A Robust Motion Signature for the Analysis of Knee Trajectories

Christian Babski, Ronan Boulic, Daniel Thalmann

Swiss Federal Institute of Technology Lausanne, Computer Graphics Laboratory,
IN-Ecublens, 1015 Lausanne, Switzerland

Pierre-François Leyvraz, Pierre-Yves Zambelli

Hôpital Orthopédique de la Suisse Romande, P.Decker 4, 1005 Lausanne

Patrick Genoud

Laboratoire de Cinésiologie, Clinique Orthopédique, Hopital Cantonal Universitaire de Genève

Abstract : We propose a new approach for the characterization of walking motion based on the information of marker trajectories. From these data we derive a set of time-related parameters which depend only on the relative configuration of the markers. The resulting parameter's trajectories present two qualities: an important robustness with respect to the soft tissues perturbations together with a high correlation with the anatomical angle's variations. This make them good candidates for the qualitative comparison of motions acquired with the same marker set. We illustrate the method on the knee joint for which a normal walking motion and a reference motion were recorded. Finally, we indicate an alternate application of this information.

1 Introduction

The analysis of walking motion is an operation which presently requires a significant clinical experience in order to evaluate precisely a patient gait. The motion analysis with optical systems still suffers from too strong hypothesis on the definition of anatomical axies in the process of kinematic angles determination. This is especially true for the knee because the flexion axis is changing along with the motion, both in direction and center of rotation.

In our approach we propose a set of parameters which is independent of the anatomical axies. We directly exploit the marker trajectories to derive an information which depends only on the relative configuration of the markers. The resulting set of trajectories is called the *signature* of the motion. The intrinsic robustness of the parameter's trajectories make them good candidates for the qualitative comparison of different motions acquired with the same marker set. We illustrate this with the knee joint where it is especially interesting to compare two classes of movement: a classic walking motion and a so-called *reference motion* (a passive flexion-extension of the knee while standing, one for each leg, according to [2]).

In this paper we first describe the construction of the signature from the marker's trajectories. Then we examine its interest for various knee motions (walking and reference). Finally, we suggest an alternate application for the walking movement's signature.

2. Construction of the Motion Signature

We propose a general set of parameters that help us in the analysis of the human knee trajectories. The idea is that such parameter set is very robust to perturbation coming from soft tissues deformation dynamics and that it highlights sensible differences between motions acquired with the same marker set.

2.1 Principle

We have retained to construct a set of geometric parameters derived from the marker's positions. As the first constraint is to be independent of the trajectory of the patient we have chosen to express this information in a local frame attached to the thigh. Basically, we address the problem of identifying *one* optimal ellipsoid (in position, orientation and dimension) from *all* the markers attached to the thigh and the shank of one leg (generally six markers). The ellipsoid can be interpreted as gathering the information of the center of mass and the volume distribution of the markers cloud in some optimal sense. The volume distribution information is especially sensitive to the current anatomical angles, thus allowing us to extract information highly correlated with the anatomical angle without making strong hypothesis on the underlying anatomic structure.

The orientation of the ellipsoid frame (e1,e2,e3) is defined by angles between the 3 ellipse axes and the absolute Lab reference system (Lab frame in short). The ellipsoid dimensions are defined by the three parameters a1, a2, a3 which are of primary importance for the gait analysis (Figure 1). In order to derive the optimal ellipsoid parameters from the six markers location several minimization methods and several distances were tested [1]. We present here the minimization criteria providing the best results in terms of information to noise ratio. The most significant parameters are the three dimensions of the ellipse because they directly represent the leg configuration during motion and as such they are very sensitive to the anatomical angles. On the other hand, the remaining parameters are determinant to decrease the noise in the minimization method.

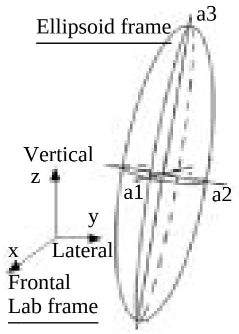


Figure 1 :

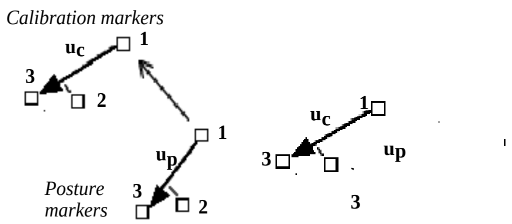
Ellipsoid frame convention exhibited in a usual orientation with respect to the Lab frame.

2.2 Methodology

Our approach requires the following four stages :

- Data acquisition : we have placed six markers on each leg: three on the thigh and three on the shank. The marker's positions are obtained from an optical VICON system with five infra-red cameras.

