# Characterization of sensor placement variability on the human body upon repeated donnings and doffings

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## Objective

With increased emphasis on long duration travel beyond Earth's gravitational influence, there is a growing need for human health monitoring technologies with improved reliability, self-sufficiency, and minimal-logistical needs [1]. A necessary requirement to enable such systems is to understand the variability of humans, specifically non-experts, during repeated system use. Here we specifically consider wearable technology for estimating human motion. Currently, Inertial Measurement Units (IMUs), which are small electronic devices that measure acceleration and orientation, are used for estimating motion in a lab environment with expert placement. In this work, we characterize the uncertainty in IMU placement when placed by a non-expert user. These data will aid in algorithm development to minimize and compensate for the donning and doffing variability measured in relevant motions.

## Experiment

A human study was conducted to analyze the variability in placement of four IMUs on the upper body for two different mounting configurations. Participants were instructed to self-place IMUs during the study. In the first configuration, the IMUs were mounted on the body using Velcro straps. The second configuration utilized form fitting garments with IMUs embedded external to the garment. Prior to data collection, passive reflective markers were placed on the participant and IMUs to permit standard motion capture analysis. The IMU data was wirelessly logged in real-time and synchronized to enable comparison of the optical and inertial data. Each subject performed 5 donnings of each configuration, and performed 6 predetermined motions 6 times each during each donning. The motions were chosen to include a range of both single and complex (more than one) degrees of freedom. Results from 11 subjects in the strap configureation are presentated.

