Development and validation of an ankle range of motion measurement system with AR image tracking technology

Dong Hyun Kim

Abstract—**Ankle injuries are one of the most common injuries and this is partially due to muscle stiffness and strength imbalance. They also linger and may be related to other injuries of the body. Most conventional ankle range of motion measurement methods are widepsread and inexpensive. However, the results may be inconsistent and could also be affected by the users' experience levels. They may also be difficult to execute without the supervision of an expert and sometimes require other joints of the body. A number of attempts were made to develop devices measuring ankle range of motion, but they were limited to passive range of motion measurement and specific development costs remain unknown. Augmented reality image tracking technology is an intuitive, consistent and automated way of measuring ankle range of motion. It could also help reduce human errors when inputting data manually and also provide a casual way of testing out joint mobility and help with potential diagnosis. Additionally, the setup is easy and inexpensive while opening the option of measuring both active and passive range of motion. There is no app on the market currently for the Android that measures ankle range of motion and this study is also the first documented attempt to validate the accuracy of this augmented reality image tracking method. ArUco codes which are square markers with a black boarder and an inner binary matrix with a distinct identifier, were used as fiducial markers. These images were attached to plastic platforms of matching sizes and a Velcro strap was added to enable the platforms to be strapped on the body. 15 participants were asked to perform ankle plantarflexion 10 times in a natural manner. They were all seated and asked to place their foot onto a stool for levelness. Angle measurement was simultaneously done with both a digital goniometer and the developed app. The initial and final angles were read through the app and the overall movement angle was calculated with the angle displacement. The mean value of the readings were used for statistical validation. A series of statistical tests were conducted to check the normality of the two datasets. Then, a Paired-Samples T Test was run. Analysis of the data confirmed there was not a significant difference between the results of the two modalities. The results show that the image tracking method is a valid method and give room for speculations such as it being able to be used for telemedicine. However, some changes in the hardware and software alongside improvements in the study would help support the objective validation of the modality.**

Index Terms—**Augmented Reality, Range of Motion, Android, Plantarflexion, Fiducial Markers**

I. Introduction

Ankle injuries are among one of the most commonly occurring injuries not only in sports but also in daily life. Lateral ligament sprains in the ankle are responsible for between 3% to 5% of all emergency department attendances in the UK [1] and these ankle injuries are related to the stiffness and muscle strength imbalance of the ankle [2]. According to Hiller et al. [3], close to 20% of Australians suffer from chronic ankle disorders mostly due to past ankle injuries. This implies the importance of constant ankle range of motion (ROM) assessment to not only prevent any injury, but also post-injury for evaluating successful rehabilitation. Also, poor ankle ROM may lead to other injuries in the body such as Anterior Cruciate Ligament (ACL) injuries [4], Patellar Tendinopathy [5], or potential impairments to dynamic balance [6]. Thus, correctly assessing ankle ROM not only leads to a healthy ankle, but also to an overall healthy body.

Wilken et al. categorizes the ankle ROM measurement methods to three broad fields [7]. Goniometry uses a standard goniometer to measure ROM. These are widely available and are usually quite inexpensive. However, according to Youdas et al., even amongst trained physical therapists with 5 to 13 years of experience, the intertester reliability of the method was quite poor [8]. Konor et al. suggest in their study that even a novice tester with no prior experience can acquire reliable reusults with a goniometer [9]. However, they stated the possibility that experienced testers using the device may influence the results of these measurements [9] thus indicating the method could be inconsistent depending on the testers.

Weight-bearing methods ask the patients to perform certain tests such as the weight-bearing lunge (WBL) to assess ankle ROM. The results are then measured using a goniometer, inclinometer, or tape measure [9]. For the WBL, patients are usually asked to stand facing a wall and follow a specific set of instructions. The testers then place the goniometer or the inclinometer onto the respective anatomical landmarks to make measurements and check the distance from the wall to the toe for the tape measure [9]. While these tests have shown promising results, they come with some limitations. First, they require the supervision of an expert to ensure the patients are in the right stance or position. Since the position of the foot would change as the patient moves, constant supervision would be essential to ensure accurate results. The application would also be limited to individuals that have no problems moving joints other than the ankle (e.g., knee) since the tests require them to do so. Individuals with injury or disorder that prevent them from moving those other joints may not be able to assess ankle ROM which contradicts the entire objective of the tests. Also, since the results are measured using goniometric methods, it can be vulnerable to the problems of goniometry.

