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Portable inertial motion unit for continuous assessment of in-shoe foot movement

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Abstract

Objective. The validity and reliability of a new prototype (PT) to measure tibio-calcaneal eversion/inversion, internal/external rotation, and plantar/dorsiflexion angle during running were investigated. Design. Test-retest measurements by a 3D accelerometer and gyroscope inertial motion unit (IMU) were compared to a motion capture (MC) based system both capturing in-shoe rearfoot and tibia kinematics. Background. Laboratory running tests may not reflect movement characteristics experienced during outdoor training. Lower extremity running kinematics have not been obtained by 3D IMU measurement within the shoe previously. Methods. 3D motion of two IMUs attached to the tibia and calcaneus, as well as retroreflective markers through windows in the running shoes, were determined during running. Intersegmental motion was extracted by a complementary filter fusing accelerometer data with integrated gyroscope angular velocity. PT measurements for motion along main anatomical axes were similar to MC derived curves based on coefficients of multiple correlation. Intraclass correlation correlations (ICC) showed a low correlation between PT and MC in three out of four parameters, but high repeatability for PT between test and retest measures. PT underestimated angular motion with a root mean square error (RMSe) of 182.5°/s and bias of 176.3°/s. Eversion was underestimated by PT with RMSe of 6.3°. The PT method was found inadequate to determine valid tibio-calcaneal motion while it was reliable for repeated tests and may allow for intra-subject comparisons of different footwear or inserts.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: Running injuries, eversion, tibio-calcaneal movement, in shoe measurements, gyroscope, accelerometer, IMU, complementary filter

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1. Introduction

Increasing interest in running activities makes injury prevention through correct footwear ever more important. Injury mechanisms have often been related to tibia-calcaneal movements Nigg (2001). However, studies regarding injury mechanisms often use laboratory tests creating shortcomings in regard to ecological validity. Wiegerinck et al. (2009) indicated that the short running distance used may not represent regular running training outdoors which would make measurements during training much more relevant. Further, external shoe markers have often been used to estimate skeletal movement with overestimating eversion compared to skin markers observed through windows cut into the heel cup (Reinschmidt et al. 1997).

Advances in sensor technology may provide the basis for the collection of data in the true training situation (Mathie et al. 2004). Mayagoitia et al. (2002) have successfully implemented inertial motion units (IMUs) to measure sagittal plane kinematics while walking. Externally positioned gyroscopes were used to measure eversion angular velocity (Lederer et al. 2011). To our knowledge, no previous study employed a portable measurement device to record tibio-calcaneal skeletal movement inside a shoe.

The aim of this study was to investigate the validity and reliability of a proposed new measurement device for tibio-calcaneal skeletal movement. A prototype was constructed using two IMUs located on tibia and calcaneus, with an algorithm to obtain orientation estimations. The prototype was compared to a traditional MC system.

2. Method

Seventeen male subjects (age 28.6, SD 7.5 years), running on average 31.7 (SD 16.6) km/week participated under informed consent by the local ethics committee (N-20130015).

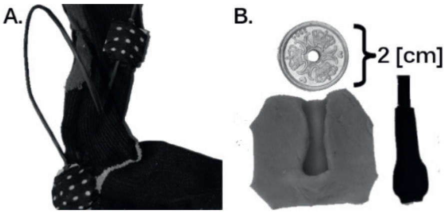

Figure 1. A; compression sock with pockets and IMU inserted. B; a silicone fitted material and IMU

2.1. Materials

The PT consisted of two IMUs placed on bony landmarks (medial tibial aspect and calcaneus lateralis). Each IMU was fitted into silicone material and inserted in a commercial compression sock (Fig. 1). Each IMU consisted of a 3D accelerometer and gyroscope (16 g and 800°/s, 16 bit) (Debus und Diebold Messsysteme, GmbH). Both IMUs were connected to a data logger placed on the lower back (800 Hz). 3D local axes of the IMUs were manually aligned that their x-axes pointing anteriorly, y-axes medially and z-axes vertically.

