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Body center of mass trajectory and mechanical energy using inertial sensors: a feasible stride?

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Highlights

- Inertial sensors were used to obtain body center of mass trajectory and energetics
- Sensor- and marker-based estimates were compared to gold-standard force plates
- Larger errors were found for sensor-based trajectory compared to marker-based
- Trajectory errors largely affect mechanical work and energy recovery estimation
- The quantification of energetics in real-life situations remains an open challenge

Abstract

Background: The description of the three-dimensional (3D) trajectory of the body center of mass (BCoM) provides useful insights on the mechanics of locomotion. The BCoM trajectory can be estimated from ground reaction forces, recorded by force platforms (GRF, gold standard), or from marker trajectories recorded by stereophotogrammetric systems (MKR). However, both instruments do not allow for monitoring locomotion in real-life environment. In this perspective, magneto-inertial measurement units (MIMUs) are particularly attractive being wearable, thus enabling to collect movement data out of the laboratory.

Research questions: To investigate the feasibility and accuracy of a recent marketed full-body MIMU-based method for the estimation of the 3D BCoM trajectory and energetics during walking.

Methods: Twelve subjects walked at self-selected and slow speed along a 12 m long walkway. GRF and MKR were acquired using three force platforms and a stereophotogrammetric system. MIMU data were collected using a full-body MIMU-based motion capture system (Xsens MTw Awinda). The 3D BCoM trajectory, external mechanical work and energy recovery were extracted from the data acquired by the three measurement systems, using state-of-the-art methods. The accuracy of both MKR- and MIMU-based estimates compared with GRF was assessed for the BCoM trajectory (maximum, minimum, range, and RMSD), as well as for mechanical work and energy recovery.

Results: A total number of 108 strides were analyzed. MIMU-based BCoM trajectory displayed larger errors than GRF (and MKR) for the trajectory ranges: 89±47(93±44)% in antero-posterior, 46±25(40±79)% medio-lateral and -13±23(-5±25)% vertical directions, leading to a 3D RMSD of 17±5(12±5) mm (mean±SD). These discrepancies largely affected the estimation of both mechanical work and energy recovery (+115±85% and -28±21%, respectively).

Significance: Preliminary findings highlighted that the tested MIMU-based method for BCoM trajectory estimation still lacks accuracy and that the quantification of energetics in real-life situations remains an open challenge.

Keywords: Mechanical Work; Magneto-Inertial Measurement Units; Wearable sensors; Walking; Kinematics; Ground Reaction Forces

1. Introduction

Human gait consists in a repeated sequence of basic limb motions aimed at moving the body along a desired direction, while maintaining weightbearing stability, conserving energy, and absorbing the floor shocks [1]. From a mechanical point of view, the body can be represented by its center of mass (BCoM), whose trajectory describes how the whole body progresses/moves.

The three-dimensional (3D) trajectory of the BCoM during locomotion provides an insight about the mechanical work done [2] and energy saving strategies [3]. Furthermore, the study of the 3D BCoM contour [4] may reveal information about gait asymmetry [5,6], stability [7] or efficiency [5], in both typical [4] and pathological gait [8].

Traditionally, two measurement systems are used to estimate the 3D BCoM trajectory: force platforms and marker-based stereophotogrammetry [9]. The former provides net ground reactions forces (GRF), exerted by the foot to the ground, which are numerically integrated twice to obtain speed and displacement, once initial conditions are known [10]. The latter measures the 3D positions of markers located on specific anatomical landmarks. From these positions and information about the body segment inertial parameters, the 3D BCoM trajectory is estimated as a weighted mean of body segments CoM position [11].

Commonly, force platforms are considered as the gold standard, since no rigid body assumptions nor anthropometric models are needed. Only, for the integration process, initial conditions about the 3D BCoM velocity and position are required, and constant average walking speed is assumed within each considered stride, which may not be the case in overground walking [9]. With force platforms, however, only few steps can be acquired due to the limited number of platforms generally available in a laboratory. On the other hand, when considering stereophotogrammetry, constant speed assumptions can be met using a treadmill, which also allows obtaining a greater number of strides. However, the biomechanical model adopted can significantly affect the estimated BCoM trajectory [9]. Finally, both instruments constrain the analysis to laboratory settings.

With a view to monitor human locomotion in real-life environment, magneto-inertial measurement units (MIMUs) are particularly attractive, being small, wearable, easy to set up, and with low power consumption and cost. MIMUs embed 3D gyroscopes, accelerometers and magnetic sensors and provide movement-related quantities including their 3D orientation with respect to an inertial coordinate system [12]. Under strict assumptions of a linked kinematic chain, based on individual body segment orientations, rotations between segments can be estimated. By knowing segment lengths and positions with respect to an inertial coordinate system can be finally derived. At this point, similarly to stereophotogrammetric approaches, the 3D BCoM trajectory can be estimated as a weighted mean of body segment CoM 3D positions. Alternatively, single-MIMU approaches have been proposed, assuming that a MIMU located on the back may represent the BCoM. This approach, however, is more prone to errors: pelvic rotations lead to BCoM displacement overestimation and need to be compensated through *ad hoc* procedures [13]; drift errors typically characterizing MIMU-based orientation estimation can be hardly compensated without relying on MIMU redundancy and biomechanical modelling. Briefly, using a single-MIMU approach the essence of the 3D complex body movement is not fully and accurately captured [9,14].

