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Development and pilot testing of a new device for q-angle measurement

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ABSTRACT
Patellofemoral pain syndrome (PPS) is a joint disorder responsible for 25% of knee injuries, affecting one in four people in the general population. The increased Q-angle is one of the main factors for the onset of this clinical condition; however, the methods used for Q-angle measurement are still inaccurate. This study aims to develop and test a new device for accurate and reproducible Q-angle measurement. The device developed in this study has a fixed part, which has a reference part, and a moving part that has an Arduino pro mini microcontroller, a potentiometer, a laser, a LED screen, a hollow hole, and an adjustable piece similar to a crosshair. For testing the device, an system usability test was performed by experts; it was also performed a system validation test and intra-examiner and inter-examiner reliability tests. Statistical analysis of the results was performed using the Pearson correlation coefficient, which demonstrated that this device is accurate, reproducible, and widely accepted by experts.
Keywords – Device, Patellofemoral pain syndrome, Q-angle

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I. INTRODUCTION

Patellofemoral pain syndrome (PPS) is a joint disorder manifested by pain in the anterior knee, peripatellar edema, and crackle of the patellofemoral joint, which compromises everyday activities [1, 2]. This disorder is responsible for 25% of knee lesions, affecting one in four people in the general population [3,4].

Although PPS is usually found in the clinical practice, it is still a controversial matter due to the absence of clinical tests and specific image exams for its proper diagnosis. The hypothesis most cited about the onset of this pathology is the poor alignment of the patellofemoral joint [5,6]; this alignment is measured by the quadriceps angle or Q-angle [7,8].

The Q-angle is set by the intersection of two imaginary lines: one extending from the anterior superior iliac spine to the midpoint of the patella, and the other one extending from the anterior tibial tuberosity to the midpoint of the patella [9]. Its normal value is found between 12 and 20 degrees [8]. Huberti and Hayes [10] reported that a 10º increase in the Q-angle increases the stress on the patellofemoral joint by 45%, which may lead to the degeneration of the patella articular cartilage, contributing to the onset of PPS [11]; also, Belchior et al. [12] observed that individuals with PPS have a higher Q-angle than asymptomatic individuals.

The measurement of this angle can be done by radiography [13] and the patient is exposed to radiation when using photogrammetry [14]. However, the evaluation of this angle cannot be done instantaneously because it is necessary to take pictures of the individual and edit them using a goniometer and computer software [15]. This method is the most widely used in clinical practice, because it is accessible to professionals, easy to handle, and has a low cost [15, 16].

Although the Q-angle is more commonly measured by the goniometry, Tomsich et al. [17] evaluated the reliability of this method and their results have shown that these measures were not considered trustful by their examiners – they have concluded that the measurement by the goniometry of the Q-angle is not a reproducible technique. Also, Sanfridsson et al. [18] have evaluated reproducibility between clinical and radiological Q-angle measurements and have concluded that there was no correlation between them. Therefore, standardized evaluation methods have been sought to avoid Q-angle differences in different studies, improving the accuracy of this measurement [19].

The development of a device able to show a precise and reproducible Q-angle would contribute with the study and diagnosis of PPS by clinicians and researchers; thus, this study aims to develop and

test a device that could perform a precise and reproducible measurement of the Q-angle.

II. MATERIALS AND METHODS

2.1 Device development

The device developed in this study has a fixed part and a moving part. The fixed part has a reference part that must be positioned on the individual's anterior superior iliac spine; the moving part has an Arduino pro mini microcontroller, a potentiometer, a laser, a LED screen, an adjustable sight-like piece positioned over the anterior tibial tuberosity of the individual, and a hollow hole positioned over the midpoint of the patella.

2.1.1 Virtual prototype

The virtual prototyping technique was used to model our device. The device structure was developed in Autodesk® Inventor 2019 3D modeling software (Fig. 1).

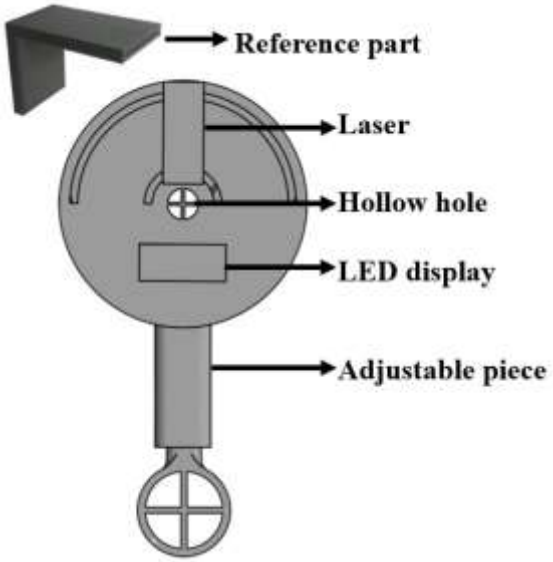

Fig. 1. Three-dimensional modeling of the device.

