GonioPi: Towards Developing a Scalable, Versatile, Reliable and Accurate Handheld-Wearable Digital Goniometer

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***Abstract*—Range of Motion (ROM) Testing is an important physical examination performed in physical therapy used in assessing the ROM of a patient's joint. The most commonly used instrument for ROM Testing is the universal goniometer. The most common cause for unreliable and inaccurate joint angle ROM measurements is measurement errors. Multiple studies have been done to mitigate measurement errors in clinical goniometry by designing and developing wearable digital goniometers using sensor technology. This study aims to design and develop a handheld-wearable digital goniometer called the GonioPi that is versatile, scalable, reliable and accurate when using the MPU-6050 IMU sensor and Raspberry Pi Pico as the main components. The results showed that the GonioPi is versatile and scalable as it is able to support multiple ROM Tests using multiple different positions on people with varying heights, weights, and BMI categories. The results also showed that the GonioPi is reliable and accurate as it was able to record joint angle ROM measurements of less than 5 degrees and 10 degrees which are the accepted standard values for reliability and accuracy, respectively.**

***Keywords*—Range of Motion (ROM); goniometer; physical therapy; goniometry; wearable; sensors; MPU-6050; Raspberry Pi Pico**

I. Introduction

Range of Motion (ROM) Testing is one of the important physical examinations performed in physical therapy and rehabilitative sciences. ROM Testing can be used to identify a patient's underlying conditions to help with diagnosis and rehabilitative treatment.

A goniometer is the most used instrument for ROM Testing. It is used to measure the angle of a patient's ROM at a joint. Goniometers have different types that vary in shape and size depending on which joint is being tested. The most used goniometer are the short arm and long arm universal goniometers. These universal goniometers are still analog which lead to the most common complication in clinical goniometry – measurement errors. Errors in measurement can be caused by systematic errors such as improper technique, improper use of the instrument, the instrument being used, or visual estimation when an instrument is not available. These measurement errors result in unreliable and inaccurate joint angle ROM measurements. A universal goniometer is considered reliable, its mean joint angle ROM measurement should be < 5 degrees [1, 2]. Moreover, it was shown that universal goniometers have a minimum significant difference of 10 to 14 degrees which is considered unreliable and inaccurate when used to measure joint angle ROM [3].

To mitigate measurement errors in clinical goniometry, wearable digital goniometers using sensor technology has been designed and developed by some [4, 5]. Wearable devices using sensor technology in physical therapy and rehabilitative science have shown high reliability and accuracy when used for the application of clinical goniometry. However, gaps in the research can be seen with other factors of the devices such as versatility, scalability, and cost-efficiency.

Previous attempts to develop wearable digital goniometers using sensor technology are neither versatile nor scalable. These studies only considered some of the 34 different ROM tests [6] such as wrist flexion and extension, forearm supination and pronation, radial deviation, and ulnar deviation [7, 8]; elbow joint [9 ,10]; hip flexion [11]; and knee flexion and extension [12]. There is no study which attempted to develop a scalable and versatile digital goniometer - one that can support all possible ROM tests in multiple different positions on people with varying heights, weights, and BMI categories.

Developing a scalable and versatile, not just an accurate and reliable, digital goniometer is important in the field of clinical goniometry [13]. Such an instrument will provide a dependable single device to users without the need to use multiple different instruments to perform different ROM tests. This reduces cost and eliminates the need to train in multiple different instruments.

Therefore, this research aims to design and develop a versatile and scalable handheld-wearable digital goniometer with the use of affordable components that is at the same time accurate and reliable in terms of joint angle ROM measurements when performing ROM Testing. The device is referred here as GonioPi – a portmanteau of the word's goniometer and Raspberry Pi, the microcontroller used to develop the device.

II. Review of Related Literature

A. Physical Therapy and Clinical Goniometry

Physical therapy and rehabilitative science is a field of medicine that focuses on the care of patients with medical conditions related to movement and health. Patient care in this

field is done by physical therapists by providing services that prevent or limit dysfunction.

The concepts of kinesiology and goniometry are important in the field of physical therapy and rehabilitative science as they focus on the study of human motion and joint angle measurements [6, 14]. Moreover, both these concepts are important in identifying and assessing medical conditions related to muscle performance and neurological function [14].

Clinical kinesiology and goniometry involve range of motion which is a technique used to examine the angle created at a joint to assess the need for physical rehabilitation [15, 16]. This is done through different types of range of motion tests such as flexion, extension, abduction, adduction, and rotation among others. Reliable and accurate range of motion tests are needed in diagnosing, assessing, evaluating, and tracking of a patient's physical rehabilitation progress.

B. Range of Motion Instruments

A patient's range of motion can be assessed with the use of different range of motion instruments with the universal goniometer being the most used. Other instruments include the gravity-dependent goniometer (inclinometer), electrogoniometer, and visual estimation [14]. Although these manual instruments (universal goniometer, inclinometer, and visual estimation) are inexpensive, the common issue shared by these instruments are their susceptibility to systematic errors which lead to measurement errors. Electrogoniometers on the other hand, provide better accuracy and reliability as they use electronic components. However, this instrument is often used for the purposes of research rather than in the clinical setting because it is expensive.

C. Wearable Devices using Sensor Technology for Clinical Goniometry

The emerging trend of wearable electronics has extended into the field of medicine with fitness trackers like the Fitbit being the most sold product in the commercial market. Wearable devices are categorized as electronic devices that can be worn, embedded, or implanted in a person's body or clothing. In healthcare, specifically, wearable devices should perform a specific medical function [17]. Wearable devices that monitor biochemical measurements, blood oxygen saturation, blood pressure, cardiac activity, and respiration are currently used in the clinical settings [18].

