Characterization of inertial measurement unit placement on the human body upon repeated donnings

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***Abstract*—Accurate estimations of variability in multiple donnings of sensor suites may aid algorithm development for wearable motion capture systems that make use of Inertial Measurement Units (IMUs). The accuracy of any algorithm incorporating these sensors is limited by the accuracy of the sensor to segment calibration. When either sensor placement (use by a non-expert) or limb motion during calibration (natural human variation) vary, the estimations are affected. In this study, 22 participants self-placed IMUs on three locations and performed six prescribed motions during each of these five donnings. For absolute placement of the sensors, the chest location mean was less than the forearm, which was less than the bicep. For sensor orientation, the opposite ordering of location was found. No difference in sensor rotation was found between the bicep and forearm, but both locations differed from the chest location. Results were analyzed at the beginning of prescribed motions.**

Keywords—Variability, Inertial Measurement Unit, Sensor Suites, Donning, Doffing.

I. INTRODUCTION

According to the 2014 IHS MEMS & Sensors for Wearable Report [1], consumers will be wearing close to 500 million sensors by 2019. This estimate includes devices for motion measurement, user interfaces, and health industry products, with an emphasis on personal devices that are used daily by non-experts. A necessary requirement to enable such portable and continually-used consumer systems that are reliable, self-sufficient, and require minimal-logistical needs is to understand and appropriately incorporate the variability of humans during repeated use in the system architecture. This study specifically considers wearable technology systems for estimating human motion.

A common method for estimating rigid body motion is the use of Inertial Measurement Units (IMUs), which are small electronic sensor suites of accelerometers, rate gyros, and magnetometers that measure linear acceleration, angular velocity, and local magnetic field. Compared to other motion capture technologies like optical, image-based, and magnetic, IMUs provide an inexpensive and portable solution. Recent technological advances have improved the energy consumption, cost, and availability of these sensors [2]. Whereas optical and acoustic devices require a source emission to track objects, IMUs do not, which simplifies system integration and increases portability.

Despite these benefits, IMUs have disadvantages. Accelerometers measure the sum of linear acceleration and gravity. In a quasi-static movement, linear acceleration can be neglected. In a dynamic situation, it is difficult to decouple the two measures and may lead to difficulty calculating attitude accurately [3]. Angular velocity measurements by gyroscopes are prone to sensor drift over time, and magnetometers are susceptible and influenced by ferrous material. With an estimated orientation for a given IMU, there is still a need to calibrate individual sensors to the global body coordinate system every time the sensor suite is donned.

To overcome these individual sensor disadvantages, fusion techniques have been implemented. Starting in 1970, Bortz [4] computed sensor orientation by integrating angular velocity. Since then, others have extended fusion methods and examined Kalman Filter algorithms to obtain dynamic orientations of IMUs by implementing an Euler angle representation [5][6]. To avoid singularities in Euler angles and to limit the need for linearizing, quaternion-based Extended Kalman Filters (EKF) have been implemented [7][8], although this method still requires an embedded physical model linearization and is limited to slow motions due to the computation time.

Results of the use of IMUs on robotic hinges rather than on humans [9] show that if accelerometers can be placed exactly on the joint center, a simpler algorithm (common-mode rejection algorithm) can accurately predict joint-angles without the need for computationally heavy filters. The need for the IMU to be placed exactly on the joint center indicates that the variability of sensor placement by humans during repeated use may be a large cause of motion estimation errors. As Luinge et al. [10] also conclude, the accuracy of any method is limited by the accuracy of the sensor to segment calibration.

IMU calibration can be either static or dynamic (e.g. [11], [12], respectively). The most common pose held for a static calibration is a “T” pose in which both arms are held straight out to each side. Dynamic calibration motions vary but may include simple one degree of freedom motions for relevant segments. Wu et al. [13] developed a self-calibration process incorporating sensor misplacement for in-plane orientation misalignment, but it was not able to aid misalignment in rotations along local body curvature. All these calibrations relate the local coordinate system of the IMU to the global placement of the IMU on the body. Calibration poses increase preparation time for a system and are also only as accurate as the ability of a human to perform a specified motion.

