CONTACT TIME AND FOOT STRIKE ANGLES ESTIMATION USING FOOT WORN INERTIAL SENSORS IN RUNNING

Mathieu Falbriard[1], Frédéric Meyer[2], Benoît Mariani[3], Grégoire P. Millet[2], Kamiar Aminian[1]

Laboratory of Movement Analysis and Measurement, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland[1]
Institut des sciences du sport de l'Université de Lausanne, UNIL, Lausanne, Switzerland[2]
Gaitup, Lausanne, Switzerland[3]

The purpose of this study was to evaluate the performance of new algorithms based on foot-worn inertial measurement units (IMUs), to detect foot contact time and foot strike angles in running. Treadmill instrumented with force plate and camera-based motion capture system were use as reference system. For 35 participants running on treadmill with different speeds, contact time and foot strike angle values obtained from IMUs were compared with those measured by force plate and motion cameras, respectively, with a relative error (mean ± SD) of -10.5 ± 2.2% and 3.9 ± 5.3°. This error could be further reduced using a corrective model based on the runner’s speed and foot strike angle.

KEY WORDS: running, inertial measurement units, validation, ground contact time, foot strike angles.

INTRODUCTION: Contact time and foot strike angle (foot-treadmill angle at initial contact) are two important parameters for running analysis: Short contact time is generally associated with a good running economy (Santos-Concejero et al., 2013; Weyand, Sandell, Prime & Bundle, 2010) and paramount for leg stiffness estimated with spring-mass model (Morin, Samozino, Zameziati & Belli, 2007). Similarly, foot strike angle was shown to influence landing impact and running efficiency (Ardigo, Lafortuna, Minetti, Mognoni, & Saibene, 1995; Gruber, Boyer, Derrick & Hamill, 2014). Force plate and contact mat (e.g. ergojump) are frequently used as reference measurement system for running temporal analysis while motion cameras are the gold standard for spatial analysis. However, these systems are limited in the volume they can capture which restrict their use to indoor laboratories.
Recent studies have investigated the potential of Inertial Measurement Units (IMUs) to fill the gap between subjective observational running analysis and bulky in-laboratory installations. Although only few running gait parameters have been investigated to date (Giandolini et al., 2014; Rahel, 2016; Strohrmann, Harms, Tröster, Hensler & Müller, 2011), previous researches in walking gait analysis (Mariani, Rouhani, Crevoisier & Aminian, 2013) suggest that there is more to expect from IMUs in running analysis. In addition, only a few studies have validated their results with gold standard systems. Therefore the goal of the present study was to estimate the performance of foot-worn IMUs for measurement of foot contact time and foot strike angles in running.

METHODS: 41 participants (28 males, 13 females, age 31 ± 6 years, size 174 ± 6 cm, weight 70 ± 10 kg) were asked to run for 40 seconds at different speeds, starting at 8 km/h and increasing by 2 km/h up to their maximum speed, on an instrumented treadmill (T-170-FMT, Arsalis, Belgium) equipped with 3D force plate sampled at 1000 Hz. As testing was carried out on a treadmill, participants were taken through a 6 minutes’ familiarization session prior to the measurements (Lavcanska, Taylor & Schache, 2005). Participants worn their usual running shoes and were equipped with one IMU (Physilog, Gaitup, Switzerland) affixed to the upper part of each shoe, measuring 3D acceleration and 3D angular velocity at 500 Hz, and 7 reflective markers fixed on the shoes to measure the 3D orientation of the foot with 8 infrared motion cameras (BTS Smart 400, BTS Bioengineering, USA) sampled at 100 Hz. IMUs, force plate and motion cameras were synchronized using a trigger signal recorded on

