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A low-cost video-based tool for clinical gait analysis

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Abstract— **In physical and rehabilitation medicine physicians need to perform clinical gait analysis to assess patients walking ability. Despite the relevant research on motion tracking, gait analysis technologies are far to be commonly diffused in clinical practice since they are quite expensive, need high-structured laboratories and trained personnel who are not always available. In order to overcome such limitations, this work proposes a low-cost, video-based portable tool for clinical gait analysis which provides the bi-dimensional kinematic analysis of walking. The system processes a video stream by means of tracking different markers placed in five anatomical landmarks of the subject's leg, applying Kalman filter in conjunction with a method that copes with occlusions. The system has been validated on a healthy subject, showing that it is able to reconstruct marker position and leg kinematics even if several occlusions occur.**

I. INTRODUCTION

Clinical gait analysis could play a key role in physical and rehabilitation medicine (PRM) [1], since physicians need to perform a complete assessment on their patients in order to analyze all the factors liable to interfere with their ability to walk and to propose the best solutions for maintaining or improving their walking performance [2]-[3].

According to Brand [4] and Baker [3], there are four principal reasons to perform clinical gait analysis:

1) to diagnose between disease entities;
2) to assess the severity, extent or nature of a disease or injury;
3) to monitor progress in the presence or absence of intervention;
4) to predict the outcome of intervention (or the absence of intervention).

Usually, physicians in PRM evaluate gait performance of patients using qualitative observational methods [2] or semi-quantitative clinical scales, such as the Timed Up-and-Go test (TUG) [5], the Functional Ambulation Categories (FAC) [6], the Berg Balance Scale (BBS) [7] and the Postural Assessment Scale for Stroke Patients (PASS) [8].

In the last 30 years, techniques for motion tracking provided useful tools to objectively assess and evaluate walking characteristics [3]. In particular, stereophotogrammetric technology has reached a mature state of development delivering all features required by conventional gait analysis [9]-[10]. Several studies deeply described the patterns of normal walking [11]-[13], enabling the definition of walking strategies abnormalities in different kind of patients [14]-[16].

Even if the usefulness of gait analysis for clinical rehabilitation has been widely accepted, the use of such technologies in clinical practice is far to be commonly diffused. In fact, despite to high accuracy, repeatability and reliability of actual technologies for motion analysis, such systems suffer of some practical problems which limit their diffusion in clinical centers. Firstly, they are quite expensive, so to not assure a good cost/benefit tradeoff. Secondly, they need high-structured, dedicated laboratories and personnel which are often difficult to find in clinical centers. Finally, they provide a large amount of data, which require complex pre and post processing and are not straightforward to be interpreted by clinicians.

In order to overcome such limitations, this work proposes a low-cost, video-based portable tool for gait analysis which is simple to use, require few minutes for the setup and acquisition of clinical data, and provide few simple indices which are of interest for physicians. The developed system use a single conventional camera to record subjects' movements and provide a bi-dimensional kinematic analysis in the sagittal plane of the hip, knee and ankle joints during walking. In the literature, a similar system is presented in [17], where the authors addressed the problem of tracking feature points along images sequences to analyze undergoing human movement. With respect to [17], our system is able to provide also the bi-dimensional kinematic analysis of walking.

A dedicated software, implementing a Kalman filter, elaborate the recorded videos and reconstruct marker position in the image plane. A kinematic toolbox use the position of the markers, placed in five specific anatomical landmarks of the subject, to calculate the time course of the hip, knee and ankle angles in the sagittal plane during a gait cycle and provide some quantitative indices of clinical interest.

II. METHODS

The system automatically tracks human movements without requiring a gait analysis laboratory in order to used even by non-experts operators, providing quickly and easily interpretable results. The set up consists of a workstation connected with a camera, a dark background, a dark tracksuit with gloves to be worn by patients, a reference marker used for system calibration, and as many colour markers as required to perform kinematics analysis (left panel of figure 2). Since we are interested in performing a bi-dimensinal

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gait analysis in the sagittal plane, we have used ten passive markers (five per leg), six red and four yellow. Indeed, they have been set on the following five anatomical landmarks for each leg: (i) anterior superior iliac spine (red marker), (ii) femur greater trochanter (yellow marker), (iii) lateral epicondyle of the femur (red marker), (iv) heel (yellow marker), (v) fifth metatarsal bone (red marker). The camera has been mounted on a tripod one meter high, at a distance of 4 meters, approximately. The patients' gaits have been recorded for several cycles.