The literature suggests that a motion capture system using IMUs where both sensor placement and calibration poses and motions are exact and repeatable provide good estimates of the system state. However, when either sensor placement (non-expert) or limb motion during calibration (natural human variation) vary, the estimations are affected. This study will test the hypotheses that initial placement (defined as distance, orientation, and rotation) of IMUs located at the chest, bicep, and forearm by a non-expert are affected by (1) the number of times the sensors are donned, (2) the type of functional motions performed, and (3) the location of the IMU. Here, the uncertainty in IMU placement when donned by a non-expert user is characterized. These data will aid in algorithm development to minimize and compensate for the donning and doffing variability measured in relevant motions.

II. METHODS

A. Participants

The study included 22 subjects (6 female) aged 23.3 ± 3.0 years. The study was carried out in the Man-Vehicle Laboratory within the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. Procedures were approved by the MIT Committee on the Use of Humans as Experimental Subjects (COUHES) and participants provided written consent. Participants received a $20 gift card as compensation.

B. Experimental Protocol

Participants were instructed to self-place four IMUs (APDM, Opal 425) during the study to analyze the variability in placement on the upper body for two mounting configurations, straps and garment based. In this paper, the straps mounting configuration is highlighted.

Prior to data collection, researchers placed 24 passive reflective markers (12 9.5mm diameter markers on the participant and 12 6.4 mm diameter markers on the IMUs) to permit standard motion capture analysis (Vicon 10-camera Bonita system) (Fig. 1).

For data collection, all subjects were asked to perform five donnings and doffings of each of the two IMU configurations. During each donning, one calibration pose was performed prior to the six predetermined motions (Fig. 2) that were performed randomly a total of six times each (total of 36 motions during each donning). The motions were randomized to prevent learning effects.

An instructional donning was performed during the first mounting configuration, in which all straps were adjusted for fit and comfort using the participant's feedback. This instructional donning was purely for fit and none of the predetermined motions were performed. The participants were also fitted for

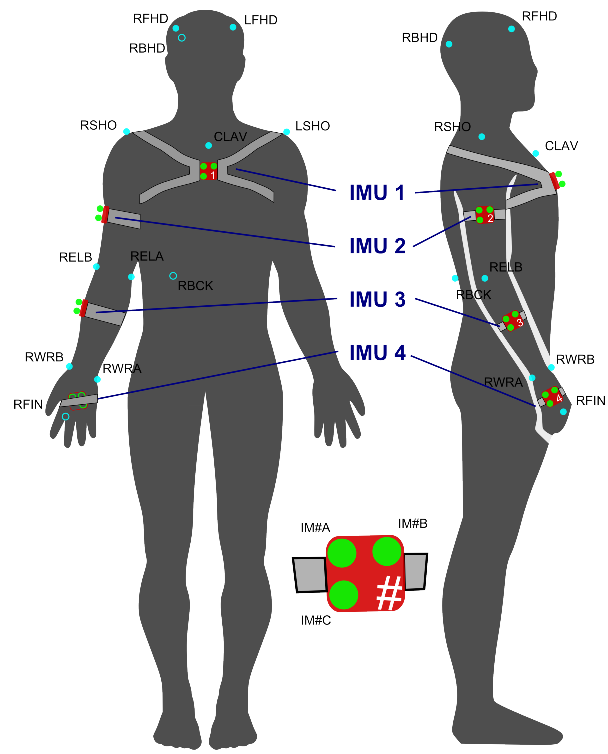

Fig. 1: Recommended sensor placement (boxes on straps) and researcher placed optical motion capture markers. Sensor placement labelling scheme is shown in the bottom of the figure.

fabric arm braces, placed on the right forearm and bicep, to prevent subjects from using the imprint of the IMU on the skin as a reference for placement during repeated donnings. The braces were not removed during the multiple donnings of the IMUs. During the garment fit, the second configuration, a trace of the silhouette of the participant was created and used as a guide to participants when they repeated the calibration pose, limiting variability. The strap and garment configurations were not resized after this instructional donning.

