Accuracy of Inertial Motion Sensors in Static, Quasistatic, and Complex Dynamic Motion

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Inertial motion sensors (IMSs) combine three sensors to produce a reportedly stable and accurate orientation estimate in three dimensions. Although accuracy has been reported within the range of 2 deg of error by manufacturers, the sensors are rarely tested in the challenging motion present in human motion. Their accuracy was tested in static, quasistatic, and dynamic situations against gold-standard Vicon camera data. It was found that static and quasistatic rms error was even less than manufacturers' technical specifications. Quasistatic rms error was minimal at 0.3 deg (±0.15 deg SD) on the roll axis, 0.29 deg (±0.20 deg SD) on the pitch axis, and 0.73 deg (±0.81 deg SD) on the yaw axis. The dynamic rms error was between 1.9 deg and 3.5 deg on the main axes of motion but it increased considerably on off-axis during planar pendulum motion. Complex arm motion in the forward reaching plane proved to be a greater challenge for the sensors to track but results are arguably better than previously reported studies considering the large range of motion used.
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1 Introduction

Tracking of human kinematic motion has traditionally been accomplished via optoelectronic or electromagnetic systems that are tied to a lab-based setting. They require proximity to both software and hardware components making them unsuited for portable data collection in the field. Field testing is desirable from an ergonomic perspective because human kinematics can be recorded as they occur in their real-world environment and eliminate the cost of mock-up situations that do not adequately simulate the workplace. Until recently, field-based kinematic descriptions of human motion have relied on digital video, with its many known difficulties and two-dimensional limitations.

Lately, researchers have attempted to acquire consistent and stable three-dimensional human motion data from both accelerometers and gyroscopes [1–4]. Both systems have disadvantages that limit their utility in obtaining accurate human kinematic data: It is difficult to extract the acceleration due to motion from the effect of gravity using accelerometer data, while integrated angular velocity from gyroscopes is subject to a large amount of drift [5]. Several companies now produce units under a variety of acronyms inertial motion sensors (IMS), micro-electro-mechanical systems (MEMS), and inertial motion units (IMU) that use three technologies (accelerometers, gyroscopes, and magnetometers) along with proprietary filters and algorithms to provide drift-free and accurate orientation values [6–9].

Manufacturers of IMS report orientation values accurate to within 2 deg rms error in dynamic motion (Xsens Technologies, Enschede, The Netherlands); however, the reported accuracy of these next-generation inertial units has recently been questioned by Brodie et al. [10]. In pendulum motion, Brodie et al. [10] reported errors as high as 30 deg, which caused them to question the utility of the sensors in ambulatory settings. Notably, Luinge et al. [11] observed that arm motion during activities of daily living was associated with errors in excess of 40 deg, subsequently corrected with a constraint approach that dropped the error to 20 deg. In addition, Pfau et al. [12] reported errors as high as 5.4 deg when measuring horse trunk motion. Picerno et al. [13] used a calibration protocol akin to accepted stereophotogrammetric methods [14] with static errors as high as 8.3 deg for an upright posture and absolute errors across a gait cycle ranging from 3.0 deg to 21.7 deg. To date, experiments that challenge the sensors to track human motion using a gold-standard method of comparison are limited to a single gait stride, a slow box lifting task, and a few activities of daily living. This work will measure orientation accuracy during upper-body movements occurring within the entire reach envelope.

This technical note will demonstrate the accuracy of IMSs in reproducing static and quasistatic motion. It will also report the accuracy of simple pendulum motion and complex human dynamic motion when compared against a gold-standard optical tracking system.

