Clinical Validation Study: Accuracy and Reliability of Markerless Motion Capture (MMC)

Whitepaper

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Abstract

ARPLO, a med-tech company, has developed a smartphone-compatible markerless motion capture (MMC) technology for remote measurement of joint angles, facilitating telemedicine between physical therapy patients and medical professionals. This study aims to validate the accuracy and reliability of ARPLO's MMC system by comparing it to the gold standard goniometer measurements conducted by clinical professionals. The primary objective was to assess the accuracy of kinematic joint angle measurements in a clinical setting by comparing MMC software measurements to goniometer measurements. The hypothesis was that there would be no statistically significant difference in shoulder, elbow, and knee joint angle measurements between the two methods.

Data were collected from 72 physical therapy patients, with 299 frames derived for each outcome variable per patient using the MMC software. Joint angles were measured for shoulder abduction/adduction, elbow flexion/extension, and knee flexion/extension by study-affiliated clinicians. Paired t-tests were conducted to compare the MMC and goniometer measurements, excluding approximately 20 measurements per limb due to high flutter in MMC measurements.

The paired t-tests indicated no significant differences between MMC and goniometer measurements for the shoulder, elbow, and knee joints. The mean difference was found to be lower than 1.5 degrees (excluding outliers), with a standard deviation of less than 5.5 degrees. These results validate ARPLO-MMC against gold standard measurements for joint angle assessment.

ARPLO's MMC software demonstrated high accuracy in measuring kinematic joint angles, proving to be a simple, cost-effective alternative to traditional methods. Future work will focus on validating additional joint angle measurements, dynamic tests, and other medical performance criteria. This technology promises to eliminate economic and logistical barriers to healthcare, providing accurate health status markers through smartphone teleoperation.

Introduction

ARPLO is a med-tech company building a healthcare solution centered around smart-phone compatible markerless motion capture (MMC) technology. The company's software application creates a telemedicine pipeline between physical therapy patients and medical professionals by remotely measuring joint angles and facilitating the assessment of mobility.

ARPLO's MMC powered app captures limb mobility parameters from video recordings using a smartphone or tablet. The data can be utilized for clinical evaluation by healthcare providers. The ARPLO solution has clear advantages over traditional marker-based systems including accessibility, cost effectiveness and ease of use. It only requires a personal smartphone, eliminating the equipment and labor costs. The software automatically evaluates the joint angles without using special equipment such as goniometers or sophisticated multiple camera-based solutions.

ARPLO's MMC system promises accurate measurement of kinematic joint angles and related dynamic motion parameters based on the differentiated joint kinematic variables including velocities, accelerations, and torques. Errors in kinematic joint angles must be minimized in such MMC systems not only because accurate joint angles are essential, but also differentiation of kinematic variables while calculating the dynamic parameters amplifies any noise and error exist in the kinematic measurements. Therefore, kinematic joint angle measurements must be validated for ARPLO's acceptance and widespread use in clinical and research settings.

The gold standard validation method for MMC systems is comparison to goniometer measurements done by clinical professionals, or marker-based motion capture systems. This research focuses on results for direct comparison MMC software with clinical professionals using a goniometer, the current standard-of-care technique.

Research Aims and Hypotheses

- The primary objective is to assess accuracy of kinematic joint angle measurements in the clinical setting via comparison of limb angle measurements by the MMC software and goniometer measurements done by clinical professionals which is a standard care technique.

- The research hypothesis for this analysis was: there were no statistically significant difference for the three outcome measurements (shoulder joint angle, elbow joint angle, and knee joint angle) between the MMC software and goniometer measurements done by the clinical professionals as a standard care technique.

