applied sciences

MDPI

Article

Comparison of the Wrist Range of Motion Measurement between Inertial Measurement Unit Glove, Smartphone Device and Standard Goniometer

Decho Surangsrirat [1,*], Tapiya Bualuangngam [2], Panyawut Sri-iesaranusorn [3], Attawit Chaiyaroj [4], Chatchai Buekban [1], Chusak Thanawattano [1] and Sompob Poopitaya [2]

[1] Assistive Technology and Medical Devices Research Center, National Science and Technology Development Agency, Pathum Thani 12120, Thailand; chatchai.bue@nstda.or.th (C.B.); chusak.tha@nstda.or.th (C.T.)
[2] Orthopedic Surgery, Phramongkutklao College of Medicine, Bangkok 10400, Thailand; ny_dew_na@hotmail.com (T.B.); ortho-pmk@pcm.ac.th (S.P.)
[3] Information Science, Nara Institute of Science and Technology, Nara 630-0101, Japan; sri-iesaranusorn.panyawut.sg0@is.naist.jp
[4] School of Information Science, Japan Advanced Institute of Science and Technology, Ishikawa 923-1211, Japan; s2010410@jaist.ac.jp
* Correspondence: decho.sur@nstda.or.th

Abstract: A goniometer is currently the gold standard for range of motion (ROM) measurements. However, trained staff are required for accurate measurements. The objective of this study is to assess an agreement between the proposed standalone inertial measurement unit glove, smartphone device, and a standard goniometer for the measurement of wrist range of motion. Twenty participants performed wrist flexion, wrist extension, pronation, supination, ulnar deviation, and radial deviation movements with three operators measuring the movements with three devices. Average measurements from the three approaches had within 1.5 degrees of difference from each other for all of the movements. Both the proposed IMU glove and smartphone showed a strong correlation to the goniometer in most of the movements, with an intraclass correlation coefficient (ICC) between 0.914 and 0.961, and between 0.929 and 0.951, respectively. Only wrist supination using the smartphone has an ICC of 0.828. In comparison with a standard goniometer, a smartphone device is a more convenient method and readily available. The proposed IMU glove requires additional hardware but is easier to use and is more suitable for measuring and monitoring dynamic motion than a smartphone or a goniometer. These patient-friendly approaches could be used by the patients at home and provide remote quantitative monitoring during the wrist rehabilitation process.

Keywords: wrist rehabilitation; range of motion; goniometer; inertial measurement unit glove; smartphone

Citation: Surangsrirat, D.; Bualuangngam, T.; Sri-iesaranusorn, P.; Chaiyaroj, A.; Buekban, C.; Thanawattano, C.; Poopitaya, S. Comparison of the Wrist Range of Motion Measurement between Inertial Measurement Unit Glove, Smartphone Device and Standard Goniometer. *Appl. Sci.* **2022**, *12*, 3418. https://doi.org/10.3390/app12073418

Academic Editors: Redha Taiar, Yuri Ivanenko and João R. Vaz

Received: 21 February 2022
Accepted: 21 March 2022
Published: 27 March 2022

1. Introduction

Joint stiffness is a condition in which the movement of a joint is difficult or limited in a way that is not caused by weakness or pain [1]. This condition affects the patient's daily life by requiring more effort or force to perform the movement. Usually, joint stiffness occurs after surgery or prolonged immobilization [2]. It is one of the major problems for orthopedic patients. Physical therapies such as joint range exercise or joint rehabilitation play an important role in helping patients to prevent and relieve joint stiffness [3–5]. Range of motion (ROM) assessment is the most commonly used method to assess the effectiveness of joint motion and measure the distances and directions that a joint can move [6,7]. Medical usage of ROM includes assisting in the diagnosis, monitoring symptoms, or following up on the treatment of orthopedic diseases [8,9].

A goniometer is a standard device for the measurement of wrist ROM [10–14]. However, a trained staff is required to accurately measure the ROM using the device [15,16].

With the advancement of technology and smart devices, the use of a gyroscope for home physiotherapy and an outpatient setting has been explored by many research teams [13,17–19]. As of now, a gyroscope is usually integrated into a smartphone and is accessible via an application, making it an easy-to-use and viable option for patients [20]. However, measuring the wrist ROM by using a smartphone could be troublesome and inaccurate in some movements because the smartphone needs to be fixed securely to the wrist [13,21].

