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Accuracy and repeatability of single-pose calibration of inertial measurement units for whole-body motion analysis

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Highlights

- The T-pose with passive placement was more accurate for MVN model calibration.
- The chair-pose shows potential to increase the accuracy of IMUs calibration.
- Different single-pose calibrations showed similar repeatability.
- Similarity to laboratory motion analysis increased with passive placement of the subject.

Abstract

Portable inertial measurement units (IMUs) are suitable for motion analysis outside the laboratory. However, IMUs depend on the calibration of each body segment to measure human movement. Different calibration approaches have been developed for simplicity of use or similarity to laboratory motion analysis, but they have not been extensively examined. The main objective of the study was to determine the accuracy and repeatability of two common single-pose calibrations (N-pose and T-pose) under different conditions of placement (self-placement and passive placement), as well as their similarity to laboratory analysis based on anatomical landmarks. A further aim of the study was to develop two additional single-pose calibrations (chair-pose and stool-pose) and determine their accuracy and repeatability. Postures and movements of 12 healthy participants were recorded simultaneously with a full-body IMU suit and an optoelectronic system as the criterion measure. Three repetitions of the T-pose and the N-pose were executed by self-placement and passive placement, and three repetitions of the chair-pose and stool-pose were also performed. Repeatability for each single-pose calibration showed an average intraclass correlation coefficient for all axes and joints between 0.90 and 0.94 and a standard error of measurement between 1.5° and 2.1°. The T-pose with passive placement is recommended to reduce longitudinal axis offset error and to increase similarity to laboratory motion analysis. Finally, the chair-pose obtained the least longitudinal axis offset error amongst the tested poses, which shows potential for IMU calibration.

Keywords: inertial sensor; calibration; pose; error; motion analysis; precision

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1. Introduction

Thanks to recent improvements to technologies, including greater ease of setup, inertial measurement units (IMUs) can be used outside the laboratory for gait or motion analysis in clinical, sports and ergonomics settings [1-4]. Since the positions of anatomical landmarks are unknown with IMUs, calibration is needed to establish the relationship between the sensor and body segment orientation. The most common calibration approaches rely on single-pose [5, 6], double-pose [5, 7], technical placement of the IMUs on the segments [4, 8], functional movement [1, 9] or combination of single-pose and functional movement [8, 10, 11]. In addition, calibration devices equipped with IMUs were developed to estimate anatomical axes based on landmark palpation [2, 12]. Ideally, the calibration approach should be simple, accurate and precise. Previous studies have presented only one approach [2, 4, 6, 12] or a few joints [1, 7, 8, 10, 11], hence the choice of calibration method remains problematic, especially for whole-body motion analysis.

A few studies have evaluated the reliability of different calibration approaches or their similarity to laboratory motion analysis [8, 10, 11], but accuracy is usually not considered in the calibration recommendations. Commercial software such as MVN offer two different standing static single-pose calibrations, T-pose and N-pose, which have the advantage of being fast and simple for calibrating all body segments simultaneously [5, 6]. However, the accuracy and repeatability of single-pose calibration has not been thoroughly tested. The condition of placement is often based on an image shown to the subject, who replicates the posture [5, 6, 9]. It remains unclear whether an experienced operator passively placing the subject would be beneficial to the calibration. In addition, human anatomy is often neglected in the premise of calibration poses. For example, the lateral deviation of the lower arm renders its alignment with the upper arm difficult when the elbow is fully extended [13], and vertical placement of the upper arms as in the N-pose would require them to penetrate the thorax [14]. Postures involving many 90° joint angles may be more convenient for individuals to execute during calibration and may increase accuracy and repeatability [13]. Moreover, the human eye can identify small deviations from a 90° angle [15].

The main objective was to determine the accuracy and repeatability of the T-pose and N-pose with self-placement and passive placement of the subject. The hypothesis was that the T-pose would be more accurate than the N-pose and that passive placement would increase accuracy. Additionally, seated static postures were developed and hypothesized to increase accuracy and repeatability based on the many joints at 90°. The secondary objective was to determine the similarity of the joint angles obtained from IMU calibration with those resulting from anatomical landmarks as per the International Society of Biomechanics (ISB) recommendations [16, 17].

