

Shoulder Range of Motion Measurement

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Abstract— This paper describes a new accurate, reliable, and cost-effective tool to measure the range of motion of a joint, specifically the shoulder joint. The system consists of three string potentiometers which are mounted in a known orientation and whose ends converge at a point attached to handle. A test consists of having a patient grabbing and moving the handle through the desired motion for the specified test time. During the test, a microcontroller is used to read the potentiometer voltages as the patient moves the handle. Upon completion of the test, the data is analyzed to determine the range of motion and also to provide 3-D plots of the motion. In addition, the changing position of the center of rotation can be determined for large motions. A number of tests were performed which showed good results (accuracy within 2°) in all cases when the system was properly used. The system provides a simple and intuitive user interface to display, store and recall test results. Although the system was originally intended for use with the shoulder joint, it could be used to measure the range of motion of other joints, such as the elbow and knee, provided a different attachment is created.

Keywords—shoulder joint, range of motion, microcontroller, MatLab, Graphical User Interface Interface (GUI).

Digital Object Identifier (DOI):

<http://dx.doi.org/10.18687/LACCEI2015.1.1.023>

ISBN: 13 978-0-9822896-8-6

ISSN: 2414-6668

13th LACCEI Annual International Conference: “Engineering Education Facing the Grand Challenges, What Are We Doing?” July 29-31, 2015, Santo Domingo, Dominican Republic

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I. INTRODUCTION

Of all the joints in the human body, the shoulder is the one with the most complicated articulation. Due to its complexity, it is prone to injury and numerous medical problems can occur. Some of these include: dislocated shoulder, separated shoulder, sternoclavicular separation, tendonitis, bursitis, impingement syndrome, rotator cuff tear, fracture, and arthritis of the shoulder. In 2006, approximately 7.5 million people went to the doctor's office for a shoulder problem, including shoulder and upper arm sprains and strains [1]. More than 4.1 million of these visits were for rotator cuff problems. Today, about 53,000 people in the U.S. have shoulder replacement surgery each year, according to the Agency for Healthcare Research and Quality.

The shoulder is the third most commonly injured joint during athletic activities, after the knee and the ankle. Sports-related injuries of the shoulder may result from either direct traumatic events or repetitive overuse. For example, the clavicle is one of the most commonly fractured bones in the body, while any activity that requires arm motion, particularly overhead arm motion such as throwing, may stress the soft tissues surrounding the glenohumeral joint to the point of injury. The mobility of the shoulder joint is partly as a result of minimal containment of the large humeral head by the shallow and smaller glenoid fossa. The trade-off for this mobility is less structural restraint to undesirable and potentially damaging movements. Thus, a fine balance must be struck to maintain full range of shoulder motion and normal glenohumeral joint stability [4].

In addition to more traditionally recognized sources of shoulder issues, more than 100,000 new cases of breast cancer

are diagnosed in the U.S. every year (in 2001 211,731 new cases were diagnosed in women and 2001 in men [9]). Most of these cases will be treated by surgery, Lumpectomy or Mastectomy, and removal of some lymph nodes. These surgical procedures are then followed with physical therapy to improve arm motion.

Regardless of the cause of the injury, treatment often includes physical therapy, usually consisting of numerous sessions for several months [5]. Because physical therapy is quite expensive, costing anywhere from \$50 to \$250 per session, the cost to patients as well as insurance companies for these sessions is extremely high. At some point, the treatments will also lose effectiveness and the patient outcomes will plateau. Therefore, objectively measuring the progress in the rehabilitation of shoulder range of motion will allow for a more accurate determination of when the treatment is no longer effective and the sessions can be discontinued.