2.1.2 Device manufacturing

The structures of the fixed part and the moving part of our device were made in an Ender 3pro 3D printer using the polylactic acid filament (PLA), which is the material that presents the highest strength among the materials for 3D printing.

2.1.3 Microcontroller

An Arduino pro mini microcontroller was used to receive, process, and display the angular variation data of the potentiometer on the LED screen of the device; this microcontroller was chosen because of its compactness and high processing power.

2.1.4 Potentiometer

A 10K linear potentiometer was used to measure the angular variation of the device.

2.1.5 LED display

A 0.91-inch LED screen was used to show the Q-angle value to the evaluator.

2.1.6 Laser

A laser pointer was positioned on the upper part of the moving part, with the purpose of guiding the Q-angle measurement, because when the laser touches the fixed part of the equipment, positioned on the individual's anterior superior iliac spine, the evaluator must stop rotating the moving part so that the Q-angle value is displayed on the device screen.

2.1.7 Adjustable piece

This piece is similar to a crosshair, it is positioned over the anterior tibial tuberosity of the individual and defines the starting point at 0° of the potentiometer. It also has a height adjustment to best suit the individual.

2.1.8 Hollow hole

Our device has a hollow hole that is positioned over the midpoint of the individual's patella and aims to align the device to measure the Q-angle.

2.1.9 Reference part

This piece must be positioned on the individual's anterior superior iliac spine in order to mark the end point of the Q-angle measurement; when the laser touches this piece, the evaluator should stop moving the device so that the Q-angle value is displayed on the LED screen of the device.

2.2 Device functionality

Figure 2 shows the operation of the device.

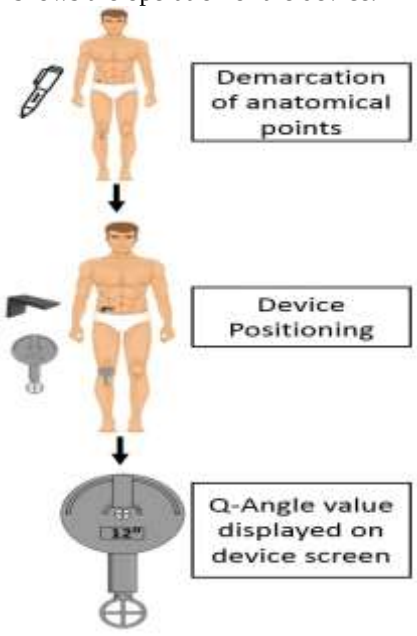

Fig. 2. Q-Angle device implementation diagram.

For performing the Q-angle measurement, the evaluator must delimit three anatomical points in the individual: (i) anterior superior iliac spine, (ii) patellar midpoint, and (iii) anterior tibial tuberosity. The reference part should be positioned on the anterior superior iliac spine, the vena bore should be positioned over the patellar midpoint, and the adjustable part should be positioned over the anterior tibial tuberosity; also, the evaluator simply must move the moving part of the device until the laser touches the reference part. Then, the Q-angle value was displayed on the device screen.

2.3 System usability test

Aiming the evaluation of our device, four experts have participated in this study - two electrical engineers and two physical therapists. For measuring the system usability, each expert tested the device and answered the System Usability Scale (SUS) assessment. This is a fast and reliable scale consisting of a 10-item assessment with five answer options ranging from strongly agree to strongly disagree.

2.4 Pilot test

2.4.1 Sample

Five volunteers have participated in the pilot test. Inclusion criteria were: male, healthy, aged 18-30 years. Exclusion criteria were: lower limb surgery, lower limb fractures, and knee pain, as described in the literature [20]. This study was approved by the Research Ethics Committee of the University of Mogi das Cruzes, under protocol [18933419.60000.5497]. All volunteers received information about the project and signed informed consent, agreeing to participate in the research.

