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SPRINT MECHANICS EVALUATION USING INERTIAL SENSOR-BASED TECHNOLOGY: A LABORATORY VALIDATION STUDY

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ABSTRACT

Advances in micro-electromechanical systems have turned magnetic inertial measurement units (MIMUs) into a suitable tool for vertical jumping biomechanical evaluation. Thus, the presented study aimed to determine if appropriate reliability and agreement reports could also be obtained when analysing 20m sprint mechanics. Four bouts of 20 m sprints were evaluated to determine if the data provided by a MIMU placed at the lumbar spine could reliably assess sprint mechanics and to examine the validity of the MIMU sensor compared to force plate recordings. Maximal power (P_0), force (F_0) and velocity (V_0), as well as other mechanical determinants of sprint performance associated with the Force – Velocity, Power – Velocity and Ratio of Forces – Velocity, such as applied horizontal force loss (S_{fv}) and decrease in ratio of forces (D_{rf}), were calculated and compared between instrumentations. Extremely large to very large correlation levels between MIMU sensor based sprint mechanics variables and force plate recordings were obtained (mean \pm standard deviation, force plate vs. MIMU; V_0 , 8.61 ± 0.85 vs. 8.42 ± 0.69 ; F_0 , 383 ± 110 vs. 391 ± 103 ; P_0 , 873 ± 246 vs. 799 ± 241 ; S_{fv} , -44.6 ± 12.7 vs. -46.2 ± 10.7), ranging from 0.88 to 0.94, except for D_{rf} , which showed weak to moderate correlation level ($r=0.45$; -6.32 ± 1.08 vs. -5.76 ± 0.68). Step-averaged force values measured with both systems were highly correlated ($r = 0.88$), with a regression slope close to the identity (1.01). Bland & Altman graphical representation showed a not random distribution of measured force values. Finally, very large to extremely large retest correlation coefficients were found for the inter-trial reliability of MIMU measurements of sprint performance variables (r value ranging from 0.72 to 0.96). Therefore, MIMUs showed appropriate validity and reliability values for 20-m sprint performance variables.

Keywords: Sprint Mechanics, Inertial Unit, Validation, Biomechanics

INTRODUCTION

Sprinting performance is a key component of many training routines in numerous sport disciplines and conditioning programs (1). Moreover, in the last 30 years, many high speed athletic tasks have been implemented by athletic coaches to maximize performance in explosive activities (2). In the field of sports science, sprint mechanics have been widely studied, focusing on putting some light into several concerns related to the adaptations of the human body to exercise and to describe basic movement patterns (3). To this end, direct mechanics-based procedures have been traditionally employed to estimate the center of mass displacement and to detail the biomechanics during sprinting and jumping tasks (3;4). In this context, the force-velocity ($F - v$) and power-velocity ($P - v$) relationships have been used during the last decades to describe the runner's capability to produce horizontal external force during the sprint (3;5;6). In the case of sprint running and other multijoint lower limb movements, these relationships have been found to be linear and parabolic, respectively. Therefore, they can be characterized by a small number of parameters such as: The theoretical maximal horizontal force the runner can apply at zero velocity (F_0), velocity for zero horizontal force (v_0), maximum power developed by the runner (P_0), rate of loss of horizontal force (S_{fv}) and rate of decrease of ratio of forces (D_{rf}). In practice, these parameters are determined from the linear or parabolic fit of measured data and in turn can help coaches and physiotherapists to decide on the most appropriate training action.

Several technological procedures and methodological approaches have historically been used for sprint mechanics description in humans; including 6- to 10-m force plates indoors (5;6), electromyography (7), instrumented treadmills (8;9) and the more recently developed radar systems (9). All but the last approaches require a considerable financial investment and highly trained staff familiarized with such laboratory-derived procedures. Consequently, radar systems constitute a relevant and valuable contribution to the field since they provided the means to describe for the first time an athlete's velocity-by-time curve when sprinting in real training conditions. This innovation has enabled more researchers and clinicians to measure certain biomechanical variables without resorting to time

consuming and expensive equipment-based sprint mechanics analysis. However, although radar systems have shown very high correlation levels with respect to ground reaction horizontal forces recordings from force plate systems, they calculate such forces from time by distance derived variables. It is also likely that inter-step variability is not detectable by the current technologies and proposed methods as the models give the average tendency of change in ground reaction forces components with time of both limbs.

The most recent advances in micro-electromechanical systems have made magnetic inertial measurement units (MIMUs) a robust and reliable tool for sports motion analysis in the fields of performance evaluation (10) and injury rehabilitation and prevention (11). A possible major advantage of MIMUs compared to force plate-based procedures is that MIMUs enable non-conditioned foot landing and outdoor testing, thereby allowing functional and unplanned movement analyses both in a laboratory and field conditions.

In this context, the purposes of the present study were (1) to examine the validity of MIMUs compared to force plate platform recordings when evaluating force – velocity relationship of the sprint mechanics and (2) to determine whether the data provided by a MIMU placed at the lumbar spine could reliably assess this sprint mechanics related variables such as V_0 , F_0 , P_0 , S_{df} and D_{rf} . The study hypothesis was that the proposed method would provide robust agreement between MIMUs and force plate recordings as well as acceptable reliability when evaluating sprint mechanics based on direct mechanics procedures. Due to the involvement of sprint performance in training and conditioning, the population of interest range from recreational runners to elite sprinters. Therefore, MIMUs should exhibit high reliability and agreement for a wide range of performance variables values.

