2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

# Improving skin artifacts compensation for knee flexion/extension and knee internal/external rotation

Marta Moltedo[1] and Sophie Sakka[2]

***Abstract*— When the motion of the human body is studied by means of marker-based motion capture systems, one of the main source of error in this analysis is caused by the markers movements with respect to the underlying bones due to skin motion and deformation. In the kinematics estimation of the lower limbs this error is particularly notable for the rotations in the frontal and axial planes. Many algorithms exist trying to compensate this problem, most of them giving satisfactory results in the estimation of the knee flexion/extension, but correcting the effects of the skin deformation in other rotations is still an open issue. We have implemented a new algorithm to compensate this problem. This method was evaluated on a motion of the human lower limbs and compared with another existing global approach. The results of this experiment showed that the proposed algorithm gives much better results in the analysis of human motion, particularly for the internal/external rotation of the knee.**

## I. INTRODUCTION

When the motion of the human body is studied, we usually want to describe in the most realistic possible way the motion of the human skeleton. A common method to analyze it is to record the positions of some markers directly attached to the segments and positioned on them in order to represent the bony landmarks necessary to determine the positions and the orientations of the bones. From the spacial coordinates of more than three markers attached on the same segment, it is possible to define a frame representing at each instant the pose of the segment with respect to an arbitrary defined absolute frame. If the human segment maintains a rigid shape during its motion, the relative positions of the markers attached on the same segment do not change during the whole motion. A direct consequence is that if we consider a marker, attached to the segment *k*, its measured 3D position (${}^{0}\mathbf{P_j}$) with respect to the absolute reference frame and its calculated position (${}^{k}\mathbf{P_j}$) computed with respect to the segment frame, are related by

$$ {}^{0}\mathbf{P_j} = {}^{0}\mathbf{R}_k \, {}^{k}\mathbf{P_j} + {}^{0}\mathbf{t}_k \tag{1} $$

where ${}^{0}\mathbf{R}_k$ and ${}^{0}\mathbf{t}_k$ are respectively the rotation matrix and the translation vector representing the pose of the segment with respect to the absolute frame.

Because the markers are not directly attached to the bones but to the skin, due to the deformation of the skin during the segment motion, the rigid assumption for the segment shape is not met. Skin motions lead to relative movements among the markers attached to the same segment. These movements are called *skin artifacts*. In this case (1) is not valid and a residual error $\varepsilon_k$ can be computed for the $k^{th}$ segment as:

$$ \varepsilon_k = \sum_{j=1}^{M_k} ||{}^{0}\mathbf{P_j} - ({}^{0}\mathbf{R}_k \, {}^{k}\mathbf{P_j} + {}^{0}\mathbf{t}_k)||^2 \tag{2} $$

where $M_k$ is the number of markers attached to segment $k$. Skin artifacts is one of the main source of errors in the analysis of the human motion [1], [2]. It was shown that it causes noticeable problems in the estimation of joint kinematics for the lower limbs especially in the axial and frontal planes, because these rotations have small possible range of motion [3]. The assessment and compensation of its effects is still an open issue. The effects of skin artifacts on the set of markers attached on the same segment can be seen as the sum of two different components: a deformation of the cluster of markers and a rigid displacement of the set of markers from the underlying bones [2].

Many works were done trying to find a method to counteract this problem in the kinematics estimation. Most of the existing methods propose a local approach which compensate skin artifacts on each segment of the human body independently from the other segments. In this case, a solid reference shape for the segment is found and superposed to the measured shape in order to reduce the deformation of the cluster of markers [4], [5], [6], [7]. Other works compensate this problem by lowering the markers virtual displacements due to the motion of the skin, with respect to the underlying bones [8], [9]. The main disadvantage of all these local methods is that they take into account only one segment. As a consequence, when the motion of more than one segment is to be considered, their resulting relative position could represent a non-anatomical configuration such as superposition or dislocation of the body segments during the motion.