- Calibration : We want to obtain an ellipsoid which characterizes the leg configuration independently of any reference frame. This is important to allow the comparison of different motions. For this reason, a particular leg posture is first selected in one of the studied motion. The corresponding three markers on the thigh are called the *calibration markers*. They are used to define a specific rigid transformation for each posture bringing the thigh markers as close as possible to the calibration makers (Figure 2). The so-called mapping algorithm exploits the long vector in the calibration set (noted u_c) and the posture set (noted u_p). The transformation decomposes into three steps:



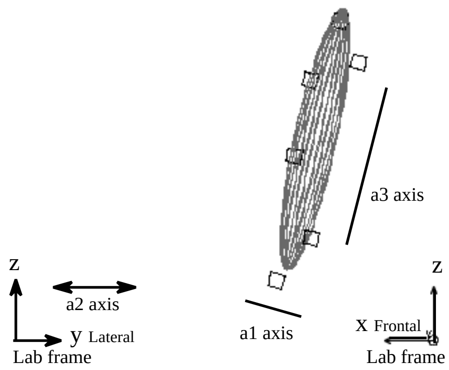


Figure 3 : optimal ellipsoid for a leg posture

- Smoothing : The parameter's trajectories are finally filtered with a butterworth filter with a 7 Hz cutoff frequency [4].

2.3 The cost function

The choice of the cost function is very important in order to obtain some stable results over the whole motion. Various tests [1] brought us to consider the two normals of the ellipsoid surface passing through a marker (Figure 4). The cost function is the sum of the norm of these normals for all the markers.

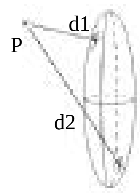


Figure 4 : The two distances between a marker and the ellipsoid along normals to the ellipsoid

2.4 The Minimization Method

Simulation results lead us to retain an effective multi-dimension method, the "Downhill simplex method" [3], rather than a mono-dimension method used in a multiple dimension context (the "Powell method" [3]). A dimension is a parameter which is used in the cost function evaluation and which is modified to minimize the cost function. In such a multi-dimensional method, the research is made in all directions at the same time. Then, a choice is made regarding the use of each direction to minimize the function.

In order to obtain good results, it is necessary to make a good initialization. We already mentioned our choice of a sphere placed at the marker's center of gravity of our six markers and oriented as the Lab frame (Figure 1). The nine parameters were used to obtain a good continuity of the resulting ellipsoid dimension trajectories. The search step size is also an important parameter to guaranty the continuity. Given marker position expressed in millimiters, the search step sizes were one millimiter for the position and dimension directions, and 0.1 radian for the orientation directions.

Regarding Performances, the signature computation for both legs of a 300 frame motion took 70 seconds on a R4000 CPU cadenced at 150Hz.

3. Results

3.1 The Movement Signature

With our choice of cost function, the a1 and a3 dimensions translating the volume distribution of the markers (Figure 3) become very characteristic and we can base our analysis on the corresponding temporal curves (Figure 5). The position parameters over time translate a kind of center of mass of the marker distribution. They are not exploited because the ellipsoid dimensions emphasized more the interesting information. Finally, the orientation of the ellipsoid is necessary to ensure the convergence of the optimization but their variation over time does not convey meaningfull information.

When the trajectory is displayed in the a1-a3 space we see its intrinsic robustness by noticing how closely it overlaps itself for each motion cycle (Figure 6a). Moreover, Figure 5 highlights their high correlation with the flexion-extension angle (evaluated with the approach from[2]). For this reason, the trajectory in the a1-a3 space is called one *signature* of the motion

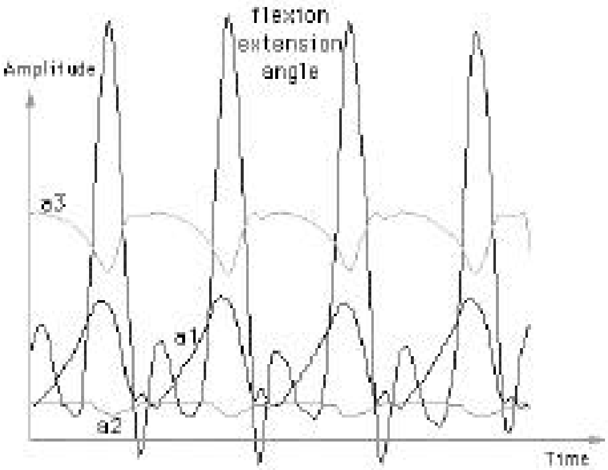
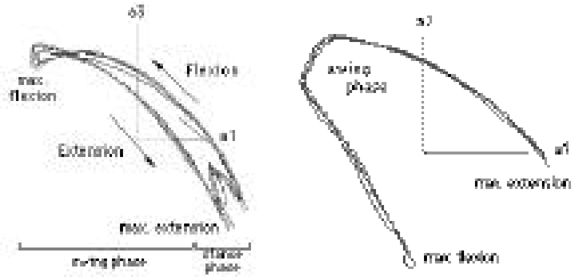


Figure 5 : Temporal evolution of the ellipsoid dimensions and the flexion-extension angle.

