Video-analysis Interface for Angular Joint Measurement

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Abstract. Real-time quantification of joint articular movement is instrumental in the comprehensive assessment of significant biomechanical gestures. The development of an interface, based on an automatic algorithm for 3D-motion analysis, is presented in this work. The graphical interface uses open-source libraries for video processing, and its use is intuitive. The proposed method is low-cost, of acceptable precision ($|\varepsilon_\theta| < 1°$), and minimally invasive. It allows to obtain angular movement of joints in different planes, synchronized with the video of the gesture, as well as to make comparisons and calculate parameters of interest from the acquired angular kinematics.

1. Introduction

The systematic study of different stages found in normal and dysfunctional gait involves relevant kinematic variables, concerning the angular functions of hip, knee and ankle joints, throughout the full gait cycle [1]. The need to supplement previous studies based on 3D-accelerometry in adult patients with a higher risk of falling [2-4] motivated the development of a system that would allow the accurate assessment of joint movements.

Over the past years, there has been an enormous production of different, alternative methods for the evaluation of joint angles [5-7], with relative advantages related to performance, cost and ease of use. The measurement of angles between body segments consists in measuring the spatial orientation of one body segment with respect to another adjacent to it, separated from the first by the studied joint, or in relation to a constant reference, like the vertical line. Measuring of lower-limb joints is essential in the different stages of walking, as in any other gesture [8-9]. This knowledge completes the evaluation of the active and passive mobility, the characterization of axial deviations and, finally, the search of abnormal movements. It is also one of the parameters used for the complete evaluation of a running cycle.

This paper presents a method for measuring joint movements during any gesture, in particular walking, that is simple, low-cost and with excellent results. It is based on a video-analysis algorithm, which isolates active linear markers that are fixed to the moving segments, and acquires information

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concerning the dynamics of such joint angle over a gesture. The results are displayed in a dedicated graphical interface that was developed for that purpose.

2. Materials and Methods.

2.1. Light-emitting linear markers

The procedure for measuring angles between adjacent body segments in this work relies on a specially-developed software that identifies and measures the angle between light-emitting linear markers during joint movements for body segments and gestures of interest.

The most common markers are spherical markers that either reflect light from a separate lighting system, or emit visible light as well as in the infrared range (which allows an easier detection, when using the appropriate hardware). Self-adhesive markers, which have a printed pattern, are also available in the market. This pattern is looked upon on each frame of the video.

Markers of low cost using plastic, cylindrical, flexible rods were built for this work. As an example, this paper presents the markers developed for the study of knee joint movement. The rod dimensions were 15 cm long and 1 cm in diameter (see figure 1), being adaptable to any other size, if necessary. Light emission is obtained by adhering a strip of light-emitting diodes (LEDs) in front of which a diffusing paper is placed to generate uniform light. The shape of the markers makes the system more resistant to partial occlusions and is easier to associate with a straight line. A 12 Volt DC source provides power to the system (with an approximate consumption of 45 mA per marker). Strips are fixed to the concerned corporal segments by hook and loop (Velcro) elastic clamps (see figure 2), facilitating the free movement of the segments. The markers must be attached parallel to the corporal segments to ensure the correct measurement of the joint angle. Two high speed cameras were used for video recording (Casio EXFH25) capturing images at 120 fps, at the same time recording the sagittal and frontal planes of the moving subject, respectively.

Figure 1. Linear cylindrical optical marker with two elastic clamps and power cable.

Figure 2. Markers located in the lower limb to study the angular dynamics of the movement of the knee.

2.2 Algorithm for acquisition and calculation of angles

In order to calculate the angle between the segments that are instrumented with the markers, an algorithm that associates a straight line to each marker in each video frame was developed. The algorithm further calculates the angle of inclination and the centroid of each of the markers, and the angle between relevant adjacent segments.

OpenCV computer-vision libraries and tools, developed by Intel and freely distributed under BSD license, were used.

The stages of the algorithm were as follows:

- *Pre-processing stage*: Each video frame is smoothed with a Gaussian blur to eliminate details that could be wrongly detected as markers (false detection), thus the borders of the markers are also smoothed. This allows calculating the marker's tilt more accurately. Then, a binary threshold is applied (luminance level), resulting in a black and white image. See figures 3 and 4 for an example of this stage.

Figure 3. Video frame of a subject under study, with markers in lower limb, from which the pre-processing stage begins.