A widely accepted measure of patient recovery is the DASH (Disabilities of the Arm, Shoulder, and Hand) score developed by the American Association of Orthopedic Surgeons (AAOS) and the Institute for Work and Health. [2] The DASH questionnaire consists of questions about a person's difficulty in completing a variety of tasks in daily life involving the arm, shoulder, and hand. These range from tasks like carrying a briefcase, opening doors, washing their back, putting on a sweater, etc. [3] These results are then used to gauge the level of disability incurred as a result of injuries and carry with them financial consequences. Although these questions are subjectively answered, research in the field concludes that the most important objectively measurable quantities correlating to this score, for various injuries, are strength and range of motion. [4] This kind of evaluation is very subjective and demonstrates the need for a system which objectively and accurately measures a patient's shoulder range of motion.

A. Shoulder Range of Motion Measurements

To fully characterize the range of motion of the shoulder joint, six basic measurements can be used, as shown in Figures 1 & 2. Figure 1 displays the motions of an extended arm in the three planes of motion, while Figure 2 displays the rotational motions of the same planes.

It is important to note that physicians tend to use some combination of these measurements, and it must be made clear during any testing and reporting which motion was used. For example, in Figure 1, both of the 2nd and 3rd motions are named Abduction/Adduction even though they are in different planes – one parallel to the ground and one perpendicular to the ground. Specific, standardized procedures for each of these measurement types need to be developed when using this

system based on series of tests which determine the optimal orientation and fitting used to define the motion.

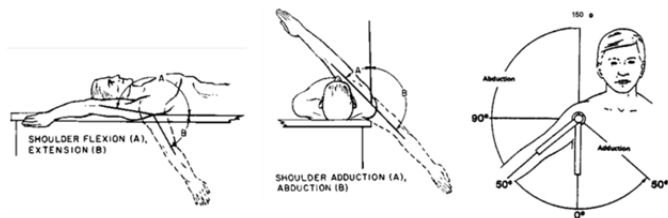


Fig. 1: Shoulder Motions (Extended Arm)

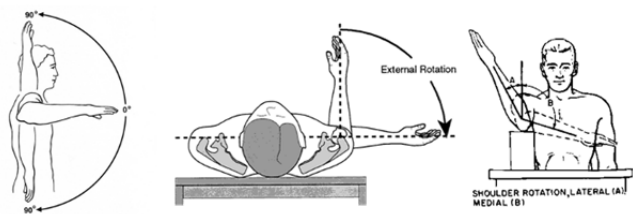


Fig. 2: Shoulder Motions (Bent Arm - Rotations)

B. Current Devices

Devices currently in use, like the most commonly used goniometer, are often inaccurate and have great variability. The variability of measurements using the standard goniometer lies primarily in two categories: 1) Large errors result from variability in the person doing the measuring and human eyesight. 2) The inability to locate the true center of rotation for the shoulder joint (as it is inside the body), as well as the assumption that its location is fixed throughout a motion, leads to an inherent inability to measure the angular displacement of this joint. The limits of this method are plainly observable, and countless academic papers have been written about the variability associated with this measurement device. These levels of variability would be unacceptable in any other field of measurement. Despite its shortcomings, it is still the primarily used option due to its low cost and ease of use.

The solution to the first category is to remove the human element from performing the measurement. A number of systems have been developed to address this issue, and an example of a modern state-of-the-art measurement system is the Cybex [6]. This system still suffers from numerous problems. Not only is this system expensive, but it suffers from the same basic fault as the goniometer does. Although it removes the human component from the visual obtainment of the measurement, it presupposes an exact location for the center of rotation and the plane of motion for the user. The solution to the problem is therefore a system which not only

removes the inaccuracies induced by the measurer, but also by the presupposition of a center of rotation and rotation plane.

A review of the literature regarding goniometry of the shoulder leads one to see a number of proposed solutions. Most of these devices use modern computing power to redress the two problems described previously. The method common to all serious solutions of the problem involves accurately tracking the position of the arm while then using a computer algorithm to calculate the rotation values one wishes to know. Because the algorithms used are not computationally intensive when considering modern computing power, the difference between these systems lies in the method of tracking the motion.

Opti-track systems, whereby a network of cameras follows the motion of target points placed on the body are one of these solutions. While these can very accurately trace the path of motion independent of any error induced by the human measurer and thus provide the proper analysis data, they are both expensive to buy and complicated to set up.

