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Abstract:

Background: Sprint performance can be characterized through the centre of mass (COM) velocity over time. *In-field* computation of the COM is key in sprint training. **Research question:** To compare the stance-averaged COM velocity computation from a Magneto-Inertial Measurement Units (MIMU) to a reference system: force platforms (FP), over the early acceleration phase in both straight and curve sprinting. **Methods:** Nineteen experienced-to-elite track sprinters performed 1 maximal sprint on both the straight and the curve (radius = 41.58 m) in a randomized order. Utilizing a MIMU-based system (Xsens MVN Link) and compared to FP (Kistler), COM velocity was computed with both systems. Averaged stance-by-stance COM velocity over straight-line and curve sprinting following the vertical axis (respectively V_{zMIMU} and V_{zFP}) and the norm of the two axes lying on the horizontal plane: x and y, approximately anteroposterior and mediolateral (respectively V_{xyMIMU} and V_{xyFP}) over the starting-blocks (SB) and initial acceleration (IA – composed out of the first four stances following the SB) were compared using mean bias, 95% limits of agreements and Pearson's correlation coefficients. **Results:** 148 stances were analyzed. V_{xyMIMU} mean bias was comprised between 0.26 and 2.03% (expressed in % with respect to the FP) for SB, 5.63 and 7.29% over IA respectively on the straight and the curve. Pearson's correlation coefficients ranged between 0.943 and 0.990 for V_{xy}, 0.423 and 0.938 for V_z. On the other hand, V_{zMIMU} mean bias ranged between 2.33 and 4.69% for SB, between 1.44 and 19.95% over IA respectively on the straight and the curve. **Significance:** The present findings suggest that the MIMU-based system tested slightly underestimated V_{xyMIMU}, though within narrow limits which supports its utilization. On the other hand, V_{zMIMU} computation in sprint running is not fully mature yet. Therefore, this MIMU-based system represents an interesting device for *in-field* V_{xyMIMU} computation either for straight-line and curve sprinting.

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1. Introduction

Sprint performance can be characterized through the centre of mass (COM) velocity over time [1-2]. For this reason, it is of interest to easily evaluate COM kinematics with accuracy within the athletes' ecological environment to preserve the measures' ecological validity. Yet, analyzing accurately the human movement *in-field* remains an everyday challenge especially within the curve. In fact, sprinting in the curve represents ~58% of the total distance for all track events starting from the 200 m (World Ahletics, 2019). Unfortunately, within the curve, systems such as radars or lasers become immediately inoperable. A few experimentations have described COM velocity in curve sprinting at specific instants [4-7]; however, the literature describing the COM velocity within this sprinting condition remains limited. Therefore, it is of importance to look for *in-field* devices able to quickly evaluate the COM velocity within the curve over an entire sprint. Outside the laboratory, deciding which device to use relies on a trade-off between accuracy and feasibility. Considering their portability, convenience and range, full-body magneto-inertial measurement unit systems (MIMU) have become popular over the past decade. Yet, several authors have highlighted the limitations of such systems and overall there is no consensus regarding MIMU-based system's concurrent validity against reference systems for joints and segments kinematics [8–15].

At the COM, comparison between a MIMU-based system and an opto-electronic systems (OS) COM position while standing still showed a difference in the measurement from 0.73 mm (vertical axis) to 5.45 mm (medio-lateral axis) as well as very high correlations ($r > 0.99$; $p < 0.001$) [16].

Based on Newton's second law, force platforms (FP) have been considered as the reference system for COM velocity computation in sprint running [17–21], since correct computation does not rely on either accurate marker positioning or assumptions regarding the anthropometrical properties [22–25].

Using FP, Pavei et al. (2020) computed the COM displacement during overground walking and compared to a MIMU-based system [26]. They found differences between systems up to 98.7 ± 60.2% [26], likely resulting from the sensors drift and the anthropometrical assumptions.

In sprint running, computations of the force-velocity profiles (FVP) from a MIMU-based system to a radar showed good agreements between both systems for the maximal velocity and the maximal theoretical force, velocity and power ($0.81 < r < 0.97$) [27]. However, despite their broad utilization for straight-line sprinting velocity computation [28–31], radars do not estimate neither the COM nor the frontal plane velocity, but only the participants' horizontal velocity [32-33]. Moreover, measurement can be impaired with such devices since radars detect all moving objects within their field of view.

