Proceedings of the 2010 3rd IEEE RAS & EMBS
International Conference on Biomedical Robotics and Biomechatronics,
The University of Tokyo, Tokyo, Japan, September 26-29, 2010

Development of Robotic System with Artificial Vision for the Evaluation of Rehabilitation in Underwater Gait Therapy

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***Abstract*—This paper describes the implementation of a robotic system using artificial vision as a computational tool developed for the evaluation of kinematic parameters during underwater gait therapy. This work is focused in the estimation of some angular kinematic variables during the gait process through video processing techniques. Two video acquisition protocols that differ in the limitations imposed to patients are proposed, these protocols lead to different processing methods.**

This study is entitled in a research project aimed at developing a tool that allows evaluating the underwater therapy benefits as part of the lower members' rehabilitation in patients that present human gait pathologies.

I. INTRODUCTION

Aquatic therapy has been used in the process of rehabilitation of people with gait diseases; however, there is a few of literature focused on the evaluation of the effectiveness that such therapies have in patients' recovery. To evaluate the ongoing rehabilitation process, it is possible to determine linear and angular kinematic variables as a part of a complete study in order to establish patient's evolution.

II. STATE OF THE ART

A. *Human gait process*

Human gait process has been defined by Cifuentes [1] like "a group of joint movements that allows body displacement over a solid surface".

For an accurate analysis of the process mechanics the kinematics and kinetic sciences must be studied. The kinematic science studies the "motion of objects without considering the causes leading to the motion". The kinetic science is the study of every human organ involved in movement. The kinematic study includes different variables that evaluate the gait process by describing velocity, direction, and joints' motion state or corporal segments involved [2]. The present study deals with the latter definition.

The lower corporal segments responsible for gait process are the thigh, shin and foot [3]. These are connected by the hips, knees and ankle that correspond to the joints between the pelvis with the thigh, and the thigh with the shin, and lastly the shin with the foot.

The process of human gait has different states classified in two unique phases: the support and the balance phase. During these stages, knee extension and knee flexion are performed.

B. *Angular Kinematic*

There exist two study areas useful to evaluate gait quality in a person; linear kinematic, which studies variables such as velocity, acceleration, corporal segments orientation, gravity centers, etc, and the angular kinematic study, which is focused in the relative orientation of segments or allows establishing relative position of segments with respect to the environment [4].

There are also three important angles when is necessary to know orientation of a segment with respect to another, they are called: "joint articulation". The first angle is measured from the pelvis to the thigh and it is called hips angle; the second is formed by the thigh and the shin and it corresponds to the knee angle, the third one is the ankle angle formed by the shin and the foot.

The presented study develops estimation of the second angle mentioned above; with the aim to identify the process of knee flexion and extension. Knee angle modification allows developing every event of gait process during support and balance phases. Estimation of this angle and its variation shows a notion of a patient's gait state, because in many patient's lesions there are problems with flexion and extension processes which modify the knee angle by not showing a complete performance.

C. *Gait rehabilitation therapy techniques*

Is known that physical therapies developed in underwater environments cause less impact and pain that therapies outside the water [5]. According to Pyhonen citing Tovin et. al (1994) it is proved that this kind of rehabilitation has been of great help for patients in post-surgical recovering of the anterior cross ligament.

Aquatic therapy facilitates patient's movement since it reduces gravitational forces because human body floats on water, plus the benefits of water temperature [6].

This work was partly supported by the financial aid from the Escuela Colombiana de Ingeniería University's invitation to research projects 2009-I and TELETON University Hospital.

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978-1-4244-7709-8/10/$26.00 ©2010 IEEE

Gait analysis gives important information for patients' treatment with pathologies and post-surgical situations. The techniques include visual analysis of patient's gait, measurement methods with goniometers, use of force platforms, accelerometers, and electromyography including camera systems analysis and video treatment techniques [7]. This last one helps the research project, because it gives information about the individual body segments motion, and it provides information about the environment in which the movement is produced. It also helps to determine the correct pose of the patient and the correlational motion from a segment with respect to the other [8].

