

# *Design and Testing of an App-based Wearable Device to Measure Joint Angle and Muscle Activity*

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**Abstract**— In physiotherapy and rehabilitation sector, initial patient diagnosis on movement is done using manual techniques. Recently, use of sensor technology is mostly preferred to understand movements precisely. The rapid technological advancements with growing demand for the use of innovative medical in the field of medicine aim to improve the quality of health-care delivery. This study aims to design a wireless wearable system that senses and measures motor variables needed in physiotherapy assessments. After developing the product, an initial device characterisation test was done to establish its accuracy. Separate comparative investigations were conducted for measuring muscle activity with Biometrics EMG sensors and joint angle range of motion (ROM) with standard goniometer, android mobile applications called Goniometer Recorder, and Angle Meter Pro respectively. Data analysis was done using Pearson correlation coefficient method. An accuracy of 98% for joint angle measurements and 96% for muscle activity measurements was found when compared with gold standard devices. The findings of this study suggest use of this device as a movement sensing and measuring tool that can be advantageous to existing tools used in current practice.

**Keywords**—assessment tools, digital devices, EMG, medical devices, physiotherapy, electronic reporting technology.

## I. Introduction

Physiotherapy is a health profession where hands-on techniques are used majorly for initial patient diagnoses such as assessing joint range and muscle strength. Patients mainly seek physiotherapy to restore poor muscle strength or joint function [1]. These healthcare professionals do not have a handy prognostic tool that measures physiotherapy variables easily. But, with rapid technological advancements physiotherapists are seeking the use of newest devices to improve the quality of care provided [2]. This is supported by the report submitted on Digital Practice Experiences and insights during COVID-19 [3]. This is because the biomedical wearable sensor technology that measures movement variables in real-time with objective data positively impacts clinical decision making [4,5] that streamlines the therapy outcomes while providing evidence of improvement [6].

Even though, PTs have been using conventional methods of grading system such as Manual Muscle Testing (MMT) to assess muscle strength [7-9] and goniometer to measure joint angle [10, 11]. These manual assessment techniques impose subjective results as they are dependent on the therapist's skill and experience [12]. This leads to varied assessment results between the practitioners for the same patient with the same illness [13, 14]. This will affect the treatment protocols given to the same patient by different physiotherapists, thereby leaving the patient usually unclear of the treatment done. Another challenge is time taken to implement conventional

assessment methods and their respective documentation in a busy physiotherapy centres. For example, in MMT grading muscle strength is tested against the PT's resistance with one hand requiring equal or more strength than the patient at regular intervals with constant patient positional adjustments [15, 16]. The use of standard goniometer proposes complexities as well requiring proper skill of using both hands of the examiner to measure and stabilize body part [17-19].

Alternative diagnostic methods available are using dynamometers (both hand-held and digital), movement sensors, smartphone mobile applications, radiography, and photography [20-27]. But due to the factors of being expensive, requiring prolonged duration for setting up, experienced personnel, being unsuitable for lower to medium structured physiotherapy clinics, and complex data storage techniques their implementation is limited to only highly infrastructure hospitals [28, 29]. In a report submitted by Deloitte, it is found that almost 75% of medical devices are imported to India which are quite expensive and usually not affordable by most healthcare centres [30]. As a result, most of the rehabilitation centres are bind to use conventional assessment methods in low-to-medium income rehabilitation settings in India. Therefore, a sensor system has been designed and developed that connects wirelessly to a mobile phone based android application to measure the activity of muscle and the joint motion. The current study presents device architecture and initial characterization by comparing with Biometrics EMG sensors, standard goniometer, and android mobile applications respectively.

## II. Methods

### A. System Architecture

Phzeeze<sup>®</sup> is wearable, low power battery operated device, which communicates wirelessly to an Android phone running a bus of ten wires (Fig. 1). The *upper module* consists of

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power management, device health monitoring circuits, and ROM sensor circuitry. The *lower module* consists of the main micro-processor, the Bluetooth<sup>®</sup> radio, EMG bio-amplifier

circuitry and the movement sensors. Both the upper and lower modules are connected by a bus of wires that acts like a bridge between the modules for power transmission, control signals and data exchange during device operation as shown in block diagram of Pheeze<sup>®</sup> (Fig. 2).

The raw data is acquired, pre-processed on the hardware before it is sampled by the on-board analogue to digital converter (ADC) in the microcontroller. The pre-processed data is then further processed using proprietary algorithms and digital filters implemented in the on-board processor. The digitally filtered data is then transmitted wirelessly to the smart phone to custom designed application, over low power Bluetooth<sup>®</sup> (BLE) channel. The device is powered using rechargeable LiPo (Lithium Polymer) battery and has an average run-time of 35 hours, once completely charged. The smart phone acts like the display device for the product and also acts like a bridge between the device and the cloud, where the data is further stored and processed. The analyzed results are downloaded back into the phone.



