DEVELOPMENT OF VERTEBRAL METRICS
An Instrument to Study the Vertebral Column

António Jordão
Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
Quinta da Torre P-2829-516, Caparica, Portugal
Instituto de Biofísica e Eng. Biomédica, Faculdade de Ciências da Universidade de Lisboa
Campo Grande, P-1749-016, Lisboa, Portugal

Pedro Duque
Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
Quinta da Torre, P-2829-516, Caparica, Portugal

Claudia Quaresma
CEFITEC, Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
Quinta da Torre, P-2829-516, Caparica, Portugal

Pedro Vieira
Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
Quinta da Torre P-2829-516, Caparica, Portugal
Instituto de Biofísica e Eng. Biomédica, Faculdade de Ciências da Universidade de Lisboa
Campo Grande, P-1749-016, Lisboa, Portugal

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Abstract: The purpose of this article is to present a new instrument to study the vertebral column. This device is an evolution from Vertebral Metrics (Quaresma, 2010). In this new device, the detection of the spinous process is semi-automatic, non-invasive and it is prepared to analyse the entire population. The data acquired from the instrument will allow three dimensional analysis of the vertebral column in standing position. With this instrument, hospital staff will be able to study biomechanical changes in the vertebral column due to incorrect exercise, injury, congenital malformations, obesity, pregnancies, etc. The device uses a system of movement in two axes that is controlled by software. The software uses a video camera and image processing algorithm to detect points that were previously marked in the spinous process of the individual under study. The software gives orders to the mechanic part to move the equipment to position the mark made by laser upon the spinous process. In these conditions, the spatial coordinates of the spinous process are stored and the process is repeated for the others spinous processes. A complete examination takes approximately 2 minutes and 25 seconds after manual tracing of the spine and improving is being made to the software to reach the 30 seconds mark. This instrument has the possibility of performing consecutive sweeps, for dynamic accommodation studies.

1 INTRODUCTION

The spinal column supports and protects the spinal cord and roots, as well as offer flexibility that is vital to the movement of the trunk.

Diseases of the spinal column have been increasing worldwide, due to several factors, in particularly congenital malformations, sedentary lifestyle, incorrect eating habits, posture and

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exercise. In many of these factors, the study of the spinal curvature will be an important tool to detect and try to solve them.

The radiological studies are the most widely used methods for assessing the spinal column curvatures; however these are invasive, since the patient is subjected to ionizing radiation. (Quaresma, 2009a)

There are other non-invasive alternatives for measuring the curvature of the spinal column, yet most of them only allow the study of one plane and those that analyse the spinal column in three dimensions normally use infrared cameras (Vismara, 2010) making the equipment very expensive.

Figure 1: Image of Vertebral Metrics.

Vertebral Metrics (Figure 1) is a non-invasive mechanical apparatus that was built to identify the X, Y and Z positions of each vertebra, from the first cervical vertebra to the first sacral vertebra (Secca, 2008). In a global way Vertebral Metrics evaluates the curvatures and lateral deviations of the spinal column in the standing position. (Quaresma, 2009a, 2009b, 2009c)

In the Vertebral Metrics the examiner, starts by marking on the skin of the person under study the spinous processes, from the first cervical vertebra to the first sacral vertebra, using a washable pen. The evaluation starts by placing the first horizontal piece in the occipital region. Then it is necessary to move each piece and place it in line with each mark. In this device the data collection takes about seven minutes after the manual marking. (Quaresma, 2009b, 2010)

The aim of this study is to improve the Vertebral Metrics and take a step forward, performing an automated measurement of the spine column. With this new equipment the tests will be faster, simpler and with a better resolution.

In this new device the same method of tagging the spinal processes is going to be used, but instead of a manual measuring, the device will perform it automatically.

For a better understanding of how the instrument works, the axis system used will be defined as following: the transversal distance as our X coordinate, the antero-posterior distance as the Y coordinate and the height as Z coordinate.

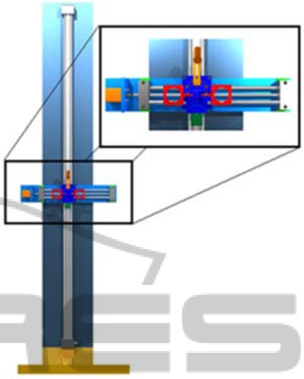

Figure 2: Aspect of the instrument.

To measure the distance between the device and the spinal process (Y), a CCD camera, a laser diode and a lighting system were used. To get an accurate measurement of the Y distance it is necessary that the laser spot and the skin mark be coincident. So this apparatus was assembled over a high precision X, Z positioner (Figure 2). In order to control the X, Z movement an image processing software was develop to find the spinal processes marks and laser spot, so we can calculate the necessary movements of the system. When laser spot and spinal process marks are coincident the system stores the X, Y, Z coordinates.