In previous works, researchers have developed some video processing techniques in order to identify angular kinematic parameters. However, this works were mostly focused in gait rehabilitation that takes place out of the water [9].

III. MATERIALS

A. Mechanical Structure

The developed tool consists of a robot axis that allows horizontal and vertical movement of an underwater camera attached to it, the system tracks the person during their march into Aquatherapy tank, making the acquisition of the sequence of images subsequently is processed for the calculation of knee angle and its variation over time. The mechanical axis robotic system consists of an actuator (DC motor), a gear - chain system and a movable platform on the tank floor, that adjusts the final position of the underwater camera. Figure 1 shows the tank running underwater (a) and the axis robot (b) and in Figure 2 shows the block diagram of the robot control system.

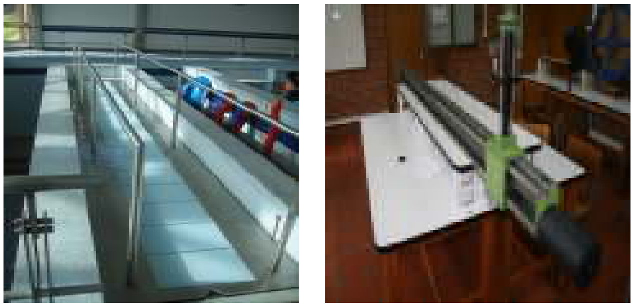


Fig. 1. (a) Motion underwater tank (b) axis robotic.

The pool has 6 meters of length and a width of 1.5 meters, there is a space of 15 cm wide between the pool's wall and lateral support bars, the camera is supported by a platform on the robot; to facilitate the construction of the robot, it has a length of 3 meters. Its location is between the pool's wall and lateral support bars, as shown in Figure 1. (a).

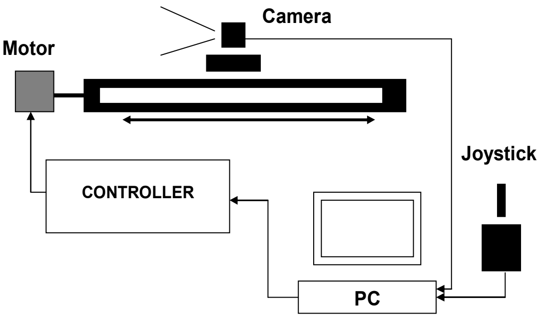


Fig. 2. The block diagram robot control system.

B. The propulsion and Control System

For the system that moves the video camera there are used two systems: the first with a chain and gear system that drags the chain on its links, the second prototype consisted of a synthetic thread band roller that allows a DC motor totally isolated by a special box and a mechanical seal to drag the platform that holds the camera, the two systems have been tested in the pool area of the hospital.

It should be noticed that the current control system is working in open loop, so it is impossible in this moment to have automatic patient's tracking.

Some of the best characteristics of systems are shown in the figure below.

Fig. 3. (a) Gear – chain system (b) Synthetic thread band roller.

The system is controlled electronically and their management is done by a joystick. A user interface allows the physician to monitor the progress of the patient and decide when to save the images. The electronic controller is based on a commercial microcontroller. The vision system is composed by a sub aquatic analogue camera branded Helmet Camera® that has a 2.6mm lens, with 120 degrees of optical wide angle, and 560 resolution lines in a NTSC format. This device submerges in an aqua-therapy tank, to acquire a video of the lower extremities movement of two volunteers. These are two individuals about 25 to 30 years old that do not suffer of any pathology in their extremities or during their gait process. The capture and the digitalization of the image sequence are done through a Pinnacle® video importer card, which transmits the information to a laptop through its USB port. The video in AVI format is stored initially in the laptop and then in an external hard disk backup.

IV. METHOD

The vision artificial method is composed by three stages. The first one consists in the video acquisition of sub aquatic gait. Next one is the processing of the sequence obtained. Thirdly is knee angle variations estimation.

