Application of MOBILE for Accurate Bone Motion Reconstruction Using Motion-Measurements and MRI Measurements

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Summary. Accurate reconstruction of bone motion using marker tracking is still an open issue in biomechanics. In this paper a novel approach for gait motion reconstruction is presented that is based on the analysis of kinematical loops and the reconstruction of functional skeleton features from segmented MRI data. The method uses an alternative path for concatenating relative motion, starting at the feet and closing at the hip joints. The discrepancies between predicted and geometrically identified functional data, such as knee axis and hip joint centers, gives rise to a cost function, which is the basis for model addaptation. Computations are performed with the object-oriented library MOBILE.

1 Motivation

The Vicon motion capture systems (www.vicon.com) is a widely used tool for the determination of motions of body segments upon the motion of skin-mounted markers. The "Plug-in-Gait marker model" is the marker setup used in the current version of the Vicon analysis software Nexus. Figure 1(a) shows the right leg with the markers used for this leg motion reconstruction model. For this model, a pelvis-fixed frame $\mathcal{K}_{\mathrm{p}}$ is defined using the hip markers RASI, LASI, RPSI, LPSI, such that the z-axis is aligned with the line connecting the markers RASI and LASI, and the centroid of the RPSI and LPSI markers lies in the xz-plane. For the pelvis, the position of hip joint centers is estimated using the Newington-Gage model [2] making use of the inter-ASI distance. The motion of the other leg segments is reconstructed starting at the hip joints, advancing down to the foot, sequentially computing new segment orientations using joint centers already determined and markers fixed to the next body part, according to the algorithm described in [8].

In the application of this procedure, accuracy problems can occur manifesting in wrong hip joint center positions and large (axial) rotations of tibia and femur. These errors result from inaccurate marker placement, skin motion at knee and ankle or soft tissue artifacts of the thigh marker (RTHI). These

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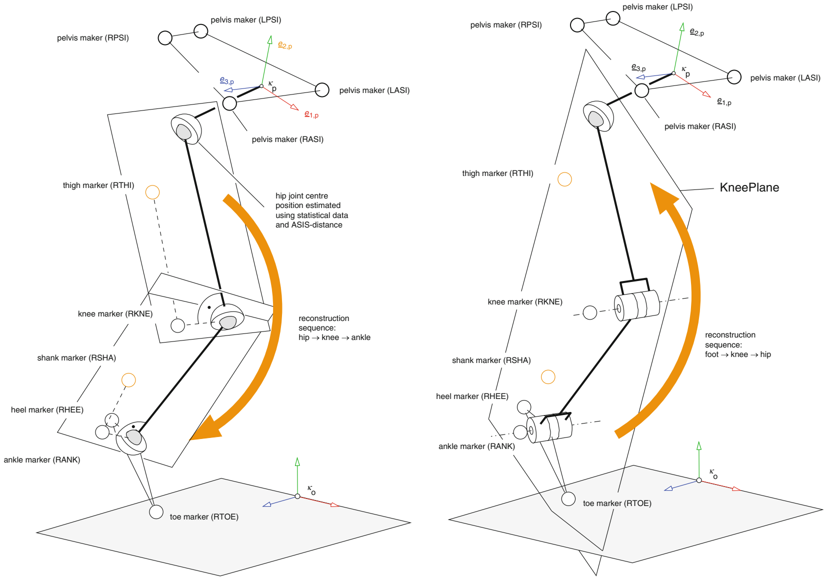


a) VICON "Plug-in-Gait" model b) suggested kinematic model

Fig. 1. Kinematic structure of the Plug-in-Gait model and the proposed model

errors could be reduced by careful marker placement and performing new measurements with improved marker positions, but this is hardly possible in routine measurements with patients.

Approaches for reducing these errors after the measurement are presented in [1], and in [5], where the latter reduces model bone length variations by identifying the unknown constant offsets between the joint centres delivered by the motion capture system (prediction) and the anatomical joint centres.

In the approach presented in this paper the axes of the ankle joint and the knee joint are computed starting at the foot markers, and proceeding upward to the knee, using foot- and knee markers, which are subject to less (or at lest more predictable) soft tissue motion. It is assumed that the ankle joints $\mathrm{R}_{\text{ankle}}$ and the knee joints R_{knee} can be represented by revolute joints. Another assumption is that the line connecting the heel and the toe marker (unit vector $\underline{u}_{\text{foot}}$) is perpendicular to both the ankle joint axis and the knee joint axis (Fig. 2a). An approximation of the hip joint center position is computed at the end of the procedure in a way that the relative motion of one femur point with respect to the pelvis is minimized. The segment motion is determined with respect to an inertially fixed frame $\mathcal{K}_0$, usually coinciding with the reference frame of the motion capture system. For describing vectors using cartesian coordinate frames, the notation ${}^{k}_{i}\underline{b}_{j}$ is used, where k denotes the frame of decomposition, i denotes the frame with respect to which the motion is measured, and j denotes the target frame. For motion measured with respect to $\mathcal{K}_0$, the index $i = 0$ is omitted. Likewise, for decompositions in the target frame $k = j$, the index k is omitted. Hence $\underline{b}_1$ is equivalent ${}^1_0\underline{b}_1$.

