Laser goniometer: smartphone goniometer with laser guidance for range of motion measurement in musculo-skeletal medicine

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Abstract

Musculoskeletal disease is a common clinical problem, part of the physical examination of these body systems is the range of motion measurement of the joints. Current clinical tools for estimation of this parameters are visual estimation and the universal goniometer, With the advent of less expensive smartphones and widespread sensor availability, there was the development of a great number of apps that allowed the use of a smartphone as a goniometer. The purpose of this paper is to document research developments of creating a laser-aided goniometer with a smartphone, and suggests to create a business opportunity from this idea.

Index Terms- **MEMS**: Microelectromechanical Machines, **APC**: Automatic Power Control, **USA**: United States of America, **ROM**: Range Of Motion, **Ni-MH**: Nickel-Metal Hydride, **MCP**: Metacarpophalangeal, **PIP**: Proximal interphalangeal, **DIP**: Distal interphalangeal, **CMC**: Carpometacarpal, **IP**: Interphalangeal, **MTP**: Metatarsophalangeal, **ABS**: Acrylonitrile butadiene styrene, **CAD**: Computer Aided Design

1. INTRODUCTION

1.1 Background: Use of active and passive range of motion in musculoskeletal medicine.

In primary care clinical practice, the most common complaints are upper respiratory infections and gastrointestinal issues, followed by musculoskeletal problems.[1] There is a great variety of orthopedic and rehabilitation clinical problems in everyday practice. For example low back pain, neck pain, knee pain, hip pain, wrist pain, finger contractures, among others. [1] After a clinical interview and beginning a physical examination, the clinician seeing patients with orthopedic complaints eventually finds the need to measure the passive and active range of motion of a joint or body part. This clinical parameter is affected in different musculoskeletal diseases, for instance, increased wrist range of motion can indicate ligament hyperlaxity, and decreased or restricted passive range of motion can be found in patients with fractures, muscular spasms, muscle contractures, among other disease states.[2] An accurate assessment of the range of motion is also useful in patients who have a suspected diagnosis of scoliosis. [3]The main tool used to make a quantitative assessment of spine range of motion is the measuring tape or the inclinometer.[4] The goniometer can also be used for the evaluation of the range of motion of all the joint elements of the upper and lower extremities.

1.2 Currently used tools: plastic goniometers, inclinometers, halo goniometer, smartphone without case.

The most commonly used tool to measure the range of motion is the goniometer, and by 2019 in clinical practice most goniometers consist of plastic rulers. A goniometer is comprised of three elements. The first element is the axis, the second element is the stationary arm, and the third element is a moving arm. The moving arm of the goniometer is usually aligned to some anatomical landmark while the patient performs an anatomical motion so that the range of motion can be measured. In a sense, the goniometer is a special kind of protractor. The goniometer is used by a variety of health professionals that work with muscular-skeletal complaints, but many health professionals estimate range of motion measurements visually. Poulsen et al.[5] evaluated the reproducibility of goniometric measurements between experienced orthopedic surgeons and experienced chiropractors evaluating patients with hip osteoarthritis. The reproducibility was low between both groups of clinicians. Even though the subjects of Poulsen study were using conventional goniometers to evaluate the range of motion. Therefore a new kind of tool is needed for precise physical diagnosis of patients with orthopedic complaints.

1.3 Smartphone statistics and capabilities

By 2019 the United States of America has a population of more than 328 million persons, and the world has more than 7,500 million individuals.[6] Smartphone adoption and operating systems trends are different between the USA and the world. There are an estimated 257 million smartphone users in the USA in 2019 [7], which means that 67.3% of the population has access to a smartphone and to the whole array of sensors that they include. The market share value is different in the USA vs the world. Apple iOS is among the most commonly used operative systems in the USA with 44.8% of smartphone owners using this operating system. The rest of the American market is divided between several smartphone companies that use the Android operative system. An estimated 53.4% of Americans smartphones are Android OS based in 2019. [7] In the rest of the world., by 2019 Android-based smartphones owned 75% of the smartphone market, and Apple iOS had a global 22.4% market share. [8]The remainder of the market share (less than 1%) is based on Nokia, and KaiOS. Modern day smartphones are surprisingly powerful computers most of them count with a great variety of sensors that can be explored for medical diagnostics. Among the most commonly installed sensors and circuits in smartphones are MEMS accelerometers [9], gyroscope, magnetometer, pedometer [10], proximity sensor, and thermoreceptors. Some smartphones even include pulse oximetry and heart rate sensors.

1.4 Health professionals

There is a large number of clinicians that see patients with musculoskeletal complaints. Therefore these professionals would benefit from a faster and more accurate way of measuring the range of motion. The third generation laser goniometer intends to position itself as a leading tool by providing smartphone assisted goniometric measurements with added laser guidance for improved alignment of the phones axis to anatomical landmarks. Among the health professionals that could benefit from a next-generation goniometer are: orthopedic surgeons, physical medicine and rehabilitation specialists, rheumatologists, sports medicine physicians, personal trainers, physical therapists, sports-aficionados, athletes, coaches, and healthy young men and women with interest in health and fitness. What I propose in this paper is for the creation of the first type of real multifunctional tool for health professionals. The world is filled with smartphones and sensors. And appropriate hardware adaptations and sensor capabilities will improve the smartphones capacities to become useful tools in the evaluation of disease.

2. METHODS

2.1 Circuit software simulation

An online circuit simulator that runs on Java [11] was used for building a simulation of the basic circuit for the second generation laser goniometer. In the following image one can see the following abbreviations: B = Battery, S1 = Switch 1, S2 = Switch 2, L1 = Laser 1, and L2 = Laser 2. For an image of the second generation laser goniometer circuit simulation, refer to Appendix A.