2. Materials and methods

2.1 Subjects

Before participating, the 12 participants (9 men, 3 women, age 26.3 ± 4.4 years, height 171.4 ± 6.8 cm and weight 74.4 ± 18.3 kg) completed a consent form approved by the Université de Sherbrooke Ethics Committee. The inclusion criterion was the absence of self-reported bone, joint and musculoskeletal disorders during the last year.

2.2 Instrumentation

Whole-body kinematics were recorded at 30 Hz with an 8-camera Optotrak system (Northern Digital Inc., Ontario, Canada) and a full-body Xsens system (MVN, Xsens Technologies, Enschede, Netherlands), simultaneously. The systems were synchronized using MVN Studio 3.5 with a trigger signal coming from the Optotrak system. The Xsens system is composed of 17 IMUs over the feet, shanks, thighs, pelvis, sternum, head, scapulae, upper arms, forearms and hands (Fig. 1). To reduce soft tissue artefact, the IMUs were strapped over bone rather than muscle, wherever possible. A four-LED Optotrak cluster was rigidly affixed to the top of each IMU with Velcro and tie-wrap (Fig. 1). Wires were securely attached around the waist to ensure freedom of movement and reduce load on the limbs. The Xsens IMUs were connected to each other and to two Xbus devices attached at the waist, which transferred the data wirelessly.

2.3 Experimental protocol

Anthropometrics including height, shoe sole height, arm span, shoulder width, foot length, ankle height, knee height, hip height and hip width were gathered for each subject. Anatomical landmarks respecting the ISB recommendations were then identified with a probe from the Optotrak system with the subject in a supine static neutral position.

The two calibration poses available with the MVN model were executed three times in random order under two conditions of placement: first, a picture of the T-pose or the N-pose (Fig. 1) was shown to the subject, who was asked to replicate and hold the pose without further instructions (self-placement). Second, the subject was passively placed by the operator, who asked the subject to maintain the posture.

Three repetitions of manual material handling task involving turning gait were executed by the subjects after each T-pose or N-pose calibration. The subjects were standing on a rectangular platform (size 130 × 190 × 18 cm). Two stations were set up at opposite corners of the platform, one at a height of 106 cm and the other at 14 cm. An empty box (size 26 × 33 × 34 cm, mass 500 g) was moved from the first station to the second and then returned to the first station.

Two additional postures were tested three times for their potential as a calibration pose, using only the optoelectronic system since they could not be used in the MVN model. A wooden chair was built with adjustable armrests to standardize the seating posture we named the chair-pose. The operator positioned the subjects with feet pointing forward and ankles flexed at 90°, shanks vertical, thighs pointing forward with knees and hips flexed at 90°, trunk straight, upper arms abducted to 30° and resting on the adjustable armrest, elbows flexed at 90°, lower arms pointing forward and resting on the adjustable arm rest, and wrists straight with fingers pointing forward. A similar posture named the stool-pose was tested, where the subjects were placed on a wooden stool and held the same position as the chair-pose, except for the arms, which were abducted to 90°. For both the chair-pose and the stool-pose, foam boards of different thicknesses were used to adjust the height of the lower limbs.

2.4 Biomechanical models

Two segmental biomechanical models were used in accordance with a recent study [3]. The first one, which we call the ISB model, used the CAST protocol [18] to construct anatomical coordinate systems with anatomical landmarks and joint centres in line with the ISB guidelines [16, 17]. The second model, MVN, is included in the Xsens commercial software. It uses anthropometric measures to estimate segment lengths according to regression equations [6]. The calibration can only be done with either the T-pose or the N-pose, during which time the relationship between each IMU and segment orientation is established [6].

2.5 Data analysis

To compare IMU data with optoelectronic system data, the local coordinate systems of each segment must be aligned. A method relying on angular velocities [19] was used to align the coordinate systems of the two systems, as recommended [20].