Wearable devices along with other technologies such as video games and consoles, virtual and augmented realities, exoskeletons, and robots have influenced the medical specialty of physical therapy and rehabilitative science. Over the past decade multiple studies focusing on wearable devices using sensor technology in physical therapy and rehabilitative science have been published [13]. The most used types of sensors in these studies were flex sensors, inertial measurement unit (IMU) sensors, hall-effect sensors, magnetometers, and e-textile and stitched sensors [5]. The studies presented that all these types of sensors have high accuracy and reliability when used for clinical goniometry. However, it is important to consider the advantages and disadvantages of these sensors with regards to other factors such as versatility, scalability, and cost-efficiency.

D. Applications of the MPU-6050 IMU Sensor for Clinical Goniometry

Based on the acquired information from the related literature of wearable devices using sensor technology, it was clear that IMU sensors were the most suitable type of sensor for the design and development of a digital goniometer since they were not limited in versatility, and they had high reliability and accuracy. Thus, the MPU-6050 IMU sensor was chosen as the specific IMU sensor for this research.

The MPU-6050 IMU sensor has multiple applications for both non-medical and medical purposes. The MPU-6050 IMU sensor is used widely across different fields for different purposes utilizing the sensor's 6 degrees of freedom (DOF) with its 3-axis accelerometer and 3-axis gyroscope.

Focusing specifically on the applications of the MPU-6050 IMU sensor for clinical goniometry, related literature has explored the sensor's use in devices that measure the joint angle ROM of the fingers, wrist, forearm, elbow, hip, and knee mostly focusing on the motions of flexion and extension. A data glove for finger joint measurement using three MPU-6050 IMU sensors coupled with two 2.2-inch flex sensors connected to an Arduino microcontroller with all the components sewn onto a cloth glove was used for finger joint flexion – the results showed that the use of MPU-6050 IMU sensor for the device was highly accurate as it recorded low percentage of error ranging from 0.81% to 5.41% [19]. This study only considered fingers, wrist, forearm, elbow, hip, and knee and mostly focused on the motions of flexion and extension. It can be said that the developed device is not versatile. It also did not mention testing for different body sizes, so its scalability is not proven.

Two related studies using the MPU-6050 IMU sensor on a wearable device focused on the ROM Tests of wrist flexion and extension, forearm supination and pronation, radial deviation, and ulnar deviation – the results of both studies were considered reliable since all the ROM Tests recorded joint angle ROM measurements with a standard deviation of < 5 degrees [7, 8]. Similarly, these two developed devices, although found to be reliable, are not versatile. There was also no mention in the studies if the devices were tested for scalability as only one or two test subjects were able to test them.

Another two related studies used the MPU-6050 IMU sensor on wearable devices for the elbow joint [9 ,10]. The first study focused on the ROM Tests of elbow flexion and extension as well as forearm supination and pronation while the second study only focused on the ROM Tests of elbow flexion and extension. The wearable devices of both studies were also considered reliable as they were also able to record average standard deviations for joint angle ROM measurements of < 5 degrees. Both studies also did not consider versatility and scalability, although the devices are found to be reliable.

A study that focused on measuring pelvic retroversion during hip flexion used two MPU-6050 IMU sensors connected an Arduino microcontroller that were attached to elastic Velcro-like straps recorded an average angle of 7.30

degrees which is considered reliable for pelvic retroversion – with this result the researchers concluded that the MPU-6050 IMU sensor was considered reliable when performing the ROM Test of hip flexion [11]. The device, however, cannot be considered versatile or scalable. Although 12 testers tested the device, the BMI categories of the testers were not known.

Finally, a custom physical activity and knee angle measurement sensor system for patients with neuromuscular disorders and gait abnormalities was developed using two MPU-6050 IMU sensors and an 8-bit RISC microprocessor attached to a knee sleeve [12]. The wearable device was used to perform knee joint angle measurements for the ROM Tests of knee flexion and extension and the results were considered reliable as the recorded data showed a standard deviation of < 5 degrees when compared to ground truth data recorded from an electromechanical goniometer. The study did not consider versatility and scalability.

Overall, the MPU-6050 IMU sensor is highly reliable and accurate in measuring joint angle ROM for the application of clinical goniometry. However, it can also be seen with the related literature that the developed wearable devices were limited in versatility and scalability since they generally conform to only some joints or body segments.

III. Methodology

The methodology includes the design, development, testing, and evaluation of the GonioPi and its Assisted Mode feature. The design and development of the GonioPi focuses on achieving high reliability and accuracy as well as satisfying the factors and requirements of versatility and scalability.

A. Design and Development of the GonioPi

The design of the GonioPi is comprised of three parts – the digital goniometer, the acrylic case, and the wearable attachable container.

The digital goniometer is the main component of the GonioPi. It is the instrument that allows users to perform ROM Tests and measure joint angle ROM. To satisfy the factors and requirements of versatility and scalability, the design of the GonioPi's digital goniometer considered components that would allow the MPU-6050 IMU sensor to measure reliable and accurate joint angle ROM measurements. Moreover, these components would have also been of a small and compact form factor. Therefore, the components of the GonioPi's digital goniometer were composed of the Raspberry Pi Pico microcontroller, MPU-6050 IMU sensor, Waveshare Dual GPIO Expander, Waveshare 1.14" LCD Display, DIYMORE 18650 Battery Shield V8, and two 18650 Li-ion rechargeable batteries.