The terms “reliability” and “agreement” have been given different meanings in the literature, and often used interchangeably. In this work we adhere to what is customary in sports measurements analysis and take “reliability” as repeatability (12) or intrarater agreement (16) and “agreement” as reproducibility (12) or interrater agreement (16).

Materials and methods

Participants:

A validation study design was adopted. Several approaches can be used to estimate the optimal sample size. We adopted the methodology suggested in (12) based on the anticipated intraclass correlation coefficient (ICC) value and 95% confidence interval (CI) width. For a target, ICC of 0.9 with a 95% CI of 0.2, the minimum number of subjects is 15. Sixteen recreational runners volunteered to participate in this study: eight men (mean \pm standard deviation; age: 31.5 ± 6.3 years; body mass 78.3 ± 13.0 kg; height 1.77 ± 0.07 m) and eight women (age: 26.1 ± 4.4 years; weight: 59.8 ± 8.0 kg; height: 166.3 ± 7.4 cm). The mean running experience and training frequency of the participants were 7.9 ± 5.0 years and 3.7 ± 1.7 days weekly, respectively.

The previous and current injury records of the participants at the time of testing is summarized in Table 1.

The experiment was carried out in a biomechanics laboratory. The participants performed a sprint test battery of 20-m maximal sprint runs. All measurements were acquired by the same team (IG, PL and MI).

Instrumentation:

Participants were equipped with a micro-electromechanical system (MIMU) (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, Netherlands). The MIMU was attached over the L4- L5 region of the subject's lumbar spine, where the human's centre of mass is considered to be located in (13). A technical explanation of the MIMU-derived analysed variables has been previously provided (14). The trials were simultaneously recorded by the MIMU and by a 10-m-long force platform system (custom build, force transducers manufactured by Raute Precision, Lahti, Finland). Ground reaction forces were recorded by Signal 4.04 software (Cambridge Electronic Design, UK). Furthermore, three photocells gates (Newtest, Oulu, Finland) were positioned along the force plate length at 0.5, 5.5 and 10.5 m from its edge. Synchronization of all systems was achieved by means of two pulse signals present at different channels of the force platform A/D converter (Power1401, Cambridge Electronic Design, UK) with a sampling frequency of 1000 Hz. A manual trigger produced a rising-edge pulse which started the MIMU measurement and the first photocell triggered another pulse when light was obstructed. These signals were processed to obtain the split times for each cell position. In order to reduce errors related to the integration process, the highest sampling rate for data recording was selected for both instruments: 1000 Hz for the force platform and 120 Hz for the MIMU. Before each trial, the participants were asked to assume a vertical posture during the calibration process for both instrumentations.

Procedures:

The testing procedure comprised the execution of several maximal sprint bouts. The participants were asked to execute four 20-m sprint trials; two starting at the edge of the 10-m force plate hall, and two additional trials starting 10 m away from the force plate. In that manner, the recordings

contained complete 20-m sprint data and thus, the entire accelerative phase of the sprinting task could be analyzed. The participants performed a standardized 20-min warm up that included lower leg range of motion exercises, progressive resistance exercises and running technique maneuvers, before starting the testing protocol. The resting period was 90 seconds between every consecutive running trial.

The validity and reliability of the proposed methods were evaluated using the performance variables associated with the Force – Velocity ($F - v$), Power – Velocity ($P - v$), and Ratio of Forces – Velocity ($RF - v$) relationships previously described by Samozino et al (9). These performance variables are horizontal force at zero velocity (F_0), velocity for zero horizontal force (v_0), maximum power (P_0), rate of loss of horizontal force (S_{fv}) and rate of decrease of ratio of forces (D_{rf}). The procedure for their computation required the average values of horizontal force (F_h), vertical force (F_v), resultant force (F_{res}) and velocity for all steps.

Direct mechanics-based procedures were used to estimate the center of mass displacement and to detail the biomechanics of the sprinting action. Direct mechanics procedure are based on the description of the subject as a mechanical system and the estimation of movement and acting forces through the center of mass displacement (4) The following subsections show the procedures followed to obtain these data from force platform and MIMU measurements.

The experimental protocol was approved by the ethics committee of the Public University of Navarra according to the ethical principles of the Declaration of Helsinki. All participants gave their consent to participate in the experiment after being informed of the aims and risks of the testing procedures.

Force platform data processing

The force platform signals were low-pass filtered (200-Hz cut-off frequency, third-order zero-phase Butterworth). The horizontal and vertical components of the ground reaction force (GRF) in the sagittal plane were provided by the force platform. The resultant force samples were computed as

$$F_{res} = \sqrt{F_h^2 + F_v^2}. \quad (1)$$

Initial contact times

To compute the average values in each step, the time of contact must first be determined. A 20-N threshold on the F_v signal was used for this task, except in the case of the initial two of steps when participants started the sprint on the platform. In this case, as participants were stepping on the platform, the measured vertical force was equal to their bodyweight before the actual start of the run. The beginning of the sprint and the second support were estimated using the acceleration signals provided by the MIMU (see details below).