When the acquisition is done all the data is collected by the software and stored it in a single file, for further offline processing.

2 MECHANICAL SYSTEM – X/Z POSITIONER

There were two main goals for the mechanical structure: resolution and speed. The instrument was constructed based on the following pre-requisites:

- The mechanical system should move all the hardware necessary for the image acquisition in two directions, up and down (Z direction), left and right (X direction).
- Must move 2000 mm in Z and 300 mm in X.
- Resolution must be better than 0.5 mm.

- Travel speed, must move 1000 mm in Z direction in 30s (33.3 mm/s).
- Must move in X direction fast enough to position the camera and laser before the system arrives at the corresponding Z position.
- Must have a communications protocol controlled by software.

For the Z positioner a 2 meters DryLin ZLW belt drive from Igus™ was used. It travels 66 mm per revolution, and supports speeds up to 5 m/s. The X positioner is a linear slide table DryLin SHTS Fast. It has a high helix pitch leadscrew providing high speed positioner, 50 mm per revolution.

The motors are step by step motor type, for precision positioning, each step rotates the motor shaft 0.9^o, so a full rotation or revolution is 400 steps (360^o / 0.9^o = 400). For increased torque, motor Z has a gear box that reduces 7 revolutions to 1 (7:1).

Knowing this we can define the resolution for the positioners:

Table 1: Resolution of the positioners.

Axe	[Step/rev]	[mm/rev]	Resolution [mm/step]
X	400	50	0.125
Z	400*7 = 2800	66	0.024

The selected motors are both from Lin Engineering™. In terms of Z direction a high torque bipolar motor, model 5709L-01P with 1 Nm of maximum torque and 6.25 rev/s maximum speed. The X motor, is a high torque bipolar motor, model 4209L-01P with 0.35 Nm of maximum torque and 18.75 rev/s maximum speed. Both motors have independent drivers from Lin Engineering™, model R325. These drivers provide smooth motor rotation and micro stepping configuration, also includes Pole Damping Technology™ (PDT) that enhances step motor performance by dampening each full step in order to create a more accurate and smooth motion profile.

The motion and control of the motors will be performed by a microcontroller PIC16F877 from Microchip™. This microprocessor will work with a 16MHz clock and independently generate the two pulse clocks for step by step motion of the motors. It will also monitor limit switches, control serial RS232 communications and control laser and lights relays.

In terms of RS232 communication a protocol was developed based on instructions and replies, the microprocessor will be a slave system, i.e., will only answer and execute commands from the PC.

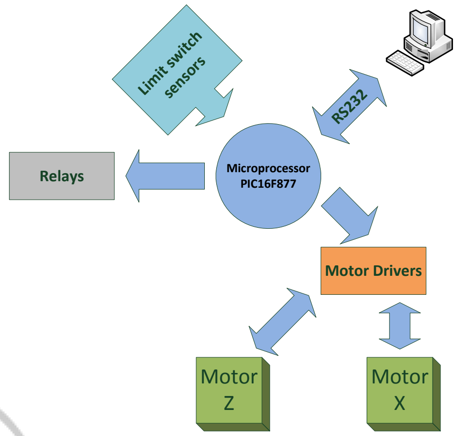

Figure 3: Scheme of the communication system.

3 CALCULATION OF DISTANCE USING THE LASER DIODE MARK

The laser diode is situated on top of the camera in a fixed height and angle. Through trigonometric equations the distance between the equipment and the individual that is under study can be calculated.

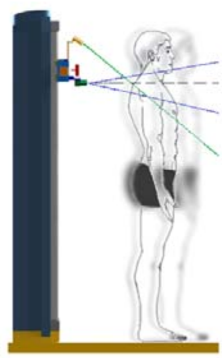

Figure 4: Representation of the measurement of the antero-posterior distance.

In the Figure 4 the blue lines represent the viewing angle of the camera and the green line represents the laser beam.

Knowing the angle of the laser diode, angles of the camera, the real dimensions of each pixel in the reference plane (orange plane), as well as the distance between the reference plane and the focal centre of the camera, the distance between the laser diode mark and the focal plane of the camera can be obtained.