2 Method

All testing was performed with the MTx version of the Xsens inertial motion sensor (Xsens Technologies, Enschede, The Netherlands) in an area known to be free of any large pieces of metal or other electromagnetic disturbances. Data were collected with manufacturer-provided software while data analysis was done with a customized LABVIEW program (National Instruments, Austin, TX) and Excel spreadsheets (Microsoft Office, Seattle, OR). Manufacturer default settings for the sensor fusion algorithm settings (weighting factor and filter gain) were used while the adapt to magnetic disturbance function was turned off for reported results. Investigations in our lab suggested that for optimal filter performance, the sensors required a settling period of 10 s prior to beginning a trial and this protocol has been accepted as common practice for all recording sessions. For the static, quasistatic, and dynamic pendulum trials, the global reset function was reset at the start of every trial. A static test was completed by holding the unit in a fixed orientation while quantifying the amount of drift that occurred on the three axes after a period of 10 min. The quasistatic testing mode was completed with one sensor attached to a rotating block affixed to a protractor with a fine arrow indicator (Fig. 1). The unit was zeroed (with the global reset function) at 0 deg and then moved to 10 deg and held stationary for 3 s before moving to the next measurement. Measurements were taken in 10 deg increments from 0 deg to 180 deg and repeated for three trials on three axes (roll, pitch, and yaw). rms errors for the quasistatic testing were averaged across trials and across the 19 increments from 0 deg to 180 deg.

The dynamic pendulum testing was completed in a 12-camera Vicon (Vicon PEAK, Oxford, UK) lab, calibrated with a previously reported spatial accuracy of 1 mm. For the first experiment, a single IMS unit was affixed to a suspended L-shaped form that allowed free pendular motion. Four retroreflective markers were also affixed to the structure in a noncollinear arrangement to determine orientation in x, y, and z axes from 3D Vicon coordinates. Three trials of pendulum motion of approximately 2 Hz lasting

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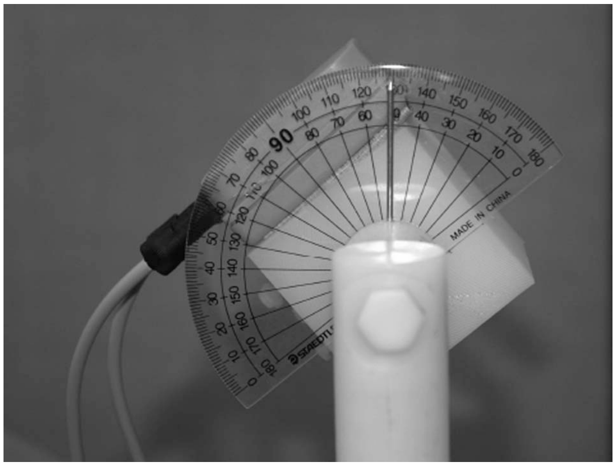

Fig. 1 IMS setup for static testing. Sensor is attached to rotating white block and rotated while the metal pointer indicated the orientation estimate on the protractor.

about 15–20 s each were recorded simultaneously in a trial lasting about 1 min, with the pendulum arm being stopped and started between trials. The IMS was tested with motion occurring along all three main axes using the same protocol. Since IMS data were sampled at 100 Hz and Vicon data at 120 Hz, the Vicon data were resampled in MATLAB to 100 Hz, and peaks were aligned using the correlation between the two signals. rms errors and correlation values were calculated for each trial and about all axes rotation (roll, pitch, and yaw).

Another experiment to test complex human motion consisted of sweeping arm motions within the subject's comfortable reach envelope using a six-camera Peak Motus optical system. Two trials of arm-only sweeping motion was followed by three trials of more complex sweeping and reaching movements that mimicked table washing and also included involvement of the trunk in the forward plane. One trial was completed to mimic a series of six asymmetric box lifts without actually picking up a physical box.

After obtaining informed consent for a protocol approved by the University Ethics Review Board, the subject was instrumented with at least three noncollinear retroreflective markers and one IMS unit on each segment of interest: lumbar spine, thoracic spine, head, right and left upper arm and forearm. A 10-s trial with the subject standing in a standardized soldier posture was recorded. The average 3D x,y,z retroreflective marker positions reconstructed from the optical camera system during the soldier trial were used to create a calibration coordinate system. A similar calibration coordinate system matrix was created for the IMS unit during the soldier trial. All subsequent trial data in both collection systems were expressed with respect to the calculated calibration matrices. The orientation of the segment was determined using a Cardan decomposition that extracted orientation angles in the order of decreasing range of motion [15]. The orientation estimates from both the optical system and IMS system were resampled to 60 Hz and aligned using correlation. Since the IMS world system could not be perfectly aligned with the Vicon global system, the method reported by Picerno et al. [13] was used to align the two curves with respect to the offset value between the two curves—calculated as the mean absolute error between the two curves. Once aligned, the dissimilarity of the curves was expressed using the rms error between the two aligned curves for the duration of each trial for all segment axes [13].

