CAN IMUs ACCURATELY DETECT THE KINEMATICS OF DYNAMIC AND CONSTRAINT-BASED TASKS? APPLICATION TO THE BASKETBALL LAYUP

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The purpose of this study was to assess the validity and reliability of an inertial measurement unit (IMU) system against an optical motion capture system during the basketball layup shot; a dynamic and complex task, that is influenced by game-based constraints. Eight players performed 10 trials with and 10 without a defender. Kinematic variables (jump height, take-off angle, joint angles, COM displacement) were derived and agreement (ICC, BA plots) and disagreement (RMSE, SPM) calculations were carried out for each trial. The IMU provided agreeable results for discrete measures, while joint angles and COM displacement agreement were plane-specific. A between-condition analysis demonstrated IMU's reliability in detecting joint angle differences between defended and undefended conditions comparable to the optical system for nine out of twelve joint angles.

KEYWORDS: IMUs, layup shot, basketball, validity, reliability.

INTRODUCTION: Compared to optical motion capture systems inertial measurement units (IMUs) have the advantage of being more flexible in terms of where they can be used and the volume they can capture over (Poitras et al., 2019). For these reasons, IMUs have become increasingly popular (Golfrey, 2008) for analysing human movement. Optical motion capture systems have been shown to provide high quality multi-plane data and are considered the 'gold standard' measure in the field of biomechanics (Ceseracciu et al., 2014). The basketball layup shot is a dynamic movement that features multi-plane upper and lower body motions and is context-driven (i.e., influenced by game-based constraints), requiring testing to be performed in as representative an environment as possible. However, before this can be undertaken with confidence, the ability for IMUs to accurately and consistently measure more complex whole-body tasks needs to be established over the more constrained and more planar jumping actions they have commonly been validated on (Al-Amri et al., 2018). Although accuracy of measurement is typically key for biomechanical analyses there are also questions that can be answered if the data are precise and have sufficient resolution to detect changes between conditions, a question not typically addressed by studies assessing IMUs' accuracy Thus, the purpose of this study was to examine the difference (RMSE) and agreement (Intra-class correlations (ICC), Bland-Altman plots) of the Xsens (Awinda, Xsens, Enschede, the Netherlands), system with the Vicon motion capture system (Vicon Motion Systems Ltd, Oxford, UK) for the basketball layup shot. Additionally, the ability of Xsens to detect similar magnitudes of changes in technique to Vicon under different constraints was assessed.

METHODS: Eight recreational basketball players, five males and three females (age = 23.5 ± 4 years, height = 1.73 ± 0.12 m, body mass = 71.04 ± 9.74 kg) were recruited. Seventeen Xsens sensors sampling at 60 Hz were placed on 14 body segments. Concurrently, 52 reflective markers (diameter 14 mm) were attached to the participant. The markers were tracked by eighteen T40/T20 Vicon cameras recording at 240 Hz. A total of 20 layup shots were performed, from the right at a 45° angle, 10 defended and 10 undefended, where defence was administered through a padded wooden stick. Raw marker data were labelled and filtered in Nexus 2.15 (Vicon Motion Systems Ltd, Oxford, UK) using a fourth–order zero lag Butterworth low pass filter at 10 Hz (Benjaminse et al., 2017). Joint angles were constructed using Bodybuilder code, with joint angles adjusted to match the Xsens' joint angle convention. The Vicon captured data were down-sampled to 60 Hz to match the Xsens data. Xsens data filtering and sensor fusion of the accelerometer, gyroscope and magnetometer data was achieved through the proprietary Xsens Kalman Filter. The start of the movement was defined at the instant following heel strike, of the step preceding the layup jump (0% of movement), and the end defined at the instant of ground contact on landing after ball release (100% of movement). Event detection was carried out manually and achieved through cross correlation of the acceleration profiles of the foot and toe segments. Whole-body COM location of the VICON data was computed using De Leva's (1996) anthropometric conventions to obtain 3D-coordinates of the COM pathway. COM velocity, which was used to calculate resultant jump take-off angle, was obtained from the numerical differentiation of the COM position data. Jump height was calculated as the difference between COM position in the vertical direction (z) at the maximum height achieved during the jump and the COM vertical position during standing. Take-off angle and jump height were compared using a paired sample t-test, absolute-agreement 2-way mixed-effect ICC and Bland-Altman plots, (SPSS Inc, Chicago, IL). Joint angle and COM data were compared using RMSE difference, and Statistical Parametric Mapping (SPM) analysis was employed to inspect the timing and duration of any differences. The statistical significance of all tests was assessed with an alpha level of 5%.

