# ROMBandAR: Development of an AR-Based Wrist ROM Assessment Prototype for Rehabilitation

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***Abstract*—Wrist range of motion (ROM) assessment is important in rehabilitation because wrist movement supports hand positioning and functional hand use. Limited wrist movement can be caused by a variety of conditions, including neurological conditions such as stroke and musculoskeletal or orthopedic injuries such as distal radius fractures or tendon repairs. In current practice, wrist ROM is commonly assessed using a goniometer. Although the tool is widely used, the reading still depends on correct positioning, therapist handling, and visual judgment. Augmented reality has the potential to support this process because it can show digital feedback together with the real wrist movement. However, AR is still not widely explored for wrist-specific ROM assessment compared with virtual reality, robotics, and wearable or sensor-based systems. This study presents the development of ROMBandAR, an AR-based wrist ROM assessment prototype for rehabilitation. The prototype uses a wrist armband as a model target for AR tracking. The armband was first scanned using KIRI Engine software, then trained using Vuforia Model Target Generator, and lastly imported into Unity for AR integration. MediaPipeUnityPlugin was also integrated to show hand landmarks on the detected hand via the smartphone camera. After that, custom C# scripts were developed to display wrist ROM readings, classify movement, show real-time feedback, save assessment readings, and support report submission for therapist review. This study follows the Design Science Research Methodology and, at this stage, focuses on development-level testing. Three test cases were carried out: device compatibility testing, application functionality testing, and screenshot-based ROM reading consistency testing. The results show that ROMBandAR can run on different Android devices, successfully detect the wrist armband, display hand landmarks, show ROM readings, and save assessment results. These findings provide an early foundation for future evaluation of the proposed framework, especially the extrinsic feedback provided during wrist ROM assessment. Repeated trials, inter-rater reliability, direct goniometer measurement of the wrist, and further evaluation of the feedback were not part of this development stage and are planned as future work.**

***Keywords*—ROMBandAR; augmented reality; wrist range of motion; rehabilitation; pose estimation; MediaPipe; vuforia; extrinsic feedback***

## I. Introduction

Rehabilitation helps people recover movement and regain the ability to carry out daily activities after an injury, illness, or medical condition. For the upper limb, recovery depends on how well the shoulder, elbow, wrist, and hand work together. Wrist movement can become limited in different rehabilitation cases. For example, in neurological rehabilitation, stroke can reduce upper limb motor control and affect simple daily activities such as holding, grasping, and object manipulation [1]-[3]. On the other hand, in musculoskeletal or orthopaedic rehabilitation, wrist stiffness and loss of motion can also follow distal radius fracture and tendon injury or repair [4]-[6]. So, although the causes are different, therapists still need to observe wrist movement and monitor recovery of their patients over time.

Wrist range of motion (ROM) is commonly measured using a goniometer [7]. A goniometer is an angle-measuring protractor that has extending ruler-like arms, and it comes in different varieties for different body parts. This method is simple and widely used in rehabilitation practice and is still the gold standard today. However, the accuracy and reliability still depend on correct wrist positioning and therapist handling. This is because wrist assessment can also be sensitive and less reliable because sometimes the joint is small, so the hand position can change easily during measurement. When the assessment is repeated across sessions, small differences in goniometer placement or wrist posture may then affect the final reading.

Therefore, different technologies have been introduced to support upper limb rehabilitation. This includes technologies like virtual reality, robotic and haptic devices, wearable or sensor-based systems, telerehabilitation, and augmented reality [8]-[21]. Virtual reality and robotic systems often focus on repeated exercise or physical assistance, while wearable and sensor-based systems collect movement data. AR takes a different approach because it functions by combining the real world with the virtual overlay. This ensures the real limb is always visible, and it's possible to place digital information in the same view. So, for wrist ROM assessment, the user can see the actual wrist together with the angle and movement feedback.

In this study, AR refers to the digital labels and information that appear over the smartphone camera view. ROMBandAR uses model-based AR, which means that the system recognises a physical object from a trained three-dimensional model. In this case, the wrist armband acts as the model target. Once Vuforia detects it, the application uses the armband as a reference for placing the AR content around the wrist [22], [23], [24]. MediaPipe performs a separate task by detecting the hand landmarks needed for the wrist angle calculation [25]-[27].

Besides model-based AR, pose estimation is the part of the prototype that identifies key points from the camera image and follows how those points change during movement. For the hand, MediaPipe estimates 21 landmarks at the wrist, palm, and finger joints [25], [26]. ROMBandAR uses these landmarks as movement references, but the landmark display alone does not provide a clinical ROM value. Hence, custom calculation is needed; with the armband reference, the selected assessment plane, and the neutral reset to reset the hands' position, patients' hands can be detected; thus, the angle is shown to the user accurately in the form of feedback.

ROMBandAR also applies the feedback theory. There are two types of feedback, intrinsic and extrinsic. Extrinsic feedback is information provided by an external source to help the user understand a movement or its result [28]-[30]. The angle reading provides knowledge of results because it shows the measured outcome. The movement label, guidance panel, and AR labels provide knowledge of performance because they show how the wrist is moving. The feedback appears during the assessment, so the user can view it while performing the movement.

This study presents ROMBandAR, an AR-based prototype for wrist ROM assessment in rehabilitation. The intended scope includes neurological and musculoskeletal or orthopaedic rehabilitation, with stroke, distal radius fracture, and tendon injury or repair as possible future case groups. The prototype is not tied to one diagnosis because it measures wrist movement rather than the cause of the impairment.