The objective of this study is to develop a glove embedded with a six-axis inertial measurement unit (IMU) and assess an agreement between the developed device, smartphone, and standard goniometer for the measurement of wrist ROM. The proposed IMU glove is easier and more convenient to use than a goniometer and suitable for any wrist movements in comparison to the smartphone device. In this study, we focus on the wrist joint movements in several motion patterns in all three axes including flexion, extension, supination, pronation, ulnar deviation, and radial deviation, [8,13].

The contributions of this study are as follows: (1) development of the glove embedded with IMU; (2) comparison of the measurements of wrist flexion, wrist extension, ulnar deviation, radial deviation, supination, and pronation between goniometer, smartphone, and IMU glove; (3) comparison of intraclass correlation coefficient (ICC) for smartphone and the proposed IMU glove with the goniometer as the gold standard; and (4) comparison of the ICC between different levels of expertise for the three devices.

2. Materials and Methods

The experiment was conducted according to the principles expressed in the Declaration of Helsinki, the Belmont Report, and the International Conference on Harmonization Good Clinical Practice (ICH GCP). It was reviewed and approved by the human research ethics committee of the Royal Thai Army medical department. The research study number and the study document number are R111h/61 and IRBRTA 1754/2561, respectively. All of the participants provided their written informed consent to participate in this study. The clinical trial was registered according to the WHO International Clinical Trials Registry Platform (WHO-ICTRP) at Thai Clinical Trials Registry (TCTR). The registry ID is TCTR20220110006.

2.1. Participants and Operators

This cross-sectional descriptive study includes ten males and ten females for a total of 20 participants with an average age of 29.25 ± 2.53 years. For dominant hands, sixteen participants were right-handed and four were left-handed. All participants were without a previous history of surgery, post-traumatic events, musculoskeletal diseases, or neurovascular problems, as well as any movement disorders of both wrists, forearms, and elbows. To evaluate the operator bias between the different levels of practitioner, the experiment was performed three times for each device by an orthopedic staff, an orthopedic resident, and a medical student, respectively.

2.2. Instrumentation

Each operator was asked to perform the experiment with three devices, a standard goniometer, a smartphone device, and the proposed IMU glove. A universal goniometer with a plastic 360° goniometer face and 7-inch movable arms was used as a standard goniometer. An iPhone 6 with a measurement application was used as the smartphone device. The proposed IMU glove is equipped with a six-axis MPU-6050 MEMS MotionTracking^{TM}, which contains a three-axis gyroscope and a three-axis accelerometer. The measurement signal is sent to the application for recording and visualization.

2.3. Procedure

Each participant was asked to perform six active wrist ROM movements in all three axes; flexion (x), extension (x), pronation (y), supination (y), radial deviation (z), and ulnar deviation (z). Each movement was performed nine times for the three operators; each operator measured the movement three times with three different devices. Figure 1 demonstrates the procedures of the three devices used in this study.

Figure 1. The measurements of wrist range of motion using a standard goniometer, smartphone, and the proposed inertial measurement unit glove for wrist flexion (x), wrist extension (x), pronation (y), supination (y), radial deviation (z), and ulnar deviation (z).

A goniometer was placed at the ulnar styloid next to the little finger and set the initial state as the zero-degree position for wrist flexion and extension measurements. For pronation and supination, participants were instructed to place their elbows and upper arms against the wall before attaching a goniometer to the hand. Then, the goniometer was set to the zero-degree position over the head of the third metacarpal bone. The radial deviation and ulnar deviation were measured by placing the goniometer at the center of the hand and in the middle of the middle finger. For the measurement using a smartphone, the iPhone 6 was placed on the wrists with elbows and upper arms against the wall and flat along their torsos for all of the movements. As for the proposed IMU glove, the participants were instructed to wear it as a regular glove before performing the wrist ROM movements.

2.4. Statistical Analysis

Mean, standard deviation (SD), and ICC are used for statistical analysis in this study [22,23]. Mean and SD are used to assess an agreement between the three devices for the measurements of the six active wrist ROM movements. To validate the reliability of using the proposed IMU glove and a smartphone device,the ICC is calculated by using a standard goniometer as the gold standard. The ICC is also used to illustrate the operator bias and reliability between three different operators with different levels of expertise.

3. Results

Table 1 shows the means of active wrist ROM movements measured from a standard goniometer, a smartphone device, and the proposed IMU glove for the flexion (x), extension (x), supination (y), pronation (y), ulnar deviation (z), and radial deviation (z). Average measurements from the three devices had within 0.5 degrees of differences from each other for flexion, ulnar deviation, and pronation. Extension and supination motions had within 1 degree of difference, whereas radial deviation had within 1.5 degrees of differences from each other.