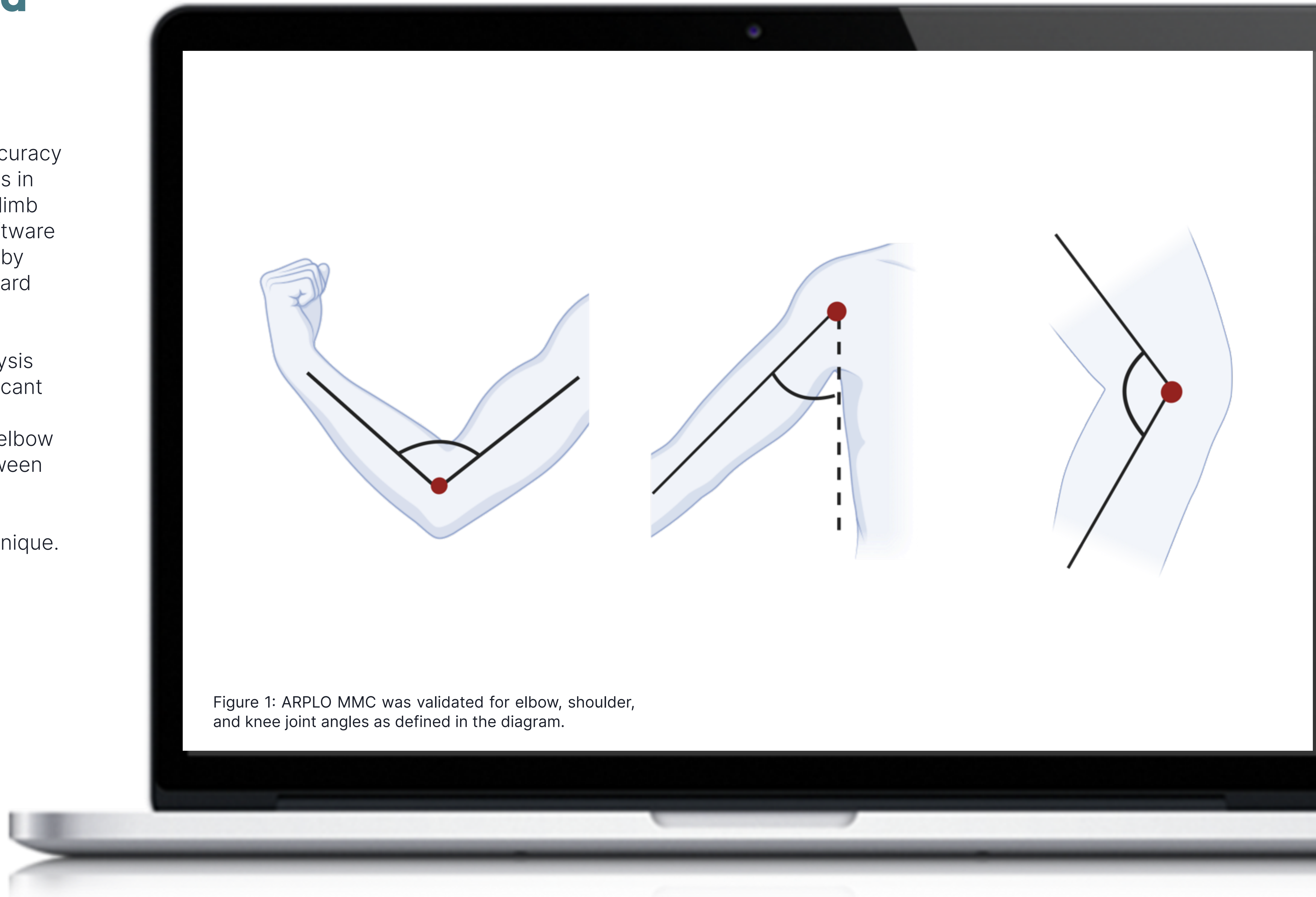


Figure 1: ARPLO MMC was validated for elbow, shoulder, and knee joint angles as defined in the diagram.

Study Population

Data collected from study participants for this included: demographic information (e.g., age, gender/sex, and ethnicity/race) and general health data (e.g., weight, height, and BMI, etc.).