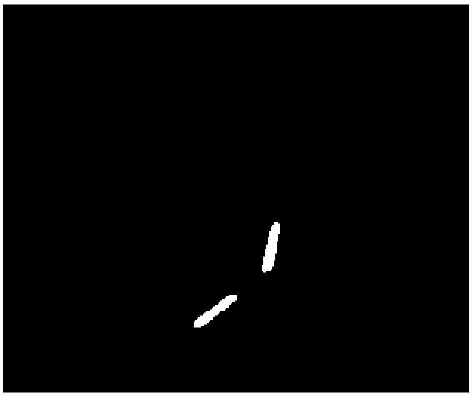

Figure 4. Black-and-white image of markers obtained by processing the image with a binary threshold.

- *Valid contour detection stage*: on the resulting image of the pre-processing stage (see figure 4) all contours are acquired, followed by a Hough-transform process. This transform can be used to find parametric curves in an image, which allows to find all the lines whose length (in pixels) is greater than a specified minimum. Once these lines are found, an analysis of which of the obtained contours contain, at least, one of these lines, is carried out. Therefore, the contours that contain a line are the ones that have the appropriate length (the linear marker length) and any other contour found in the figure, not eliminated by the binary threshold, is removed.

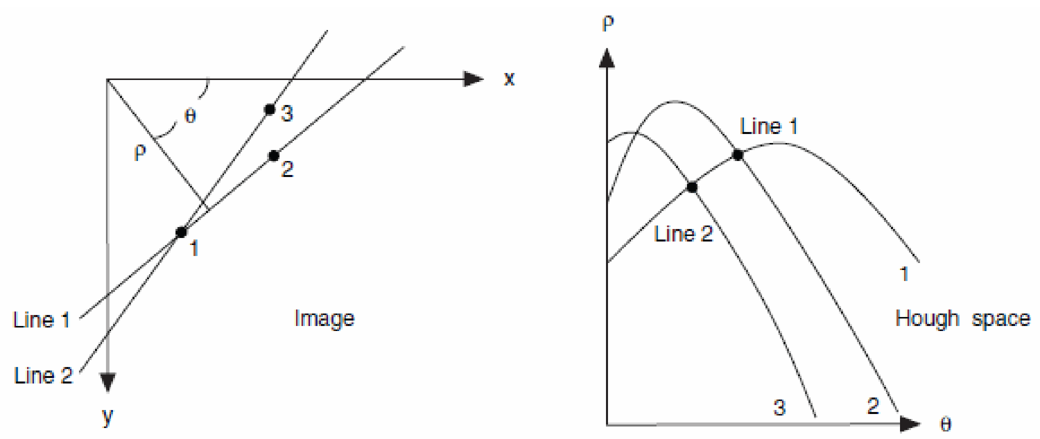

Figure 5. Illustrative diagram of stage 2: a) Hough-transform parameters (θ and ρ) of the intersection of example straight lines; b) Shape graph illustrating how the Hough transform operates on these lines.

Figure 5 shows how the Hough transform works for this algorithm. A series of straight lines of different angles are crossed through each point of interest of the image under analysis in order to measure the normal distance between the origin and each of these lines. Subsequently, a point in space (x, y) of the image leads to a sinusoid in the Hough space (ρ, θ). The number of lines running through each point will depend on the discretization of the parameter θ. The straight line joining two points in the space (x, y) will be found by the intersection of the sine waves produced by those two points in the Hough space. This point will indicate the value of ρ and θ that describe the selected straight line.

- *Segment calculation stage:* The theory of image moments is applied once contours are correctly identified in order to find the centroid and the inclination of each of these contours (thus of each body segment) as detailed in equation (1) [10]:

$$m_{p,q} = \iint x^p y^q f(x,y)\, dx\, dy \tag{1}$$

being:

$$f(x,y) \rightarrow b(x,y) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{2}$$

the moment orders determined by parameter *p+q*. The orders of interest applied for this work were:

- $m_{0,0}$ → Related to the contour area
- $m_{1,0}$ / $m_{0,0}$ → x coordinate of the contour centroid
- $m_{0,1}$ / $m_{0,0}$ → y coordinate of the contour centroid

The central moments are obtained employing definition (1), as shown in equation (3)

$$\mu_{p,q} = \iint (x - x_C)^p (y - y_c)^q f(x,y)\, dx\, dy \tag{3}$$

where x_c and y_c are the coordinates of each contour centroid. These coordinates are obtained on the basis of the above mentioned moments. The inclination of the contour can be calculated using equation (4):