2.2 Circuit assembly

For the circuit assembly 4 AAA batteries were used. They were 1.2-volt Nickel-Metal hydride (Ni-MH) batteries. With an 1100 mAh lifetime per charge cycle. The batteries were feeding current to L1 and L2. These lasers are used for improved alignment of the phone with anatomical landmarks so that a proper measurement of range of motion can be used with this device. S1 and S2 are switch buttons that run from the negative cable of both lasers to the negative pole of the power cells B. The lasers used for the construction of the second generation laser goniometer prototype are the HLM1230 laser modules [12] They are 650 nm red laser modules with a power output of 5mW, a focusable acrylic lens, an APC driver for an input voltage of 3.5-4.5V direct current, an operating current of<25 mA. These are practical for the construction of further prototypes or marketable products because they are quite affordable at only 5-10 dollars per piece. These lasers are classified as IIIa lasers which means that retinal injuries can occur if the laser beam hits the retina for more than 2-3 minutes [13] However they are considered safe for medical devices. The lasers also come with a chrome brass heatsink and therefore do not need cooling equipment. For an image of the laser and the measurements refer to Appendix B.

2.3 Casing assemble

For the second generation laser goniometer a piece of polyvinyl chloride (PVC) tube was used for the housing of the electronics. The tube had an external diameter of 40 millimeters and an internal diameter of 36 millimeters. The length of the tube used was of 22 cm. With a top cap and a bottom cap. The top cap is also made of PVC and has the following dimensions: internal diameter of 36 mm, the external diameter of 42 mm, and length of 40 mm. The top cap houses the laser number 2 and it also has two attachment holes for two screws in the event that a voltage booster taser module is added. The bottom cap of the second generation laser goniometer houses a security switch intended to use for one of the lasers, or for a voltage booster taser module.

2.4 Software considerations

For the second generation laser goniometer a search was performed on the apple app store for any application that allowed for easy use of the phone accelerometers to use in the laser goniometer. I performed a 4 word search on the apple app store with the following terms: inclinometer, goniometer, level, and protractor. Seven apps were downloaded to the laser goniometer phone in order to investigate their accelerometer capabilities. The following apps were installed for study: Angle Pro, Protractor360, Goniometer, yROM Lite, Bubble Level, Orthophysical, and Angle. Of them the application called Angle was the most minimalistic and easy to use. However, it lacked any memory features that would allow for storing measurements. Furthermore, there was no access to the camera in the app. This restricts an augmented reality visualization of the angles that could be developed if new software was written specifically to merge the laser, accelerometer, and camera phone capabilities. For the remainder of the paper, clinical measurements of range of motion are made with the app Angle. One limitation of this app is that it does not estimate Azimuth or movements of the Z-axis in the phone. All of the apps installed lack the feature of integrating the feedback from the magnetometer with the accelerometer to measure the movement of the phone in the Z-axis. Any marketable laser goniometer, therefore, would need to run its own iOS or Android app [14].

3. RESULTS

3.1 Second generation laser goniometer

The second generation laser goniometer has the capabilities to measure angles in three-dimensional space by using the smartphone accelerometer, magnetometer and the laser modules for improved alignment of the phone axes with clinical landmarks. One laser module Laser 1, projects a red cross because of the specially collimated lens. This laser, in particular, is aligned parallel to the Z-axis of the phone which allow for measurements on the X and Y axes. The second generation goniometer also has an additional laser module Laser 2 that projects a dot or a laser line. This module is aligned parallel to the Y axis of the phone so that measurements of the Z-axis or azimuth can be recorded. This device would be suitable for the goniometric evaluation of all the body joints. The joints of the body are basically divided into body groups: axial skeleton, upper extremity, and lower extremity. [17] Any clinical evaluation of the range of motion of a joint makes use of a goniometer. A goniometer is usually a plastic ruler and it consists of three parts: the first part is a goniometer axis, the axis should be aligned with a clinical landmark for correct measurement of range of motion. The second part is the stationary arm, and the third part or measuring part is the moving arm. The three elements of a goniometer previously described can be easily replicated with the sensor capabilities of any smartphone, provided the correct software is developed that allows for measurement of angle measurements in all three axes of the smartphone. For photos of this device refer to appendix C-F

For a clinical demonstration of the second generation, laser goniometer refer to appendixes G-J. Appendix G shows the clinical alignment necessary for measurement of the ulnar deviation of the left hand, the picture depicts the starting position and alignment of the laser goniometer to a clinical landmark, in this case, the space between the second and third metacarpals. Appendix H shows the measurement done on this hand with an estimated absolute value of the ulnar deviation of 37º degrees. Appendix I depicts the zero starting position for measurement of the left leg extension value, in this case, the laser cross is centered on the knee. Appendix J shows the ROM measurement of the knee as 66º degrees. The same principles depicted to measure these joints can be used to measure all of the joints in the body as discussed below.

3.2 First generation laser goniometer

The first generation laser goniometer was developed by the author while completing the social service in Monterrey, Mexico. I began the design of this device while working with children with cerebral palsy and needed an accurate way to measure the internal and external rotation of the hip, so the risk of hip subluxation in these population could be estimated in this population [4] , that expended most of their day using wheelchairs and sitting for prolonged periods of time. The first laser goniometer was only an iPhone 4 case that was 3D printed in ABS plastic and that had a special ring with a screw to attach a laser pointer. The device proved useful in my personal experience for seeing a great number of patients with hip issues. For a clinical demonstration of this device efficacy refer to Appendix K and L.