The pilot test was divided into three steps: (i) system validation test, (ii) inter-examiner reliability test, and (iii) intra-examiner reliability test (Fig. 3).

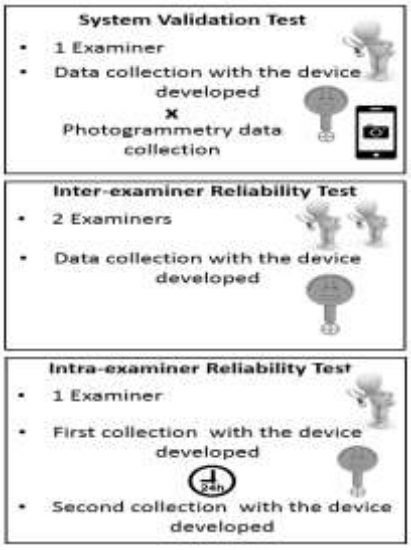

Fig. 3. Conducting the pilot test

2.4.2 System validation test

To validate the system, a comparison was made between the Q-angle values obtained with the our device and photogrammetry, a validated technique widely used in the literature [14]. A physical therapist measured the Q-angle of both knees of the volunteers with the device and also took a picture of the lower limbs of the individuals to perform the Q-angle measurement by photogrammetry.

The measurement of the Q-angle by our device consisted in the following steps: (i) the physical therapist demarcated three anatomical points in the individuals (anterior superior iliac spine, midpoint of the patella, and anterior tibial tuberosity); (ii) after the demarcations, the physical therapist positioned the reference piece on the anterior superior iliac spine, the vented hole on the patellar midpoint, and the adjustable piece on the anterior tibial tuberosity of the volunteers; and (iii) the physical therapist measured the Q-angle of the individuals.

The Q-angle measurement by photogrammetry consisted in the following steps: (i) the physical therapist took a picture of the individuals' lower limbs using a smartphone camera, transferred these images to Photoshop cc 2019, and drew two lines on the knees of the subjects –one between the anterior superior iliac spine and the midpoint of the patella and the other one between the anterior tibial tuberosity and the midpoint of the patella. The Q-angle was then calculated by the distance between these two lines (Fig. 4).

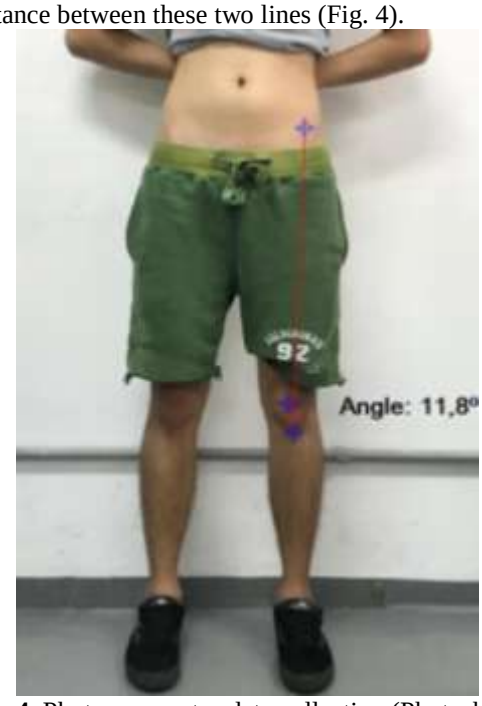

Fig. 4. Photogrammetry data collection (Photoshop).

2.4.3 Inter-examiner reliability test

To assess the inter-examiner reliability of our device, two physical therapists measured the Q-angle of both knees from the volunteers, on the same day, using our device. The physical therapists performed the measurements at different times; after data collection, the anatomical points were removed with alcohol. Also, one examiner was unaware of the anatomical point demarcated by the other.

2.4.4 Intra-examiner reliability test

To assess the intra-examiner reliability of our device, one of the physical therapists repeated the measurements 24 hours after the first measurements.

2.5 Data analysis

Pearson correlation coefficient was performed for verifying the existence of correlation between Q-angle values from our device and photogrammetry; inter and intra-examiner reliability tests were also performed.

III. RESULTS

3.1 Developed device

Figure 5 shows the final version of device developed in this study.

Fig. 5. Final version of device.

3.2 System usability test

Four experts evaluated our device using the System Usability Scale (SUS). According to Nielsen [21], this number of participants is ideal to identify 80% of system usability issues, which fulfills our purposes. Table 1 shows the results of the experts' assessments.