3-D Electromagnetic measurement systems, such as the Fastrak [9, 10], consist of a number of sensors placed on the body whose position can be tracked relative to a source sensor. Like the opti-track system, this system does solve both of the problems associated with the goniometer and is applicable to any body movements. However, also like the opti-track, it requires expensive hardware, complicated software, and professional operation. As such it is not commonly used in a typical rehabilitation center.

One last system attempts to use a combination of accelerometers and gyroscopes, both of which are relatively cheap and compact today. Two approaches have been mentioned in the literature. The first involves the double integration of acceleration measurements to record the position, yet this method is inherently inaccurate and limited due to the rapid propagation of any initial velocity errors or accelerometer noise during the measurement. To remedy this, a system has been developed which uses a combination of several accelerometers and gyroscopes attached to the patient in different locations [8]. This system eliminates the need for integration and does offer advantages in some settings, such as extended wear and real-time gait analysis. However, the developers admit that motion of the skin to which the accelerometers are attached is a large source of error, and the mean errors are comparable to the system described in this paper. In addition, the joint center of rotation was estimated in a 2-D plane only, with a fixed center of rotation.

II. MEASURING SYSTEM DESCRIPTION

A. System Overview

The basic configuration of the proposed system is shown in Figure 3. The three main components of the system are the potentiometers, the microcontroller gathering the data, and the MATLAB GUI. (It is important to note that this GUI could

easily be developed on another platform, as the calculations are not computationally intensive.) The string potentiometers are excited by the microcontroller which receives its power from the PC via the USB cable used for communication and connect to the analog-in ports on the microcontroller board. Indicator lights regarding the status of a test are mounted also controlled by the digital-out microcontroller ports.

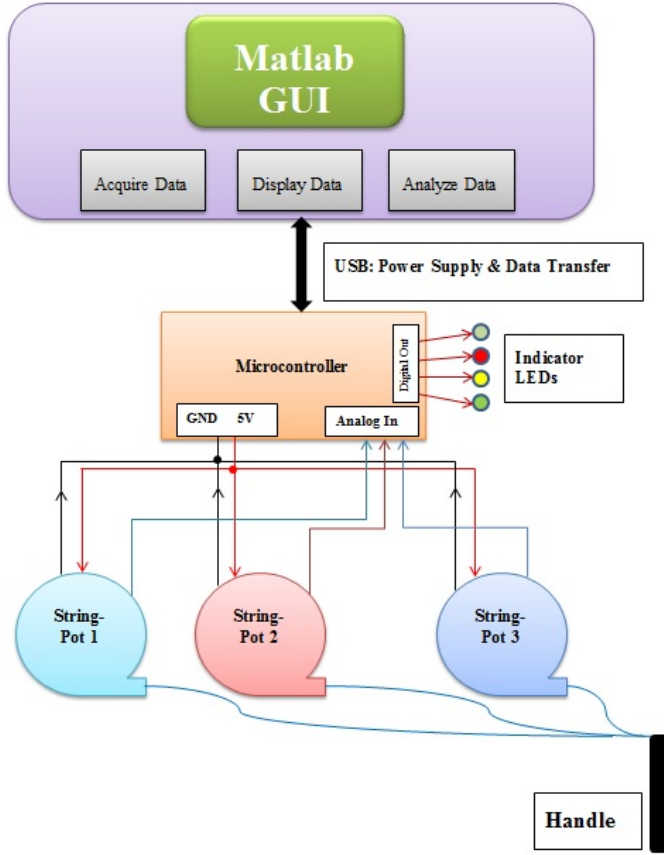


Fig. 3: System Block Diagram

B. Physical Construction

The physical system consists of the following components:

- Three string potentiometers mounted on a board at right angles and in an equally spaced manner located at the coordinates: (0,0,0), (a,0,0) and (0,a,0).
- A simple handle with an eye-screw attached to one end, which serves as a connection point for the potentiometers' strings
- An Arduino Uno microcontroller used to excite the string potentiometers with a 5VDC supply, measure the resulting voltage outputs (the three voltage lines were connected to the A0, A1, and A2 ports on the microcontroller) and also signal the system status to the user.
- Four LEDs mounted on a breadboard are used to communicate test status with the user

- A laptop computer on which the MATLAB code for the data analysis and the user interface program were implemented (not shown.)