The prototype uses a wrist armband as the model target for AR tracking. The armband is scanned using KIRI Engine, trained using Vuforia Model Target Generator, and imported into Unity. MediaPipeUnityPlugin is then integrated into Unity to display the hand landmarks and support the wrist movement output. From there, ROMBandAR provides real-time extrinsic feedback in the form of angle output, movement labels, ROM guide popups, and necessary AR labels.

This study aims to report the development phase of ROMBandAR and its early functional evaluation. At this stage, the study does not claim clinical effectiveness or full measurement validation.

The main contribution of this study is a simple development workflow for an AR-based wrist ROM assessment prototype that can later be examined in different real rehabilitation settings. The study also reports the early testing of the user interface, core AR and MediaPipe functions, screenshot-based ROM reading consistency, and an assessment library with a therapist submission function.

The rest of this study is organized as follows. Section II compares existing rehabilitation technologies and explains the gap found for this project. Section III describes the research design, proposed framework, system development, and evaluation procedure. Section IV presents the prototype implementation and test results. Section V discusses the findings, significance, and limitations, while Section VI presents the conclusion and future work.

## II. Related Works

This section compares the main technologies that have been used in upper limb rehabilitation. The comparison looks at how each technology presents the rehabilitation task, how it obtains movement information, and what hardware it requires. Their suitability for wrist ROM assessment is also considered.

### *A. Virtual Reality-Based Rehabilitation*

Virtual reality usually conducts rehabilitation activities in a simulated environment. This setup allows patients to easily repeat movements, interact with different tasks, and progress through several levels of difficulty [8]-[10]. However, most VR studies use these activities for training and motor recovery rather than for directly measuring an assessment. Fully immersive VR can also hide the user's own body from their view; thus, it is difficult to feel the real objects during rehab. This also becomes a limitation when the therapist needs to observe the actual joint position of their patients during the assessment and to control what the patient sees.

### *B. Robotic, Haptic, Wearable, and Sensor-Based Systems*

Robotic and haptic systems are commonly used when the upper limb movement needs to be assisted, resisted, or guided, as not every patient can do active rehab. Orthoses and wearable robots may also support the wrist and hand during training [11]-[14]. Sensor-based and telerehabilitation systems take a different approach by recording kinematic data and allowing movement to be monitored outside the clinic [15]. These technologies can provide useful and objective information. Even so, the setup often involves additional hardware, calibration, or equipment attached to the limb, which causes discomfort and is difficult to set up. For a simple wrist ROM check, this type of setup may be too bulky and more than what is needed and is not accessible to all.

### *C. Augmented Reality Systems*

Augmented reality keeps the real environment visible and adds digital information to it. Existing studies have used AR for rehabilitation, hand motor training, real-time upper limb kinematic feedback, and clinical data visualisation [16]-[21]. This gives AR an advantage for wrist assessment because the user and therapist can still see the real wrist while viewing movement information. However, most existing AR systems focus on exercise guidance, general upper limb movement, or data visualisation. Few studies examine a mobile wrist-specific assessment that combines a physical model target, hand landmarks, real-time angle feedback, saved results, and therapist submission.

### *D. Camera-Based Pose Estimation and Hand Landmark Tracking*

Camera-based pose estimation provides another way to obtain movement information without attaching a separate sensor to the limb. MediaPipe first locates the hand and then estimates 21 landmark points from the camera image [25], [26]. These points can be followed from frame to frame and used in a separate angle calculation. However, hand landmarks are not the same as a clinical ROM measurement. Even so, the detected landmark positions are not always stable. They may shift when part of the hand is covered, when the camera angle changes, or when the tracking briefly loses confidence.

Besides, MediaPipeUnityPlugin makes it possible to run this landmark pipeline inside Unity [27]. This provides a practical way to extend the hand landmark pipeline for use in a wrist ROM assessment application. For the current prototype, MediaPipeUnityPlugin was customized and integrated with the model-based AR components to support the wrist ROM assessment functions.

### E. Comparative Synthesis and Research Gap

Hence, AR offers a different approach from the other rehabilitation technologies discussed earlier. Unlike VR, it allows the real wrist to remain visible throughout the assessment. It can also provide visual guidance without using the mechanical support required by many robotic and haptic systems. Wearable and sensor-based systems can produce detailed movement data, but AR can display the information directly beside the wrist being observed in real time, although this still depends on clear camera visibility and stable tracking. Based on this comparison, a gap remains for a mobile model-based AR system developed specifically for wrist ROM assessment across rehabilitation settings. ROMBandAR was developed as an early prototype to examine this possibility.

## III. Materials and Methods

This section explains the steps used to design, develop, and test ROMBandAR. It begins with the research design and the proposed framework. The development process and evaluation procedure are then described in the following subsections. The main materials and software include the prototype wrist armband, Android smartphones, KIRI Engine, Vuforia Model Target Generator, Unity, MediaPipeUnityPlugin, and C# scripts.

### A. Research Design

This study follows Design Science Research Methodology because the main focus is to develop and test a digital artifact [31]. The artifact in this study is ROMBandAR. The development process includes problem identification, objective setting, design and development, demonstration, evaluation, and communication.