Next subsection presents the processing techniques that we applied to perform a bi-dimensional kinematic gait analysis on the sagittal plane.

A. Processing

To extract kinematic information on patients' gait we first need to detect the markers and then to establish correspondence between markers instances across frames. The former task is performed by means of an object detection algorithm, whereas in the latter one the tracker corresponds objects across frames.

a) Marker Detection: Identification of image objects is commonly known as segmentation, which partitions the image into perceptually similar regions. As marker detection features we exploit colour information, analyzing the *L*a*b** space. Indeed, although RGB space is usually used to represent color, it is not perceptually uniform, that is, the differences between the colors in the RGB space do not correspond to the color differences perceived by humans [18]. Furthermore, the RGB dimensions are highly correlated. In contrast, $L^*a^*b^*$ space is perceptually uniform. It consists of a luminosity L^* or brightness layer, chromaticity layer a^* indicating where color falls along the red-green axis, and chromaticity layer b^* indicating where the color falls along the blue-yellow axis.

At the beginning of marker detection phase, the user selects in one frame a point for each marker. Then, using region growing algorithm, we average out the color information of each marker in the a^*b^* space. This step permits us to calibrate the system, dealing with variation in room environment (e.g. ambient lighting condition), associating also to each marker a reference value in this space.

Next, in each frame, the color of pixels is detected according to the Nearest Neighbour rule by means of computing the Euclidean distance in the a^*b^* space between the pixel and each color marker. Through two experimental thresholds, one for each color, we can distinguish between different image colors as well as between markers and background. Notice that at each frame reference color values in the a^*b^* space are updated on the basis of values in the previous frames.

b) Marker Tracking: Tracking algorithm aims at establishing correspondence between the objects instances across frames.

We track the red markers separately from the yellow ones to reduce the ambiguity between the closest marker, i.e., the couple of markers positioned on the anterior superior iliac spine and on the femur greater trochanter, as well as those located on the heel and on the fifth metatarsal bone.

Since measurements obtained from video contain noise, object motion can suffer from random perturbation. In these cases, statistical correspondence methods are best suited to solve the tracking problem [18]. Among them, we have applied the Kalman Filter (KF), which is an optimal recursive stochastic method providing optimal estimates minimising the mean of squared errors. It uses the state space approach to model the object properties, where the system state consists of markers position and velocity in the frame. KF takes into account the measurements as well as model uncertainties during object state estimation [19]. Indeed, new measurements, consisting of marker positions obtained by the detection mechanism presented in the previous paragraph, are incorporated when a new frame is processed.

The discrete equations of the state model are:

$$\begin{cases} x[k+1] = A_d\, x[k] + N_d[k] \\ y[k] = C\, x[k] + \sigma_o\, N_o[k] \end{cases} \tag{1}$$

where x is the state vector, A_d is the matrix relating the system state $x[k]$ at the discrete time k to the state $x[k+1]$ at the successive step $k+1$, $N_d[k]$ is a sequence modelling the process noise, $y[k]$ is the measurement vector, C is the matrix relating the sistem state $x[k]$ to the measurements $y[k]$, σ_o is the standard deviation of the measurement noise $N_o[k]$.

The equations for the Kalman filter fall into two groups: time update (or prediction) equations and measurement update (or correction) equations. The former project forward (in time) the current state and error covariance estimates to obtain the *a priori* estimates for the next time step. The latter incorporate a new measurement into the *a priori* estimate to obtain an improved *a posteriori* estimate.