Instrumented techniques using torque try to isolate the ankle joint movement and measure applied external torque [7]. The

(*IAROM*) device developed by Wilken et al. [7] uses multiple plastic plates and Velcro straps to fix the patient in place during testing and provides the ability to alter knee flexion and determine angle displacement at known torque conditions [7]. However with this device, only passive ROM could be measured as the patient cannot move their foot on their own since it is fixed with plastic plates. There has been an attempt from Bae et al. to develop a soft, wearable ankle diagnostic device that aims to measure ankle ROM, but their study was done on a small sample size of three people and a specific extensive cost analysis was not done yet for all the components used [10].

To deal with some of the shortcomings of these conventional ankle ROM measurement methods, a novel method using augmented reality (AR) image tracking technology could be used. AR is a technology that augments the real world with computer-generated, virtual objects that appear on the same space as the real world [11]. Not only is the AR method more intuitive as people can see and follow in real-time what is happening when they bend their joints, it would provide the same experience to everyone using it since there is no training required to use it but only the eye test. It would also be substantially easier to digitally archive the measured data since the entire process is run on a program. This attribute could help reduce the amount of human error when trying to input data manually. The stored data can be used later for clinicians or self-assessment. The setup is easy and straightforward and there is also room for customization. It is portable since the things required are only the hardware components stated in section III-B and an Android phone. It can be recreated with materials that are commonplace and can also potentially provide the users the option of measuring both active and passive ROM. Thus, the AR image tracking method can be used to combat some of the problems the conventional methods have while providing an easier way of achieving the same objective.

The goal of this thesis is to show that the AR image tracking method can also be a valid option for ankle ROM assessment. Despite having potential, there is currently no app on the market that measures joint angles using AR image tracking for the Android. In this thesis, an Android app with AR image tracking qualities was developed using the Unity engine (Unity. (2021.3.11fl), Unity Technologies) to remedy this situation. Then, an empirical study was conducted to compare the results from the AR image tracking method to those measured with a digital goniometer and validate the effectiveness of the AR image tracking system. A series of statistical analyses will then be used to provide objective evidence to prove validity.

II. Background

At the time of writing of this thesis, there was a device on the market that measured ROM and also provided communication through an app. Aside from this device, most of the new attempts at measuring ROM were done by apps. There was an app using image-based goniometry and there was only one app on the market using AR image tracking for joint ROM assessment. However they were only for one operating system and had some limitations. There was an attempt at trying to use the AR image tracking technology to measure ROM and posture, but it wasn't polished enough to make it to the market yet. The state of the art analysis will be mainly discussing these attempts.

A. Activforce 2

There is currently one product on the market as of the writing of this thesis that measures ROM automatically. The *Activforce 2* handheld dynamometer and inclinometer measures strength and ROM, is portable, Bluetooth enabled, and connected to an app [12]. It supports a variety of movements such as knee extension, knee flexion and so on. Although it offers a lot of features, there is no display on the device itself which makes it nearly impossible for the user to interact with it real-time. Also there is no information readily available for the public on the ROM measurement capabilities of the device. There was an attempt to validate the device by Karagiannopoulos et al. [13] by using it alongside another handheld dynamometer. However, there is no documented study on how accurate the *Activforce 2* is in terms of ROM measurements. It also only ships within the United States which limits the availability of the device greatly and the price of $399 may not be affordable for some individuals.

B. Smartphone goniometers

Smartphone technology is rapidly developing nowadays and they offer a variety of new features. Goniometer apps, being one of them, have been gaining interest as a potential replacement for standard goniometers [14]. However, not many of them are validated and need further studies to prove their effectiveness. Alawna et al. measured ankle plantarflexion with a smartphone goniometer app and compared the results to those from an universal goniometer [14]. It was shown that the goniometer app had a high degree of intra- and interrater reliability and can be used alongside the universal goniometer as a valid option. Nevertheless, the smartphone goniometers share the innate shortcomings of the goniometry method in being potentially inconsistent and needing experience to obtain accurate results.