Eight cameras recorded passive retroreflective markers (*diameter*: 1.5 cm) at 200 Hz (Oqus 300, Qualisys A/S) placed according to ISB recommendations (Wu et al. 2002). Shank markers were placed directly on the skin. Metatarsal 1 and 5 markers were glued externally on the shoe. Calcaneus lateralis, posterior and medialis markers were placed as skin markers on removable 14-mm rods and windows were cut in the running shoe (ECCO Biom B). A force plate (AMTI-OR6-7-2000) recorded ground reaction force at 800 Hz. A wireless trigger (Noraxon, USA 232 Transmitter) was used for synchronization of PT and MC.

2.2. Experimental setup and procedure

Following sufficient familiarization time subjects ran along a 10 meter at 12 ± 1.2 km/h controlled by two infrared timing gates. Subjects were recorded while standing in a neutral reference position and when the leg was lifted to horizontal. Subsequently, ten successful running trials were recorded. Following removal and remounting of all equipment a retest was performed using the same procedure. A third test was performed to observe if any movement of the IMUs during a 5-min run at 12 km/h on a treadmill would affect the alignment of the sensors.

3. Data analysis

3.1. Prototype (PT)

Accelerometer and gyroscope data were filtered using a 2nd order Butterworth lowpass filter at 10 and 60 Hz, respectively. Each IMUs local coordinate system (LCS) was rotated by an intrinsic cardan sequence (x, y', z'') to match the global coordinate system based on reference trials. X' and y' rotations were calculated based on the anatomically neutral reference position, with the z-axis pointing vertically upwards. z'' was rotated based on the horizontal static trial with the x-axis pointing vertically upwards. By trigonometric calculations, the angle of rotation about x (σ), y' (τ) and z'' (υ) axes was defined by the yz-, xz-, and xy-plane. This resulting rotation matrix ($R_{x,y',z''}$) was applied to dynamic recordings.

Recording angles by integrating gyroscope signals over time typically leads to a drift (Luinge et al. 2011). A complementary filter was applied, by fusing accelerometer and gyroscope data, with the use of a proportional integral (PI). Fusion of the integrated gyroscope data and accelerometer Euler angles was performed to output, φ, θ and ψ representing rotations about x, y and z axes respectively by these calculations: $\varphi = \sin^{-1}(-a_y/g)$ and $\theta = \cos^{-1}(a_z/(\cos(\varphi) * g))$, where $g = \sqrt{a_x^2 + a_y^2 + a_z^2}$.

The parameters of interest for tibio-calcaneal movement are: β, eversion/inversion, Δρ, internal/external rotation and the horizontal sole angle (γ) as described elsewhere (Kersting and Bruggemann 2006). Signal and data analysis was carried out offline (Matlab® 2013a).

3.2. Motion capture

Marker-based data were filtered by a 30 Hz lowpass 2nd order Butterworth filter. Attitude calculations of the LCS with respect to the right hand rule for calcaneus and tibia were performed by solving an intrinsic cardan sequence rotation ($X_1Y_2Z_3$) (Winter 2009).

3.3. Statistical analysis

Coefficients of multiple correlation (CMC) were employed for variables of interest (β, ρ and γ) to compare the general curve by a mean of 10 trials with a CMC > 0.8 being considered as high (Kadaba et al. 1989).

Table 1. Coefficient of multiple correlation of general curve of MC compared to PT.

Coefficient of multiple correlation	Frontal (β)	Transverse (ρ)	Sagittal (ρ)
mean	0.822	0.789	0.997
SD	1.580	0.186	0.002

To understand how individual subjects were affected by random and systematic error when comparing MC and PT, all trials were compared using the Bland-Altman technique (Bland and Altman 1999) resulting in values for bias and limits of agreement (LOA). To investigate relative reliability of validity and reliability an Intra Class Correlations (ICC 2,k) was used. Model 2,k explains an ICC which tests for systematic and random error for k successful trials. An ICC > 0.75 was considered excellent and 0.40 > ICC < 0.75 fair-to-good reliability (Fleiss 1970). To investigate the average error of a variable the Root Mean Square error (RMSe) was used.

Table 2. Coefficients of multiple correlation of curves from MC compared to PT. Bias between MC and PT. Limits of Agreement (LOA) 95% confidence interval between deviation of MC and PT, Intra-class correlation coefficient (ICC), Root mean square error (RMSe).