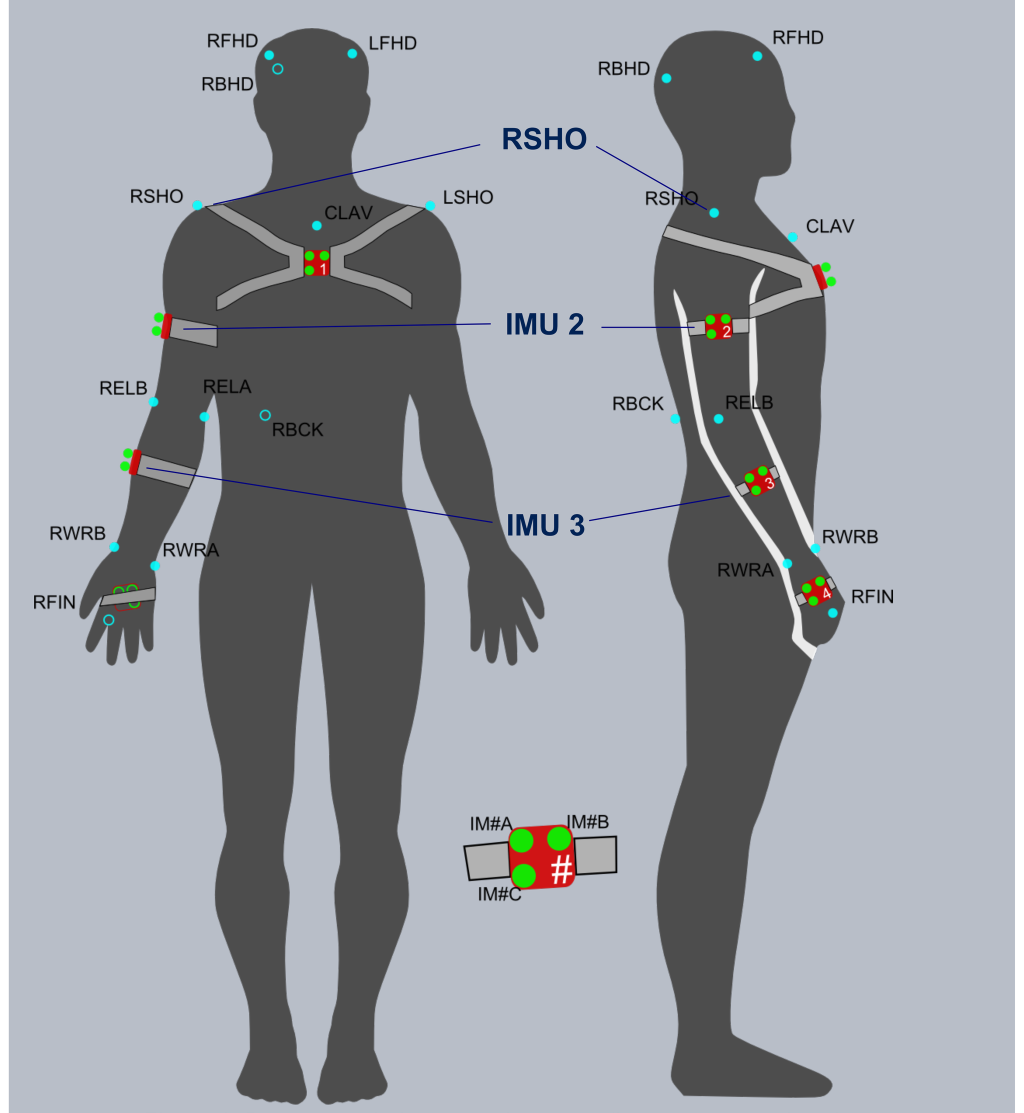



Figure 1: Recommended sensor placement (boxes on straps) and researcher placed optical motion capture markers

Experiment
- 22 subjects (6 female) aged 23.3±3.0 years
- 2 mounting configurations
- 5 donnings of each configuration
- 6 predetermined motions with 6 randomized repetition each within each donning

Tools
- Vicon 10-camera Bonita system with 24 Passive reflective markers
- Opal 425 3-axis accelerometer, gyroscope, and magnometer IMUs, produced by APDM
- 1 chest and 3 loop straps, produced by APDM
- 1 Duo Dry Max performance long sleeve garment by Champion

## Data Processing

The six motions were chosen to include a range of both single and complex (more than one) degrees of freedom. Motions included elbow, wrist, and shoulder flexion and extension; wrist pronation and supination; wrist ulnar and radial deviations; elbow lateral and medial deviation; and shoulder abduction and pronation. Participants were provided both written and visual motion descriptions. The visual motion description were placed within eye sight during the experiment. A guide to assist with the starting and ending positions for Motions A, B, C, and D was provided. Results for Motion A (simple) and Motion F (complex) are provided below. Here we present the effect of selected motion strategy on the distance between a fixed body marker and markers placed on the IMU. The distance was defined as the straight-line distance between marker RSHO and the centroid of the three markers on an IMU.

## Results

The results below show the mean distance with error bars representing ± one standard deviation for two of the four IMUs used in this study.

### Motion A

Figure 2: Motion A Visual Aid

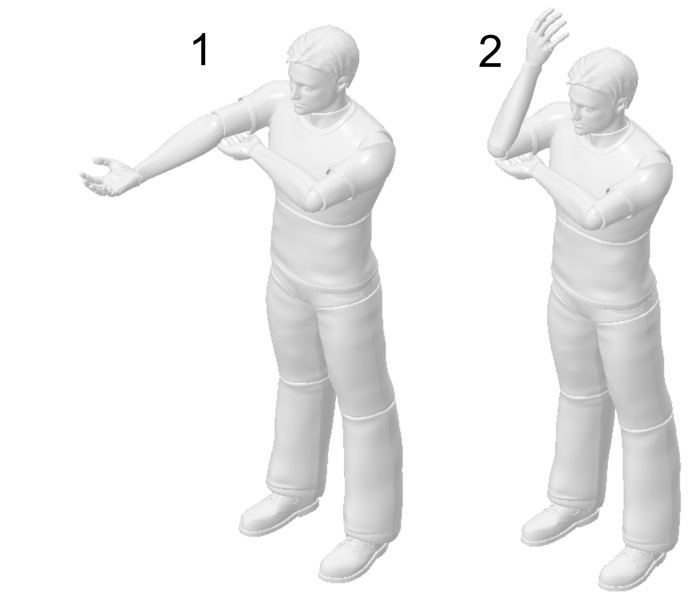



Figure 3: Distance between marker RSHO (Right Shoulder) and IMU3 (Right forearm) during repetition of Motion A of the first donning of Subject 2

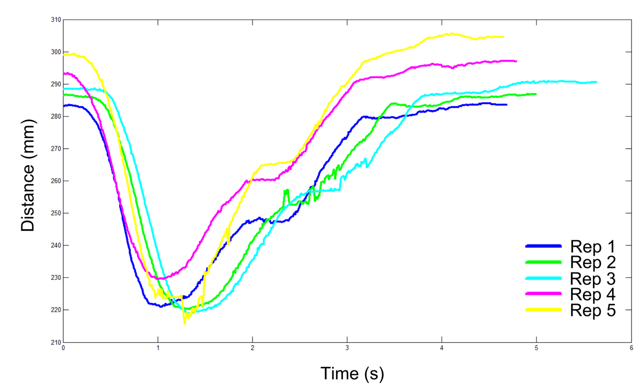



Figure 3 shows the distance between RSHO and IMU3 during Motion A for one subject. Each individual line is a different repetition of the same motion within the first donning. A 1 inch target at arm's length was used as a guide to assist with starting and ending position.