The problem identified in this study is the need for a simple AR-based prototype to support wrist ROM assessment across rehabilitation settings. The intended clinical scope includes neurological rehabilitation, such as stroke, and musculoskeletal or orthopaedic rehabilitation, such as distal radius fracture and tendon injury or repair. ROMBandAR was therefore developed to detect a wrist armband, display AR labels, show hand landmarks, provide wrist movement output, save the assessment reading in the application library, and allow the reading to be submitted to a therapist.

### B. Proposed Framework of ROMBandAR

Fig. 1 shows the proposed framework of ROMBandAR. The framework starts with the user, which includes people who require wrist rehabilitation and therapists. Possible future user groups include people recovering from stroke, distal radius fracture, or tendon injury and repair. The user performs the wrist assessment using the application, while the therapist is the intended reviewer of the submitted assessment.

The wrist armband is used as the model target for AR tracking. The armband is first scanned using KIRI Engine [32]. Then, the three-dimensional model of the armband is trained using Vuforia Model Target Generator [24]. After the model target database is exported, it is imported into Unity for AR development. In Unity, Vuforia detects the wrist armband and keeps the AR labels aligned with the model target. MediaPipe and MediaPipeUnityPlugin perform a separate task by displaying hand landmarks from the smartphone camera input [25]-[27]. Additional C# scripts use the reference information to calculate the angle, classify the movement, display feedback, save the assessment reading, and control the report submission function.

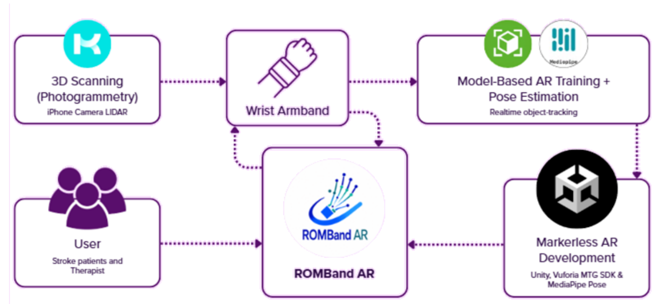



Fig. 1. Proposed ROMBandAR development framework.

### C. System Development

The development started with the preparation of the prototype wrist armband. The armband was used as the physical reference for AR tracking. A textured surface was added because a plain surface did not provide enough visual features for scanning and model target detection.

The armband was scanned using KIRI Engine. The scanning process used photogrammetry, where images of the armband were captured from different angles and processed into a 3D model [32]. The model was then imported into Vuforia Model Target Generator. In Vuforia MTG, the model orientation, scale, and guide views were set before the model target database was exported [24].

After that, the Vuforia database was imported into Unity. The AR Camera and Model Target object were configured in the Unity scene. AR labels were placed around the wrist armband so that they would appear when the armband was detected by the camera.

Before the angle output could be produced, the hand pose first had to be represented using landmark points from the camera image. In ROMBandAR, this pose-estimation step is handled through Google MediaPipe hand landmark detection.

MediaPipeUnityPlugin was then integrated into the Unity project [27]. The plugin was used to display hand landmarks from the camera input based on the MediaPipe hand tracking pipeline [25], [26]. Since the plugin does not directly provide wrist ROM output, additional C# scripts were developed. These scripts read the landmark positions, use the model target and wrist landmark as reference points, calculate the wrist angle output, classify the movement label, and update the feedback display.

From Fig. 2, MediaPipe Landmark 0 (WRIST) is used as the main hand reference. A fixed reference at the centre of the rigid armband is aligned with the forearm, and the current wrist position is stored when Reset is pressed as the neutral baseline. The neutral position is treated as 0°. The wrist movement is then compared with this baseline in the selected assessment plane to update the displayed angle and movement direction. The angle represents the angular opening from the fixed armband and forearm reference to the moving wrist reference, similar to reading an angle from the fixed arm of a protractor.

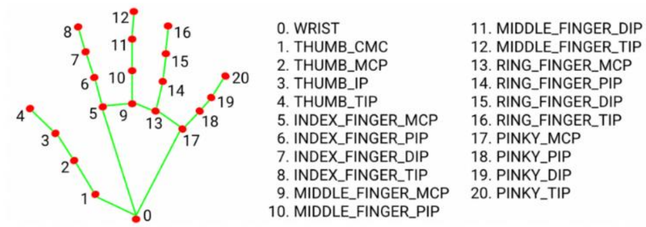



Fig. 2. Google MediaPipe hand landmarker model.

For example, as the wrist moves farther from the 0° neutral anchor, the displayed value increases according to the measured position, such as 30°, 60°, or 90°. Vuforia is used to detect and track the armband and maintain the AR registration, while the wrist movement output is produced by the custom MediaPipe-based calculation. The selected assessment plane follows the movement option chosen on the Assessment Setup Page, namely flexion, extension, ulnar or radial deviation, and pronation or supination.

The prototype also includes a Neutral output, a guide popup, an assessment library, and an assessment submission button for therapist review.


Fig. 3. Prototype wrist armband built as the model target.

Fig. 3 shows the prototype wrist armband prepared as the physical model target. The rigid body provides the textured surface needed for tracking, while the strap keeps the device positioned around the wrist. Fig. 4 shows the 3D model obtained from the KIRI Engine scan. The same model is then exported as an FBX file and imported into Vuforia MTG to be trained in Fig. 5, where the scale, orientation, and guide view for the model target were selected. Fig. 6 shows the Unity scene where the model target and MediaPipe are combined and integrated to produce an AR app for wrist ROM assessment with a clean, sleek UI design.