Fig. 1. Pheeze<sup>®</sup> toolkit with Android phone application as dashboard

### B. ROM and sEMG Data Acquisition

Both modules of the device contain Inertial Measurement Unit (IMU) sensors- which include a three degrees of freedom (3DOF) accelerometer, gyroscope, and a magnetometer. The data acquired by the sensors is processed by the on-board 32-bit ARM Cortex M3 microcontroller to calculate the exact range of motion (angle) of the joint, where the device is applied. The lower module incorporates an indigenously designed and developed EMG bioamplifier. The adhesive electrodes that are made with Ag/AgCl (Silver/Silver Chloride) are used to connect to a 3-lead EMG cable which has 3 terminals colour coded with red, green, and yellow [31]. The red electrode used as a reference electrode and the other two electrodes used to capture the differential EMG signals from the superficial muscle. The acquired surface EMG (sEMG) signal is then pre-processed using on-board electronics before de-noising using on-board digital filters. The signal chain for acquiring the ROM and the raw sEMG signal is as shown in Fig. 3 and Fig. 4. The processed data is then transferred for display to the smart phone running the Pheeze<sup>®</sup> android application, where the real-time ROM in degrees and sEMG in microvolts (uV) is displayed.

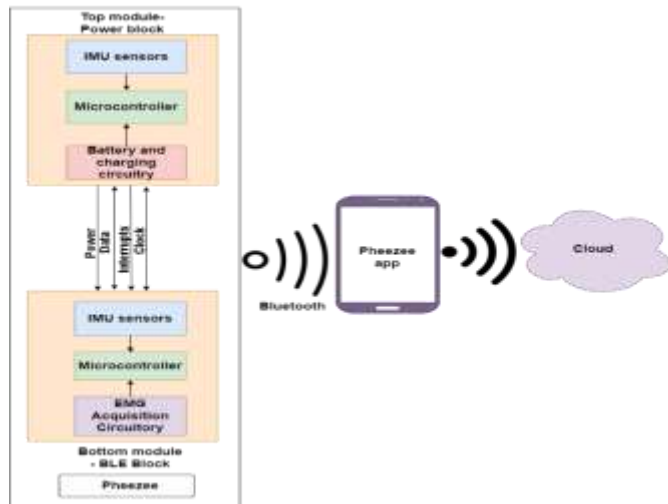


Fig. 2. Overall block diagram of Pheeze<sup>®</sup>

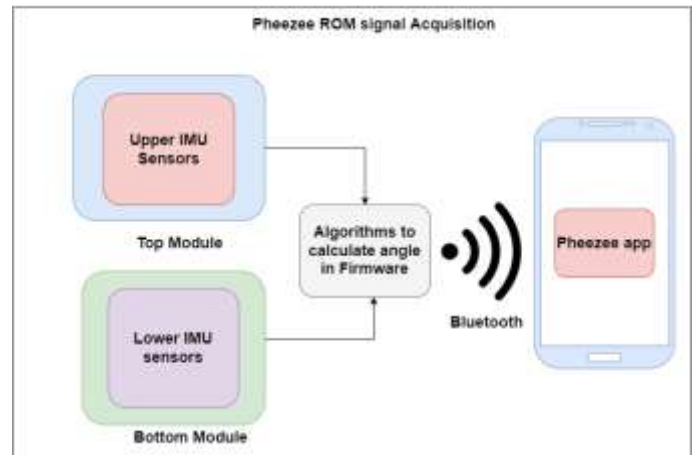


Fig. 3. Pheeze<sup>®</sup> block diagram showing capturing of ROM signal

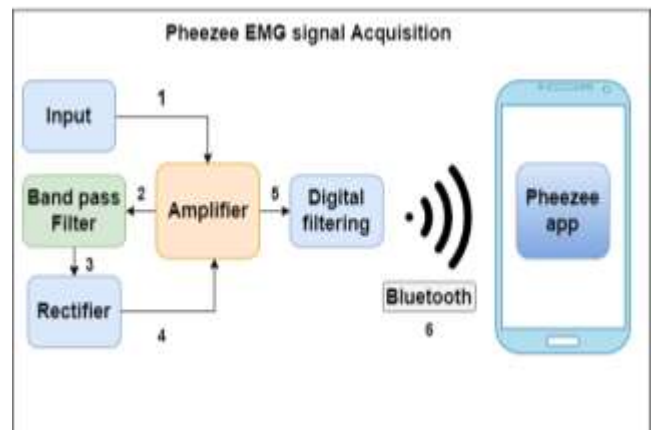


Fig. 4. Pheeze<sup>®</sup> block diagram showing capturing of EMG signal

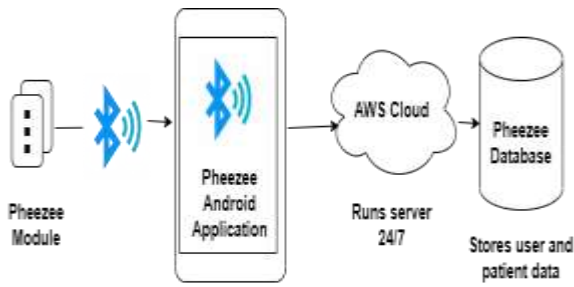


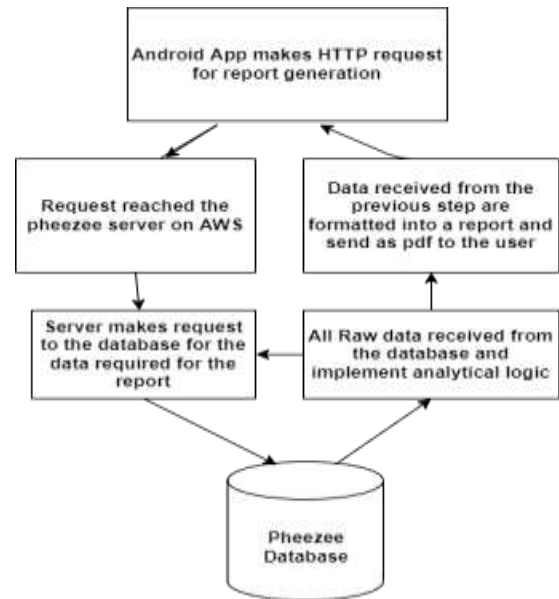
Fig. 5. Data transfer between the device, mobile app and the cloud platform

### C. sEMG Digital Filtering

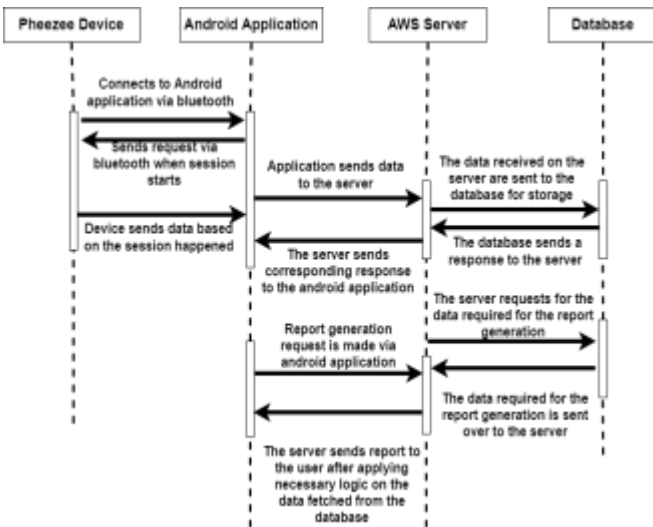