C. Data Acquisition

1) Donning Configuration: The IMU strap configuration utilized Velcro straps (APDM) to independently mount the four IMUs (Fig. 1). One single hoop strap was used for each IMU placed on the hand, forearm, and bicep. A chest strap with two connection points, two snap buttons on one side of the IMU, and hoops for each arm was used to secure an IMU to the chest.

2) Motion Capture: Vicon data were sampled at 120 Hz. The IMU data were sampled at 128 Hz and wirelessly logged in real-time and synchronized to enable comparison of the optical and inertial data. In addition, all participants were video recorded during the trials.

3) Motions: Six predetermined motions were described to the participants prior to data collection through text and visual descriptions (Fig. 2). The motions were chosen to include a range of single and multiple (more than one) degrees of freedom. Motions included elbow, wrist, and shoulder flexion

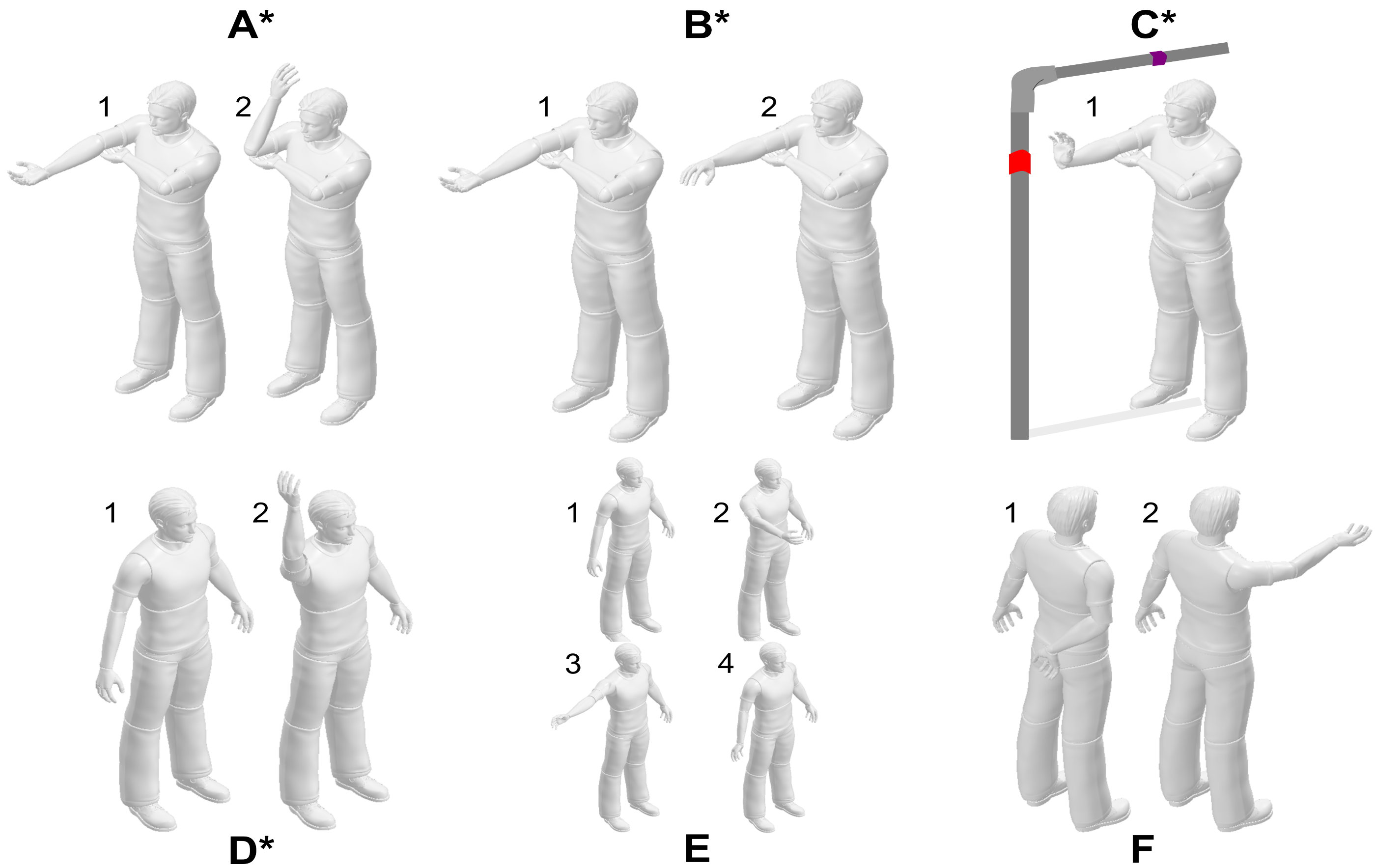

Fig. 2: Predetermined motions showing relevant degrees of freedom (A = elbow flexion and extension; B = forearm pronation and supination; C = wrist ulnar and radial deviation, wrist flexion and extension; D = Lifting arm upwards, which included elbow flexion and extension, shoulder flexion and extension; E = Lifting arm forward and to the side, which included shoulder abduction, flexion and rotation; F = Lifting arm forward from a behind the back starting position, which included wrist, elbow, and shoulder flexion and extension, shoulder abduction, and forearm pronation and supination). Motions have numbered figures to indicate sequence of poses. Subjects performed the sequence in a motion, and then returned to the first pose in the sequence. Target Apparatus only shown in Motion C but was used by four motions (A * indicates the motion used a guide).