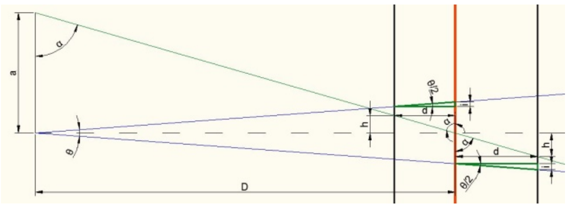

Figure 5: Scheme to demonstrate the calculation of the Antero-posterior distance.

$$\text{Distance} = \text{D} - \text{d} \quad (1)$$

Distance – Distance between the camera and the measuring point

D - Distance between the camera focal plane and the orange plane (reference plane)

d - Variation of distance between the person under study and the reference plane

The variable d is positive when the plane under study is on the left of the reference plane otherwise is negative. The variable d is calculated using following formula:

$$\text{d} = \text{h} \times \tan(\alpha) \quad (2)$$

θ – Vertical viewing angle of the camera

h – Real height of the mark of the laser diode

The viewing angle of a camera is the maximum angle at which two light beams can intersect at the secondary focal point (O, Figure 6). In other words, the viewing angle is the maximum angle of vision of the camera. The viewing angle depends on the focal length as well as the dimensions of the sensor. The viewing angle is higher when the sensor is larger and when the focal length is lower. (Hecht, 2002)

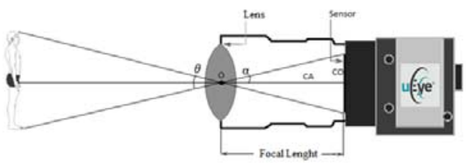

Figure 6: Representation of the viewing angle of the camera.

From the observation of Figure 6 the value of the viewing angle of the camera is obtained through the following equations:

$$\theta = 2\alpha \quad (3)$$

$$\tan\left(\frac{\theta}{2}\right) = \frac{S/2}{f} \quad (4)$$

where:

$$\theta = 2\tan^{-1}\left(\frac{S}{2f}\right) \quad (5)$$

θ – Viewing angle of the camera

S – Sensor dimension

f – Focal Length

With the viewing angle of the camera and the distance that the individual under study is from the reference plane (d), is possible to know the real dimension of the viewing window of the camera as well as the real value of each pixel in the plane under study. The real value of each pixel can be used to indicate the precise location, to which the mechanical instrument has to move in order to put the laser mark on top of the blue points.

To calculate the real value of each pixel for a specific distance of the subject under study, the following formula was applied:

$$\text{P} = \left[\frac{\left(\frac{\text{R}}{2}\text{m}\right) - \tan\left(\frac{\theta}{2}\right) d}{\frac{\text{R}}{2}}\right] \quad (6)$$

If the pixel coordinate of the laser mark is less than half of the camera resolution in the vertical axis. Otherwise P is given by:

$$\text{P} = \left[\frac{\left(\frac{\text{R}}{2}\text{m}\right) + \tan\left(\frac{\theta}{2}\right) d}{\frac{\text{R}}{2}}\right] \quad (7)$$

m – Real dimension of the pixel in the reference plane

R – Sensor Resolution

P – Real value of the pixel in the plane under study

Knowing the real pixel dimension is possible to calculate h.

$$\text{h} = \left(\frac{\text{R}}{2} - \text{p}\right)\text{P} \quad (8)$$

p – Vertical pixel coordinate of the laser

Solving equation 2 in order to d and replace the result in equation 1, it was found that the distance is given by:

$$\text{Distance} = \text{D} - \left[\frac{\left(\frac{\text{R}}{2} - \text{p}\right)\ \text{m}\ \tan(\alpha)}{1 + \frac{\left(\frac{\text{R}}{2} - \text{p}\right)\tan\left(\frac{\theta}{2}\right)\tan(\alpha)}{\frac{\text{R}}{2}}}\right] \quad (9)$$

If the pixel coordinate of the laser mark is less than half of the camera resolution in the vertical axis. Otherwise:

$$\text{Distance} = \text{D} - \left[\frac{\left(\frac{\text{R}}{2} - \text{p}\right)\ \text{m}\ \tan(\alpha)}{1 - \frac{\left(\frac{\text{R}}{2} - \text{p}\right)\tan\left(\frac{\theta}{2}\right)\tan(\alpha)}{\frac{\text{R}}{2}}}\right] \quad (10)$$

If the person under study is at 33 cm from the equipment, and using a Eye camera model 1440 (resolution 1024x1280) the resolution given by the software on the vertical plane is expected to vary from 0,04 to 0,07 mm, and on the horizontal plane 0,05 to 0,1 mm (value of the pixel).

4 DETECTION OF THE SPINOUS PROCESSES

To develop the software for detecting spinous process we used Matlab (MATrix LABoratory, a numeric computer environment for programming), where respectively, the processing code and image analysis, as well as functions for communication with the mechanical equipment were created.

