3.7 ms^{-1} (Milner and Paquette, 2015). In the current treadmill running study, the algorithm predicted most accurately at 2.68 ms^{-1} which is slower than Milner and Paquette's over ground speed (Milner and Paquette, 2015). Of importance, at least for treadmill running, is that the offset observed with IC_{Milner} is not constant across speed. Based on the regression equation developed in the current study, IC identification had to be adjusted between 6 ms and 21 ms depending on speed. There were consistent differences in the observed offset for IC_{Milner} for RFS and nRFS despite the algorithm being based on pelvis kinematics instead of foot marker kinematics. At each speed, the differences were small (less than 9 ms) and within the 95% confidence intervals. Identifying foot strike pattern from heel and toe markers (Altman and Davis, 2012) allowed the regression equation to be customized for RFS and nRFS separately. The RFS specific algorithm predicted 99% of

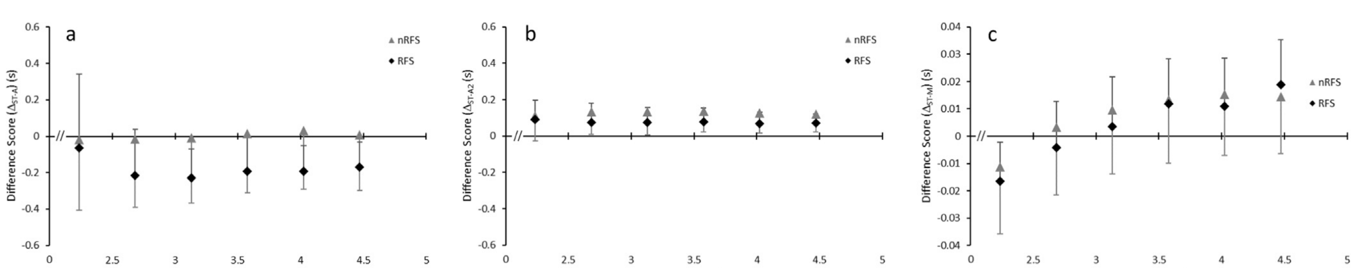

Fig. 3. ST_{Alvim} (a), $ST_{Alvim\text{-}mod}$ (b), and ST_{MIlner} (c) differences with 95% confidence interval displayed for all 6 running speeds for RFS and nRFS runners showing a linear increase in $\Delta_{ST\text{-}M}$ with speed for both foot strike patterns. Values are mean differences (±95% CI) calculated across subjects.

Table 3
Mean (SD) difference for IC_{Milner}, $IC_{Milner\text{-}adj}$ (all strike patterns, RFS, nRFS) and IC_{FP}.

Speed (ms^{-1})	IC_{Milner}	$IC_{Milner\text{-}adj}$		
		All strike patterns	RFS	nRFS
2.24	0.006 (0.023)	−0.001 (0.012)	−0.005 (0.006)	0.002 (0.015)
2.68	0.001 (0.023)	−0.005 (0.013)	−0.010 (0.006)	−0.003 (0.016)
3.13	−0.004 (0.023)	−0.007 (0.013)	−0.007 (0.009)	−0.006 (0.016)
3.58	−0.007 (0.021)	−0.007 (0.012)	−0.007 (0.007)	−0.007 (0.015)
4.02	−0.008 (0.021)	−0.008 (0.011)	−0.009 (0.007)	−0.007 (0.013)
4.48	−0.011 (0.019)	−0.007 (0.010)	−0.007 (0.007)	−0.005 (0.012)

Table 4
Mean (SD) difference for ST_{Milner}, $ST_{Milner\text{-}adj}$ (all strike patterns, RFS, nRFS) and ST_{FP}.

Speed (ms^{-1})	ST_{Milner}	$ST_{Milner\text{-}adj}$		
		All strike patterns	RFS	nRFS
2.24	−0.013 (0.020)	−0.002 (0.020)	0.013 (0.014)	−0.013 (0.020)
2.68	0.000 (0.019)	0.008 (0.019)	0.020 (0.012)	−0.002 (0.020)
3.13	0.007 (0.019)	0.014 (0.018)	0.019 (0.014)	0.009 (0.021)
3.58	0.013 (0.014)	0.013 (0.015)	0.019 (0.010)	0.009 (0.018)
4.02	0.013 (0.014)	0.013 (0.014)	0.019 (0.010)	0.007 (0.016)
4.48	0.017 (0.014)	0.012 (0.015)	0.022 (0.011)	0.004 (0.016)

ICs for RFS within20 ms. Customizing the algorithm did not improve accuracy for nRFS. Stance times were not as accurately predicted as $IC_{Milner\text{-}adj}$, likely due to the dependence of ST on both IC and TO prediction accuracy.

Given the accuracy of the Milner algorithm adjusted with the speed based linear regression equation, $IC_{Milner\text{-}adj}$ is recommended for treadmill running between 2.1 and 4.5 ms^{-1} when IC must be determined from kinematic data. If foot marker kinematic data is available, IC identification for RFS can be improved by using a RFS specific algorithm. The linearity of the algorithms' accuracies at slower or faster running speeds than those tested in the current study, should not be assumed. Not all subjects contributed equal numbers of ICs to each speed and the number of RFS and nRFS were not equal which could bias the results.

TO_{Fellin} identification errors were small averaging less than 11 ms. Difference between speeds were within the 95% confidence intervals; though at 2.24 ms^{-1} TO_{Fellin} tended to identify TO early. Average absolute errors of 5 ms are nearly half those reported by Fellin et al. (2010) identifying 89% of TOs within 20 ms. TO_{Fellin} accuracies (11–23 ms) were as low or lower than those in the literature (Alvim et al., 2015; Fellin et al., 2010; Leitch et al., 2011; Maiwald et al. 2009) over a broader range of speeds and thus is recommended for treadmill running between 2.2 and 4.5 ms^{-1}. It is unknown if the accuracy of TO_{Fellin} and $IC_{Milner\text{-}adj}$ hold at faster running speeds. Competitive middle and distance runners often run faster than 4.5 ms^{-1}, and elite runners attain speeds of 6.7 ms^{-1} or greater depending on event. Future research should test the algorithms at faster speeds, and for $IC_{Milner\text{-}adj}$, with both treadmill and over-ground running, which could elucidate differences in RFS and nRFS. Lastly, caution should be taken when calculating stance time from kinematically determined IC and TO events as errors in stance time are substantially larger than those of IC and TO.

Conflict of interest

We are reporting no conflicts of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.023.

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