4. DISCUSSION

4.1 Spine measurement capabilities.

Neck pain and back pain are a common diagnosis in primary care practice. **[1]** As discussed previously visual assessment of the range of motion and conventional goniometric measurements have poor intra-observer and inter-observer reproducibility. However, there is evidence in the literature that the use of goniometer smartphone apps helps to improve the speed and accuracy of the range of motion measurements. Pourahmadi et al [18] reported improved intra-rater and inter-rater measurement reproducibility of range of motion measurement on patients who were evaluated with the goniometer app (Goniometer Pro), one of many goniometry apps for Android and iOS. This cross-sectional study demonstrated improved accuracy range of motion measurements on patients with non-specific neck pain. The study evaluated the 6 anatomical movements of the cervical spine: flexion, extension, right lateral flexion, left lateral flexion, right rotation, left rotation. Current methodologies for measuring thoracolumbar anatomical movements make use of a measuring tape that is positioned on anatomical landmarks to make an estimation of flexion, extension, right side flexion, left side flexion, right rotation, and left rotation. A next-generation goniometer would allow for faster and more accurate range of motion evaluations of the spine. Another cross-sectional study by Pouahmadi et al. [19] also demonstrated improved reproducibility and accuracy of range of motion measurement on the thoracolumbar spine with an iPhone goniometry app. Table 1 shows the degrees of freedom of all the cervical and thoracolumbar joint complexes.

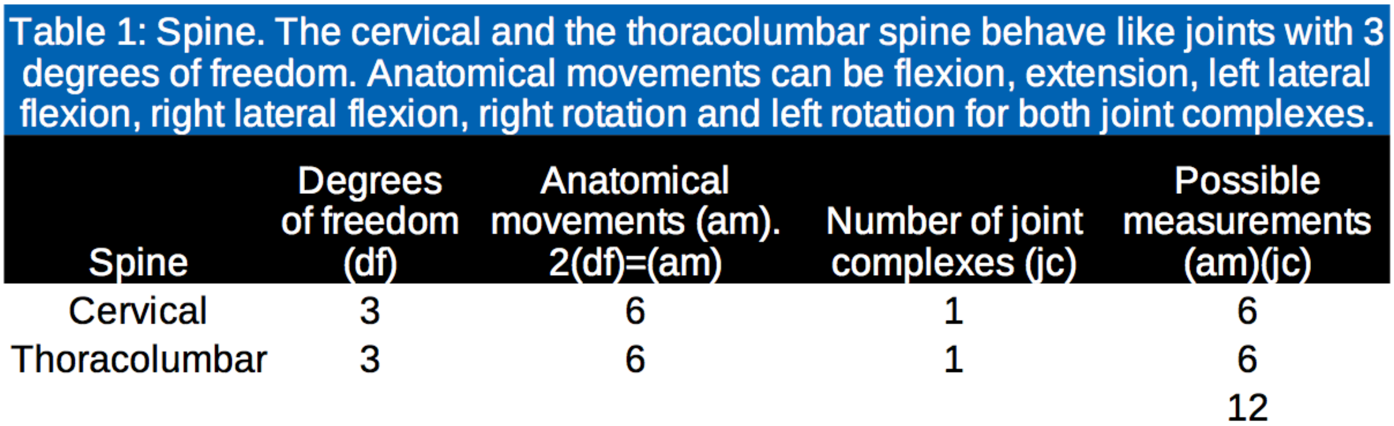

Table 1: Spine. The cervical and the thoracolumbar spine behave like joints with 3 degrees of freedom. Anatomical movements can be flexion, extension, left lateral flexion, right lateral flexion, right rotation and left rotation for both joint complexes.

Spine	Degrees of freedom (df)	Anatomical movements (am). 2(df)=(am)	Number of joint complexes (jc)	Possible measurements (am)(jc)
Cervical	3	6	1	6
Thoracolumbar	3	6	1	6
				12

4.2 Analysis of upper extremity measurement capabilities.

The upper extremity is comprised of 10 joint complexes: shoulder, elbow, forearm, wrist, the metacarpophalangeal complex of fingers 2-5, proximal interphalangeal complex of fingers 2-5, the distal interphalangeal complex of fingers 2-5, carpometacarpal complex of finger 1, metacarpophalangeal complex of finger 1, and interphalangeal complex of finger 1. There are a variety of studies that demonstrate improved goniometric readings in the upper limb, most of them with smartphone devices. In the case of the shoulder Cornell et al. [20] shows improved inter-rater and inter-rater reproducibility of ROM measurements with the use of laser goniometer (Halo Goniometer), this study only looked at healthy patients. Keijsers et al. [21] studied the inter-observer and intra-observer reproducibility of elbow range of motion evaluation with universal goniometry, a smartphone goniometry application and a photo/movie application for ROM measurement. He found out that reliability was good only for the movie application. However a study made by Vauclair [22] reported different findings. According to this study visual estimation of ROM can be as good as smartphone goniometric evaluation, but only for some anatomical movements. This study reports that only visual estimations of forearm pronation/supination were as good as smartphone goniometric measurements. Vauclair found that smartphone measurements were better than visual estimation for flexion and extension of the elbow. Improved reproducibility, accuracy and speed are also reported for goniometric measurements done with smartphone apps for the remainder of joint complexes of the upper arm, for example, improved wrist ROM measurements can be done with smartphone apps. [23] [24] [25] The same principles outlined above can be extrapolated for better ROM measurements of other joint complexes like the fingers and the thumb. Table 2 shows the degrees of freedom, anatomical movements and total goniometric measurements that can be performed on the upper limb. A total of 54 measurements are possible for each side, e.g: right and left. So a third generation goniometer could be a useful tool for professionals that are frequently exposed to musculoskeletal complaints.