As expected, the distance between RSHO and IMU3 decreases during the middle portion of Motion A, when the forearm is closer to the shoulder. All repetitions follow the same trend, with a maximum difference between all repetitions at the starting point of the motion being 18.3 mm, indicating a small deviation in starting position for repetition of Motion A

Figure 4: Distance between markers RSHO and IMU2 (as seen in figure 1) before and after 6 repetitions of Motion A within 5 donnings

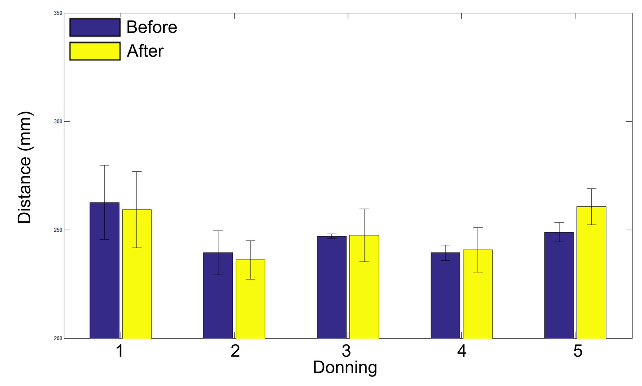
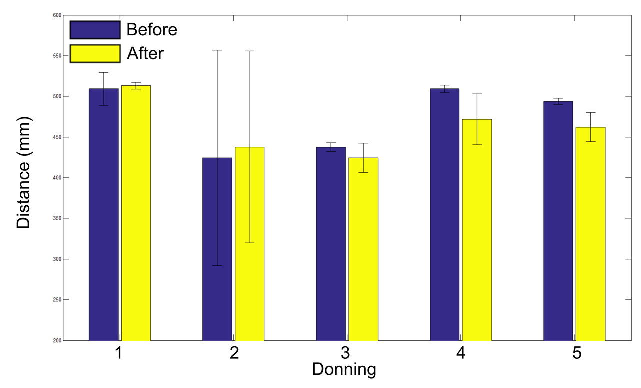



Figure 5: Distance between markers RSHO and IMU3 (as seen in figure 1) before and after 6 repetitions of Motion A within 5 donnings




Figures 4 and 5 capture the change in distance of the IMU to the RSHO marker before and after a motion by comparing the mean of the starting distance to the mean of the ending distance across the five donnings.

### Motion F

Figure 6: Motion A Visual Aid

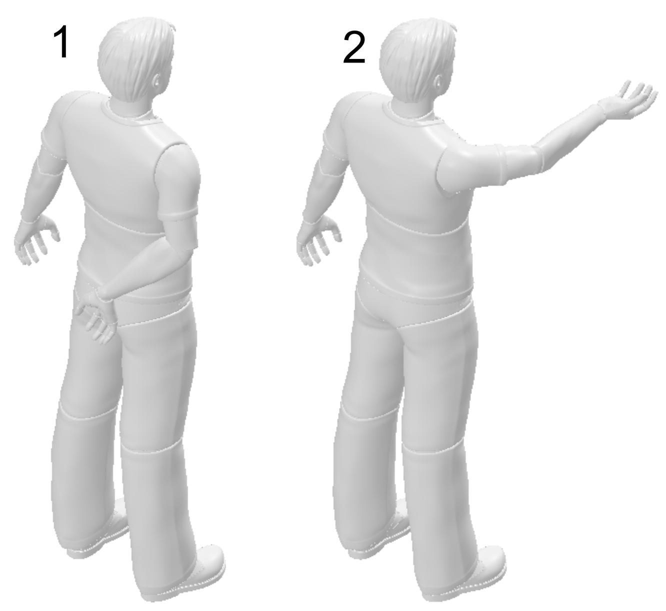



Figure 7: Distance between marker RSHO (Right Shoulder) and IMU2 (Right bicep) during repetition of Motion F of the first donning of Subject 2