The GonioPi's acrylic case also aimed to satisfy the factors and requirements of versatility and scalability when the GonioPi is used for both its handheld and wearable configuration. Considering that the components of the GonioPi's digital goniometer were chosen since they satisfied the factors and requirements of versatility and scalability, then the goal was to create a case design in which its dimensions were enough to enclose the assembled digital goniometer while maintaining the versatility and scalability of the device. Furthermore, it was taken into consideration that the components of the GonioPi's digital goniometer, especially the MPU-6050 IMU sensor, should be visible to the user in order to avoid errors in placement when positioning the GonioPi on a specific joint or body segment. Thus, the GonioPi's acrylic case was made with 3mm acrylic sheets precisely cut using a CNC machine. The dimensions of the GonioPi with its acrylic case are 7.16cm (length), 6.30cm (width), and 11.20cm (height). Fig. 1 shows the GonioPi with its assembled digital goniometer enclosed in the acrylic case.

The GonioPi's wearable attachable container still aimed in satisfying the factors and requirements of versatility and scalability.

Considering that the GonioPi's digital goniometer enclosed in its acrylic should have already satisfied the factors and requirements of versatility and scalability, then the goal was to create a wearable design that would maintain the versatility and scalability of the device. Thus, the GonioPi's wearable attachable container had a pouch-like design made of synthetic fabric, specifically spandex lined with fusible interfacing, with an adjustable buckle strap. The adjustable buckle strap of the GonioPi's wearable attachable container has a length of 133cm which allowed it to fit from the waist and chest body segments all the way down to the wrist joint. Fig. 2 shows the GonioPi inside its wearable attachable container.

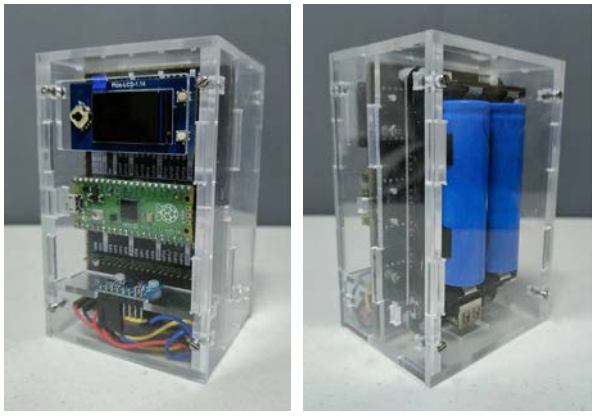

Fig. 1. GonioPi with Assembled Digital Goniometer in the Acrylic Case.

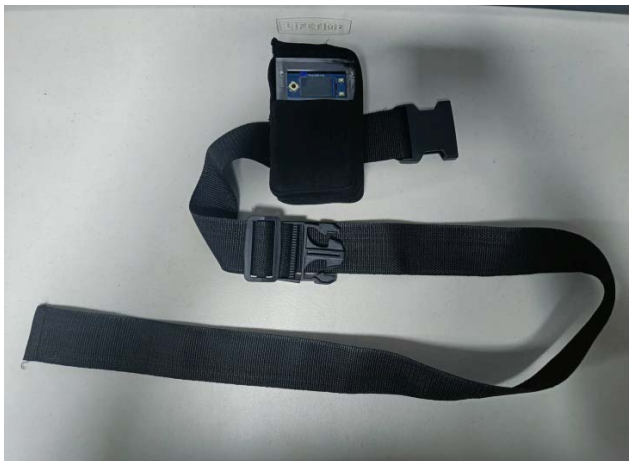

Fig. 2. GonioPi's Wearable Attachable Container.

Finally, dual-axis tilt calculation was used to calculate and output the tilt angle measured by the MPU-6050 IMU sensor. Dual-axis tilt calculation was done by solving for the ratio of the inverse sine of the x-axis and inverse cosine of the y-axis [20]. Equation (1) shows the formula for dual-axis tilt calculation. Equation (2) shows the formula to solve for the angle (theta) using dual-axis tilt calculation. With this implementation, the GonioPi was able to output angle measurements from 0 degrees to 180 degrees when it is tilted either clockwise or counterclockwise on the x-axis or z-axis.

$$\frac{A_{X,OUT}}{A_{Y,OUT}} = \frac{1\,g \times \sin(\theta)}{1\,g \times \cos(\theta)} = \tan(\theta) \quad (1)$$

$$\theta = tan^{-1}\left(\frac{A_{X,OUT}}{A_{Y,OUT}}\right) \quad (2)$$

B. Assisted Mode Feature

The Assisted Mode feature of the GonioPi has the main functionality of outputting responsive feedback to the user when the GonioPi is used to measure joint angle ROM. The feature uses the factors of age and gender to give the user feedback if the joint angle ROM measured is BELOW NORMAL, NORMAL, or ABOVE NORMAL.

The Assisted Mode feature was implemented using a finite state machine which utilized a nested switch case algorithm. The factors of age sex, type of joint, type of motion, and normal range of motion are used to assess the measured joint angle ROM.

C. Initial Device Testing

The initial device testing of the GonioPi was performed independently by the researchers with the aid of a test subject to identify the supported ROM Tests of the GonioPi. This was done using both the handheld and wearable configurations. Since the researchers are not professionals in the field of physical therapy, a criterion stating that a ROM Test was considered initially supported by GonioPi if the device was able to output a joint angle ROM with a minus 5-degree threshold from the maximum value of the full ROM of a specific joint. Fig. 3 shows the researchers performing the initial device testing on a test subject.

D. Final Device Testing

The final device testing of the GonioPi consisted of confirming which ROM Tests were supported by the GonioPi using both the handheld and wearable configurations, reliability and accuracy testing, and an evaluation of the GonioPi and its Assisted Mode feature. The final device testing of the GonioPi was performed by eight medical professionals, specifically physical therapy interns, grouped into four pairs. Fig. 4 shows the final device testing of the GonioPi performed by the testers.

