The Philippine Journal of Orthopaedics

ORIGINAL ARTICLE

OPEN ACCESS

The Hand Pose Estimation Model in Measuring Range of Motion

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ABSTRACT

Objective. The COVID pandemic has challenged medical practitioners to perform clinical examinations remotely, including assessing the range of motion of the finger joints. This sparked the development of the 3D (three-dimensional) Hand Pose Estimation Model, a software that can generate hand pose estimates and compute hand joint angles from a 2D (two-dimensional) image. The study aims to assess the accuracy of the 3D Hand Pose Estimation Model when compared with a goniometer and radiography.

Methodology. The 3D Hand Pose Estimation Model was developed by training a machine learning model with a parametric hand model and 2D hand images. Ten healthy participants with no history of trauma, disease, or deformity of the hand were enrolled in the study. Active flexion and extension joint angles of the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints of the fingers, excluding the thumb, were measured using the 3D Hand Pose Estimation Model, a goniometer, and radiographs.

Results. The mean joint angles derived from the 3D Hand Pose Estimation Model and goniometer were not significantly different in 18 out of 24 joint angles (75%). While measurements from both instruments differed greatly from those taken on radiographs, more goniometric measurements are within five degrees of the radiographic measurements.

Conclusion. The 3D Hand Pose Estimation Model can estimate joint angles given a 2D image. Improvements in the model can be made with the aid of the data obtained from this study.

Keywords. hand, range of motion, estimation model, machine learning

INTRODUCTION

Joint range of motion (ROM) is a quantitative measure of hand function. It is a measurement obtained to assess a patient's initial disability, therapeutic intervention outcomes, and disease progression or improvement. It can help establish goals and decide the surgical procedure for a patient. Hence, there is a need to measure ROM with accurate, repeatable, and reliable instruments.[1,2]

In clinical practice, doctors most often use a manual goniometer, given that it is accessible, inexpensive, and easy to understand.[1,3,4] Other reported methods include visual estimation, photogoniometers, digital goniometers, and motion sensors. Some of these tools can process digital data and have the advantage of faster data recording, saving, calculation, and sharing. While some offer high precision and accuracy, they are either expensive, or difficult to set up.[5,6]

ISSN 0118-3362 (Print)
eISSN 2012-3264 (Online)
Printed in the Philippines.

Received: August 26, 2023.
Accepted: October 2, 2023.
Published Online: November 15, 2023.
https://doi.org/10.69472/poai.2023.02

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The pandemic brought about by SARS-CoV-2 has challenged physicians to perform physical examinations with limited physical contact. While the end of the pandemic is already in sight, these adaptations and tools developed are likely to last. Van Nest et al., discussed a systematic way of doing hand examinations through telemedicine, emphasizing the current demand for remote physical examinations. In terms of measuring hand range of motion, the ideal tool must be acceptably accurate, easily accessible, and convenient to use for both clinician and patient.[7]

The 3D Hand Pose Estimation Model is a software developed by computer scientists from the University of the Philippines (UP) Diliman under the UP Surgical Innovation and Biotechnology Laboratory (UP SIBOL). It generates hand pose estimates and computes hand joint angles, given 2D hand images as input. The model is based on Mesh Graphormer, a state-of-the-art computer vision model for human pose estimation. Following the U-Net architecture, we modified the Mesh Graphormer model by replacing its backbone network with a 2D hand pose estimation model. This improved the accuracy of the estimates and hand joint angles.

The objective of the study was to compare the measurements obtained with a goniometer and with the 3D Hand Pose Estimation Model of the joint angles of the metacarpophalangeal joint (MCPJ), proximal interphalangeal joint (PIPJ), and distal interphalangeal joints (DIPJ), of the index finger (IF), middle finger (MF), ring finger (RF) and small finger (SF) in extension and flexion. The accuracy of both tools was also evaluated by comparing them to radiographic measurements, considered the gold standard of ROM measurement.

METHODOLOGY

Participants and protocols

Ten healthy participants with a mean age of 27 years old (SD 1.17) were enrolled in the study. Participants with a history of trauma, disease, or deformity of the hand were excluded. The protocol was approved by the University of the Philippines Manila Research Ethics Review Boards; informed consent was obtained from all participants.