Table 1. The means of active wrist range of motion movements measured with the three devices.

	Goniometer	Smartphone	IMU Glove
Flexion (x)	87.57 ± 2.42	87.42 ± 3.34	87.92 ± 2.54
Extension (x)	85.02 ± 4.12	85.22 ± 4.00	86.00 ± 3.69
Supination (y)	23.47 ± 2.18	23.70 ± 1.83	24.20 ± 2.08
Pronation (y)	27.70 ± 1.72	27.25 ± 1.85	27.59 ± 1.48
Ulnar deviation (z)	86.23 ± 2.30	86.28 ± 2.69	86.73 ± 2.40
Radial deviation (z)	88.27 ± 2.40	86.97 ± 3.38	87.65 ± 2.87

Table 2 shows the ICC for a smartphone device and the proposed IMU glove with a standard goniometer as the gold standard. There are strong correlations between the IMU glove and a standard goniometer for all the wrist ROM measurements with the ICCs between 0.914 and 0.961 (p-values < 0.001). For a smartphone device, except for the wrist supination with the ICC of 0.828 (p-value < 0.001), other wrist ROM measurements had strong correlations with a standard goniometer. To evaluate the operator bias, Table 3 shows the ICC for the three operators who performed the experiment. Based on the 95% confidence interval of the ICC estimation, all of the movements had strong reliability across the three devices; the ICC was greater than 0.9 with the p-value of less than 0.001.

Table 2. Intraclass correlation coefficient of a smartphone device and the proposed IMU glove with standard goniometer as the gold standard.

	ICC	95% Confidence Interval		*p*-Value
		Lower	Upper	
Flexion (x)				
Smartphone	0.929	0.820	0.972	<0.001
IMU Glove	0.955	0.887	0.982	<0.001
Extension (x)				
Smartphone	0.951	0.877	0.981	<0.001
IMU Glove	0.921	0.801	0.969	<0.001
Supination (y)				
Smartphone	0.828	0.565	0.932	<0.001
IMU Glove	0.933	0.832	0.974	<0.001

Table 2. *Cont.*

	ICC	95% Confidence Interval		*p*-Value
		Lower	Upper	
Pronation (y)				
Smartphone	0.948	0.868	0.979	<0.001
IMU Glove	0.961	0.900	0.984	<0.001
Ulnar deviation (z)				
Smartphone	0.949	0.871	0.980	<0.001
IMU Glove	0.914	0.783	0.966	<0.001
Radial deviation (z)				
Smartphone	0.937	0.841	0.975	<0.001
IMU Glove	0.955	0.885	0.982	<0.001

Table 3. Intraclass correlation coefficient for the three operators who performed the experiment.

	ICC	95% Confidence Interval		*p*-Value
		Lower	Upper	
Flexion (x)				
Goniometer	0.963	0.923	0.984	<0.001
Smartphone	0.984	0.967	0.993	<0.001
IMU Glove	0.983	0.964	0.993	<0.001
Extension (x)				
Goniometer	0.966	0.929	0.986	<0.001
Smartphone	0.989	0.976	0.995	<0.001
IMU Glove	0.977	0.952	0.990	<0.001
Supination (y)				
Goniometer	0.951	0.897	0.979	<0.001
Smartphone	0.978	0.953	0.990	<0.001
IMU Glove	0.982	0.962	0.992	<0.001
Pronation (y)				
Goniometer	0.957	0.909	0.982	<0.001
Smartphone	0.982	0.962	0.992	<0.001
IMU Glove	0.973	0.944	0.989	<0.001
Ulnar deviation (z)				
Goniometer	0.918	0.827	0.965	<0.001
Smartphone	0.964	0.924	0.985	<0.001
IMU Glove	0.929	0.851	0.970	<0.001
Radial deviation (z)				
Goniometer	0.941	0.876	0.975	<0.001
Smartphone	0.955	0.906	0.981	<0.001
IMU Glove	0.968	0.932	0.986	<0.001

4. Discussion and Limitations

Multiple research teams have investigated the use of a gyroscope in smartphone devices for wrist ROM measurement in comparison with a standard goniometer [9,13,21]. They concluded that the device is viable as a convenient and quick way for both the health professional and patient to measure ROM for a rehabilitation process. However, measuring the wrist ROM by using a smartphone could be troublesome and inaccurate because it tends to slip off when the joint motion occurs [13,21]. To address this issue, we developed a glove embedded with a six-axis IMU for measuring active wrist ROM. It is easier and more convenient to use than a goniometer and could monitor the dynamic motions without slipping off during the rehabilitation process. However, patients with bandaged or splinted wounds might require glove modification or customization. Although the experimental results show that the goniometer does not require much skill to perform due to the high ICC for the three operators, please note that the three operators are an orthopedic staff member, an orthopedic resident, and a medical student. Therefore, the results could be different if performed by patients with no prior training. Another advantage of the smartphone and the IMU glove is that there will be no human error or personal bias during the quantitative measurement process because the digital measurement data is already provided by the tools.