To overcome this problem, global approaches were proposed. In opposition to local approaches, the compensation of the effects of skin artifacts is considered in the whole model of the human body, taking into account the relative poses of two adjacent segments during the motion analysis [10], [11], [12]. Even if these global methods solve the problem of non-anatomical configurations, their main limit is that they avoid the problem restricting the possible motions between adjacent segments. Indeed, a rigid model of the joints connecting the segments is built, usually considering simple joints such as revolute or spherical. But the human

[1]Marta Moltedo is with Research Institute in Communications and Cybernetics of Nantes (IRCCyN), France and Department of Mechanical Engineering, Vrije Universiteit Brussel, Belgium. Marta.Moltedo@vub.ac.be

[2]Sophie Sakka is with IRCCyN and University of Poitiers, France Sophie.Sakka@irccyn.ec-nantes.fr

joints are very complex, so these kinds of connections restrict too much the relative motions of adjacent segments and, sometimes, they do not describe the real movements allowed by the anatomical joints [2].

Most of the existing algorithms were validated using simulated data [2]. In these cases, the relative motions of the segments were numerically reproduced and the effects of skin artifacts were added as a sinusoidal or random noise affecting the markers trajectories. In these validations the application of simple joint constraints was declared as a useful tool to improve the kinematics estimation. But applying these constraints during the analysis of a real motion of the lower limbs, it was shown that it results in a reduction of the performance of the kinematics estimation; in [13] the authors investigated if ideal joint constraints result in a better representation of the human motion, defined by the measured motion of the underlying bone. From the obtained results they claimed that no improvements were achieved by the addition of these constraints. This fact underlies two of the open problems in the estimation of human motion: a model of skin artifacts has still not been defined and its representation by means of a sinusoidal or random additive error does not meet the reality [14]. The relative motions allowed by anatomical joints are very complex and their models need to be built as 6DOF joints [13], because even if two adjacent segments cannot dislocate, their relative bones can translate one with respect to the other due to the fact that the joints connecting the human segments are composed by soft tissues as tendons and ligaments.

In this work a global method is proposed to compensate skin artifacts using the model of the whole body. The approach avoids non-anatomical relative positions of two adjacent segments, without putting constraints at the joints or considering the human segments as rigid bodies. This method was validated on real data and compared with Lu *et al.*'s global approach [10] also based on optimization. We also introduce double calibration in the methodology as to improve the precision on the joint positions during the performed movement. Two movements of the lower limb of 15 subjects were analyzed using this approach: flexion/extension and internal/external rotation. In the following sections, first Lu *et al.*'s global approach is explained, then our new global approach is presented. The experiments used to compare the two algorithms are described and finally some comments on this work are given in section IV.

## II. Global Optimization Method

The global optimization method [10] aims to compensate the problem of skin artifacts in the analysis of human motion considering the whole model of the human body. Its main idea is that the combination of joint constraints and a global error minimization could reduce the effects of skin artifacts in the motion estimation, while avoiding segments dislocation or collision. In this method, the human body is modeled as a set of segments linked together by given joint constraints. It is first calibrated using the measurements taken from the observed subject in a defined static configuration. This method was validated both for the lower and the upper limbs of the human body. The lower limbs were modeled as an articulated system of 3-links, representing the human pelvis, thigh and shank, linked by ideal ball and socket joints [10]. For the upper limbs a 4-links model of the trunk, arm, forearm and hand was considered. In this case, the wrist and the elbow were modeled as cardanic joints, while the shoulder was represented by a spherical joint [15]. These joints were not considered as perfect joints, some laxities were allowed. In both validations, the body movement was simulated applying experimental angular joint kinematics to the model, calculating the positions of the markers related to the considered segments as if they move rigidly with the related segment. These trajectories were considered as the reference trajectories of the markers during the motion. The effects of skin artifacts were simulated adding to the reference markers trajectories a sinusoidal noise in the form $A\,\sin(\omega t + \phi)$, where the values for $A$, $\omega$ and $\phi$ were randomly taken between zero and a specific upper limit [4], [16], [10]. From the perturbed trajectories of the markers, the poses of the segments at each instant were defined by the global optimization method as the ones that minimize a weighted difference between the positions of the markers at the considered instant and their positions computed such that they respect the integrity of the model, so avoiding the dislocation between the segments. From the resulting poses of the segments considered in the model, the values of the joint angles and the 3D positions of the joint centers were estimated and compared with the *real* ones.

This method was shown to improve the kinematics estimation of a simulated motion compared with approaches that do not take into account the whole human model. A strong assumption in the global optimization method is that the flexibility of the human body is not considered. The human segments are not rigid bodies and in different configurations they have different shapes. If some markers are attached to the upper arm shown in Fig. 1 in these two static configurations they will have different relative positions. This natural deformation of the human body is not taken into account by Lu *et al.*'s method. The model of the human body is in fact customized in a static configuration and it is used, in the analysis of the motion, to define the positions of the markers respecting the integrity of the model without considering that they will change during the motion because of the modification of the shape of the segment.