Recently, different MIMU-based studies have been published on the estimation of the BCoM trajectory [13,15], and mechanical work or energy recovery [16–18] during walking. However, very few works validate their results against the gold standard [19]. As a result, little is known about the accuracy of MIMUs in estimating the 3D BCoM trajectory and derived quantities during locomotion.

The aim of the present study is to fill this gap by comparing multi-unit MIMU-based estimates of the 3D BCoM trajectory, mechanical external work and energy recovery with respect to both force platforms- and marker-based estimates. To this purpose a methodological framework for comparing BCoM trajectory and the related energy parameters as obtained by different methods was presented.

2. Material and methods

a. Experimental Protocol

Twelve subjects (7 females, 1.71±0.08 m height, 66.6±8.9 kg body mass, 26.3±4.7 y.o. (mean±SD)) walked ten times at self-selected and slow speed along a 12 m long walkway. The study was approved by the University of Rome "Foro Italico" Ethics Committee (CAR 04/2019) and subjects signed an informed consent before the experimental session in accordance with the Declaration of Helsinki.

b. Data Acquisition

The 3D trajectories of 18 reflective markers located on the main joint centers according to [9, 11] (Figure 1) were recorded using a 6-camera stereophotogrammetric system (Vicon MX13, Oxford

Metrics, UK) at a sampling rate of 100 Hz. Three force plates (two AMTI, USA, 0.6x0.6 m; one Bertec Corp, USA, 0.4x0.8 m) embedded in the floor were used to collect GRF at 1000 Hz. Kinematic and GRF data were collected with the Nexus 2.0 software (Oxford Metrics, UK). An Xsens MTw Awinda motion capture system (Xsens Technologies B.V., Enschede, The Netherlands), consisting of 17 units (Figure 1), was used to collect MIMU-based data. Data were acquired at 60 Hz and processed using the Xsens MVN Analyze software (v2019.0) [20]. A preliminary spot-check of the MIMUs orientation estimates was performed according to the guidelines proposed in [21]. After MIMU positioning, a calibration procedure was performed according to the Xsens MVN Analyze User Manual, and aimed at estimating the dimensions/proportions of the person being tracked, as well as the orientation of the sensors with respect to the corresponding segments [20]. Briefly, the calibration procedure consists of three steps: *i)* scaling a generalized anthropometric model according to a set of input parameters given by the user; *ii)* sensor-to-segment calibration where the participant is asked to stand still in neutral-pose (stand still with arms and hands straight along the body), during which segment orientations are assumed to be known, and to walk a few meters back and forth for a short period of time; *iii)* axes definition, where the forward direction of the local coordinate system is defined as well as its origin (which is defined at the position of the right heel) [20]. Sensor positioning and calibration procedure were performed by the same expert operator for all MIMUs and all participants. A 5-min warm-up period was included before starting data collection. Data were synchronized by asking the subject to hit one of the force platform three times while standing on it, prior to walk.

c. Data Analysis

Marker positions were filtered through a ‘zero-lag’ 2nd order Butterworth low-pass filter with a cut-off frequency identified by a residual analysis on each marker coordinate [22]. GRF were filtered through a forward-reverse low-pass, 2nd order Butterworth filter with a cut-off frequency of 30 Hz. Data were synchronized by aligning the peaks identified on the vertical ground reaction force and on the acceleration measured by the MIMU on the kicking foot during the foot-platform impacts.

Only strides correctly performed on the force platforms were considered for further analysis, which was performed on stride-level basis. Strides were defined and segmented from midstance of the right(left) foot to the subsequent midstance of the same foot, where midstance was defined as the minimum of the trough in GRF vertical force.

The 3D BCoM trajectory was obtained from data recorded using the force platforms, the stereophotogrammetry and MVN Awinda systems, respectively. For the sake of clarity, GRF, MKR and MIMU acronyms will be used hereinafter to refer to the different methods for BCoM trajectory estimation:

- **GRF** (Gold standard): the BCoM trajectory was computed by double integration of the acceleration (GRF divided by the subject's mass) according to [10] and integration constants were calculated as described in [23]. The obtained BCoM trajectory was then down sampled (1/10) in order to match stereophotogrammetric data length.
- **MKR**: the time course of the BCoM 3D position was estimated as the weighted mean of an 11-segment model (Figure 1) [9,11] based on Dempster's inertial parameters of body segments [22].
- **MIMU** (Tested method): for the Xsens system, the BCoM trajectory was directly obtained by the MVN Analyze software using the first version that implements this feature [20]. This trajectory was filtered with the same filter used for marker trajectories [22] and interpolated with a 5th order spline and resampled at 100 Hz.