Custom designed digital filters were implemented in the on-board microcontroller to remove unwanted noise from the signal. The Root Mean Square (RMS) value of the band pass filtered signal was used to quantify impulses in muscles in microvolts (uV). The final processed signals were sent to Pheeze<sup>®</sup> app running in the Android smartphone, wirelessly over Bluetooth<sup>®</sup> (Fig. 5). The Pheeze<sup>®</sup> app also acts like a bridge between the device and the cloud based secured server [32].

### D. Device Software Information and Clinical Reports

The data in the cloud was stored by using http request (hypertext transfer protocol) through Representational State Transfer (REST) and Application Programming Interface (API) that were defined and programmed in the server itself. The sequence diagram of functioning of the Android application and the logic flow chart of Pheeze<sup>®</sup> android application (Fig. 6). Pheeze<sup>®</sup> app generates a session report per day and an overall report with a summary of all the sessions performed. The reports are accessible in a PDF format and sharable (Fig. 6c), through email or WhatsApp<sup>®</sup> [33].



6b. App flowchart



6a. App sequential diagram



6c. Pheeze<sup>®</sup> sample session report for Elbow flexion (for biceps muscle).

Fig. 6. Pheeze<sup>®</sup> Android mobile application information on; a. sequential diagram; b. flowchart & c. session report.

### E. Standard Devices: Verification Tests & Bioamplifier Characterization

For comparing joint ROM, a CE certified therapy plus goniometer (Fig. 7a) and android mobile applications Goniometer Records App [34] and Angle meter Pro [35] were used. The EMG comparison was done with Biometrics wireless EMG [36] using DataLITE-LE230 (Fig. 7b) with its software version [37] for Pheeze<sup>®</sup> generated surface electromyography (sEMG) data validation.

The standard goniometer was used to test the readings of the android apps used in this study and calibrated Pheeze<sup>®</sup>. The readings from the calibrated Android apps show consistency with goniometer for a range of 0° to 90° (Fig.8 a & b). A well calibrated Pheeze<sup>®</sup> device shows a ROM of 0° degrees when the modules are placed parallel and shows 90° when placed perpendicular to each other (Fig. 9).