Fig. 4. 3D Scanning of the wrist armband using the KIRI engine.

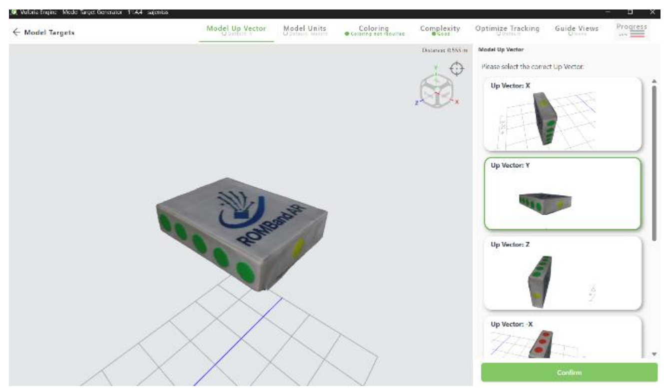



Fig. 5. Model target training in Vuforia MTG.

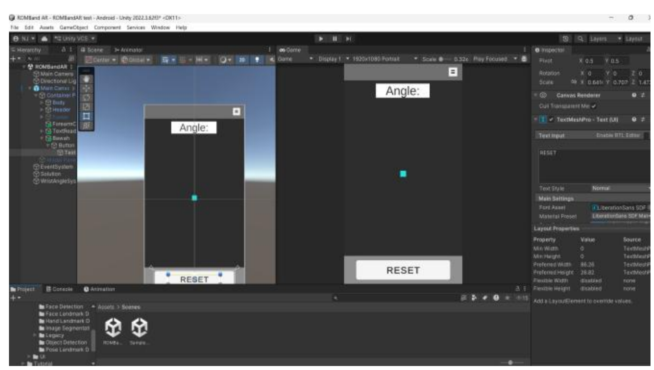



Fig. 6. ROMBandAR development in Unity.

### *D. Evaluation Procedure*

At this stage, the evaluation only covered development testing. Patient testing and clinical validation were not included in this study and are planned for the next stage of this project. Three test cases were used to check device compatibility, application functionality, and the consistency of the preliminary screenshot-based readings. The present testing did not involve repeated measurements, comparison between raters, or direct goniometer readings taken from the wrist.

Test Case 1 examined device compatibility. The purpose was to check whether ROMBandAR could be installed, opened, and run on the selected Android devices.

Test Case 2 examined the application functions. Each main function was tested to confirm that it responded as expected. These functions include page navigation, camera view, UI interaction, armband detection, hand landmark display, ROM reading, movement label, guide popup, assessment library, and submission function.

Test Case 3 was screenshot-based ROM reading consistency testing. For this test, the wrist was placed in a selected movement position and captured from the ROMBandAR assessment screen. The ROMBandAR reading shown on the screen was recorded. The ROMBandAR screenshot or static image was then measured using a goniometer by aligning the goniometer with the visible wrist posture in the image. Similar AR-based ROM research has compared software-generated joint measurements with manual goniometry [33]. In this study, the recorded ROMBandAR reading and the goniometer reading from the screenshot were compared using the absolute error, and the overall error was summarised using mean absolute error (MAE).

The absolute error for each movement was calculated using Eq. (1), while the overall MAE was calculated using Eq. (2):

$$e_i = |R_i - G_i| \quad (1)$$

$$MAE = (1/n)\ \Sigma_{i=1}^{n} |R_i - G_i| \quad (2)$$

where, $R_i$ is the ROMBandAR reading, $G_i$ is the goniometer reading taken from the same screenshot, and n is the number of movement positions.

This test was used only as an early development check and does not represent clinical validation. Its purpose was to observe whether the ROMBandAR reading followed the visible wrist posture and remained close to a manual goniometer reading taken from the same screenshot.

Fig. 7 shows how the preliminary screenshot comparison was carried out. The ROMBandAR reading remained visible on the captured image, and the goniometer was aligned with the wrist posture shown in the same image. This allowed both readings to be compared without treating the screenshot measurement as direct clinical goniometry.

Fig. 8 shows an example of the standard goniometer positioning used to measure wrist ROM directly on the hand. The figure is included only to illustrate how conventional wrist ROM measurement is normally carried out and was not used as part of the evaluation reported in this study.

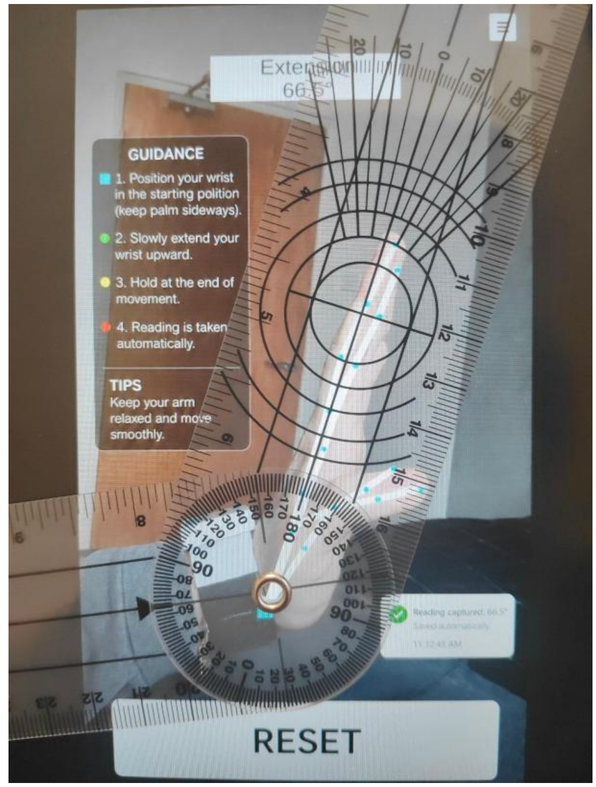



Fig. 7. Screenshot-based AR ROM reading consistency check with goniometer reference.