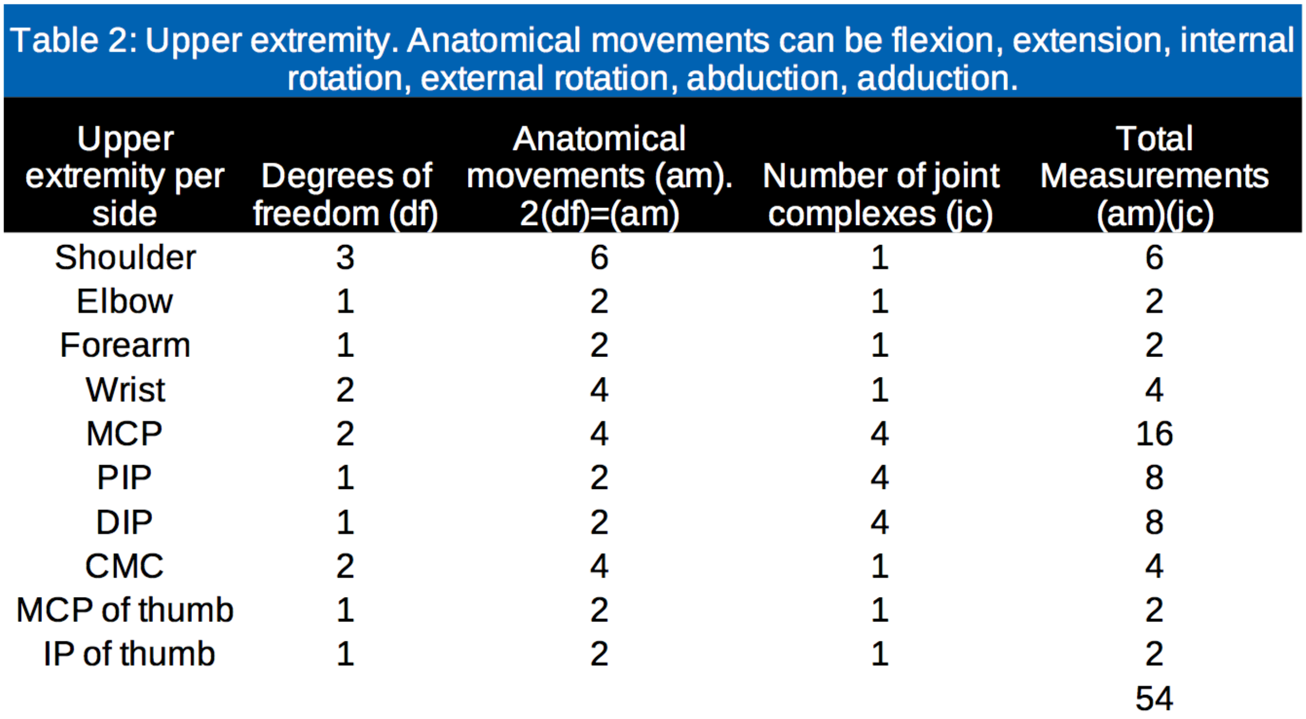

Table 2: Upper extremity. Anatomical movements can be flexion, extension, internal rotation, external rotation, abduction, adduction.

Upper extremity per side	Degrees of freedom (df)	Anatomical movements (am). 2(df)=(am)	Number of joint complexes (jc)	Total Measurements (am)(jc)
Shoulder	3	6	1	6
Elbow	1	2	1	2
Forearm	1	2	1	2
Wrist	2	4	1	4
MCP	2	4	4	16
PIP	1	2	4	8
DIP	1	2	4	8
CMC	2	4	1	4
MCP of thumb	1	2	1	2
IP of thumb	1	2	1	2
				54

4.3 Analysis of lower extremity measurement capabilities.

Table 3 shows the degrees of freedom, anatomical movements and total goniometric measurements that can be performed on the lower limb. The previous principles from the spine and upper limb also apply to the lower limb. This structure is comprised of 9 conventional joint complexes with 2 special goniometric measurements that could also be improved by a next-generation goniometer. Hip measurement of ROM has low reproducibility in a great variety of conditions. A literature search reveals poor inter-rater and intra-rater reliability of hip ROM measurements in cerebral palsy, hip osteoarthritis, and femoral acetabular impingement.[4][5][26] Knee evaluation with a smartphone goniometer is equally as good as the ones performed by experienced orthopedic surgeons using conventional goniometers, therefore it stands to reasons that improved alignment with laser diodes could improve the accuracy of goniometric measurements even further.[27] [28][29]Better goniometric measurements could also aid in the recovery of patients with issues of proprioception. [3]