5. Conclusions

The experimental results show that both the developed IMU glove and a smartphone device could be viable tools for wrist ROM measurement compared to a goniometer in terms of inter-observer reliability in all directions of wrist motion. The advantage of a smartphone device is its availability, but it could be troublesome and inaccurate because it tends to slip off when joint motion occurs. The developed IMU glove requires additional hardware, but it is easier to use and more suitable for measuring and monitoring dynamic motion than a smartphone device or a goniometer. However, patients with a wound on their hand might require customization or have difficulty wearing the glove.

Further research could also be done with a larger group of participants including the patients to validate the results, especially a patient with a wound that requires customization of the IMU glove. More experiments with novice operators, including caretakers or patients, could also highlight the difference in the ICC between different levels of operators for the three devices. Nevertheless, these patient-friendly approaches could support and provide remote quantitative monitoring for wrist rehabilitation.

Author Contributions: D.S. developed the prototype and was involved in all facets of the study and manuscript preparation. T.B. and S.P. performed the experiments and data analysis. P.S.-i. and A.C. were involved in manuscript preparation. C.B. and C.T. were involved in the prototype development process. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the National Science and Technology Development Agency (NSTDA), Thailand.

Institutional Review Board Statement: The experiment was conducted according to the principles expressed in the Declaration of Helsinki, the Belmont Report, and the International Conference on Harmonization Good Clinical Practice (ICH GCP). It was reviewed and approved by the human research ethics committee of the Royal Thai Army medical department. The research study number and the study document number are R111h/61 and IRBRTA 1754/2561, respectively. The clinical trial was registered according to the WHO International Clinical Trials Registry Platform (WHO-ICTRP) at Thai Clinical Trials Registry (TCTR). The registry id is TCTR20220110006.

Informed Consent Statement: All of the participants provided their written informed consent to participate in this study.

Data Availability Statement: The datasets generated for this study are available on request to the corresponding author.

Acknowledgments: We would like to thank the orthopedic division of Phramongkutkloa hospital and the Maha Vajiralongkorn foundation for their kindness during the research. We would also like to thank Aticha Udomdech; Cholapas Tangbutrawong; Natpawee Tanthaprabha; and Pimonwun Phoomsrikaew. This research would not be completed without support from them.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

References

1. Alexandra, V.F. *Joint Stiffness—Bone, Joint, and Muscle Disorders—MSD Manual Consumer Version*; Merck Manuals: Kenilworth, NJ, USA, 2021.
2. Copeland, S.A.; Gschwend, N.; Landi, A.; Saffar, P. *Joint Stiffness of the Upper Limb*; CRC Press: Boca Raton, FL, USA, 1997; pp. s198–s201.
3. Bhatia, D.; Bejarano, T.; Novo, M. Current interventions in the management of knee osteoarthritis. *J. Pharm. Bioallied Sci.* **2013**, *5*, 30. [CrossRef] [PubMed]
4. Deyle, G.D.; Allison, S.C.; Matekel, R.L.; Ryder, M.G.; Stang, J.M.; Gohdes, D.D.; Hutton, J.P.; Henderson, N.E.; Garber, M.B. Physical Therapy Treatment Effectiveness for Osteoarthritis of the Knee: A Randomized Comparison of Supervised Clinical Exercise and Manual Therapy Procedures Versus a Home Exercise Program. *Phys. Ther.* **2005**, *85*, 1301–1317. [CrossRef] [PubMed]