To minimize the effects of drift in the MIMU position estimates over the gait trial and to express the BCoM trajectory in the same inertial coordinate system for all methods, a right-handed motor task-specific coordinate system was defined: the vertical axis (Z upward), aligned with the gravity direction, the anterior-posterior (X) axis aligned with the direction of progression, and the medio-lateral axis (Y) obtained as the cross-product of the X and Z axes. As each participant was asked to walk along the force plate corridor, the direction of progression was defined for all methods as aligned to the force plate axis along which gait occurred (specifically the X axis, coinciding for the three force plates).

FIGURE 1

For each considered stride, the BCoM trajectory was forced to become closed loops [4,9] and, for MKR and MIMU, the average value of each trajectory coordinate was subtracted from the signal to make the BCoM trajectory centered on (0, 0, 0) [4,9]. The 3D closed and centered BCoM trajectories from MKR and MIMU were then compared with those obtained from GRF by using a point-by-point 3D root mean square distance (3D RMSD, mm) [9]. Moreover, maximum, minimum, and range of motion (i.e. peak-to-peak distance) values were computed for each trajectory component.

From the 3D BCoM trajectory, the time course of potential (PE) and kinetic (KE) energies were obtained to calculate the total mechanical energy (TE=PE+KE). The summation of all increases in TE time course constitutes the mechanical external work (Wext expressed in J/(kg m)), the work done to accelerate and lift the BCoM [2]. Energy Recovery, the ability to exchange potential and kinetic energy, was also calculated [24].

Data were analyzed with purposely written LabVIEW (v13, National Instrument, USA) and Matlab® (R2016a, The MathWorks Inc., USA) scripts.

d. Statistics

A one-way repeated measure ANOVA was performed on the extracted parameters to test for differences between GRF and both MKR and MIMU. Pearson statistical test and the square of Pearson correlation coefficient (R^2) were used to examine the linear relationship between variables. Bland-Altman plots [25] of Wext and Energy Recovery were used to assess the agreement between GRF and both MKR and MIMU values. Systematic bias and 95% limits of agreement (LoA) were computed. In addition, inspection of Bland–Altman plots and correlation exploration were performed to investigate the presence of heteroscedasticity. Finally, intra- and inter-participants reliability of 3D RMSD, Wext, and Energy Recovery parameters was assessed using Intraclass Correlation Coefficients (ICC) and their 95% confident intervals, based on absolute-agreement and 2-way mixed-effects model [26]. Statistical analysis was performed using the IBM SPSS Statistics software (v23, IBM Corp., USA, α=0.05).

3. Results

Participants walked on a wide range of speeds (0.79÷1.94 m/s) with 108 valid strides (completely performed on force platforms) analyzed and compared among the three methods. The number of valid strides for each participant varies from a minimum of six to a maximum of sixteen.

In Table 1, the BCoM excursion on the three axes was presented as minimum, maximum, range, and RMSD. MIMU showed the greatest discrepancies from GRF in all axes, with an antero-posterior range almost doubled compared to GRF. The ANOVA analysis showed a significant effect of the 'method' factor for all parameters ($F_{2,107}>19.77$, $p<0.001$, $\eta^2>0.16$), except for the minimum on the vertical axis. Pairwise comparison results are reported in Table 1.

When considering the GRF and MKR 3D BCoM trajectory during a stride (at whichever speed), the classical shape was displayed, with two peaks during the single support phases (right and left) and a valley during the double support phase, where the trajectory crossed its path from the right to the left side and vice versa. Figure 2 shows two walking strides characterized, respectively, by a low and average 3D RMSD between GRF and MIMU. When comparing the trajectories from MKR and MIMU with GRF, some peculiar aspects emerged: MKR shape well resembled GRF trajectory on the three axes (Figure 2A) with some minor discrepancies that lead to a 3D RMSD of 2.8 mm. In Figure 2B, a higher average distance between the two trajectories was obtained (3D RMSD=4.1 mm), but the MKR trajectory still maintains its above-described peculiar shape, with the left-right asymmetry of the BCoM contour. Conversely, MIMU trajectory displays a very different shape with respect to the GRF with a wider bottom part, a narrower top trajectory and with a cross on the top (Figure 2A). This inconsistent (with respect to GRF, but consistent within MIMU data) pattern led to a 3D RMSD of about 12 mm, three-times that of MKR.