Range of motion measurement

Joint angles at active extension and flexion of the MCPJ, PIPJ, and DIPJ of the IF, MF, RF, and SF were measured using the 3D Hand Pose Estimation Model, goniometry, and radiography.

With the subject sitting, the forearm and wrist were positioned in neutral on an X-ray cassette, with the X-ray machine head and smartphone camera overhead. Extension of the MCPJs, PIPJs, and DIPJs was measured with all digits simultaneously in full extension. The patient was then asked to maximally flex the DIPJ and PIPJ while extending the MCPJ (hook fist) to measure the flexion of the DIPJ and PIPJ. The participant was then asked to make a fist with the MCPJ maximally flexed to measure MCPJ flexion. For every position, a video was taken with a smartphone camera and a radiograph was taken with a portable X-ray machine. Following this, goniometry was done by placing the goniometer at the dorsal aspect of the joint and noting the value at full extension and flexion (Figure 1).

Data processing and analysis

The mean joint angles obtained with the goniometer and with the 3D Hand Pose Estimation Model were compared using a two-tailed t-test at a 5% level of significance. The median absolute difference between measurements obtained with the 3D Hand Pose Estimation Model and radiograph and between those obtained with goniometer and radiograph were compared using paired Wilcoxon signed rank test. The number of goniometric and 3D Hand Pose Estimation Model measurements that are within five degrees of the radiographic measurement was calculated to assess for accuracy; five degrees is the reported measurement error of goniometry.[3,9]

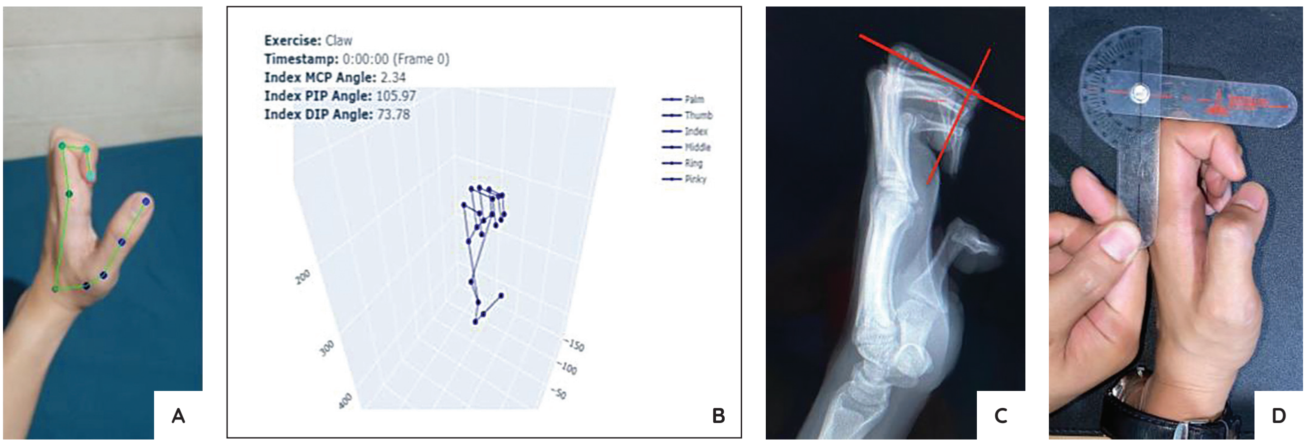

Figure 1. (A) Image of hand with keypoint assignments for Hand Pose estimation model; **(B)** ROM measurement by Hand Pose estimation model; **(C)** ROM measurement with radiographic image; **(D)** ROM measurement with a goniometer.

RESULTS

The mean joint angles for each joint in extension and flexion are shown in Table 1. The range of measured angle in maximum flexion and extension among healthy subjects is wider with the hand pose estimation model (SD 32 deg) compared to the goniometer (SD 15 deg). The 3D Hand Pose Estimation Model-estimated angles are on average higher than the goniometer-measured angle when the joint is in extension. The mean joint angles measured with the two methods were significantly different (p<0.05) for the MF MCPJ and RF PIPJ in extension, and for IF DIPJ and MCPJ, MF MCPJ, and SF MCPJ in flexion.