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{2\mu_{1,1}}{\mu_{2,0} - \mu_{0,2}}\right) \tag{4}$$

- *Search of line intersection stage*: For each line "i" of the N lines found in the previous point, the intersection with the remaining lines (N - 1) and the points of intersection are stored in a vector. The point being at the shortest distance to line "i" is selected, which will correspond to the intersection of line "i" with the closest line in the image. As an example, a case of three straight lines is shown in figure 6. The outline found in the image is shown in white and the line representing the contour appears in green (with a red dot indicating the position of the centroid). The distance between each of the lines is shown in yellow.
  Since the presence of intersection points is not constant in all frames, a tracking of each of the intersection points between the frames was carried out.

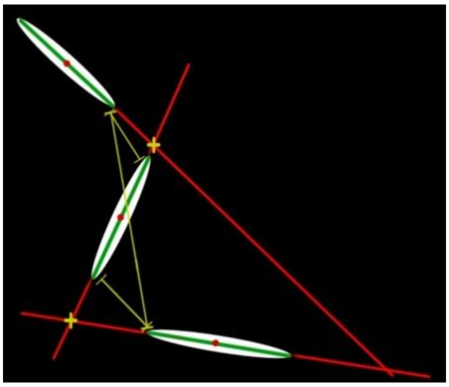

Figure 6. Example of line "i" intersection with each of the remaining N-1. The closest intersection with line "i" is obtained.

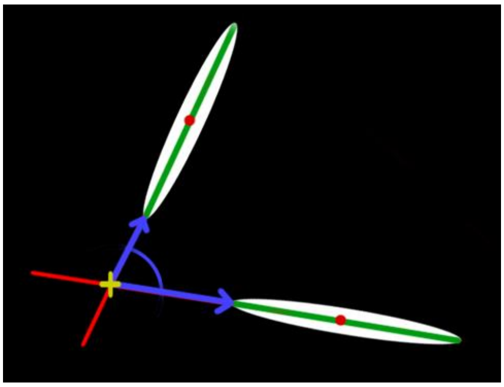

Figure 7. Example of the calculation of an angle between adjacent segments using the developed algorithm.

- *Calculation of angle between adjacent segments stage*: The angle between the vectors ranging from the intersection point to the farthest end of each intersecting line is calculated (see figure 7).

- *Three-dimensional representation of each segment stage:* This algorithm for searching segments and angular calculation is equally applied to the frames of each of the two videos (sagittal and frontal). Each pair of frames is analyzed in order to relate the obtained information to the three-dimensional representation of each segment. Thus, 3D graphs of the joint segments under study are achieved.

2.3 User interface

Figure 8 shows the graphical interface that was developed for this work. Different controls are shown on the left. The dedicated panel allows to:

- Control video.
- Set-up pre-processing parameters of each frame: smoothing level, binarization threshold.
- Determine the size of the markers to be detected, based on the specification of a minimum length (in pixels) for the lines obtained by the Hough transform.
- Set-up data visualization: Establish a reference level (for example 180°) from which measurements are plotted. The number of samples to be considered in a moving average can also be set.

Figure 8 shows video images of the moving subject during a normal walk, with markers placed on the leg and thigh –the top section shows the sagittal plane, while the bottom shows the frontal plane. In each video, the areas under which the analysis should be performed were established using vertical controls, shown on the left side of each video. Thus, a reduction of the processing time for each frame is achieved.

The controls that set the video processing parameters mentioned above are shown on the left side of the graphical interface.

On the right side, the found segments are displayed as three-dimensional shapes, through three views. The first one matches the frontal plane. The second is a free camera which can be rotated while the video is playing, simplifying the view of certain movements. The third one matches the sagittal plane.