RESULTS AND DISCUSSION: The study assessed the accuracy of Xsens IMUs in capturing two groups of kinematic variables; discrete (jump height, take-off angle) and continuous (joint angles, COM displacement) for the basketball layup shot. The paired sample t-test found no significance difference in jump height and take-off angle between the two systems ((jump height (Vicon: 0.33 m (0.039), Xsens: 0.29 m (0.039), $p \geq 0.385$), take-off angle (Vicon: 43.6° (5.00), Xsens: 41.8° (5.2)), $p \geq 0.085$). This was also confirmed by the strong agreement in the Bland-Altman test plots (**Figure.1**, indicating most data points fell within the region of acceptable difference (highest agreement: 100%, lowest agreement: 90%), with the majority of subjects displaying no data points falling outside the limits of acceptable disagreement range. A mean offset of 0.016 m and 0.4° was found for jump height and take-off angle, respectively, between the systems. Excellent reliability was found for jump height (ICC = 0.95 (95%CI: 0.77-0.99), $p < 0.001$) and take-off angle (ICC = 0.96 (95%CI: 0.82-0.99) $p < 0.001$).

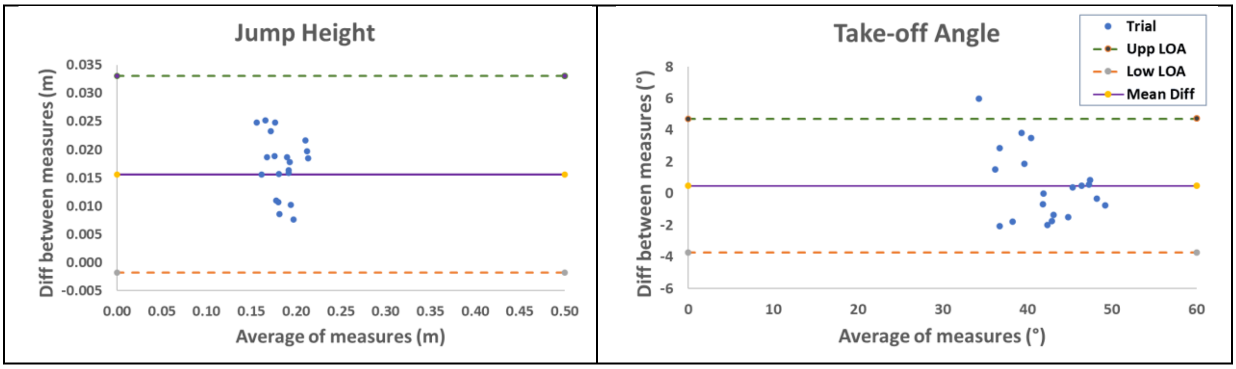

Figure.1. **Single subject example of the Bland-Altman plots of the jump height (meters) and take-off angle (°) data.**

Between-system offset (RMSE) were calculated for joint angles (**Table.1**). Sagittal shoulder joint angles exhibited consistently high RMSE levels, indicating potential inaccuracies (Right: 9.8°, Left: 9.6°). Although the time-series trajectories suggested overall consistency, occasional underestimation by Xsens was noted, particularly around ball release. Shoulder frontal and transverse plane angles demonstrated RMSE values ranging from 9.8° to 16.4°, 6.4° to 20.4° and from 5.2° to 9.5°, 5.5° to 17.1° for the right and left shoulder frontal and transverse planes motion, respectively. The validity of Xsens for detecting these complex motions of the mobile and multiplanar shoulder motion in layup shots cannot be confirmed due to high between-subject variability (Poitras et al., 2019). Similarly, inconsistencies were observed in hip frontal and transverse plane motions. Despite comparable sagittal hip angle waveforms, high error rates and significant SPM clusters questioned Xsens validity, contrary to previous findings for simpler, more planar jumping tasks (Al-Amri et al., 2018). In contrast, smaller joints (wrist and ankle) demonstrated lower RMSE values in sagittal plane motions (right wrist: 5.4°, left wrist: 5.2°, right ankle: 6.1°, left ankle: 6.9°). However, discrepancies in frontal wrist and ankle transverse plane motions were larger, potentially due to smaller ranges of motion and increased noise levels (Heuvelmans et al., 2022), or between-plane 'cross-talk' (Mok et al., 2015); a common phenomenon reported with studies featuring multi-planal complex movements. Despite relatively high errors in sagittal knee and elbow angles, the trajectories overall patterns remained similar. The differences may be in part be explained by the system’s different event detection methods, possibly introducing synchronization delays. The low sampling frequency of Xsens may present a limitation at higher speeds, however, the layup shot in this study was completed at a relatively low speed of 2.08 m/s (0.03), making it unlikely that the sampling frequency contributed markedly to the error rate. Xsens’ COM tracking (displacement in meters) during the layup shot was closest to Vicon in the vertical direction (z), with a 0.027 m (0.006) offset. The resultant horizontal displacement of the COM x and COM y had a mean 8% difference between the systems over roughly 2 m of total travel.