A. Gait video adquisition

Two different protocols of video acquisition are defined. In the first one, the person has a dark submergible suit with three passive markers along the central axis of his legs, one of them is located at the knee position. This method has been used before to analyze the kinematic in human gait, because of its ease of use and lower costs of implementation among other advantages [10]. The second protocol eliminates the use of specific clothing for the patient, with the aim to promote an alternative path in the evaluation tool that is more comfortable for the patient, as well as compliant with the hygiene standards in the tank. Examples of images obtained by the two protocols described above are shown below (fig.4).

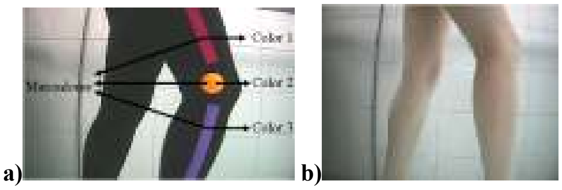


Fig.4.a) Image obtained by the first acquisition protocol. b) Image obtained by the second acquisition protocol.

B. Video processing and angle estimation

Processing algorithm for the first acquisition protocol: This algorithm is based on an automatic method for the calculation of the variation in the knee angle of human gait. Initially, there is a stage of video processing. Then there is a segmentation of the passive markers that are located in the central axis of the studied leg, followed by mathematic morphology processing. The final stage estimates the markers' centroids location and knee angle's value.

Image Sequence processing. The video (S) is composed with frames or color images (Ik) temporarily spaced for a delta of time (1/30s):

$$S = \{I_0, I_1, \ldots, I_{k-1}, I_k\} \tag{1}$$

The image (I_k) of the sequence is defined as a bi-dimensional figure in the following form:

$$I_k = f_k(x, y) = f_k(\mathbf{u}) = \langle R_x, G_x, B_x \rangle \tag{2}$$

Where u is the position vector of each pixel in the image Ik and fk(u) its value in each one of the three components that makes part of the color model RGB (Red- Green-Blue). The processes that form part of the algorithm are applied individually in each one of the images Ik of the video.

The proposed method develops a pixel transformation of each image I_k from RGB model to HSL model (Hue-Saturation-Luminance) [14], in order to prepare the image for the next stage of the processing algorithm.

Passive makers' segmentation in the image. For each matrix that belongs to the HSL color model in the image Ik, a multilevel thresholding is applied [10] in the following form:

$$b_{plano}(\overset{\circledR}{u}) = \begin{Bmatrix} 255 \;\; si \; z_1 \leq f_k(\overset{\circledR}{u}) \leq z_2 \\ 0 \;\; si \; de \; otra \; manera \end{Bmatrix} \tag{3}$$

Where the group of transformed pixels bplano(u), in the position determined by vector u, forms a thresholded image in the matrix H, S and L , and the combination of the three results generates a binary image Bk that contains the segmentation of a particular color. This type of procedure has been called by Gonzalez in [10] like multispectral thresholding, and differs from the simple thresholding by the use of a range of color values that can change with the illumination. The mentioned process is repeated three times because the passive markers have different colors. Transformation thresholds in each matrix z1 and z2 are experimentally selected.

Processing based on mathematic morphology. Each input image Bk at this stage of the algorithm has the noise and less defined forms typical of the segmented markers, for this reason some morphologic processing techniques in digital images are applied. Initially there is a process of erosion or shrinking of white areas in each binary image Bk, then a region filling is applied, and finally a hull convex operator is used, which leads to markers convexities definition. Every morphologic operation is defined with a mask of size 3x3 [11],[12]. The resulting image from the application of this stage Bmk can be observed in fig.5:

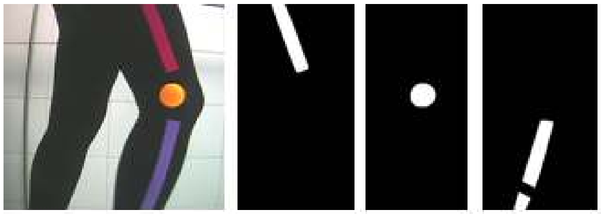


Fig.5. Thresholded image processing through morphologic techniques.