The calibration poses are based on the assumption that the posture in question is perfectly executed by the subject. Many assumptions were selected and verified with the optoelectronic system. For all poses, back, head and lower legs were oriented along the gravity vector and ankles were flexed at 90°. For the T-pose, knees and elbows were fully extended and arms were abducted to 90° (Fig. 1). For the N-pose, knees and elbows were fully extended and arms were elevated to 0° (Fig. 1). For the chair-pose and stool-pose, the assumptions were based on the postures defined in the experimental protocol (Fig. 1). The previous assumptions were verified with segment orientations relative to the vertical orientation of the global coordinate system in Optotrak, which corresponds to the gravity vector. Accuracy was evaluated on the basis of the difference between the longitudinal axis of the body segment and the vertical axis of the global coordinate system. A perfectly executed calibration pose would provide angles of 0° or 90°. The absolute difference was used for data comparison to obtain the segment longitudinal axis offset error from the calibration pose.

Following the T-pose or N-pose, during the manual material handling task, joint angles were calculated following the Z-X-Y sequence of Euler angles, with the exception of the shoulder, for which the X-Z-Y sequence was used. The difference in segment orientations between the ISB and MVN models was calculated on the three axes (X frontal axis, Y longitudinal axis and Z transverse axis).

Separate two-way repeated-measures analyses of variance (ANOVAs) were conducted to contrast the longitudinal axis offset error on the 15 body segments. The two factors were calibration pose (N-pose and T-pose) and condition of placement (self-placement and passive placement). The repeatability of the results for the three repetitions of each calibration posture was measured on the joint angles with intrarater within-day intraclass correlation coefficient (ICC (3, 1)) and 95% confidence intervals. In addition, the standard error of measurement (SEM) was calculated as the square root of the mean square error term from the two-way ANOVA. The SEM estimates the dispersion of the repeated measures of a posture in degrees. Separate two-way repeated-measures ANOVAs were also conducted to contrast the orientation difference between the ISB and MVN models on the three axes and 15 body segments with the same factors (calibration pose and condition of placement). Only the upper limb segments were analyzed for the calibration pose factor, since there was no difference in the calibration approach for the other body segments. The mean of the three repetitions was used for statistical analysis of the segment longitudinal axis offset error and the difference in segment orientation. The data were pooled for the right and left limbs as the postures were symmetrical, and the significance level was set to $\alpha = .05$.

3. Results

3.1 Longitudinal axis offset error

The T-pose systematically decreased the longitudinal axis offset error on the upper limbs compared to the N-pose, with a mean ± SD of 6.5° ± 4.7° and 12.9° ± 4.4° respectively (Fig. 2). A main effect of calibration pose was revealed on the forearm ($F_{1, 11} = 82.145$, $P < .001$) and upper arm ($F_{1, 11} = 12.182$, $P = .05$). The longitudinal axis offset error decreased when the subjects were passively placed compared to having a picture shown to them with mean ± SD on all body segments of 8.1° ± 3.9° for self-placement and 6.6° ± 3.3° for passive placement (Fig. 2). A main effect of condition of placement was observed on the forearm ($F_{1\ 11} = 23.454$, $P = .001$), upper arm ($F_{1, 11} = 28.347$, $P < .001$) and pelvis ($F_{1\ 11} = 5.674$, $P = .036$). An interaction between calibration pose and condition of placement was observed on the forearm ($F_{1\ 11} = 10.821$, P = .007), upper arm ($F_{1\ 11} = 5.161$, P = .044) and head ($F_{1\ 11} = 8.538$, P = .014).

The chair-pose and stool-pose showed a longitudinal axis offset error similar to that of the other poses for the head, trunk and lower limb. Nevertheless, the chair-pose obtained the highest accuracy values for the upper limb.

3.2 Repeatability of calibration poses

The average of all axes and joints for each single-pose calibration showed ICC between 0.90-0.94 and SEM between 1.5-2.1°. The ICC 95% confidence intervals of the calibration poses were overlapping in most cases (Fig. 3). An exception was observed where the chair-pose and stool-pose showed better ICC on the longitudinal axis of the knee. The SEM values were generally under 3° and few notable differences were observed between the calibration poses (Table 1). However, the SEM values were higher for the upper limb joints compared with the other joints.