Other authors used a single MIMU attached to the lumbar region to compute the participants' velocity [34] and compared the FVP variables obtained with those from the FP. Although these authors found "very large" to "extremely large" correlations for all but one FVP variable, they did not investigate the stance-averaged velocity itself. They also evaluated a point close to the COM, probably leading to erroneous COM estimation [22,25,33,35].

Recently, van den Tillaar et al. (2021) compared the step- velocity over 50-m sprints from a MIMU-based system to FP [36]. However, they multiplied step length and step rate rather than comparing the COM velocity, even though this parameter was found to be determinant for sprinting performance [2] and can be used to adapt training programs through FVP computation [21,37].

To our knowledge, no study compared the stance-averaged COM velocity computed from a MIMU-based system to a reference system. Additionally, the few experimentations that compared a MIMU-based system to the reference systems for other parameters only investigated the straight, notwithstanding the curve. Considering the prevalence of this sprinting condition in athletics, it appears mandatory to look for *in-field* devices able to easily evaluate the COM velocity within ecological environment.

Thus, the aim of the present study was to compare the stance-averaged COM velocity computed from a MIMU-based system to FP over the starting-blocks pushing phase and the initial acceleration during both straight-line and curve sprinting.

2. Methods

a) Participants

Nineteen (15 male and 4 female) experienced-to-elite curve sprinters (mean ± SD: age = 23.9 ± 3.7 years; body mass = 73.9 ± 7.4 kg; height = 1.78 ± 0.07 m) volunteered to participate in this study. The mean personal bests (PB) of the 6 male 200-m specialists, the 9 male 400-m specialists, the 2 female 200-m specialists and the 2 female 400-m specialists were respectively: 22.89, 49.56, 26.30 and 57.67 s. After an explanation of the protocol, the participants signed the informed consent to participate in the experimentation, conducted in accordance with the declaration of Helsinki and approved by the local ethical committee (IRB00012476-2021-29-04-107).

b) Materials

- Concurrent system

The participants were equipped with a MIMU-based system MVN Link (Xsens Technologies, Enschede, Netherlands, 240 Hz). This system is composed of 17 MIMUs (36 x 24.5 x 10 mm: 10 g) fixed to the participants with straps. Each sensor contains a 3D gyroscope (± 2000 °/s), a 3D accelerometer (scale: ± 160 m/s^2) and a 3D magnetometer (± 1.9 Gauss). Sensors were placed according to the manufacturer's recommendations (see figure 1). Participants' height and foot length were measured and inputted into the MVN software which estimated segment lengths with regression equations [38], [39]. The calibration process was then performed according to the manufacturer instructions and general guidelines [9-10,12] to generate sensor-to-segment alignment [38].

FIGURE 1

- Reference system

Using OS, errors can originate from marker positioning, movement on soft tissues and assumptions associated with anthropometric models [22,25-26]. Therefore, in the present experimentation we used a 6.60 m-long FP composed out of 6 individual FP (5 length-wise and 1 sideways; 1.2 x 0.6 m each, KI 9067; Kistler, Wintherthu, Switzerland, 1 000 Hz) as the reference system. FP were connected in series, covered with a tartan mat and embedded within the track, thus making them invisible to the participants. This set-up allowed for a quasi *in-field* experimentation. Anteroposterior, mediolateral and vertical components (respectively F_x, F_y and F_z) of the GRF were computed from these FP.

The MIMU-based system and FP signals were synchronized to the nearest MIMU-based system frame using a customised cable with the MIMU-based system software triggering the FP. Accurate synchronization between devices has been confirmed during pilot experimentations by gently pressing on one MIMU positioned over the FP and by checking temporal events of vertical GRF and the MIMU accelerations.

c) Protocol

The recordings took place on an indoor track between June and July 2021, which corresponded to the competition period. The participants began with at least a 45-min self-managed warm-up. They were then equipped with the MIMUs and had a 10-min additional familiarization period with the MIMUs on. Subsequently, participants performed a maximal “valid” 10-m sprint within two conditions in a randomized order: straight and curve. A replicated curve corresponding to the lane 5 (radius 41.58 m) of a standard athletics track (World Athletics, 2019) overlapped the FP area.