2 Simulation Environment

The core component of the integrated simulation environment MobileBody© [7] is the mechanical model of the musculoskeletal system. Its implementation using object oriented programming makes it easy to combine it with image processing code or visualization libraries. Furthermore, by using the multibody simulation library MOBILE [4], model components (e.g. joints, muscles) can be easily replaced with more complex and realistic implementations.

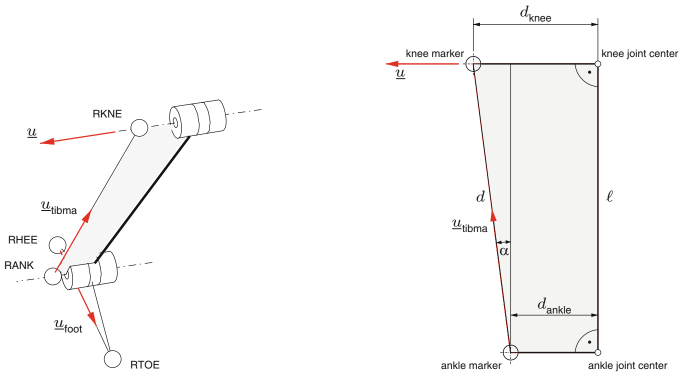
3 Segment Motion Estimation Procedure

Having measured the anthropometric distances d_{knee} and d_{ankle} between knee joint centre and ankle joint centre, and the corresponding marker (see Fig. 2b), the following simple procedure is used to determine estimates of tibia- and femur-fixed coordinate frames. By computing the distance between the ankle- and knee marker, the angle α between the connecting line of the tibia markers and the tibia joint centers is computed using the formula

$$\alpha = \arcsin \frac{d_{\text{knee}} - d_{\text{ankle}}}{d} . \tag{1}$$

With the unit direction vector $\underline{u}_{\text{tibma}}$ of the line connecting the tibia markers, the axis direction of knee- and ankle joint becomes

$${}^0\underline{u} = \cos\alpha \, \frac{{}^0\underline{u}_{\text{foot}} \times {}^0\underline{u}_{\text{tibma}}}{\| {}^0\underline{u}_{\text{foot}} \times {}^0\underline{u}_{\text{tibma}} \|} + \sin\alpha \, {}^0\underline{u}_{\text{tibma}} \qquad . \tag{2}$$



a) Direction of foot and tibia markers b) Estimation of tibia joint centers

Fig. 2. Reconstruction of the knee joint axis

Next, with ${}^{0}\underline{u}$ and the position ${}^{0}\underline{r}_{\text{knema}}$ of the knee marker, the location of the knee joint center is calculated as

$$ {}^{0}\underline{r}_{\text{knee}} = {}^{0}\underline{r}_{\text{knema}} - d_{\text{knee}}\,{}^{0}\underline{u} \tag{3} $$

and a coordinate system can be aligned with the femur by setting

$$ \begin{aligned} {}^{0}\underline{e}_{3,\text{f}} &= {}^{0}\underline{u} \\ {}^{0}\underline{e}_{1,\text{f}} &= \frac{({}^{0}\underline{r}_{\text{tibma}} - {}^{0}\underline{r}_{\text{knee}}) \times {}^{0}\underline{u}}{\| ({}^{0}\underline{r}_{\text{tibma}} - {}^{0}\underline{r}_{\text{knee}}) \times {}^{0}\underline{u} \|} \\ {}^{0}\underline{e}_{2,\text{f}} &= {}^{0}\underline{u} \times {}^{0}\underline{e}_{1,\text{f}} \end{aligned} \quad . $$

This leads to the rotation matrix

$$ {}^{0}\mathbf{R}_{\text{f}} = \left[{}^{0}\underline{e}_{1,\text{f}}\,,\ {}^{0}\underline{e}_{2,\text{f}}\,,\ {}^{0}\underline{e}_{3,\text{f}} \right] \tag{4} $$

corresponding to the femur frame $\mathcal{K}_{\text{f}}$ displayed in Fig. 3. For estimation of the hip joint centre, let the position of the femur head ($\equiv$ hip joint centre) be given relatively to the femur frame $\mathcal{K}_{\text{f}}$ by the vector

$$ {}^{\text{f}}_{\text{f}}\underline{r}_{\text{hj}} = \begin{bmatrix} x_1 \\ x_2 \\ 0 \end{bmatrix} \tag{5} $$

which lies in the thigh-shank plane Fig. 3. Relatively to the pelvis frame, the coordinates of the femur-fixed point H representing the hip joint centre are

$$ {}^{\text{p}}_{\text{p}}\underline{r}_{\text{hj},i} = \mathbf{R}_i\,{}^{\text{f}}_{\text{p}}\underline{r}_{\text{f},i} + \mathbf{R}_{12,i}\,\underline{x} \tag{6} $$