The prediction equations are:

$$\hat{x}[k+1 \mid k] = A_d\, \hat{x}[k] \tag{2}$$

$$P[k+1 \mid k] = A_d\, P[k]\, A_d^T + \psi_s \tag{3}$$

where $\hat{x}[k+1 \mid k]$ represents the prediction of the estimate state at the step $k+1$ when the measurement data at step k have been incorporated, $\hat{x}[k]$ is the estimate of the state at the time step k, $P[k+1 \mid k]$ is the covariance matrix of the prediction's error, $P[k]$ is the covariance matrix of the estimate's error, ψ_s is the covarince matrix of the process noise $N_d[k]$

The correction equations updating the predicted estimates upon the incorporation of new $y[k+1]$ measurements are given by:

$$K[k+1] = P[k+1 \mid k]\, C^T\, (C\, P[k+1 \mid k]\, C^T + \sigma_o^2\, I)^{-1} \tag{4}$$

$$\hat{x}[k+1] = A_d\, \hat{x}[k] + K[k+1]\, (y[k+1] - C\, A_d\, \hat{x}[k]) \tag{5}$$

$$P[k+1] = (I - K[k+1]\, C)\, P[k+1 \mid k] \tag{6}$$

where σ_o^2 is the measurement noise variance, K is the *gain* minimising the *a posteriori* error covariance equation $P[k+1]$, and I is the identity matrix.

According to previous equations, new marker position measurements are used to correct the position estimated by the filter. Hence, given the set of measurements and the set of estimates we need a correspondence criterion between them to introduce the new measurement data in the correction equations. To this end, the straightforward method consists of using the Nearest Neighbour approach based on Euclidean metric. However, if the markers are close to each others, the correspondence may be incorrect, failing the filter convergence. Further to set-up configurations that reduces correspondence ambiguity, e.g. markers of different colors on near anatomical landmarks, we applied the *Mahalanobis* distance as correspondence metric between measurements and estimates. It is given by:

$$D = \sqrt{(y - \hat{x})^T S^{-1} (y - \hat{x})} \tag{7}$$

where y is a measurement, $\hat{x}$ is the marker prediction and S is the covariance matrix. With reference to previous notation, D can be computed as:

$$\begin{aligned} D = ((y_i[k+1] - C_m\, \hat{x}[k+1 \mid k])^T \cdot \\ \cdot (C_m\, P[k+1 \mid k]\, C_m^T + \sigma_o^2\, I)^{-1} \cdot \\ \cdot (y_i[k+1] - C_m))^{\frac{1}{2}} \end{aligned} \tag{8}$$

where C_m is a suitable matrix that permits to select one of markers from the vector of the predictions $\hat{x}[k+1 \mid k]$, which contains both the position and the velocity of the markers. The quantity $C_m\, P[k+1 \mid k]\, C_m^T$ respresents the covariance of the prediction's error of the m-th marker, whereas $\sigma_o^2\, I$ is the covariance of the measurement error.

Finally, the prediction $\hat{x}[k+1 \mid k]$ is associated to the marker minimising the distance with the measurement $y_i[k+1]$.

The last issue that should be addressed to solve our tracking problem deals with occlusion. Indeed, when a predicted position does not get any correspondence in the measurements set, it is assumed that the marker has been occluded. In this case, typical approach consists in including the predicted position in the measurement vector. However such a solution introduces an high uncertainty since the predicted value has not been corrected by any measurements. To tackle this point, we replace the missing marker measurement with the linear interpolation between the last available estimate and the next available marker.Consider a stream where an occlusion occurs at time k and continues for n frames, so that the last available estimate is at time $k-1$, whereas the first available measurement occurs at time $k+n$. According to linear interpolation, the position of the of occluded marker at time k is given by

$$x[k] = x_{[k-1]} + \frac{x_{k+n} - x_{k-1}}{n+1} \tag{9}$$

B. Kinematic analysis

The bi-dimensional kinematic analysis is performed calculating the values of hip, knee and ankle joint angles in the sagittal plane during the gait cycle. On this plane, the subjects leg is modeled as an open kinematic chain, composed by three joints and four links, as shown in fig. 1 (left).

The links are represented as rigid bodies which connect two subsequent markers and, with reference to markers positions reported in section II, are defined as follows:

- the first link connects markers (i) and (ii);
- the second one connects markers (ii) and (iii);
- the third link connects markers (iii) and (iv);
- the last one connects markers (iv) and (v);

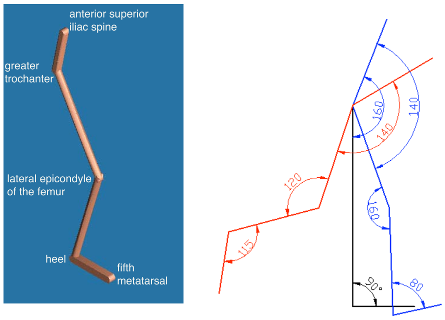

Fig. 1. A schematic representation of the open kinematic chain which models the subject's leg (left) and the definition of joint angles (right).