Prototype compared to motion capture	Bias	LOA	ICC	RMSe
$\Delta\beta_{max}$[°]	6.1	[-6.7:18.9]	-0.35	6.3
$\dot{\beta}_{max}$[°/s]	176.3	[-146.4:499]	-0.34	182.5
$\Delta\rho_{max}$[°]	0.3	[-15.8:16.3]	0.37	7.7
γ_{TD}[°]	-7.1	[-18.3:4.1]	0.92	7.0

Table 3. Coefficient of multiple correlation of general curve of MC compared to PT. Bias average deviation between MC and PT. Limits of Agreement (LOA) 95% confidence interval between deviation of MC and PT. Intra-class correlation coefficient (ICC). Root mean square.

Prototype test and re-test	Bias	LOA	ICC	RMSe
$\Delta\beta_{max}$[°]	-0.3	[-7.2:6.6]	0.84	3.3
$\dot{\beta}_{max}$[°/s]	-13.3	[-169.9:143.2]	0.68	76.6
$\Delta\rho_{max}$[°]	-0.4	[-10.6:9.9]	0.88	5.0
γ_{TD}[°]	-0.9	[-8:6.2]	0.95	3.5

4. Results

Subjects (11 and 13) were excluded, due to IMU shifting from static to start of the dynamic recordings. One subject (12) was excluded due to IMU orientation changing during recordings. High CMCs were found for β and γ (CMC > 0.8) in intra-individual comparisons (Fig. 2).

4.1. Validity

For $\Delta\beta_{max}$, the range of eversion from TD to minimum, an underestimation 6.1° was found for PT. A bias of -7.1° was found for γ_{TD} resulting in an overestimation of shoe sole angle. No general trend of error was observed (Fig. 3A), though subject specific outliers were seen (subject 5, 14, and 15) during some trials in certain individuals. Heterogeneity occurred at higher $\dot{\beta}_{max}$ as measured by PT (Fig. 3B) with subjects 5, 14, and 15 being identified as outliers (error > LOA) in one or more trials. $\dot{\beta}_{max}$ measures presented a bias of 176.3°/s. A high correlation between MC and PT (ICC > 0.75) was constituted for γ_{TD} as the only parameter.

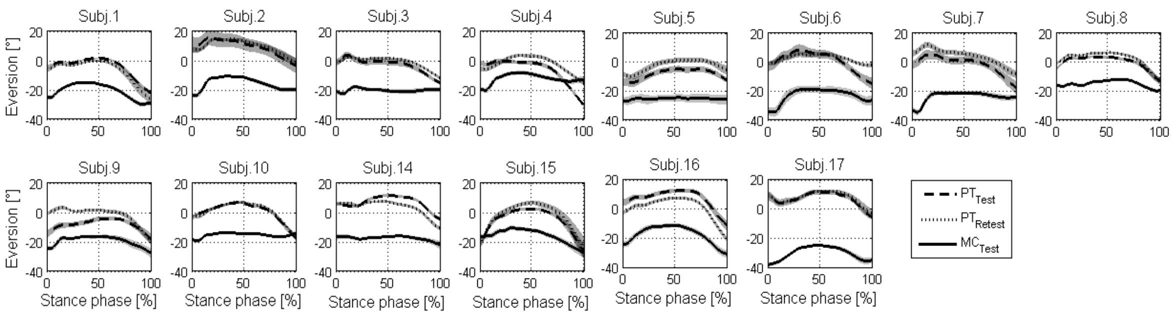

Figure 2: Average curves for eversion during stance from PT-test, PT-retest and MC-test. Shaded area is ± standard deviation.

4.2. Reliability

A high reliability was demonstrated in 9 out of 14 subjects for $\Delta\beta_{max}$, with a bias close to zero (Fig. 3B). Five subjects (4, 6, 9, 14, and 15) expressed lower reliability in test-retest comparison. PT-retest results for these subjects did not demonstrate a similar $\Delta\beta_{max}$ value as in the PT-test. An average of 3.3° RMSe was observed. For test-retest comparisons, parameters $\Delta\beta_{max}$, $\Delta\rho_{max}$ and γ_{TD} showed ICCs > 0.75 expressed by high correlations between tests. $\dot{\beta}_{max}$ showed a lower ICC (<0.75) (Results for tibia movement not shown).

