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2D video-based human gait analysis: a novel markerless approach

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***Abstract* – A 2-D markerless technique for the analysis of the lower limbs kinematics during gait is presented and preliminarily validated. Data were recorded using a single video camera placed laterally to the walkway. The preliminary validation was performed using a optoelectronic marker based system as gold standard. The lower limb facing the camera was modelled with four body segments: foot, shank, thigh and pelvis. Ankle socks and underwear garments were used as segmental markers to track the foot and the pelvis, respectively. The shank and thigh were tracked using multiple reference points defined in a calibration reference image. The comparison between the estimated segment angular kinematics and that obtained with the gold standard revealed a high correlation index and limited Root Mean Square Deviation (RMSD) values. The proposed technique can be considered as an easy-to-configure and affordable alternative to marker-based systems, for 2D human lower limb motion tracking during gait.**

I. INTRODUCTION

Quantitative human gait analysis is often used in clinical environments. Passive marker optoelectronic systems are widely used to this purpose. Although accurate and reliable, they are expensive and require space and technical expertise, therefore their use is limited to few facilities [1]. To increase the use of quantitative gait analysis in clinics, including ambulatory environments, low cost, video-based markerless (ML) techniques have been seen as a potential valuable alternative [2]. Moreover, as an additional advantage, the use of a ML technique is expected not to affect the function being measured, since it does not require any fixture applied to the skin of the patients [3]. Finally, ML solutions requiring a single color camera could be applied when a 2D sagittal joint kinematics analysis is sufficient, with a consequent reduction of the setup time, complexity and cost. In a previous study, we proposed a 2-D ML technique for the estimation of ankle kinematics [4]. In this study, we present a model-based ML method for the analysis of gait with a single color camera positioned laterally to the walkway. The ML method estimates the sagittal angular kinematics of the pelvis, thigh, shank and foot of the limb facing the camera, solving the lower limbs superimposition occurring during both the swing and stance phases of gait. A preliminary validation of the technique is carried out, by comparing the segmental angular kinematics estimated with the ML method to that obtained with simultaneous measurements provided by a stereo-photogrammetric system (gold standard).

II. MATERIAL AND METHODS

A. Experimental protocol

Nine healthy subjects (8 males and 1 female, age 33 ± 6 y.o.) wearing white ankle socks and white underwear garments, were asked to walk along a walkway. Subjects walked at three self selected speeds (comfortable, slow and fast), to verify if gait changes related to velocity would affect the ability of the method to cope with lower limb superimposition. Five trials per selected speed were captured. A RGB video camera (Vicon Bonita Video, 1280x720p, 50fps) was placed laterally to the walkway. Lens distortion was corrected using the Heikkilä undistortion algorithm [5]. A homogenous blue background was positioned on the opposite side of the walkway. A static reference image was captured at the beginning of the data acquisition session. Video files were processed using MATLAB (2010b, The MathWorks, Natick, MA). For validation purposes, marker-based data, synchronous with the video data, was captured using a 6-camera stereo-photogrammetric system (Vicon T20). The retro-reflective markers were placed as follows: two markers on the lateral surface of the underwear garment, one marker on the Greater Trochanter (GT), one on the femoral Lateral Epicondyle (LE), one on the Lateral Malleolus (LM) and two were placed on the lateral surface of the sock (Fig. 1a). The marker set used allowed to define the same segment reference systems for both the ML and marker-based techniques.

B. Model Calibration

Rigid templates of the lower limb body segments were defined from the static reference image. The operator identified LM, LE and GT by means of a mouse click on