FIGURE 2

Overall, 3D RMSD values were lower in MKR (4.9±1.3 mm) than in MIMU (16.8±5.0 mm) (Figure 3), with a small tendency to decrease as a function of speed in MKR (R^2=0.08), whereas MIMU showed an increase as a function of speed (R^2=0.20). ICC results showed a moderate and good reliability for MKR- and MIMU-based estimates, respectively (ICC MKR=0.61 [0.02;0.97], F=3.60 p=0.001; ICC MIMU=0.86 [0.53;0.99], F=7.51, p=0.025).

FIGURE 3

The mechanical external work increased as a function of speed for each method, with different slopes (GRF: Wext=0.1235speed+0.1862, R^2=0.34; MKR: Wext=0.04259speed+0.2683, R^2=0.03; MIMU: Wext=0.9341 speed-0.3945, R^2=0.59).

For what concerns Wext and Energy Recovery, Bland-Altman plots depicting the agreement between GRF and both MKR and MIMU values are presented in Figure 4. For Wext (Figure 4A), MKR showed a lower systematic bias (-0.015±0.054 J/(kg m)) and smaller 95% LoA (-0.120; 0.089) than MIMU

(0.395±0.297 J/(kg m) systematic bias and -0.187; 0.977, 95% LoA). MIMU also showed a positive random error as a function of speed (y=1.93speed-0.25; R^2=0.13; p<0.0001). Similar results were found for the Energy Recovery (Figure 4B), where errors between GRF and MKR were smaller with respect to those obtained between GRF and MIMU (GRF-MKR: 0.139±0.047 systematic bias and -0.079; 0.107 95% LoA; GRF-MIMU: -0.178±0.135 systematic bias and -0.442; 0.857, 95% LoA). As concerns Wext and Energy Recovery reliability, ICC results showed a good to excellent reliability for both methods and parameters (ICC MKR>0.91 [0.67;0.99], p<0.0001; ICC MIMU>0.85 [0.55;0.99], p<0.0001).

FIGURE 4

4. Discussion

The present study investigates the accuracy of a recently marketed full-body MIMU-based method to estimate the BCoM trajectory and relevant derived quantities, i.e. external mechanical work (Wext) and the ability to exchange potential and kinetic energy (Energy Recovery). To this aim, a validation framework for assessing the accuracy of the BCoM estimation was proposed and MIMU-based estimates were compared to those obtained using both force platforms (GRF), considered as the gold standard, and stereophotogrammetry (MKR), which is often considered a silver standard.

The present results confirmed that GRF and MKR provide comparable results for the BCoM trajectory, Wext and Energy Recovery. On the other hand, although the use of magneto-inertial technology to estimate BCoM-related parameters by tracking the full-body motion is very promising and relevant, our findings suggest that the use of this technology is not mature yet.

Results about the BCoM displacement along the antero-posterior, medio-lateral and vertical axes agree with the existing literature [9,14] for both GRF and MKR. Differences between these two methods are below 10% of the GRF values for maximum, minimum and range of each component (Table 1). When considering the MIMU method, errors increase significantly and grow up to 98% for the antero-posterior direction. Interestingly, the lowest errors were displayed by the vertical component. This result is encouraging as it indicates that when the vertical BCoM displacement is the main parameter of interest, the considered MIMU-based approach may provide relatively reliable information (overall error of about 15%). However, as extensively indicated in the literature, the BCoM trajectory during human locomotion moves over three-dimensions [4,8] and any method validation cannot disregard these 3D characteristics.

When considering the 3D closed and centered BCoM trajectory (Figure 2) and the 3D RMSD values (Figure 3) inconsistencies between MIMU and both MKR and GRF are clearly visible. Whereas the trajectories obtained with GRF and MKR well resembled the 3D contour described in previous studies [4,9,27], MIMU-based trajectory displayed great discrepancies in the antero-posterior axis and in the medio-lateral cross from the two sides of the contour (Table 1, Figure 2). As a result, MIMU-based 3D RMSD was, on average, more than twice that of MKR with a trend to increase with the walking speed. MKR 3D RMSD values are close to those obtained by [9] and [28], whereas MIMU values are greater than those reported by previous studies testing marker-based methods (center of pelvis [9,28,29]; Plug-In-Gait model [9,30]; one marker on C7 vertebra [9]).

Different reasons may have contributed to the large errors displayed by the MIMU-based method: drift errors typically affecting orientation estimation which, in turn, affect position estimation; errors entailed in the numerous assumptions needed to estimate body segments position from their orientation (i.e. body segment length, joint modeling, global optimization criteria); errors associated with the use of anthropometric models. It was beyond the scope of this work to quantify the relative impact of each source of error on the final outcome. However, this remains an open issue which deserves attention and could drive important advancements in the development of MIMU-based methodologies.