The following step consists in the determination of reference points in the segmented markers using centroids extraction. Theory of mass moments in each Bmk image is defined by the discrete equation:

$$m_{ij} = \sum_{x \in v_1} \sum_{y \in v_1} x^i y^j f(\vec{u}) \qquad (4)$$

Where i and j corresponds to the moment order, x and y are components of the pixel position vector in the region determined by vi (in this specific case corresponds to the whole image Bmk) and f(u) is the pixel value.

$$x_{c_i} = \frac{m_{10}}{m_{00}} \qquad y_{c_i} = \frac{m_{01}}{m_{00}} \qquad (5)$$

The moments of zero and first order are useful to find the centroid coordinate points: Three points are generated, each one with coordinates (xci , yci) that corresponds to centroids of each marker [13]. The resulting centroids can be observed in fig.6.

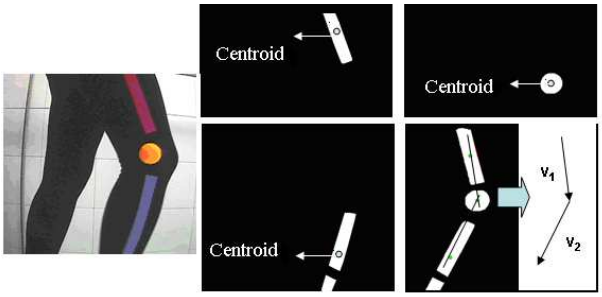


Fig.6 Binary image of the patient's markers with its corresponding centroids.

Relying on the previous coordinates of the extracted centroids, the axis vector v1 that goes from the thigh to the knee, and v2 that goes from the centroid itself in the knee to the shin are calculated (fig.6). With geometric calculations the angle formed by v1 and v2 is determined [14]. This way the angle formed by the knee, the thigh, and the shin of the patient during the gait is calculated.

The selection of the rectangular shape of the markers of the thigh and shin is done with the purpose of eliminating possible mistakes during the calculation of the centroids when using a not efficient segmentation of the markers. In fig3. It is possible to observe a non-continuous segmentation from the marker in the shin, although a centroid extraction that stays co-aliened to the central axis of the marker is visualized.

Processing algorithm for the second acquisition protocol:

This algorithm is based on an semi-automatic method for the calculation of the variation in the knee angle in human gait. It consists of the initial selection of four pixels or seeds that are located inside the leg of the patient image, where two points are located along his thigh and the other two in his shin.

Such as in the first protocol, there is an initial stage of gait video processing, followed by patient's legs segmentation, in which is added a processing based on mathematic morphology and logic operations between images to develop an extraction of the analyzed leg's central axis. To conclude, Hough transformation is applied for the vector calculus and knee angle estimation.

Image sequence processing. As in the first acquisition protocol, this procedure works with each image Ik that makes part of the sequence acquired during the gait S. The difference is that two techniques are used in each frame Ik. In the first one there is a pixel transformation that takes part on Ik in RGB to YCbCr color model (Luminance-Blue Chrominance-Red Chrominance) [10]. In the second technique, the pixels from Ik are transformed from RGB to HSL color model.

From the first approximation Blue chrominance image (Cak) is taken, and in the second one, the grayscale image from the Luminance matrix (Lk) is taken.

Cak image is treated to reduce noise through and arithmetic mean filter, giving origin to filtered image Cakf, in which patient's legs in a grayscale tone different from the background are observed (fig.7.a).

For the same purpose a median filter in Lk is used. A compound Laplacian mask is applied to the previous result in order to increase image contrasts, and a sobel operator is used, giving as a result an image Lks with contours of the patient's legs (fig.7.b) [11].