Table 1. Evaluation of experts by SUS scale.

VOLUNTARY	SCORE
1	85,0
2	80,0
3	80,0
4	80,0
AVERAGE	81,25

In the System Usability Scale (SUS), scores below 60 show systems with relatively poor experiences and user dissatisfaction. Scores above 80 show very good experiences, with a high level of satisfaction [21]. Thus, we see that the device developed in this study was evaluated by all experts as a very satisfactory system, being able to create very good experiences for the final user. These results point that the system does not show significant flaws and it was very accepted by all users.

3.3 System validation test

For system validation, Q-angle values were compared between the device developed and photogrammetry. Table 2 shows the Q-angle values of the two measurement techniques which were used.

Table 2. System validation test.

DEVICE X PHOTOGRAMMETRY (RIGHT KNEE)		
VOLUNTARY	**DEVICE**	**PHOTOGRAMMETRY**
1	12	11,8
2	19	19,5
3	11	11,5
4	12	11,8
5	14	14,9
Pearson's correlation r=0.99		
DEVICE X PHOTOGRAMMETRY (LEFT KNEE)		
VOLUNTARY	**DEVICE**	**PHOTOGRAMMETRY**
1	17	18,6
2	23	22,9
3	11	11
4	18	18
5	15	15,7
Pearson's correlation r=0.98		

Based on the data, an analysis by Pearson correlation coefficient was performed, showing (r = 0.99 right knee) and (r = 0.98 Left knee) between the Q-angle values from the developed device and

photogrammetry, which shows a correlation almost perfect [21,22]. Thus, we can observe that our device behaves similarly to a validated tool widely used in the literature (Fig. 6).

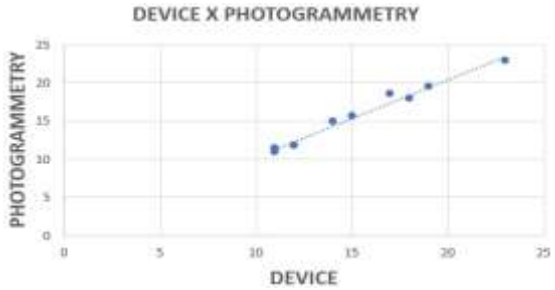

Fig. 6. Correlation graph between the values of the developed device and the photogrammetry.

3.4 Inter-examiner reliability test

Table 3 shows the values obtained in the inter-examiner reliability test.

Table 3. Inter-examiner reliability test

INTER-EXAMINER RELIABILITY (RIGHT KNEE)		
VOLUNTARY	**EXAMINER 1**	**EXAMINER 2**
1	12	12
2	19	19
3	11	12
4	12	12
5	14	14
Pearson's correlation r=0.99		
INTER-EXAMINER RELIABILITY (LEFT KNEE)		
VOLUNTARY	**EXAMINER 1**	**EXAMINER 2**
1	17	18
2	23	23
3	11	12
4	18	18
5	15	15
Pearson's correlation r=0.99		

For verifying the inter-examiner reliability of device, an analysis by Pearson correlation coefficient was performed between the Q-angle values obtained by two physiotherapists, showing (r = 0.99 right knee) and (r = 0.99 left knee), which shows a correlation almost perfect [21,22]. Thus, we can observe that the device enables data reproducibility (Fig. 7).

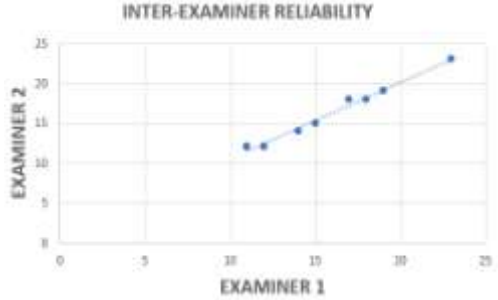

Fig. 7. Correlation graph between the values obtained inter-examiner.

3.5 Intra-examiner reliability test

Table 4 shows the values obtained in the intra-examiner reliability test.