C. DrGoniometer

The *DrGoniometer* app uses photographs to determine ROM. It can be used to judge images taken from both static and dynamic states. The user selects the desired joint or exercise from a provided list and takes a picture of the limb to compare angular displacement [15]. It is shown in a study by Mitchell et al. that the *DrGoniometer* app may be reliable enough to replace standard goniometers as it showed great intra- and intertester reliability of 0.81 and 0.92 respectively [16]. However, this method only allows analysis on images taken after or during a certain movement and not live situations. In a situation where context and progression matters, being unable to track live movements may not be ideal.

D. Dynamic Goniometer

There is an AR image tracking system named the *Dynamic Goniometer* aimed at measuring joint angles developed by orthopractics.com on the Apple app store. Their product works extremely similar to the one developed in this thesis but their system is solely for Apple products. The fiducial markers used in their product are QR codes and they are specified to be 1 square inch of size [17] which may cause some trouble when the images prove to be too small or too big. Their app is yet to be validated and it is stated that it should not be used for diagnosis [18]. They also attach printed-out labels with the QR codes directly onto the body but this may potentially cause some tracking problems due to the occlusion and image noise [19] caused by the curves of the human joints.

E. BAR-M

Basiratzadeh et al. made an attempt to measure human posture and ROM using an app developed for a Samsung Galaxy smartphone [20]. The developed app was named *BAR-M*. They also used fiducial markers, AprilTags, for AR image tracking and used a Body Opponent Bag (BOB) mannequin to compare with human results. They developed specific adapters with the fiducial markers and Velcro adapters to fasten to the body. Then, they performed arm abduction and measured pelvis obliquity and shoulder position while running the app. The results were then compared to those from a Vicon motion capture system. For the pelvis and shoulders, the difference between the two modalities for both the BOB and human tests were satisfactory, but the arm abduction difference was not. This was mainly due to chest and arm errors caused by the movement of the markers because of not having a flat surface and clothing movement. This study provided a possibility for measuring ROM using an AR image tracking Android app and was one of the first attempts to so. However this study mainly focused on the upper body and the pelvis, not the lower body. They also compared their measurement results to a Vicon motion capture system, which is immensely more expensive than a goniometer and their study might not be easily reproducible. Also, the movements they focused on such as arm abduction, pelvic obliquity, and shoulder position, did not involve any directly bending joints like ankle ROM.

Thus it is safe to say that there is currently no real gold standard on the market for measuring joint ROM using AR image tracking for the Android. Even if there is a commercialized app on the market for Apple, the app is yet to be validated and cannot be used for any diagnosis alongside several potential limitations. This thesis will be the first attempt to develop and validate an app that focuses on measuring ankle ROM using AR image tracking and provide people with an inexpensive option that outputs consistent automated results.

AR image tracking has been around for quite some time. For mobile devices, due to the lack of computing power compared to PCs, image tracking has been focused on tracking fiducial markers [21]. Fiducial markers are images that are simple to detect with the AR application placed into the environment. These markers are crucial to applications using the camera and computer vision since the camera needs cues in the environment to determine the location and orientation of it. As the AR system detects the fiducial marker, it can determine the position and orientation of the camera with respect to the marker. Not only can the fiducial markers provide positional details of the camera with respect to the markers, but they can also trigger certain functions of the AR application [22]. For this thesis, a sphere is spawned on top of the detected markers and the positions of the spawned spheres will be used for the main application.

The fiducial markers used in this paper are Artificial Reality University of Cordoba (ArUco) codes developed by S.Garrido-Jurado et al. [23]. ArUco codes are square markers with a black boarder and an inner binary matrix with a distinct identifier. The codes were generated on an online ArUco code generator [24].

The ArUco codes were selected for this thesis due to its performance compared to other widespread fiducial markers such as AprilTag, ARTag, STag etc. According to Kalaitzakis et.al. [25], it was shown that the ArUco code was a safe choice when determining the position and the orientation of the markers as it was consistently second in both categories. Also, according to a study by Zakiev et al. [26], ArUco codes had a much better reliable detection rate when rotated in moderate background noise levels compared to AprilTag. Since one of the markers used in this thesis had a possibility of being rotated and considering the likelihood of moderate background noise in the study setting, it was apparent that ArUco was the right choice to make over other markers.