3 Results

All results for the static and quasistatic tests were considered to be within reason of the manufacturer's suggested ranges of error (Table 1). A 10-min static test yielded minimal drift of 0.09 deg (±0.05 deg SD) on the roll axis, 0.03 deg (±0.03 deg SD) on the pitch axis, and 0.84 deg (±0.38 deg SD) on the yaw axis—all values were considered negligible over the long testing period. The quasistatic testing trials yielded less than 0.30 deg rms error on the roll and pitch axes and 0.73 deg on the yaw axes. Dynamic testing for the pendulum motion yielded between 1.9 deg and 3.5 deg rms error on the main axes of motion. In addition, dynamic pendulum IMS orientation data were highly correlated with Vicon-derived orientation estimates (R^2 from 0.870 to 0.999) on the main axis of motion. There were no significant differences across the three trials, and data were subsequently averaged to produce error estimates along each dominant axis of motion (Table 2). Error estimates along the nondominant axes of motion were higher when averaging across trials, ranging up to 9.4 deg (Table 2). A typical pendulum motion depicting one trial of motion on dominant and nondominant axes is presented in Figs. 2(*a*)–2(*c*); although substantial, the increasing drift from the inertial sensor on the nondominant axis as time progressed was not significant across trials. Maximal rms error averaged across trials was 10–14 deg on the dominant axis but increased as high as 38 deg on the nondominant axis.

Orientation error in trunk segments (lumbar, thorax, and head) during the arm sweep trials remained less than 2 deg error but increased to about 4 deg on all axes during the table washing trials. Some individual angular estimates of error were as high as 17 deg for trunk segments. The range of angular motion occurring in the arm for both trials (sweeping and table washing) was much higher than in the trunk as demonstrated in Fig. 3. The absolute value of corresponding rms error was higher in right arm segments compared with the observed trunk error. Sweeping trials ranged between 3 deg and 9 deg rms on all axes for the right arm with even greater increases (>10 deg and as high as 26 deg) recorded for table washing trials. Instances of maximal error for the arm segments reached >30 deg in some trials.

During motions that mimicked asymmetric lifting tasks, trunk estimates of error increased substantially compared with the sweeping and reaching trials, which typically limited trunk motion to the sagittal plane. For the head, lumbar, and thorax segments, rms ranged from 5 deg to 14 deg with maximal error reported at 31 deg for the head (Table 3). Similarly, the arm segments had increased levels of rms error across the lifting trial, typically between 8 deg and 13 deg but error on some axes was >20 deg. However, this range of error represented at most, about 22% of the total range of motion for the arm segments and about 8–23% of the trunk range of motion.

Table 1 Mean rms errors (deg) (standard deviation) for roll, pitch, and yaw axes

	Roll	Pitch	Yaw
Static	0.09 deg (±0.09)	0.03 deg (±0.03)	0.84 deg (±0.38)
Quasistatic	0.30 deg (±0.15)	0.29 deg (±0.20)	0.73 deg (±0.81)

Table 2 Mean rms errors (deg) (standard deviation) for all axes (dominant and nondominant) during pendulum trials. Dominant motion is in boldface.

	X	*Y*	*Z*
Roll	**2.0 deg (±0.17)**	4.0 deg (±1.6)	0.8 deg (±24.11)
Pitch	2.5 deg (±0.35)	**1.9 deg (±0.08)**	8.8 deg (±7.0)
Yaw	3.2 deg (±0.53)	9.4 deg (±0.38)	**3.5 deg (±0.26)**