E. Final Device Testing for Confirmed Supported ROM Tests

The final device testing for confirmed supported ROM Test was done by making the testers use the GonioPi to perform a specific ROM Test on their partner. The testers were then asked to record if whether a specific ROM Test was either supported or unsupported by the GonioPi. Considering that the testers were professionals in the field of physical therapy, the decision of labeling whether a specific ROM Test was considered supported or unsupported by the GonioPi was purely based on the tester's assessment of the device when using it in both its handheld and wearable configurations respectively.

The results recorded by the medical professionals were then collected and tallied. A specific ROM Test was then confirmed to be supported by the GonioPi if 60% or five out of eight testers labeled it as supported, otherwise it was confirmed to be unsupported by the GonioPi.

F. Final Device Testing for Reliability and Accuracy

The final device testing for reliability and accuracy of the GonioPi was limited to the ROM Tests of flexion and extension for the shoulder, elbow, hip, and knee. The GonioPi's reliability and accuracy were evaluated using the statistical methods of standard deviation and significant difference, respectively.

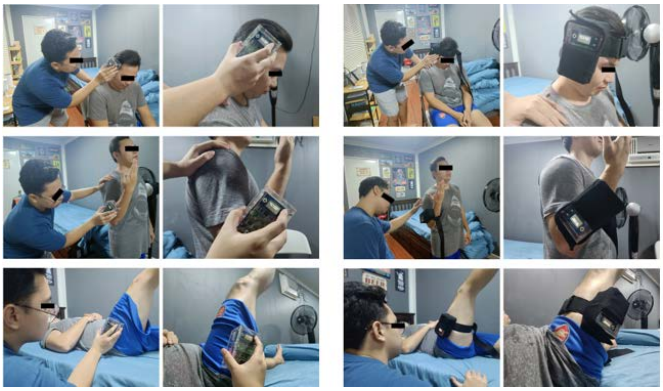

Fig. 3. Initial Device Testing of the GonioPi.

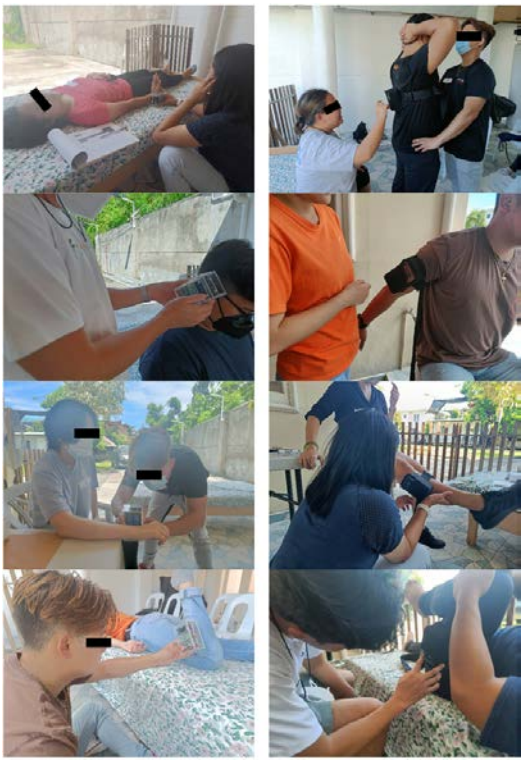

Fig. 4. Final Device Testing of the GonioPi.

It is important to note that the ROM Tests of shoulder and elbow flexion and extension were performed using the in sitting position, the ROM Test of hip flexion was done using the supine position, and the ROM Tests of hip extension as well as knee flexion and extension were done using the prone position.

The testers measured the joint angle ROM of each ROM Test being tested for reliability five times on their partner. Once the data was gathered and collected, the standard deviation for a specific ROM Test of each test subject was computed by the researchers. This was done for both the handheld and wearable configuration. The average standard deviation for each ROM Test was then computed by the researchers using the values of the individual standard deviation for a specific ROM Test of each test subject.

An average joint angle ROM measurement of <= 5 degrees must have been achieved by the GonioPi for it to be considered reliable when performing a specific ROM Test, otherwise it was considered unreliable.

The accuracy of the GonioPi was evaluated using significant difference. A Bland Altman plot using 1.96 multiplied by the standard deviation generates a 95% confidence interval for evaluating a ROM Test [3]. Thus, the GonioPi's accuracy for each ROM Test was solved by multiplying 1.96 with the values of the average standard deviation of each ROM Test collected from the GonioPi's reliability testing.

An average joint angle ROM measurement of <= 10 degrees must have been achieved by the GonioPi for it to be considered accurate when performing a specific ROM Test, otherwise it was considered inaccurate.

G. Versatility and Scalability of the GonioPi

Versatility is the ability of a device to perform multiple ROM Tests on different joints using different types of motions and scalability is the ability of a device to handle different body sizes [13].

The versatility and scalability of the GonioPi were evaluated based on the results of the GonioPi's final device testing for the confirmed supported ROM Tests. Versatility of the GonioPi was evaluated based on the number of ROM Tests supported by the GonioPi – specifically considering how many out of the 11 joints and 15 motions were supported by the GonioPi using its handheld and wearable configurations, respectively. Scalability of the GonioPi was also evaluated based on the number of ROM Tests supported by the GonioPi – specifically considering the varying heights, weights, and BMI categories of the test subjects.

H. Evaluation of the GonioPi and the Assisted Mode Feature

Both the GonioPi and its Assisted Mode feature were evaluated through a survey with a series of qualitative questions. The GonioPi was evaluated based on its perceived usefulness, perceived ease of use, emotions, attitudes, and comfort. The Assisted Mode feature was evaluated based on its importance, usefulness, helpfulness, and design.

IV. Results and Discussion

The results and discussion include a general overview of the results for initial device testing as well as the evaluation of the GonioPi and its Assisted Mode feature. Meanwhile, detailed results of the final device testing for the confirmed ROM Tests of the GonioPi and device reliability and accuracy testing are presented.