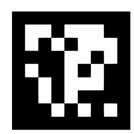


Fig. 1: Example of an ArUco code

To further validate the effectiveness of ArUco codes as fiducial markers, a test was run using the arcorimg tool [27] supported by Google. The image tracking system developed in this thesis uses Google's ARCore software development kit (SDK) and the arcoreimg tool is used to check the quality of an image when used as a fiducial marker in that setting. When one uses the tool on an image, they can expect a quality score between 0 and 100 and are advised to use images with a score of at least 75 for image tracking [28]. The results for the ArUco codes used for this thesis are as shown on figure 2.

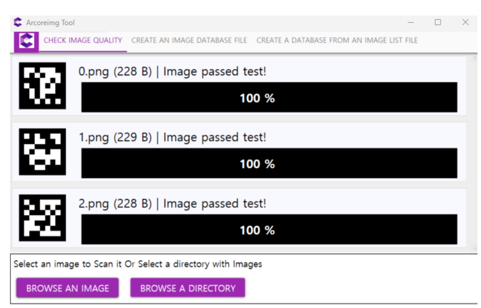


Fig. 2: The arcoreimg tool

The image tracking system was developed for Android using the Unity engine. The Unity engine is a game engine and integrated development environment used to create immersive media, most notably games [29]. The Unity engine was selected as the method of development due to its vast amount of provided packages that support AR image tracking and the convenience of deployment of the app. The image tracking system was developed using the AR Foundation package distributed by Unity. AR Foundation is a package that enables the user to create AR apps in a variety of platforms [30]. Since it does not implement any features by itself, a separate provider plug-in package, for the case of this thesis the *Google ARCore XR Plug-in*, is needed for the app to function. GameObjects, which are a fundamental part of the Unity engine, are basically every object in the system. They need to be configured and given properties, which are called Components, to perform a certain task [31]. Additional information on how these GameObjects are used in the system is described in the next section.

III. Methods

A. Software

The AR image tracking app, named *AnkleReview*, is comprised of two major scenes. The main screen contains two buttons. The Start button redirects the users to the scene used for angle measurement, *angleMeasure*. A detailed explanation of the method of angle measurement can be found in section III-A4. The Quit button is used to exit the app. After moving on to the *angleMeasure* scene, the ArUco codes can be detected and the angle formed by them is displayed on the upper left corner of the screen. There is also a button on the bottom which redirects the user back to the main screen. The screenshots of the scenes can be found in figure 3.

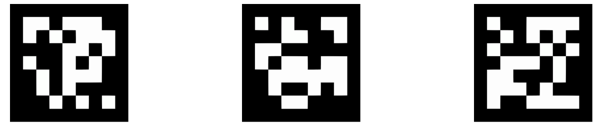
(a) Main screen (b) angleMeasure

Fig. 3: Scenes of the AnkleReview app

The script written for the app can be divided into 4 notable parts.

1) Setup: The ArUco codes used in this thesis are stored in a reference image library as target images for the image tracking system to recognize. The sizes of the images are also adjustable according to the user's convenience. The exact sizes of the images can be set both in pixel size and centimeters. This feature is essential to the customization of the system and by using a physical printed copy of the image with the same size specified in the system, one can expect better image tracking results.

The script is written in C# on Visual Studio (Microsoft Visual Studio Community 2019, (version 16.11.20), Microsoft). It is started with adding packages required for



(a) "0" (b) "1" (c) "2"

Fig. 4: ArUco codes used in the thesis

AR image tracking. Alongside default packages, the *UnityEngine.XR.ARFoundation* package is used to make use of AR Foundation. Then, various variables are defined for the execution of the program.

