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EXECUTIVE SUMMARY OF THE THESIS

Validation of the reliability and accuracy of a method based on an inertial sensor for the evaluation of spatio-temporal parameters in vertical jumping tasks

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

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1. Introduction

Vertical jump testing is a widely used method of assessing motor development and physical ability. Although jump performance can be assessed using optoelectronic system and force platforms, these solutions have some drawbacks, linked to the fact that they are quite expensive and can't be used in real-world conditions. The spread of wearable technologies has paved the way for the extension of quantitative motion analysis in ecological environments and cost-effectively as well.

This study aims to verify the validity of an inertial measurement unit (IMU) from Xsens DOT (Xsens Technologies - NL), in the context of vertical jump assessment. Specifically, the main objective was to validate the accuracy of spatio-temporal parameters derived from acceleration data acquired through the IMU. These parameters were evaluated both through the use of the sensor and laboratory gold standards technologies which are the force platforms (FP) and the optoelectronic system (OS). In addition, the effectiveness of a new integration method, referred to as New_Method, was explored.

2. State of art

Biomechanical analyses of vertical jumps include both ecologically implementable tests and laboratory tests, for an enhanced accuracy. The primary parameters of interest studied in the literature are jump height (VHJ), which indicates explosive lower limb power, and time of flight (FT). VHJ is gauged through knowledge of the center of mass (CoM) trajectory obtained through OS technology, which is nowadays considered the gold standard method for VHJ measurement. The center of mass (CoM) can be determined using the "Weighted Segmental Method" [1], which derives the position of the CoM from the coordinates of individual body segment centers of gravity. Alternatively, if a marker protocol is reduced, the CoM trajectory can be estimated by averaging the

trajectories of only the markers affixed to the iliac spines [2].
The gold standard system for calculating time variables, instead, is the FP. The FT is calculated from the signal recorded by the FP, observing when it is equal to zero. Deriving the FT, VHJ can be calculated by applying Bosco's formula [3]:

$$VHJ_{Bosco} = \frac{g \cdot FT^2}{8} \quad (1)$$

Currently, the IMU for vertical jump characterization is mainly used for CMJs. Only few studies have used it to analyze monopodalic and plyometric jumps.
In most of the studies in the literature, the IMU is placed at the level of the subject's L5 vertebra. The main methods for calculating the VHJ through IMU were reported by Nielsen et al. [4]:

1) Double acceleration integration (NDI) method. The condition for deriving the subject's vertical displacement is that the initial acceleration is zero, which means that the jump height is equal to the maximum displacement value recorded.
2) Take Off velocity (TOV) method. The body is assumed to be subjected only to gravity, and the free fall equation is applied from the Take Off velocity value obtained by single integration of the acceleration recorded by the IMU.
3) Flight Time (FT) method. The free fall equation is applied from the FT parameter measured by the IMU.

For each method, the Take Off and landing postures are assumed to be identical.
In further studies, IMU placement at the heel and toe was evaluated [5]. Again, VHJ was evaluated from the FT time value by applying the free fall equation. The positive results indicate that this method could be used in the objective evaluation of vertical jumps.
From the literature review, there is a lack of an established standard to confirm the accuracy of IMU-based methods for evaluating CMJ performance parameters against gold standards. This data gap is even more evident for monopodalic and plyometric jumps.
For this reason, the aim of this study was to assess the accuracy of spatio-temporal parameters obtained from the vertical acceleration data processing recorded by the Xsens DOT IMU in the context of bipodalic CMJ, monopodalic CMJ and plyometric jumps.

3. Materials and methods

The study was conducted at the "Luigi Divieti" Posture and Movement Analysis Laboratory of Politecnico di Milano. A total of 20 healthy subjects (13 F - 7 M; mean age of 24.0 ± 1.0 years; mean height of 1.68 ± 0.07 m; mean body mass of 57.0 ± 10.0 kg) were included in the study.
Each subject consented to the use of their data by signing the Informed Consent form. The research was previously authorized by the Ethics Committee of the Politecnico di Milano (Protoc. No. 22/2021, 14 June 2021).
Data were recorded simultaneously using an IMU sensor (Xsens DOT, Xsens Technologies – NL, sampling frequency = 60 Hz), two force platforms (AMTI, USA, sampling frequency = 200 Hz), and an optoelectronic system (OS, SMART DX, BTS-Bioengineering, Milan, Italy, sampling frequency = 100 Hz) equipped with 8 cameras.
The IMU was placed on the right side of the hip for all tasks, except for the left monopodalic CMJs where the IMU was moved to the opposite flank.
In addition, 22 passive markers were placed on each individual following the Davis marker set-up (Figure 1):