Velocity computation

The instantaneous horizontal velocity was computed by time-integrating the horizontal acceleration $a_h = F_h/m$, where m stands for the participant's mass:

$$v_h(t) = v_h(t_0) + \int_{t_0}^t a_h(\tau) d\tau = v_h(t_0) + \frac{1}{m} \int_{t_0}^t F_h(\tau) d\tau \quad (2)$$

t_0 is the contact time of the first stance on the force platform and $v_h(t_0)$ is the initial velocity at that time point. Note that as time-discrete data was being analysed, trapezoidal approximation was used for the numerical computation of this and subsequent integrals. For

those sprint bouts starting from the edge of the force platform time and velocity were set as, $t_0 = 0\text{ s}$ and $v_h(t_0) = 0\text{ m/s}$. When the participant's starting position was located 10 m away from the edge of the platform, the initial velocity $v_h(t_0)$ was estimated using an exponential model fitted to the time data provided by the photoelectric cells (9). Briefly, an exponential model is assumed for the participant's velocity,

$$v_h(t) = V_0(1 - \exp(-t/\tau)), \quad (3)$$

which yields the following expression for displacement:

$$d_h(t) = V_0t - V_0\tau \cdot (1 - \exp(-t/\tau)) \quad (4)$$

The photoelectric cells gave the times t_i so that $d(t_i) = d_i$, where d_i is the distance from the starting point to the i -th photoelectric cell. This allowed to estimate the parameters V_0 , τ from equation (4) using least squares minimization. Once these parameters have been obtained, the initial velocity $v_h(t_0)$ is computed using equation 3.

MIMU data processing

The MIMU comprises three-axis accelerometers, gyroscopes and magnetometers. The accelerometers provide acceleration data in a sensor-based reference frame. Its X, Y and Z axes, aligned with the unit housing, lie along the vertical, medial-lateral and anterior-posterior directions, respectively, when the participant is at rest in upright position. Note that this reference frame rotates along with the participant's torso. The output from the MIMU sensors is processed on-chip to provide orientation data (i.e., the time-dependent rotation of the sensor-based reference frame around an Earth-fixed reference frame). The latter has a positive Z direction that points upwards on the vertical, and the X and Y axes lie on the horizontal plane with the positive X direction pointing towards the magnetic north pole. Note

that neither reference frame is aligned with the direction of the sprint; this direction must be estimated from measurement data, as explained below.

The orientation data provided by the MIMU allows the computation of the instantaneous angle between the sensor's Z axis (anterior-posterior direction) and the Earth-fixed reference frame X axis on the horizontal plane. This effectively indicates the heading of the participant within a fixed reference frame at each time instant. The signals from the MIMU and the force platform were time-synchronized, so the initial contact times found from the vertical GRF could be readily translated to the acceleration and orientation signals. The direction of the sprint was estimated as the participants' average heading during his or her last four steps on the force platform. Figure 1 shows the range of the heading of a participant's torso, that is, the directions the MIMU's Z axis is pointing to, during these last four steps, as well as its mean. Once this direction was found, a track-fixed reference frame was defined with its positive Y axis aligned with the running direction and its Z axis pointing upwards on the vertical direction. Henceforth all acceleration signals are expressed in this reference frame.

Initial contact times

For the validity study, only the steps performed on the force platform were considered. Therefore, the initial contact times were accurately estimated from the vertical GRF signal as explained above, with the exception of the first pair of steps at the beginning of the sprint. In this case, and for all steps in the reliability study, the initial contact times were derived from the acceleration signals as follows: The first time the horizontal forward acceleration exceeded 3 m/s^2 marked the beginning of the sprint. The joint plots of vertical

GRF and accelerations (Figure 2) show that the vertical acceleration of the centre of mass (CM) rises above the gravity acceleration value well after the initial contact time. Around this time, a noticeable drop in forward acceleration occurs, corresponding to the braking forces produced at the beginning of the stance phase of the sprint action. The peak in forward acceleration preceding this drop was used to determine the initial contact time for subsequent supports (Figure 2).

Velocity computation

The horizontal velocity signal was found by integrating the acceleration component in the direction of the sprint.

$$v_h(t) = \int_0^t a_h(\tau) d\tau \quad (5)$$

Note that unlike velocity computed from GRF, the lower limit of the integral is always 0 s, since the acceleration of the CM was recorded from the beginning of the sprint. Similarly, the distance covered by the participant was found by integrating the velocity signal:

$$d_h(t) = \int_0^t v_h(\tau) d\tau \quad (6)$$

Small bias and integration errors accumulate and cause a noticeable drift in velocity and distance that render their values useless after a few seconds. The split times provided by the photoelectric cells at 0.5, 5 and 10 m for the first measurement protocol (starting at the edge of the force platform) and at 10, 15 and 20 m for the second measurement protocol were used to correct the drift effect. A least squares fit was used to estimate the bias in the acceleration for the position signals in order to reach those distances at the designated times. Velocity was then computed again based on the corrected acceleration (5). The split times at 0.5, 5, and 10 m for the sprints starting at the edge of the force platform were 0.35 ± 0.10 ,

1.67 ± 0.10 and 2.48 ± 0.13 s, respectively. When the participants began their sprint 10 m from the force platform, the split times at 10, 15 and 20 m were 2.46 ± 0.18, 3.18 ± 0.22, 3.87 ± 0.25 s, respectively. These distances and split times were used to adjust the bias of the measured acceleration as described above. The r coefficient for the distance computed from the corrected acceleration and position of the photoelectric cells exceeded 0.99 in all trials.

The instantaneous horizontal and vertical GRF force components were taken as the product of the instantaneous CM acceleration of each component and the participant's mass:

$$F_h = m \cdot a_h, F_v = m \cdot a_v$$

Common procedures

Once instantaneous forces and velocity signals were obtained, the variables used for the validity and repeatability assessment could be computed. This section describes the procedures used for both force platform and MIMU data. First, the instantaneous power output P_h is obtained as the product of F_h and v_h .

$$P_h = F_h \cdot v_h \quad (7)$$

The average values of F_h , F_v , F_{res} , v_h , P_h produced in each step are required to estimate the F – v, P – v, and RF – v relationships:

$$x_i = \frac{1}{t_{i+1} - t_i} \int_{t_i}^{t_{i+1}} x(t) dt, i = 1, \dots, N - 1, \quad (8)$$

where x_i denotes the average value of variable x for the i-th step. The number of steps considered is N and t_i is the initial contact time of the i-th step.