To assess which method most approximated radiographs, the median absolute difference was obtained (Table 2). Median differences between goniometry and radiography are smaller compared to the median difference between the 3D Hand Pose Estimation Model and radiographs. Wilcoxon signed rank test showed that most differences are statistically significant especially during flexion (10 out of 12 joints) compared to extension (5 out of 12 joints). More goniometric (15 to 70%) than 3D Hand Pose Estimation Model measurements (5 to 45%) are within five degrees of radiographic measurements.

DISCUSSION

The goniometer is the most used device to measure joint ROM. Groth found that 14 out of 16 (13%) goniometric measurements of the interphalangeal joints of the index and middle fingers were significantly different from their radiographic measurement.[1] In our study, 14 of the 24 joint angles measured with a goniometer were not significantly different from radiograph-measured angles (p>0.05, 58.3%). Mcveigh likewise reported that the proportion of goniometric measurements that are within 5 degrees of the radiographic measurement varies from 23 to 58%.[3]

With the advent of telemedicine, motion analysis systems are being developed for remote and dynamic evaluation of joints (e.g., while doing activities of daily living). Meals et al.,[8] compared a photogoniometer with a goniometer in measuring wrist and digit ROM. While they reported good interrater reliability (correlation coefficient ranging from 0.7–0.96) depending on the joint being measured, most of the measurements taken were not in acceptable agreement (correlation coefficient ranging from 0.06–0.86). They encountered problems with the effect of tenodesis, and occlusion of joints (i.e., the joint in study is being covered by

Table 1. Range of motion of (mean and SD) for 3D Hand Pose Estimation Model and goniometer

Digit	Joint	3D Hand Pose Estimation Model, ° mean, (SD)	Goniometer, ° mean, (SD)	*p*
Extension				
IF	DIP	-5 (11)	-3 (4)	0.517
	PIP	-8 (18)	-8 (10)	0.857
	MCP	-2 (18)	4 (14)	0.096
MF	DIP	-7 (17)	-6 (8)	0.782
	PIP	-9 (19)	-10 (11)	0.717
	MCP	-2 (18)	5 (11)	0.030*
RF	DIP	-6 (14)	-3 (9)	0.316
	PIP	-8 (17)	-16 (8)	0.016*
	MCP	-2 (20)	-2 (10)	0.209
SF	DIP	-6 (15)	-5 (7)	0.763
	PIP	-8 (16)	-10 (8)	0.476
	MCP	-2 (16)	-2 (14)	0.901
Flexion				
IF	DIP	51 (22)	71 (9)	<0.001*
	PIP	108 (23)	102 (9)	0.311
	MCP	72 (15)	82 (11)	0.004*
MF	DIP	73 (32)	81 (8)	0.303
	PIP	114 (24)	105 (8)	0.177
	MCP	84 (10)	71 (15)	<0.001*
RF	DIP	64 (28)	72 (12)	0.297
	PIP	104 (22)	104 (8)	0.949
	MCP	80 (17)	81 (10)	0.704
SF	DIP	66 (29)	73 (12)	0.312
	PIP	100 (21)	92 (11)	0.189
	MCP	62 (13)	82 (10)	<0.001*

* statistically significant at a 5% level of significance

Table 2. Comparison of 3D Hand Pose Estimation Model and goniometer with radiographs