The following inclusion and exclusion criteria were used to define the study population:

Inclusion Criteria

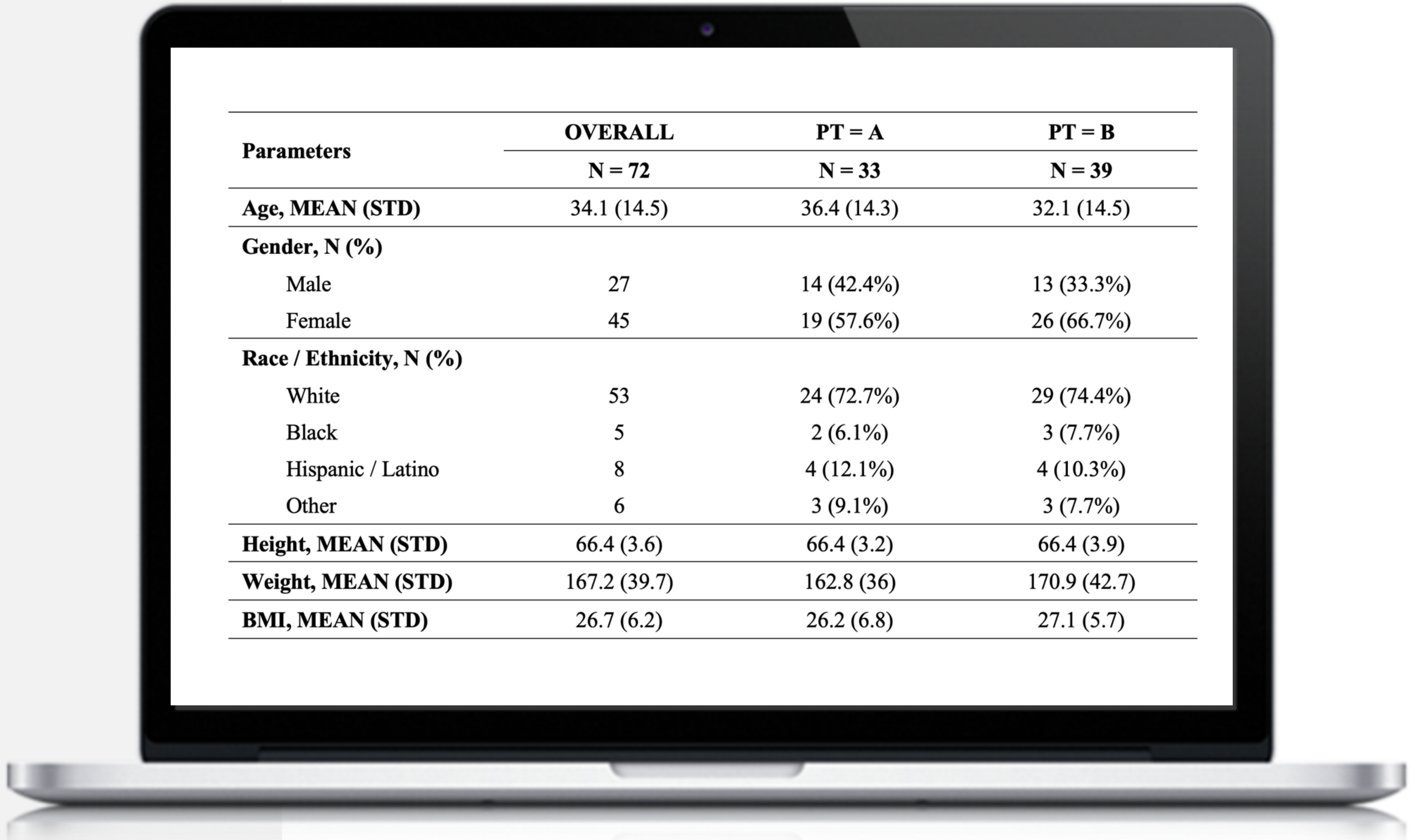
The initial selection of patients for the analysis is comprised of records where:

- All participants with availability to complete the study protocol on the scheduled date and time.
- All participants had the ability to read, write, and comprehend English at a 3rd grade level.
- All participants were active physical therapy patients.