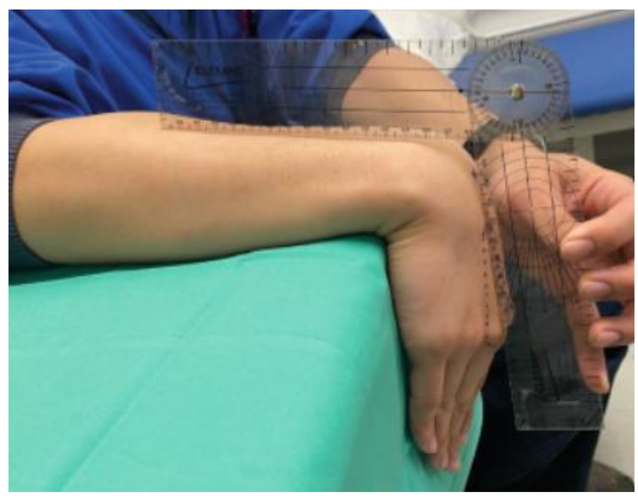


Fig. 8. Direct Wrist ROM measurement on an actual hand using a goniometer.

## IV. Analysis and Results

This section presents the implementation and development-level test results of ROMBandAR. It first describes the development environment, deployment configuration, and application interfaces. It then reports the results of device compatibility testing, application functionality testing, and screenshot-based ROM reading consistency testing. The results in this section therefore reflect prototype-level testing only. Repeated measurements, inter-rater analysis, and direct wrist measurement with a goniometer were not carried out in this study.

### A. Prototype Implementation

ROMBandAR was developed as an Android prototype with eight main pages: the splash page, start page, home page, notes page, assessment setup page, AR ROM reading page, assessment library, and submission page. During the assessment, the main AR page shows the live camera view together with the AR overlay, detected hand landmarks, angle reading, and movement label in real time.

Once the prototype was ready, it was installed on selected devices and tested under the intended conditions, which is by checking two basic points: whether the application could run properly and whether its main functions responded correctly and smoothly. The following subsections describe the development environment, device setup, application interfaces, and the results obtained.

Table I summarizes the main development environment, tools, platform, physical reference, and prototype outputs used in ROMBandAR.

TABLE I. DEVELOPMENT ENVIRONMENT

| ITEM | SPECIFICATION |
|---|---|
| Development engine | Unity |
| Programming language | C# |
| AR tracking | Vuforia Engine and Vuforia MTG |
| 3D scanning | KIRI Engine |
| Hand landmark detection | MediaPipeUnityPlugin |
| Target platform | Android |
| Physical reference | Prototype wrist armband |
| Main output | AR labels, hand landmarks, angle output, movement label, saved ROM reading, and report submission |

*1)* Deployment and configuration: ROMBandAR was developed as a mobile Android application using Unity, Vuforia Engine, and C#. The application was developed on an ASUS TUF Gaming A15 laptop with an AMD Ryzen 5 processor, NVIDIA GeForce graphics card, 15.6-inch display, and Windows 11 operating system. For device testing, the application was installed on a Realme C35 running Android 11, a Xiaomi Redmi Note 12 running Android 13, and a Samsung Galaxy A25 5G running Android 14.

The wrist armband serves as the physical model target for Vuforia detection. When the camera recognises the rigid armband body, the application places the AR labels around the wrist reference. MediaPipe separately detects the hand landmarks, while the custom scripts use the reference data to update the movement type, angle reading, and guidance in real time.

*2) Interfaces:* The outputs of the proposed framework can be seen through the application interfaces. ROMBandAR has eight main pages.

As shown in Fig. 9, the Splash Page appears when the application is launched. After the loading process is completed, the user is directed to the Start Page shown in Fig. 10. The page displays the ROMBandAR logo, a Start button, and a How to use? option. Clicking the Start button then opens the Home Page shown in Fig. 11.


Fig. 9. Splash page.

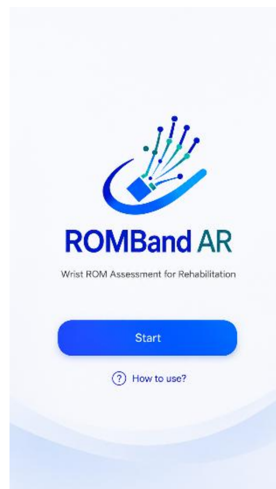



Fig. 10. Start page.

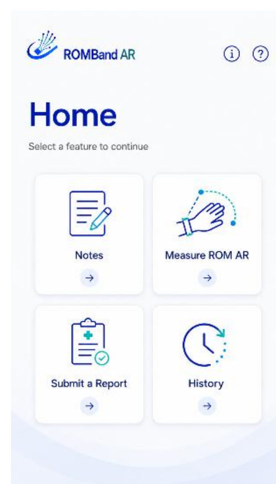



Fig. 11. Home page.