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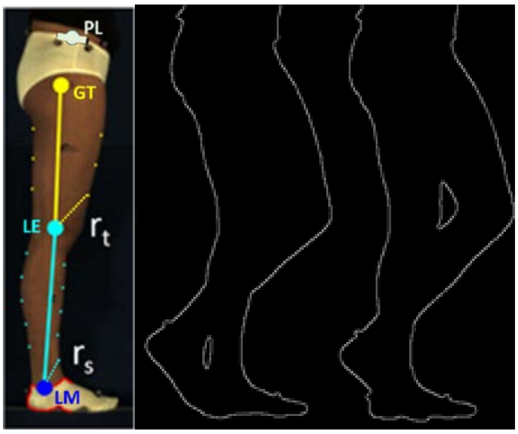
the reference image. After extracting the foot (identified with the sock) using a white color filter, the foot reference system was defined with the positive X axis coincident with the line fitting the lower-posterior part of the sock contour and oriented towards the toes. The shank and thigh local reference systems were defined having the X-axes joining LM with LE (origin on LM), and LE with GT (origin on LE), respectively. The subject silhouette contour was extracted using a blue color filter. The foot model template was defined as the posterior portion of the ankle sock contour, and LM was rigidly associated with it (Fig. 1a). Rigid model templates for the shank and thigh were defined based on ten and six model reference points respectively ($\mathbf{x}_k^0, k = 1,..,10(6)$), identified on the silhouette as the intersection points between the silhouette contour and circles of radius r_k, centred in the relevant origins (Fig. 1a). LM and LE were calibrated with respect to the shank model template, while LE and GT were calibrated with respect to the thigh model template.

The pelvis X-axis was identified as the segment (40 pixels) fitting the upper contour of the underwear garment, isolated using a white color filter, and centred in its most lateral point (PL). The pelvis model calibration was performed using a double calibration approach, in order to compensate for errors caused by the parallax effect and the motion of the pelvis on the transverse plane during gait. The double calibration approach consisted in visually identifying PL at the first and last frame of the gait cycle: for both instants of time, the distance between PL and the most posterior point (MP) of the pelvis upper contour was calculated along the horizontal direction. The difference between such distances was assumed to linearly vary throughout the gait cycle.

C. Data processing

A single gait cycle was extracted from each walking trial. The moving subject in the scene was separated from the background using a segmentation procedure based on foreground subtraction [6], and the Canny's edge operator [7] was applied in order to extract the silhouette contour (Fig. 1b). The foot segment was tracked using a matching procedure between the current image of the foot, extracted using a white color filter, and the foot template, by means of an iterative contour subtraction technique: the foot template was rotated and translated within a bounding box containing the foot segment contour of the current image frame, until the foot template contour and the current frame foot contour exhibited the maximum superimposition.

Due to soft tissues deformation and, to a greater extent to leg superimposition, the silhouette contour of both shank and thigh greatly changes during the gait cycle (Fig.1b).



a *b*

Fig. 1. (a) processed reference image. Yellow points: thigh reference points; yellow line: thigh segment; cyan points: shank reference points; cyan line: shank segment, grey line: pelvis segment. (b) contour extraction result and legs superimposition effect.

To take into account the silhouette deformations and to track the shank and the thigh, it is first necessary to identify the corresponding reference points on the contours of the deformed shank and thigh segments ($\mathbf{y}_k$). To accomplish this result, the shank (thigh) model template was first registered to the current frame by using LM (LE) and a prediction of the position of LE (GT), based on its velocity in the previous three frames. A bounding box of 10 × 10 (14 × 14) pixels was centred around each reference point of the template configuration based on the prediction; the reference point $\mathbf{y}_k$ was detected as the intersection – where available – between the portion of the silhouette within the bounding box and the circle of radius r_k used to define the corresponding template reference point in the static reference image (Fig.2). The above-mentioned procedure was repeated for each image frame. A fitting between the points $\mathbf{x}_k^0$ of the model template and the corresponding points $\mathbf{y}_k$ was performed using a SVD procedure [8], after excluding from the template those points that were not identified due to leg superimposition. The pelvis orientation was determined from the position of MP, using the information relative to the distance between MP and PL as determined during the pelvis calibration procedure.

To determine the segmental angular kinematics, the angle of the pelvis and foot X-axes with respect to the horizontal direction, and the angle of the shank and thigh X-axes with respect to the vertical direction were calculated for each video frame of the gait cycle. For each gait speed, results were averaged across all subjects and trials. The segment angular kinematics provided by the ML technique were compared with the gold standard angular kinematics in terms of: correlation coefficient (CC), root mean square deviation (RMSD), and RMSD normalized to the range of motion (%RMSD).