## III. Proposed Algorithm

A new approach to compensate skin artifacts in the analysis of human motion is here proposed. This method is motivated by three basic observations:

- Firstly, the effects of skin artifacts have to be compensated globally (i.e. using the complete model of the human body) so that the estimated poses of two adjacent segments do not result in a non-anatomical configuration such as colliding or dislocated segments.
- Secondly, the description of the relative rotations and translations allowed by the anatomical joints is complex,

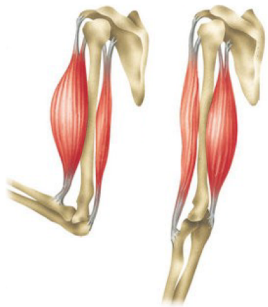


Fig. 1: Different shapes in different configurations

but a simplification in the definitions of the joints could limit too much the possible motions and lead to the addition of an error in the kinematics estimation comparable with the one, due to skin artifacts, that we were trying to avoid. Therefore the application of joint constraints in the model has to be avoided.

- Thirdly, the flexibility of human segments must be taken into account: they are non-rigid bodies and their respective shapes depend on the current configuration of the body.

Let us consider two adjacent segments ($\mathcal{S}_{k_1}$) and ($\mathcal{S}_{k_2}$) connected by a joint whose center is defined by the point $J_{k_1k_2}$. We first describe the calibration procedure in what follows.

The arrays of markers attached to the two adjacent segments are calibrated in two different configurations denoted by $c_1$ and $c_2$ and respectively related to the two extreme possible values ($\delta_1$ and $\delta_2$) of the studied joint angles $\delta$. This angle has to be chosen taking into account the type of motion that will be analyzed in the experiment: $\delta$ may represent either the flexion/extension, the external/internal rotation or the abduction/adduction angle. Let ${}^0\mathbf{P}_j^{c_1}$ and ${}^0\mathbf{P}_j^{c_2}$ denote the measured absolute positions of the markers in configurations $c_1$ and $c_2$, Respectively. From these positions, the frames $\mathcal{F}_k$ ($k = 1, 2$) related to the two bodies are defined. The reference positions of the markers in the local segment frames, denoted by ${}^k\overline{\mathbf{P}}_j^{c_1}$ and ${}^k\overline{\mathbf{P}}_j^{c_2}$, can be calculated for both configurations. The same operations are performed on the position of the joint connecting the two segments in the two calibrated configurations; from its measured absolute positions (${}^0\mathbf{J}_{k_1k_2}^{c_1}$ and ${}^0\mathbf{J}_{k_1k_2}^{c_2}$), its reference positions in the two segments are computed for both the configurations, leading to ${}^{k_1}\overline{\mathbf{J}}_{k_1k_2}^{c_1}$ and ${}^{k_2}\overline{\mathbf{J}}_{k_1k_2}^{c_1}$, ${}^{k_1}\overline{\mathbf{J}}_{k_1k_2}^{c_2}$ and ${}^{k_2}\overline{\mathbf{J}}_{k_1k_2}^{c_2}$.

Once the calibration is performed, the studied motion is analyzed. During the motion, the positions of the markers with respect to the absolute frame ${}^0\mathbf{P}_j$ are recorded. From these positions, at each instant, the best estimation of the pose of the segments are defined by an homogeneous position matrix denoted ${}^0\mathbf{T}_k$. Let $\xi$ be a matrix grouping the poses ${}^0\mathbf{T}_k$ of all the segments composing the model of the human body, as shown in (3).

$$\xi = [{}^0\mathbf{T}_1 \, {}^0\mathbf{T}_2 \, \dots \, {}^0\mathbf{T}_N] \tag{3}$$

These poses are the ones that minimize the weighted error function (4) for each segment $k$.