Fig. 7. Standard devices to compare Pheeze<sup>®</sup>

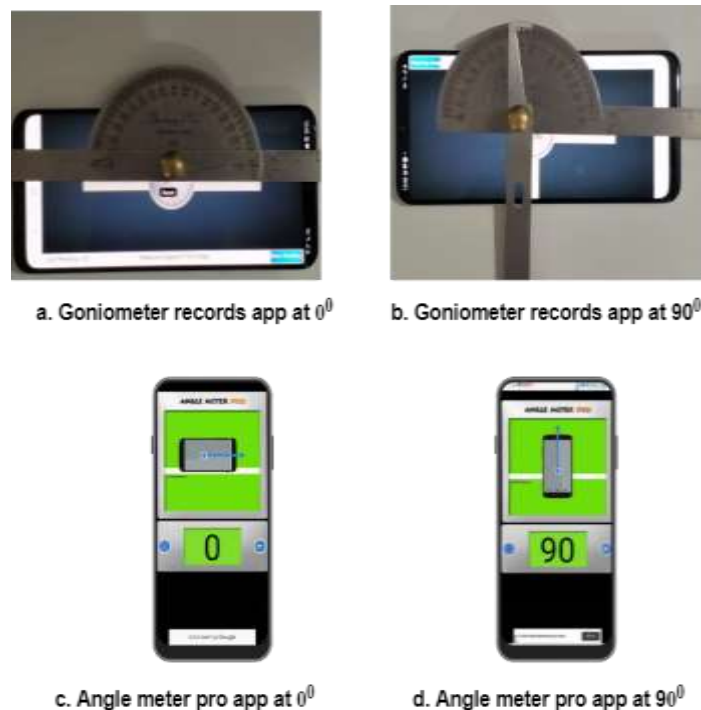


Fig. 8. Calibration verification tests of android mobile applications goniometer records & angle meter pro with standard goniometer.



Fig. 9. Pheeze<sup>®</sup> calibration verification tests with modules placed parallel: A) Pheeze app 0° B) goniometer 0° and perpendicular: A) Pheeze app 90° B) goniometer 90°.

A test set up was made prior to EMG amplifier characterization (Fig. 10), which consists of a signal generator (generating a signal in the valid EMG signal bandwidth), a power supply to power the input stage of the amplifier and an oscilloscope to measure the signals at the input and output terminals of the amplifier. Fig. 11a shows the input signal of 3.3 mV, 30 Hz as generated by the signal generator as fed to the Pheeze<sup>®</sup>. Fig 11b shows the output signal at the Pheeze<sup>®</sup> bioamplifier. It has an amplitude of 456 mV and a frequency of 30 Hz. Hence, the gain of the amplifier in the passband is found to be around 138 V/V, which is as per the design of the bioamplifier. Due to the ambient noises, the device shows anywhere between 0 to 5 microvolts (uV) when no signal available to feed the input of the amplifier (Fig. 12). Hence, from the values generated by Pheeze<sup>®</sup> as seen in Figures 9, 10, 11, and 12, it is seen that the bioamplifier of Pheeze<sup>®</sup> is well characterized from the engineering front. With these verification of calibrated ROM sensors and EMG bioamplifier, the device was ready to be used on a healthy subject.

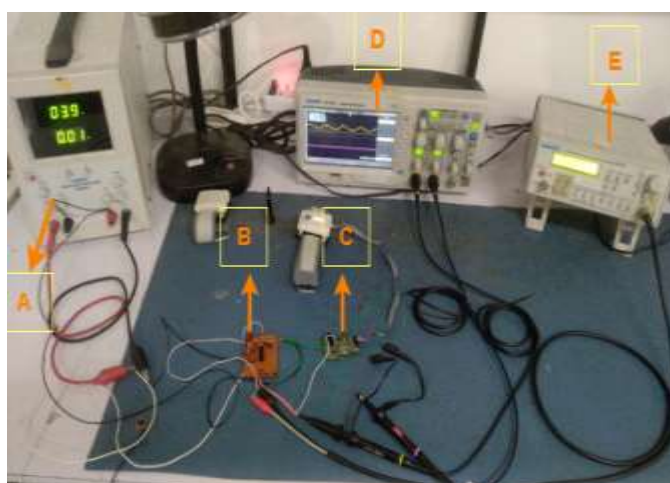


Fig. 10. Pheeze<sup>™</sup> EMG bioamplifier characterization test set up; A. power supply, B. buffer CKT at input, C. EMG bioamplifier, D. DSO for output visualization, and E. signal source.

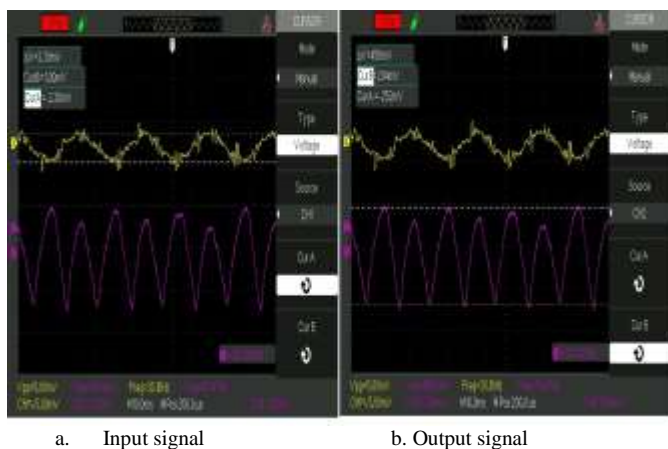


Fig. 11. Digital Storage Oscilloscope showing signals.