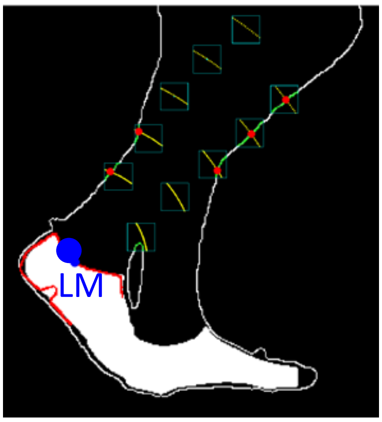


Fig. 2. Reference points $\mathbf{y}_k$ identified on the shank deformed contour. Yellow curves: arcs of circumference of radius r_k; red circles: points $\mathbf{y}_k$.

III. RESULTS

The estimated angular kinematics of the pelvis, thigh, shank and foot, expressed as functions of the percentage of the gait cycle are reported, along with the gold standard, in figures 3-6. Results relative to the evaluation of the estimated angular kinematics variables are reported in Tables I-IV.

Table I. Pelvis.

Gait Speed	CC	RMSD [°]	%RMSD
normal	0.75	1.96	25%
fast	0.81	2.05	17%
slow	0.70	2.00	23%

Table II. Thigh.

Gait Speed	CC	RMSD [°]	%RMSD
normal	0.99	2.30	6%
fast	0.98	3.21	7%
slow	0.99	1.84	5%

Table III. Shank.

Gait Speed	CC	RMSD [°]	%RMSD
normal	0.99	2.44	3%
fast	0.99	2.74	3%
slow	0.99	2.18	3%

Table IV. Foot.

Gait Speed	CC	RMSD [°]	%RMSD
normal	0.99	3.53	4%
fast	0.98	4.62	5%
slow	0.99	3.48	5%

IV. DISCUSSION AND CONCLUSION

In this study, a novel, single camera ML technique is presented. The technique allows for the estimation of 2-D segmental angular kinematics of pelvis, thigh, shank and foot, from video images captured using a RGB video camera.

The model calibration is performed from a static reference image for foot, shank and thigh, while the first and last frame of the gait cycle are used to calibrate the pelvis model.

Segmental angular kinematics were estimated with limited errors (4% average %RMSD for foot and shank, 6% for thigh), while greater errors were found for the pelvis (22% average %RMSD). Correlation between ML and gold standard was strong, particularly for foot, shank and thigh segments (pelvis CC varying from 0.70 to 0.81; foot, shank, thigh CC varying from 0.92 to 0.99). Not surprisingly, due to the limited range of motion, pelvis angular kinematics results showed high %RMSD values, suggesting, however, that improvements to the tracking algorithm should be carried out. Nonetheless, in our opinion, the results obtained suggest that the proposed ML method may offer a valid alternative to more expensive and difficult to use marker-based systems, for clinical and ambulatory environments.

In addition to segment angular kinematics, the proposed method may estimate also segment linear kinematics and gait spatio-temporal parameters. However, their assessment was out of the scope of the present study and, therefore, they were not reported. The analysis of the results obtained at different walking speeds confirmed that the number of video frames in which lower limb superimposition occurs does not have an effect on the accuracy of the ML method in estimating the angular kinematics.

This preliminary study has some limitations: kinematics is available only for the leg in the foreground, a blue background is needed in order to obtain good segmentation results, and only white socks and underwear garments can be used at present. Due to the feet tracking technique and experimental setup conditions, only the limb in the foreground is analysed. As future development, a segmentation procedure which does not require a uniform background, will be sought. The removal of the homogenous background would represent an important step for acquiring bilateral joint kinematics, since it would allow for the use of one camera on each side of the subject. Furthermore, removing the homogeneous background would allow the use of the current methodology in environments where the experimental conditions are less controlled (i.e. clinical and ambulatory environments). In fact, at the current development stage, recreating the experimental conditions needed for the technique to perform at its best is particularly demanding.

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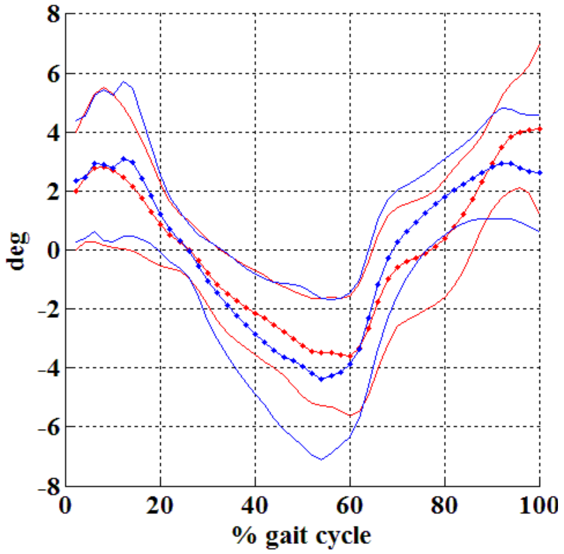

*Fig. 3. Pelvis sagittal rotation. Mean (dotted line) ± one standard deviation kinematic curves for all subjects and trials. Blue=gold standard, Red=*ML.