FIGURE 5

The external mechanical work values computed by GRF and MKR were in line with previous literature [2,11,31] and the discrepancies between GRF and MKR were slightly smaller than those reported in [9]. Wext values were largely overestimated when considering MIMU with respect to GRF (115±85%), with a positive random error (Figure 4A). To better understand this result, the contribution of potential and kinetic energies to the total BCoM mechanical energy must be analyzed and compared between GRF and MIMU methods. As depicted in Figure 5, despite the slightly different pattern displayed by the MIMU method, the magnitude of the potential energy is similar between the two methods. Conversely, a large difference is shown in the antero-posterior kinetic energy (KEx), which, for MIMU, is more than twice that of GRF. This inconsistency derives by the errors displayed by MIMU in the 3D trajectory estimation (Table 1, Figure 2): specifically, when focusing on the antero-posterior component, MIMU-based BCoM trajectory travels a much wider distance with respect to GRF. This causes large errors in the antero-posterior velocity and, in turn, in the kinetic energy which, for MIMU, is almost twice that of GRF. As Wext is the sum of the increments of the total energy, these errors linearly affect Wext estimation (more than 2x higher in MIMU than GRF). These discrepancies, together with differences in both amplitude and phase of KEx and PE (Figure 5), led to a lower Energy Recovery (-28±21%, Figure 4B) in MIMU than GRF. Both Wext and Energy Recovery results were reliable within and between participants, and variability of all accuracy-related parameters was comparable between MKR and MIMU methods.

The results of the present study must be considered at the light of the following considerations: GRF is commonly considered the gold standard method when BCoM trajectory is aimed. However, assumptions about integration initial conditions must be made, i.e. initial and final progression speeds must be the same within each considered stride. Whereas this assumption holds when treadmill locomotion is considered, when walking over ground it could introduce a certain degree of uncertainness to the GRF BCoM trajectory. It can be assumed, however, that this uncertainness does not have a significant impact on the final results of the present study and on their generalizability. It is worth to underline that the data collected in this study are tested, and conclusions are drawn, only for walking. Evidence exists that accuracy in estimating the BCoM trajectory could vary in different locomotion tasks [9,19]. Last but not least, due to the lack of information about the tested methodology, only general speculations could be provided about the possible elements that contributed to the large errors displayed by the MIMU-based method. Further investigations in this respect would be beneficial for the whole scientific community.

5. Conclusions

This study shows that the tested recently marketed method based on the use of multiple MIMUs for the estimation of the 3D BCoM trajectory during walking still lacks accuracy and is not mature yet to be used in real-life situations. Discrepancies in estimating the 3D BCoM trajectory strongly affect the estimation of the external mechanical work and energy recovery, characterized by errors up to 115%. Efforts should be addressed to improve the accuracy of the antero-posterior component of the BCoM trajectory, being the most affected by these errors. Finally, it is desired that any future MIMU-based methodologies or software versions will be tested using a similar experimental and analytical validation framework as that proposed in the present study.

CRediT author statement

Gaspare Pavei: Conceptualization, Methodology, Software, Formal Analysis, Writing–Original Draft, Visualization. **Francesca Salis**: Investigation, Software, Writing–Review & Edition. **Andrea Cereatti**: Conceptualization, Resources, Writing–Reviewing and Editing, Supervision. **Elena Bergamini:** Conceptualization, Investigation, Methodology, Software, Formal Analysis, Resources, Writing–Original Draft, Supervision.

Conflict of interest statement

None of the authors have any conflict of interest to report.