The joint angles are calculated as the angles described by two following links. In particular:

- hip angle is defined as the angle between link 1 and link 2;
- knee angle is defined as the angle between link 2 and link 3;
- ankle angle is defined as the angle between link 3 and link 4;

A schematic representation of links and angles, as defined in this paper, is reported in fig. 1 (right).

III. RESULTS

The device presented in this paper has been validated with a healthy subject. Since the system has been designed to be used with both neurological and orthopedic patients, the subject has been asked to walk on two standard crutches (see fig. 2). In fact the crutches, which are commonly used by patients during the clinical analysis of the gait, can often cause occlusions of the markers during the trials. The presented experiment has been performed to simulate the normal operative conditions in which the device will be used, and to test the capability of the system in reconstructing the positions of the markers even when several occlusions occur during a typical evaluation session.

Figure 2 shows the results of the application of KF in conjunction with the methods handling occlusions. Left panel shows the measured marker positions during the stream, whereas the right panel shows the trajectories computed applying the KF with linear interpolation.

Using the positions of the markers estimated by the KF, a kinematic analysis of gait cycle in the sagittal plane can be performed. Figure 3 shows the stick diagram of the subject's leg during a single gait cycle. In fig. 4 the time course of the hip, knee and ankle joint angles calculated for the same gait cycle are reported. In fig. 4 the time is normalized with respect to the step period (from the beginning of a stance phase to the end of the swing phase).

IV. CONCLUSIONS

This paper presented a low-cost, portable tool for bi-dimensional gait analysis, which is purposively conceived to be used in clinical practice. In fact, the system has been designed to be simple to use and easy to setup; it requires few

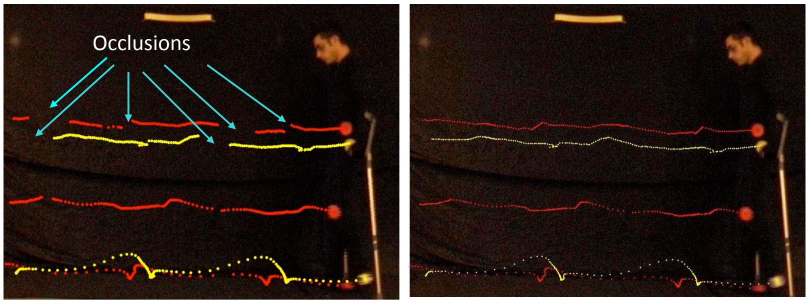

Fig. 2. Example of markers tracking.

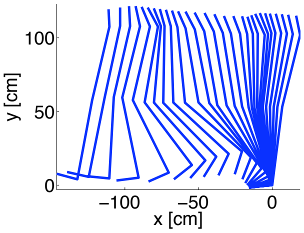

Fig. 3. Stick diagram of the subject's leg during a single gait cycle.

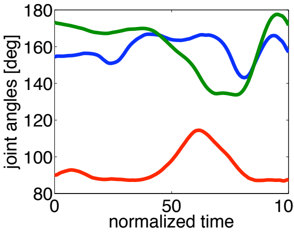

Fig. 4. Hip (blue), knee (green) and ankle (red) joint angles during a single gait cycle. The time is normalized with respect to the step period.

minutes for acquisition of clinical data and provides some kinematic indices of clinical interest. The developed software first executes an automatic tracking of the markers (that are applied on five anatomical landmarks of the subject's leg) using Kalman filter in conjunction with Mahalanobis distance for estimates correction and interpolation to cope with occlusions. Then it calculates the values of hip, knee and ankle joint angles in the sagittal plane during the gait cycle. The proposed device has been tested on one healthy subject walking on two standard crutches. Preliminary results showed that the system is able to reconstruct marker position and leg kinematics even if several occlusions occur.

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