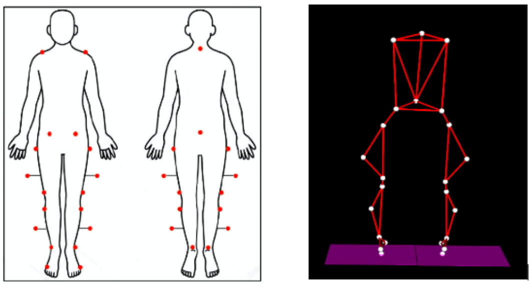

Figure 1 - Marker protocol and digital reconstruction using Davis model.

Each movement type was performed 5 times and included bipodalic CMJs, right monopodalic CMJs, left monopodalic CMJs, and plyometric jumps. For the latter task, 5 jumps had to be performed consecutively. After simultaneous acquisition, the data acquired from the OS and FP were processed using the SMART Tracker software and then processed using custom scripts in Matlab® (v.2023a, MathWorks, Natick, MA, USA).

All the signals under analysis were all unified at a frequency of 60 Hz in order to make the data acquired from the different systems comparable.
Derived parameters included jump height (VHJ), flight time (FT), Take Off (TO) and landing (LA) velocity, and contact time (CT, only for plyometric jumps).
Specifically, VHJ was calculated considering the maximum vertical displacement obtained by double integration of the vertical acceleration from the IMU, by the OS and by applying Bosco's formula in the case of the FP.
The flight time was defined as the time between TO and LA and was calculated according to the formula:

$$FT = \left(\frac{LA - TO}{freq}\right) \cdot 1000 \qquad (2)$$

where the transition from Hz to ms is made by dividing by the sampling frequency.
The contact time was defined as the time the foot was on the ground between the LA of one jump and the TO of the following jump and was calculated in ms using the following equation:

$$CT = \left(\frac{(\sum_{i=1}^{4}(TO_{i+1} - LA_i))/freq}{n}\right) \cdot 1000 \qquad (3)$$

Where n indicates the number of ground contacts while performing five consecutive jumps. In the study it was set to 4.
Finally, velocity parameters were obtained by single integration of the vertical acceleration.
To verify the validity of the sensor for the calculation of spatial and temporal parameters, statistical tests were performed, including the calculation of Pearson's correlation coefficient R, accuracy analysis, Bland-Altman plots and root mean square error (RMSE). These tests were performed in order to compare the sensor with the two different reference systems, both with the New_Method and with the BIA_Method.

4. Results

The results for spatial, temporal, and velocity parameters are discussed separately.

4.1. Spatial parameters

The Pearson's correlation coefficient between IMU and OS for VHJ, calculated with New_Method was 0.84. In contrast, the value for BIA_Method was 0.78. By comparing VHJ measurements with IMU and FP, using Bosco's formula, correlations described by Pearson's coefficients with the value of 0.88 and 0.91 were obtained for New_Method and BIA_Method, respectively.
Considering the accuracy of the IMU, the New_Method had an average accuracy of 83.47% compared to the OS, while the BIA_Method had 76.24%. Specifically, accuracy above 80% was recorded for all tasks, except for plyometric jumps, where values were lower, but still above 70%. In the calculation of VHJ by Bosco's formula, however, the BIA_Method was the most accurate (91.75%).
Bland-Altman analysis found agreement between the various systems, although a systematic error of 1.33 cm and of 5.49 cm emerged between OS and IMU New_Method and between OS and IMU BIA_Method (Figure 2) respectively.

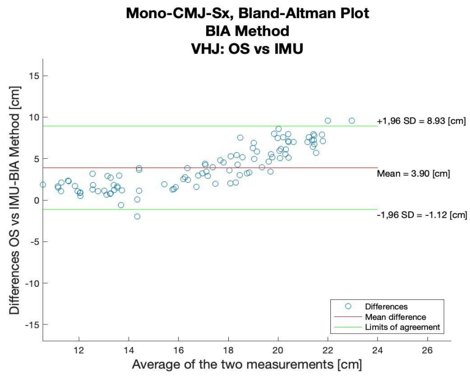

Figure 2 - Bland-Altman plot VHJ.

When comparing FP and IMU with Bosco's formula, the systematic errors averaged less than 1 cm.
Finally, in the comparison between OS and IMU, the mean RMSE values were 3.84±1.57 cm for the New_Method and 5.62±1.32 in the case of the BIA_Method. In the comparison between IMU and FP, the mean index value was 1.87±0.54 cm for the New_Method and 1.49±0.31 cm for the BIA_Method.
Table 1 summarizes the results for the spatial parameters. Each column shows the average

results of the OS vs IMU and FP vs IMU comparisons.