each system. Force plate was used as reference system for running gait temporal events detection and motion cameras as reference system for the spatial orientation of the foot.
At first, recorded inertial signals had to be calibrated (e.g. aligned with foot anatomical frame) in order to avoid the influence of sensor location, so we designed an automatic method for anatomical alignment of the foot-worn sensors internal frames which made use of the cyclic nature of the running movement and required only a short static period where participants were standing still with their feet flat on the treadmill.
Using IMUs data, an algorithm for foot contact time estimation was devised which first extracted several relevant time events from the foot kinematics signals. Then several estimators were proposed to detect the initial contact (IC) and toe-off (TO) in the presence of high impact noise due to shocks at each foot strike. In order to keep the best estimators, we compared them with IC and TO obtained from the force plate using a threshold on the filtered vertical force signal of each step. Because the detection accuracy depends on the value of this reference threshold, we have tested multiple thresholds in absolute value and in percent of the participant's body weight. Finally, we combined the best candidates for IC (Ki with i =1,2,..,13) and the best candidates for TO (Tj with j =1,2,..,9) into a total of 117 pairs and evaluated their performance to assess contact time.
Using strap down integration and the temporal event previously detected, another algorithm was designed to estimate the foot-treadmill angle at initial contact (foot strike angle). As the data recorded with IMUs provide derivatives of kinematics (e.g. acceleration and angular velocity), integration operation to obtain angle involves some drift errors in our measurements, which was reduced using the hypothesis that a foot-flat period always occurs during stance phase. Finally we compared the IMU based estimation of the foot strike angle with the orientation measures with motion capture cameras.
For the validation, in order to avoid over fitting, the algorithms were tested using a randomly selected subset of 10 participants and were then validated over the entire dataset.

RESULTS: After removing some trials with missing data, 35 participants were left for the design and validation of our algorithms. The best estimator (K8,T1) for contact time had an mean error (accuracy) and standard deviation (SD) of error (precision) of -21.8 ± 5 ms when averaged over 238 runs (i.e. all subjects from 8 to 20 km/h) and when the reference threshold was set to 7%BW. Similarly, when expressed relatively to the force plate reference value, the relative mean ± standard deviation error was -10.5 ± 2.2%. The range of contact times measured vary from 139 to 382 ms. Moreover, the two kinematic features (K8 and T1) used to estimate IC and TO were detected for more than 99.6% of the 18895 steps (i.e. 76 steps were dropped). When considered individually, K8 and T1 have a mean and SD error of 0.6 ± 2.6 ms and -24.6 ± 4.3 ms, respectively. Table 1 shows the detailed foot contact time estimation errors for the 6 best candidates with respect to the different force plate reference thresholds.

Table 1
Contact time estimation errors (mean ± std) for the 6 best estimators *(Ki-Tj)* expressed in percent of the reference contact time obtained from the ground reaction force using fixed threshold or 3%, 5% 7% and 9% of body weight (BW).

REF.	*K8-T1*	*K10-T1*	*K1-T1*	*K13-T1*	*K2-T1*	*K12-T1*
20N	-13.9 ± 2.8	-17.7 ± 2.8	-18.3 ± 2.8	-19.1 ± 2.8	-11.3 ± 3.2	-18.7 ± 2.9
30N	-12.5 ± 2.6	-16.4 ± 2.6	-17 ± 2.6	-17.8 ± 2.6	-9.8 ± 2.9	-17.4 ± 2.7
40N	-11.3 ± 2.3	-15.2 ± 2.3	-15.8 ± 2.3	-16.6 ± 2.3	-8.6 ± 2.6	-16.2 ± 2.5
50N	-10.3 ± 2.2	-14.2 ± 2.3	-14.8 ± 2.3	-15.6 ± 2.3	-7.5 ± 2.6	-15.2 ± 2.4
3%BW	-13.9 ± 2.8	-17.7 ± 2.8	-18.2 ± 2.8	-19.1 ± 2.8	-11.2 ± 3.2	-18.7 ± 2.9
5%BW	-12 ± 2.4	-15.9 ± 2.4	-16.5 ± 2.4	-17.3 ± 2.4	-9.3 ± 2.7	-16.9 ± 2.6
7%BW	-10.5 ± 2.2	-14.4 ± 2.3	-15.1 ± 2.3	-15.9 ± 2.3	-7.8 ± 2.6	-15.5 ± 2.5
9%BW	-9.2 ± 2.2	-13.2 ± 2.2	-13.8 ± 2.2	-14.7 ± 2.3	-6.4 ± 2.5	-14.2 ± 2.4

Results of foot strike angles estimation errors, evaluated over N=2661 steps, show a mean±SD of error of 3.9 ± 5.3° and a correlation coefficient with reference values r = 0.89. The Bland-Altman plot on Figure 1 shows the agreement between the foot strike angle estimated with IMU and the reference angles obtained with motion capture cameras. The range of foot strike angles found on the reference system vary from -16° to 29°, with negative values occurring for forefoot strikers (i.e. the ball of the foot lands first) and positive values for rear-foot strikers (i.e. heel lands first).