Exclusion Criteria

Participants were excluded from the selection if:

- They were unable to consent to perform the test procedure.
- They were unable to stand or sit in the upright position unassisted.
- They lacked range of motion at the shoulder, elbow, and/or knee joint.

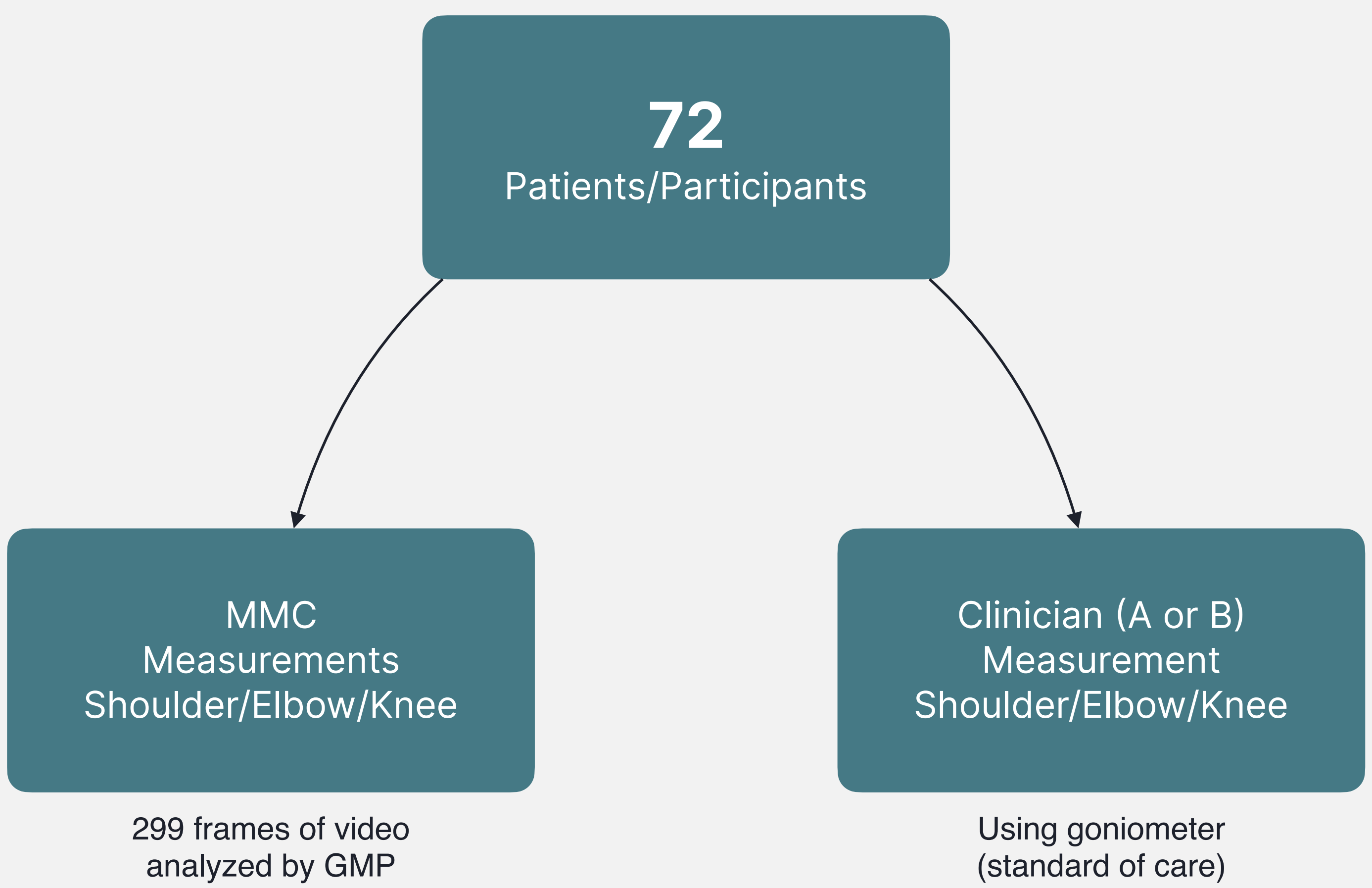


Parameters	OVERALL	PT = A	PT = B
	N = 72	N = 33	N = 39
Age, MEAN (STD)	34.1 (14.5)	36.4 (14.3)	32.1 (14.5)
Gender, N (%)			
Male	27	14 (42.4%)	13 (33.3%)
Female	45	19 (57.6%)	26 (66.7%)
Race / Ethnicity, N (%)			
White	53	24 (72.7%)	29 (74.4%)
Black	5	2 (6.1%)	3 (7.7%)
Hispanic / Latino	8	4 (12.1%)	4 (10.3%)
Other	6	3 (9.1%)	3 (7.7%)
Height, MEAN (STD)	66.4 (3.6)	66.4 (3.2)	66.4 (3.9)
Weight, MEAN (STD)	167.2 (39.7)	162.8 (36)	170.9 (42.7)
BMI, MEAN (STD)	26.7 (6.2)	26.2 (6.8)	27.1 (5.7)

Experimental Data Management

72 patients were included in the analytic sample (2 below).

- For the measurements collected by the MMC software, for each patient, 299 frames were derived regarding each outcome variable (shoulder joint angle, elbow joint angle, and knee joint angle).
- For the data collected by clinical professionals, physical therapist A measured joint angles of 33 participants, and physical therapist B measured the joint angles for the remaining 39 participants.



Methods

Joint Angle Measurement

Measurements of participant joint angles were collected as follows:

- Shoulder joint angle during abduction/adduction: beginning with their arms by their sides, the patients will be directed to laterally raise one of their arms until it is extended over their head, abducting their shoulder. The patient will then be directed to lower their arm and repeat the movement with the other arm. Shoulder joint angles will be measured by a study affiliated clinician.
- Elbow joint angle during flexion/extension: beginning with their arms by their sides, the patients will be directed to elevate their hand by flexing their arm at the elbow. The patient will then be directed to lower their arm extending their elbow and then repeat the movement using their other arm. Elbow joint angles will be measured by a study affiliated clinician.