The ratio of force application at each step was computed as the quotient of the average horizontal force and the average resultant force:

$$RF_i = \frac{F_{hi}}{F_{resi}} \quad (9)$$

A linear model for the $F - v$ relation between step-averaged horizontal force and velocity values was obtained using least squares fitting. From this model, the theoretical F_0 , (force at zero velocity), and v_0 , (velocity at zero force), values were computed. The rate of the applied force loss with increasing velocity was given by the slope of the model S_{fv} .

$$S_{fv} = -\frac{F_0}{v_0} \quad (10)$$

Least squares fitting was used to find out a linear model for the $RF - v$ relationship. The slope of the linear model, D_{rf} , was used to quantify the decrease in force ratio at increasing velocity. All the detailed calculations were previously published by Samozino et al (9) in relation to sprint mechanics analysis.

A second-order polynomial curve passing through the origin was fitted to the (v_h, P_h) data to estimate the parameters of the $P - v$ relationship. P_0 is taken as the maximum value of the curve. This fitting procedures have also been wide reported in sprint mechanics analysis previously(9).

Statistical analysis

Validity study

The proposed method was compared to the force platform by comparing the force (average value of F_h , F_v , in each step) and performance variables (F_0 , v_0 , P_0 , S_{fv} , D_{rf}) measured with both instrumentations. First, the correlation between both measures for each variable was assessed by using a linear regression model. Note that Pearson's correlation coefficient is not suitable for assessing agreement between measurements. Lin's concordance correlation coefficient, on the other hand, takes into account how close is the best linear fit to the identity line and so it can be used as a measure of agreement. The following regression parameters are reported: mean value of the variable (\pm standard deviation), slope (95%

confidence interval), typical estimation error, Pearson's correlation coefficient (95% confidence interval) and Lin's concordance correlation coefficient (95% confidence interval).

The agreement levels between the variables obtained with both methods were assessed using the change in the mean, typical measurement error and agreement limits. Bland and Altman plots were created to check the dependency of the differences with respect to the average of both measures. A regression analysis was performed to report the statistical significance of linear relationships and check for systematic bias of the analysed values from both instrumentations. The slope of the linear model (95% confidence interval) is reported.

Finally, the relative error for each performance variable was computed:

$$RelErr = \left| \frac{x_{MIMU} - x_{FP}}{x_{FP}} \right| \cdot 100, \quad (11)$$

where X_{MIMU} and X_{FP} denote the values of the variable obtained from MIMU and force platform data, respectively. The mean relative error across subjects (\pm SD) is reported.

Correlation coefficients are interpreted in accordance with the scale of magnitude proposed by Hopkins (15): $r \leq 0.1$, trivial; $r \in (0.1, 0.3]$, small; $r \in (0.3, 0.5]$, moderate; $r \in (0.5, 0.7]$, large; $r \in (0.7, 0.9]$, very large; $r > 0.9$, extremely large.

Reliability study

To assess the repeatability of the proposed method, the performance variables obtained for each participant in two sprint trials were compared. The change in the mean (\pm standard deviation) and standard error of measurement (95% confidence interval) were computed for each variable, along with their limits of agreement. Using the standard error of measurement (SEM) and the between-subject standard deviation (SD_{inter}), the smallest worthwhile changes (SWC) can be computed, both intra-individual (SWC_{intra}) and inter-individual (SWC_{inter}):

$$SWC_{intra} = 0.3 \cdot SEM \quad (12)$$

$$SWC_{inter} = 0.2 \cdot SD_{inter} \quad (13)$$

Finally, the retest correlation, computed as the intraclass correlation coefficient (95% confidence interval) is also reported. All data processing and statistical analysis were performed with a scientific computation software (MatlabR2015a, The Mathworks Inc., Natick, MA, 2015).

Results

Validity study

The values of the step-averaged horizontal force, F_h and vertical force, F_v , computed from the MIMU data matched those measured with the force platform. Their mean values (standard deviation) for both systems are given in Table 2. The standard errors between systems were 49.83 ± 19.18 N and 70.05 ± 31.71 N, respectively. The force values measured with both systems were highly correlated ($r = 0.88$), with the regression slope close to the identity (1.01). Consequently, Lin's concordance is also very large ($rc = 0.87$). Figure 3 shows the scatter plot for F_h along with the identity line, the estimated regression line and the estimation \pm estimation error curves.

Correlation between the measured points (v_h, F_h) and best linear model for each subject was extremely large in the case of the force platform data (median $r = 0.95$, range from 0.62 to 0.96) and large for the MIMU data (median $r = 0.85$, range from 0.71 to 0.94). In the case of the step-averaged (v_h, P_h) points, the correlation between the measurements and the second-order polynomial model was extremely large (median $r = 0.91$, range from 0.79 to 0.96) and moderate (median $r = 0.56$, range from 0.16 to 0.80) for the force platform and MIMU measurements, respectively. For the $RF - v$ relationship, the correlation

attained were extremely large for force platform measurements (median $r = 0.94$, range from 0.82 to 0.98) and large for MIMU measurements (median $r = 0.85$, range from 0.67 to 0.91). The performance variables F_0 , v_0 , P_0 , S_{fv} and D_{rf} were derived from the models of the $F - v$, $P - v$ and $RF - v$ relationships. The parameters of the correlation between the variables obtained with the force platform and the MIMU are presented in Table 2.