A. Results of the Initial Device Testing

The initial device testing of the GonioPi showed promising results for both the handheld and wearable configurations. Majority of the ROM Tests for both configurations were considered initially supported by the GonioPi using multiple different positions based on the set criterion. Specifically, the handheld configuration supported 30 out of 34 ROM Tests and the wearable configuration supported 21 out of 34 ROM Tests. With these promising results, it was evident that final device testing with medical professionals had to be performed to confirm the supported ROM Tests of the GonioPi.

B. Results of the Final Device Testing of the GonioPi for Confirmed Supported ROM Tests

The results for the final device testing of the GonioPi for the confirmed supported ROM Tests of the GonioPi showed that using its handheld configuration, the GonioPi supports 34 out of 34 ROM Tests using multiple different positions such as supine, prone, in sitting, and standing. Notably, all 34 ROM Tests were unanimously confirmed to be supported by the testers.

Furthermore, using its wearable configuration, the GonioPi supports 18 out of 34 ROM Tests using multiple different positions such as supine, prone, in sitting, and standing. The other 16 ROM Tests were confirmed by the testers to be unsupported by the GonioPi when used as a wearable device. Out of the 16 ROM Tests confirmed to be unsupported by the testers, 8 of which consists of the wrist and ankle joints – these were the ROM Tests of wrist flexion, wrist extension, ulnar deviation, radial deviation, ankle dorsiflexion, ankle plantarflexion, ankle inversion, and ankle eversion. These ROM Tests were considered unsupported by the testers because the GonioPi's size was too bulky when attached to these joints which did not allow the testers to properly position the device to perform these ROM Tests. Moreover, the testers stated that the bulkiness of the GonioPi also impeded the movement of the joint when attached to the test subject. Four ROM Tests, specifically cervical extension, cervical lateral flexion, trunk flexion, and trunk extension were considered unsupported by the testers because the GonioPi could not output joint angle ROM measurements that were satisfactory for the testers to consider them supported. Moreover, the testers stated that due to the bulkiness and weight of the GonioPi, testing these ROM Tests using the wearable configuration was greatly affected by gravity. The GonioPi in in its attachable container would sag which affected the joint angle ROM measurement being outputted by the GonioPi. Also, for the ROM Tests of trunk flexion and extension the testers stated that they could not position the GonioPi using its attachable container properly on the test subject's body. Finally, the last 4 ROM Tests, specifically forearm supination, forearm pronation, hip abduction, and hip adduction – these

ROM Tests were considered unsupported by the testers because the GonioPi's sensor does not work and could not output a proper joint angle ROM measurement when attached to the body segment or joint of these ROM Tests as the sensor was oriented on the y-axis. The GonioPi's dual-axis tilt calculation implementation only allows for it to output angle measurements when the sensor is oriented on its x-axis or z-axis.

Table I shows a summary of all the confirmed supported and unsupported ROM Tests of the GonioPi both using its handheld and wearable configurations.

TABLE I. SUMMARY OF THE CONFIRMED SUPPORTED ROM TESTS FOR HANDHELD AND WEARABLE CONFIGURATIONS

GonioPi Final Device Testing Results		
Range of Motion Test	**Handheld**	**Wearable**
1. Cervical Flexion	(8/8) Supported	(7/8) Supported
2. Cervical Extension	(8/8) Supported	(1/8) Unsupported
3. Cervical Lateral Flexion	(8/8) Supported	(0/8) Unsupported
4. Cervical Rotation	(8/8) Supported	(8/8) Supported
5. Wrist Flexion	(8/8) Supported	(0/8) Unsupported
6. Wrist Extension	(8/8) Supported	(0/8) Unsupported
7. Ulnar Deviation	(8/8) Supported	(0/8) Unsupported
8. Radial Deviation	(8/8) Supported	(0/8) Unsupported
9. Shoulder Flexion	(8/8) Supported	(8/8) Supported
10. Shoulder Extension	(8/8) Supported	(8/8) Supported
11. Shoulder Abduction	(8/8) Supported	(8/8) Supported
12. Shoulder Adduction	(8/8) Supported	(8/8) Supported
13. Shoulder Lateral Rotation	(8/8) Supported	(8/8) Supported
14. Shoulder Medial Rotation	(8/8) Supported	(8/8) Supported
15. Forearm Supination	(8/8) Supported	(0/8) Unsupported
16. Forearm Pronation	(8/8) Supported	(0/8) Unsupported
17. Elbow Flexion	(8/8) Supported	(8/8) Supported
18. Elbow Extension	(8/8) Supported	(8/8) Supported
19. Trunk Flexion	(8/8) Supported	(0/8) Unsupported
20. Trunk Extension	(8/8) Supported	(0/8) Unsupported
21. Trunk Lateral Flexion	(8/8) Supported	(6/8) Supported
22. Trunk Rotation	(8/8) Supported	(5/8) Supported
23. Hip Flexion	(8/8) Supported	(7/8) Supported
24. Hip Extension	(8/8) Supported	(8/8) Supported
25. Hip Abduction	(8/8) Supported	(0/8) Unsupported
26. Hip Adduction	(8/8) Supported	(0/8) Unsupported
27. Hip Lateral Rotation (ER)	(8/8) Supported	(8/8) Supported
28. Hip Medial Rotation (IR)	(8/8) Supported	(8/8) Supported
29. Knee Flexion	(8/8) Supported	(8/8) Supported
30. Knee Extension	(8/8) Supported	(8/8) Supported
31. Ankle Dorsiflexion	(8/8) Supported	(0/8) Unsupported
32. Ankle Plantarflexion	(8/8) Supported	(0/8) Unsupported
33. Ankle Inversion	(8/8) Supported	(0/8) Unsupported
34. Ankle Eversion	(8/8) Supported	(0/8) Unsupported