- Knee joint angle during flexion/extension: from a seated position, the patient will be directed to extend and flex their knee to their best ability. The patient will then be directed to repeat the movement using their other leg. Knee joint angles will be measured by a study affiliated clinician.

Data Analysis

To validate ARPLO's MMC system against the gold standard goniometer measurements, paired t-tests were conducted between both measurement techniques in separately for elbow, shoulder, and knee measurements for 72 patients, who performed the motions described in the methods section. Approximately 20 patients for each limb were disregarded from the data because of the high flutter in the MMC measurements, which is defined as when the MMC software cannot lock into the limb points due to environmental reasons affecting the data collection of the camera such as light reflection or background noise. For each limb, data points corrupted by the high flutter was simply detected by checking the data with MMC and goniometer differences exceeds three times the standard deviation of the population and excluded from the statistical analysis.

The statistical analyses were performed using the current version of open-source statistical programming language SAS 9.4. Summary statistics were done using PROC FREQ / PROC MEANS, descriptive statistics were done using PROC NPAR1WAY, and univariable and multivariable linear mixed model were done using PROC GLM. Plots in the results section were generated via PRISM software.

Results and Discussion

Paired t-test results shown in Figure 1 concludes that, for the elbow, the shoulder, and the knee studies, there were no significant differences in between the goniometer based and the MMC based measurements. The difference between the goniometer and the MMC measurements for each patient (excluding the data points identified as corrupted by high flutter) is shown in Figure 2 with mean difference overall found as lower than 1.5 degrees (excluding outliers) with standard deviation less than 5.5 degrees. The results overall validate the ARPLO-MMC against golden standard measurements for measuring the angle of elbow, shoulder and knee joint.