$$f(\xi) = [{}^0\mathbf{P_j} - {}^k\overline{\mathbb{P}_\mathbf{j}}(\xi)]^T \, \mathbf{W} \, [{}^0\mathbf{P_j} - {}^k\overline{\mathbb{P}_\mathbf{j}}(\xi)] \tag{4}$$

where ${}^k\overline{\mathbb{P}_\mathbf{j}}(\xi)$ is calculated as shown in (5)

$$\begin{bmatrix} {}^k\overline{\mathbb{P}_\mathbf{j}}(\xi) \\ 1 \end{bmatrix} = {}^0\mathbf{T}_k \begin{bmatrix} {}^k\overline{\mathbf{P}_\mathbf{j}}(\delta) \\ 1 \end{bmatrix} \tag{5}$$

and ${}^k\overline{\mathbf{P}}_j(\delta)$ is the position of the marker $\mathbf{P}_j$ in the segment frame to which it is attached, computed as a linear interpolation between the positions of the markers in the segment frames calculated during the two calibrations (${}^k\overline{\mathbf{P}}_j^{c_1}$ and ${}^k\overline{\mathbf{P}}_j^{c_2}$) with respect to the current value of the observed joint angle $\delta$.

Until a minimum value of $f(\xi)$ is found, at each iteration in the minimization problem from the current value of $\xi$, the current poses of each segment (${}^0\mathbf{T}_k$) are extracted; using these poses the current value for the joint angle named $\delta$ during the calibration is computed; this value is used to calculate the current positions of the markers in the segment frames to which they are attached by means of the linear interpolation (6) and substituted in (4).

$${}^k\overline{\mathbf{P}}_j(\delta) = {}^k\overline{\mathbf{P}}_j^{c_1} + \frac{({}^k\overline{\mathbf{P}}_j^{c_2} - {}^k\overline{\mathbf{P}}_j^{c_1})(\delta - \delta_1)}{\delta_2 - \delta_1} \tag{6}$$

To solve the minimization problem a first initial guess for the segment poses in $\xi$ has to be defined. For each one of the segments in the model two different guesses for the initial pose are computed (${}^0\mathbf{T}_k^{01}$ and ${}^0\mathbf{T}_k^{02}$), each one minimizing the residual error ($\varepsilon_{1k}$ and $\varepsilon_{2k}$) related to the positions of the markers in the segment frames computed in one of the two calibrations (7).

$$\begin{aligned} \varepsilon_{1k} &= \sum_{j=1}^{M_k} ||{}^0\mathbf{P}_j - ({}^0\mathbf{R}_k^{01} \, {}^k\overline{\mathbf{P}}_j^{c_1} + {}^0\mathbf{t}_k^{01})||^2 \\ \varepsilon_{2k} &= \sum_{j=1}^{M_k} ||{}^0\mathbf{P}_j - ({}^0\mathbf{R}_k^{02} \, {}^k\overline{\mathbf{P}}_j^{c_2} + {}^0\mathbf{t}_k^{02})||^2 \end{aligned} \tag{7}$$

For each segment, among these two poses, the initial one is selected as the one related to the minimum residual error. This residual error is also used to build the weighting matrix as defined in [10]; the form of this matrix is shown in (8).

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_1 & 0 & 0 & 0 \\ 0 & \mathbf{W}_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \mathbf{W}_N \end{bmatrix} \tag{8}$$

where $\mathbf{W}_k$ is the $(3M_k \times 3M_k)$ related to the $k$-th segment, with $M_k$ equal to the number of markers attached to it; this submatrix is defined as in (9)

$$\mathbf{W}_k = \frac{1}{\varepsilon_k} \mathbf{I} \tag{9}$$

In solving this minimization problem two constraints have to be taken into account. The first one is that the rotation matrices of the estimated poses for the segments have to be orthogonal matrices [17]. The second constraint is to avoid the dislocation of the adjacent segments, while taking into account the possible relative translations between them allowed by the anatomical joints; this constraint is applied imposing that the position of the joint computed with respect to the absolute frame ${}^{0}\mathbf{J}_{k_1k_2}$ is the same when it is computed using the pose of the first segment or of the second one (10). It is also assumed that the position of the joint in the segment frame of each one of the two bodies it links changes linearly with respect to the value of the joint angle $\delta$ between its position in the two calibrations (6).

$$ {}^{0}\mathbf{T}_{k1}\begin{bmatrix} {}^{k_1}\overline{\mathbf{J}}_{k_1k_2}(\delta) \\ 1 \end{bmatrix} = {}^{0}\mathbf{T}_{k2}\begin{bmatrix} {}^{k_2}\overline{\mathbf{J}}_{k_1k_2}(\delta) \\ 1 \end{bmatrix} \tag{10} $$

## IV. Experiments and results

This method was validated on the analysis of the motion of the human lower limbs and the results were compared with the ones obtained by the application of the global optimization method.