The agreement between both measurement systems is depicted in Table 3. A slope value different from zero reveals a discrepancy between systems that depends on the measured value. The only variables showing those discrepancies were F_h ($p < 0.001$) and F_v ($p = 0.002$) values. Their Bland and Altman plots are shown in Figure 4.

Reliability study

Table 4 presents the inter-trial reliability of the performance variables measured with the MIMU. It includes the change in the mean, the slope of the linear dependency between the difference in measures and their average value, the typical error of measurement, SWC_{intra} and SWC_{inter} and the retest correlation coefficient, which was large or extremely large for all variables.

Discussion

The present study aimed (1) to determine whether the data provided by an inertial sensor unit placed at the lumbar spine could reliably assess sprint mechanics and (2) to examine the validity of the magnetic inertial measurement units (MIMU) compared with force plate platform recordings. The primary findings of this study supported the study hypothesis. A robust level of agreement was found between the force curve patterns calculated from the MIMU recordings and those provided by a force

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plate during the sprint biomechanical evaluation. Accordingly, the force values measured with both systems were highly correlated ($r = 0.88$), with a regression slope close to the identity (1.01). Furthermore, extremely large to very large retest correlation coefficients were found with respect to the inter-trial reliability of the performance variables measured with the MIMU for the analysed variables V_0 , F_0 , P_0 , S_{fv} and D_{rf} .

Several investigations in the last century have focused on sprint mechanics and how the human body can run faster over time (1;3;18). The inverse relationship between force and velocity during sprinting was reported 45 years ago by Cavagna et al. (19). Mero et al. (6) later elucidated the relationship between the electromyographic activity of the biceps femoris and gastrocnemius muscles and the resultant GRF during the propulsive phase of the stance phase of sprinting. These investigations were later corroborated by Weyand et al. (2), who reported that the resultant GRF is more strongly related to the maximal velocity during a sprint than to the segmental leg movement speed. More recently, Morin et al. (8) established significant relationships between the eccentric knee flexor isokinetic peak torque and the horizontal component of the GRF exerted during the propulsive phase of the stance during the sprint on an instrumented treadmill.

The ratio of forces (RF) has been studied to quantify the runner's horizontal force application capacity at increasing velocities (9;20) However, the methods for computing this variable differ slightly among studies. In the mentioned study of Morin et al. (16), the instantaneous RF was computed at each time instant as the ratio of F_h to the F_{res} in the sagittal plane. The RF for a step was thus calculated as the average of the instantaneous ratio during the contact period. In contrast, in a latter research (9) the RF was computed for a step as the ratio of the average F_h to the average F_{res} for the whole step (contact plus aerial phase).

One of the main difficulties in comparing data from a MIMU placed at the centre of mass with force platform recordings lies in the registration of the medial-lateral and anterior-posterior forces acting at this level. These forces include torsion and leaning movements that contribute to the runner's dynamic stabilization. This precludes the use of the RF computation method presented in Morin et al. (20), since the presence of these dissenting forces distorts the instantaneous acting forces recordings that until recently could only be recorded with force plate devices. Moreover, although these forces tend to cancel out during a step period, their contribution to the instantaneous resultant force does not. Therefore, the method described by Samozino et al. (9) would not have allowed for a direct comparison between MIMU and force platform RF measurements. To overcome these difficulties, we computed F_{res} from the average value of F_h and F_v during the step period.

Moreover, the confluence of forces at the CM level results in greater variability in the D_{rf} obtained from MIMU data. This explains the moderate correlation between the MIMU and force platform measurements of D_{rf} (0.45, $p < 0.05$). Note that the aforementioned forces depend on the runner's technique and/or ability to apply horizontal GRF during the sprinting action at increasing velocities. Therefore, the error in D_{rf} may be considerable for some subjects. In fact, the correlation coefficient increased to 0.85 when an outlier was removed from the data pool. Lastly, the higher variability of force measurements at the CM level also affects other variables, such as F_h . The number of steps with low F_h exceeds the number of steps with high F_h , which are performed at the beginning of the acceleration phase. Hence the high value obtained for the relative error of F_h . Despite these shortcomings, the relative error of the sprint performance variables remains low. These results, together with the high retest correlation, suggest that MIMUs can be used reliably to evaluate sprint performance.

Notably however, force tracking at the CM level in humans during sprinting is a novel contribution of the present research. In this context, the traditionally accepted assumption that the vertical and horizontal translational motions occurring at the human's CM level represent the total body mo-

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tion during running or jumping biomechanics using a force platform could be controversial (4;13;19). This potential controversy is justified by the assumptions that all body segments execute rotational and translational motions relative to the CM and that the CM itself also executes non-vertical motions in the sagittal and lateral directions. These assumptions imply that an additional amount of force at the trunk level may be underestimated during traditional analyses of sprint mechanics using a direct mechanics method based on force plate recordings. In the authors' opinion, the placement of the MIMU at the L3-L4 lumbar spine level, where the centre of mass in humans is considered to be located (13), could allow more comprehensive and between-limb discriminative monitoring of the mechanical behaviour of the human body as a whole during sprinting.