C. Results of the Final Device Testing for Reliability and Accuracy

The results of the final device testing for reliability presented that the GonioPi using the handheld configuration is reliable for 6 out of the 8 ROM Tests that were evaluated. Specifically, the ROM Tests of shoulder flexion, shoulder extension, elbow flexion, hip extension, knee flexion, and knee extension. The GonioPi was considered reliable in performing these ROM Tests because their individual average standard deviations when using the GonioPi in its handheld configuration was <= 5 degrees. As for the ROM Tests considered as unreliable, specifically elbow extension and hip flexion – they were considered unreliable because their individual standard deviations were > 5 degrees. However, it is important to note that for the ROM Test of elbow extension the average standard deviation was only greater by 0.13 degrees and for the ROM Test of hip flexion the average standard deviation was only greater by 0.41 degrees.

Moreover, using the wearable configuration, the GonioPi is reliable for 5 out of 8 ROM Tests that were evaluated. Specifically, the ROM Tests of shoulder extension, elbow flexion, elbow extension, hip flexion, and knee extension. The GonioPi was considered reliable in performing these ROM Tests because their individual average standard deviations when using the GonioPi in its handheld configuration was <= 5 degrees. As for the ROM Tests considered as unreliable, specifically shoulder flexion, hip extension, and knee flexion – they were considered unreliable because their individual standard deviations were > 5 degrees. However, it is important to note that for the ROM Test of shoulder flexion the average standard deviation was only greater by 0.91 degrees. Furthermore, for the ROM Test of hip extension the average standard deviation was only greater by 0.47 degrees and for the ROM Test of knee flexion the average standard deviation was only greater by 0.35 degrees.

Table II shows a summary of the results for the GonioPi's reliability testing.

Considering the accuracy testing of the GonioPi for the 8 ROM Tests being evaluated was dependent of the average standard deviation values for the GonioPi's reliability testing, it was expected that the results would be consistent in the sense that the ROM Tests considered reliable were also accurate and the ROM Tests considered unreliable were also inaccurate.

Therefore, for the handheld configuration the 6 ROM Tests of shoulder flexion, shoulder extension, elbow flexion, hip extension, knee flexion, and knee extension the GonioPi was accurate in performing these ROM Tests because their individual significant differences were <= 10 degrees. As for the 2 ROM Tests of elbow extension and hip flexion, the GonioPi was inaccurate in performing these ROM Tests because their individual significant differences were > 10 degrees. However, it is still important to note that the significant difference for the ROM Test of elbow extension was only greater by 0.05 degrees and for the ROM Test of hip flexion the significant difference was only greater by 0.60 degrees.

TABLE II. SUMMARY OF THE AVERAGE STANDARD DEVIATIONS FOR RELAIBLITY TESTING USING THE HANDHELD AND WEARABLE CONFIGURATIONS

GonioPi Reliability Testing Results for Handheld Configuration		
Range of Motion Test	**Average Standard Deviation**	**Remarks**
Shoulder Flexion	4.01°	Reliable
Shoulder Extension	3.64°	Reliable
Elbow Flexion	4.42°	Reliable
Elbow Extension	5.13°	Unreliable
Hip Flexion	5.41°	Unreliable
Hip Extension	4.61°	Reliable
Knee Flexion	4.06°	Reliable
Knee Extension	4.87°	Reliable
GonioPi Reliability Testing Results for Wearable Configuration		
Range of Motion Test	**Average Standard Deviation**	**Remarks**
Shoulder Flexion	5.91°	Unreliable
Shoulder Extension	4.18°	Reliable
Elbow Flexion	3.74°	Reliable
Elbow Extension	4.36°	Reliable
Hip Flexion	4.17°	Reliable
Hip Extension	5.47°	Unreliable
Knee Flexion	5.35°	Unreliable
Knee Extension	4.85°	Reliable

Moreover, for the wearable configuration, the 5 ROM Tests of shoulder extension, elbow flexion, elbow extension, hip flexion, and knee extension the GonioPi was accurate in performing these ROM Tests because their individual significant differences were <= 10 degrees. As for the 3 ROM Tests of shoulder flexion, hip extension, and knee flexion, the GonioPi was inaccurate in performing these ROM Tests because their individual significant differences were > 10 degrees. However, it is also still important to note that for the ROM Test of shoulder flexion the significant difference was only greater by 1.58 degrees. Furthermore, for the ROM Test of hip extension, the significant difference was only greater by 0.72 degrees. Finally, for the ROM Test of knee flexion, the significant difference was only greater by 0.49 degrees.

Table III shows the summary of the results for the GonioPi's accuracy testing.

There is no consistency with the ROM Tests considered as unreliable and inaccurate when comparing the results for both the handheld and wearable configurations. Thus, retesting these ROM Tests for reliability using the GonioPi or an improved version of the device should be considered in a future study.

Overall, it can be said that the GonioPi can be considered as reliable and accurate for the 8 ROM Tests evaluated for reliability and accuracy since most of them were considered reliable and accurate and those considered unreliable and inaccurate were only a few decimal points greater than accepted standard values of 5 degrees and 10 degrees respectively.

