A NOVEL METHOD FOR INITIAL CONTACT DETECTION IN TREADMILL RUNNING USING SIDE RAIL REFLECTIVE MARKER

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Treadmill running analysis is often preferred to overground running due to the small observation volume. Splitting the cyclic running motion into single cycles requires the robust detection of common features identifying the initial contact (IC). Kinematic features such as HEEL marker velocity zero-crossing (ZC) in vertical or anteroposterior direction are proposed in literature. In this study (n = 14 male, 3.5 m/s, 3 right steps, 8 VICON MX cameras, 250 fps) a novel treadmill mounted marker (TREA) is compared to these two features. TREA vertical velocity ZC appears (6.8 ± 12.8) ms after HEEL anteroposterior ZC and can therefore be used as an easy-to-use feature for IC detection in treadmill running. HEEL vertical velocity ZC is to be doubted as it appears (59.0 ± 19.7) ms later than TREA vertical velocity ZC.

KEY WORDS: biomechanics, 3D motion analysis, running cycle, heel marker, velocity zero-crossing.

INTRODUCTION: Performance testing, running style evaluation or testing of sports equipment is often done on the treadmill due to the advantage of constant speed and smaller observation volume required (Sinclair et al., 2013). The cyclic motion structure implies that the whole treadmill running sequence needs to be split into single cycles. The beginning of the running cycle is defined by the time instant of initial contact (IC) when any part of the foot touches the ground in overground running or the treadmill belt, respectively. Finding IC requires the robust detection of a common data feature occurring irrespectively of the individual running style. Force plates under left and right foot separately are regarded as the golden standard (Sinclair et al., 2013), while pressure insoles until recently had limited sample rate. Inertial measurement units on the foot or lower leg must be placed firmly on both limbs (Khandelwal & Wickström, 2017; Savelberg et al., 1998), or onto the sacrum (Trojaniello, Cereatti & Della Croce, 2104).

If no additional sensors should be applied, a valid and robust feature must be detected from kinematics only. In overground running, IC is mostly determined by the HEEL marker velocity zero-crossing (ZC) in vertical direction (e.g. Fellin, Manal & Davis, 2010). In treadmill running, both vertical (Fellin, Manal & Davis, 2010) and anteroposterior HEEL velocity ZC (Zeni, Richards & Higginson, 2008) have been proposed, but not yet cross-validated. For the purpose of test economy in future sports equipment testing, a novel treadmill marker TREA should be developed and compared to these two HEEL features. It is hypothesized that TREA vertical velocity ZC can be used as an IC feature for both limbs in treadmill running.

METHODS: 14 healthy male participants (age 25.4 ± 1.15 years, height 181.3 ± 3.34 m, weight 78.6 ± 6.41 kg) ran at 3.5 m/s on a single belt treadmill (cardiostrong TX50, Sport-Tiedje GmbH, Germany). Retroreflective markers (Ø 9 mm) were used on the right foot only, comprising tuberositas calcanei (HEEL) and 5th metatarsal head (MET5). An additional treadmill marker (TREA) was attached to the left side rail 25 cm from the front right before the area where participants would jump off the belt; see Figure 1 for TREA position. Pre-tests showed that there was no significant time lag between left and right rail marker placement. Eight Vicon MX cameras were placed evenly around the treadmill and three single strides were recorded at the end of 6 min runs at 250 fps using Vicon Nexus 2.5.

Raw kinematic data was filtered in Vicon Nexus 2.5 using 4th order zero-lag Butterworth low-pass with a cut-off frequency of 10 Hz as recommended by Winter (2005) for treadmill running. The time instant of zero-crossing was determined using rising or falling edge monitors in Vicon Nexus 2.5. Rising edge was detected for HEEL vertical velocity and falling edge for HEEL anteroposterior and TREA vertical velocity, with the X-axis pointing in the direction of human locomotion and the Y-axis pointing upwards according to the ISB recommendation (Wu & Cavanagh, 1995). From all 42 recorded strides, arithmetic mean and standard deviation of the time lag between these ZC events were calculated in [ms].