Fig. 12. Pheeze® EMG readings showing ambient noise of 1 uV (A) when no EMG source is connected

### F. Data Collection

Two healthy volunteers were chosen for the tests. The subjects were explained about the characterization and testing procedure of Pheeze® later an informed consent was taken. The study was conducted following ethical principles for medical research involving human subjects (2008) mentioned in world medical association declaration of Helsinki [40].

In this study, the superficial muscles and major joints of upper limb, lower limb, and spine region were tested. The device was worn by the patient and is connected to the android phone over Bluetooth connection. The participant's details were entered in the app followed by selecting the related muscle, joint, and its movement in the app. After selection, an image with device placement was prompted on the mobile screen as a reference for device placement. For joint range measurement the upper module wrapped above and the lower module below the measuring joint (Fig. 13). After a visual demo by the examiner, each movement was recorded. Skin

preparation steps were followed prior using Surface EMG for the Non-Invasive Assessment of Muscles (SENIAM) guidelines on their website [38]. During the EMG recording, the electrodes of Pheeze® and Biometrics placed closely on the muscle surface area [39] to capture signals simultaneously of superficial muscles of upper and lower extremities (Fig. 14).

After the data was collected, the Microsoft excel (2019 version) was used for analysis. The data for ROM and sEMG was retrieved from Pheeze® report and the backend server while Biometrics computer software. The same method was followed for ROM values as well, while the ROM data from traditional goniometer was entered directly in the computer when the readings were taken. The data was analysed using Python script and analysis was done using Pearson correlation coefficient method for sEMG. Average differences between the traditional goniometer and the Pheeze® values obtained were analysed to arrive at the accuracy of Pheeze® for ROM on real human application.



Fig. 13. Pheeze® device placement on joints of upper extremity; A. shoulder, B. elbow, C. wrist, and lower extremity of D. Hip, E. Knee, F. Ankle.

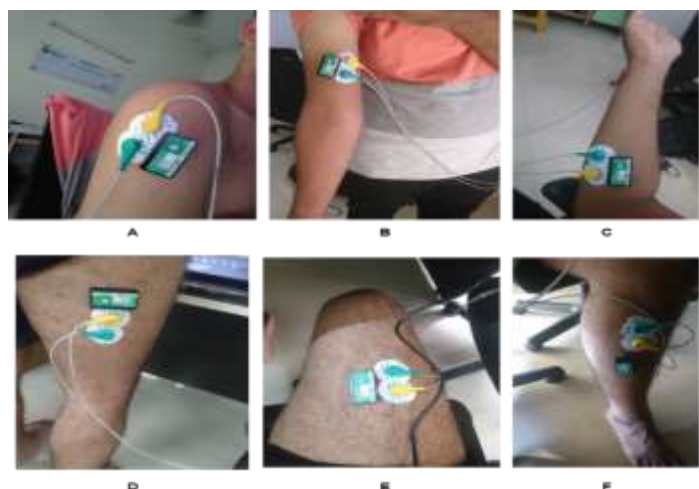


Fig. 14. Pheeze® and Biometrics Ltd. EMG recording of superficial muscles of upper extremity; A. Deltoid, B. Biceps, C. Flexor carpi ulnaris, and lower extremity; D. Biceps femoris, E. Quadriceps femoris, F. Tibialis anterior.

### III. Results

A series of ROM graphs of joint movements of upper extremity, lower extremity, and spine region for thoracic and lumbar are given in the figures 15, 16, and 17 respectively. The readings from each of the devices recorded is shown in different colours in the graphs. The comparative results of sEMG signal obtained using Pheezee® and Biometrics LE230 device are presented in Fig. 18 and Fig. 19 for superficial muscles of upper and lower extremities. The overall average error in ROM assessments using Pheezee® as compared to gold standard tools used in current study are given in Table I and the calculated correlation co-efficient values of Pheezee® sEMG readings are presented in Table II.

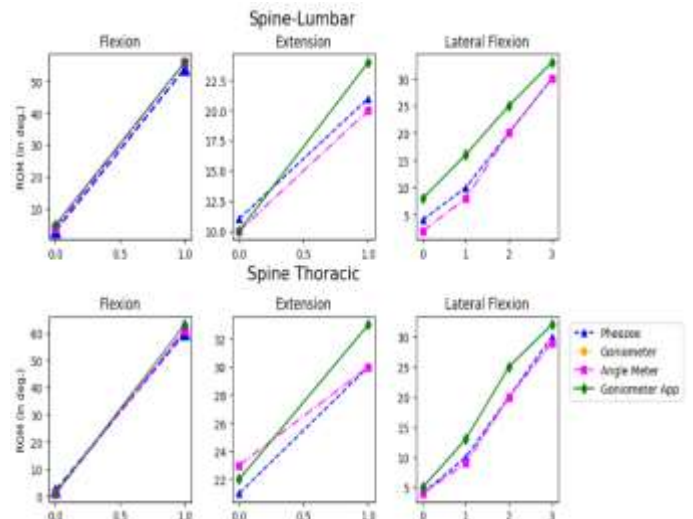


Fig. 17. Comparison ROM graphs for Spine movements of thoracic and lumbar region.