Table.1. **Offset between joint angles of both systems in degrees (º), presented as group mean (standard deviation) and the between-condition changes detected by each system and the offset between the systems; results of the jumping leg (right side).**

		Between-system **RMSE (°)**		Between-condition **RMSD (°)**		
Joint Angle		**Right Limb**	**Left Limb**	**XSENS**	**VICON**	**Offset***
Shoulder	**Sagittal**	9.8 (0.83)	9.6 (2.80)	**22.8**	**25.3**	**2.5**
	Frontal	11.9 (0.97)	7.1 (1.26)	**11.6**	**11.5**	**0.2**
	Transverse	12.2 (0.80)	10.8 (3.17)	**18.8**	**24.0**	**5.2**
Elbow	**Sagittal**	7.5 (0.81)	5.0 (1.39)	**18.5**	**18.3**	**0.2**
	Transverse	10.7 (0.95)	7.3 (1.20)	**17.5**	**21.2**	**3.8**
Wrist	**Sagittal**	5.4 (0.94)	5.2 (3.94)	**17.8**	**17.6**	**0.2**
	Frontal	5.4 (0.55)	4.5 (1.30)	**8.3**	**7.5**	**0.8**
Hip	**Sagittal**	10.1 (0.81)	10.3 (0.52)	**13.6**	**12.8**	**0.7**
	Frontal	8.5 (1.50)	8.0 (0.61)	**7.2**	**6.3**	**0.9**
	Transverse	7.8 (0.68)	8.2 (0.82)	**9.4**	**7.7**	**1.7**
Knee	**Sagittal**	7.4 (0.52)	8.0 (3.32)	**13.5**	**13.5**	**0.0**
Ankle	**Sagittal**	6.1 (0.38)	6.9 (0.73)	**9.7**	**9.1**	**0.6**
	Transverse	4.8 (0.54)	6.7 (0.67)	**5.0**	**4.1**	**0.9**

*Difference between the change detected by Xsens and change detected by Vicon when comparing defended to undefended conditions.

As a result of Xsens’ inability to conclusively replicate some joint angles, functionality was additionally assessed through examining Xsens’ consistency in the replication of Vicon’s detection of change between the defended and undefended conditions (**Table.1**). The between-condition analysis can classify joint angles into 3 categories: (1) similar changes are detected by both systems at the same time window/s across the time-series (**Figure.2 (A)**), (2) both systems detected similar changes between conditions but not at the same time window/s (**Figure.2 (B)**), and (3) high offset is found (above 5°) between the systems. The mean offset was 0.4°, with the highest in the transverse-plane shoulder angle, 5.2°, and lowest in the sagittal-plane knee angle,0.0°, while most joint angles showed difference of less than 1.0°.

Inherent distinctions in output between inertial and optical systems are inevitable, even during simpler tasks, owing to their distinct data tracking and capturing methods, calibration procedures and their underlying data processing algorithms. However, there are times when absolute accuracy of measures is not needed but the capacity to identify comparable magnitudes of technique changes under constraints that are relevant to the sport are. The Xsens performance was very similar to Vicon when changes between conditions were assessed. It seems likely that assessing changes in relative measures such as, angle-angle relationships, phase diagrams, relative timings etc, would be as reliable with Xsens as with Vicon even if some absolute kinematics are not.

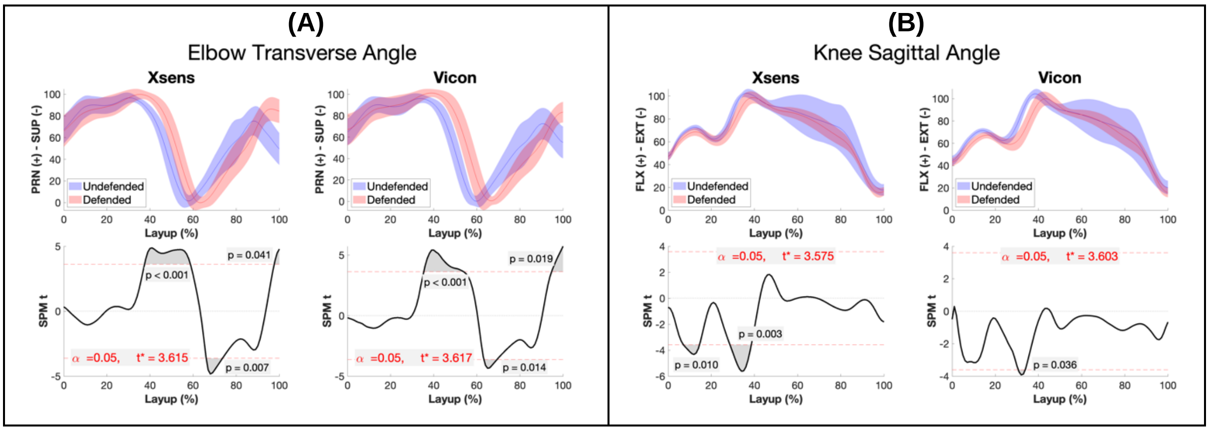

Figure.2. SPM plots of the between-condition difference (blue: undefended, red: defended) of the Xsens and Vicon systems.

CONCLUSION: While Xsens demonstrated reasonable accuracy compared to Vicon for smaller joint movements, its validity in capturing complex multi-planal motions, especially in the shoulder and hip during a layup shot, remains questionable. However, the consistency in changes between conditions for Xsens was generally comparable to Vicon and could be reliably used for such comparative measures with confidence. Future studies investigating system validity may find value in an approach that incorporates game conditions and game-specific constraints when addressing between-system difference, to make the assessment hold relevance to the specific nature of a sport.

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