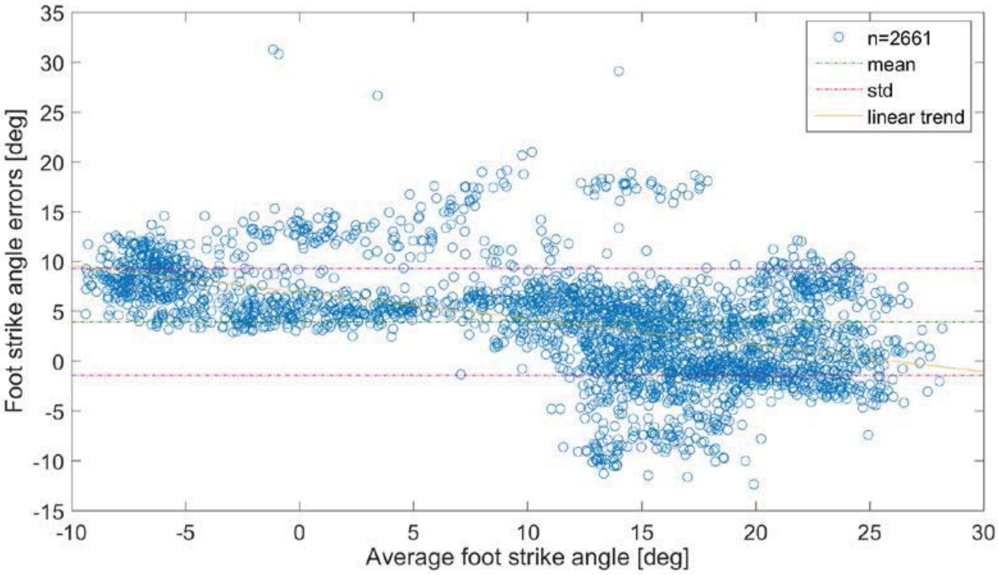

Figure 1: Bland-Altman agreement between the foot strike angle estimations based on the left foot IMU data and the reference angles obtained with motion capture cameras. Positive values on the y-axis imply an overestimation of the angles found with the IMU while negative values imply an underestimation.

DISCUSSION: This study aimed to examine the performance of foot-worn IMUs to assess contact time and foot strike angle in running. The results show that IMU system is valid and reliable for contact time estimation with a precision of 2.2% which is better the results of a previous study that found a precision of 6.1% when compared with high-speed cameras (Rahel, 2016). Moreover, accurate detection of temporal events (e.g., IC and TO) allows to measure all temporal parameters flight time, cadence, stride-to-stride variability. We observed a trend between the system accuracy and the speed of the treadmill. This suggests that we could further optimize the accuracy of our algorithm using a corrective model based on the runner’s velocity. The kinematic features used to detect initial contact and toe-off are often based on the measurements from a single axis of the accelerometer and/or the gyroscope, therefore, the repeatability and robustness of the proposed detection methods also suggest that our automatic anatomical alignment of the foot-worn sensors internal frames is valid for running applications. Finally, the influence of the reference threshold used on the vertical force signal still has to be further investigated. Our choice of using the 7%BW reference threshold was based on its robustness to detect stance phase temporal events at low running velocities, and preferred to 9%BW.

Our preliminary results on foot strike angle estimations highlight the IMUs capacity to measure the foot 3D orientation in running when an appropriate drift correction method is applied to the algorithms. The current accuracy (3.9°) and precision (5.3°) of our algorithms were sufficient to classify each step either as rear-foot strike (i.e. heel lands first) or forefoot strike (i.e. the ball of the foot lands first). Similar results were found in Giandolini et al. (2014) where two IMUs were used on each foot and where the foot strike angle was modelled from the time between heel and metatarsal peak accelerations.

The large spectrum of running speeds and foot strikes patterns used in the present study suggest high potential for IMU as a valid tool for running analysis outside of a laboratory, opening this way to many new applications in outdoor running. Further studies are needed to extract other useful running features such as foot angle in frontal plane, and the impact of the type of ground surface (uphill, downhill).

CONCLUSION: Foot worn IMU can be used to estimate the foot contact time and foot strike angle with a relative error (mean ± SD) of -10.5 ± 2.2% and 3.9 ± 5.3° respectively in the speed range of 8km/h to 20km/h. It offers the possibility to perform running analysis indoor but also in outdoor setting and in-field measurements. Further studies are needed to estimate the influence of inclined surface on system performance.

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