### A. Experimental Protocol and calibration process

Fifteen subjects (8 males and 7 females) were used in the experiments. On their right thigh and right shank the markers, defining the positions of the landmarks as determined in [8], were attached directly to the skin. The motion of the markers was recorded at 50 Hz by a ART motion capture system with 8 infrared cameras. During the whole experiment (calibrations and motions) each subject was seated on a chair. He/she was first asked to maintain for some seconds four different static postures, respectively with the knee completely extended, with the knee completely flexed, with the knee flexed at 90 degrees and performing a complete knee internal rotation and with the knee flexed at 90 degrees and performing a complete knee external rotation. After these calibrations two different movements were recorded: the **first movement** consisted in:

1) start the motion in the completely flexed configuration;
2) extend the knee to reach the completely extended configuration;
3) go back to the initial completely flexed configuration.

The **second movement** consisted in:

1) start with the knee flexed at 90 degrees and in a complete knee internal rotation;
2) rotate the knee until complete external rotation configuration, while keeping the flexion angle at 90 degrees;
3) go back to the initial configuration.

During both the actions the subjects were asked to perform the motion without moving the thigh from its initial position. The two movements were performed at three different speeds: the subjects had to complete the motion in 6 seconds, 4 seconds and 2 seconds. Only one repetition for each motion was recorded. The choice of these motions was due to the fact that they are simple motions allowing to test the performance of the proposed algorithm in comparison to the one of Lu *et al.*'s global optimization method.

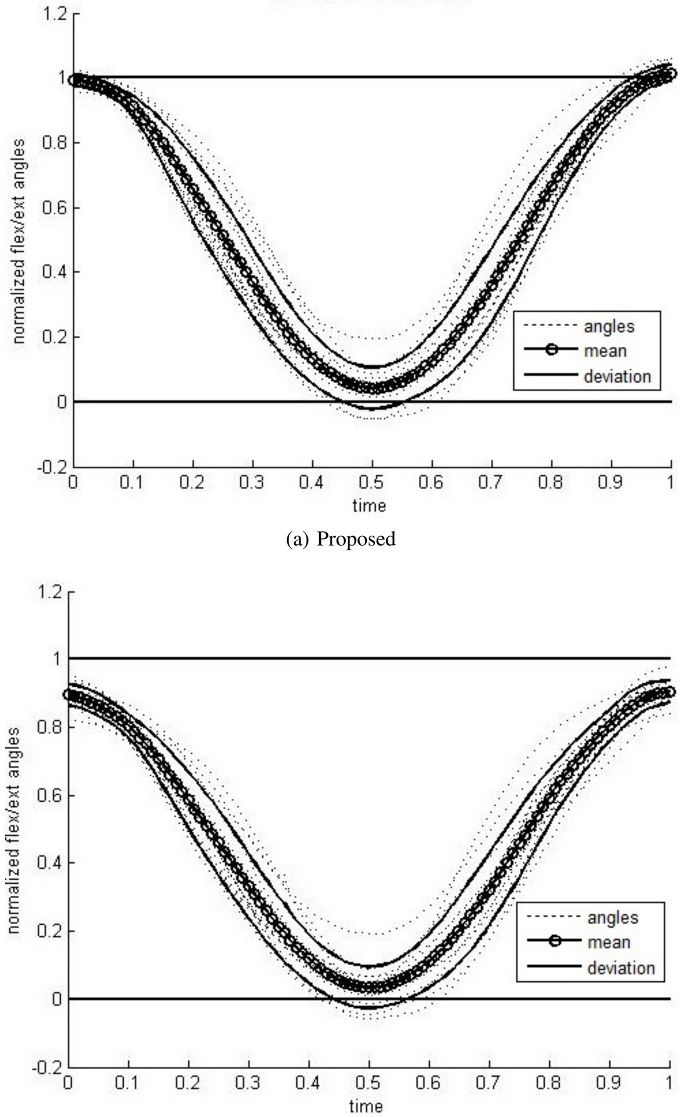
The model in the global optimization method was calibrated using the extended configuration for both the analyzed motions, while for the proposed method the two configurations for the calibration and the definition of the analyzed angle $\delta$ depend on the motion analyzed: for the first one they were respectively the configurations with the knee completely flexed and the knee completely extended and $\delta$ was chosen as the knee flexion/extension angle; for the second motion the two configurations for the calibration were the ones with the knee completely internally rotated and completely externally rotated, while $\delta$ was defined as the knee internal/external rotation angle.