The dictionary *_instantiatedPrefabs* is defined to store GameObjects alongside a string. This is where information on the spheres that are supposed to be spawned are stored. The *_trackedImageManager* is then defined to track the target images and store information on their Transform, which is information on position, rotation and scale [32]. The GameObject *m_TrackedImagePrefab* is then used to physically spawn the sphere onto the target image. The float *angle* is used to store the measured angle values from the app. The *vec1* and *vec2* variables contain information on the vectors formed by target images "0" to "1" and "0" to "2". The target images can be found in figure 4. Then *obj* is defined to store the array of Transforms of the spawned spheres. A line renderer is used to visualize the vectors connecting the spawned spheres. It connects the two points in a straight line.

2) Detecting image targets: The method *Awake* is called only at the initiation of the script. It initiates the *_trackedImageManager*. The methods *OnEnable* and *OnDisable* are used to store the Transform of a moved image and delete the previous Transform. The method *OnTrackedImagesChanged* covers both detecting the target images from scratch and detecting the updated Transforms of the images. When a target image is detected for the first time, a sphere is spawned on top of the target image according to the Transform of the image. The information is then stored in the dictionary *_instantiatedPrefabs* and is labelled with the name of the image. For instance, the sphere that spawns on top of image "0" is labelled 0 and the same applies to images "1" and "2". Then, the Transform of each sphere is stored in *obj*, each in *obj[0]*, *obj[1]*, and *obj[2]* according to the names of the spheres. Using the position property of these variables, the vectors required for angle measurement are calculated. *vec1* and *vec2* are calculated as follows:

- *vec1 = obj[1].position - obj[0].position;*
- *vec2 = obj[2].position - obj[0].position;*

The vectors are subsequently visualized with a line renderer. Default values for the width and material for the lines were used, and the color was set to green. The line renderers use the positions of the spheres to connect two of them to form a line.

3) Tracking moving images: As the images move, so do the Transforms of the spawned spheres. The *_instantiatedPrefabs* stores new information on the updated Transform of the images as they move. Then, the *obj* is updated according to the changes and *vec1* and *vec2* are recalculated as well.

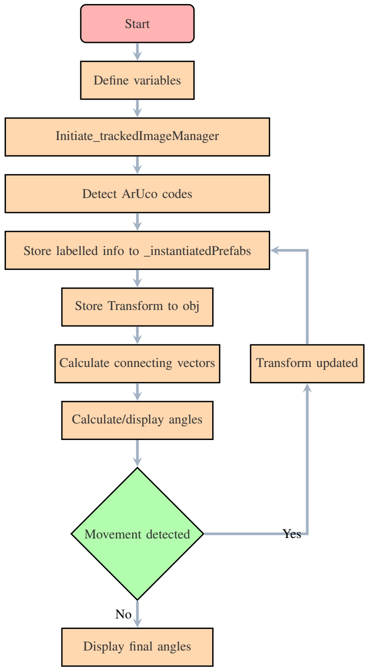


Fig. 5: Flowchart of script

Subsequently, the line renderers use the updated positions of the spheres so the lines stay connected to the spheres.

4) Method of angle measurement: Unity provides several methods of angle measurement. For this thesis, the Vector3.Angle method was selected due to the high level of relevance to the theme of the app using vectors. It also allowed direct computation of angles formed by the vectors unlike the other methods which require converting vectors to other units such as quaternions or Euler angles. Furthermore, since the perpendicular axis that extends from the images is disregarded for this app, only 2 axes were of relevance and thus the Vector3 method was preferred. The angle of movement was then calculated manually by subtracting the initial angle before any movement from the final angle when the user stops moving. The numbers were rounded up to 2 decimals places. The Vector3 method uses the common approach of measuring angles formed by two different vectors. The equation used to calculate the angle is shown in equation 1 when the angle between the two vectors is θ. The two vectors *vec1* and *vec2* are used as the vectors from and to which the angular difference is measured.

$$\theta = \arccos \frac{vec1 \cdot \ vec2}{|vec1||vec2|} \tag{1}$$

The method is described as *Vector3.Angle(vec1, vec2);*. The *angle* value is then used to store the calculated angle and is a float which represents the measured angle in degrees. The method always returns a value between 0 to 180 since it shows the smallest angle between the vectors [33]. A flowchart that describes the entire script is also shown on figure 5.