TABLE I. SUMMARY OF PHEEZEE® ROM PERCENTAGE ACCURACY

Joint	Exercise	Error (in degrees)	Average Error (in degrees)	Percentage accuracy
Shoulder	Flexion	2.5	1.80	99
	Extension	1.5		
	Abduction	2.05		
	Adduction	1.16		
Elbow	Flexion	1.38	1.38	99.05
	Forearm	Pronation	1.37	1.39
Supination		1.4		
Wrist	Flexion	1	0.92	99.39
	Extension	0.83		
Spine-Thoracic	Flexion	1.5	1.54	96.92
	Extension	1.5		
	Lateral flexion	1.63		
Spine-Lumbar	Flexion	1.75	2.00	95.56
	Extension	1.5		
	Lateral flexion	2.75		
Hip	Flexion	1.41	1.94	98.56
	Extension	2.33		
	Abduction	1.91		
	Adduction	2.11		
Knee	Flexion	1.15	1.10	99.21
	Extension	1.04		
Ankle	Dorsiflexion	1.4	1.53	98.09
	Plantarflexion	1.55		
	Eversion	1.66		
	Inversion	1.5		
Average Percent Accuracy				98.33

\*ROM- Range of Motion

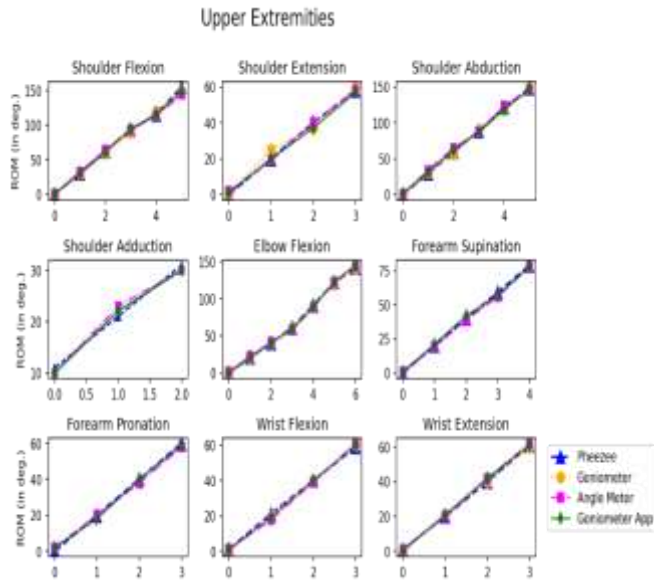


Fig. 15. Comparison ROM graphs of upper extremity movements of shoulder, elbow, & wrist joints.

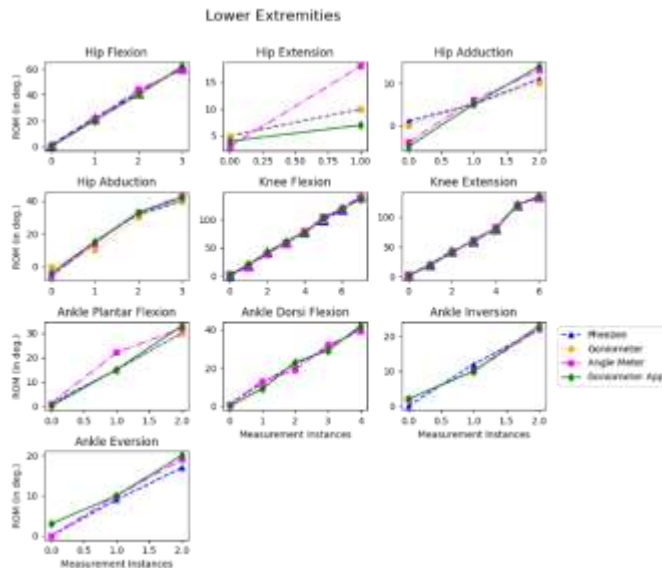


Fig. 16. Comparison ROM graphs of Lower extremity movements of Hip, Knee, and Ankle joints.

TABLE II. SUMMARY OF PHEEZEE® EMG CORRELATION COEFFICIENT

Joint	Exercise	Muscle Name	Correlation Coefficient
Shoulder	Abduction	Deltoid	0.98
	Adduction	Pectoralis Major	0.97
Elbow	Flexion	Biceps	0.95
	Extension	Triceps	0.98
Wrist	Flexion	Flexor Carpi Ulnaris	0.94
	Extension	Extensor Digitorum	0.97
Hip	Flexion	Rectus Femoris	0.98
	Extension	Bicep Femoris	0.94
Knee	Flexion	Gastrocnemius	0.96
	Extension	Rectus Femoris	0.96
Ankle	Plantarflexion	Gastrocnemius	0.96
	Dorsiflexion	Tibialis Anterior	0.94
Total Average correlation			0.96