The Home Page contains the main navigation buttons, which are Notes, Measure ROM AR, Submit a Report, and History. It also includes the About and Help buttons for additional information. As shown in Fig. 12, the Notes Page provides simple information about wrist ROM, how to measure wrist movement, and the basic steps for using ROMBandAR.


Fig. 12. Notes page.

When the user clicks Measure ROM AR, the Assessment Setup Page is displayed as shown in Fig. 13. On this page, the user can choose the right or left wrist and select the assessment type, such as flexion and extension, ulnar and radial deviation, or pronation and supination. The user can then start the AR assessment.

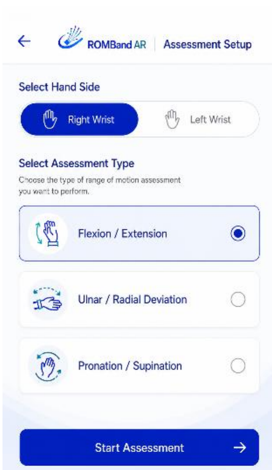



Fig. 13. Assessment setup page.

As shown in Fig. 14, the Measure ROM AR Page opens the smartphone camera to detect the wrist armband. When the armband is detected, the application displays the ROM reading, movement label, hand landmark overlay, and guidance panel. A Reset button is provided so the user can set the current arm position as the neutral reference before taking another reading. This step is needed because the arm and camera position can change between assessments.

The Submit a Report Page, shown in Fig. 15, allows the user to prepare the latest ROM assessment for therapist review through email. This page contains the selected reading, basic patient details, therapist information, and additional notes. Lastly, the History Page in Fig. 16 displays the saved ROM readings with their dates, movement types, wrist side, and reading values in one library. The user can open any saved result to view more details.

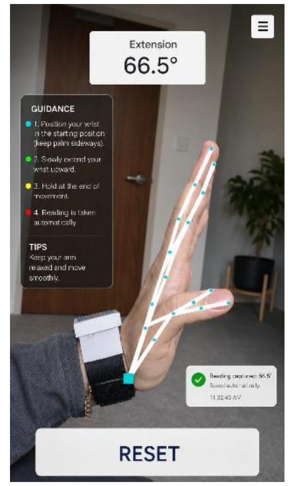



Fig. 14. AR ROM reading.

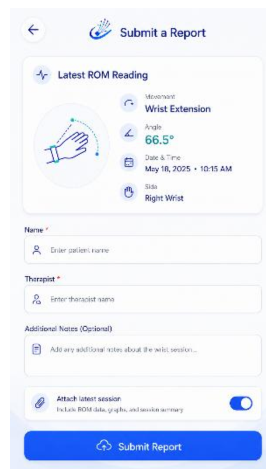



Fig. 15. Submit page.

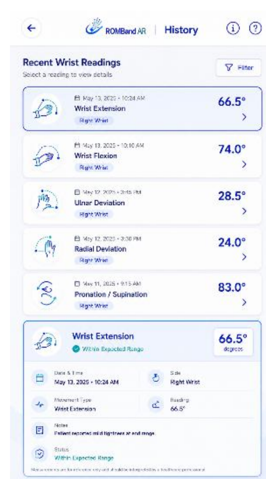



Fig. 16. History page.

## B. Test Case 1: Device Compatibility Testing

Device compatibility testing was conducted to check whether ROMBandAR could be installed and opened on different Android devices, access the camera, and display the user interface correctly. Armband detection and assessment output were evaluated under Test Case 2 because they are application functions rather than device specifications.

All three devices installed and opened ROMBandAR successfully. Camera access and the main user interface also worked on each device. The results in Table II report device compatibility only. The armband detection, hand landmarks, movement output, saving function, and submission function are reported separately in Table III.

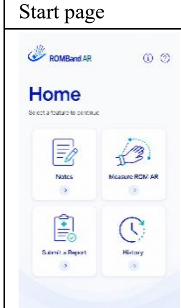
## C. Test Case 2: Application Functionality Testing

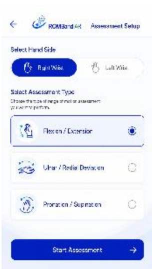
Application functionality testing was conducted to check whether the main functions worked as expected. This test includes the user interface functions, AR model target detection, MediaPipe landmark display, ROM reading, movement label, guide popup, assessment library, and submission function.

TABLE II. TEST CASE 1: DEVICE COMPATIBILITY TESTING

| TEST ITEM | EXPECTED OUTPUT | DEVICE #1 | DEVICE #2 | DEVICE #3 |
|---|---|---|---|---|
| Device Name | | Realme C35 | Xiaomi Redmi Note 12 | Samsung Galaxy A25 5G |
| Android Version | | 11 | 13 | 14 |
| Processor | | Unisoc T616 Octa-core | Qualcomm Snapdragon 685 Octa-core | Samsung Exynos 1280 Octa-core |
| RAM | | 4.00 GB | 6.00 GB | 8.00 GB |
| Storage | | 128 GB | 128 GB | 256 GB |
| Application installation | Application installs successfully | Success | Success | Success |
| Application launch and basic display | Application opens, accesses the camera, and displays the user interface correctly | Success | Success | Success |