### B. Post-treatment

From the positions of the markers recorded during the motion, the poses of the segments at each instant were estimated using the two algorithms, from these poses the values of the knee joint angles were computed as defined in [18] and [19]. In order to be able to compare the obtained results, the data were normalized such that: on the $x$-axis, 0 corresponds to the instant in which the subject began the motion. At this time the subject was in the initial configuration. 0.5 corresponds to the time in which the subject reached the first target configuration, and 1 corresponds to the time in which the subject reached the final configuration. On the $y$-axis, 0, depending on the motion analyzed, corresponds to the value of the knee flexion/extension measured during the completely extended configuration or the value of the knee internal/external rotation measured during the completely external configuration. 1 corresponds to the value of the knee flexion/extension measured during the completely flexed configuration or the value of the knee internal/external rotation measured during the completely internal configuration. Fig. 2 shows the resulting values for the angle of knee flexion/extension computed by the two algorithms when the subjects performed the knee flexion/extension motion, because the results were similar with respect to the three different velocities considered, only the ones obtained at medium velocity are shown. The dotted lines represent the angles computed for each subject involved in the experiments, the solid line with circles markers represents the mean value of all the measurements and the solid lines represent the variation of the results (computed as the values given by the following computation: $mean\ value \pm standard\ deviation$).

### C. Results

From the obtained results shown in Fig. 2, it is possible to see that when the motion is studied by means of the proposed method, the mean value of the computed angles for all the subjects reaches values that are very close to the calibrated maximum ones, for both flexed and extended configurations. So, analyzing the data with this algorithm shows clearly that the recorded motion was a flexion/extension, starting at the maximum flexed configuration, passing through the maximum extended configuration and coming back to the initial position. This fact is not noticeable in the results of



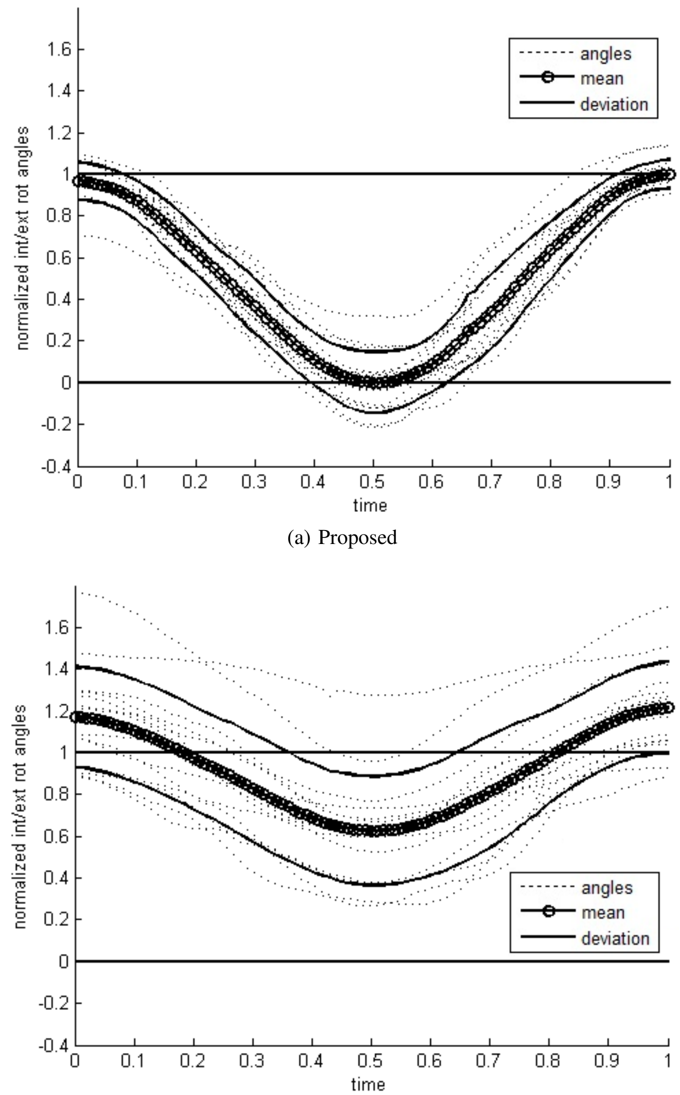

(a) Proposed

(b) Global Optimisation

Fig. 2: Flexion/extension: Resulting angles

the global optimization method, because in this case it is possible to see that from the angles computed by this method, it seems that all the subjects start and end the motion in a configuration that is not the one at the maximum knee flexion.