B. Hardware

The ArUco codes were printed on an A4 sticker paper with an Inkjet printer. Then, the adhesive labels were attached to a custom-made laser-cut 3mm thick, 70mm by 70mm (70mm x 70mm) plastic platform to ensure a flat and sturdy surface for the images to rest on. The platforms were designed on Inventor Professional (Autodesk Inventor Professional, (2024), Autodesk). The platforms were each named ”0”, ”1”, and ”2” according to the names of the ArUco codes. A Velcro strap was then wrapped around the platform to enable the device to be mounted onto the users. Between the platform and the strap, a soft, fluffy piece of cotton sheet was inserted to prevent any potential discomfort caused by the hard surface of the platform hitting the skin directly. The edges of the places used to insert the Velcro straps were rounded off to prevent any potential injury during the study. One of the three hardware components is shown in figure 6.

Fig. 6: Hardware component

C. Study

15 participants (7 men and 8 women) were chosen to participate in this study. Information on the inclusion and exclusion criteria can be found in table I.

TABLE I: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Adults over the age of 20	Refused to give informed consent
Without any significant ankle injury in the past month	Individuals who went through total ankle replacement surgery
No discomfort in daily life physically	

All of the participants were provided with an information sheet and a form of consent. The study was proceeded after the participants' approval. The study was approved by the Management Center Innsbruck (MCI) Ethics Committee. The details of the participants are listed in table II.

TABLE II: Details of the 13 study participants

Contents	Min	Max	Mean ± SD
Age	22	29	25.33 ± 1.72
Height	155	186	171.33 ± 10.01

[1]Min: minimum, Max: maximum, SD: standard deviation

The participants were seated and asked to place their foot in a relaxed manner onto a stool or chair of equal height for levelness. The hardware devices mentioned in section III-B were mounted onto the participants. The ”0” platform was attached on the lateral malleolus as a point of origin for angle measurement and the other 2 platforms were attached alongside the lateral calf and foot. All of the platforms were made sure they were all on equal planes for accurate measurements. Then, a tester with a digital goniometer and a tester with the app on an Android phone were placed on two opposite sides of the participants and measured angles simultaneously. The testers were the same for every trial and they were blinded to each other's results. The digital goniometer was chosen due to its precision and angle measurement capabilities. Specifications on the device can be found in table III.

TABLE III: Digital goniometer specifications

Name	Baseline Absolute+Axis Goniometer
Manufacturer	Fabrication Enterprises Inc.
Working range angle	0° ˜185°
Resolution	0.1°
Angle precision	± 0.5°

For the app, the initial angle before any movement and the final angle for every trial were documented alongside the measurements read by the goniometer. The ROM angle measured by the app was calculated according to the method stated in section III-A4. The tester with the goniometer aligned the device parallel to the participants' foot and followed their movement. As the participants performed plantarflexion, they were asked to hold their position for a brief moment for both the testers to record the measurements. Then, they were asked to return to their relaxed state and repeat the whole process. The participants repeated plantarflexion 10 times and the mean value of the measurements from both the goniometer and the app were used for statistical analysis. The mean values $\overline{x}$ were calculated using the standard equation shown in equation 2.

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

The setup of the study can be found in figure 7. This screenshot was taken from the perspective of the tester using the app.

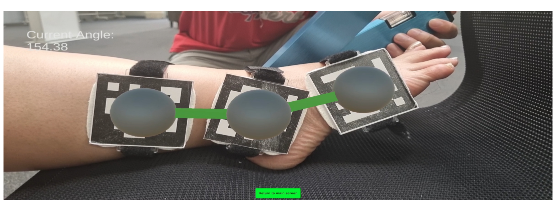


Fig. 7: Setup of the study

The measurement results from the two modalities are listed on the next section on table IV.

IV. Results

The measurement results of the digital goniometer and the app is displayed in table IV.

A series of statistical tests were conducted on the measurement results for analysis. All statistical tests were conducted on the SPSS Statistics software (IBM SPSS Statistics. (29.0.1.0), IBM).