Finally, several limitations of the present research should be highlighted. The relatively wide confidence intervals for some of the variables such as $D_{rf}(\%/m/s)$ could have hindered or contaminated some of the reported results in some manner. Whether this high reported variability was related to the measurement device or the variability associated with tracking GRF at the CM level when performing sprinting evaluations should be properly clarified in the future. Furthermore, the overall contribution of the medial-lateral forces to the efficiency of sprint mechanics should be the main focus of an appropriately designed investigation in the future.

The error in the force measurements increases with force value. This can be observed in the correlation plot for F_h (Figure 1) and the Bland and Altman plots (Figure 4). In fact, the data points in the Bland and Altman plot show a trend towards greater differences with increasing force values. This could imply that this methodology is best suited for athletes with low acceleration values. Another hypothesis is that the CM is moved abruptly during the first steps until a convenient running pose is adopted. This movement is the results of forces that are reflected in the measured CM acceleration but not on the GRF. This explains the higher values of forces measured with the MIMU during the first steps, which are the steps with the highest horizontal force values. Further analysis is required to test this hypothesis.

The participants were recreational runners with different training frequencies. This sample does not adequately represent the whole population of interest, which include professional athletes and elite sprinters. Moreover, it remains unclear how a better running technique could affect inter-limb distinction, which is facilitated by the measured torso rotation. This study focuses in the validation of MIMUs as a tool for assessing sprint performance. The placement of the unit on the center of mass is fast and convenient, but also favours the recording of concomitant forces which increase the variance of single step variables. Therefore, if a step by step analysis is required, alternative locations from the MIMU where dissenting forces are minimized, such as ankle or instep, should be considered.

In summary, the novel method proposed for evaluating sprint mechanics using the MIMU system could help to improve the functional assessments routinely conducted on the field by both medical staff and performance coaches by providing a tool that is less expensive and more widely applicable than conventional high-cost, laboratory-based technologies. In the current research, the price of a single MIMU approaches the amount of 1,500 Euros, whereas the entire 10m force plate hall setting measurement composed by 10 force plate units is calculated to be around ten times more.

From the practical point of view, the MIMU-based sprint mechanics analysis performed on the training field was shown to be a sensitive tool for evaluating several biomechanical variables related to force-by-velocity profiles in recreational runners.

Perspectives

The results of this study provide a new methodology based on MIMU system that would measure not only force-velocity profiles, but also trunk orientation information as well as average tendency of change in ground reaction forces components with time of both limbs (i.e. inter-step variability). This approach could be of great interest for coaches when tracking the sprint mechanics profile in order to improve performance of the athletes in the training court itself. Contact interval detec-

tion form acceleration signals is performed by visual inspection in this study. Once automated, the procedures described could be readily implemented into a usable coaching system.

As far as the authors know, until nowadays, it has not been published any article focusing on the mechanical description of the sprinting action through the use of a MIMU systems. However, other technologies have been employed in relation to this issue. For example, regarding hamstring strain injuries in football Brughelli et al. (21) and Mendiguchia et al. (22) performed indirect estimations of the center of mass' behavior during sprinting. Brughelli et al (21) used a non-motorized force treadmill, whereas Mendiguchia et al (22) measured mechanical properties during sprinting with a radar device. Furthermore, the former employed a direct mechanics approach for CM identification but registered the ground reaction force at the ground level, whereas the latter estimated acceleration and thus, the acting horizontal forces via linear horizontal velocity recordings.

In the present research, an IU situated on the presumed human body center of mass was employed. Thus, the three different instrumentations with different measuring validity and reliability indexes, might have contributed to the existence of the reported differences. Notably however, in the author's opinion, force tracking at the CM level in humans during sprinting is a novel contribution of the present research.

Further research is warranted to clarify whether the proposed methodology could result in a sensitive tool for monitoring horizontal GRH during sprinting over the course of the hamstring strain injury rehabilitation process.

Conflict of interest statement

The authors have no conflicts of interest to declare concerning the contents of this manuscript.

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Table1. Previous injury reports among participants

<i>subject</i>	<i>previous injury record</i>	<i>current injury</i>
2	3 ACL reconstructions (last 2009)	
4	1 ACL reconstruction	
5	1 ankle sprain	
7	2 ACL reconstructions (bilateral) 2007,2009	
9	1 ankle fracture (2003)	
11	1 ankle tendinopathy	
12		Achilles tendinopathy
14		Medial tibial stress syndrome

Table 2. Correlation values between the variables obtained with the force platform and the MIMU. Units for the typical estimation error and mean values are given after the name of the variable,

Variable	Force plate measurement	MIMU measurement	Slope (95% confidence interval)	Typical estimation error	Pearson's correlation coefficient (95% confidence interval)	Lin's concordance correlation coefficient (95 % confidence interval)
F_h (N)	119 ± 92	116 ± 105	1.01 (0.95, 1.05)	49.56	0.88 (0.86, 0.90)	0.87 (0.87, 0.87)
F_v (N)	661 ± 135	670 ± 145	0.94 (0.90, 0.99)	68.82	0.88 (0.86, 0.90)	0.88 (0.88, 0.88)
F_0 (N)	383 ± 110	391 ± 103	0.91 (0.78, 1.04)	25.44	0.97 (0.92, 0.99)	0.97 (0.96, 0.98)
v_0 (m/s)	8.61 ± 0.85	8.42 ± 0.69	0.65 (0.37, 0.94)	0.44	0.81 (0.5, 0.93)	0.76 (0.71, 0.81)
P_0 (W)	873 ± 246	799 ± 241	0.93 (0.73, 1.11)	85.16	0.94 (0.84, 0.98)	0.90 (0.88, 0.91)
S_{fv} (N/m/s)	-44.6 ± 12.7	-46.2 ± 10.7	0.81 (0.65, 0.96)	3.53	0.95 (0.86, 0.98)	0.93 (0.91, 0.94)
D_{rf} (%/m/s)	-6.32 ± 1.08	-5.76 ± 0.68	0.28 (-0.06, 0.62)	0.66	0.45 (-0.09, 0.78)	0.33 (0.26, 0.41)