Fig. 3 shows the resulting values of the internal/external rotation angle computed by the two algorithms when the subject performed the knee internal/external rotation motion. It has to be noted that in this analysis some data were eliminated because they gave results very different from the ones obtained from all the other subjects. To be precise in regarding to the slow internal/external motion the data recorded from the $7^{th}$ subject were eliminated, while for the fast internal/external rotation motion the ones coming from the $9^{th}$ and $10^{th}$ subjects were not taken into account. Also in this case the obtained results were similar with respect to the three different velocities, so only the ones relates to the medium velocity are shown.




(a) Proposed

(b) Global Optimization

Fig. 3: Internal/external rotation: Resulting angles

In this case the results obtained by the application of the two algorithms are very different. From the angles obtained applying the proposed method the mean value of the angles computed for all the subjects reaches values that are very close to the calibrated values representing the maximum internal and external rotations for the knee, so analyzing the motion by means of this algorithm it is evident that during the recorded motion the subjects start at the maximum internal configuration, reach the maximum external one and come back to the first configuration. Once again, this fact is not noticeable when the data are analyzed using the global optimization method. In this case it seems that almost all the subjects start the motion in a configuration in which the value of the knee internal rotation angle is much greater than the calibrated one (the same is valid for the configuration at the end of the motion) and that they never reach their knee maximum external rotation.

## V. CONCLUSIONS

Skin artifacts cause big errors in the estimation of human motion. Even if many methods to compensate this problem were proposed, an optimal approach does not exist yet.

In this work we proposed a new approach and analyzed its performance in the kinematics estimation of the lower limbs, and compared the results with the ones achieved by the application of an existing global algorithm.

From the results obtained in the experiments we can affirm that the proposed method greatly improves the estimation of the motion of lower limbs. The comparison shows that it gives better results in the analysis of the knee flexion/extension, but also for knee internal/external rotation, that is strongly affected by the skin artifacts.

It has to be noted that these results were obtained using experimental data coming from the measurements of a real motion, while most of the existing methods were only tested on simulated data, modeling the effects of skin artifacts as a random or sinusoidal noise, even if this does not reflect the reality.

A positive aspect of the proposed method is that its implementation is very simple and it does not require complex computations.

A negative aspect of this algorithm is that the two configurations for the calibration were chosen according to the type of motion to be analyzed: in the experiment related to the internal/external rotation of the knee the changes in the positions of the markers with respect to the current configuration were analyzed only with respect to the angle of internal/external rotation and the same was done for the knee flexion/extension motion. This could lead to some problem if the motion to be analyzed is a more complex movement such as a combination of the knee flexion/extension and the knee internal/external rotation

A possible solution for this problem could be to use four calibrations (or more) in the customization of the model. For example, the markers positions could be calibrated in the following configurations, named respectively $c_1$, $c_2$, $c_3$ and $c_4$. In $c_1$ the knee is completely flexed and completely externally rotated; in $c_2$ it is completely flexed and completely internally rotated; in $c_3$ the knee is completely extended and completely externally rotated; in $c_4$ it is completely extended and completely internally rotated. During the motion analysis, the relative movements of the markers both due to the knee flexion/extension and the knee internal/external rotation can be taken into account calculating the current position of the markers in the segment frames, with a procedure similar to the one shown in (6), but using the current values of both the two rotation angles.

Further studies could be made in order to test this algorithm on motion such as walking or the ones in which the effects of skin artifacts are very high, as for example running, especially at the moment of the heel impact.

## REFERENCES


[1] U. Della Croce, A. Leardini, L. Chiari, and A. Cappozzo, "Human movement analysis using stereophotogrammetry - part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics," *Gait & Posture*, vol. 21, pp. 226–237, 2005.