ARPLO-MMC featured stellar accuracy in measuring the joint angles. Simple data analysis techniques are utilized to eliminate environmental noise, which proves ARPLO-MMC's resilience and flexibility in ambient conditions. Therefore, ARPLO demonstrated the paramount abilities of MMC's: providing accurate, simple, and agile joint angles for physical therapists, eliminating hardships faced due to the goniometer and sophisticated digital devices. Future work involves increasing the number of joint angle measurements validated, verifying the dynamic tests in which patients will move their limbs dynamically during the test, and validating the final medical performance criteria widely used by the physical therapists with the ones measured by conventional techniques.

In addition, the comparisons were conducted by the two therapists. The results showed that the equivalence of the three outcomes still applied for both therapists between the collection from MMC software and clinical professionals using standard care techniques, as $p > 0.05$.

Figure 3: Paired t-test results assessing whether the goniometer and the MMC based measurements of the limb motions were not significantly different. For each limb, from 72 measurements, around 20 measurements were excluded due to the flutter. P values above 0.05 indicate that the difference between the manual and MMC measurements are insignificant.

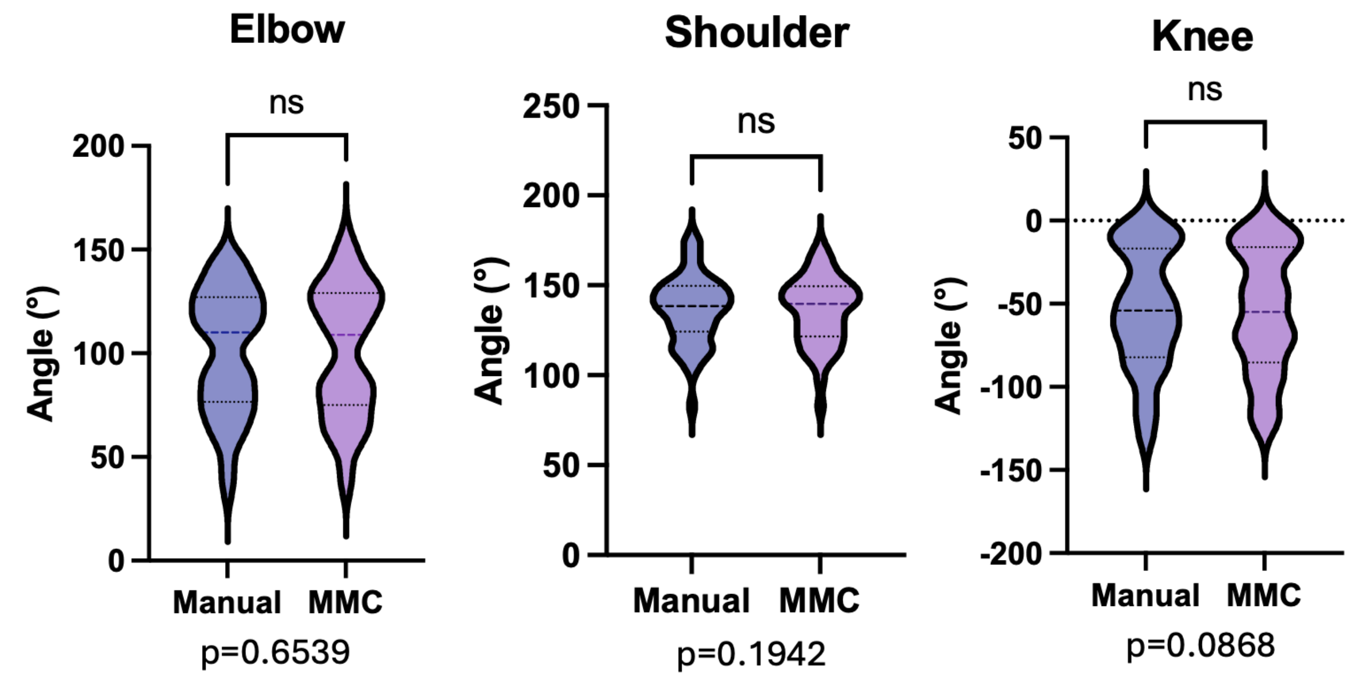