3.2 Examples

Now, we can compute the signatures of a walking motion and of a reference motion and superimpose them to analyze their differences.



a b

Figure 6 : Signatures of walking motion (a) and the reference motion (b) for the right leg

- Normal Walking Pattern

The walking motion signature presents distinct regions for the different part of the walking cycle (Figure 6a). At the lowest signature point we have the heel strike event corresponding to the maximum of the extension. Then, the signature slightly moves up and down for the partial flexion during the stance phase prior to move to the highest point corresponding to the maximum of the flexion. The swing phase extension brings back the signature to the same lowest point within a very small neighborhood.

The reference motion (Figure 6b) exhibits a different signature shape due to its nature of flexion-extension while standing (the leg is unloaded). During the reference motion the flexion angle is much bigger than in a standard walking trial. Moreover, the uniform nature of the exercice reflects itself in the close overlapping of the flexion phases with the extension phases of the signature.

When both signatures are superimposed (Fig. 7), an overlapping region clearly appears during the swing phase. This is easily explained by the fact that both motions have the same unloaded nature only during that phase (leg extension). Otherwise, during the stance the leg has to support the body which is not the case for the reference motion. These characteristics were observed for different marker sets and different subjects.

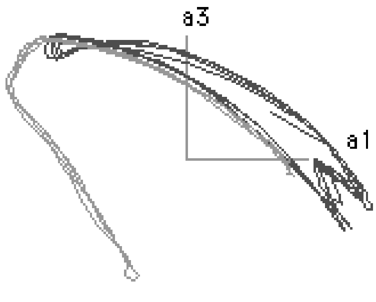


Figure 7 : Both signatures for the right leg

- Diplegic case :

Figure 8 shows reference and walking signatures of both legs of a diplegic patient. One can observe that both reference signatures do not overlap the walking signatures during the swing phase. Moreover, both legs also lack the partial flexion-extension occuring during the stance phase as in the normal case(Fig. 6a). The right leg finally shows a smaller flexion-extension compared to the left leg.

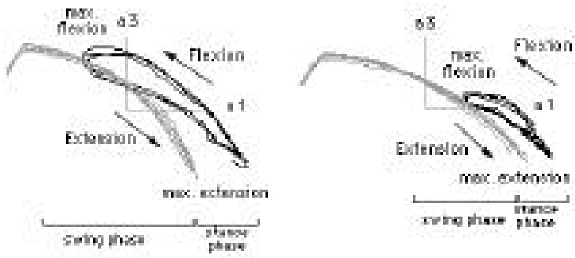
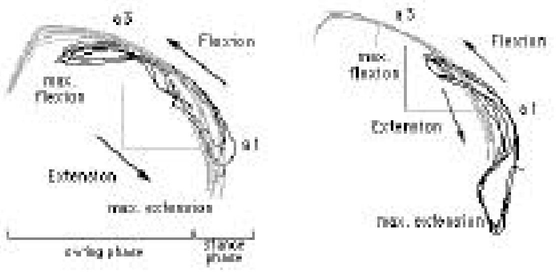


Figure 8 : left and right walking signatures (diplegic)

- Hemiplegic case (on the right leg) :

The example pictured in Figure 9 shows the same calculation performed on an hemiplegic case. The left leg signature is similar to the previous normal case in the sense that the large flexion-extension of the swing phase overlaps the one of the reference signature (Fig. 7). However, it lacks the partial flexion during the stance phase. On the other hand the right leg case shows no overlapping of both signatures and also no partial flexion during the stance phase.



a b

Figure 9 : left and right walking signatures (hemiplegic)

4. Discussion

The analysis of the cases presented here shows that it is possible to clearly differentiate them with respect to their shape and to the relative overlapping of the two signatures. More cases are necessary to establish whether each specific walking pathology provides the same kind of curves. However, one limitation comes from the dependancy of the signature shape to the marker’s positions and to the choice of the calibration posture. This prevent the application of our approach for pre and post surgery signatures comparison.

5. Future Work

An alternate exploitation of the spatio-temporal information of the walking signature alone is possible due to its intrinsic robustness and high correlation with the flexion-extension angle. These properties allow to define a phase variable from the signature curve, which in turn has a good synchronization with the walking phase. From the phase information, we now plan to explore the filtering of the marker’s trajectories from their soft tissues perturbation.

The underlying hypothesis is simple : the soft tissues perturbations are tightly coupled to the walking motion pattern, either normal or pathologic. As a consequence, the amplitude of the corresponding displacements, expressed in a local limb coordinate system, is reasonnably similar from cycle to cycle. The first idea is to use the phase variable to characterize the walking cycle progression. Then, an optimization process constructs the underlying rigid motion of each limb which maximizes the cyclical similary of the local perturbations. The quality of the optimization depends on the number of cycles, on the dispertion of the signature and on the dispertion of perturbation from cycle to cycle (both are probably linked which is another element to consider in the optimization).

6 Conclusion

We have proposed a new technique based on the direct exploitation of the markers trajectories to derive a robust information on the walking motion. Various examples showed the possible differentiation of walking pathologies with the so-called signature of the motion. However, we think that its most promising application resides in the mathematical treatment of artefacts due to soft tissues movements.

7. Acknowledgment

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8. References

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