\*EMG- Electromyography

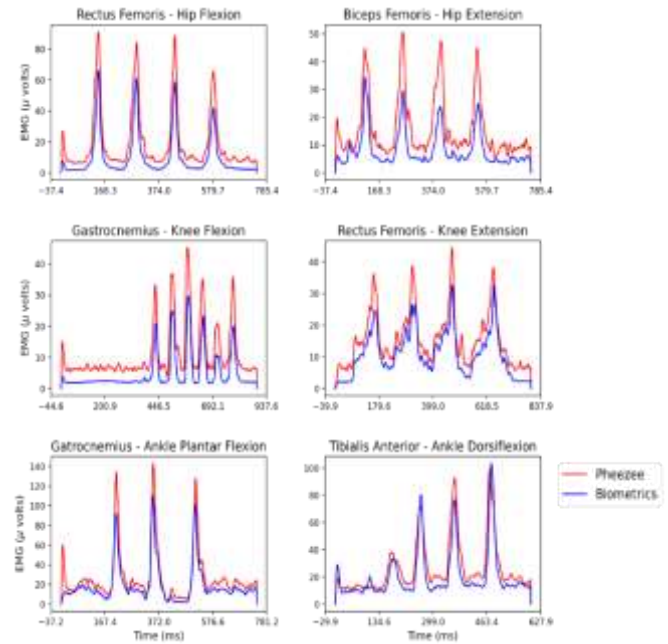


Fig. 19. Comparison of EMG graphs of muscles of upper extremities.

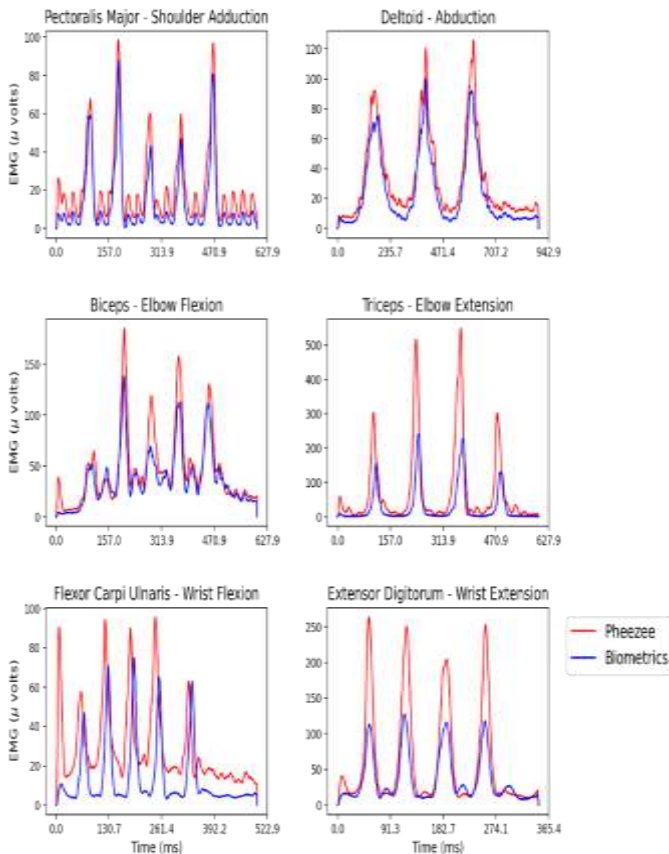


Fig. 18. Comparison of EMG graphs of upper extremity superficial muscles.

## iv. Discussion

The aim of this study was to present design and initial accuracy test of Pheeze®, a wearable sensor technology to measure motor variables. It is done by comparing Pheeze® with standard devices such as Biometrics, standard goniometer, and android mobile applications; *goniometer records and angle meter pro* respectively. From ROM graphs [Fig 15] of upper limb, the Pheeze® and android apps readings deviated slightly away around about 25 degrees from standard goniometer values for shoulder extension. The same was noted for shoulder adduction where the android mobile applications slightly deviated from standard goniometer measurements around about 25 degrees but Pheeze® values were seen in line throughout the ROM. A great deviation from the standard goniometer values has been noted for goniometer records app during hip extension, adduction, and a moderate deviation for all the ankle joint movements. It is clearly seen from the all the graphs [Fig. 15-17], that Pheeze® scores are more in line with standard goniometer, moderately with angle meter app, and minimally with goniometer records app. Because the angle meter pro and Pheeze® values are more closely associated with standard goniometer, for the movements wherever goniometer was not used, such as for spine extension, the angle meter pro was used as a reference for Pheeze® accuracy [Fig. 15-17]. The overall ROM results Pheeze® scored an average percent accuracy of 98% to suggesting an excellent validity (as shown in table I). Therefore, Pheeze® can be used to measure joint ROM during patient assessments whenever the priority is to avoid tedious conventional procedures. Even though using mobile applications was considered easy, in this study we noted it as moderately difficult as the examiner had to hold the phone in a defined position until a derivative measure was reached. As a result, multiple trials had to be done to ensure no technical errors that may affect the results. In such scenarios, Pheeze®