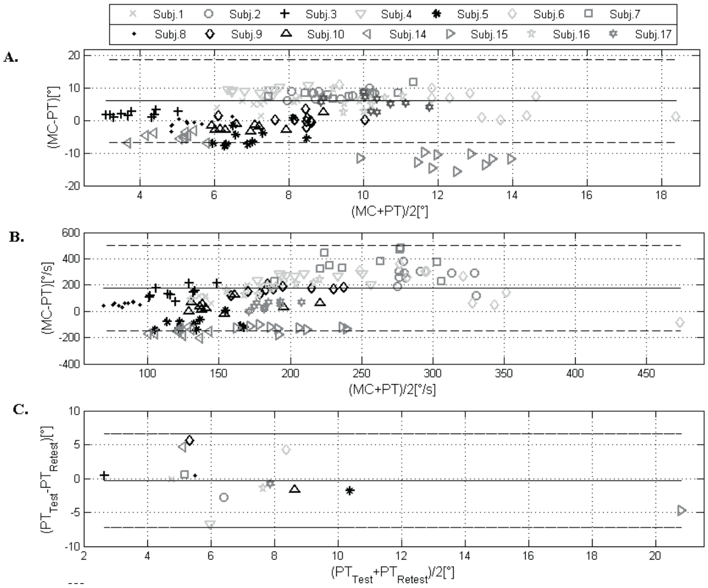

Figure 3: **A**. Blandt-Altman plot of β_{max}. **B**. Blandt-Altman plot of $\Delta\beta_{max}$. Each symbol representing one trial comparison of one subject. **C**. shows β_{max} in test-retest for subjects mean.

5. Discussion

The aim of this study was to investigate the validity and reliability between the prototype and MC. A high intraclass correlation of normalized mean curves between PT and MC was found. Reliability results showed a high correlation (ICC > 0.75) for repeated tests. The RMSe was between 3.3 - 5.0° for absolute angles and 76.6°/s for $\dot{\beta}_{max}$. The magnitude of PT did not coincide with MC (ICC < 0.75), resulting in an absolute RMSe of 6.3° and a bias of 6.1°. Overall, a difference between the MC and PT representations of tibia and calcaneus movement occurred. This error was systematic across all subjects, which suggested a general alignment problem. This may be explained by the rotational procedure of the PT which aligns the IMU with respect to global reference system. This alignment deviates from the MC anatomical reference procedure and may be resolved by a more elaborate reference measurement.

An underestimation occurred for $\Delta\beta_{max}$ (bias = 6.1°) which may be considered opposed to Reinschmidt et al. (1997) who described an overestimation of $\Delta\beta_{max}$ by 7.4° by external shoe markers compared to skin markers. The present results may be explained by skin movement artefacts. Individuals differed between test and retest possibly explained by positioning of the IMU on the calcaneus. Error magnitudes varied between test and retest for individual subjects possibly explained by artefacts, such as cable "pulling", or an influence by the lateral malleolus or the marker on the lateral calcaneus. Largest errors were found in early stance for individual subjects at the IMU on the calcaneus. Earlier findings suggest that vibrations of gyroscope and accelerometer at heel strike could lead to an error, e.g., during walking (Mayagoitia et al. 2002).

A systematic overestimation of absolute IMU calcaneus angle and γ_{TD} may be explained by the applied complementary filter including a PI-controller. Subsequent experiments showed that the PI-controller requires a settling time of appr. 10 s. Since the recording time in the present study was a priori set to 4 s, it is well possible that the insufficient measurement interval lead to the described overestimation.

An additional error source may arise from an orientation change of the IMU. This was examined in a follow-up study in which static orientations pre and post a running test on a treadmill were compared. A rotation about the z-axis of up to 7.5° occurred from pre to post for both the IMUs on the calcaneus the tibia indicating an inconsistent rotation axis. A simple improvement will be a better fixation of the sensors on the skin.

6. Conclusion

The validity of prototype is likely inadequate to determine relative eversion/inversion, angular velocity, and internal/external rotation. PT is adequate at determining plantar/dorsiflexion motion of the ankle. The reliability of prototype was very high. Based on the findings of this study the PT may only be used for estimates of between-subjects tests. However, the high repeatability makes it well suited for intra-individual assessments of inserts or shoe modifications. Further testing is required to understand the importance of IMU location, fixation and the possibility of vibration removal. Following improvements a re-evaluation of the PT is planned.

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