Table 4. Intra-examiner reliability test

INTRA-EXAMINER RELIABILITY (RIGHT KNEE)		
VOLUNTARY	**EXAMINER 1**	**EXAMINER 1**
1	12	12
2	19	19
3	11	11
4	12	12
5	14	14
Pearson's correlation r=1		
INTRA-EXAMINER RELIABILITY (LEFT KNEE)		
VOLUNTARY	**EXAMINER 1**	**EXAMINER 1**
1	17	17
2	23	23
3	11	11
4	18	18
5	15	15
Pearson's correlation r=1		

For verifying the intra-examiner reliability of device, an analysis by Pearson correlation coefficient was performed between the Q-angle values obtained by a single physical therapist at two different times, presenting (r = 1 right knee) and (r = 1 left knee), which shows a correlation almost perfect [21, 22]. Thus, we can observe that this device enables the repeatability of the data (Fig. 8).

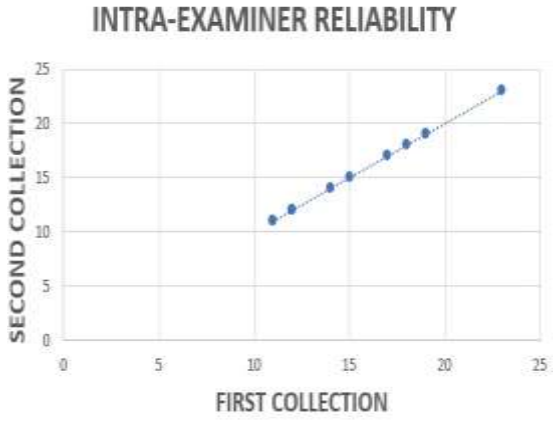

Fig. 8. Correlation graph between the values obtained intra-examiner.

3.6 Cost

The final version of our device costs less than $ 25, allowing more people to access an accurate and reproducible tool at an affordable price.

IV. DISCUSSION

The importance of investigating patellofemoral pain syndrome is given by its high prevalence in the general population; also, the increase of Q-angle is a determining factor for the onset of this clinical condition [9]. For Dye [23], PPS is an orthopedic puzzle, which makes this disease one of the most difficult pathologies to manage; however, existing methods for Q-angle analysis are inaccurate [19]. The device developed in this study contributes substantially to the diagnosis and understanding of the pathology since it was able to accurately show the Q-angle data of the evaluated individuals.

Currently, techniques used for Q-angle measurement are radiographs, computed tomography, goniometers, and photogrammetry. In the study by Dickschas et al. [6], Q-angle was measured by radiographs and computed tomography; however, the patient's exposure to radiation and the high cost of these techniques make their use impracticable in many studies. Such problems are not found in the device we developed because not only it is simple to handle but it also has low cost and shows no risk to users.

Goniometry also has these same user-friendly characteristics and low cost and it is a technique widely used in clinical practice to measure Q-angle simply and safely to individuals; however, some studies are testing its reliability. In the study by Bandeira et al. [15], the intra-examiner and inter-examiner reliability of Q-angle measurements were analyzed using a conventional goniometer. The results have shown that there was no correlation between the values obtained by the evaluators at the same moment as well as there was no correlation between the values obtained by the same evaluator at different times.

In contrast to the findings by Bandeira et al. [15], our study analyzed the intra and inter-examiner reliability of Q-angle measurement using the developed device. The results showed that there was a correlation between the measurements obtained by the evaluators at the same time and by the same evaluator at different times, showing that our device overcomes the use of the conventional goniometer in repeatability and reproducibility.

Moreover, for validating our device it was necessary to compare it with a scientifically consolidated tool. Therefore, the photogrammetry was used for comparison because studies show that goniometry for Q-angle measurement shows inaccurate data, and the use of computed tomography and radiography is unfeasible because of its high cost and risk to the patient. For Candotti et al. [24], the wide use of photogrammetry is due to its high precision, ease of interpretation, and reproducibility of the results.

Thus, when comparing our device with photogrammetry, a strong correlation between them was identified, which demonstrates that the newly developed tool behaves similarly to a technique already consolidated. However, Q-angle measurement by photogrammetry requires additional tools such as cameras and a computer, which slows the evaluation process; in contrast, the device of this study can show data instantly, ensuring agility to measurements.

Therefore, we note that the device of this study fills a gap identified in the literature by Draper et al. [19], who pointed out the need for the creation of methods to improve the accuracy of clinical Q-angle measurements since it presents intra and inter-examiner precision and reliability.

V. CONCLUSION

This study has developed and tested a new device for accurate and reproducible Q-angle measurements; thus, standardization of intra-examiner and inter-examiner measurements has also become possible, which contributes to the diagnosis and understanding of patellofemoral pain syndrome by clinicians and researchers.

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