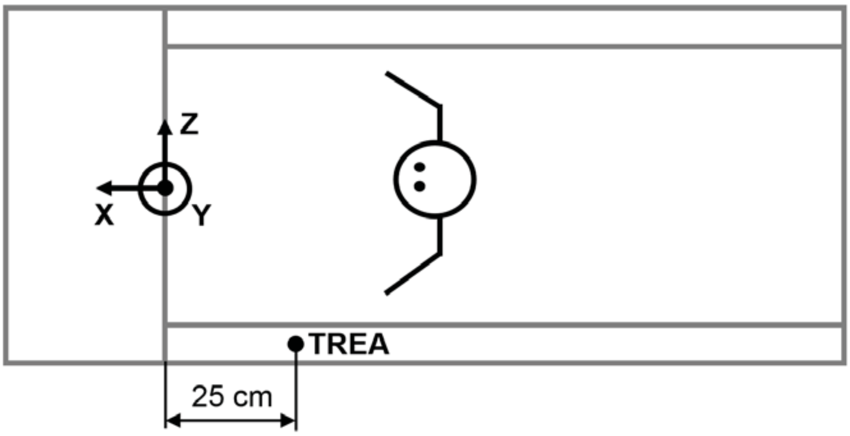

Figure 1: Treadmill with TREA marker and global coordinate system.

RESULTS: All 42 strides showed a comparable up-and-down-pattern of treadmill marker (TREA). Figure 2 shows the averaged pattern (solid line) and standard deviation (shaded area) of three individual strides for participant P1, indicating flight and stance phase of running cycle. During flight phase, TREA marker remains close to its resting position (dashed line). The foot impacts the treadmill at the time instant of initial contact (IC) leading to a downward motion of TREA.

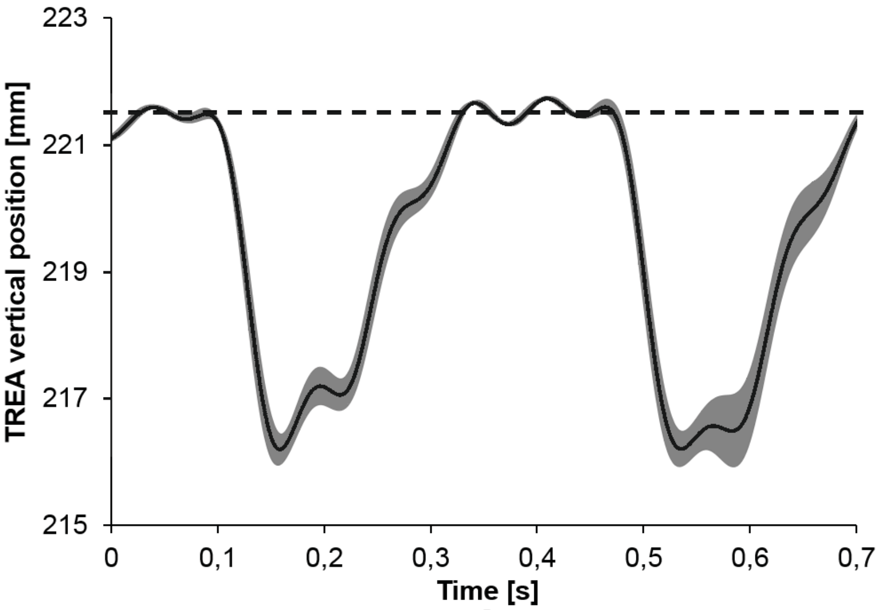

Figure 2: Example of TREA vertical position for participant P1, including TREA resting position.

Hence, TREA vertical velocity had several recurring zero-crossings, from which the falling edge before the lowest local minimum could be uniquely defined as corresponding to IC, as pointed out in Figure 3.