C. Programming

Microcontroller programming: The microcontroller was used for only two purposes:

- To sample the signals from the string potentiometers and communicate the results to the laptop. The average sampling rate that was used achieved was 195Hz per channel. Communication with between the MATLAB interface and the microcontroller was achieved with the Arduino I/O Package for MATLAB [7].
- Turn ON/OFF 4 LEDs that indicate the state of the data collection process. At the start of the process all LEDs are turned ON and then OFF together, followed by a countdown from the top light to the bottom indicating that data collection started. The bottom green light will blink while data is recorded, and the red light will turn ON once data acquisition has stopped.

MATLAB programming on the laptop: The codes can be separated into two categories:

- Mathematical functions which include filtering the data obtained from the potentiometers and fitting the data to spheres and planar circles
- The Graphical User Interface (GUI) which will be described in detail in section 4.

III. MATHEMATICAL ANALYSIS OF THE POTENTIOMETES READINGS

A. Coordinate Calculations

Once the distances from the known potentiometer locations to the handle attachment point are known (given by D_1 , D_2 and D_3), the coordinates of the handle can be calculated using simple geometric relationships.

The coordinates of the handle are given by:

$$\begin{aligned} x &= D_1 \cos\alpha \\ y &= D_2 \cos\beta \\ z &= D_1 \cos\gamma \end{aligned} \quad (1)$$

where α , β and γ are the angles between the string D_1 and the axis x,y,z axes, respectively. These angles are given by:

$$\cos\alpha = \frac{D_2^2 - a^2 - D_1^2}{-2aD_1} \quad (2)$$

$$\cos\beta = \frac{D_3^2 - a^2 - D_1^2}{-2aD_1} \quad (3)$$

$$\cos\gamma = \sqrt{1 - \cos^2\alpha - \cos^2\beta} \quad (4)$$

Note that although this system does not allow for negative values of γ , which means that the z-value is always positive, this is not a problem because the physical setup of the system is such that it is only used in positive-z direction.

B. Motion Analysis

At this point in the process, the coordinates of all points sampled during the motion have been calculated based on the recorded voltages. Several analyses will now be performed. The first part is to fit a sphere to the data. This is done by minimizing the sum of quantity

$$[(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 - R^2] \quad (5)$$

for the data set by varying $x_0, y_0, z_0,$ and R .

The spherical range of motion is arrived at by comparing the distance between averaged groups of points furthest from one another to the radius returned by the spherical fit.

The second fit performed upon the data is a planar fit. This involves determining the coefficients of the following equation such that the sum of the squares of the distances of each point from the plane is minimized.

$$z = C(1)x + C(2)y + C(3) \quad (6)$$

The planar range of motion is arrived at by projecting the spherical center onto the plane returned by the plane-fit function when applied to the coordinates, and comparing the distances to this point from the averaged groups of end-points. Therefore, the success of the planar range of motion depends on how well the plane fit algorithm has been applied.

In **Figure 4**, one can see the spherical center plotted in RED vs. its projection on the fitted plane, in BLACK. Generally, the spherical center will correlate to the internal center of rotation the shoulder joint while the plane center will be shifted by a few inches (as seen above). This is representative of the offset between the point of contact between the potentiometers and the handle vs. the center of one's palm.