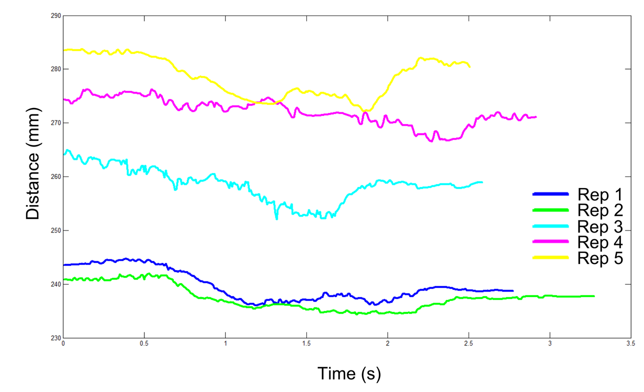



Figure 7 presents the distance between RSHO and IMU3 during Motion F for one subject. Each individual line is a different repetition of the same motion within the first donning.

Since there is no guide present for Motion F, motions are more similar to a natural environment and thus differences in performance can be expected. Although all repetitions still follow a similar trend, the maximum difference between all repetitions at the starting point of Motion F for the first donning of subject 2 is 45.2 mm. This large offset carries through throughout the entire motion.

Figure 8: Distance between markers RSHO and IMU2 (as seen in figure 1) before and after 6 repetitions of Motion F within 5 donnings

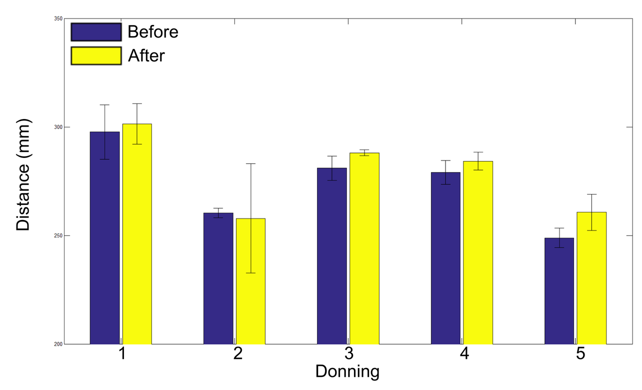
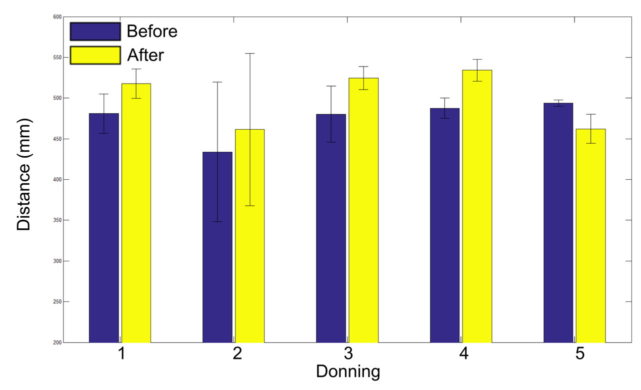



Figure 9: Distance between markers RSHO and IMU3 (as seen in figure 1) before and after 6 repetitions of Motion F within 5 donnings