3.3 Similarity between MVN and ISB models

The difference in orientation between the MVN and ISB models was not significant on the upper limb segments for all axes ($P > .05$) for calibration pose (Fig. 4). When the subject was passively placed, the difference between the two models was significantly reduced compared to self-placement for the hand ($F_{1\ 11} = 5.269$, $P = .042$), forearm ($F_{1\ 11} = 5.327$, $P = .041$) and head ($F_{1\ 11} = 8.648$, $P = .014$) on the transverse Z axis, for the forearm ($F_{1\ 11} = 58.326$, $P < .001$), upper arm ($F_{1\ 11} = 50.288$, $P \leq .001$), lower leg ($F_{1\ 11} = 5.045$, $P = .046$) and upper leg ($F_{1\ 11} = 12.769$, $P = .004$) on the frontal X axis and for the hand ($F_{1\ 11} = 30.517$, $P \leq .001$) and foot ($F_{1\ 11} = 8.472$, $P = .014$) on the longitudinal Y axis (Fig. 4). No significant interaction between calibration pose and condition of placement was observed ($P > .05$).

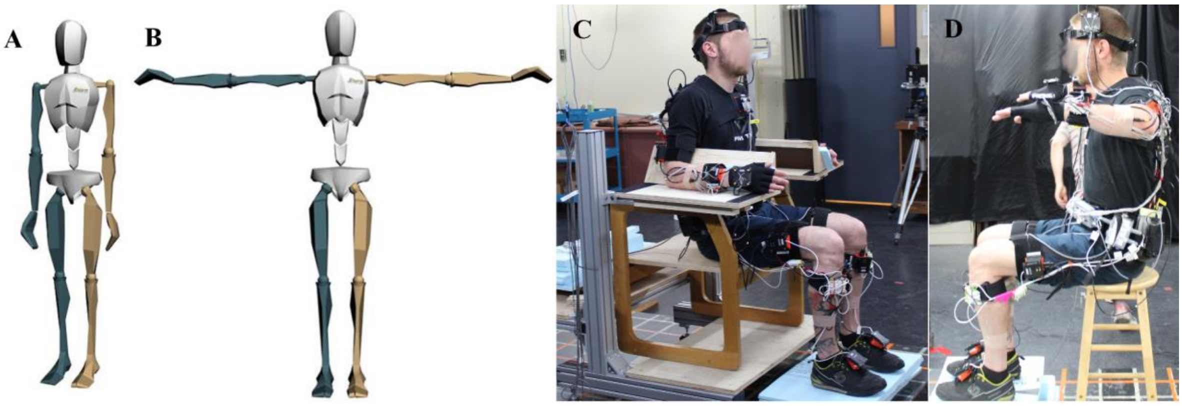

Figure 1. MVN commercial software single-pose calibrations: N-pose (A) and T-pose (B). Subject setup with the 17 Xsens inertial measurement units (IMUs) and Optotrak marker clusters affixed to the top of each IMU, shown during the additional calibration poses, namely chair-pose (C) and stool-pose (D).