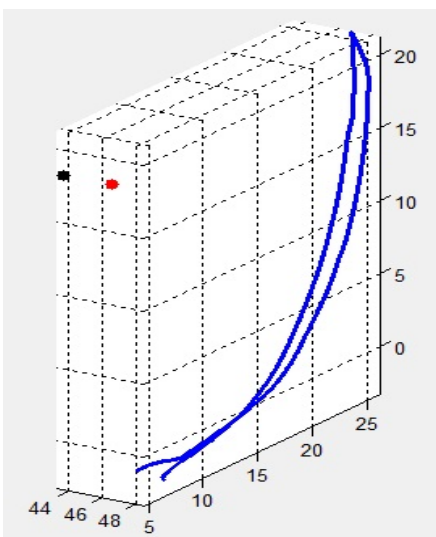


Fig. 4: Spherical Center vs. Planar Center.

Two other methods of calculating the planar range of motion are possible. One method involves first calculating the plane of motion then fitting a sphere to the points subject to the constraint that its center lies on this defined plane. The second method also involves first defining the plane of motion but this is followed by projecting each point onto the plane and then performing a circular fit on the projected points. [Note that an option to switch between these methods is not currently programmed into the system but could be quickly be added.]

Some user discretion must be exercised when using this system. For example, the choices of what orientation relative to the board to perform the motion and when to consider the spherical fit or consider the planar fit is important. (The tests in section 5 of this paper show how the performance can vary with the orientation of the motion.) Additionally, the choice of which algorithm to use for which motion is important (e.g. the motions in **Figure 1** should use the traditional spherical / planar fit, while those in **Figure 2** are best done with the modified-planar fits.)

The last analysis which can be performed is tracking the changing center of rotation. This is achieved by tracking the change in the results of the center of rotation fit when only a section of data (in a moving window) is used in the calculation. In other words, one can see how the center of rotation changes during the motion (e.g. once the arm is lifted past a certain angle, different muscles are engaged and the shoulder joint is not the center of rotation anymore.) A patient during physical therapy will have a natural inclination to “cheat” when having the range of motion measured, i.e. the body will unconsciously engage extra muscles to lift the arm unless one concentrates on suppressing this reaction.

IV. USER INTERFACE

A. The Graphical User Interface Interface (GUI)

The main GUI window, shown in **Figure 5**, consists of four main parts:

- 1) Top line that includes a place to enter the patient name (which is needed to save or load results files), an exit button to close the program, and a display for system messages. System messages not only display upon successful completion of tasks such as saving, loading, or analysis, but also display error messages when the user has done something incorrect (e.g. clicked “Analyze Motion” without specifying an analysis type, or tried to load a file that doesn't exist.)
- 2) Main control panel, shown in **Figure 6** on the next page, by which the user controls all system's functions: Acquire Data, Plot Motion, Analyze Motion, Save Results, Load Previous Results, as well as all options relating to these operations. These options will be detailed later.
- 3) The motion plotting window, which consists of the axes to which the data is plotted as well as buttons to change the viewing orientation of the data.

- 4) The Patient History Table in which saved results are displayed including: Test dates, Test type, Test results, associated raw-data file numbers (if this option was chosen) and comments. Note that another option instead of using The Patient History Table is to load the associated text file.

