Implantation Parameter Designation for Total Hip Prosthesis based on Multibody Musculoskeletal Modeling

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EXTENDED ABSTRACT

1 Introduction

Total hip arthroplasty (THA) is a widely used surgical intervention to address hip pain. Recently, with the help of robotic-assisted THA, surgeons can reduce the prosthesis assembly error to less than 1 deg. However, it is still a challenging task to evaluate the hip movement functions after the surgery. Musculoskeletal multibody simulation provides a feasible solution for implantation optimization. Most existing models were driven by infrared marker-based motion tracking, which is difficult for patients with low compliance. The obtained kinematics data also lacks accuracy in the patient-specific hip postures. The foot–ground reaction force data measured by force plates were unreliable because the patients cannot guarantee only one foot on one sensor. Moreover, the static optimization (SO) algorithm widely used in musculoskeletal simulations neglected nonlinear muscle biomechanics and the time delay between neural excitation and its corresponding muscular activation [1]. This study provides a musculoskeletal simulation framework for optimizing the THA implantation parameters combining hybrid motion capture, foot–ground contact parameter identifications, and forward–inverse dynamics simulations.

2 CT-assisted hybrid motion capture

The study protocol was approved by the Institutional Review Board of Beijing Jishuitan Hospital. Three patients with femoral head necrosis (two males and one female, 33–46 years old, BMI = 20.50 ± 6.89) were recruited. A hybrid motion capture system with eight infrared and four video cameras was utilized to obtain patient-specific kinematics. With the help of markerless pose estimation software (Fast Move Tech., Dalian, China), one can get twenty-one anatomical landmarks without attaching external markers. The sagittal knee and ankle angles were obtained via the intersection angle between two vectors connecting each limb's proximal and distal landmarks.

However, virtual surgical planning relies on accurate hip joint angles. Therefore, we measured hip kinematics via infrared motion capture. A rigid marker cluster with four markers was placed on each anterolateral thigh. Another four markers were attached to the anterior superior iliac spine and iliac crest on both sides. Then, patient-specific CT images were measured and reconstructed to register the relationship between the infrared marker and its underlying bone. Considering the soft tissue artifact, we introduced a virtual spring–damper unit [1] between the measured marker locations and their corresponding initial positions obtained via CT reconstruction.

3 Parameter identification of foot–ground contact

A full-body musculoskeletal model including seven rigid bones and forty-three Hill-type musculotendon units was developed based on our in-house code [1]. The generic biomechanical parameters were adopted from the OpenSim gait2392 model. It was then linearly scaled based on the stick diagram obtained by standing posture recognition. Driven by the CT imaging data, the patient-specific muscle moment arm at the hip joint was obtained via the convex wrapping algorithm [2].

The foot–ground reaction forces were described by a soft-tissue contact model considering energy dissipation [3]. The foot sole contact geometry was simplified as four viscoelastic spheres, and the static and kinetic friction coefficients were assumed to share the same value. Thus, all the parameters needed identification include the contact stiffness, nonlinear index, friction coefficient, and the contact radius of spheres. A global optimization method was proposed to identify each parameter simultaneously. Here, the sagittal movements of the pelvic mass center $d_x,\ d_y$ were obtained by forward dynamic analysis, and other joint kinematics were constrained by the gait measurements. The objective function J_{cont} was expressed as:

$$J_{\mathrm{cont}} = \frac{1}{t_{\mathrm{f}}} \int_{t_0}^{t_{\mathrm{f}}} [w_1 M_{\mathrm{sagit}}^2 + w_2 \Delta d_x^2 + w_3 \Delta d_y^2 + w_4 \sum_{i=1}^{2} (\Delta F_{\mathrm{cont}}^i)^2 + w_5 \sum_{i=1}^{2} (\Delta F_{\mathrm{fric}}^i)^2] \mathrm{d}t\,. \tag{1}$$

Here, M_{sagit} corresponds to the residual sagittal moment that acts on the pelvis, and $F_{\mathrm{cont}}^i,\ F_{\mathrm{fric}}^i$ are the foot–ground contact and friction forces of both sides, respectively. Δ denotes the difference between the measurement and simulation data, and $w_i,\ i = 1, \cdots, 5$ are the weights for each term.