TABLE III. TEST CASE 2: APPLICATION FUNCTIONALITY TESTING

| PAGE | PROCEDURES | EXPECTATION | RESULTS | | |
|---|---|---|---|---|---|
| | | | DEVICE #1 | DEVICE #2 | DEVICE #3 |
|  Splash page | Launch the ROMBandAR application<br>Wait for the loading process | Splash screen with ROMBandAR logo is displayed<br>Application goes to the Start page automatically | Success | Success | Success |
|  Start page | Click on the Start button | Go to the Home Page | Success | Success | Success |
| | Click on the How to Use text | Help or guideline popup/page is displayed | Success | Success | Success |
| | Close the How to Use? popup/page | Return to the Start page | Success | Success | Success |
|  Home page | Click on the Notes button | Go to the Notes page | Success | Success | Success |
| | Click on the Measure ROM AR button | Go to the assessment setup page | Success | Success | Success |
| | Click on the Submit a Report button | Go to the submit report page | Success | Success | Success |
| | Click on the History button | Go to the history page | Success | Success | Success |
| | Click on the 'i' button | Open about popup | Success | Success | Success |
| | Click on the '?' button | Open Help page | Success | Success | Success |

| | | | | | |
|---|---|---|---|---|---|
| <br>Notes page | Display notes content<br>Click on each note<br>Click the back button | Notes about wrist ROM, how to measure ROM, and a step-by-step guide are displayed<br>Note details will pop up<br>Go to the Home page | Success<br>Success<br>Success | Success<br>Success<br>Success | Success<br>Success<br>Success |
| <br>Assessment Setup page | Click the left or right wrist button<br>Click assessment type<br>Click Start Assessment button<br>Click back button | Side of hand is selected<br>Assessment type is selected<br>Go to Measure ROM page<br>Go to Home page | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success |
| <br>Measure ROM page | Click the reset button<br>Click the 3-bar option in the top-right corner<br>Detect wrist armband model target<br>Move wrist based on selected assessment | ROM reading is reset to neutral position<br>Home, Settings, and Quick Action options are displayed<br>Wrist armband is detected by the application<br>ROM reading and movement label are updated | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success |
| <br>Submit a Report page | Display the latest ROM reading<br>Enter patient and therapist details<br>Enter additional notes<br>Click the Submit Report button | Latest reading details are displayed correctly<br>User details can be entered<br>Notes can be added before submission<br>Report is submitted successfully | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success |
| <br>History page | Display saved ROM readings<br>Display selected result detail<br>Click selected reading<br>Scroll history list<br>Click back button | Saved ROM readings are shown in the list<br>Result detail is displayed<br>Date, side, movement type, reading, and notes are displayed<br>User can view more saved readings<br>Go back to the Home page | Success<br>Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success<br>Success | Success<br>Success<br>Success<br>Success<br>Success |

The result shows that the main functions of ROMBandAR worked as intended at the prototype level. The armband was detected, the hand landmarks and movement output were displayed, and the assessment reading could be saved in the library and prepared for therapist review through the submission function.

*D. Test Case 3: Screenshot-Based ROM Reading Consistency Testing*

Screenshot-based ROM reading consistency testing was conducted to compare the ROMBandAR reading with a goniometer measurement taken from the wrist screenshot. The wrist movement screen was captured from ROMBandAR with the wrist in a selected movement position. The ROMBandAR reading shown on the screen was recorded. Then, the same screenshot was measured manually using a goniometer as the reference. Table IV presents the ROMBandAR readings, the goniometer readings measured from the captured wrist screenshots, and the absolute error for each movement tested.

The screenshot-based test showed that the ROMBandAR readings were close to the manual goniometer readings taken from the ROMBandAR wrist screenshots. Based on Eq. (1), the absolute errors ranged from 0.8° to 1.5°. Based on Eq. (2), the overall MAE was 1.19°, showing only a small average difference between the ROMBandAR readings and the screenshot-based goniometer measurements. This error is below the approximately 5° measurement error that has been reported as acceptable for wrist goniometry [34]. Therefore, the result gives an encouraging indication that the prototype readings were close to the reference measurements and showed good consistency at this early stage, although it should not yet be interpreted as clinical accuracy or reliability.

TABLE IV. TEST CASE 3: SCREENSHOT-BASED ROM READING CONSISTENCY TESTING

| WRIST/FOREARM MOVEMENT | ROMBANDAR READING | GONIOMETER READING FROM SCREENSHOT | ABSOLUTE ERROR | OBSERVATION |
|---|---|---|---|---|
| Neutral | 0.8° | 0.0° | 0.8° | Consistent |
| Flexion | 74.0° | 73.0° | 1.0° | Consistent |
| Extension | 66.5° | 65.0° | 1.5° | Consistent |
| Radial Deviation | 23.5° | 22.5° | 1.0° | Consistent |
| Ulnar Deviation | 28.5° | 29.5° | 1.0° | Consistent |
| Pronation | 79.0° | 80.5° | 1.5° | Consistent |
| Supination | 82.5° | 81.0° | 1.5° | Consistent |

## V. DISCUSSION

This section discusses what the development results mean, how ROMBandAR differs from the existing rehabilitation technologies, the significance of the prototype, and the limitations that must be addressed before clinical evaluation.

The development of ROMBandAR shows that the rigid body of a wrist armband can be used as a model target for AR-based wrist ROM assessment. The flexible strap is more difficult to track because its shape changes according to the user's wrist size. For this reason, the current model target focuses on the rigid armband body. The textured surface also helped the armband become more suitable for scanning and detection because the plain surface did not provide enough visual features.