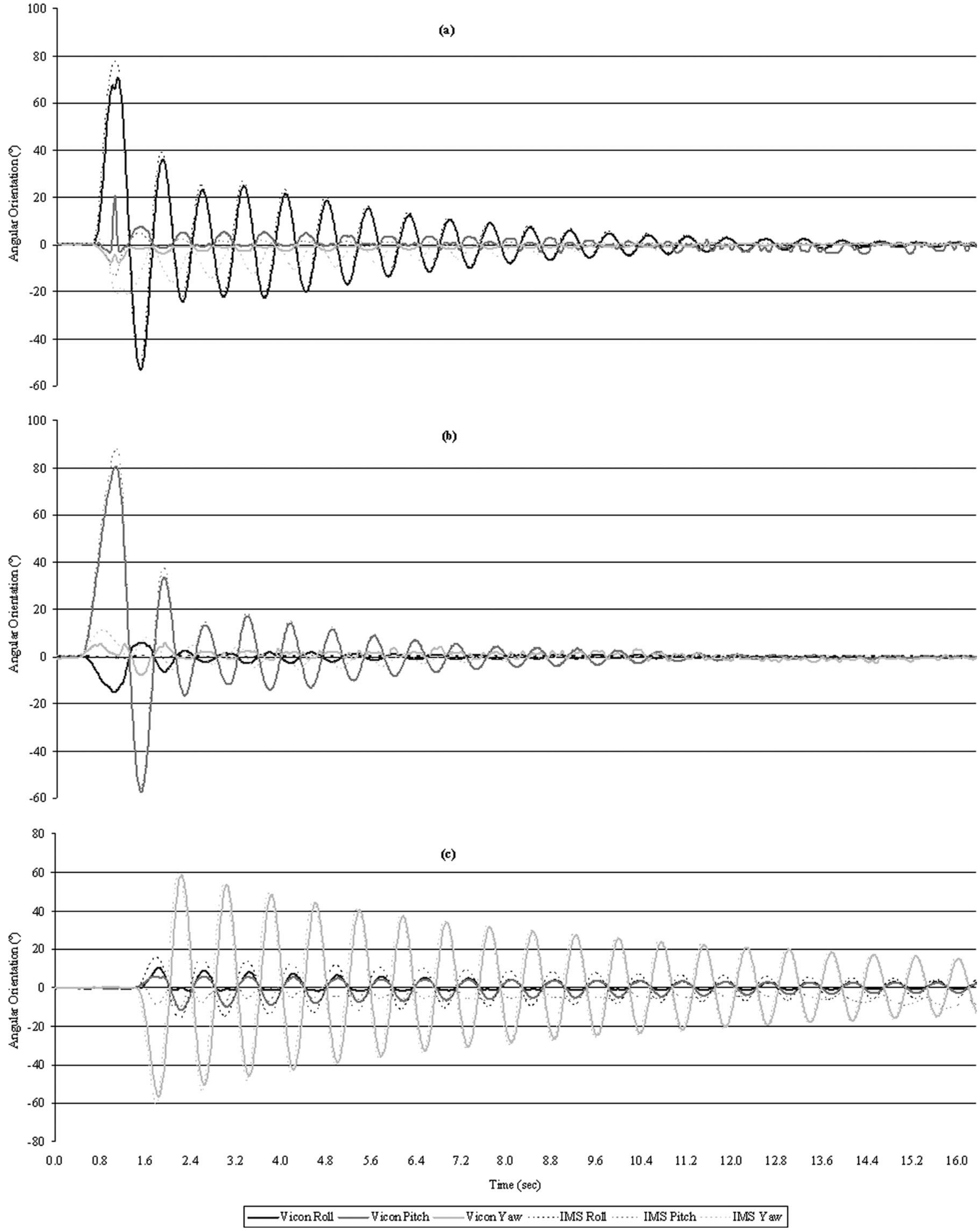

Fig. 2 Angular orientation time series from gold-standard Vicon estimate versus IMS during pendulum motion occurring about dominant axis of (*a*) roll axis, (*b*) pitch axis, and (*c*) yaw axis