Digit	Joint	3D Hand Pose Estimation Model measurement vs radiograph		Goniometer measurement vs radiograph		*p*
		Median (range), absolute difference	Number (%) of absolute differences ≤5 deg	Median (range), absolute difference	Number (%) of absolute differences ≤5 deg	
Extension						
IF	DIP	8 (0,33)	6 (30)	3 (0,9)	12 (60)	0.008*
	PIP	8 (0,32)	9 (45)	4 (0,14)	14 (70)	0.204
	MCP	8 (1,43)	8 (40)	11 (0,22)	4 (20)	0.478
MF	DIP	9 (1,37)	8 (40)	4 (1,18)	14 (70)	0.006*
	PIP	10 (0,34)	6 (30)	6 (0,20)	9 (45)	0.005*
	MCP	11 (0,42)	4 (20)	4 (0,23)	11 (55)	0.001*
RF	DIP	9 (0,38)	6 (30)	5 (0,14)	11 (55)	0.070
	PIP	15 (0,36)	6 (30)	7 (0,22)	7 (35)	0.009*
	MCP	13 (1,50)	6 (30)	6 (0,19)	9 (45)	0.073
SF	DIP	6 (0,36)	8 (40)	4 (0,15)	13 (65)	0.020*
	PIP	7 (1,34)	7 (35)	5 (1,26)	12 (60)	0.083
	MCP	9 (3,50)	5 (25)	9 (0,17)	9 (45)	0.145
Flexion						
IF	DIP	14 (2,81)	4 (20)	7 (0,47)	8 (40)	0.011*
	PIP	14 (0,86)	5 (25)	5 (0,32)	12 (60)	0.025*
	MCP	7 (0,33)	5 (25)	16 (3,38)	3 (15)	0.022*
MF	DIP	14 (2,51)	2 (10)	4 (1,10)	11 (55)	0.002*
	PIP	12 (3,90)	1 (5)	5 (1,21)	11 (55)	0.002*
	MCP	9 (1,21)	9 (45)	6 (0,19)	10 (50)	0.137
RF	DIP	7 (1,83)	5 (25)	5 (1,104)	11 (55)	0.036*
	PIP	14 (0,38)	4 (20)	8 (1,18)	5 (25)	0.020*
	MCP	11 (3,28)	1 (5)	4 (0,17)	13 (65)	0.006*
SF	DIP	12 (1,53)	7 (35)	5 (0,30)	11 (55)	0.005*
	PIP	12 (0,80)	5 (25)	7 (0.16)	8 (40)	0.126
	MCP	13 (3,45)	4 (20)	8 (0,21)	7 (35)	0.018*

* statistically significant at a 5% level of significance

another structure in the image), and recommend obtaining other views of the hand to increase accuracy.

Reissner[9] used a 3D motion capture system (using skin markers to identify key points) to measure the ROM of the hand and wrist and compared it to a goniometric measurement; their measurements were not significantly different. Since the true measure of a joint angle is based on the movement of the bones, the accuracy of ROM measurement using skin markers is limited by the fact that there is skin movement relative to the bone. This is also true for our 3D Hand Pose Estimation Model since assigning key points for those joints that are not occluded is based on skin landmarks like creases or bony prominences. Another limitation reported by Reissner was marker loss; in this regard, our 3D Hand Pose Estimation Model's digitally assigned key points may be advantageous.

The accuracy of 2D images to measure ROM decreases as anatomic landmarks are occluded. Lim et al.,[10] proposed a system using at least three plane mirrors and a camera. By increasing the number of mirrors, multiple simultaneous views of the hand can be obtained and processed to calculate ROM with greater accuracy. They also reported that increasing the number of views from three to five views does not affect accuracy. The 3D Hand Pose Estimation Model is trained using a series of 2D images as well as a parametric hand model; this constraint prevents the program from making estimates for occluded joints that are considered unnatural or impossible joint positions. This is postulated to contribute to the high mean difference in measurements.

Most digital tools are tested by checking for interrater reliability.[8–11] Zhao et al.,[11] reported limitations in using smartphone photography which included the high dependence on the patient taking the photo. The angle measured can be altered by the background, the angle from which the photo was taken, and the quality of the photograph. The 3D Hand Pose Estimation Model should be validated, considering factors such as video lighting, video noise, and camera angulation that can change the assignment of point estimates. This is also to test the applicability of the 3D Hand Pose Estimation Model in a less controlled setting like telemedicine.

CONCLUSION

The goniometer is the most used instrument to measure ROM despite variable accuracy. Our findings show the feasibility of using the 3D Hand Pose Estimation Model in measuring the range of motion of digits; its measurements are comparable to those obtained by a goniometer despite the low accuracy rate when compared to radiographic measurement. This study serves to guide the development of future estimation models.

STATEMENT OF AUTHORSHIP

All authors certified fulfillment of ICMJE authorship criteria.

AUTHORS DISCLOSURE

The authors declared no conflict of interest.

FUNDING SOURCE

Funding for the radiographic tests was given by the Philippine General Hospital Expanded Hospital Research Office.

ACKNOWLEDGMENTS

The authors acknowledge Benjamin Christian J. Esguerra for his help in the data collection and literature review.

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