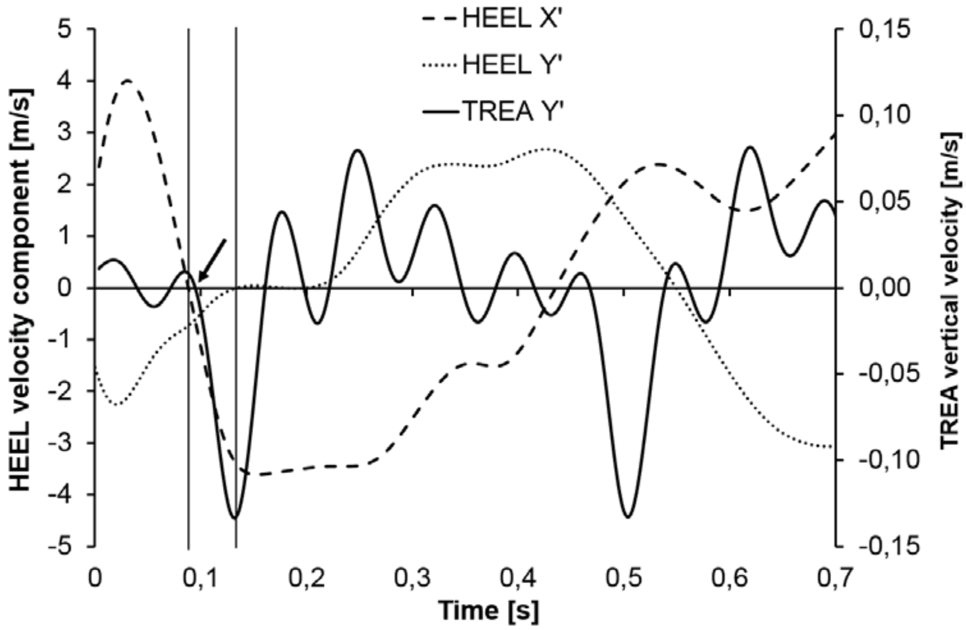

Figure 3: Example of TREA and HEEL marker velocity components for participant P1. Note: HEEL ZCs are marked by vertical lines, TREA ZC by an arrow.

On average, TREA vertical ZC occurred (6.8 ± 12.8) ms after HEEL anteroposterior velocity falling edge, while in 6 out of 42 strides it occurred slightly before. HEEL anteroposterior ZC indicates front reversal point of foot within running cycle and is denoted as IC on the treadmill according to Zeni, Richards and Higginson (2008). HEEL vertical ZC appeared later in all strides by (59.0 ± 19.7) ms, slightly before first local minimum of TREA vertical position (see Figure 2).

DISCUSSION: This study compared a novel treadmill mounted marker (TREA) with two kinematic HEEL marker features indicating initial contact (IC) according to literature. To the best of our knowledge, this is the first study using a marker attached to the side rail of a treadmill instead of attaching markers to the participant. Chow et al. (2010) followed a comparable aim using a light curtain 5 mm above the belt. Another possible source of data might be the instantaneous belt speed mentioned by e.g. Savelberg et al. (1998), but only the method of Olson and Klute (2015) does not require synchronisation with kinematics which is detrimental in all sensor-based methods.

The short time lag between HEEL anteroposterior ZC and TREA vertical ZC due to the distance between belt and steel plate below is probably enlarged by the shock wave propagation within the steel plate of the treadmill. Yet the delay due to placement of HEEL marker suffering from the limited stiffness of human lower limb as well as from the non-rigid connection between bony calcaneus and the outside of the shoe can be expected to be much higher. This novel method has been applied only for healthy male subjects at one defined speed on one single treadmill so far. It can be assumed that treadmills with higher mass and higher stiffness of belt will further reduce this time lag.

The individual running style and initial contact (heel or midfoot strike) might influence accuracy of IC detection using TREA, which was not the focus of this study. Positioning TREA marker 25 cm from the front is closest to the supposed area of foot contact while not interfering participants when jumping off the belt. Variation of anteroposterior distance between HEEL and TREA markers at initial contact might influence time lag.

This study provided the first indication that HEEL vertical ZC might not be the perfect correspondence of initial contact (IC) in treadmill running as proposed by e.g. Fellin, Manal and Davis (2010). Based on the fact that there is some distance between belt and steel plate below, the shoe-belt contact is followed by further lowering of HEEL vertical position. HEEL vertical velocity ZC will occur later when pinching the belt between the shoe and the steel plate (Davis, 2012), causing instantaneous belt speed fluctuations (Savelberg et al., 1998). Using this HEEL marker feature will therefore cause a significant phase shift in determination of running cycle. Instead, HEEL anteroposterior ZC is supposed to represent IC better, as it occurs closer to TREA vertical ZC. TREA acts in a similar way as a force plate acquiring the time instant of initial contact, as it will move downwards if there is an external force acting on the treadmill.

CONCLUSION: Validation of these results against force plate data is still pending, as Zeni, Richards and Higginson (2008) reported an average time lag of 23 ms between force plate detected IC and HEEL anteroposterior velocity ZC. Possible effects of filtering should be considered as there was no previous analysis of frequency content for TREA raw data as in Fellin, Manal and Davis (2010). In addition, it would be favourable to find a common TREA feature to detect also the second important gait event besides initial contact, namely toe-off, instead of deriving it from MET5 marker on 5th metatarsal head.
The use of only one TREA marker instead of two HEEL markers on both limbs of the participant saves time and effort, meeting a frequently occurring issue in kinematic studies of treadmill running: sudden treadmill stop requests by the researchers and re-placement in case of marker loss are avoided. Based on these results, TREA vertical ZC can be used as a feature for IC detection in future treadmill studies, especially when using low-cost non-instrumented treadmills. If other aspects than foot kinematics are of interest and/or if there is no need for distinguishing between left and right IC, this method could be an inexpensive and easy-to-use alternative.

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