The development pipeline also demonstrates that KIRI Engine, Vuforia MTG, Unity, and MediaPipeUnityPlugin can be combined in one prototype. KIRI Engine was used to scan and prepare the three-dimensional model, Vuforia was used for model target training and armband detection, and MediaPipeUnityPlugin was used to display hand landmarks. The custom C# scripts then connected these components with the angle reading, movement label, guide popup, saving function, and report submission function.

At the prototype stage, the main functions worked during testing. ROMBandAR could be installed and opened on the three selected Android devices. The page navigation, armband detection, hand landmark display, ROM output, assessment saving, and report submission functions also operated as expected. For the preliminary screenshot check, the ROMBandAR readings remained close to the goniometer readings taken from the same images. The calculated MAE was 1.19°.

Although ROMBandAR was initially considered for stroke rehabilitation, its measurement function is not limited to stroke. Wrist or forearm movement is also assessed after conditions such as distal radius fracture and tendon injury or repair. The reason for the movement limitation may be different, but therapists still need to observe and record the available movement. Since the basic measurement task remains similar, the prototype can later be tested with more than one rehabilitation group without changing its main function.

At this stage, the main value or significance of ROMBandAR is that several assessment functions are brought together in one mobile application. The system combines model-based AR tracking with hand landmark display, live angle output, movement guidance, assessment saving, and therapist submission. Unlike VR, ROMBandAR allows the real wrist to remain visible during the assessment. It also does not require the mechanical equipment or separate sensor packages used in many robotic and wearable systems. This approach may later support supervised assessment or home-based follow-up. However, usability, validity, and reliability still need to be examined before the prototype can be considered for clinical use.

Also, these results still need to be interpreted as an early development check. No patient or clinical evaluation was carried out, so this study cannot show that ROMBandAR is clinically accurate or better than a goniometer. The screenshot comparison was only used to check the consistency, whether the displayed reading feedback followed and was close to the goniometer measurement or not. The result may still be influenced by the image used, camera angle, wrist posture, and the way the goniometer was aligned. Therefore, the next stage should involve a controlled study with repeated measurements.

Some practical limitations also appeared during this development stage, such as the current armband is still an early prototype and needs a more stable, neat, and comfortable design. Furthermore, tracking performance may also change when the lighting is poor, the camera is too near or too far, the viewing angle changes, or part of the armband is hidden. The hand landmarks may also become unstable when the hand is partly covered or moved too quickly. Besides, the guidance provided by the application is also still general and does not yet consider the movement limits of different rehabilitation conditions.

Taken together, the prototype shows potential for different rehabilitation cases, but the next evaluation should not treat all users in the same way. Stroke, distal radius fracture, and tendon repair involve different movement limitations, so each group will need its own testing protocol before the accuracy and reliability of ROMBandAR can be properly established. Following this development stage, future work will evaluate the proposed framework through its ROM measurement performance and the extrinsic feedback provided during wrist ROM assessment.

## VI. CONCLUSION AND FUTURE WORK

This study presents the development of ROMBandAR, an AR-based prototype for wrist ROM assessment in rehabilitation. The project was first considered for stroke rehabilitation, but the system is not limited to stroke only. It may also be used in musculoskeletal and orthopaedic rehabilitation, where wrist movement still needs to be measured and monitored. For the AR tracking, a wrist armband was used as the model target. The armband was scanned using KIRI Engine, trained in Vuforia MTG, and later imported into Unity. MediaPipeUnityPlugin was then added to display the hand landmarks from the camera view. Several C# scripts were also written to handle the angle reading, movement label, feedback, guide popup, saving function, and therapist submission.

At this point, the prototype was tested with three test cases at the development level. These were tests of device compatibility, application functionality, and the consistency of ROM reading based on screenshots. ROMBandAR runs successfully on all selected Android devices. It also detected the wrist armband, displayed the AR overlay and hand landmarks, updated the movement reading, saved the result, and opened the submit page successfully. For the screenshot-based comparison, ROMBandAR produced an MAE of 1.19°, which was below the approximately 5° measurement error reported as acceptable for wrist goniometry [35]. This provides an encouraging preliminary result, although clinical accuracy and reliability still need to be established through controlled testing.

So, future work will mainly focus on improving the armband design so that it is more stable and comfortable to wear. There are some parts of the application that still need some refinement, particularly the tracking performance, the interface layout, the angle calculation, and movement guidance. After these improvements, the prototype will be tested in a more controlled setting by comparing its readings with a standard goniometer. ROMBandAR will also be used together with a newly developed ROM assessment form during selected rehabilitation assessments. This evaluation will help determine whether the system can provide consistent readings and support wrist ROM assessment in practice. These findings will support the next stage of framework evaluation, including the extrinsic feedback provided during selected wrist ROM assessments.

## ACKNOWLEDGMENT AND FUNDING

The authors would like to acknowledge the Ministry of Higher Education (MoHE) and Center for Research Excellence and Incubation Management (CREIM) as well as Center for Management of Academic Excellence and Innovation, Universiti Zainal Abidin for their financial support through the Scholarship of Teaching and Learning (SoTL) Grant. We also want to thank the Sultan Zainal Abidin Hospital (HoSZA), Faculty of Medicine UniSZA, and Besut District Health Center.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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