A sprint was considered “valid” when at least the first stance out of the blocks fully landed within the FP area [20-21]. All participants used starting-blocks (SB) that were positioned on the FP which allowed the GRF computation over the SB pushing-phase.

d) Data analysis

- Concurrent system

Using the temporal synchronization between systems, touchdown (TD) and toe-off (TO) for both systems were determined from the FP data using a 20-N threshold on F_z [37].

MIMU-based system anteroposterior, mediolateral and vertical instantaneous COM velocities (respectively V_{xMIMU}, V_{yMIMU} and V_{zMIMU}) based on the manufacturer’s proprietary sensor fusion algorithm were retrieved directly from the MVN software. V_{xMIMU}, V_{yMIMU} and V_{zMIMU} were low-pass filtered (20-Hz cut-off, third-order zero-phase Butterworth filter) chosen after residual analysis [40].

Thereafter, although the MIMU-based system calibration was realized such that its coordinate system coincides with that of FP, both devices’ coordinate systems are unlikely to be perfectly aligned. Consequently, we computed the norm of the horizontal plane of the MIMU-based system COM velocity (V_{xyMIMU}):

$$V_{xyMIMU} = \sqrt{{V_{xFP}}^2 + {V_{xFP}}^2} \qquad 1$$

- Reference system

GRF raw signals were low-pass filtered (200-Hz cut-off, third-order zero-phase Butterworth filter) chosen after residual analysis [40].

Based on Newton’s Second Law and according to previous literature [17,19–21,23,25-26,41] the three COM orthogonal acceleration components were calculated by dividing GRF by the body mass (- m · g for the vertical acceleration). Thereafter, we computed instantaneous anteroposterior (V_{xFP}), mediolateral (V_{yFP}) and vertical (V_{zFP}) velocities by simple integration of the three orthogonal acceleration components over each stance:

$$V_{xFP} = V_{0xFP} + \int \frac{F_x}{m} dt \quad (2)$$

$$V_{yFP} = V_{0yFP} + \int \frac{F_y}{m} dt \quad (3)$$

$$V_{zFP} = V_{0zFP} + \int \frac{F_z - m \cdot g}{m} dt \quad (4)$$

with, *m* the participant's body mass, V_{0xFP}, V_{0yFP} and V_{0zFP} the initial velocity conditions taken as integration constants and set to 0 since SB were placed over the FP and the sprinters started from a stationary position.

Finally, we computed the norm of the horizontal plane of the FP COM velocity (V_{xyFP}):

$$V_{xyFP} = \sqrt{{V_{xFP}}^2 + {V_{yFP}}^2} \quad (5)$$

Analysis was split within two conditions (figure 3), a) the SB phase (which includes only the starting-blocks pushing phase) and b) the initial acceleration, thereafter referred as IA (beginning at the first touchdown after the SB phase and ending at toe-off of the last stance computed).

The norm of the horizontal plane COM velocity (V_{xy}) and the vertical COM velocity (V_z) computed from both the FP and the MIMU-based system were averaged over each "valid' stance.

e) Statistical analysis

All descriptive statistics are presented as means ± standard deviations (SD). Normality of the distribution was verified using the Shapiro-Wilk test. Then, V_{xy} and V_z obtained with both devices were compared using a) mean bias (expressed in % in comparison to the FP) and 95% limits of agreement [42]; b) Pearson's correlation coefficient (*r*) with threshold values of 0.3, 0.5, 0.7 and 0.9 representing respectively low, moderate, high and very high relationships [43,44]. For all statistical analyses, the alpha level was set as $p = 0.05$.

3) Results

The number of valid stances for each participant varied between two (SB and the following stance) to five (SB and the following four stances) for both sprinting conditions. Overall, 75 and 73 valid stances were computed respectively for the straight and the curve.

Table 1 presents the mean ± SD for the sprint variables of both systems within the straight and the curve conditions for the SB and IA phases as well as the mean bias, 95% agreement limits and correlation coefficients.