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Figures captions

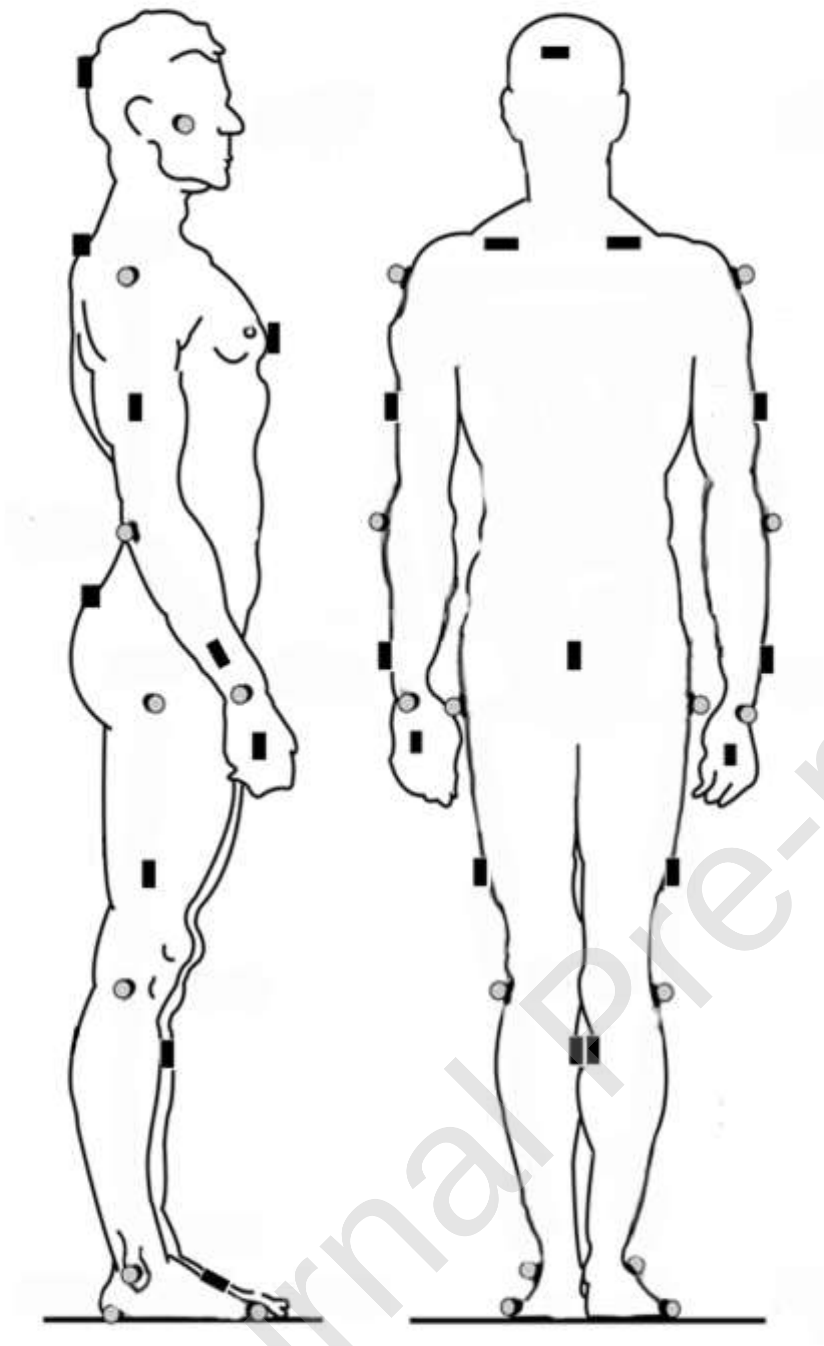
Figure 1: Markers (grey dot) and MIMUs (black rectangle) position on the participant (adapted from [32]) in sagittal and posterior view (left and right side, respectively). Marker positions are from [11] and [9]; MIMU positions are from the Xsens MVN Analyze User Manual.

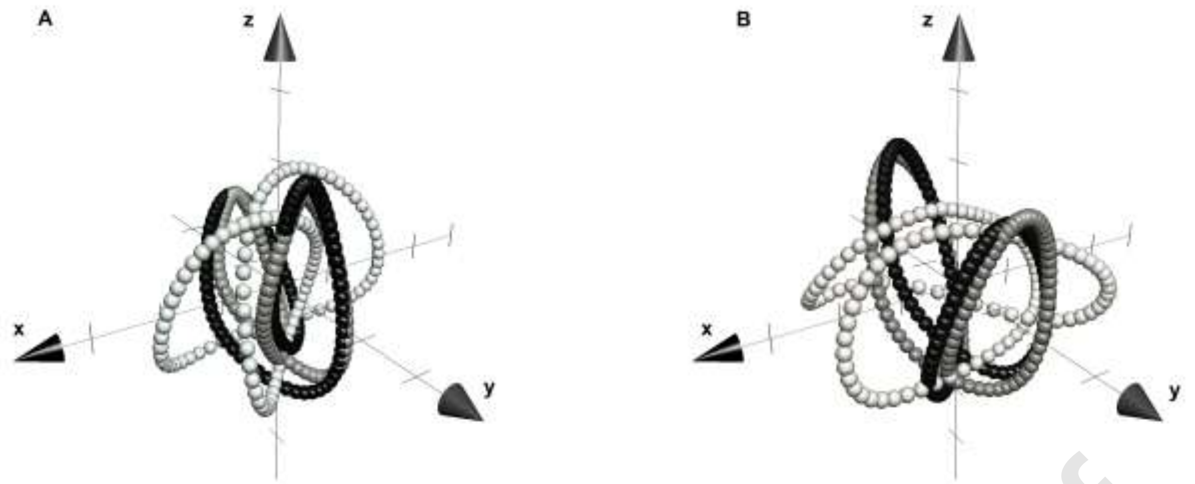
Figure 2: 3D BCoM trajectory of a walking stride as obtained by MKR (dark grey) and MIMU (white) compared to the gold standard GRF (black). Arrow on X-axis indicates the progression direction, axes ticks are located at 0.01 m step increment. Two strides performed by different subjects at different speeds are presented: A) walking at 1.3 m/s, MKR 3D RMSD=2.8 mm; MIMU 3D RMSD=12.9 mm. B) walking at 1.2 m/s, MKR 3D RMSD=4.1 mm; MIMU 3D RMSD=11.9 mm.