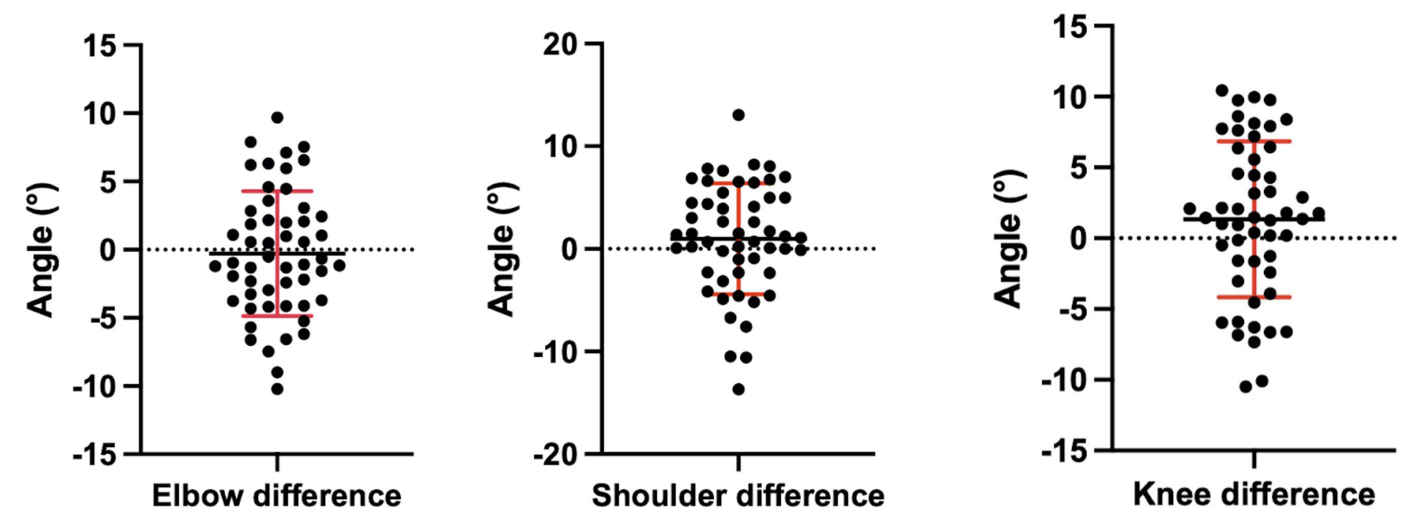


Figure 4: For each limb, differences between the goniometer and the MMC based measurements are shown. Both paired t-test results, the mean difference, and the standard deviation of the difference showed that the knee measurements were the most challenging ones for the MMC.



Conclusions and Future Work

Results of the validation study shows that ARPLO features highly accurate kinematic shoulder, knee, and elbow joint angle measurements through its MMC software. Therefore, the app promises accurate, simple, and cheap physiological joint angle measurements, essential in health screening.

Strong kinematic measurement foundation allows the future versions of ARPLO to provide accurate dynamic motion parameters such as limb speeds, limb accelerations, and joint torques lead towards more descriptive health status information of patients via ARPLO telemedicine MMC system. Such kinematic and dynamic variables are useful not only in orthopedic evaluation but also crucial in cardiovascular, neuronal, or lymphatic studies, informing critical health status markers.

The validation study highlights the future accomplishments of ARPLO, bringing the measurement accurate health status markers solely by teleoperation through smartphones, eliminating the boundaries between the patients and economical or logistical inaccessibility regarding in-person healthcare.

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