A. Normality tests

Determining whether a dataset follows a normal distribution or not is crucial to selecting appropriate subsequent statistical tests. In order to test the datasets acquired from both the goniometer and the app, a Shapiro-Wilk Test was used. This

TABLE IV: Measurements from the goniometer and Vector3 method

Participants	DG (°) ± SD (°)	V3 (°) ± SD
p1	40.78 ± 4.38	39.74 ± 4.00
p2	24.50 ± 2.35	24.06 ± 2.91
p3	16.87 ± 2.62	16.62 ± 3.29
p4	17.23 ± 1.22	17.38 ± 1.63
p5	14.31 ± 1.54	14.99 ± 1.59
p6	26.72 ± 2.66	26.04 ± 2.65
p7	18.13 ± 1.15	18.41 ± 1.35
p8	23.35 ± 1.54	23.21 ± 1.19
p9	25.01 ± 2.52	24.92 ± 2.40
p10	26.28 ± 2.79	26.10 ± 3.53
p11	29.09 ± 1.78	29.47 ± 2.25
p12	16.45 ± 1.34	16.08 ± 1.65
p13	27.68 ± 1.76	28.03 ± 1.69
p14	14.27 ± 1.52	14.12 ± 2.21
p15	15.32 ± 1.76	15.17 ± 1.79

[2]DG: Digital Goniometer, V3: Vector3

test was appropriate for this application due to the small number of sample size. The confidence interval (CI) was set to 95% and the α value was set to 0.05. The null hypothesis for this test is set as "The samples in the dataset comes from a normally distributed population". If the returned p value for the test has a greater value than 0.05, then the null hypothesis cannot be rejected. The p value is represented as *Sig.* in SPSS. The DG method was described as *Method 1* and the app was described as *Method 2*. The results can be found in figure 8. The dependent variable was the measured angle and the independent variable was the measurement method.

Tests of Normality

		Kolmogorov–Smirnov[a]			Shapiro–Wilk		
	Method	Statistic	df	Sig.	Statistic	df	Sig.
Angles	1.00	.187	15	.167	.888	15	.062
	2.00	.174	15	.200*	.900	15	.094

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Fig. 8: Shapiro-Wilk test results

Since the p values for both test results were greater than 0.05 (0.062 and 0.094), the null hypothesis could not be rejected and was thus proven that the samples from the two datasets are normally distributed. The results were additionally supported by a quantile-quantile (Q-Q) plot. If the data points lie closely alongside the straight line, it indicates that they are normally distributed. The plots can be found in figure 9.

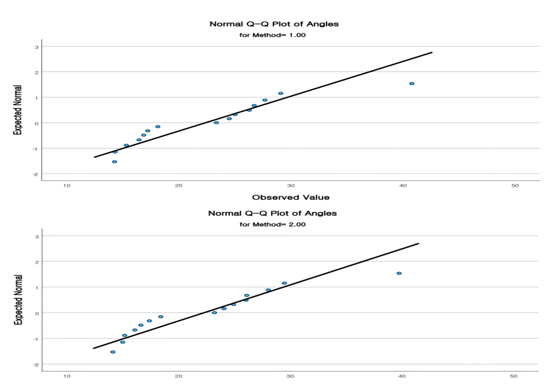


Fig. 9: Q-Q plot results

Since most of the data points were closely aligned with the line, it was also shown that the samples from the dataset are normally distributed.

Thus, by combining the results from the two tests, it was apparent that the two datasets from the two different methods of angle measurement followed a normal distribution.

B. Paired-Samples T Test

As the two datasets followed a normal distribution, a Paired-Samples T Test (PSTT) was run to compare the mean values of the readings. The PSTT was chosen since the study was done on the same group. Since the PSTT on the SPSS software computes the differences between values of the two variables for each case and tests whether the average differs from 0 [34], the null hypothesis was set as ”There is no significant difference between the readings of the two modalities”. The CI was also set to 95% and the α value was set to 0.05. The result was as shown in figure 10. The correlation between the two modalities is also shown in figure 11.