4 Discussion

Quasistatic testing of the IMS against gold-standard data demonstrated that manufacturer claims for rms errors are within reason—this experiment produced a similar amount of negligible rms error of 0.44 deg averaged across all three axes. Furthermore, in simple pendulum motion about each axis of the sensor, the sensors performed as advertised (<2 deg error) by manufacturers (Xsens Technologies, Enschede, The Netherlands) on two of the dominant motion axes and only slightly higher on the yaw axis (3.5 deg rms error). These results are considerably better than the results found by Brodie et al. [10], who observed rms errors across the trial as high as 11.7 deg when using the proprietary Kalman filter, in addition to a peak error of 30 deg. When considering the error occurring on the nondominant motion axis, mean rms error increased to as much as 9.4 deg rms error in addition to a peak maximal error of 38 deg. The range of movement in our experiment was slightly less (maximal amplitude between 60–80 deg) and the duration was slightly less (~45 s) than in the Brodie et al. [10] experiment, which may have impacted our results favorably. Brodie et al. [10] also observed that error accu-

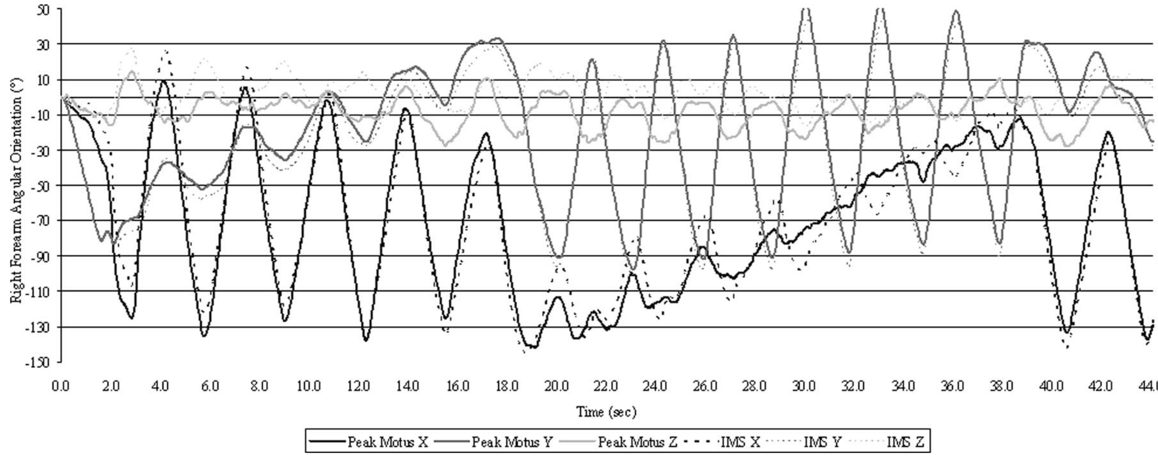

Fig. 3 Angular orientation in three dimensions of the forearm performing a back and forth, up and down sweeping motions in the forward reach space envelope of the subject

mulated across time, but that stopping and starting the sensors could eliminate that tendency and improve the angular estimate. Despite the same start and stop method used in this experiment across the three trials, considerable drift appeared on a nondominant axis for trials involving primarily roll and pitch motions. A working knowledge of the sensors' performance over time will help to develop calibration routines that will maximize orientation estimates in long-duration collections.

A field-based motion capture device must have the ability to accurately capture large ranges of motion during complex movements of many different segments. For this reason, a dynamic arm sweep test and table washing task was used to test the ability of the sensors to capture upper-body movement within the extreme reach space envelope: up-down, side-to-side, and forward-backward. Although rms errors for arm segments in our experiment are generally larger than previously reported, the motion also involved a much larger range of reach motion than previously measured. During these tasks, orientation error using the IMS unit on the upper arm and forearm was as high as 46 deg but typically between 3 deg and 15 deg for a movement that had a range of motion close to 100 deg on two axes. In a motion involving lower body segments with a much smaller range of motion, Picerno et al. [13] tracked a gait cycle with an IMS and found rms errors as high as 21.7 deg for the internal-external rotation measure, representing 32.5% of the range of motion. In the sweeping trials used in our experiment, where the trunk segments moved very little (range of motion is 25 deg), rms was reported between 1 deg and 4 deg rms error for all segments and all axes.