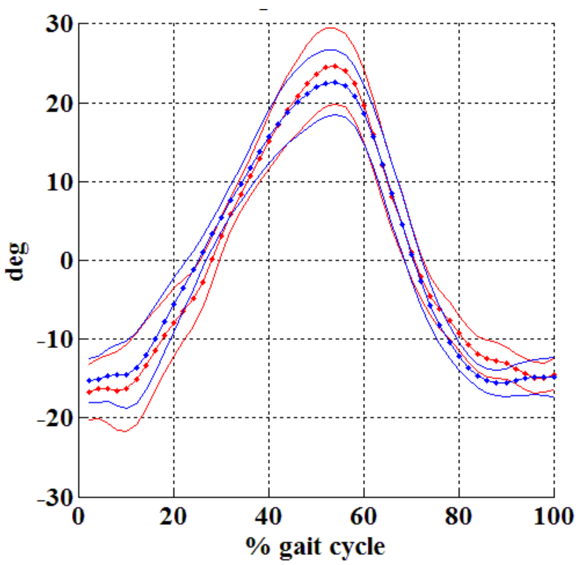

*Fig. 4. Thigh sagittal rotation. Mean (dotted line) ± one standard deviation for all subjects and trials. Blue=gold standard, Red=*ML.

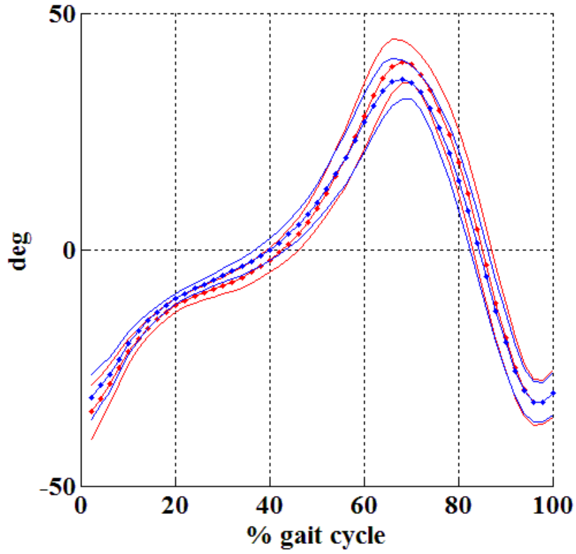

*Fig. 5. Shank sagittal rotation. Mean (dotted line) ± one standard deviation for all subjects and trials. Blue=gold standard, Red=*ML.

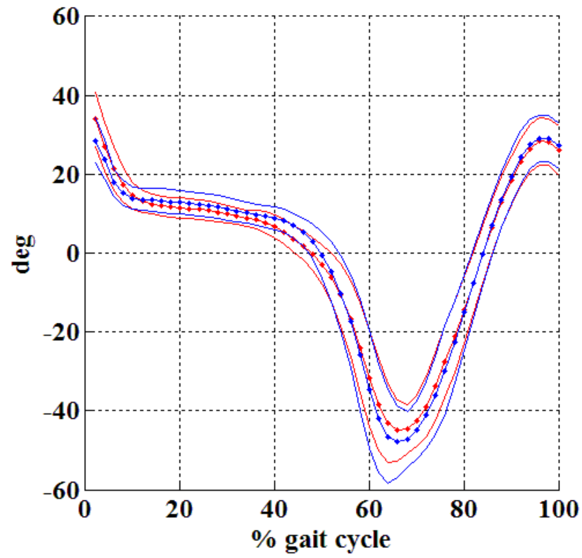

*Fig. 6. Foot sagittal rotation. Mean (dotted line) ± one standard deviation for all subjects and trials. Blue=gold standard, Red=*ML.