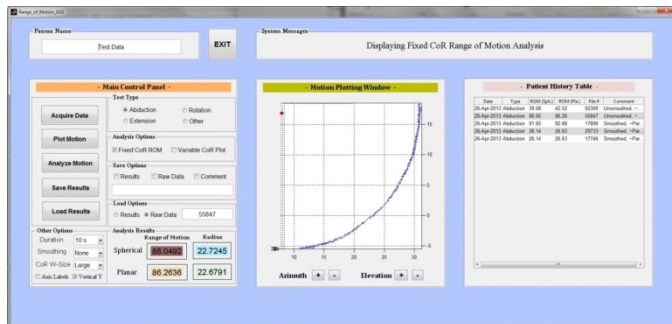


Fig. 5: Main GUI Window

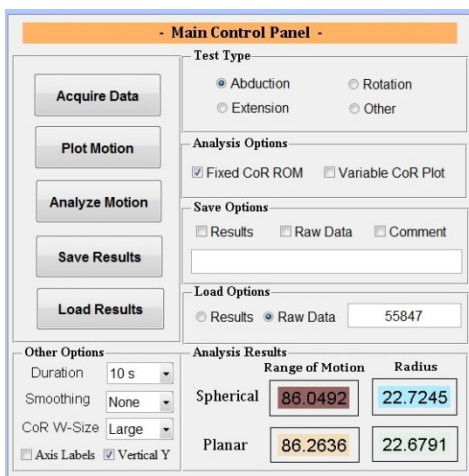


Fig. 6: Main Control Panel

B. Data Acquisition and Analysis

Data Acquisition & Analysis: When the “Acquire Data” button is pushed, a timed data acquisition sequence according to the “Duration” option, is initiated. The LEDs connected to the microcontroller board will all turn on then off together, followed by a countdown from the top light to the bottom. The green LED will blink while data is collected, and the red LED will turn on once data acquisition has been completed. The voltages are then sent from the micro controller to the laptop.

Data processing and analysis: If the user feels that the data was properly collected, the motion should be analyzed. Two options are available here: “Fixed CoR ROM” and “Variable CoR Plot”. The first returns the radius and range of motion of a spherical fit as well as the equivalent planar fit from the sphere center projection onto the plane of motion. The spherical center of rotation is plotted onto the graph in red

while the projected center onto the plane is plotted in black. The second option will plot the variable center of rotation, whereby the center of rotation is calculated for a moving window of points whose size is chosen in the “CoR W-Size” menu.

If one wishes to smooth the data and reanalyze it, the smoothing option should be changed and the “Plot Data” button repressed. This smoothing option sets the number of points included in a moving average of the data. was made in the bottom window. Note that if the plotting phase is skipped and the analyze button pressed, the data will still be plotted but any change in the smoothing option will not be reflected.

Plotting the results: The ‘axis labels’ toggle option will change whether axis labels are applied or not, while the ‘vertical Y’ option will direct the system whether to fix the y-axis (which is normally vertical when the system is in use) to the vertical axis in the plot. The plot view will by default align itself normal to the plane returned by a plane-fit of the coordinates (or smoothed coordinates).

Data Saving & Loading: If the user wishes to save the data, several toggle options are available: “Results”, “Raw Data” and “Comment”. Choosing results will add the current result to a patient’s history file (if it exists) or create a new patient history file. If the “Raw Data” option is selected, a file will be created whose name is displayed in the system message window as well as in the patient history file. The “Comment” option allows for the user to enter a comment into the results and raw data files. An example of a patient history file can be seen below in Figure 7.

For each measurement, patient name, test date, test type, analysis results and the file number to which the raw data was stored (if this option was selected) and the comments that may have been entered, are recorded. An example of a raw data file is shown in Figure . Note that this is the file number “46283” referenced in the above patient file.

When loading data, two options are available: “Results” and “Raw Data”. If “Results” is chosen, the system checks for a patient file matching the name of the patient entered into the system. If the file exists, the patient history window is populated as mentioned earlier. If the “Raw Data” file is chosen, the system checks for the raw data file number specified in the text input box next to that option. If it finds the file, the patient name written into that file is listed in the patient name window, the test type is shown, the comment box displays the comment, and the “Coordinates” variable inside the GUI now contains the saved data.

Test Date	Test Type	ROM Sph.	ROM Pla.	File #	Comment
20-Apr-2013	Abduction	39.85	40.49	46283	Josh Semi-perpendicular, 6 pt smooth 10s, perfect Radius
20-Apr-2013	Abduction	58.30	60.12	50170	Josh perpendicular (Reverse) Radius 70s 5s11
20-Apr-2013	Abduction	30.47	31.18	55504	Josh perpendicular (Reverse) Spherical Radius Perfect (10 pt smoothing)

Fig. 7: Example Patient History File.

```

Patient Name:      Test Data Perpendicular
File Creation Date: 26-Apr-2013
Selected Test Type: Abduction

Comments:      Josh Semi-Perpendicular, 6 pt smooth 10s, Perfect Radius
X              Y              Z
-----
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292
-22.607566    -3.029025    32.016292

```

Fig. 8: Raw Data File.