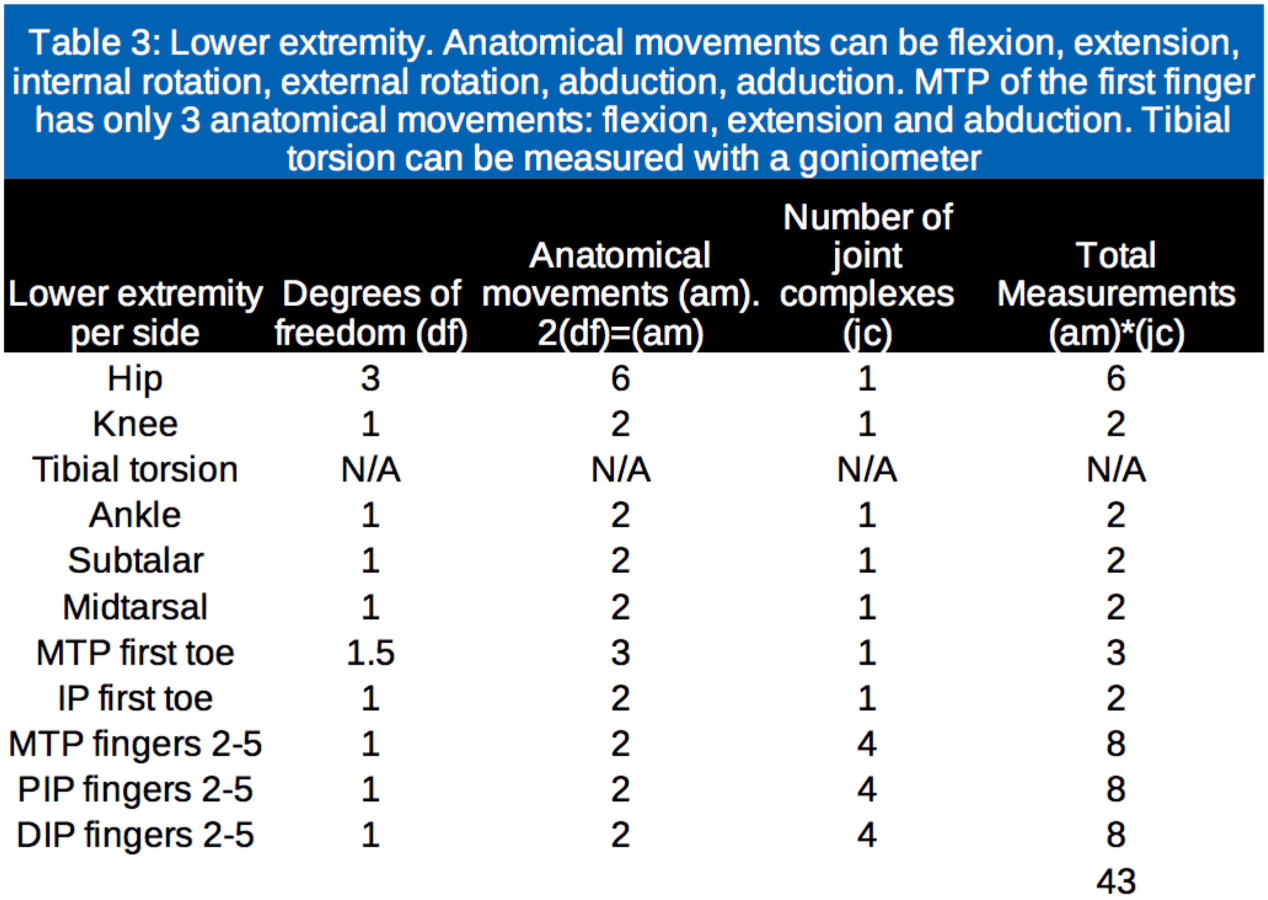

Table 3: Lower extremity. Anatomical movements can be flexion, extension, internal rotation, external rotation, abduction, adduction. MTP of the first finger has only 3 anatomical movements: flexion, extension and abduction. Tibial torsion can be measured with a goniometer

Lower extremity per side	Degrees of freedom (df)	Anatomical movements (am). 2(df)=(am)	Number of joint complexes (jc)	Total Measurements (am)*(jc)
Hip	3	6	1	6
Knee	1	2	1	2
Tibial torsion	N/A	N/A	N/A	N/A
Ankle	1	2	1	2
Subtalar	1	2	1	2
Midtarsal	1	2	1	2
MTP first toe	1.5	3	1	3
IP first toe	1	2	1	2
MTP fingers 2-5	1	2	4	8
PIP fingers 2-5	1	2	4	8
DIP fingers 2-5	1	2	4	8
				43

5. CONCLUSIONS

It is clear that there is a need for more precise orthopedic diagnostic instruments at affordable prices, with the advent of fast printing of circuit boards and the decreasing cost of using 3D printers. The possibility of creating an actual product is a daunting task. Ideally, a third generation laser goniometer would consist of an exterior smartphone case that could be added to any smartphone. The medical smartphone case could be 3D printed and would need to house 1 to 2 battery cells. An excellent ideal candidate for power cell is the 18650 lithium ion battery. The battery has a measurement of 18 mm in diameter at the base and top, and 65 mm of length as it is evident from its name. It also has a working voltage of 3.7-4.2 volts and an electrical charge capacity of between 1500-2500 mAh.[30] Therefore it could be compatible with any HLM1230 laser module.[15] [16] [12] Smartphone case material could be either polylactic acid or ABS [31]. 3D printer advancement and the development of new materials in the industry would allow for different smartphone case materials. Additional components that would need housing for the third-generation model are a TP4056 module or any other module that would allow for USB charging of the power cell and eventually the laser. [32] The TP4056 module is a constant- current/constant/voltage linear charger and it limits the current of the battery to 4.2 volts. Additional components include any cables and switches for turning on and off the third generation device. The next step is to get sufficient funding for creating the first 3D printed prototypes and study how the customers could interact with this product. The market for this kind of technology is obviously global thanks to the advancement of e-commerce by 2019.