and extension; forearm pronation and supination; wrist ulnar and radial deviation; and shoulder abduction and rotation. The visual descriptions of the motions were within eye sight of the participants during data gathering for reference. During 4 of the 6 motions, a target apparatus was used to determine the starting and ending positions (Fig. 2). The apparatus was created out of 3/4" PVC pipe and consisted of two poles at 90 degrees, one vertical at arms reach of the participant and one horizontal above the head of the participant. The vertical bar had a red target at shoulder height. The horizontal bar had a purple target above the participant, at a height just above the reach of the participant. The apparatus was adjusted to the height of each participant and was not adjusted during data collection.

D. Data Processing

Vicon Nexus software was used to reconstruct, label markers, fill in gaps, and export the optical data. A Biomecahnical Toolkit was used to import these data to Matlab. In-house code was used to calculate IMU position, orientation, and rotation. Here, data for IMUs 1, 2, and 3 are presented.

As as shown in Fig. 1, each IMU had a triad of markers labeled A, B, and C corresponding to the top left, top right, and bottom left markers, respectively. The centroid of each IMU was defined as the midpoint between markers B and C. IMU position was defined as the distance between the IMU's centroid and a pre-specified body-fixed marker for each IMU (Fig. 3). IMU orientation was defined as the angle (in degrees) the IMU had rotated along the plane of initial placement. A vector from the IMU centroid to the pre-specified body-fixed marker defined zero degrees. The angle between this vector, and a vector created from marker C to A on each IMU, defined the IMU orientation (Fig. 3).

IMU rotation was defined as the angle about the local body curvature (Torso, bicep, and forearm for IMU 1, 2, and 3, respectively). IMU rotation was calculated as the dot product of a normal vector to the IMU plane and a normal vector created from surrounding body-fixed markers (Fig. 3). An example of IMU 2 rotation being calculated can be found in Fig. 4. IMU 1, 2, and 3 distance, orientation, and rotation were scaled by torso, bicep, and forearm length, respectively, for each subject. These normalized values then had the overall means by IMU number subtracted such that comparisons between IMUs could be made.