V. TESTING

A. Calibration

The basic premise of this system is that one uses the voltage measurements from the potentiometers to reconstruct the motion of the patient and analyze this motion. The first step in this process is accurately determining the distance of the connection point from each potentiometer. To achieve this, a series of calibration tests were performed where 1000 samples were taken from each potentiometer at 5 different known distances and linear regression was used to fit the voltage data to actual distance (see example in [Figure 9](#)). In this Figure, the x-axis represents the translated voltage from the 10-bit A/D converter while the y-axis represents the distance measurement. (Note that the string length connecting the end of the potentiometer to the handle was then added.) The Correlation factor, R^2 , for all three potentiometers to the linear fit was better than 0.9999 which indicates that the potentiometers outputs are very linear, as noted in the sheets provided by the manufacturer.

To test the accuracy of the device, a number of tests were performed whereby the handle was mounted on an accurate rotary table. The table was mounted in three different orientations (parallel to XY, XZ and YZ planes with respect to the system) and tests were performed whereby the rotary table was turned to a known angle while the system took measurements. The rotational angle determined by the system was then compared to the one set by the table. The different orientations and the results of the tests are summarized in Tables 1. Note that the data smoothing used was a 16-point moving average.

Note that the angles returned were done with the traditional planar method. In other words, a spherical center of rotation was determined (there are an infinite number of spheres which could fit to truly-planar motion, but their centers will lie on a single line) and it was projected onto a planar-fit surface. Despite the combination of error of both procedures, the test results show that for the first two orientations, whereby the rotation of the table made use of more potentiometer line length, the errors were consistently small. The third orientation had larger errors, likely due to any

distortions or noise in the potentiometer length measurements being oriented perpendicular to the intended plane.

Also, for human testing, the inherent variability in the motion of the arm (it is in fact not exactly planar) removes the ‘infinite spheres’ possibility and leads to a very good determination of the spherical center of rotation.

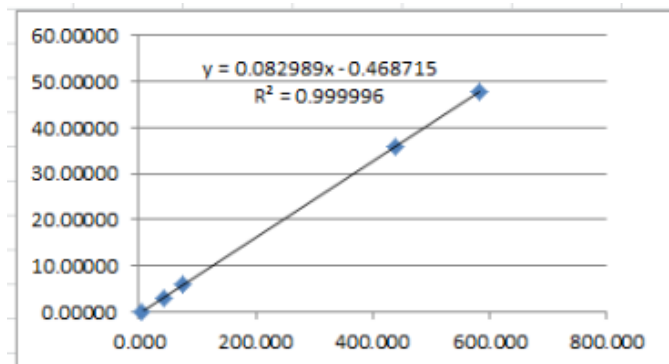


Fig. 9: Potentiometer Voltage to Distance Fit.

Table 1: Tests' results with rotary table.

Rotary Table Orientation								
Parallel to XY			Parallel to XZ			Parallel to YZ		
Table Angle [°]	Meas. Angle [°]	R [in]	Table Angle [°]	Meas. Angle [°]	R [in]	Table Angle [°]	Meas. Angle [°]	R [in]
26.0	24.7	22.9	27.0	23.1	27.4	30.5	31.7	24.0
40.0	40.0	21.7	29.0	27.8	24.0	30.0	36.6	20.6
40.0	41.0	23.0	51.5	51.1	23.2	70.0	67.2	23.8
44.0	44.9	23.7	56.0	54.6	23.9	88.0	85.2	23.4
55.5	50.2	25.1	60.8	61.7	24.1	49.0	46.5	23.9
57.5	54.7	24.6	62.5	61.6	23.6	84.0	78.4	24.4

VI. TESTS ON OBJECTS

The device was tested on three subjects: 1) A 64 year old male; 2) A 50 year old female; and 3) A 25 year old male. While the particular results are not important, the following few charts will demonstrate the features of this measurement system that cannot be found in other systems.