Table 3. Agreement levels between MIMU and force plates for the sprint mechanics

analyzed variables

Variable	Change in the mean	Slope (95% confidence interval)	Typical measurement error	Agreement limits	Relative error (%)
F_h (N)	-3.93	0.14 (0.09, 0.19)	34.96	-100.84 – 92.98	45.29 ± 54.98
F_v (N)	8.90	0.08 (0.03, 0.12)	48.82	-126.45 – 144.24	7.27 ± 7.97
F_0 (N)	7.60	-0.07 (-0.21, 0.07)	25.44	-42.68 – 57.89	5.24 ± 3.24
v_0 (m/s)	-0.19	-0.23 (-0.62, 0.16)	0.36	-1.28 – 0.80	3.35 ± 4.07
P_0 (W)	-75.12	0.02 (-0.22, 0.18)	57.40	-234.22 – 83.98	10.46 ± 7.46
S_{fv} (N/m/s)	-1.63	0.17 (-0.36, 0.02)	2.89	-9.64 – 6.39	7.24 ± 7.10
D_{rf} (%/m/s)	0.56	-0.61 (-1.30, 0.08)	0.70	-1.38 – 2.50	11.53 ± 11.02

Table 4. Reliability results for MIMU measurements.

Variable	Change in the mean	Slope (95% confidence interval)	Typical measurement error	Agreement limits	SWC _{intra}	SWC _{inter}	Intraclass correlation coefficient (95% confidence interval)
F_0 (N)	-17.80	-0.21 (-0.40, -0.01)	28.74	-97.46 – 61.84	8.62	23.14	0.93 (0.79, 0.98)
v_0 (m/s)	-0.03	0.31 (0.03, 0.60)	0.20	-0.58 – 0.51	0.06	0.11	0.88 (0.65, 0.96)
P_0 (W)	-35.05	-0.20 (-0.35, -0.05)	50.54	-175.15 – 105.04	15.16	47.32	0.95 (0.83, 0.98)
S_{fv} (N/m/s)	1.83	-0.26 (-0.52, 0.01)	4.03	-9.34 – 13.01	1.21	2.50	0.89 (0.70, 0.97)
D_{rf} (%/m/s)	0.16	0.32 (-0.25, 0.89)	0.79	-2.03 – 2.36	0.24	0.27	0.66 (0.20, 0.88)

Figure 1. Range of torso heading (grey area) with respect to the Earth-fixed reference frame during the last four steps for one participant. Direction of sprint (dark grey arrow) is estimated as the mean heading.

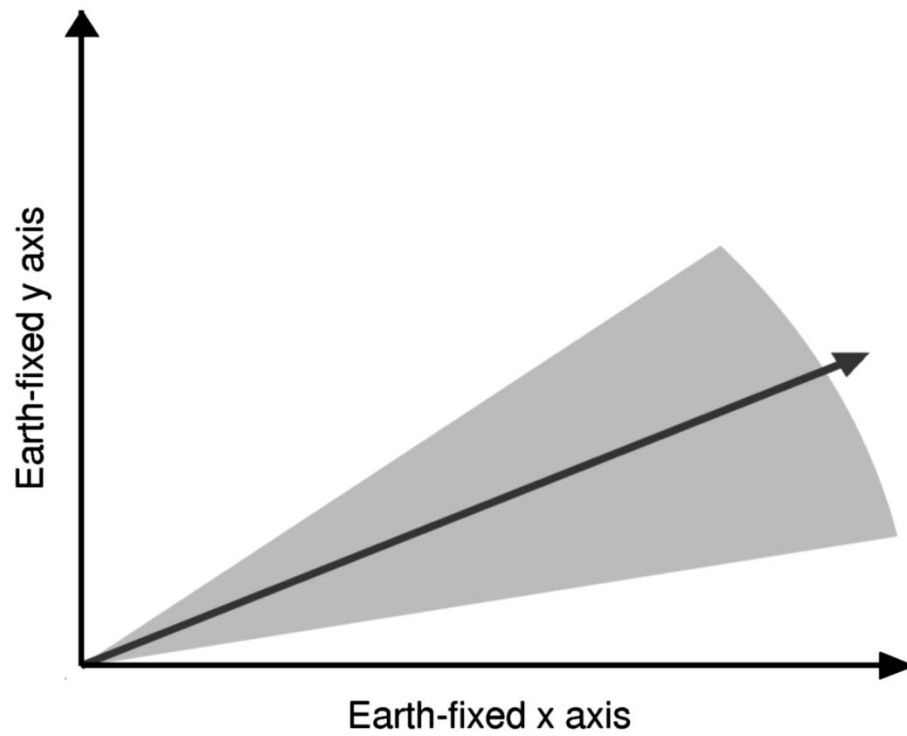


Figure 2. Vertical GRF (grey), CM vertical acceleration (dashed black) and CM horizontal acceleration (solid black) during three consecutive steps.

