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Detection of foot contact in treadmill running with inertial and optical measurement systems

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ABSTRACT

In running assessments, biomechanics of the stance phase are often measured to understand external loads applied to the body. Identifying time of initial foot contact can be challenging in runners with different strike patterns. Peak downward velocity of the pelvis (PDVP) has been validated in a laboratory setting to detect initial contact. Inertial measurement units (IMUs) allow measurements of kinematic variables outside laboratory settings. The aim of this study was to validate the PDVP method using an inertial and optical motion capture system to detect initial contact at different speeds and foot strike patterns compared to the force sensing criterion. Twenty healthy runners ran for two minutes at 11, 13, and 15 km/h on a force-instrumented treadmill. 3D kinematics were obtained from an optical motion capture system and an 8-sensor inertial system.

A generalized estimating equation showed no effect of footstrike pattern on the time difference (offset) between initial contact based on an inertial or optical system and the force sensing criterion. There was a significant main effect of speed on offset, in which offsets decreased with higher speeds. There was no interaction effect of speed and foot strike pattern on the offsets. Offsets ranged from 21.7 ± 0.2 ms for subjects running at 15 km/h (inertial versus force sensing criterion) to 27.2 ± 0.1 ms for subjects running at 11 km/h (optical versus force sensing criterion). These findings support the validity of the PDVP method obtained from optical and inertial systems to detect initial contact in different footstrike patterns and at different running speeds.

1. Introduction

The biomechanics of running is frequently studied in relation to injury prevention and performance. When studying the biomechanics of running, external loading variables such as impact, vertical ground reaction force, tibial acceleration and lower limb kinematics are suggested to be of importance (Milner et al., 2006; Reenalda et al., 2019; Reenalda et al., 2016; van Gent et al., 2007). The body attenuates these loads during the stance phase after the foot contacts the ground and therefore, biomechanical variables during this phase of the running gait cycle are often studied.

The stance phase begins when the foot contacts the ground, a time point referred to as initial contact (IC), and ends when the foot leaves the ground, a time point referred to as toe-off. Accurate detection of these gait events is therefore critical to identify the stance phase of the gait cycle in order to assess biomechanical changes during this phase. Traditionally, the analysis of running mechanics has been limited to a gait laboratory where advanced instrumentation such as three-dimensional (3D) optical motion capture systems or force platforms are used to collect data and identify gait events. In laboratory settings, force platforms are commonly used to detect time of IC and toe-off during running using set thresholds of the vertical component of the ground reaction force vector (e.g., 10 N to 50 N). When force platforms are unavailable, kinematic data collected using motion capture systems can be used to detect gait events.

The peak downward velocity of the pelvis (PDVP) was recently proposed and validated as a kinematic method to detect IC in running regardless of running strike pattern (Milner and Paquette, 2015). This method was validated using an optical motion capture system and was therefore restricted to laboratory testing. Inertial sensors or inertial measurement units (IMUs) allow measurements of some kinematic variables outside laboratory settings. They

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provide the opportunity for biomechanical assessment, real-time feedback and gait retraining in the field. Inertial-based systems have been proposed recently to detect IC in running outside the lab setting (Benson et al., 2019; Giandolini et al., 2014). These methods typically use the peak acceleration and deceleration values of a sensor at the foot and/or lower back to identify IC. Another method that used the local minimum in the resultant tibial acceleration waveform has been proposed recently (Aubol and Milner, 2020). This method showed good potential for identifying IC, especially in the absence of low impact peaks, but was only tested on runners with a rearfoot strike. Different strike patterns during running yield different lower limb joint and segmental angular positions at foot contact. This influences the various kinematic methods used to detect IC, hence, strike pattern must be considered when assessing the validity of these methods using optical or inertial sensors for IC detection. A method for IC detection at the pelvis might overcome the influence of different segmental and angular positions at foot contact. We therefore present an alternative foot contact identification method based on the PDVP that can be used in IMU systems consisting of a sensor at the pelvis.

The aim of this study was to determine the validity of the peak downward velocity of the pelvis method to detect initial foot contact during running using both 3D optical and inertial motion capture systems. Validity was determined for different speeds and different foot strike patterns by comparison to the reference standard using vertical ground reaction force. It was hypothesized that the inertial sensor-based method would perform similarly to the optical based method of detecting IC relative to the force platform-based criterion.