TABLE 1

Figure 2 and 3 display the Bland & Altman plots respectively for SB and IA. Mean bias between the MIMU-based system and the FP was lower on the straight than the curve. Mean V_{zMIMU} showed a bias of 1.44 and 19.95% respectively on the straight and the curve with random errors up to 108%. Correlation coefficients between devices ranged between $r = 0.943 < r < 0.990$ for V_{xy} and $0.423 < r < 0.938$ for V_z.

FIGURE 2

4) Discussion

This experimentation compared the COM stance-averaged velocity measured from a MIMU-based system to 6 FP over the early acceleration phase in both straight-line and curve sprinting among 19 experienced-to-elite curve sprinters with different anthropometric characteristics, sprinting expertise and mechanical capacities. V_{xyMIMU} mean bias either for SB (respectively 0.26 and 2.03% for the straight and the curve) and IA (respectively 5.63 and 7.29% for the straight and the curve) was low. Further, correlation coefficients for V_{xy} were very high for both SB and IA ($r > 0.943$). These correlation coefficients show that although slightly underestimated, a change of magnitude of V_{xyFP} is very well associated with a similar change of magnitude of V_{xyMIMU} either during SB and IA.

FIGURE 3

Throughout IA, we did not find any trend for the mean bias with increasing V_{xy}. The last stances' V_{xy} were ~5-6 $m.s^{-1}$ which corresponded to ~60-70% of the participants' maximal velocity. Those findings suggest that differences between systems would not increase with velocity although further experimentations evaluating V_{xy} later on during the acceleration phase or at maximal velocity are needed to confirm our findings.

Contrastingly, V_{zMIMU} showed a greater mean bias (up to ~20%) with large limits of agreement (up to ~108%). Despite very high correlation coefficients for the SB between devices, IA showed small correlation coefficients meaning that a change of magnitude in V_{zFP} is poorly associated with a change of magnitude in V_{zMIMU} over the IA.

FIGURE 4

The findings of the present experimentation for V_{xyFP} over the SB and the first two stances are slightly below those reported by Nagahara et al. (2020) among male sprinters (100-m time PBs: 11.27 ± 0.27 s) [45]. In their experimentation, Nagahara et al. (2020) found a V_{xyFP} of respectively 3.92, 4.93, 5.70 and 6.30 $m.s^{-1}$ for the first, second, third and fourth stances following the SB phase [45] while we found a V_{xyFP} of respectively 3.59, 4.62, 5.36 and 6.02 $m.s^{-1}$ for the corresponding stances. Considering their athletes' PBs and that all participants were male in their experimentation, the findings of the present experimentation are thus in line with those of Nagahara et al. (2020). Regarding V_{zFP}, to our knowledge, no experimentation investigated the mean vertical velocity over the first stances. Slawinski et al. (2020) found vertical velocities of 0.52, 0.35 and 0.35 $m.s^{-1}$ among elite sprinters respectively at SB clearing, first and second stances toe-off [27] while we found mean V_{zFP} of 0.44, 0.19 and 0.24 $m.s^{-1}$ for the corresponding stances.

FIGURE 5

To the best of our knowledge, only one study compared the step velocity between a MIMU-based system and FP [36]. These authors found that the MIMU-based system velocity was underestimated for all steps. They reported a mean bias from 0.45 to over 0.60 m.s^{-1} as opposed to 0.26 m.s^{-1} in the present study. These discrepancies likely result from the different methods used to compute the velocity. While we have simply retrieved the COM velocity from the MIMU-based system software, these authors have multiplied step length and step frequency, determined from ankle angular velocity to identify TD and TO using MIMUs placed on both feet, yet based on currently unpublished algorithm [36].

Moreover, when comparing data computed from a MIMU-based system ~~and~~ to those obtained with FP, care must be taken with regards to the coordinate system orientation. The MIMU-based system antero-posterior axis is likely neither aligned with the FP coordinate system nor with the sprinting path. Van den Tilaar et al. (2021) may have considered the antero-posterior axis only. To ensure accurate calculation it is therefore mandatory to compute the norm of the horizontal and mediolateral velocities (V_{xyMIMU} in the present study) which represents a limitation of this system if someone is willing to analyze each axis distinctly on the field.

