A CALIBRATION PROCEDURE FOR MIMU SENSORS ALLOWING FOR THE CALCULATION OF ELBOW ANGLES

Denny Wells[1], Andrea Cereatti[2,4], Valentina Camomilla[3,4], Cyril Donnelly[1], Bruce Elliott[1] & Jacqueline Alderson[1]
[1]The School of Sport Science, Exercise and Health, The University of Western Australia, Perth, Australia
[2]University of Sassari, Sassari, Italy
[3] University of Rome ''Foro Italico'', Rome, Italy
[4] Interuniversity Centre of Bioengineering of the Human Neuromusculoskeletal System, Sassari, Italy

Non-optical wearable sensors such as magnetic and inertial measurement units (MIMUs) are gaining popularity in sport and clinical settings owing to their ease of application, relative affordability and potential for improved ecological validity. We propose a method for the standardised reference calibration of a simple two-sensor MIMU system for the estimation of anatomically meaningful elbow kinematics. The participant poses with the elbow at 90° flexion and neutral (0°) pronation, allowing for the relative orientation of the MIMU on the forearm to be determined with reference to the MIMU located on the arm. Comparisons were with traditional kinematic marker method results. Root mean squared errors of less than 1° in flex/ext and < 2° (pro/sup) found in simple movements. Results with simple movements provide rationale to expand research to complex movements.

KEY WORDS: inertial sensor, elbow, kinematics, standardisation.

INTRODUCTION: A number of studies have utilised multiple-sensor (accelerometer, gyroscope, magnetometer) information to collect data in sports such as cricket (Wixted and Portus, 2011) and golf (King et al., 2008); and in gait (Little et al., 2013), posture (Bonnet et al., 2012) and occupational settings (Zhou et al., 2008). While these studies have highlighted the efficacy in the adopting of multiple-sensor systems, there remains an overriding limitation pertaining to the determination of standardised and anatomically referenced kinematic outputs, serving to limit their applicability in research designs involving test-retest and between subject comparisons.

Such limitations can be addressed by devising a standardised calibration procedure that, in effect, provides a surrogate representation of segment based anatomical coordinate systems similar to those generated using traditional optically based three dimensional (3D) marker based modelling approaches. This has been attempted by previous researchers who have employed purpose built calibration devices (Picerno et al., 2008); an optimisation approach (Zhou et al., 2008); and several variants of a technique involving the arms hanging beside the body - assuming that the arms will hang parallel to the gravity vector such that it coincides with the long axis of the segment (de Vries et al., 2010, Galinski and Dehez, 2012). Although promising, the above approaches rely on the imprecise definition of initial sensor unit orientation to a segment's anatomical axis. Subsequently a calibration methodology that defines, references and stores the orientation of the sensor unit relative to its associated rigid anatomical segment (e.g. arm, forearm) is required to obtain standardised repeatable and anatomically meaningful joint kinematic descriptions.

In this study we propose an easily administered field based calibration protocol capable of estimating standardised elbow joint angles using a simple two sensor unit system.

METHODS: The methodology below was tested on a) a non-ferrous mechanical linkage representative of a human arm, and b) a single human participant (25 year old male, 178 cm, 82 kg).

Two magnetic and inertial measuring unit (MIMU) sensors (Xsens MTW) sampling at 75 Hz were mounted on the distal lateral upper arm and the distal posterior forearm (Figure 1). Each sensor also comprised of a triad of reflective kinematic markers rigidly attached for validation purposes Marker data was tracked and captured at 100 Hz using a 12 camera (MX and T-series) Vicon system. Both motion capture systems were synchronised to initiate data capture on a single signal such that all trials consisted of dual captured data from both systems. For the purposes of this paper, the MIMU methodology will be referred to as MIMU, whilst the stereo-photogrammetric, traditional kinematic marker approach will be referred to as Marker.

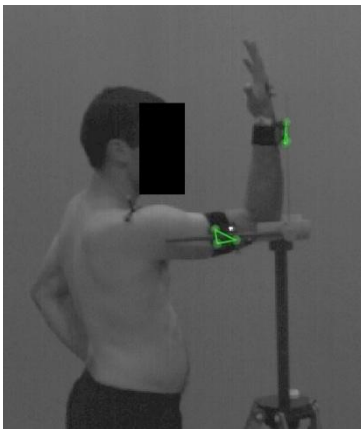

Figure 1: Participant in the calibration rig for the static trial. The kinematic markers are overlayed on MIMUs

The calibration procedure was the same for both the mechanical linkage and the participant and consisted of a single static trial (arm horizontal, forearm vertical, relative elbow angle 90° flexion, 0° pronation); and two functional trials (1. *elbow flexion/extension (FE)*: arm horizontal, forearm flexed and extended through a comfortable range of motion repeated five times; and 2. *elbow pronation/supination (PS):* arm horizontal, forearm flexed to 90°, forearm moved through a comfortable range avoiding the extreme ends of motion, again repeated five times). A non-ferromagnetic tripod was customised to aid in support and positioning of the arm and forearm in the required calibration poses.

