WITHIN-SUBJECT REPEATABILITY AND BETWEEN-SUBJECT VARIABILITY IN POSTURE DURING CALIBRATION OF AN INERTIAL MEASUREMENT UNIT SYSTEM

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Inertial measurement units (IMUs) are a valuable tool for field based sports research, but within- and between-subject comparisons may be affected by variation in the 0° position established by a standing calibration position. This study assessed within-subject repeatability and between-subject variability in IMU sensor orientations during calibration. Calibration posture was reliable within-subjects given standardised instructions (typical error < 1.9°). Sensor angles relative to a global vertical axis had large between-subject ranges for upper spine (21–35°), lower spine (1–23°) and pelvis (11–35°), while lower limb segment angles had much lower variability (0-6°). Thus, a standing calibration posture is repeatable within participants given suitable instructions, however variability in standing posture may need to be accounted for before making between-subject comparisons, particularly with regard to spine and pelvis segments.

KEYWORDS: IMU, repeatability, calibration, variability.

INTRODUCTION: Inertial measurement units (IMU) are a practical field-based alternative to optical motion capture (OMC) systems for 3D motion capture, allowing researchers to assess technique in ecologically valid environments such as training and competition, as well as in research labs. Further, IMUs can facilitate research in elite athletes – whose scheduling often precludes lab testing outside their regular training program – during dynamic sports movements such as sprinting where absolute segment angles (eg. shin and trunk) are common technique measures. However, there may be certain constraints that must be considered before using IMUs. A wide range of IMU systems exist, with differences in both hardware and fusion algorithms. Consequently, the validity and reliability of each system needs to be considered separately and specifically in the context of the intended use.

The Noraxon MyoMotion IMU system (Noraxon, USA) has been shown to be valid and reliable compared to optical systems for static knee flexion angles (Balasubramanian, 2013), walking gait (Berner, Cockcroft, Morris, et al., 2020; Seidel et al., 2015), shoulder external rotation (Yoon, 2017) and trunk range of motion tasks and cricket bowling (Cottam, 2019). However, while Mundt et al. (2017), Berner et al. (2020) and Seidel et al. (2015) reported similar changes in direction and magnitude between IMU and OMC systems, there were differences between absolute angles reported by each system. These differences appear to stem from differences in the calibration procedures and models used by each system. IMUs are calibrated in a neutral standing posture to establish the 0° reference position in a local coordinate system, as opposed to OMCs that determine segment orientations based on anatomical landmarks in relation to the global coordinate system. As such, the calibration may introduce differences in the zero positions, which, if unaccounted for in the model, increase differences in absolute segment angles reported by IMUs and OMCs (Berner, Cockcroft, Morris, et al., 2020; Mundt et al., 2017). For IMUs, postural calibration is repeated before each trial recording – reducing potential drift error between each short trial typical in sprinting or cricket bowling. Participants therefore repeat calibration multiple times in performing multiple trials. Thus, reliability in performing the calibration position could have considerable influence on recorded segment angles for repeated trials. Standing posture may also vary across individuals, thus between-subject differences in angular recordings may simply reflect differences in their reference position and not a practically meaningful difference in technique.

Due to the influence of the calibration posture as the 0° position from which subsequent segment angles are determined, this study aimed to quantify the within-subject repeatability and between-subject variability of sagittal plane segment angles in the calibration posture in order to provide context for within- and between-subject comparisons made using this IMU system.

METHODS: Six participants (two male, four female) volunteered to be a part of this study (age = 23.7 ± 2.1 years, stature = 167 ± 2 cm, mass = 65.7 ± 7.5 kg). Ethical approval was provided by the institutional research ethics comittee. Tests were performed using a commercially available IMU system (MyoMotion, Noraxon, USA) sampling at 200 Hz. A synchronised sagittal plane video (Ninox-250, 100 Hz) recorded the calibration position. Video and IMU data were captured and processed using the MyoResearch 3.14 software (Noraxon, USA). Participants were fitted with nine IMU sensors attached to the upper spine (T1), lower spine (T12), pelvis (sacrum) and lateral aspects of each thigh, medial aspects of each shank and the dorsal surface of each foot according to the manufacturer's instructions. Sensors were secured with custom Velcro straps and double sided tape. For the lower limbs, the exact sensor placement was chosen to minimise sensor movement due to soft tissue artefact in order to reflect locations that would be used in research contexts such as sprinting or cricket bowling. Participants stood in an upright vertical posture on a calibration board which aligned the feet at hip width, facing forward. Participants were given standardised instructions to "maintain an upright, neutral posture with hands placed at the sides and head looking forward". Sensor calibration was performed in this position, after which participants were allowed to walk around freely as desired. After approximately one minute, they resumed the calibration position and maintained it for at least 30 seconds. This was repeated three times such that each participant recorded an initial calibration and three subsequent repeats of the calibration position.