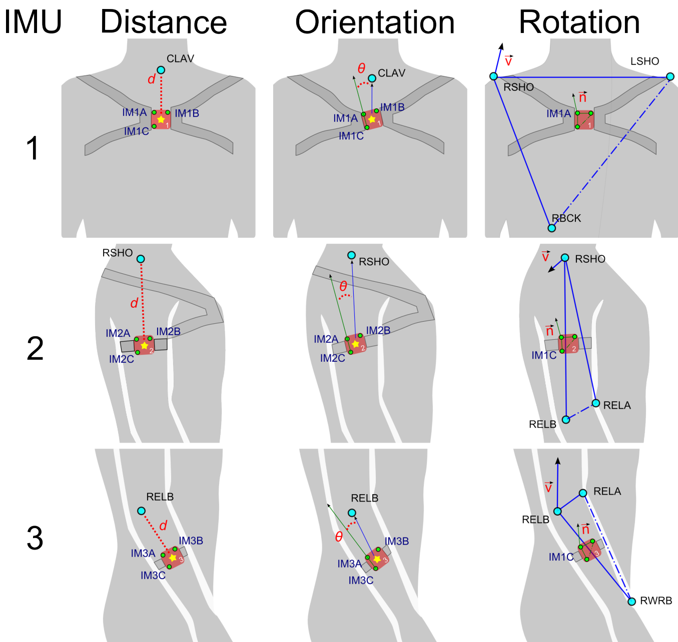

Fig. 3: Definition of the three IMU measurements for each of the three IMUs and associated markers. IMUs had three markers, labeled A, B, and C, used to define the local IMU coordinate system. Each subfigure shows the surrounding markers used in the IMU's measurement calculation.

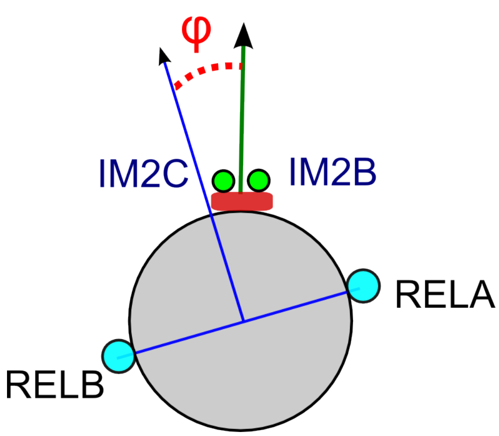

Fig. 4: Example of how rotation is calculated on IMU 2. This view is from the elbow looking towards the shoulder. The rotation angle is the angle between the IMU normal vector and the surrounding body markers' normal vector. From this view, markers IM2A and RSHO are masked.

E. Statistical Analysis

Data are presented as scaled IMU distance, orientation, and rotation. ANOVAs were performed to examine the main and interaction effects of the independent variables (location, donning, and motion). A p value <0.05 was used to indicate statistical significance. The Tukey Difference test and the Student-Newman-Keuls test were used for post-hoc comparisons. Levene's test was used to assess the equality of variances. SYSTAT software was used for calculations.

III. Results

A three-factor ANOVA was conducted for each dependent variable (distance, orientation, and rotation) to test for main and interaction effects of location, donning, and motion. Significant effects were found for all main effects, two-way, and three-way interactions ($p < 0.0005$) for all three IMU dependent measurements.

Post-hoc pairwise comparisons of the IMU location using Tukey's Difference Test showed significant differences between all three locations for IMU distance ($p < 0.0005$). For IMU orientation, significant differences were found between locations 1 and 2 ($p < 0.0005$), and locations 1 and 3 ($p < 0.0005$), but not between locations 2 and 3 ($p = 0.554$). Similarly, for IMU rotation, significant differences were found between locations 1 and 2 ($p < 0.0005$), and locations 1 and 3 ($p < 0.0005$), but not for locations 2 and 3 ($p = 0.837$). Pairwise comparisons for donning showed no significant difference between donnings 1 and 3 ($p = 0.225$), 1 and 5 ($p = 0.485$), and 3 and 5 ($p = 0.995$). Donnings 2 and 4 were significantly different from the other donnings ($p < 0.0005$). Student-Newman-Keuls post-hoc tests were used to group similar motions. For IMU distance and orientation, there were 3 groupings: motion A, motions B and C, and motions D, E, and F. For IMU rotation, there were also three groupings: motion B, motions A and C, and motions D, E, and F.