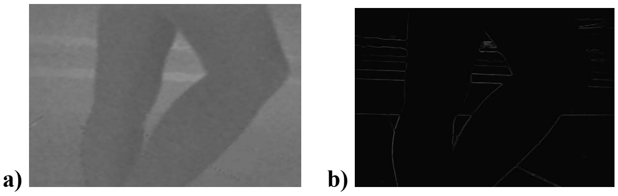

a) b)

Fig.7.a) Image resulting from Cak processing. b) Image resulting from

Passives markers' segmentation in each image. With the purpose to obtain a binary image with the first technique, a global threshold [15] to patient's legs extracted from the Ca_{kf} image in the following form is applied:

$$b_{ca}(\vec{u}) = \begin{cases} 255 \text{ si } \mathrm{Ca}_{kf} \geq z_3 \\ 0 \ \textit{si de otra manera} \end{cases} \qquad (6)$$

Obtaining the bca(u) image in the position located by the vector u. The threshold z3 is automatically calculated with the grayscale levels average of the pixels or seeds which were previously chosen.

In the same form, the similar type of thresholding in the second technique, to obtain the binary image blks(u) based on Lks is used. The threshold z3 is estimated according to the maximum grayscale level detected in image Lks.

Processing based in mathematic morphology and logic operations. The thresholded images b_{ca} and b_{lks} contain information that does not correspond to patient's legs and its contours. Algorithms that combine open and close operators (combinations between erosions and dilations) with masks of size 3x3 are used to define the objects of interest [10][11]. The resulting images from the described processing (fig.8.a) are operated through an AND, giving origin to an image without noise and with complete leg's contours segmentation denominated r_k. The described processing below is shown (fig.8.b):

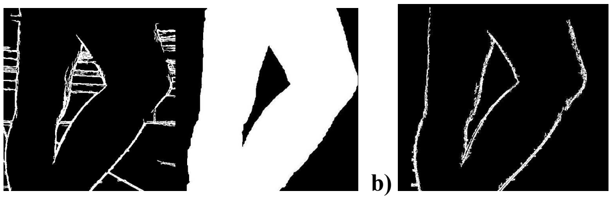


Fig. 8. a) Result from the binary images bca and blks processing. b) Image rk.

Central axis extraction. The algorithm is based on calculating a central axis in the thigh, and another in the person's shin. Based on the position of previously selected pixels or seeds, the image rk is skimmed by starting from top to bottom, and medium points between the contours that define the leg are determined. This generates a group of points that require a linear approximation for establishing the central axis of the thigh and the shin. For this purpose the Hough transformation [14] that also estimates the knee angle is used.

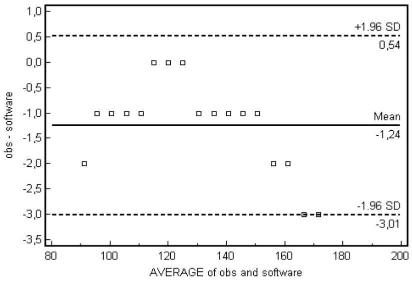
V. RESULTS

The measures obtained from the angles formed by: the leg, knee and thigh are defined with one degree of precision. This specification is based in the therapist's needs of Teletón Hydrotherapy Centre, in order to improve the actual measuring system, which is based almost totally in a visual criterion with limited precision of five degrees.

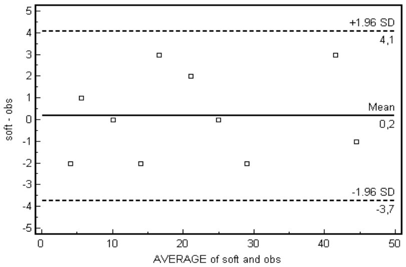
A. *Method validation*

For the vision system validation, a comparison was made between determined angles by an external observer using a goniometer as a measure instrument (method one), and the estimations calculated through the algorithms based on the first and second acquisition protocols (method two). Bland - Altman method [16] is used to determine the concordance between measurement method one and method two.