5. Taylor, A.L.; Wilken, J.M.; Deyle, G.D.; Gill, N.W. Knee Extension and Stiffness in Osteoarthritic and Normal Knees: A Videofluoroscopic Analysis of the Effect of a Single Session of Manual Therapy. *J. Orthop. Sport. Phys. Ther.* **2014**, *44*, 273–282. [CrossRef] [PubMed]
6. Nalam, V.; Lee, H. Development of a Two-Axis Robotic Platform for the Characterization of Two-Dimensional Ankle Mechanics. *IEEE/ASME Trans. Mechatron.* **2019**, *24*, 459–470. [CrossRef]
7. Steultjens, M.P.M.; Dekker, J.; van Baar, M.E.; Oostendorp, R.A.B.; Bijlsma, J.W.J. Range of joint motion and disability in patients with osteoarthritis of the knee or hip. *Rheumatology* **2000**, *39*, 955–961. [CrossRef] [PubMed]
8. Magee, D.J. *Orthopedic Physical Assessment*, 4th ed.; Saunders: Philadelphia, PA, USA, 2006.
9. Muir, S.W.; Corea, C.L.; Beaupre, L. Evaluating change in clinical status: Reliability and measures of agreement for the assessment of glenohumeral range of motion. *N. Am. J. Sport. Phys. Ther. NAJSPT* **2010**, *5*, 98–110.
10. Adams, P.S.; Keyserling, W. Three methods for measuring range of motion while wearing protective clothing: A comparative study. *Int. J. Ind. Ergon.* **1993**, *12*, 177–191. [CrossRef]
11. Macionis, V. A Technique for Graphical Recording of Range of Motion Using an Improvised Paper Goniometer. *J. Hand Ther.* **2011**, *24*, 374–377. [CrossRef] [PubMed]
12. Macionis, V. Reliability of the standard goniometry and diagrammatic recording of finger joint angles: A comparative study with healthy subjects and non-professional raters. *BMC Musculoskelet. Disord.* **2013**, *14*, 17. [CrossRef] [PubMed]
13. Kim, T.S.; Park, D.D.H.; Lee, Y.B.; Han, D.G.; Shim, J.S.; Lee, Y.J.; Kim, P.C.W. A study on the measurement of wrist motion range using the iPhone 4 gyroscope application. *Ann. Plast. Surg.* **2014**, *73*, 215–218. [CrossRef] [PubMed]
14. Choi, B.R.; Kang, S.Y. Intra- and inter-examiner reliability of goniometer and inclinometer use in Craig's test. *J. Phys. Ther. Sci.* **2015**, *27*, 1141–1144. [CrossRef] [PubMed]
15. Jahn, W. Musculoskeletal examination—Range of motion. *J. Can. Chiropr. Assoc.* **1979**, *23*, 51–60.
16. Kolber, M.J.; Pizzini, M.; Robinson, A.; Yanez, D.; Hanney, W.J. The reliability and concurrent validity of measurements used to quantify lumbar spine mobility: An analysis of an iphone® application and gravity based inclinometry. *Int. J. Sport. Phys. Ther.* **2013**, *8*, 129–137.
17. An, Q.; Ishikawa, Y.; Nakagawa, J.; Kuroda, A.; Oka, H.; Yamakawa, H.; Yamashita, A.; Asama, H. Evaluation of wearable gyroscope and accelerometer sensor (PocketIMU2) during walking and sit-to-stand motions. In Proceedings of the 2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication, Paris, France, 9–13 September 2012; pp. 731–736. [CrossRef]
18. Rovini, E.; Maremmani, C.; Cavallo, F. How Wearable Sensors Can Support Parkinson's Disease Diagnosis and Treatment: A Systematic Review. *Front. Neurosci.* **2017**, *11*, 555. [CrossRef]
19. Fahmi, F.; Utomo, N.; Nasution, I.K.; Sawaluddin, S. Stroke therapy using an interactive game with accelerometer and gyroscope sensor device. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *1003*, 012157. [CrossRef]
20. Modest, J.; Clair, B.; DeMasi, R.; Meulenaere, S.; Howley, A.; Aubin, M.; Jones, M. Self-measured wrist range of motion by wrist-injured and wrist-healthy study participants using a built-in iPhone feature as compared with a universal goniometer. *J. Hand Ther.* **2019**, *32*, 507–514. [CrossRef] [PubMed]
21. Santos, C.; Pauchard, N.; Guilloteau, A. Reliability assessment of measuring active wrist pronation and supination range of motion with a smartphone. *Hand Surg. Rehabil.* **2017**, *36*, 338–345. [CrossRef] [PubMed]
22. Koo, T.K.; Li, M.Y. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J. Chiropr. Med.* **2016**, *15*, 155–163. [CrossRef] [PubMed]
23. Liljequist, D.; Elfving, B.; Roaldsen, K.S. Intraclass correlation—A discussion and demonstration of basic features. *PLoS ONE* **2019**, *14*, e0219854. [CrossRef] [PubMed]