Tracking the location of the center of rotation: [Figure 10](#) illustrates (a) the recording of an abduction test on subject #3 and (b) rotation test on subject #2. The mark at the center of each figure shows the change in the location of the center of rotation during the motion.

Motion trajectory: Since positions along the trajectory are recorded, it is possible to display the trajectory projection on any plane. This information can provide additional insight to the shoulder joint behavior. [Figure 11](#) illustrates 3 tests: (a) Abduction test on subject #1; (b) Abduction test on subject #2; and (c) Extension test on subject #3.

VII. CONCLUSIONS

This paper describes a simple, easy to use, low cost measuring and reliable device by which the range of motion of the shoulder and other joint can be measured following a simple procedure. The device records positions along the motion's trajectory and determine the angular displacement as well as the location of the center of rotation. The trajectory can be view from different orientation which might provide information not available by other measuring techniques. A friendly user interface allows the selection of some processing variables, to store the collected data and additional test information for later use or reference.

Future improvement of this device is the replacement of the string potentiometer by optical encoders which are immune to noise. In addition, the code, which is written in Matlab, should be converted to other language, such as C++) in order to provide portability and generation of a standalone system. Additionally, large volumes of benchmark data should be collected using a fixed apparatus in order to demonstrate, statistically, the reliability and consistency of the measurements.

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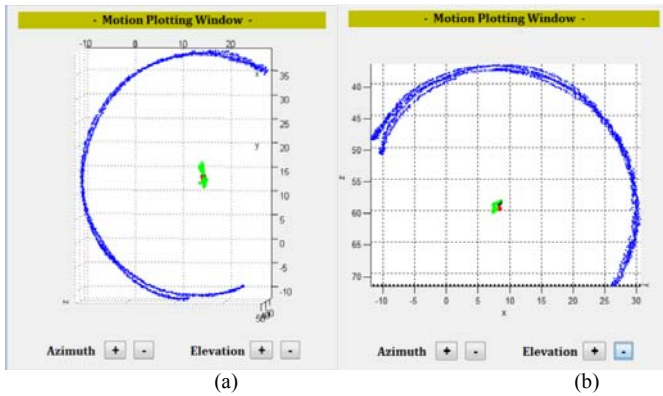


Fig. 10: Tracking the location of the center of rotation.

The flexibility of the device allows the measurements of motions which are not typically performed when it comes to range of motion evaluation. As an example, Figure 12 illustrates a trajectory where subject #1 rotated his arm 360 degrees to the extreme of his capability.

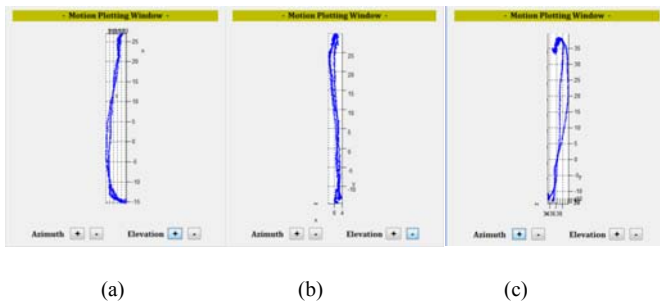


Fig. 11: Projection of motion on plane perpendicular to the trajectory

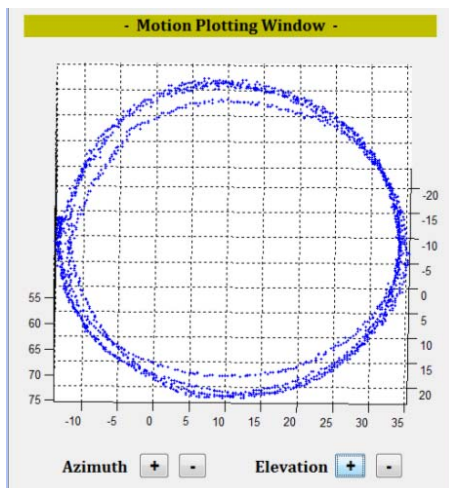


Fig. 12: Full 360 degree trace of arm full rotation.