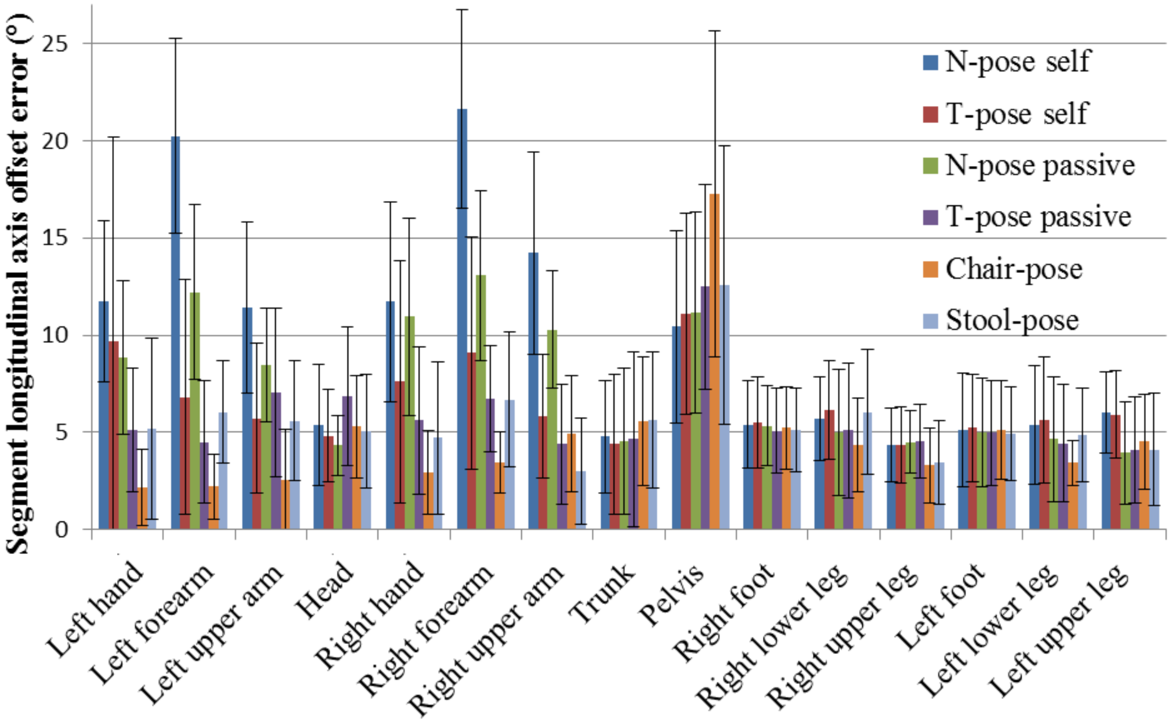

Figure 2. Segment longitudinal axis offset error (mean ± SD) on all body segments during the N-pose and T-pose with their two conditions of placement (self-placement and passive placement) and during the chair-pose and stool-pose.