2. Methods

2.1. Participants

Twenty runners were recruited (15 men/5 women, age: 30.1 ± 9.2 years, height: 184.3 ± 7.9 cm, mass: 68.7 ± 7.5 kg) who ran at least 15 km a week for the last year or longer (distance per week: 38.1 ± 18.0 km, years of running: 8.5 ± 7.3 years). Runners reported no lower extremity injuries in the past six months and wore their own running shoes during the experiment. The local medical ethical committee approved the protocol and participants signed an informed consent before the start of the experiment.

2.2. Experimental protocol

After a six-minute warm-up at a self-selected treadmill speed, participants ran for two minutes at three different speeds (11 km/h, 13 km/h, 15 km/h) in a random order on the treadmill. The treadmill was stopped after each two-minute trial and participants could rest before starting a new trial at a different speed.

2.3. Instrumentation

An instrumented treadmill (C-Mill, ForceLink, Culemborg, the Netherlands) with a surface area of 250x100 cm captured vertical ground reaction forces (GRF) at 1000 Hz. The 3D kinematics were obtained using both an 8-camera optical motion capture system (100 Hz, Vantage, Vicon, Oxford, United Kingdom) and inertial motion capture system (240 Hz, MVN Link, Xsens, Enschede, the Netherlands). Reflective markers were placed on the participants according to the Plug-in Gait lower-body marker model (Davis et al., 1991) with a total of 18 markers as part of a larger study in which lower body kinematics were assessed. For the inertial motion capture system, eight IMUs were attached to the participants, as part of a larger study as well, at the sternum, sacrum, and bilaterally at the medio-lateral part of the thigh on the skin covering the iliotibial band, proximal anteromedial part of the tibia, just below the tibial tuberosity, attached with double-sided adhesive tape and secured with additional adhesive tape. Sensors on the feet were placed in the shoes and over the mid-foot and kept in place by the tongue and laces of the shoes. IMUs collected 3D linear accelerations, 3D angular velocity, and 3D magnetic field.

Calibration trials for both the optical motion capture system (standing still) and the inertial motion capture system (standing still and walking back and forth for 10 m, for sensor to segment calibration) were performed before data collection. Force platform data from the instrumented treadmill and kinematic data from the optical motion capture system were synchronized using an analogue synchronization start and end pulse. Data from the inertial motion captures system were then synchronized with the optical motion capture system by cross-correlation of the sagittal knee angles (a variable only used for synchronization in this study) at the start and end of each trial.

2.4. Data analyses

Kinematic variables were obtained from the sensor data using a dedicated software package (MVN Analyze 2018.2, Xsens, Enschede, The Netherlands) and custom code (MATLAB R2018, MathWorks Inc., MA, USA). The optical and inertial motion capture data were linearly interpolated to 1000 Hz to match sampling frequency of the force plate. The first 30 s per trial were excluded to exclude the effect of getting up to speed. The first one hundred IC events for each leg were then selected for all participants at each running speed. The criterion for detecting IC was defined with a commonly used vertical GRF threshold of 20 N (Milner and Paquette, 2015), applied on raw GRF data. PDVP using the optical motion capture system was computed as the minimum of the first derivative of position in the global vertical axis of a virtual pelvis marker (i.e. the mean position of the reflective markers on the left and right posterior superior iliac spine) (Milner and Paquette, 2015). The velocity of the virtual pelvis marker was filtered with a third order low pass filter with a cut-off frequency of 20 Hz. PDVP for the inertial measurement system was defined as the minimum of the integral of linear acceleration in the global vertical axis of the IMU on the sacrum. The acceleration value was provided by the Xsens software. Within this software proprietary filtering is performed. Foot contact angle in the sagittal plane was computed for each leg separately as the inclination angle of the foot relative to the global horizontal axis at initial contact. A mean inclination angle over all trials larger than 8 degrees was defined as a rearfoot strike pattern and smaller than 8 degrees as a non-rearfoot strike pattern.