can be used as a better alternative tool for assessments in conditions where the patient's mobility is limited or for complex joints, where traditional methods of assessment are cumbersome. Second clinical parameter tested in this study was sEMG muscle activity (measured in microvolts). The graphs [fig. 18, 19] represent excellent correlation in terms of amplitude with Biometrics LE230 which suggest that Pheeze<sup>®</sup> can be used as a tool to detect muscle activity. The same was shown in the graphs (Fig. 18 & 19) where the sEMG acquired by Pheeze<sup>®</sup> was similar to that of gold standard device Biometrics LE230 for chosen muscles. An excellent correlation coefficient of 0.96 suggests that Pheeze<sup>®</sup> can be used as a sEMG device to monitor muscle activity. High correlation coefficient has been seen in the data obtained on pectoralis major, deltoid, triceps, rectus femoris, and extensor digitorum muscles. In Fig. 20, the sequence of sEMG wave filtration has been shown for biceps muscle in the study. There were reported challenges for the usage of sEMG devices as they are expensive, not being portable, and needing an expert for using the products. However, these challenges were majorly faced in medium-to-low-income rehabilitation settings [41]. But even in high income rehabilitation settings, only limited sources of EMG available which imposes a limited access to the patients. In such scenarios Pheeze<sup>®</sup> can be a great addition to a well-structured physiotherapy treatment protocol.

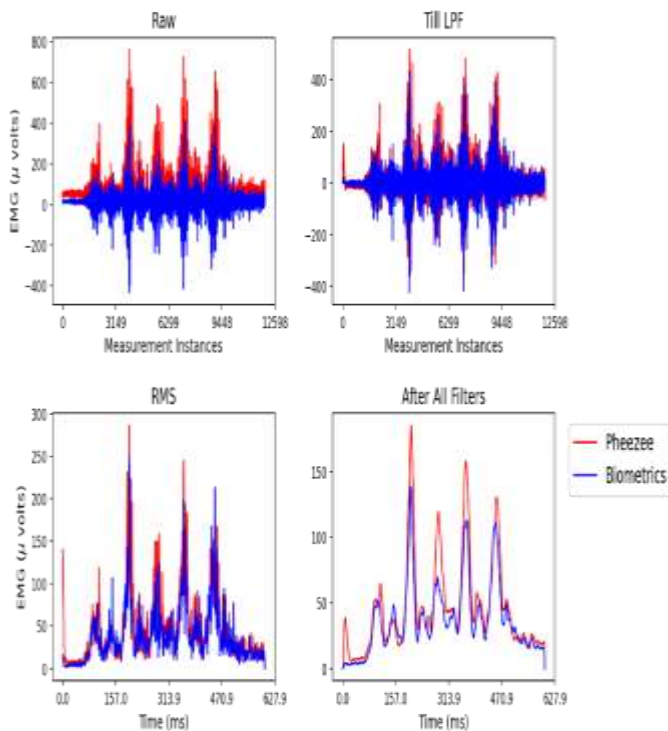
stethoscope to be used during initial assessments and also for live monitoring and tracking of physiotherapy sessions. As there is a growing need for adapting digitalized ways that are feasible, affordable, and accessible, Pheeze<sup>®</sup> can be a great addition to physiotherapy healthcare settings. The ability to record two different clinical parameters simultaneously makes Pheeze<sup>®</sup> a unique and convenient device for physiotherapists as it saves time, gives accurate assessment information, and not cumbersome as existing methods. The reporting facility help the physiotherapists understand how well the patient is recovering as a consequence of the treatment protocols prescribed by the practitioner. Pheeze<sup>®</sup> reports eases transfer of patient information to the involved healthcare team, patients, and or caregivers with assured confidentiality that are otherwise challenging using conventional methods.

## V. CONCLUSIONS

To this day, a handy prognostic tool similar to a stethoscope is unavailable for physiotherapy practitioners, hence we intended to present Pheeze<sup>®</sup> device as a stethoscope of physiotherapists. This is because of its core feature of providing real-time quantified information of motor variables that are considered important during initial assessments during physiotherapy sessions. Future research will be focused on conducting Pheeze<sup>®</sup> clinical investigations and its accuracy in testing more joints and muscles. Due to its limited scope for the present paper only characterization, calibration, and verification of product have been the focus. Pheeze<sup>®</sup> also has the capability to assess isometric contractions, and this feature will be presented in detail in another publication.

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**Fig. 20.** Series of sEMG wave filtration graphs for biceps muscle in sequence of raw EMG signal, after low-pass filtration, after Root Mean Square calculation and after final filtration.

As one of the important aspects of providing physiotherapy care is to monitor and assess patient progression [42], from the findings, Pheeze<sup>®</sup> device, adds value to physiotherapists as an assistive tool to provide care efficiently and effortlessly. As the device is portable, it can be considered as physiotherapist's



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## About Author (s):



Being an innovator, I firmly believe innovations like Pheeze<sup>®</sup> will bring about a “revolutionary change” in the way physiotherapy assessments are



Pheeze<sup>®</sup> aims to bring objectivity thereby “quantifying recovery” of patients undergoing physiotherapy post orthopedic and musculoskeletal ailments.



As a physiotherapist I feel like we need a handy prognostic tool like a “Stethoscope” that makes assessments effortless and accurate.