By observing Bland Altman graphics (fig. 9), the mean difference between the measurements of method one and method two is cero or close to cero. In addition, all the values of the differences are located in the limits of the 95 % confidence interval, indicating concordance between the two measurement methods.



a)



b)

Fig.9. a)) Bland - Altman graphic for the comparison between the method one and the measurement method based on the first acquisition protocol. b) Bland- Altman graphic for the comparison between the method one and the measurement method based on the second acquisition protocol.

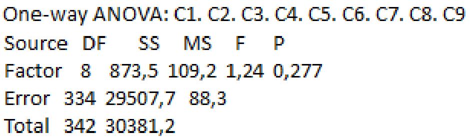
B. *Results analysis*

To determine the reliability in the first protocol of acquisition algorithm, an ANOVA analysis was performed [17] to estimate the mean variations of knee angles obtained in the same test by different steps.

A step classification was made a inside each video, finding in this way the data of the corresponding angles in each individual step. Then a list of data containing the maximum flexion angles and maximum extension angles during the balance phase was chosen. An unilateral ANOVA test (fig.10) was developed. Four different videos were used to develop four different tests.

Using ANOVA charts as a tool, it was possible to conclude that in two videos the null hypothesis was accepted, because the testing statistic (f=1,24) was lower that the critic statistic. This result was calculated based on a 95% confidence interval.

On the other hand, it becomes necessary to make several tests to validate the second acquisition protocol method in order to obtain confident results.



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One-way ANOVA: C1. C2. C3. C4. C5. C6. C7. C8. C9
Source  DF     SS      MS    F     P
Factor   8   873,5  109,2  1,24  0,277
Error  334 29507,7   88,3
Total  342 30381,2
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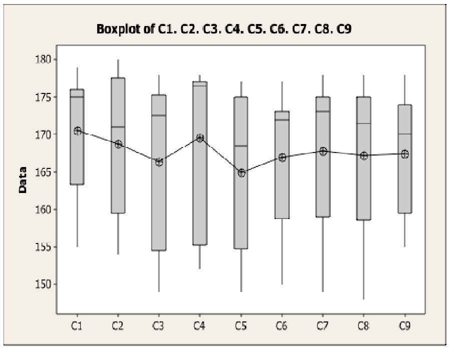

Fig.10. ANOVA chart and boxes diagram that presents the statistics from one of the acquired videos.

VI. CONCLUSION

Results have been obtained following the premises of the Teletón University Hospital, with the aim of testing the system in the environment for which it was designed. Therefore, the tool has the endorsement of the group of specialists to be the end users of the system.

Currently the robotic control system is working as open loop control system; however, a closed loop control for automatic patient tracking will be implemented in the future.

The presented method can be applied only in kinematic angular analysis for the knee joint, however it is also part of the study of kinematics of the lower member angular variables, as a support for the human gait analysis and the evaluation of the sub aquatic therapy benefits in rehab processes.

The ANOVA analysis of flexion and extension data, obtained from the first acquisition protocol algorithm, has few concluding results in relation with the angles' means similarity in different steps. A possible factor that leads to reject the nule hypothesis could be the lack of therapist or physician supervision, who should guide patient's movements in the gait process. Then it is required additional data acquisition in guided human gait.

The positive results of method validation helps to improve the actual measurement methods of this kind of variables used by physicians or therapists, raising data precision and decreasing subjective measures. The results also show that the developed system has easy replication and implementation, plus it can be adapted to environmental conditions in the gait tank where the tests take place. In addition, the information extraction process is simple and does not affect the gait because the vision system has no contact with the patient.

In a future stage of the project, this tool should be used to evaluate benefits of aquatic therapy in the rehabilitation process, testing it in a significant sample of patients with gait problems. Nowadays the developed tool has just been applied to healthy persons.

In addition, the robotic system will need to attach a new underwater camera in order to improve and increase the view angle in the video acquisition process. Nevertheless, the structure of the system was designed having in mind these future needs.

ACKNOWLEDGMENT

The authors acknowledge the contribution of the medical team, Dr. Catalina Gomez from TELETON and the student Daniel Borda from Escuela Colombiana de Ingeniería and other engineers who work in robotic and image processing areas.

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