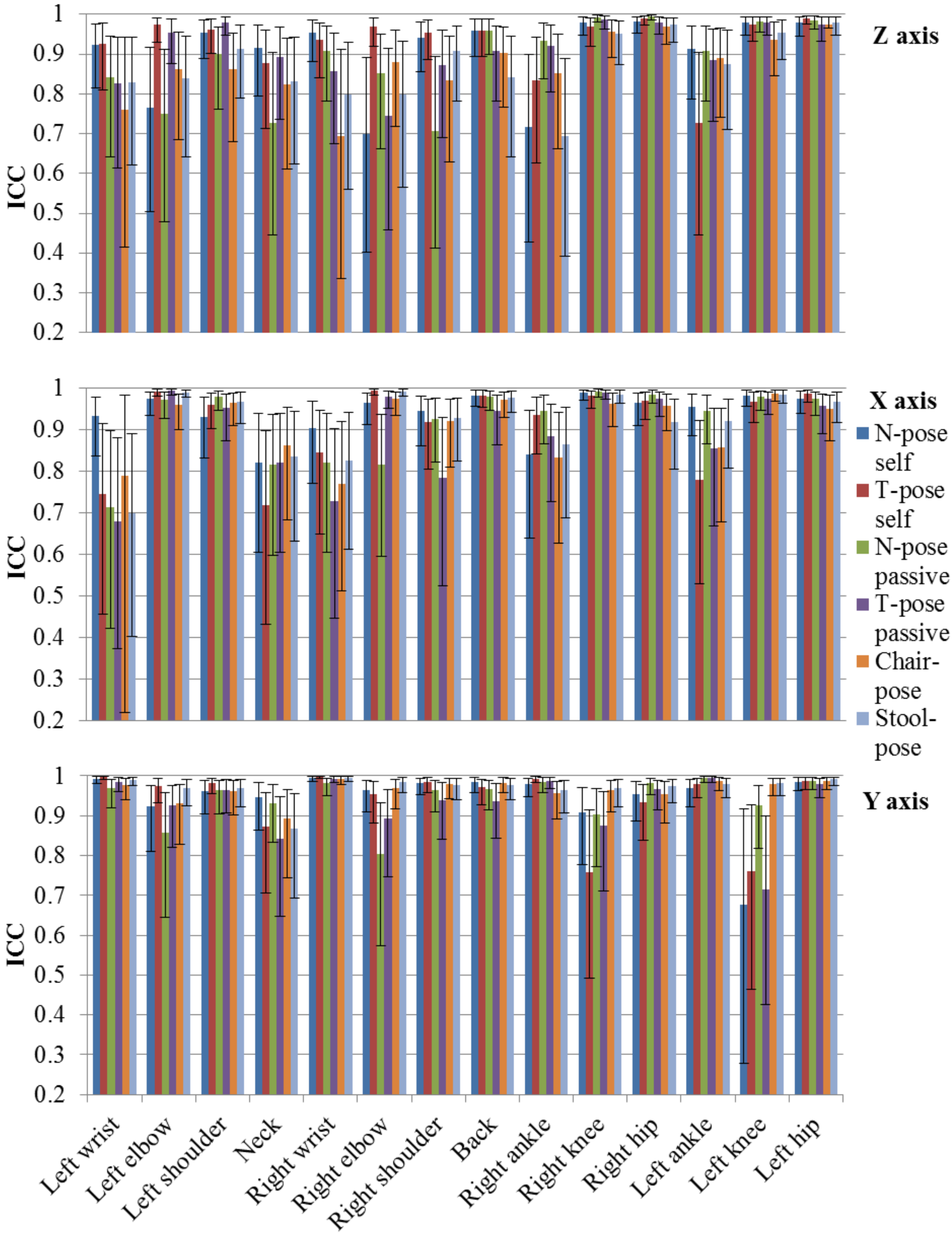

Figure 3. Repeatability of joint angles for the three repetitions of each calibration pose measured with intrarater within-day intraclass correlation coefficient (ICC) ± 95% confidence intervals on the Z transverse, X frontal and Y longitudinal axes.

Table 1. Standard error of measurement (SEM) on joint angles (degrees) for the three repetitions of each calibration pose on the Z transverse, X frontal and Y longitudinal axes.

	N-pose self			T-pose self			N-pose passive			T-pose passive			Chair-pose			Stool-pose		
	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y
Wrist	1.8	1.2	1.8	2.3	2.2	1.4	3.5	2.7	3.8	3.3	3.3	2.4	3.3	2.1	1.6	2.7	1.9	2.6
Elbow	2.1	1.3	3.5	1.0	0.5	1.6	3.4	1.8	4.9	2.2	0.6	2.7	1.3	0.4	1.9	2.1	2.0	3.5
Shoulder	1.5	1.5	2.7	3.5	2.0	3.8	2.0	1.2	3.4	3.0	2.4	5.1	3.9	1.8	4.8	2.2	1.7	2.2
Neck	2.0	0.9	1.1	2.6	1.1	1.4	4.1	0.9	1.0	2.3	1.1	2.2	2.4	0.9	1.5	3.1	1.1	1.3
Back	1.7	0.5	0.6	1.6	0.5	0.8	1.5	0.6	0.8	2.1	0.9	1.1	1.7	0.5	0.6	3.4	0.8	0.6
Ankle	1.6	0.8	1.8	1.0	0.4	1.5	1.8	1.3	3.2	2.1	0.5	2.0	1.0	0.4	1.3	1.6	1.5	2.2
Knee	1.5	1.1	2.0	2.1	1.3	2.6	1.5	0.9	2.4	2.6	1.7	3.4	2.3	1.3	2.5	2.5	1.4	1.8
Hip	1.1	0.5	1.0	1.0	0.6	1.1	0.9	0.5	0.8	1.3	0.8	0.9	1.1	0.5	1.0	2.4	0.9	0.8