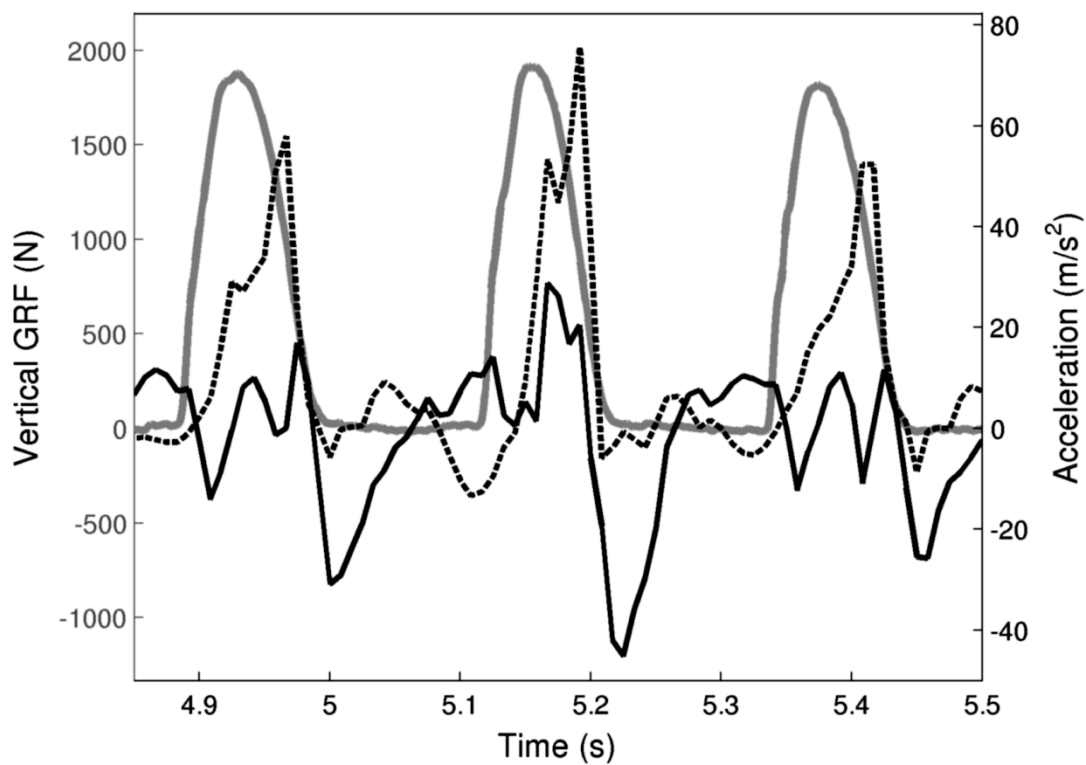


Figure 3. Scatter plot for F_h along with the identity line (grey), the estimated regression line (solid black) and the estimation \pm estimation error curves (dashed black).

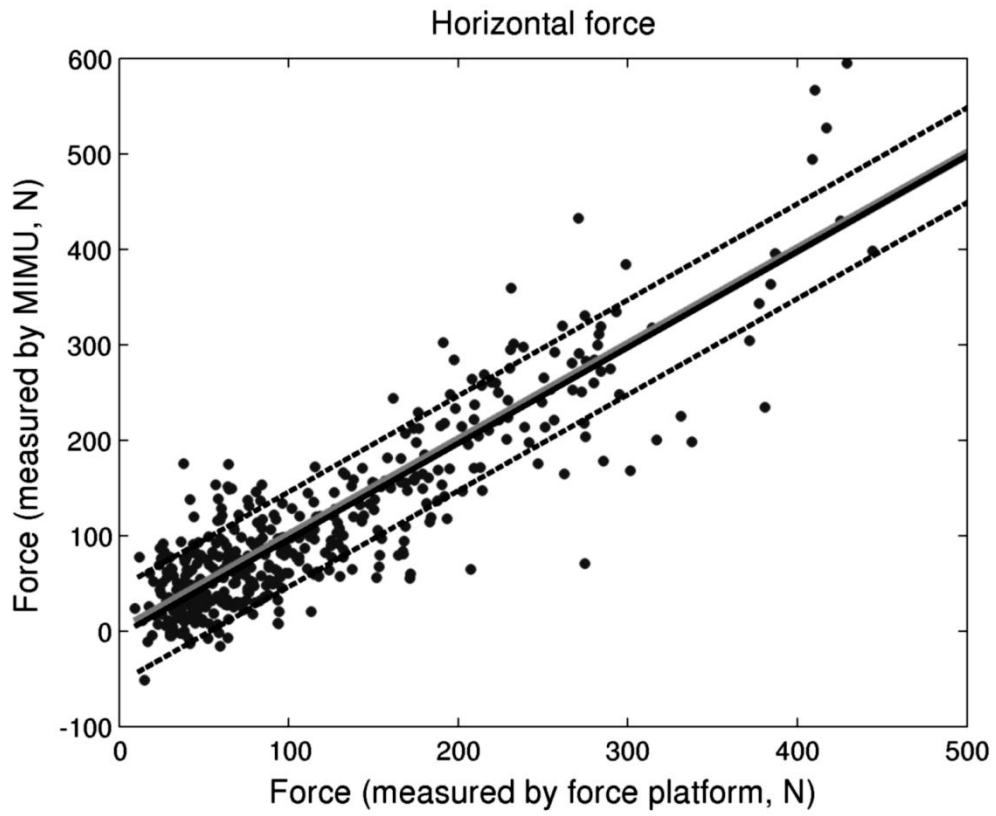


Figure 4. Bland and Altman plots for horizontal (a) and vertical (b) GRF values obtained from MIMU and force plate instrumentations. The plots also show the change in the mean (dashed black), the agreement limits (dashed grey) and the linear regression model (solid gray).