Sensors recorded continuously from the completion of the initial calibration until the end of the third repeat of the calibration position, resulting in a single recording for each participant. Mean and standard deviation of the sagittal plane segment angle over a 20 second period was calculated for each repeat of the calibration position from IMU sensor recordings, a 20 second period was chosen as the initial calibration lasts 20 seconds. The measured angle during each repeat represented the change from the 0° established during the initial calibration.

To assess repeatability, typical error was calculated from this change according to Hopkins (Hopkins, 2000) for each repeat of the calibration position. Additionally, typical error was calculated from the change in angle between each repeat calibration (cal-3 vs cal-2, cal-2 vs cal-1). During the initial calibration and each subsequent repeat, the absolute angle of the upper spine, lower spine and pelvis sensors relative to a 0° absolute vertical was recorded using a mobile phone inclinometer application (Clinometer, plaincode app development, USA). Finally, sagittal plane angles of the right thigh (greater trochanter to lateral femoral condyle) and shank (lateral femoral condyle to lateral malleolus) segments during the initial calibration and each repeat were measured from the sagittal plane video digitised using the open source Kinovea software package (Kinovea 0.8.15).

RESULTS: Relative to the initial calibration, typical error ranged from 0.44° to 1.36° for the first repeat, 0.43° to 1.90° for the second and 0.56° to 1.38° for the third (Table 1). Typical error between repeats was similar, with ranges of 0.31 – 1.17° between repeat 1 and 2 and 0.24 – 1.00° between repeat 3 and 2.

Table 1: Typical error (°) values for each repeat of the calibration position relative to the initial calibration, between each repeat and overall mean typical error

Sensor	Cal - 1	Cal - 2	Cal - 3	Cal 2 - 1	Cal 3 - 2	Mean
Upper Spine	1.32	1.90	1.38	1.17	0.91	1.34
Lower Spine	1.36	1.49	1.37	0.75	0.55	1.10
Pelvis	1.28	1.39	1.32	0.58	0.51	1.01
Left Thigh	0.99	1.24	0.97	0.91	0.75	0.97
Right Thigh	1.12	0.98	0.27	0.58	1.00	0.79
Left Shank	0.47	0.43	0.56	0.42	0.65	0.51
Right Shank	0.44	0.54	0.56	0.31	0.24	0.42

Absolute sensor angles relative to the global 0° vertical for the trunk segment were variable between participants, ranging from 21 – 35° and 11 – 35° for the upper spine and pelvis sensors (anterior tilt) respectively and 1 – 23° for the lower spine (posterior tilt) (Figure 1A). Sagittal plane angles for the lower body segments were less variable, 0 – 6° and 0 – 5° for thigh and shank respectively and were closer to the absolute reference angle of 0°. Mean sagittal plane angles for the thigh segment were 3.2 ± 1.3°, 2.0 ± 1.7° and 2.5 ± 1.2° for the first, second and third repeat of the calibration position respectively. For the shank the respective values were 2.7 ± 1.0°, 2.5 ± 1.4° and 2.5 ± 1.5°.