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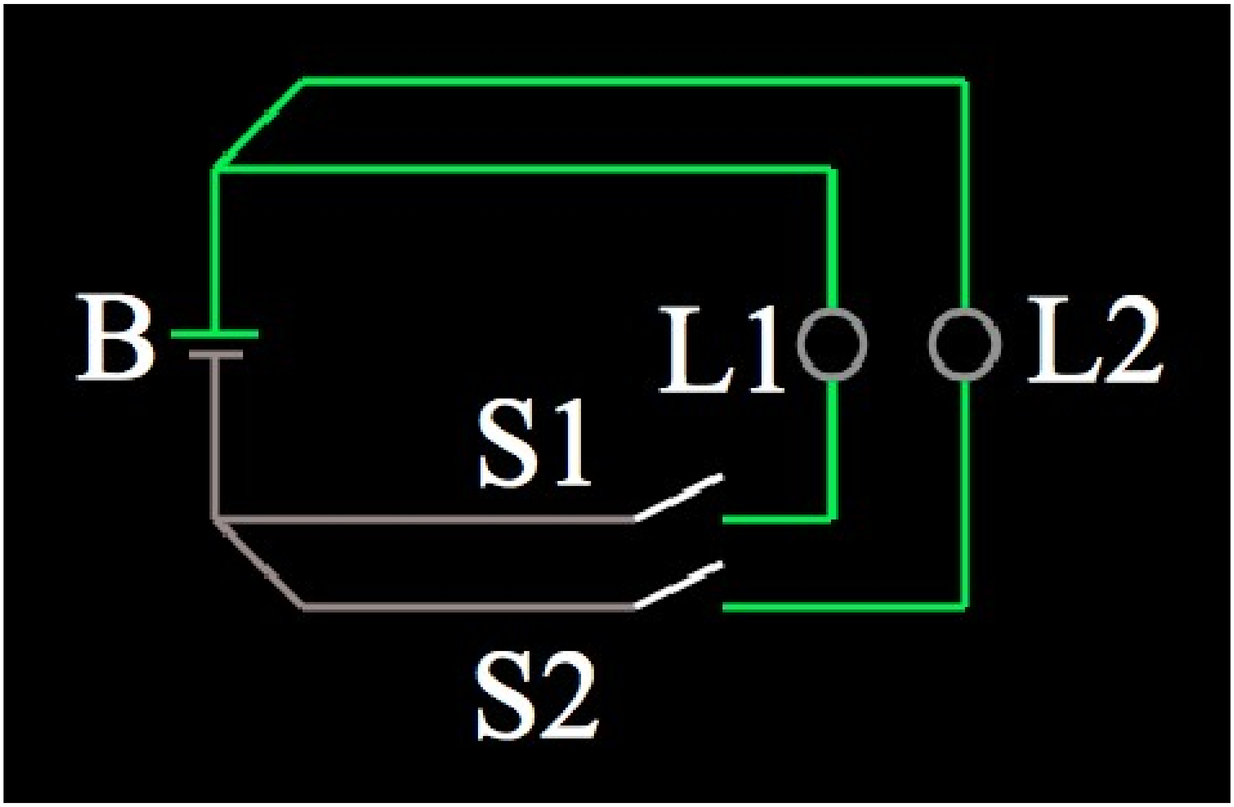
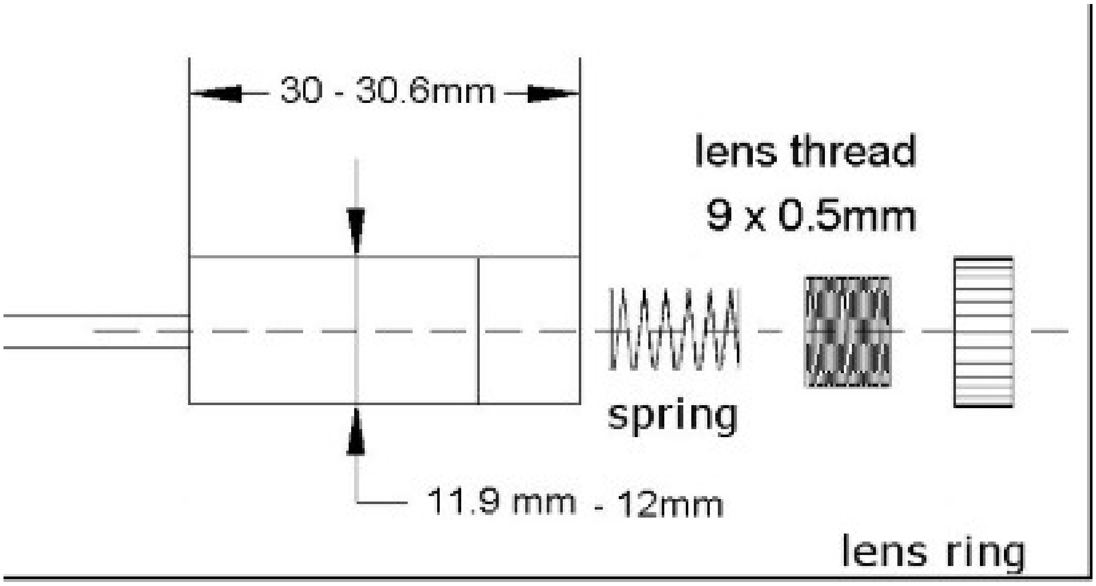
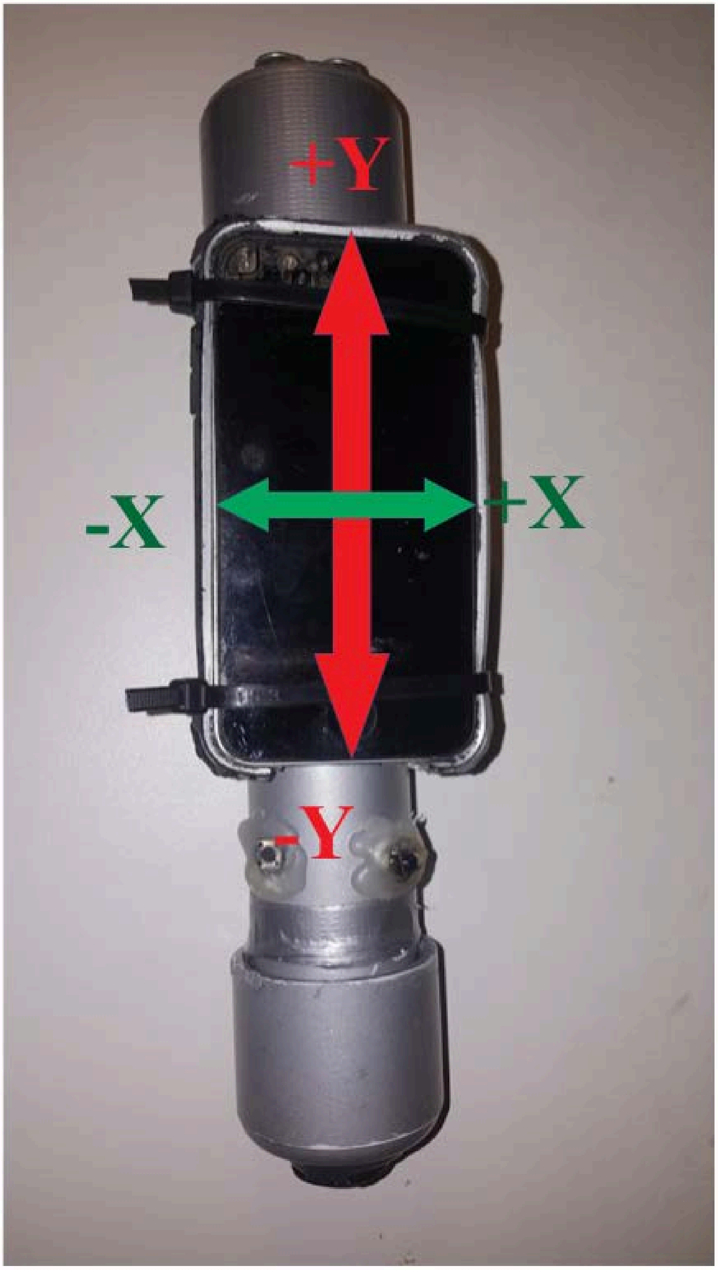
7. APPENDIXES