TABLE III. SUMMARY OF THE SIGNIFICANT DIFFERENCE FOR ACCURACY TESTING USING THE HANDHELD AND WEARABLE CONFIGURATIONS

GonioPi Accuracy Testing Results for Handheld Configuration		
Range of Motion Test	**Average Significant Difference**	**Remarks**
Shoulder Flexion	7.86°	Accurate
Shoulder Extension	7.13°	Accurate
Elbow Flexion	8.66°	Accurate
Elbow Extension	10.05°	Inaccurate
Hip Flexion	10.60°	Inaccurate
Hip Extension	9.04°	Accurate
Knee Flexion	7.96°	Accurate
Knee Extension	9.55°	Accurate
GonioPi Accuracy Testing Results for Wearable Configuration		
Range of Motion Test	**Average Significant Difference**	**Remarks**
Shoulder Flexion	11.58°	Inaccurate
Shoulder Extension	8.19°	Accurate
Elbow Flexion	7.33°	Accurate
Elbow Extension	8.55°	Accurate
Hip Flexion	8.17°	Accurate
Hip Extension	10.72°	Inaccurate
Knee Flexion	10.49°	Inaccurate
Knee Extension	9.51°	Accurate

D. Results for the Versatility and Scalability of the GonioPi

In terms of versatility, considering that 34 out of 34 ROM Tests are supported by the GonioPi using its handheld configuration and out of those 34 supported ROM Tests 11 out of 11 joints and 15 out of 15 motions are supported, then it can be said that the GonioPi is versatile when used as a handheld digital goniometer.

Furthermore, still in terms of versatility, considering that 18 out of 34 ROM Tests (52%) are supported by the GonioPi using its wearable configuration and out of those 18 supported ROM Tests, 6 out of 11 joints (54%) and 8 out of 15 motions (53%) are supported then it can be said that the GonioPi is relatively versatile when used as a wearable digital goniometer. The GonioPi's issue with versatility using its wearable configuration is due to its bulky size and improper sensor orientation when attached to a specific unsupported joint. The issue of the GonioPi's bulky size can be resolved by making the design of the GonioPi smaller and more compact. The issue of improper sensor orientation can be resolved by using triple-axis tilt calculation for solving the joint angle ROM measurement rather than the current implementation which uses dual-axis tilt calculation.

In terms of scalability, considering that the GonioPi using both its handheld and wearable configurations was tested on test subjects of varying heights, weights, and BMIs – specifically, five (5) normal, (2) overweight, and (2) obese then it can be said that the GonioPi is scalable as both a handheld and wearable digital goniometer. However, a future study can be performed to include the underweight BMI category to

better establish the GonioPi's scalability. Moreover, the GonioPi using its handheld configuration can be used to perform ROM Tests for both large and small joints of the body while the GonioPi using its wearable configuration can be used to perform ROM Tests for mostly large joints on the body. Both configurations, however, do not allow for ROM Tests for the finger joint. Finally, it is important to note that the GonioPi's wearable attachable container design can conform to all joints of the body except for the fingers.

E. Results of the Evaluation of the GonioPi and Assisted Mode Feature

The results of the survey for the evaluation of the GonioPi presented that majority of the testers found the GonioPi to be useful, easy to use, likeable, and comfortable when used as a digital goniometer by medical professionals for both its handheld and wearable configurations. Majority of the positive feedback from the testers regarding the GonioPi highlighted its efficiency, convenience, and ease of use. A tester also mentioned that it is a nice and useful innovation. Moreover, the testers mentioned that the GonioPi helps them in their profession by allowing them to get ROM measurements faster and easier. When it comes to the negative feedback of the GonioPi, the testers highlighted its size being too bulky. Moreover, the testers also stated that its wearable configuration limits some motions and that because of its weight it is greatly influenced by gravity. The testers also mentioned that the sensor is quite sensitive and picks up some unnecessary motions. A tester also mentioned that the GonioPi has a lack of visual markers such as a fulcrum and arm like the universal goniometer. Finally, as for the wearable attachable container's design, they found it a bit loose, and the adjustable buckle strap a hassle to adjust. The testers stated that the GonioPi can be improved by decreasing its size – making it less bulky and more compact. Moreover, adding visual markers such as an indicator of a fulcrum and an arm on the acrylic case could help getting joint angle ROM measurements easier in the sense that it decreases user error of overcompensating or undercompensating the tilt of the device. One tester mentioned that a bigger switch and buttons would be beneficial for them. Finally, as for the wearable attachable container, the testers suggested that the strap should be thinner and smoother while the attachable container should be more secure.

The results for the survey of the Assisted Mode feature of the GonioPi presented that majority of the testers found the Assisted Mode feature to be important, useful, helpful, and user friendly which increases the usability and relevance of the GonioPi. Moreover, the feature also makes the GonioPi a better device overall. Majority of the positive feedback from the testers regarding the Assisted Mode feature of the GonioPi highlighted how it makes it easier for a user to determine whether or not the joint angle ROM measurement of a patient is within normal range or not. Moreover, the testers mentioned that it is helpful in aiding physical therapists determine the state of a patient's ROM. Lastly, a tester stated that it is useful and effective especially for "newbies". When it comes to the negative feedback from the testers regarding the Assisted Mode feature of the GonioPi, the testers highlighted how the feature only has limited motions and joints. A couple of testers stated that the feature may be at risk for inaccuracy due to human error when using the GonioPi. Lastly, a tester stated that the feature has no indication of the normal values of each joint. The testers stated that the GonioPi's Assisted Mode feature can be improved by adding more options of joints and motions to be tested. Moreover, a tester stated that adding the normal values of each joint for a user's awareness and knowledge can be helpful. Finally, a tester also stated that a warning message requesting the tester to immobilize patient's joint being tested may help in decreasing human errors that may lead to measurement errors in the joint angle ROM measurement.

F. Limitations of the Final Device Testing

It should be noted that the method for the final device testing of the GonioPi for confirmed supported ROM Tests was done by making each tester perform 9 ROM Tests using different positions on their partner while the other pairs observed and gave their remarks based on their observation of the ROM Test being performed. This means that all testers have not tested each ROM tests using the device. This may have effects on the collected data as actually using the device for measurement may give a different result compared with just observing.