Since no consistent trend in any dependent variable was found with consecutive donnings, the donnings were pooled and interaction effects of motion with location were analyzed. Fig. 5 shows the significant difference within motions for all IMUs.

Levene's test showed significant differences in the variances for the distance ($p < 0.0005$) and orientation ($p < 0.0005$) for all three IMU locations (Table I). For distance, location 2 was the most variable and location 1 was the least variable. For orientation, location 1 was the most variable while location 2 was the least variable. There was no significant difference in rotation variance between locations 2 and 3.

IV. Discussion

This study aimed to characterize the uncertainty in IMU distance, orientation, and rotation during donning by a non-expert. Participants performed five donnings of self-placed IMUs on the chest, bicep, and forearm. Within each donning, participants performed six repetitions each of six prescribed motions. This study tested the hypotheses that initial distance,

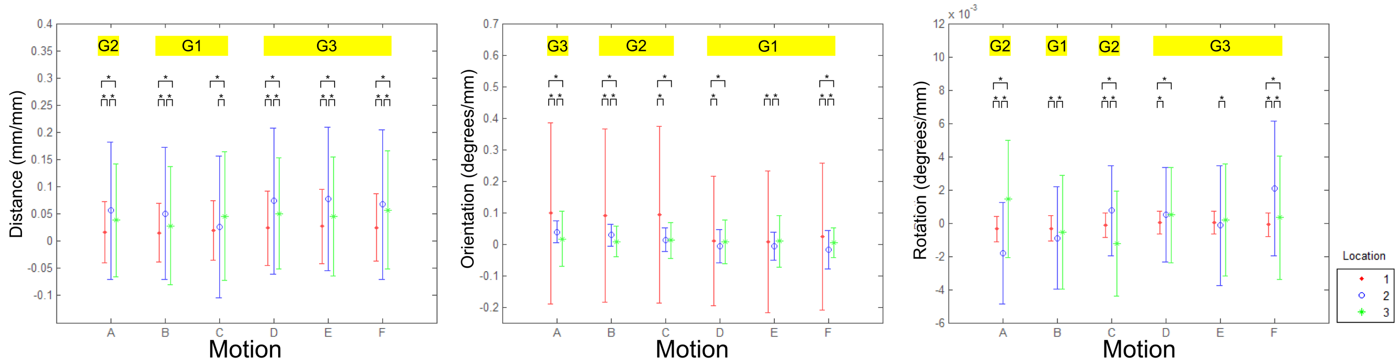

Fig. 5: Shown are the within motion interaction effects between location. Additional significant effects across motions are not shown. Main effect groupings are shown in horizontal bars above graphs in the order of group means from smallest (G1) to largest (G3). Bars show one standard deviation from the mean. Above each graph, asterisks (*) indicate significant difference according to Tukey's Difference Test (p <0.05).

TABLE I: Normalized and mean shifted location variances for all independent variables

Variable	Variance		
	IMU 1	IMU 2	IMU 3
Distance (mm/mm)	0.0038 $\star\diamond$	0.0172 $\star\triangleleft$	0.0119 $\diamond\triangleleft$
Orientation (degrees/mm)	0.0646 $\star\diamond$	0.0024 $\star\triangleleft$	0.0044 $\diamond\triangleleft$
Rotation (degrees/mm)	5.5×10^{-7} $\star\diamond$	1.24×10^{-5} $\star$	1.21×10^{-5} $\diamond$

$\star$, $\diamond$, and $\triangleleft$ indicate significance (p <0.0005) between IMUs 1 and 2, 1 and 3, and 2 and 3, respectively.

orientation, and rotation of IMUs are affected by (1) the number of times the sensors are donned, (2) the type of functional motions performed, and (3) the location of the IMU.