Appendix A: Circuit model simulation made on Java. B=Battery of 4.8V. L1 = Laser 1, L2 = Laser 2, S1 = Switch 1, S2 = Switch 2.



Appendix B : HLM1230 laser module components and measurement, this image is included in the user manual available online and listed in the references.





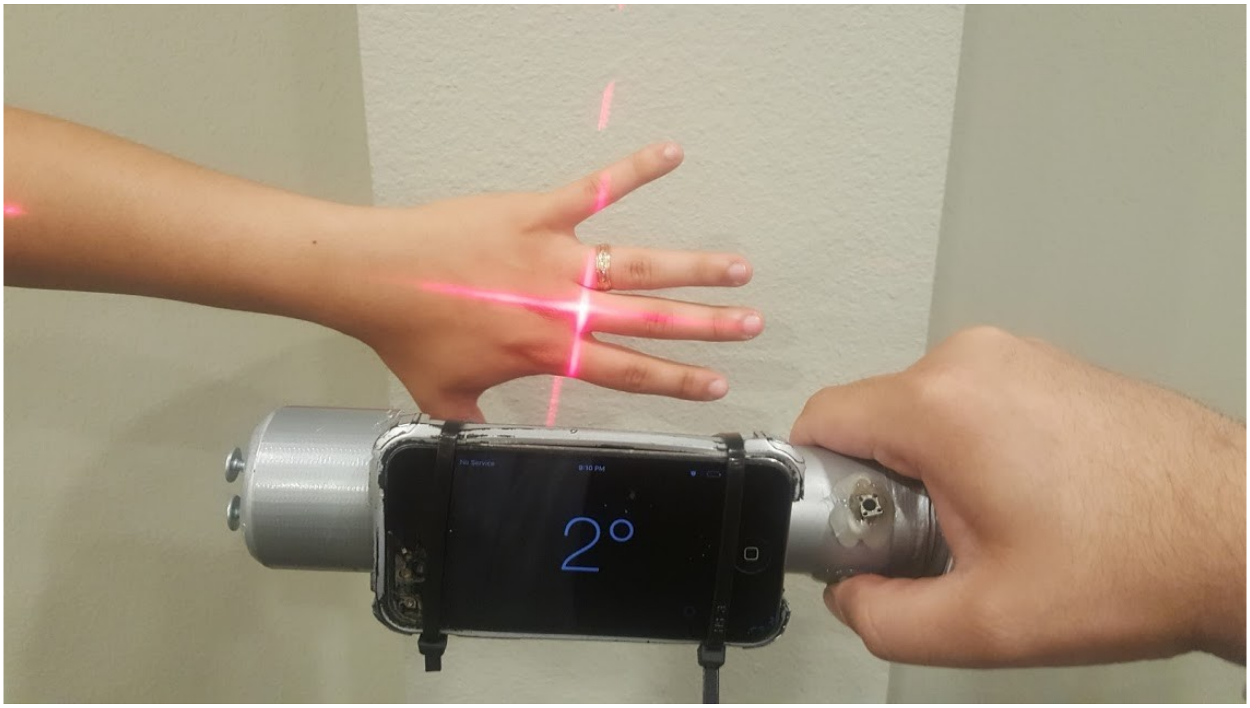
Appendix C: Second generation laser goniometer. iPhone 4s in image. Buttons are for controlling Laser 1 and Laser 2. The iPhone 4s in built MEMS accelerometer measures changes in position in the Y and X axis of the phone. Z-axis is orthogonal to the X and Y axes.