VHJ	New_Method	BIA_Method
Correlation	R = 0.86	R = 0.84
Accuracy	86.16%	83.99%
Systematic bias [cm]	1.15	2.74
RMSE [cm]	2.85	3.55

Table 1 – Mean value of results of statistical analysis for VHJ.

4.2. Temporal parameters

Comparisons were made between IMU and FP, considering both the integration methods. The parameters evaluated in this case were FT and CT, the latter only for plyometric jumps.

Pearson's correlation coefficient values averaged 0.92 for FT and 0.98 for CT in plyometric jumps. An example of correlation plot is shown in Figure 3.

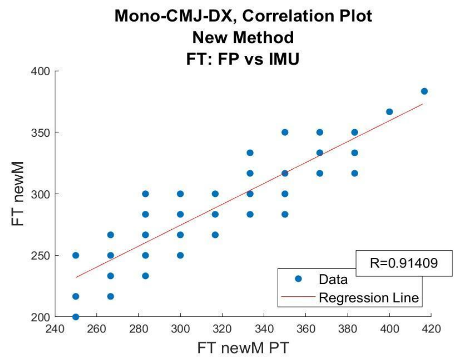

Figure 3 - Correlation plot FT.

Considering the accuracy of the FT calculation with the IMU, the values between the two integration methods were comparable in the bipodalic and plyometric jumps. In contrast, the New_Method recorded lower percentage accuracy indices in monopodalic jumps with respect to the BIA_Method. In any case, in both algorithms analyzed, accuracy above 90% was found. As for the CT variable, accuracy values above 94% were recorded in both cases.

From Bland-Altman plot analysis, an average systematic bias of 15 ms was observed between FP and IMU in the New_Method case. In contrast, in the comparison between FP and IMU BIA_Method the systematic bias was 1.7 ms.

For the CT variable, the observed bias was -4.3 ms for both the integration methods used.

Finally, comparable mean RMSE values were obtained for the bipodalic and plyometric jumps, while larger errors were found in the monopodalic jumps in the case of the New_Method. On average, the RMSE value related to FT was 22.12±10.16 ms for the New_Method and 16.57±3.86 ms for the BIA_Method. For CT, approximately equal index values were obtained for both algorithms. Tables 2 and 3 show the results obtained.

FT	New_Method	BIA_Method
Correlation	R = 0.92	R = 0.92
Accuracy	93.96%	95.68%
Systematic bias [ms]	15	1.7
RMSE [ms]	22.12 (10.16)	16.57 (3.86)

Table 2 - Results of statistical analysis for FT.

CT	New_Method	BIA_Method
Correlation	R = 0.98	R = 0.98
Accuracy	94.30%	94.34%
Systematic bias [ms]	-4.38	-4.33
RMSE [ms]	11.60	11.94

Table 3 - Results of statistical analysis for CT.

4.3. Velocity parameters

The velocity variables evaluated were MaxVel and MinVel, corresponding to the velocities recorded at TO (MaxVel) and at LA (MinVel) respectively. Accuracy-related analysis was not conducted for these variables.

The correlation coefficients found for the speed variables were lower than those obtained for the other parameters evaluated. The most significant linear correlations were observed for plyometric jumps, specifically for MinVel. In contrast, the lowest correlation (R = 0.24) was found for MaxVel, in the case of New_Method in bipodalic CMJs (Figure 4).

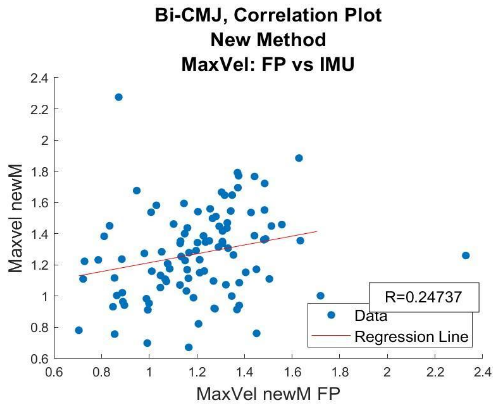

Figure 4 – Correlation plot for MaxVel.

Differently, from the Bland-Altman analysis, good agreement was found between FP and IMU, for both integration methods (Figure 5). The systematic errors found for MaxVel were 0.18 m/s in the case of New_Method and -0.15 m/s for BIA_Method. For the MinVel, the biases between FP and IMU were 0.13 m/s for the New_Method and 0.2 m/s in the case of the BIA_Method.