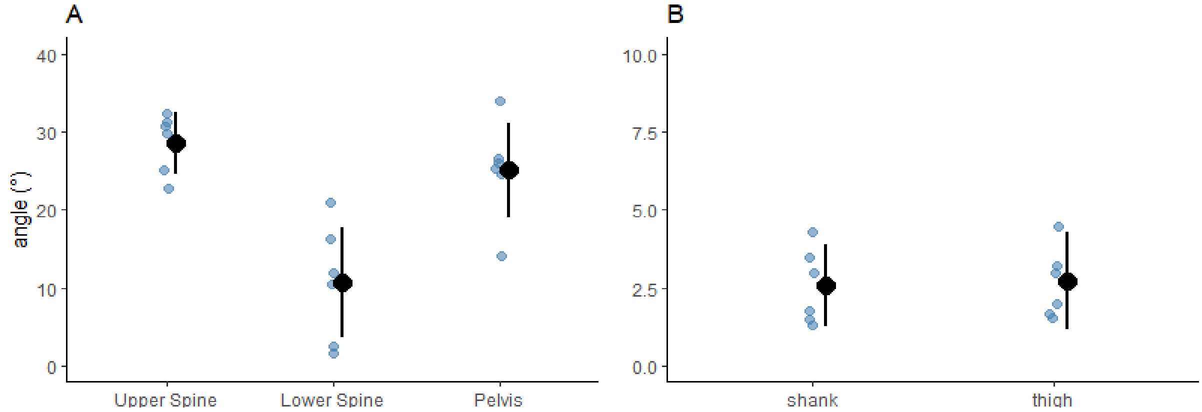

Figure 1: Mean, standard deviation and individual absolute angles relative to the global 0° vertical for (A) trunk segment sensors and (B) lower limb segments.

DISCUSSION: This study assessed the within-subject repeatability and the between-subject variability of the segment orientations of a standing calibration position in a commercially available IMU system. The calibration position was repeatable to less than 2.5° within participants when given standardised instructions. Between participants, sagittal plane sensor orientations of upper body segments varied by up to 23°, but the thigh and shank segment orientations were contained in a much narrower range of 6°. Repeats of the calibration position were characterised by low typical error values for each repeat relative to the initial calibration as well as between repeats, with all typical error values below 2°, for all segments (Table 1). This suggests that within-subject the calibration position can be reliably repeated given a calibration frame and a standardised set of instructions. These observations support results reported by Berner et al. (2020) who reported a similarly narrow range of joint and segment angles (SEM 0.3 – 2.2°).

The absolute angle of sensors for the upper spine, lower spine and pelvis deviated by as much as 35° from the 'true vertical' and showed large variation between participants (Figure 1). This may be due to greater degrees of freedom in the trunk compared to more distal segments closer the stable base of the feet or differences in the curvature of the spine and musculature of the upper back which may also influence sensor placement and orientation. These results align with those of Berner et al. (2020) which indicated that joint and segment angles for the pelvis and lower limbs in the calibration pose differed from 0° as measured by an OMC system, suggesting that , despite standardised instructions, differences in standing posture occur between different people. Thus caution is needed in making between participant comparisons for upper body segments based on IMU measurements alone. Depending on the research question, investigators may need to account for the differences in the reference position. For some research questions these differences may be advantageous - for example, if researchers are interested in participants' relative deviation from their standing posture rather than angles in absolute space. Sagittal plane angles of the thigh and shank were typically less than 3.2° from a true 0° vertical and within a narrow range (< 4°), less than the 5° limit for clinically meaningful differences suggested by McGinley et al. (2009), and in the context of a dynamic movement such as sprinting, similar to between-subject variation in peak thigh flexion and extension angles during maximal effort sprinting (standard error range 0.7-3.8°) reported by Clark et al. (2020).

Thus, between-subject sagittal plane lower limb segment angles are more similar than upper body segments in the standing posture. As such, researchers can have more confidence making between-subject comparisons in angles for these segments, however it may still be advisable to account for differences in the standing posture depending on the application and population.

This study had several limitations. Primarily, it had a small sample size and only considered sagittal plane segment orientations. Further research is needed to determine between-subject differences in other movement planes. Lastly, absolute sensor orientations were measured using a mobile phone application and digitisation rather than a gold standard OMC system.

Previous literature suggests that while IMU and OMC systems demonstrate similar trends and magnitudes in recorded angles, they measure something slightly different owing to differences in the reference position (Berner, Cockcroft, Morris, et al., 2020; Mundt et al., 2017; Seidel et al., 2015). The results here suggest differences in standing posture between participants may also require consideration. That said, the calibration position shows good within-subject repeatability. The Noraxon MyoMotion system presents a reliable method of assessing angular kinematics in the field, with accurate sensor tracking over time, and good within-subject reliability (Berner, Cockcroft, & Louw, 2020; Berner, Cockcroft, Morris, et al., 2020), offering researchers working with athletes in applied settings - where OMC systems are typically not a viable option - a reliable alternative for investigating 3D motion.

Researchers should be wary of the instructions and procedure during calibration and careful attention should be paid to the sensor attachment for the pelvis and spine. Depending on the goals of the research, differences in standing posture between participants may need to be accounted for before making between-subject comparisons.

CONCLUSION: A standing calibration position can be reliably repeated by participants when given standardised instructions and a suitable reference frame. However, this posture deviates from a true 0° relative to the global coordinate plane and may vary between participants, particularly in trunk segments. Researchers may need to account for differences in standing posture when using an IMU system to make between-subject comparisons, especially for the spine and pelvis.

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