While hypothesis 1 was confirmed, that there were significant main effects of donning, no consistent trend in any dependent variable with consecutive donnings were found. This implies that multiple donnings do not show learning effects. For initial placement, multiple donnings did not lead to more or less accurate placement.

Hypothesis 2 suggested that prescribed motions may affect the dependent measurements. Although motions A and B had the same starting position, the dependent measures were significantly different from each other. Motions D, E, and F were consistently grouped together for all IMU dependent variables. These three motions had different starting positions than motions A, B, and C, but similar starting positions to each other. It is clear that the starting point has an effect on the dependent variables. Relative placements are important because the relationship between the local and global coordinate system is defined in the calibration pose.

Hypothesis 3 suggests that location of IMU may affect the dependent variables. IMU distance showed significant differences across all locations, with the group mean lowest for location 1. This is consistent as the torso enabled the most precise placement of the IMU centroid due to having more constraints than the straps on IMUs 2 and 3 (Fig. 1). IMU 1 orientation was also found to be significantly different from IMUs 2 and 3. The similarity in orientation between IMUs 2 and 3 is consistent with the strap configurations. For the attachment method evaluated, the location of the IMU had an effect on IMU placement. There is a component of IMU placement that may be due to the user's natural placement variability, but there is also a portion that can be influenced by the strap type.

As a component may be attributed to strap type, it is important to consider how the straps were implemented. The straps associated with IMU 1 were constrained by four incoming straps with two connection points while IMUs 2 and 3 had two incoming straps and two connection points (Fig. 1). The loop on IMUs 2 and 3 that secured the IMU to the bicep and forearm allowed for more freedom of movement along the limb as well as movement along the local body curvature. In order to don these straps, the Velcro was looped through a buckle that was the same width as the IMU. This fixture limited changes in orientation of the IMU because the Velcro was as wide as the buckle, causing the IMU to align with the strap more consistently. The strap on IMU 1 was donned by looping each arm (much like a sweater is put on) and then snapping two buttons on one side of the IMU. Since the strap lengths were not changed, the chest strap was expected to provide consistent placement of the IMU centroid and to limit rotation about the torso. However, each of the two buttons had snaps that allowed some pivot, and thus small changes in strap location on the shoulder and under the armpit induced changes in IMU orientation. The data were consistent with these strap types and showed IMU 1 variance to be highest for orientation, but lowest for distance and rotation as compared to the other two IMUs.

This study made use of strap mounting configurations for the IMUs and understands that not all sensors are mounted in this manner. These results, however, can inform sensor attachment design. While an arm brace was used to limit the imprint on the skin, participants still had proprioceptive feedback which could aid in re-alignment of the IMU.

All these results were analyzed at the initial time point of the six motions studied. However, calibrations affect estimations throughout a time trajectory so it is important to study how these relationships change throughout the entire motion. When the data are studied across time points, different similarity groupings may arise due to the changes in orientation of the limb. Future work will present the effect of IMU distance, orientation, and rotation changes across each motion. The data collected on the garment, which has fewer attachments points, will also be analyzed. From the current analysis, the hypothesis is that garments, which have less embedded structure, may show increased placement variability. Next steps are to understand how the effect size of these distance, orientation, and rotation variations affect motion estimations using current algorithms.

V. Conclusion

The accuracy of rigid body motion estimation is dependent on sensor placement and calibration. Therefore, characterization of sensor placement is needed to aid in development of algorithms and sensor attachment design for wearable motion capture systems. The results presented in this study examined the effects of self-donning on IMU distance, orientation, and rotation at the chest, bicep, and forearm. This study made use of off-the-shelf strap mounting configurations for the IMUs and found that the chest mount varied the least in initial placement in terms of distance and rotation, but its orientation varied more than when the IMUs were placed on the bicep and forearm.

This research was the first to characterize the way users vary placement of sensors on the human body. Relating mounting locations, motions, and number of donnings to IMU placement provides data to assist in designs for housing sensors and can aid the development of quick don and doff sensor suites that can be reliably used by a non-expert for real-time decision making.

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