2.5. Statistical analyses

Time of IC obtained from the optical and inertial motion capture systems were compared to the time of IC obtained from the force platform at different speeds. Mean value of 100 steps for each leg (40 legs from 20 subjects) were used. Normality of the data was visually confirmed. A generalized estimating equation was used to test for significant ($p < 0.05$) main effects of speed and strike pattern and interaction effect of speed and strike pattern on offsets in initial contact detection for both systems against the force sensing criterion. Bland-Altman plots were created for both systems and for each strike pattern and speed separately (Bland and Altman, 1986).

3. Results

A total of 28 legs were classified as rearfoot striking legs (RFS) while 12 legs were classified as non-rearfoot striking legs (NRFS). There was a significant main effect of speed on offsets for both the optical and inertial system ($p < 0.05$). Offsets became smaller with higher running speeds. There was no significant main effect of foot strike pattern or a significant interaction effect of speed and foot strike pattern on offsets for both systems.

Bland-Altman plots showing the offsets against the force sensing criterion with the 95% confidence intervals for both the inertial and optical systems at the three different speeds are displayed in Fig. 1.

Post-hoc paired sample t-tests showed that the offset in IC detection relative to the force sensing criterion at 15 km/h was significantly smaller than for the offset at 11 and 13 km/h ($p < 0.05$).

4. Discussion

This study aimed to determine the validity of the peak downward velocity of the pelvis method to detect initial foot contact during running using both 3D optical and inertial motion capture systems. In support of our hypothesis, the inertial sensor-based system performed similarly to the optical system regardless of footstrike pattern or speed. This finding suggests that the inertial system can be used to detect IC, with a similar accuracy as optical systems. The inertial system has an advantage in that it can be used out of the laboratory setting which is relevant for the emerging market of (pelvis mounted) wearable systems that analyse running biomechanics.

Both measurement systems showed a systematic positive offset in IC detection compared to the force platform, however with different confidence limits, as can be seen in the Bland Altman plots. Offsets ranged from 21.7 ± 0.2 ms for subjects running at 15 km/h (inertial system versus force sensing criterion) to 27.2 ± 0.1 ms for subjects running at 11 km/h (optical system versus force sensing criterion). These offsets are comparable to or slightly higher than other studies that demonstrated IC offsets values between 14 and 20 ms when comparing optical motion capture systems and force platforms (Fellin et al., 2010; Milner and Paquette, 2015; Smith et al., 2015). Other studies using inertial systems found slightly lower offset values for foot contact detection based on foot and back sensor accelerations values (Benson et al., 2019; Giandolini et al., 2014). However, the current study is the first to compare a method for IC detection derived from an inertial system as well as an optical system against a force sensing criterion at different speeds and with different footstrike patterns during running. Our findings suggest that the offset in IC detection during running, using the PDVP method, is only dependent on speed and not on footstrike pattern or measurement system.

In this study it was shown that the offset decreased systematically with an increase in speed. This might suggest that at faster running speeds, the impact shock caused by deceleration of the body propagates faster through the body, resulting in a sharper sinusoidal vertical velocity pattern of the pelvis and IC is detected earlier. It can also be suggested that at faster speeds the movement is more constrained making segmental positions at IC more consistent while COM movement might be fairly similar (Brughelli et al., 2011). No speed effects were observed for IC detection in a previous study using an accelerometer placed on the foot in contrast to the present study where IC was identified using instruments placed on the pelvis (Benson et al., 2019). The speed dependent differences in offset are small, although statistically different. For the inertial system they are of a similar magnitude (21–25 ms) to the values reported by Benson et al. (Benson et al., 2019) and slightly higher (21–27 ms of magnitude) than previously reported values for the optical systems. Therefore, the higher offset may require some caution when using this method with a mocap system at