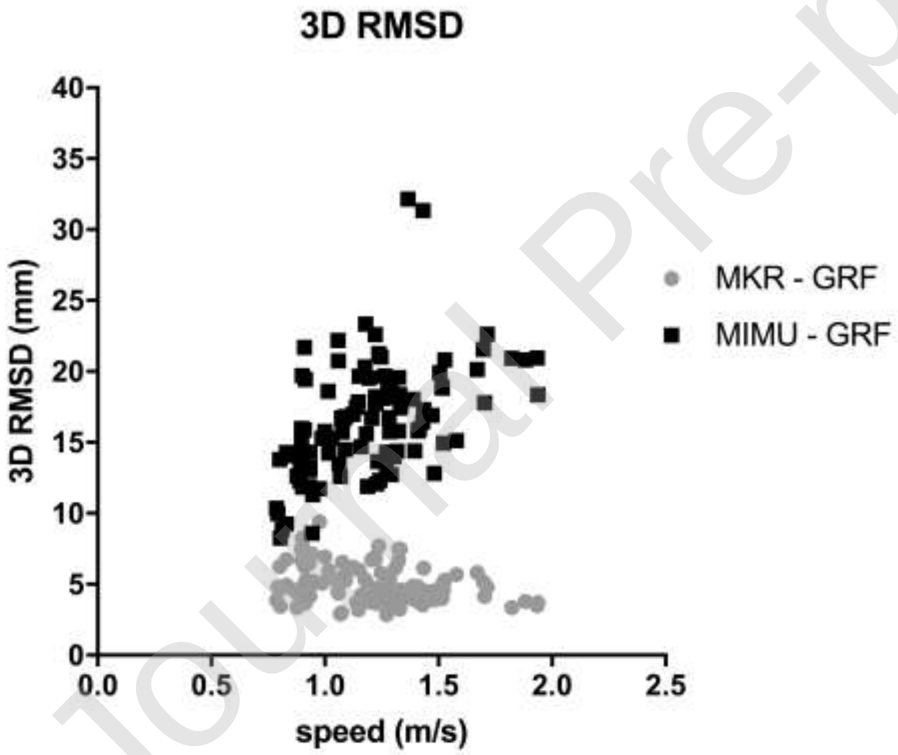
Figure 3: 3D RMSD (mm) between BCoM trajectories from GRF and MKR (grey circles) and from GRF and MIMU (black squares) as a function of walking speed (m/s).

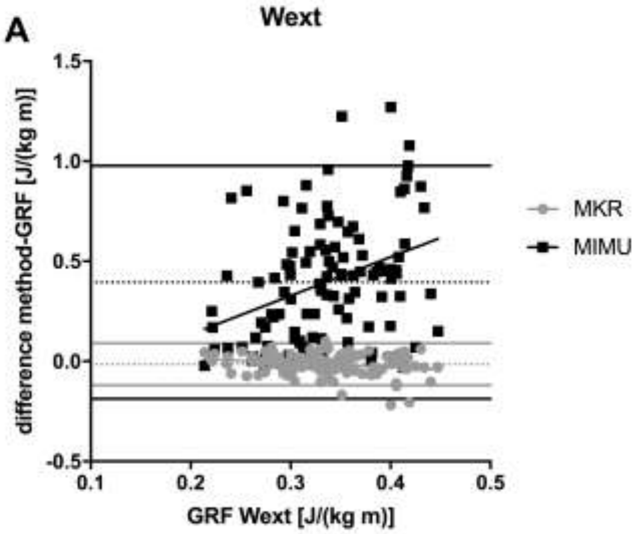
Figure 4: Bland-Altman plots of A) Wext (J/(kg m)) and B) Energy Recovery. The label on the ordinate axis represents the difference between the method (MKR, grey circles; MIMU, black squares) and the gold standard (GRF): positive values indicate an overestimation with respect to GRF. On the abscissa axis the gold standard (GRF) values are reported. Dotted lines and continuous lines represent mean difference and 95% limits of agreement, respectively (in grey for MKR, in black for MIMU).

Figure 5: The BCoM mechanical energies (J/kg) time course is presented as a function of stride percentage when computed from A) GRF BCoM trajectory, and B) MIMU BCoM trajectory. KEx antero-posterior kinetic energy, KEy medio-lateral kinetic energy, KEz vertical kinetic energy, PE potential energy and TE total energy (the sum of kinetic energies and potential energy). Wext is the sum of all increases in TE.