The error in this experiment was similar to that reported by Pfau et al. [12] when using IMS units to measure trunk motion from a horse in walk, trot, and canter motions and not unlike the results presented by Picerno et al. [13] for a walking gait. The final trial of more complex motion used in our study (asymmetric lifts) resulted in larger absolute values of rms error. However, when presented in the context of a percentage of the range of motion, the upper end of the error range was roughly 23% of the

Table 3 Mean rms error in orientation (deg) of segment during complex dynamic motion

		rms error			Maximum rms error		
Motion	Segment	*X* axis	*Y* axis	*Z* axis	*X* axis	*Y* axis	*Z* axis
Sweep	Lumbar	1.4	1.3	1.0	5.7	6.3	5.1
	Thorax	2.3	1.5	3.8	5.8	4.6	10.3
	Head	1.7	1.3	0.7	5.2	5.6	3.5
	Right arm	12.7	8.9	25.5	34.1	30.8	53.9
	Right forearm	8.6	2.2	5.6	19.4	6.5	19.3
	Left arm	2.8	3.3	2.8	11.5	13.3	10.9
	Left forearm	1.0	0.6	1.8	5.8	2.5	7.0
Table wash	Lumbar	4.1	3.5	2.0	12.5	10.5	8.1
	Thorax	4.0	3.4	6.0	13.1	7.7	17.4
	Head	2.2	3.0	9.8	12.8	11.0	40.6
	Right arm	14.8	12.4	25.6	45.8	39.5	64.1
	Right forearm	9.7	6.3	13.4	30.6	19.2	38.1
	Left arm	7.1	9.3	12.1	31.8	32.3	64.5
	Left forearm	4.5	3.5	2.9	17.6	14.6	14.1
Asymmetric lifting	Lumbar	5.5	9.8	11.2	12.9	26.3	26.2
	Thorax	4.9	6.9	12.4	15.4	17.1	32.1
	Head	11.7	6.3	14.4	30.9	18.4	47.1
	Right arm	9.6	13.1	17.1	33.1	33.2	55.5
	Right forearm	9.6	11.1	19.4	28.1	30.2	59.1
	Left arm	12.9	16.2	23.6	49.8	42.2	74.2
	Left forearm	7.8	9.5	20.9	24.4	30.7	65.2

range of motion for the task. It was noted that the orientation error tended to peak at times when the segments were changing direction, particularly evident on the *X* and *Y* axes in Fig. 3. Zhou and Hu [16] previously noted this phenomenon in conjunction with inertial motion sensors and attributed it to overshoots of the inertial sensors during periods of fast orientation change. The back and forth motions of the sweeping and table washing trials used in this experiment likely resulted in the magnified error at points when the segments would be reversing direction. Additionally, the quasistatic and pendulum trials demonstrated considerably more error and drift on the nondominant yaw axis, which might speak to the ability of the sensors and algorithm to detect and use gravity to produce accurate orientation estimates. The quality of the Kalman filter has also been questioned due to its focus on predicting orientation from motion with a known Gaussian-error distribution [10,17].

Compared with lab-bound systems with well-established sources of error, IMSs demonstrate motion-dependent error [10,11] that would not be acceptable for lab-based investigation. Additional sources of error that must be controlled to produce better orientation estimates include soft-tissue artifact and positioning of the sensors with respect to the anatomical axes in the calibration frame. The assumption used in this experiment was that the anatomical axes were aligned with the world coordinate system during the calibration pose and a rotation matrix was used to describe this pose. Recently, several works have advocated the need for a more sophisticated calibration strategy [11,13,18,19]. Additionally, when calibrating the IMS system in a second externally referenced system, the researcher must take care to align the two world systems. In the current work, an extra IMS was situated at the origin of the lab-based system, which allowed transformation of coordinates collected in one space to be expressed in the second world space. However, as noted by Rachid et al. [20], it is possible that systematic misalignment between the two world coordinate systems may induce additional error into the orientation estimates of the IMS units. Future work should aim to properly align all orientations of the lab coordinate system with the Xsens world coordinate system. The IMS system was attached to the segment of interest using an elastic cuff and Velcro system. However, considerable extraneous movement was observed between the IMS and the underlying segment and large amounts of adhesive tape were used to minimize that error. A more secure system would be required for field-based studies. Despite these current limitations, ongoing development may reveal that IMS units produce acceptable levels of motion tracking for ambulatory studies of human motion.

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