[2] A. Leardini, L. Chiari, U. Della Croce, and A. Cappozzo, "Human movement analysis using stereophotogrammetry: Part 3. soft tissue artifact assessment and compensation," *Gait & Posture*, vol. 21, no. 2, pp. 212–225, 2005.

[3] R. Stagni, S. Fantozzi, and A. Cappello, "Propagation of anatomical landmark misplacement to knee kinematics: Performance of single and double calibration," *Gait & Posture*, vol. 24, pp. 137–141, 2006.

[4] L. Chèze, B. Fregly, and J. Dimnet, "A solidification procedure to facilitate kinematic analyses based on video system data," *Journal of Biomechanics*, vol. 28, no. 7, pp. 879–884, 1995.

[5] K. A. Ball and M. R. Pierrynowski, "Modeling of the pliant surfaces of the thigh and leg during gait," vol. 3254, 1998, pp. 435–446. [Online]. Available: http://dx.doi.org/10.1117/12.308193

[6] T. Andriacchi, E. Alexander, M. Toney, C. Dyrby, and J. Sum, "A point cluster method for in vivo motion analysis : Applied to a study of knee kinematics," *Journal of biomechanical engineering*, vol. 120, pp. 743–749, 1998.

[7] J. H. Mun, "A method for the reduction of skin marker artifacts during walking : Application to the knee," *Journal of Mechanical Science and Technology*, vol. 17, no. 6, pp. 825–835, 2003.

[8] A. Cappozzo, F. Catani, U. Della Croce, and A. Leardini, "Position and orientation in space of bones during movement: anatomical frame definition and determination," *Clinical Biomechanics*, vol. 10, no. 4, pp. 171–178, 1995.

[9] L. Lucchetti, A. Cappozzo, A. Cappello, and U. Della Croce, "Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics," *Journal of Biomechanics*, vol. 31, pp. 977–984, 1998.

[10] T. Lu and J. O'Connor, "Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints," *Journal of Biomechanics*, vol. 32, pp. 129–134, 1999.

[11] P. Cerveri, M. Rabuffetti, A. Pedotti, and G. Ferrigno, "Real-time human motion estimation using biomechanical models and non-linear state-space filters," *Medical and Biological Engineering and Computing*, vol. 41, no. 2, pp. 109–123, 2003. [Online]. Available: http://dx.doi.org/10.1007/BF02344878

[12] P. Cerveri, A. Pedotti, and G. Ferrigno, "Kinematical models to reduce the effect of skin artifacts on marker-based human motion estimation," *Journal of Biomechanics*, vol. 38, pp. 2228–2236, 2005.

[13] M. S. Andersen, D. L. Benoit, M. Damsgaard, D. K. Ramsey, and J. Rasmussen, "Do kinematic models reduce the effects of soft tissue artefacts in skin marker-based motion analysis? an in vivo study of knee kinematics," *Journal of Biomechanics*, vol. 43, pp. 268–273, 2010.

[14] R. Stagni, S. Fantozzi, A. Cappello, and A. Leardini, "Quantification of soft tissue artefact in motion analysis by combining 3d fluoroscopy and stereophotogrammetry: a study on two subjects," *Clinical Biomechanics*, vol. 20, no. 3, pp. 320 – 329, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0268003304002839

[15] E. Roux, S. Buuilland, A. Godillon-Maquinghen, and D. Bouttens, "Evaluation of the global optimisation method within the upper limb kinematics analysis," *Journal of Biomechanics*, vol. 35, pp. 1279–1283, 2002.

[16] A. Cappozzo, F. Catani, A. Leardini, M. Benedetti, and U. Della Croce, "Position and orientation in space of bones during movement: experimental artefacts," *Clinical Biomechanics*, vol. 11, no. 2, pp. 90–100, 1996.

[17] J. H. Challis, "A procedure for determining rigid body transformation parameters," *Journal of Biomechanics*, vol. 28, pp. 733–737, 1995.

[18] G. Wu and P. R. Cavanag, "Isb recommandations for standardization in the reporting of kinematic data," *Journal of Biomechanics*, vol. 28, no. 10, pp. 1257–1261, 1995.

[19] G. Wu, S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D. D. D'Lima, L. Cristofolini, H. Witte, O. Schmid, and I. A. Stokes, "Isb recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion – part i: ankle, hip, and spine," *Journal of Biomechanics*, vol. 35, pp. 543–548, 2002.