The Mechanical Linkage was manually manoeuvred through three trials: pure FE, pure PS and combination of FE and PS. The Human Participant completed only pure FE and pure PS trials.

Marker method: data was processed and labelled using Vicon Nexus software (V1.8). Functional axes were calculated from the corresponding calibration trials and stored in the relative local co-ordinate system.

MIMU method: data was processed by the native Xsens (MT Manager V4.2) software (via inbuilt sensor fusion algorithms) to output each sensor's orientation and angular rate of turn data. The individual sensor unit relative orientations were calculated in the static trial position. The elbow joint was modelled as a two degree of freedom (DoF) joint. The direction of the elbow FE axis was determined with respect to the arm MIMU, whereas the direction of the pronation/supination PS axis was determined with respect to the forearm MIMU (Luinge and Veltink, 2005).

Elbow angles for both methodologies were obtained by decomposing the relative orientation of the MIMUs attached to the arm and forearm into two rotations about the FE and PS axes.

Comparison of MIMU derived time-varying waveforms with Marker waveforms was performed using a) root mean square error (RMSE), for each DoF for each trial, and b) statistical parametric mapping (Pataky et al., 2013) to compare all MIMU waveforms to all Marker waveforms, across each DoF.

RESULTS: For both the Mechanical Linkage and the Human Participant session trials, the FE joint angle displayed average RMSE values of < 1° across the two isolated movement studies (Table 1). PS angle output comparisons returned a maximum between 1.6° ± 1.5° for the same trials. The Combination Movement had in general a higher RMSE, with FE angle (1.7° ± 2.3°) again demonstrating less between system variance than the PS angle data (3.6° ± 3.1°).

Table 1: RMSE ± SD comparing derived elbow angles using Marker and MIMU datasets across the Mechanical Linkage and Human Participant conditions. (°)

Movement	**Flexion/Extension**		**Pronation/Supination**		**Combination Movement**	
DoF	Flex/Ext (°)	Pro/Sup (°)	Flex/Ext (°)	Pro/Sup (°)	Flex/Ext (°)	Pro/Sup (°)
Mechanical Linkage	0.5 ± 0.4	1.71 ± 1.2	0.7 ± 0.4	1.6 ± 1.5	1.7 ± 2.3	3.6 ± 3.1
Human Participant	0.4 ± 0.3	1.6 ± 1.1	0.7 ± 0.6	0.92 ± 0.5		