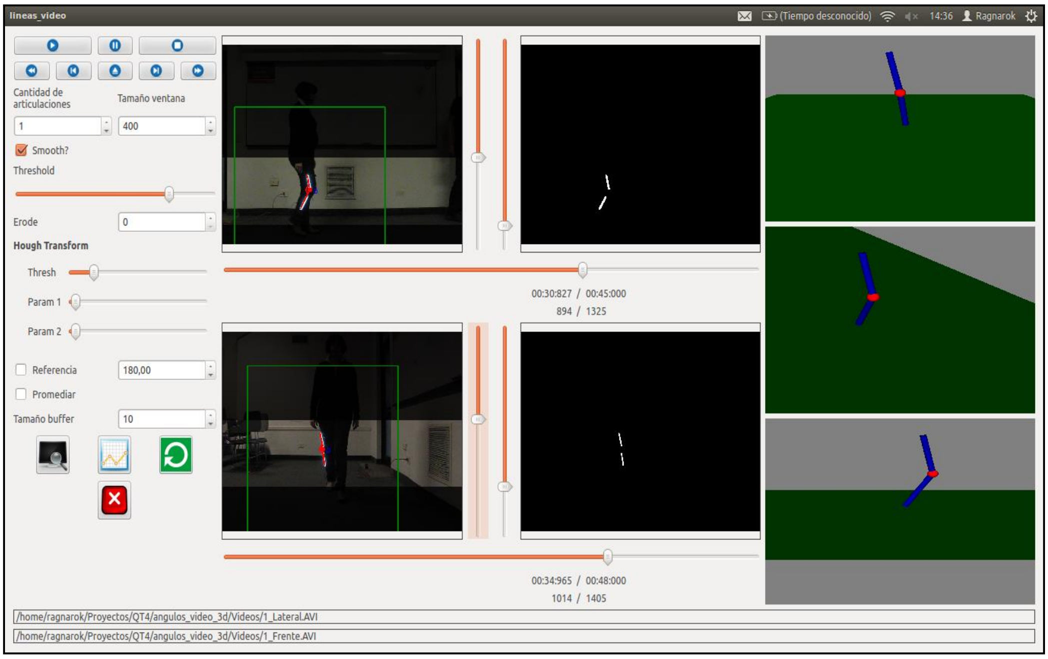

Figure 8. Graphical interface that allows the simultaneous view of both videos and the three-dimensional representation of the found segments.

Synchronization between both videos is essential for this method. An easy way to achieve synchronization is through the adequate starting of the markers, by initiating the recording on both planes with the markers turned off, and powering them when both cameras are running. The graphical interface has an option that finds the first frame in which the number of requested joints appears. Once the corresponding frames in each video are found, the video processing strategy can take place.

3. Results
Figure 9 shows the angular motion results from a test video, for the frontal plane (bottom), as well as sagittal (top).

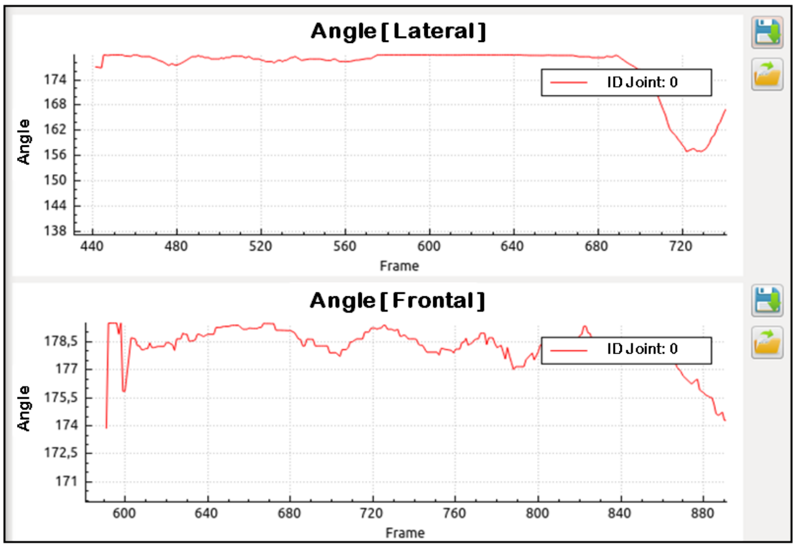

Figure 9. Time-graphs from test recording in the sagittal plane (upper image) and frontal plane (lower image).

Figure 10 illustrates the absolute error of the adjacent segments angle in the range of 1° to 150 °. To measure the error, the algorithm described in this paper was compared with an analog goniometer. The absolute error of this algorithm was obtained using the goniometer's measurement as a reference value (universal goniometer, see [11]). The displayed error (ε_θ) is less than 0.8°, which indicates that this measuring method is within the order of magnitude of many commercial electrogoniometers.