The first step in the development of the software to detect the spinous process consisted of choosing the marker to sign the spinous process in the skin. For this purpose, several tests were made to find the best marker, this tests were made to see how the markers behaved in the skin. It was observed that if the ink of the marker spread in contact with the skin the marker could not be used, because the detection of the point would became harder or could even fail. The tests showed that skin has mainly the red and green components in a RBG camera, so the blue will be the best bet for the marker.

As the processing and image analysis is based on logical operators, it was necessary to binarize the image. However, since the processing of the image in terms of the detection of the points and the laser mark had to be done in real time and as swiftly as possible, complex binarization algorithms could not be used. Therefore, it was decided to make a binarization by comparing the green and blue components of the image to detect the blue marks.

This binarization option is the result of tests performed with the markers. It was observed that only the area of the blue mark had the blue image component higher than the green. In other areas of the skin, the red component of the image dominated, followed by the green and finally blue. More tests must be performed to see if this is compatible with all skin types (Caucasian restricted at this point), but for now this feature was taken in advantage to make the image binarization.

An opening operation was applied to the image in order to reduce the artefacts caused by binarization. This operation is the result of an erosion followed by dilatation of the image with the same mask. This image processing operation keeps only the structures that are similar to the mask, and also the ones that are contained within the area of those same structures.

After this treatment, an algorithm of connected components (Gonzalez, 2002, 2004) was applied to the image. This algorithm allows the detection of objects in binarized images.

Following the detection of objects and using image analyses the dimensions and centroids of the objects were calculated. Subsequently, some comparisons were made to test whether the object being analyzed is actually the point made by the marker or not. If the object detected is really a mark, its coordinates are stored.

The detection of the laser mark is made in a similar manner to that used in the detection of the points, yet its binarization is different.

To find the mark position of the laser diode the red component of the image is compared with the green component. When the green component has a higher level than the red component this means that it is in the area of the laser mark.

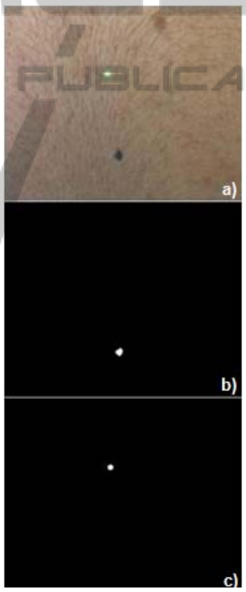

Figure 7: Aspect of the blue and green laser mark on the skin (a); Binarization plus opening operation of the blue mark (b); Binarization of the laser mark (c).

In order to move the mechanical equipment to put the mark of the laser diode on top of the blue dots it is necessary to calculate the distance from the laser point to the blue point in pixels and convert it into real values. For this conversion a reference in the image is needed, the reference used was the mark of the laser diode. The mark of the laser diode was also used to calculate distances allowing us to calculate the third spatial coordinate of the blue mark (Muljowidodo K, 2009).

When the equipment is on the right spot, the software will store the Y coordinate of the spinal process and will indicate to the hardware (mechanical system) the exact moment when it must save the X and Z coordinates.

5 CONCLUSIONS

This project is still in the test stage, but it already managed to detect each spinal process in 95 ms and a complete examination after manual tracing of the spinal process is taking 2 minutes and 25 seconds. This time can be improved if the software code is change for a C language format, most of this time is being expended in the communication, our goal is to reach the 30 second mark. The initial intend is to analyze 25 spinal processes from the first cervical vertebra to the first sacral vertebra in the standing position, in the same exam. This option can be explained by the method used for the manual marking by palpation and also due to the difficulty in visualizing the spinal processes that are near the hair line. In the measurements made with the equipment it was obtained a maximum error of 1.3 mm in Y, 0.6 mm in X and 0.4 mm in the Z coordinate, taking into account that the markers have 2 mm in diameter this result is acceptable. However further tests must be made to improve the detection of the markers as well as a comparison test to validate the instrument. At this moment tests are being made with florescent markers, confident that this will work for all skin types.

This equipment will allow the possibility of consecutive sweeps allowing the analysis of the dynamic postural adjustments of the spine. The results obtained with this apparatus will allow a posterior spinal reconstruction in three dimensions and the calculus of the intervertebral forces. This instrument will contribute for a detailed study of the dysfunctions and / or pathologies of the spinal column.

This device will promote a more efficient and accurate data acquisition, and it will allow a faster and simpler mode to study the curvatures and lateral deviations of the column. The data acquired from the device can be used in the future to study the vertebral discs stress and will take a key role in the biomechanical study of the spinal column.

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