In addition, the testers in the final device testing are physical therapy interns. While it is assumed that they have sufficient knowledge in clinical goniometry, it might provide different results if the test was carried out by experienced physical therapists.

Looking at the results for reliability of the GonioPi for both the handheld and wearable configurations, there is no consistency with the ROM Tests considered as unreliable. Moreover, comparing the individual data collected from the test subjects, the first two pairs of testers-test subjects (testers 1, 2, 3, and 4) had higher values of individual standard deviations for the different ROM Tests compared to the next two pairs of testers-test subjects (testers 3, 4, 5, and 6). The possibility of these differences in results may have been caused by tester-test subject/patient fatigue as manifested by the testers themselves during testing. Considering that the first two pairs of testers-test subjects extended their testing time during the first day, it raises the possibility that by the time they were collecting the data for reliability testing they were already tired and could not properly and consistently perform the different ROM Tests being evaluated. Compared to the next two pairs of testers-test subjects who performed the data gathering for the reliability testing during the second day of testing – they were able to perform the different ROM Tests more consistently as they were not affected by fatigue from an entire day of testing.

V. Future Works and Recommendations

The current size of the GonioPi is too bulky. An improvement that can be made to resolve this issue would be to look for and use smaller and more compact components to reduce the overall size of the GonioPi. The researchers suggest future works consider using the Pimoroni LiPo SHIM for Pico power supply. It is a small and compact power supply that can be powered by a LiPo/Li-Ion battery and soldered onto the back of the Rapsberry Pi Pico microcontroller. Using this component as a substitute power supply of the battery shield

V8 would reduce the thickness of the GonioPi by about 2.70cm which would result to an overall thickness of 3.60cm for the next version of the GonioPi.

A reduction in the overall size and weight of the GonioPi would allow the attachable container to be more secure since it will be affected less by gravity due to the reduced weight of the GonioPi. Moreover, as for the adjustable straps of the wearable attachable container, an improvement can be made by reducing its thickness and changing the adjustable buckle strap to an adjustable belt strap and lock as suggested by one of the testers.

For the GonioPi to support more ROM Tests using its wearable configuration as well as improving its reliability and accuracy, it is suggested that future works pursue on implementing a triple-axis tilt calculation for measuring joint angle ROM. Implementing a triple-axis tilt calculation would allow the GonioPi to calculate and measure joint angle ROM measurements when the sensor is oriented on the y-axis. Moreover, implementing a triple-axis tilt calculation would also slightly improve the sensor's reliability and accuracy.

It is also suggested that future studies perform testing that include a participant with BMI categories of underweight and higher classes of obesity. This would mean that the scalability of the device can be evaluated for much smaller and larger participants, respectively.

An improvement can also be made by implementing a sampling window. Implementing a sampling window would allow the sensor to output stable data to the Raspberry Pi Pico microcontroller before outputting it on the display. This would mean that the joint angle ROM measurement outputted on the display won't update every second with the slightest movement but rather it will stabilize first and output an average value of a chosen number of samples.

It is also recommended to add a straight edge ruler component at the back of the acrylic case design of the GonioPi as suggested by a tester in order for them to know that they are neither undercompensating nor overcompensating the tilt of the device when performing a ROM Test. Moreover, another tester suggested that a visual marker be added to midsection of the top of the acrylic case design to act as visual marker for rotation, and deviation motions of joints.

An improvement can also be made in the Assisted Mode Feature by adding more joints and motions as the testers considered the current implementation of the feature important, useful, and helpful.

A retest of the eight (8) ROM Tests evaluated in this research should be conducted to make the results of the handheld configuration testing consistent with the wearable configuration testing. The researchers also suggest that the testing for device reliability and accuracy should be performed independently from any other device testing to avoid tester-test subject/patient fatigue.

The researchers suggest the use of other sensors such as the ADXL335 3-axis Accelerometer Module, ADXL345 Accelerometer Module, BNO055 9-DOF IMU sensor, and MPU-9250 9-Axis IMU sensor. The researchers also recommend exploring the use of the accelerometers of modern smartphones for the application of clinical goniometry, like existing apps such as PhysioMaster.

VI. Conclusion

In conclusion, the design and development of the GonioPi has shown that a versatile, scalable, reliable, and accurate digital goniometer can be made using the MPU-6050 IMU sensor along with the components of the Raspberry Pi Pico microcontroller, Waveshare Dual GPIO Expander, Waveshare 1.14" LCD Display, 18650 Battery Shield V8, and two (2) 18650 Li-ion rechargeable batteries enclosed in an acrylic case with a wearable design of a pouch like attachable container with adjustable buckle straps.

In terms of versatility and scalability, the GonioPi has shown that it is versatile and scalable as it supports 34 ROM Tests of 11 different joints using 15 different motions, and 18 ROM Tests of 6 different joints using 8 different motions in multiple different positions using both the handheld and wearable configurations respectively for people of varying heights, weights, and BMIs. Improvements can be made for the wearable configuration to support more ROM Tests by using triple-axis tilt calculation and reducing the size of the GonioPi by substituting its power supply component.

In terms of reliability and accuracy, the GonioPi has shown high reliability and accuracy as it was reliable and accurate for majority of the ROM Tests of flexion and extension for the shoulder, elbow, hip, and knee joints for both the handheld and wearable configurations as its joint angle ROM measurements of $< 5°$ for device reliability, and joint angle ROM measurements of $< 10°$ for device accuracy. Improvements can be made for the GonioPi's reliability and accuracy by adding visual markers to the device in order to minimize user error when using the GonioPi.

Finally, regarding the Assisted Mode feature of the GonioPi – the feature has proven to be important, useful, and helpful with the feedback of the testers who also requested for more joints and motions to be added to the feature as an improvement.

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