4 Forward–inverse dynamics simulation

With the optimized foot–ground contact parameters, one can predict hip constraint forces on both sides during gait. The obtained hip reaction forces can be depicted as two force cones, i.e., a contact force cone and another one formed by soft tissue extensions. The contact force cone determined proper implant orientation (anteversion, inclination) to prevent edge loading of the hip implants. The tissue extension cone constrains the muscle forces around the hip joint without considering residual ligaments.

Moreover, we utilized the forward-muscular inverse-skeletal (FMIS) framework [1] to optimize the femur offset in THA. Here, the dynamic equilibrium constraint within the SO algorithm was replaced by introducing the torque tracking errors $\Delta M^{i}_{\mathrm{joint}}$ into the objective function. Neural excitation of each muscle was first calculated by SO without consideration of musculotendon equilibrium, and the initial values of muscle activations a_i were obtained via a first-order differential equation. Therefore, the objective function J_{FMIS} of the hybrid optimization problem was then expressed as:

$$J_{\mathrm{FMIS}} = (1-\gamma)\sum_{i=1}^{N_{\mathrm{mus}}}[\overline{PCSA}_i a_i(t)]^2 + \gamma\sum_{i=1}^{N_{\mathrm{joint}}}\Delta M_{\mathrm{joint}}(t)^2 + \sum_{i=1}^{N_{\mathrm{mus}}}[a_i(t)-a_i(t-\mathrm{d}t)]^2\,, \tag{2}$$

where γ is the weight of joint moment, $\overline{PCSA}$ is the normalized physiological cross-sectional area, and $\mathrm{d}t$ is the time step. N_{mus} and N_{joint} denote the number of muscles and joints, respectively. Alternating the femur offsets can influence the muscle moment arms and change the optimized activation patterns. We chose the offset values with minimum optimized J_{FMIS} data.

5 Results and conclusion

The measurements of CT-assisted motion tracking improved the accuracy of the obtained hip angles, and the observed kinematics data were validated based on smooth orthogonal decomposition. The simulated foot–ground reaction forces were qualitatively in agreement with the force plate measurements. The estimated contact and tissue extension cones of a typical subject are depicted in Figure 1. The proposed framework successfully provided a geometric approach to optimize the implantation parameters.

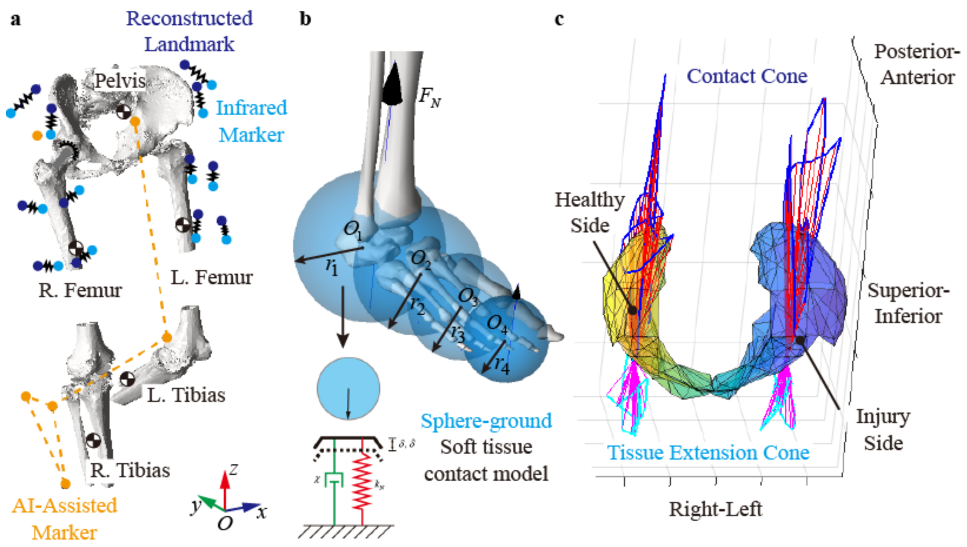

Figure 1: **a**. CT-assisted gait analysis; **b**. Foot–ground contact parameter identification; **c** Hip force cones of a typical subject

Acknowledgments

This work was supported in part by National Natural Science Foundations of China (12102035, 12132009) and Beijing Natural Science Foundation (L212008).

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