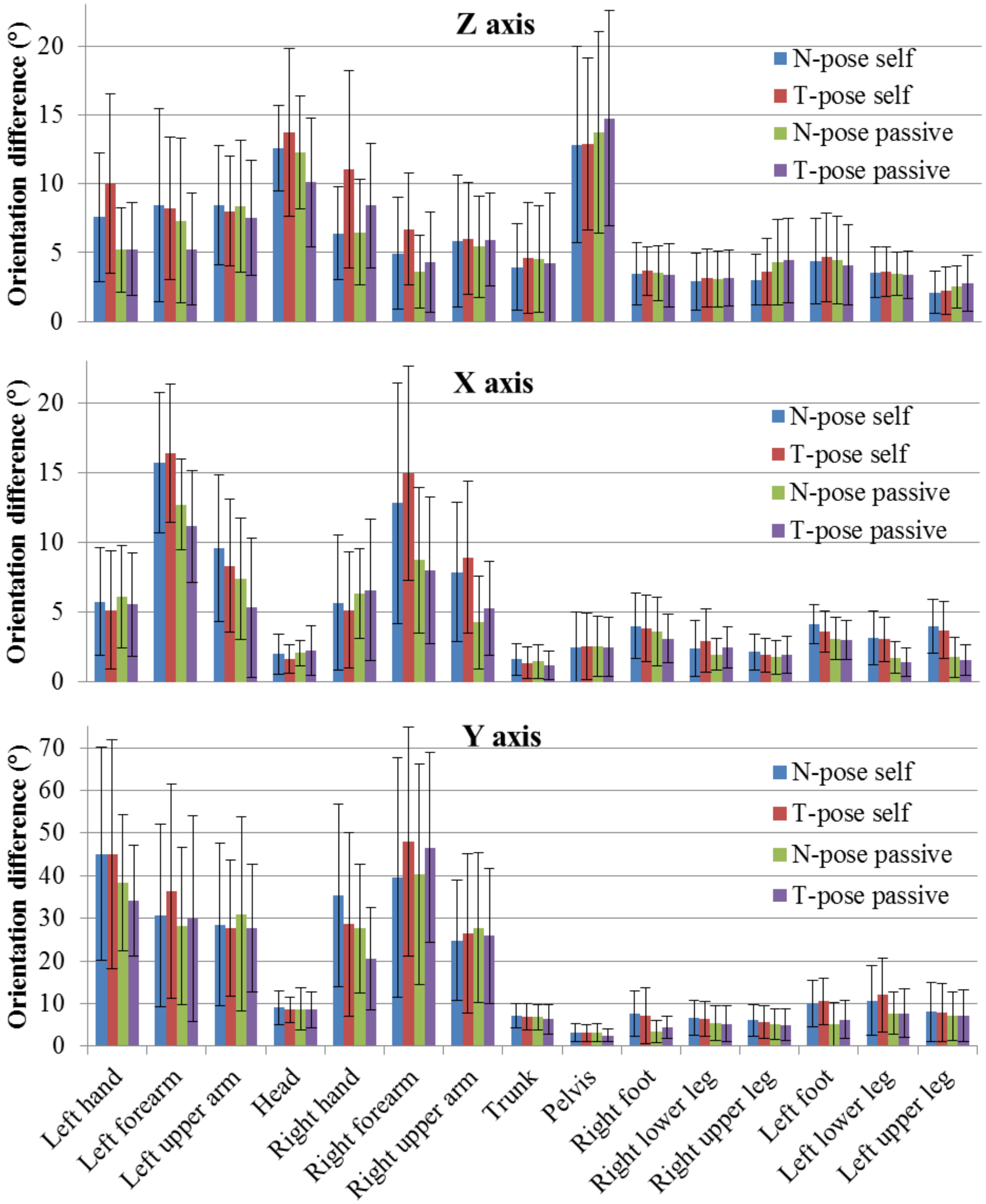

Figure 4. Segment orientation difference (mean ± SD) between MVN commercial software and International Society of Biomechanics (ISB) models on the Z transverse, X frontal and Y longitudinal axes during a short manual material handling task following each calibration pose.

4. Discussion

Two single-pose calibrations offered by commercial IMUs and two conditions of placement were evaluated. The results, in terms of accuracy and similarity to laboratory motion analysis, indicate that the T-pose performed better than the N-pose and passive placement performed better than self-placement. In addition, the potential for calibration of two single-poses developed, the chair-pose and the stool-pose, was also evaluated. The chair-pose showed a reduction of the longitudinal segment offset error on the upper limbs compared to the other poses. The lower limbs obtained more accuracy, repeatability and similarity to laboratory motion analysis than the upper limbs.

4.1 Longitudinal axis offset error

Studies usually measure reliability, repeatability or similarity to laboratory motion analysis [7, 8, 10, 11], but do not consider the accuracy of the segment orientation. The problem is mainly due to the difficulty of establishing a valid reference. One study measured the error of different IMU calibrations on an artificial anthropomorphic upper limb equipped with absolute encoders, where the ideally executed functional calibration performed better than the static pose [9]. But the inability for humans to perform a perfect mono-axial rotation [10] hampers the practical application of the results. For this reason, the accuracy of the calibration pose was evaluated with the longitudinal axis offset error. A single-pose calibration is based on a priori defined segment orientations that the subject must execute. The optoelectronic global coordinate system was used as a reference to evaluate the accuracy of the longitudinal axis during the calibration pose. Results indicate that the T-pose reduced the error compared to the N-pose. In addition, passive placement of the subject by an experienced operator reduced the longitudinal axis offset error compared to self-placement. The chair-pose reduced the longitudinal axis offset error for most of the segments, especially for the upper limbs. Since upper limbs are more problematic for calibration, the chair-pose shows good potential for future development as a single-pose for calibration. In addition, the chair-pose is convenient for wheelchair users and similar to the static pose [21, 22]. The stool-pose, a simpler alternative to the chair-pose, showed similar values to the T-pose with passive placement. The more complex support system in the chair-pose improved the achievement of the desired posture.