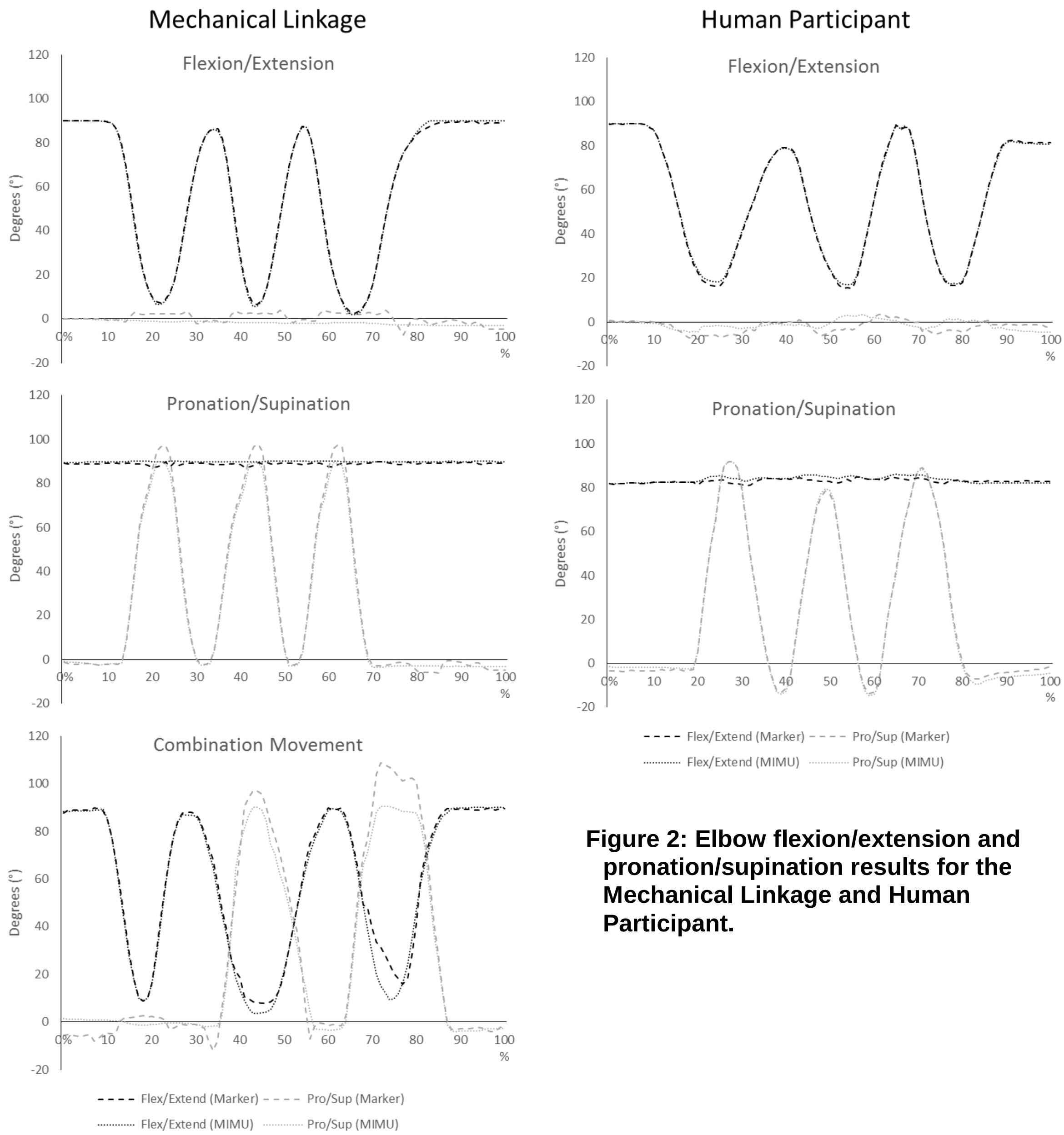

Figure 2: Elbow flexion/extension and pronation/supination results for the Mechanical Linkage and Human Participant.

Statistical parametric mapping found no areas of difference across the FE waveforms between the two methodologies. The mapping of the PS waveforms found a minor period of difference (p = 0.01) at approximately 90%, though this equated to only 2% of the total trial time.

DISCUSSION: The purpose of this study was to asses a calibration technique for MIMU sensors, capable of estimating elbow joint kinematics. The calibration procedure advances on previously published techniques through a more refined calculation of the orientation of sensor units to associated body segments. Although previous research has successfully used the MIMUs for orientation and positional information, extracting accurate joint kinematics has remained problematic. Currently published calibration procedures employ techniques with a high level of subjectivity (e.g. stand with arms by side). The nature of MIMU systems does require some level of compromise: the advantage of MIMU systems is the ability to capture data in-field, and as such the calibrations must also be able to be performed in-field. Unfortunately, some degree of subjectivity is unavoidable, as no technology currently exists for the completely objective aligning of anatomical axes outside of the laboratory.

The proposed calibration aims to reduce the level of subjectivity by placing the participant in a prescribed static pose (arm horizontal, elbow flexed to 90°) during sensor orientation

calculation. We acknowledge that this approach also involves some degree of subjective estimation of anatomical axis alignment.
The RMSE agreement between the two methodologies was high, indicating that the proposed MIMU calibration technique is capable of providing a standardised reference to derived joint angles. Although the agreement was high for elbow FE and PS, it was not surprising that the PS angles showed a lower RMSE agreement. It is the last DoF to be decomposed and long axis rotation is consistently found to be the most variable DoF when modelling long segments. The experiment conducted was designed as a proof of concept, and as such, more testing is required before the proposed calibration procedure can be recommended as a valid and accurate system for the estimation of elbow kinematics. However the results do show the system is capable of producing highly comparable elbow FE and PS angles (Figure 2) in both a constrained (mechanical linkage) system and a human participant, providing a basis for further research. The reliance on subjective anatomical axis alignment still exists and is acknowledged, but is unavoidable with current technology.

CONCLUSION: The calculation of MIMU derived functionally meaningful and standardised elbow joint angles is possible with the simple calibration procedure presented, designed to correctly define initial orientation of the sensor units relative to the associated segments of the arm. Such a procedure will increase the functionality and accuracy of multi-sensor systems for use with a broader user base and for a growing number of applications in sport and industry. The authors are currently testing the applicability of this approach in the assessment of cricket bowling actions in the context of delivery legality.

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