Paired Samples Test

		Paired Differences							Significance	
					95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Pair 1	DG - AR	.11000	.43841	.11320	-.13278	.35278	.972	14	.174	.348

Fig. 10: Paired-Samples T Test result

Paired Samples Correlations

				Significance	
		N	Correlation	One-Sided p	Two-Sided p
Pair 1	DG & AR	15	.999	<.001	<.001

Fig. 11: Correlation between two modalities

V. Discussion

A. Interpretation of tests

According to the result shown in figure 11, there was a positive correlation between the measurements using the two modalities and the level of correlation was high. As for the PSTT, since the direction of the difference was not a focus of this study, the two-sided p value was used for interpretation. As the two-sided p value returned was greater than 0.05 (0.348) and the t value (0.972) was smaller than the critical t value on the Student’s t Table (2.145) as shown in figure 10, the null hypothesis could not be rejected. Thus, there was not a significant difference between the readings from the two modalities implying a possibility that the AR image tracking method can be a valid method of ankle ROM measurement. The difference in means was small (0.11000) and the standard deviation of the differences was also small (0.43841). The standard error of the mean was 0.11320, which implied that the the two means of the two methods were extremely similar.

B. Future outlook

Compared to conventional methods of ankle ROM measurement, the AR image tracking method provides the users with visual cues for potential self-assessment. By screen recording when using the app, the users can look back at the recordings and evaluate their performance during a certain movement or exercise. With this feature, self-assessment of ankle ROM will be more intuitive and straightforward compared to specific and complicated mobility tests. There will be no need for expensive equipment as all one needs is a smartphone and all the hardware components can either be found or purchased easily without much financial burden. There is also a possibility that this technology can be applied to other joints such as the knee or the elbow. Also, since the data collection when using AR image tracking is automated, digitally archiving measurement data will be made much easier. This will greatly reduce the amount of human errors when inputting measurement data manually and will make workflow faster in clinical settings. It can also provide a gateway to telemedicine for joint ROM measurement since sharing information instantly through the app is definitely a possibility. In order for that to happen, the information would have to be stored in a database or in the app directly for both the users and the clinicians to access. Furthermore, it would allow the users to provide clinicians with potentially meaningful data without multiple unnecessary trips to the clinic which could be beneficial to both parties.

C. Limitations

However there were some limitations of this study. The target group for this occasion was mainly healthy people in their 20s to obtain a more consistent and accurate result, but a diverse age group would be better for a more objective conclusion. A bigger study sample size would also be beneficial for reaching a generalized conclusion. Since the app will ultimately be targeted at people of all age groups and injury levels, a more complete study would greatly support the credibility of the app. An additional study testing intertester reliability would also show the AR method can produce consistent results regardless of the users’ experience levels or occupation.

Also, there were some aspects that were left to be desired in terms of both the hardware and software components. For the hardware, due to the Velcro straps that held the platforms in place, some movements, notably dorsiflexion, were unable to be performed comfortably according to some participants. Thus, a different design and attachment mechanism should be thought of to cover every other kind of ankle movement for the app to measure. As for the software, some quality-of-life improvements could be added to improve the usability of the app. Most notably, providing the users with the ability to determine when to start and stop the angle measurement would be greatly beneficial to the accuracy of the measurement. Developing a way to store and access the data through a database or the app would also be immense for the potential for telemedicine. Since the thesis was focused more on evaluating the validity of the AR method, the implementation of these additional features would be topics for potential follow-up studies regarding this topic.

VI. Conclusion

This thesis aimed at comparing the conventional ankle ROM measurement method to a more novel approach of AR image tracking. It was done by strapping three platforms with image targets onto anatomical landmarks to form an angle. Then, a number of statistical tests such as the Shapiro-Wilk test and the Paired-Samples T test were conducted with the 15 samples collected for each modality. The results of the tests proved that the AR image tracking method could be a potential valid replacement to the standard goniometer method. With more development of this technology, casual self-assessment of ankle ROM would be made more intuitive and digitally archiving data in a clinical setting would be easier, opening the door to telemedicine in this field. However, some improvements to both the hardware and software setup, alongside a more completely designed study with increased size and diversity in terms of age groups and health levels will be essential to the completeness of the app and eventual commercialization of this technology.

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Dong Hyun Kim is with the Department of Medical and Health Technologies, MCI, Innsbruck, Austria. Among others he is responsible for the activities in medical engineering in which he is regularly publishing.