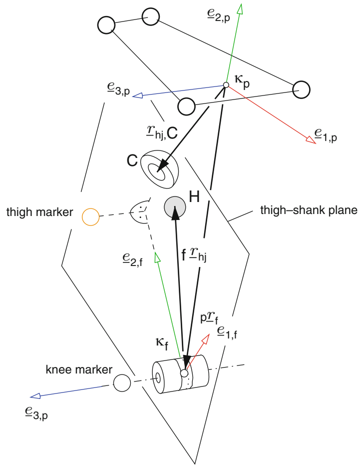


Fig. 3. Estimation of the hip joint centre location in the thigh-shank plane

where $\mathbf{R}_i = {}^{\mathrm{p}}\mathbf{R}_{\mathrm{f},i}$ is the rotation matrix between the estimated pelvis frame $\mathcal{K}_{\mathrm{p}}$ and the estimated femur frame $\mathcal{K}_{\mathrm{f}}$ at time t_i. Likewise, $\mathbf{R}_{12,i}$ is the matrix of the first two columns of $\mathbf{R}_i$ and $\underline{x} = [\, x_1 \,,\, x_2 \,]^{\mathrm{T}}$. The position of the femur frame relative to the pelvis frame at time t_i is given by ${}^{\mathrm{f}}_{\mathrm{p}}\underline{r}_{\mathrm{f},i}$. According to the "centre transformation technique" [3], the coordinates x_1 and x_2 are chosen such that the squared norm of errors

$$\mathrm{f}(\underline{x}) = \sum_{i=1}^{m} ({}^{\mathrm{p}}_{\mathrm{p}}\underline{r}_{\mathrm{hj},i} - {}^{\mathrm{p}}_{\mathrm{p}}\underline{r}_{\mathrm{hj,C}})^2 \tag{7}$$

between the points H_i of this trajectory and their centroid C (visualized as "cup" in Fig. 3)

$${}^{\mathrm{p}}\underline{r}_{\mathrm{hj,C}} = \frac{1}{m} \sum_{i=1}^{m} (\mathbf{R}_i {}^{\mathrm{f}}_{\mathrm{p}}\underline{r}_{\mathrm{f},i} + \mathbf{R}_{12,i}\, \underline{x}) = \underline{a} + \mathbf{B}\, \underline{x} \tag{8}$$

is minimized over all m measured poses summing over $i = 1, \ldots, m$. By summing up and factoring out $\underline{x}$ one obtains

$${}^{\mathrm{p}}\underline{r}_{\mathrm{hj,C}} = \underline{a} + \mathbf{B}\, \underline{x} \tag{9}$$

with $\underline{a}$ and $\mathbf{B}$ being constant. The first order conditions for the optimum become

$$\frac{\partial\, \mathrm{f}}{\partial\, \underline{x}}(\underline{x}) = \sum_{i=1}^{m} (\mathbf{R}_{12,i} - \mathbf{B})^{\mathrm{T}} \big((\mathbf{R}_i {}^{\mathrm{f}}_{\mathrm{p}}\underline{r}_{\mathrm{f},i} - \underline{a}) + (\mathbf{R}_{12,i} - \mathbf{B})\, \underline{x} \big) = \underline{a}_1 + \mathbf{B}_1\, \underline{x} = \underline{0} \tag{10}$$

with shortcuts $\underline{a}_1$ and $\mathbf{B}_1$, leading to the optimal point

$$\underline{x}^{\star} = -\mathbf{B}_1^{-1} \underline{a}_1. \tag{11}$$

When choosing the position of the hip joint relatively to the femur frame as

$${}^{\mathrm{f}}_{\mathrm{f}}\underline{r}^{\star}_{\mathrm{hj}} = \begin{bmatrix} x_1^{\star} \\ x_2^{\star} \\ 0 \end{bmatrix}, \tag{12}$$

the oscillation of the hip joint center with respect to the pelvis frame is minimized. This vector and the positions of the hip joint relatively to the pelvis frame are used to define the segment lengths of an open-chain kinematic model of the leg such as that described in [5]. The joint coordinates of the hip joint are obtained from the relative rotation matrix ${}^{\mathrm{p}}\mathbf{R}_{\mathrm{f},i}$. Analogously, the segment lengths of the shank and the joint coordinates in knee and ankle are computed.

4 Discussion

The described model displays a simplified kinematic model of the knee- and ankle joint, neglecting any axial rotation in these joints. This restricts its application to gait motion with low knee flexion angles, since larger external/internal rotation (up to 37°) in the knee are possible for large flexion angles according to a survey in [6]. In standard gait analysis, the model avoids huge, unrealistic internal/external rotations of the tibia and the femur, without requiring more markers than when using the "Plug-In-Gait model". On the other hand, the actual rotations in knee and ankle are not reflected in this model, which may lead to an inaccurate identification of the hip joint center if the distance between knee marker and knee joint center is not known precisely or in the case of valgus/varus deformities. If the distance between the hip joints is known from X-Ray or MRI images, this information can be exploited to improve the estimation of the hip joint centre in transversal direction, which is the focus of ongoing work.

Measurements are currently being produced and will be published in future.

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