4.2 Repeatability of calibration poses

Repeatability, measured with reliability index, coefficient of multiple correlation (CMC), variation in orientation and ICC, is commonly used to recommend IMU calibration approaches. A systematic review stated that CMC is influenced by range of motion and should not be used in isolation and recommended reporting SEM or SD [23]. We opted for ICC and SEM to measure repeatability since they are often used for clinical tools [24-26]. The reliability studies were mostly dedicated to the upper limbs [8, 10, 11], which may be associated to lower accuracy and higher differences between models compared to the lower limbs.

A previous study used variation in segment orientation over the trials to recommend IMU calibration based on the most repeatable axes, which often combined a single-pose and functional movement and obtained 1.2° to 2.9° of mean dispersion [11]. A study reported repeatability of the knee joint angles of 0.4° to 0.8° as the average of eight movement combinations [1]. Another study found higher repeatability on children when combining the N-pose and functional movement [10]. Intra- and inter-operator precision were examined in many combinations of a single-pose and functional calibration where the various approaches showed similar precision [8]. The literature appears quite divergent regarding which calibration approach is more repeatable or reliable, whereas our results indicate similar repeatability in the tested single-poses, in agreement with a previous study [8].

4.3 Similarity between MVN and ISB models

Passive placement of the subject increased the similarity between the MVN and ISB models, while the calibration pose showed no significant differences ($P > .05$). The substantial differences between models observed on the upper limbs are mostly due to misalignment of the local coordinate systems between single-pose or anatomical landmark approaches, as previously described in detail [3]. A few studies have measured the similarity between various combinations of IMU calibration approaches and a protocol based on the ISB recommendations [7, 8, 11]. The mean segment orientation differences under 5° for the lower limbs in our study appear smaller than the mean absolute variability under 10° reported with a double-pose calibration [7]. Our similarity results obtained with the passive placement on the upper and lower leg are comparable to a functional approach on the knee who reported means from 8.1° to 4.0° [1]. Compared to our similarity results for the upper limbs, De Vries et al. [11] obtained smaller differences on the Y axis of 4.0° to 14.8°, but greater differences on the X and Z axes of 5.9° to 16.9° and 3.8° to 17° respectively. Finally, a recent study observed that none of the upper limb single-pose and functional calibration approaches tested clearly stood out, [8] in agreement with our similarity findings between the T-pose and N-pose.

4.4 Limitations

A few limitations are present in this study. Although the ISB model measured with the optoelectronic system served as a reference to evaluate accuracy, errors can still arise from the palpation and identification of anatomical landmarks [27] and soft tissue artifact [28].

The current protocol measured the accuracy of the segment longitudinal axis. Research dedicated to segment orientation accuracy along the two other axes remains a challenge. Scapulothoracic motion was not considered in the study, as specific calibration is required for this segment [29, 30]. Finally, repeatability was measured in the present study, but interrater and between-days reliability of the single-pose calibrations should be further investigated.

5. Conclusion

The analysis of common single-pose calibration for IMUs revealed that accuracy was increased with the T-pose compared to the N-pose. In addition, passive placement of the subject by an experienced operator (compared to self-placement after being shown a picture) increased accuracy and contributed to greater similarity between the MVN and ISB models in terms of body segment orientations. Based on better accuracy and similarity to ISB recommendations, the T-pose is preferred to the N-pose, and passive placement of the subject is recommended for single-pose calibration of IMUs with the MVN model for whole-body motion analysis. The hypotheses that the T-pose would be more accurate than the N-pose and that passive placement would increase accuracy are confirmed. In general, the tested calibration poses yielded similar repeatability measures. Finally, the newly developed chair-pose shows potential for increasing the accuracy of IMU calibration, as hypothesized.

Conflict of interest statement

The authors have no conflicts of interest related to this manuscript.

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