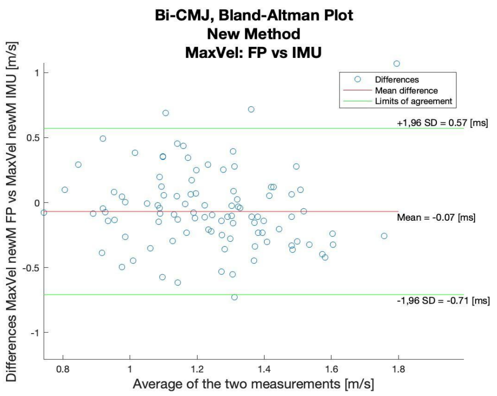

Figure 5 - Bland-Altman plot for MaxVel.

Finally, the mean values of the RMSE were evaluated. Comparable error values were observed for both proposed integration methods, with an average of 0.33 m/s for the MaxVel and an average value of 0.34 m/s for MinVel. Tables 4 and 5 show the results obtained.

MaxVel	New_Method	BIA_Method
Correlation	R = 0.36	R = 0.44
Systematic bias [m/s]	0.18	-0.15
RMSE [m/s]	0.33 (0.029)	0.34 (0.16)

Table 4 - Results of statistical analysis for MaxVel.

MinVel	New_Method	BIA_Method
Correlation	R = 0.40	R = 0.42
Systematic bias [m/s]	0.13	0.2
RMSE [m/s]	0.32 (0.11)	0.36 (0.10)

Table 5 - Results of statistical analysis for MinVel.

5. Discussion

For the analysis of the results obtained from the statistical evaluation, the results related to the spatial parameters are presented first, followed by the discussion of the results related to the temporal and velocity parameters.

5.1. Spatial parameters

Comparisons between IMUs and reference systems showed excellent correlation, as evidenced by Pearson's coefficients higher than 0.73. This confirms the reliability and accuracy of measurements obtained with IMUs in most of the motor tasks examined.
In terms of accuracy, the data processed using the BIA_Method showed lower values (83.99%) than those obtained with the New_Method (86.16%).
The Bland-Altman plot analysis confirmed the convergence of both methods of double integration of acceleration data, except for some outlier values. However, there was evidence of systematic error in the BIA_Method given by the apparent linear trend in the distribution of samples. This suggests that the IMU underestimated the value of the VHJ variable at high jump heights. The same linear trend in the distribution of samples was also found in the Bland-Altman plots of the plyometric jumps for both the New_Method and the BIA_Method. The RMSE value showed that, for each motor task, the New_Method had lower average index values than the BIA_Method (2.85 cm vs 3.55 cm), indicating its higher accuracy in comparison with the reference system.

5.2. Temporal parameters

A strong positive correlation between the measurements obtained with the gold standard and the IMU was identified. A peculiar arrangement of the samples was found in the correlation plots. This is due to the fact that FT values resulted the same for the different tests performed by the different subjects, since it is calculated as the difference of integer indices. Moreover, accuracy analysis showed that FT and CT values obtained with the IMU were in remarkable agreement with the gold standard system, with an accuracy higher than 93%. However, Bland-Altman plots revealed bigger systematic errors for the New_Method. In particular, the New_Method showed a tendency to underestimate the FT in monopodalic CMJs. Finally, for the RMSE, both methods reported small errors on average, confirming their reliability in calculating temporal variables.

5.3. Velocity parameters

Correlation analysis showed significantly lower Pearson's coefficients, suggesting limited correlation between IMU and the gold standard. This indicates that the two systems do not have a strong linear relationship.
This contrasts with the results of the Bland-Altman plots, which show good agreement between FP and IMU. Thus, the analyses performed suggest the existence of a non-linear relationship between the variables studied.
The calculated RMSE was found to be comparable between MaxVel and MinVel (0.33 m/s). Finally, for the variables under consideration, it can be said that the error cannot be neglected, which calls into question the reliability of the IMU system for measuring these variables.

6. Conclusions

In this work, spatio-temporal parameters related to vertical jumps have been calculated from acceleration data acquired by IMU Xsens DOT. Their validation was carried out by comparing the same variables coming from the optoelectronic system and two force platforms. The results obtained showed a good correlation between the systems compared. Although systematic biases of different magnitude depending on the measured parameter were found.
It can be concluded that the IMU Xsens DOT (Xsens Technologies - NL) has the potential to be used as a measurement tool for the characterization of vertical jumps in the ecological environment and in a rehabilitation context.

7. Bibliography

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