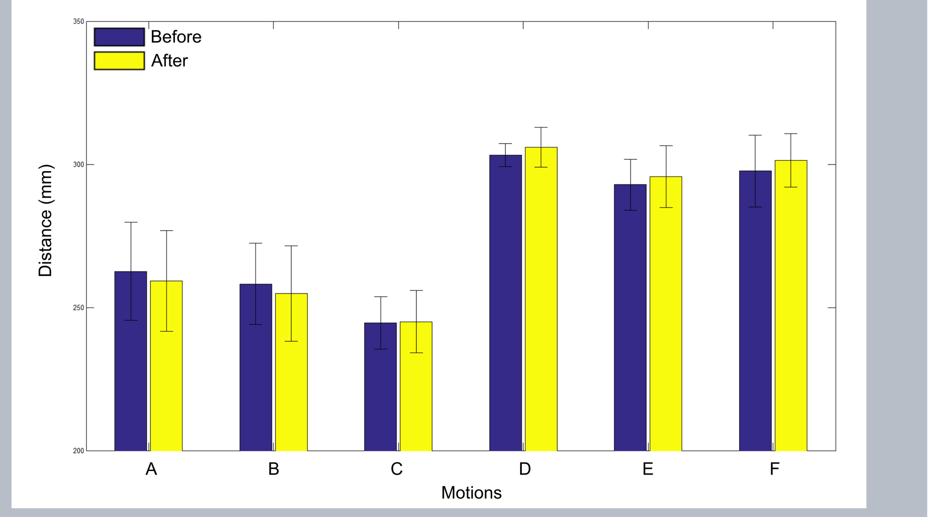



Figures 8 and 9 compare the mean of the starting distance to the mean of the ending distance across five donnings to capture the change in distance of the IMU to the RSHO marker before and after a motion.

## Continued Results

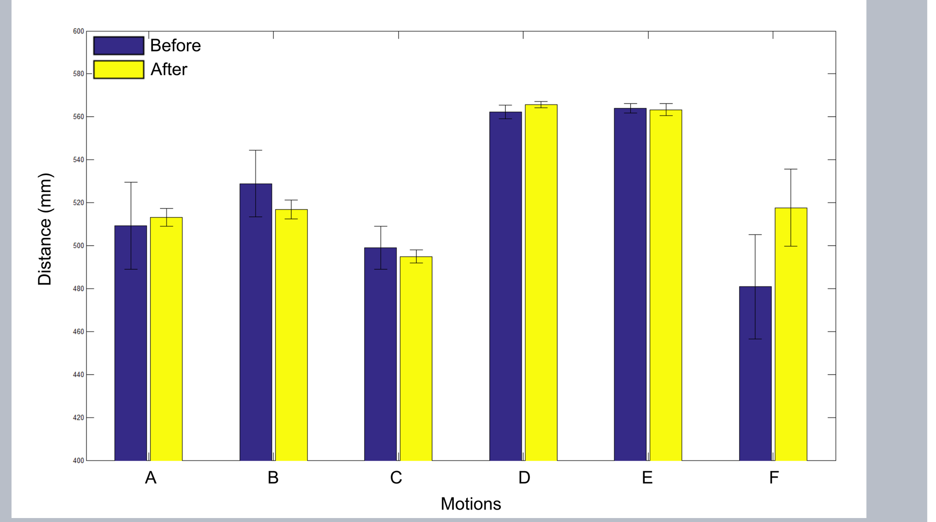
The figures below compare the distances between the RSHO marker and IMUs 2 and 3 for all six motions.

Figure 10: Distance between markers RSHO and IMU2 before and after 6 repetitions of all motions within the first donning for 11 subjects




Marker RSHO and the markers on IMU2 are connected by one shoulder joint, as seen in Figure 1. Because Motions A, B, and C all start with the right arm extended in front of the subject, and Motions D, E, and F start with the right arm on the side of the body, we see a trend where the first three motions have a smaller relative distance between IMU2 and the shoulder. The change in distance can be caused by the posture of the participant and their sholder joint alignment at the beginning and end of the motion.

Figure 11: Distance between markers RSHO and IMU3 before and after 6 repetitions of all motions within the first donning for 11 subjects




Marker RSHO and the markers on IMU3 are connected by a shoulder and an elbow joint, as seen in Figure 1. The distance between these two positions has a greater dependency on the starting position of the motion because of this extra degree of freedom. The relative distance between the shoulder and IMU for complex motions has greater dependency on the degree of freedoms within the measure.

## Conclusion

Here we highlight a subset of features of the natural motion variability. In particular, we highlight how IMU position placement can change with the same instructions across multiple donnings, how natural motions appear to have increased differences across repetitions compared to simpler motions, and how it is important to consider placement of IMUs with respect to the underlying degrees of freedom.

This research is the first to characterize the way users vary sensor placement on the human body. Relating anthropometry, mounting configurations, mounting locations, and don and doff times to IMU placement variability provides data to assist in designs for housing sensors and allows for the development of quick don and doff sensor suites that can be reliably used by a non-expert for real-time decision making. The algorithms for these sensor suites can then include an understanding of the underlying uncertainty in placement and what components affect this variability.

## References

[1] Hulbert K. et al (2012) Human Health, Life Support and Habitation Systems TA06-12.
[2] Delp S. et al (1990) IEEE Transactions on Biomedical Engineering 37, 757-767

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