A
z
x
y
B
z
x
y


3D RMSD
3D RMSD (mm)
speed (m/s)
0
5
10
15
20
25
30
35
40
0.0
0.5
1.0
1.5
2.0
2.5
MKR - GRF
MIMU - GRF


A
Wext
difference method-GRF [J/(kg m)]
GRF Wext [J/(kg m)]
MKR
MIMU
B
Energy Recovery
difference method-GRF
GRF Energy Recovery

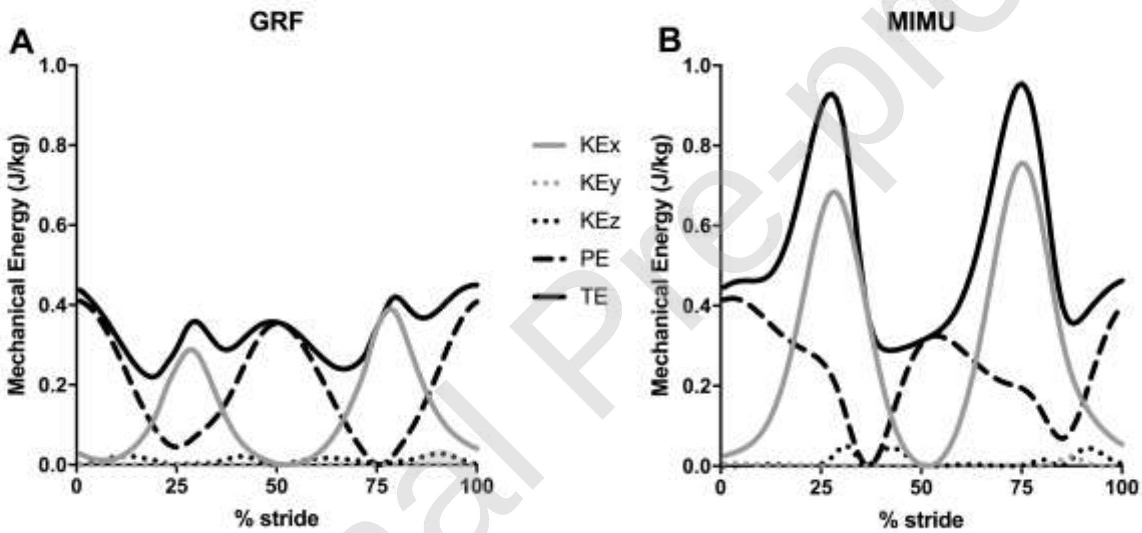

A
GRF
Mechanical Energy (J/kg)
% stride
KEx
KEy
KEz
PE
TE
B
MIMU
Mechanical Energy (J/kg)
% stride

Table 1

		GRF	MKR	MIMU	GRF-MKR		GRF-MIMU	
		(mm)	**(mm)**	**(mm)**	**(mm)**	**(%)**	**(mm)**	**(%)**
X	max	12.3±2.5	12.5±2.7	23.6±5.6 [#a,b]	0.2±3.1	4.7±25.7	11.3±5.8	98.7±60.2
	min	-13.4±3.0	-12.4±2.6 [*a]	-23.8±5.2 [#a,b]	1.0±2.8	-4.5±21.8	-10.4±5.2	84.3±51.8
	range	25.7±4.8	25.0±4.6	47.4±10.1 [#a,b]	-0.7±4.6	-1.2±18.0	21.7±10.0	88.9±47.5
	RMSD				3.6±1.2	14.2±4.5	9.4±3.3	37.6±14.2
Y	max	13.6±4.1	14.1±5.0	17.6±7.3 [#a,b]	0.5±2.8	4.2±21.5	4.0±8.2	40.9±70.6
	min	-13.7±4.2	-14.3±5.1	-17.6±7.2 [#a,b]	-0.6±2.8	4.5±20.7	-3.9±8.2	41.1±72.1
	range	27.2±8.3	28.3±10.0	35.2±13.9 [#a,b]	1.1±5.5	4.4±20.5	7.9±15.6	40.8±67.6
	RMSD				2.2±1.1	8.6±4.4	11.2±4.8	45.6±24.6
Z	max	20.4±3.9	17.6±3.7 [#a]	15.7±4.2 [#a,b]	-2.8±2.0	-13.7±9.2	-4.8±3.6	-22.9±15.8
	min	-20.1±2.9	-19.4±3.2 [*a]	-19.2±6.8	0.7±1.8	-3.3±9.0	0.9±6.9	-3.1±35.2
	range	40.5±6.4	37.0±6.6 [#a]	34.9±10.3 [#a]	-3.5±3.1	-8.7±7.3	-5.6±9.4	-13.5±22.7
	RMSD				2.8±0.9	6.9±2.2	8.8±3.8	22.0±9.9

Table 1. BCoM displacement (mean±SD) for the three axes (mm; X antero-posterior, Y medio-lateral, Z vertical) as maximum value (max), minimum value (min) and range. For each parameter, the difference between the gold standard (GRF) and both MKR and MIMU methods is also reported, both in absolute (mm) and relative (%) values. The root mean square difference (RMSD) between GRF and both MKR and MIMU is also presented both in absolute (mm) and relative (% of range) values, for each axis. Statistical differences: * $p<0.01$; # $p<0.001$; a vs. GRF; b vs. MKR.