Overall, the mean bias found in the present experimentation lies within similar range to those reported by Samozino et al. (2016) in their field method validation. They found absolute bias ranging from ~2 to 8% against FP [21]. These authors concluded that this bias was "low" and this method is widely used in sport science and sprint training since. Similarly, differences between two reference systems (FP and OS) compared together for the COM trajectory reached ~9% in walking at constant speed [26]. Those results show that even with two "reference systems", differences - likely due to anthropometrical assumptions - comparable to the present findings can be found. Therefore, the present experimentation provides hints in the choice of the optimal system considering their cost, accuracy and easy-of-use ratio that meet the requirement of the experimental conditions.

V_{zMIMU} displayed the largest systematic bias (up to ~20%) and random errors (up to ~108%). Those results are in contrast with the findings of Pavei et al. (2020) who found the lowest bias on the vertical axis [26]. However, they compared the point-by-point root mean square distance, range of motion, minimum and maximum positions on the 3 orthogonal axes [26] while we analyzed the stance-averaged velocities in the present experimentation. Further, these authors have used a different system, sampling at 60 Hz with wireless MIMUs which can account for some of the variance between the experimentations [10]. Finally, their protocol also differed from ours since they analyzed walking strides with constant velocities of 0.79 ÷ 1.94 m.s^{-1} [26] while we evaluated accelerated sprinting (velocities up to ~6 m.s^{-1}). It is also important to note that since V_{zFP} values are much lower than V_{xyFP}, an error of 0.05 m.s^{-1} would yield greater discrepancies when expressed in percentage. However, considering the large random errors as well as the small correlation coefficients, it must be acknowledged that this MIMU-based system is not fully mature yet for accurately computing V_{zMIMU} in sprint running.

Other points likely resulting in differences between the FP and the MIMU-based system are worth mentioning. First and foremost, the anthropometrical model used with the MIMU-based system represents one of the main source of errors arising from either OS or MIMU-based systems in comparison to FP [15,25-26]. Although not one of the aims of this study, mean bias was greater for female than male: 4.64% for male and 8.23% for female over IA within the straight. While this shed some light on the possibility that this MIMU-based system anthropometric model is more adapted to male, this must be interpreted cautiously since only 4 females participated in this study.

The differences between the FP and the MIMU-based system should also be balanced since this experimentation focussed on the early acceleration phase, where sprinters produce their greatest acceleration [2]. In addition, at this very time of the sprint, participants are in a crouched-to-semi-straightened position which could challenge the biomechanical model computation. Therefore, the COM velocity of both systems should also be compared when the participant has straightened up.

Discrepancies between devices could also result from the systems' synchronization and the different sampling rate. Since synchronization between systems was at the nearest MIMU-based system's frame, we have tested on two random participants what could be the differences for V_{xyMIMU} with plus or minus 1 frame. We found mean discrepancies of ~3.5% and maximum differences reaching ~8.5%, which could also account for some of the differences between systems.

MIMU-based system sensitivity to magnetic fields has also been widely discussed [10,12]. It is of importance to avoid ferromagnetic objects nearby the analysis area to limit sensors drift and ensure following guidelines for MIMU-based system use [10]. Considering the wooden indoor stadium where the experimentation took place and that the FP were embeded underneath the track surface, we can assume that this likely resulted in little disturbances.

The last source of discrepancy between the MIMU-based system and the FP could result from FP measurement errors. Albeit considered a reference system with pros well detailed by Pavei et al. (2017), FP can also be prone to measurement errors related mainly to a) integration with errors originating from the initial conditions and b) long recordings leading up to FP drift [25].

5) Conclusion

Evaluating the COM kinematics within *in-field* environments is a challenging process, especially when seeking for portable system you can use either inside or outside, with a simple setup and a wide range to capture the entire motion. This experimentation brings new insight into the use of this MIMU-based system as a valuable alternative of FP or OS for *in-field* computation of V_{xy} over the starting-blocks and the initial acceleration phase be it on the straight or the curve. Further, this MIMU-based system would provide the unique opportunity to access V_{xy} over an entire sprint, be it a 200 or 400-m sprint. Contrastingly, V_{zMIMU} computation is not fully mature yet and further improvement must be made in order for this MIMU-based system to become an alternative to reference system for this parameter.

7) Conflict of interest statement

Declaration of interest: none.

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