Appendix D: Lower cap removed to expose the 4 capacity battery holder for the 1.2 volt 4 AAA batteries powering the second generation goniometer

Appendix E: Laser module aligned parallel to Z-axis of the phone. This laser configuration allows for measurements of degrees on the X and Y axes.

Appendix F: Laser 2. This laser module is aligned parallel to the Y axis of the smartphone.

Appendix G: Ulnar deviation starting position 2º degrees. Laser cross is aligned to the space between the 2nd and 3rd metacarpals.

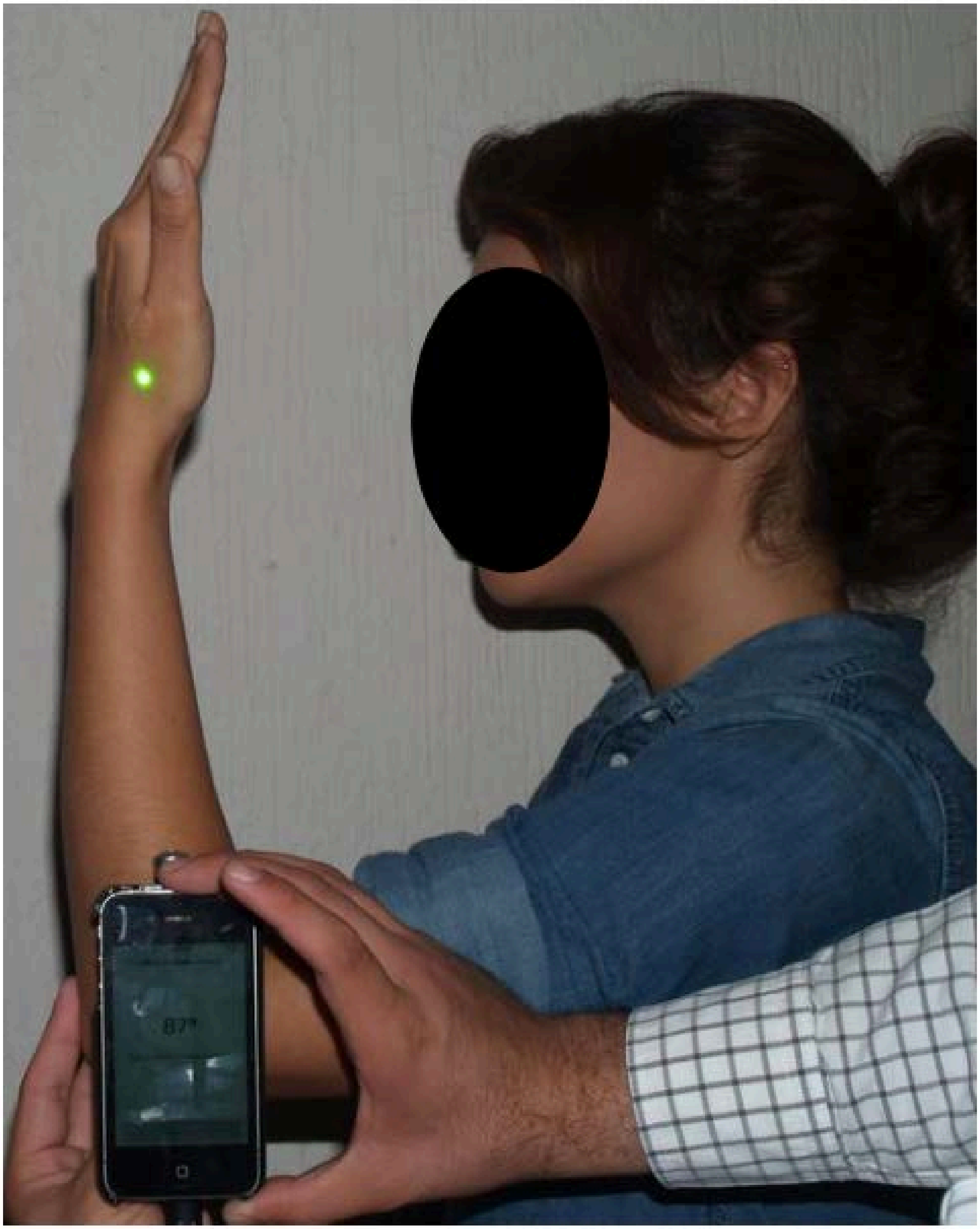


Appendix H: Ulnar deviation of -35º degrees. Zero starting position 2º degrees. Total arc of ulnar deviation = 37 degrees.

Appendix I: Left leg extension ROM measurement. Zero starting position. Laser cross aligned to center of the knee.

Appendix J: Left leg extension ROM measurement of 66º degrees. Laser is aligned to center of the knee.

Appendix K: First generation laser goniometer. ROM of left elbow 0º. Zero starting position. The first generation laser goniometer was a 3D printed ABS plastic case that held a green laser pointer in place.



Appendix L: First generation laser goniometer. ROM of left elbow flexion 87º degrees.

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