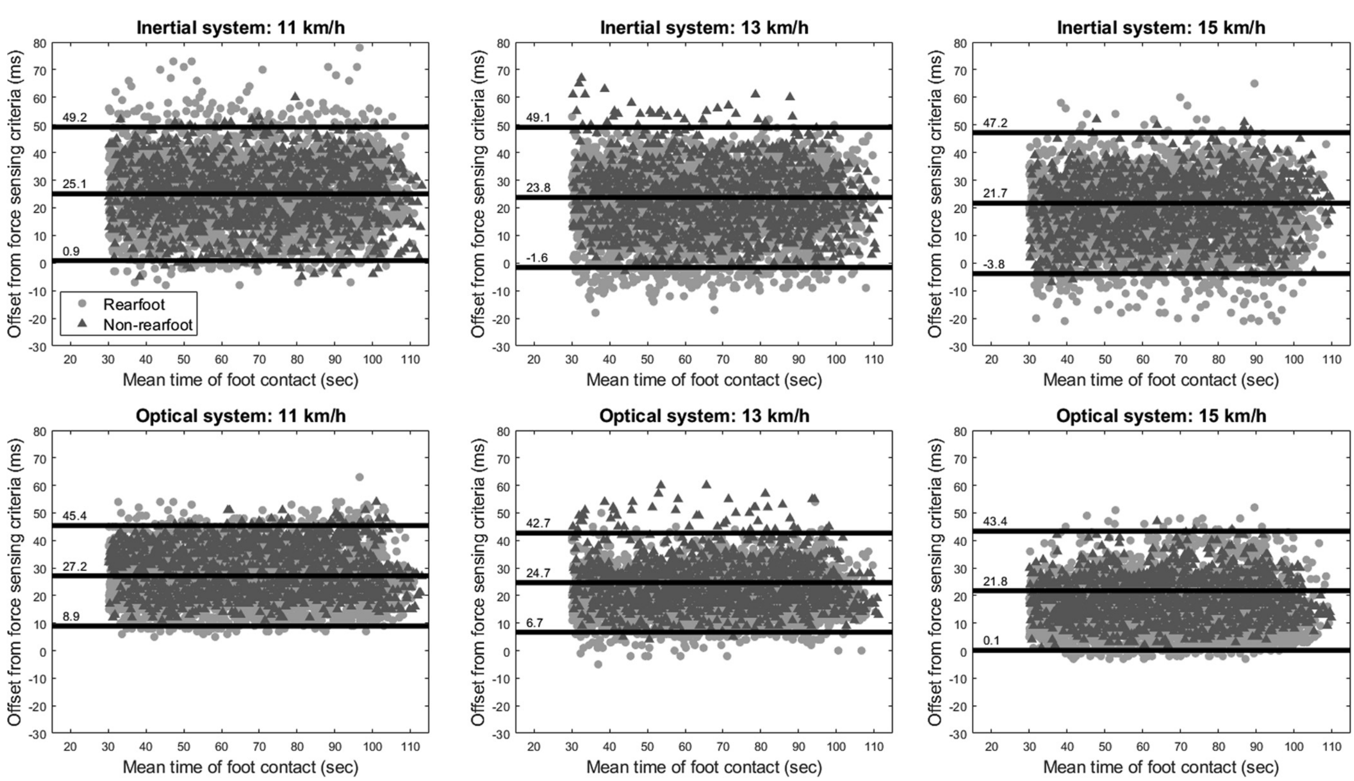

Fig. 1. Bland-Altman plot showing the offset (time difference) between Initial Contact detected with the inertial and optical systems against the force sensing criterion at the three different speeds (11, 13 and 15 km/h).

slower speeds. The value of a small but decreasing offset for the inertial system versus the force platform at all speeds has practical implications for in-field assessments of stance phase biomechanics using wearable technology.

It is important to note that the current study was performed on a treadmill while the study of Milner and Paquette (2015) was performed while running overground in the gait laboratory. Despite the differences that may exist between running on a treadmill and running overground it is reasonable to suggest that the current results are applicable to overground running outdoors. However, in the absence of a "gold standard" approach for detecting IC outside the laboratory this claim remains to be confirmed, since running outdoors is associated with different surfaces and slopes and greater stride and speed variability. Inertial sensors open up the opportunity to validate this assumption in future studies.

5. Conclusion

Findings from the present study demonstrate that a method based on the peak downward velocity of the pelvis measured with an inertial-based system to detect IC was comparable to a method based on an optical system and that neither were significantly different from an instrumented force sensing treadmill system regardless of footstrike patterns. However, the accuracy of IC detection using the PDVP method for both systems was dependent on speed, such that lower running speeds were associated with significantly greater delays relative to the force-sensing criterion. Consequently, IC detection during overground running using an IMU-based PDVP method may be less valid at slower running speeds.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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