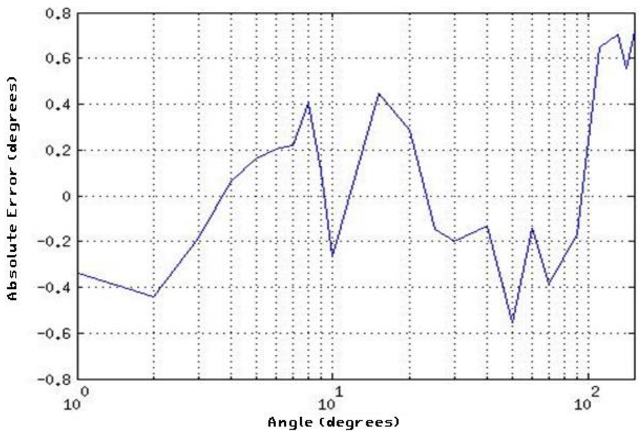

Figure 10 Absolute error achieved by the developed method.

From the acquired gesture graphs, a full study of the angular movement during any gesture can be performed. As an example, Figure 11 shows an analysis of the knee-joint angle over the sagittal plane, with the user performing a barefoot normal walk (blue line), and while performing the same gesture, wearing tennis shoes featuring a special sole, with a modified support surface in the heel (red line). Stages of initial contact, loading response, pre-swing and swing [12] are observed:

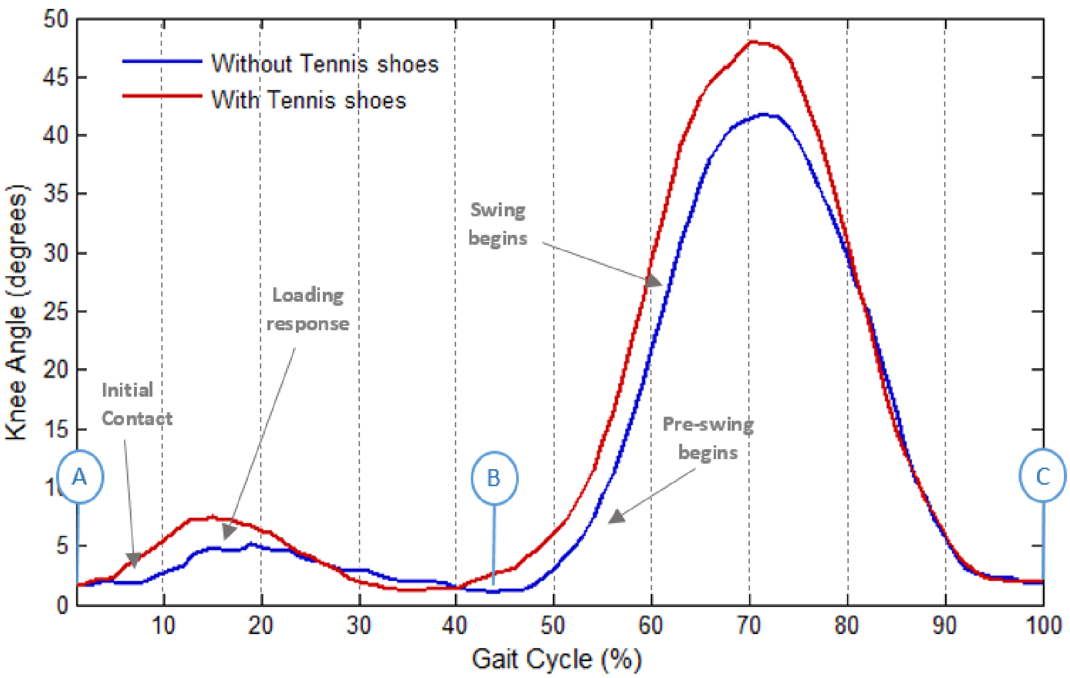

Figure 11. Gait cycle graph of knee joint movement in sagittal plane with (red) and without (blue) special tennis shoes

4. Conclusions

This work presented the development of a low-cost, acceptably precise ($|\varepsilon_\theta| < 1°$) and minimally invasive method for quantifying joint movements. The graphical interface that was developed for this work uses open-source libraries and its use is intuitive. The way in which the algorithm was designed allows extending the number of markers for different tests, thus allowing the potential simultaneous study of two or more joints. The inclusion of two cameras prevents marker overlapping in the recording. The current logic for finding and tracking the markers in each video frame requires a proper analysis to improve its efficiency. Potential improvements for this system include the optimization of algorithms as well as the introduction of new functions, allowing to quantify and compare joint angular movement, in real time, with other measurements of the same subject as well as with those considered as reference.

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