Convex wrapping algorithm for multi-joint muscles and its applications in hip musculoskeletal modeling

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EXTENDED ABSTRACT

1 Introduction

Total hip arthroplasty (THA) is an efficient treatment for patients with hip disorders. While implanting the prosthesis, some fibers of the gluteal muscle group need to be loosened or detached, potentially causing postoperative dysfunction during daily activities. Musculoskeletal multibody modeling is an effective tool for predicting the hip joint moments and the muscle forces around this joint. Its simulation accuracy strongly relies on the quantification of the muscle moment arm. Existing models (e.g., OpenSim, Anybody, etc.) often used the via-point algorithm to deal with the muscle wrapping problem, while the obtained muscle path cannot keep smooth and convex. Meanwhile, the selection of via points largely depends on the clinicians' experience.

To overcome these shortcomings, Desailly et al. [1] proposed a convex wrapping algorithm based on the computational geometry framework. The feasible muscle path was selected as the shortest curve wrapping over a convex hull. However, multi-joint muscles path like iliopsoas may penetrate through bone during the shortest path search, which is inconsistent with anatomy. Moreover, the obtained convex hull for the gluteal muscles did not include enough mesh points to determine a smooth curve for the muscle moment arm. This study provides a modified convex wrapping algorithm for multi-joint muscles by introducing a bone penetration criterion and the mesh refinement technique. It was validated and utilized in predicting the hip muscle forces before the surgery, which can help surgeons determine the muscle bundles that should be prevented rather than cut off.

2 Method

2.1 Convex wrapping algorithm

The study protocol was approved by the ethics committee of Beijing Institute of Technology (BIT-EC-H-2021111). Three volunteers (two male and one female, 35-48 years old) with femoroacetabula impingement syndrome were recruited. The CT images of each patient were obtained by a Siemens SOMATOM Definition Scanner (Siemens Medical Solutions USA, Inc, Malvern, PA, USA) and then reconstructed using Mimics 21.0 software (Materialise, Leuven, Belgium). The surface electromyography (EMG) was synchronously measured through an 8-channel EMG system (Fast Move Tech., Dalian, China) with the sampling rate of 1000Hz.

Each muscle fiber was regarded as a massless and frictionless tether connected to the bone via origin and insertion points. The positions were usually palpated manually based on skeletal anatomy, which cannot be adapted to subject-specific modeling. In this study, the locations of each attachment point were registered automatically based on the non-rigid closest point (NICP) method [2]. Here, only the subject-specific bone geometries and a state-of-art musculoskeletal model (e.g., OpenSim gait2392 model) were used as the system inputs, preventing tedious statistics modeling.

The wrapping path of each muscle was determined based on the convex hull generated based on patient-specific CT data and the shortest path search. Firstly, the possible muscle-bone contact regions from the pelvis and femur STL geometries were selected. The obtained point set and the muscle attachment sites were utilized to generate a convex hull surface. The optimized muscle path should be the shortest curve from the original to the insertion points constrained within the convex hull surface, which can be easily realized via the Dijkstra searching algorithm.

2.2 Anti-penetration criterion and wrapping geometry refinement

A criterion was then proposed to ensure the muscle wrapping path stays outside the underlying bone geometries. Here, we took the iliopsoas as an example. A plane γ (Fig 1a) was fitted by the pelvic mesh vertices within the convex hull. While searching for the shortest path, a possible choice might intersect with γ via vertex P_{int}. The weight of P_{int} in calculating the muscle path length will be altered to infinity to discard this penetrating solution.

However, the moment arm data were not smooth because the obtained convex hull only included a tiny number of vertices. The nth-order subdivision using the loop subdivision method was performed to refine the convex hull geometry discretized by triangular meshes. Here, each triangular mesh was split into four segments by connecting its edge midpoints. The generated vertex positions were updated by a weighted average of their neighboring positions:

$$ep = \frac{1}{8}(V_0 + V_2) + \frac{3}{8}(V_1 + V_3), \quad (1)$$

where V_0, V_1, V_2, V_3 denote the original vertex positions of two adjacent triangular meshes.

2.3 Applications in musculoskeletal modeling

The obtained muscle moment arms were utilized as the model inputs of a patient-specific musculoskeletal model [3]. Bone rigid geometries were obtained from reconstructed CT data, and the corresponding joint locations were obtained from EOS measurements. The number of muscles controlling the hip movements is larger than the joint degrees of freedom (DOFs), so the static optimization (SO) method was applied to solve the muscle redundancy problem. Here, the static standing postures were collected via EOS imaging, and the EMG measurements were also performed for obtaining the activations of hip muscles. As a validation, the calculated muscle activations during standing were compared with the normalized EMG data. We further performed the musculoskeletal simulations of gait and squat maneuvers, and their kinematics were measured via a hybrid motion capture system.

3 Results and conclusion

Compared with the via-points method, the proposed algorithm avoided the non-smoothness and penetration problems for the iliopsoas path; see Fig. 1a. However, the calculated moment arms without subdivisions could be unrealistic when the hip joint flexed over 40deg; see Fig. 1c. The modified convex wrapping algorithm with mesh subdivisions guaranteed feasible muscle paths regardless of the hip postures. Moreover, the simulated hip muscle activations during standing (gluteus maximus: 0.12, gluteus medius: 0.07) were in agreement with the normalized EMG data.

In conclusion, the multi-joint muscle wrapping method successfully proposed an automatic way to determine subject-specific muscle paths around the hip joint, which can be used in developing a subject-specific musculoskeletal model for THA surgical planning and postoperative rehabilitation.

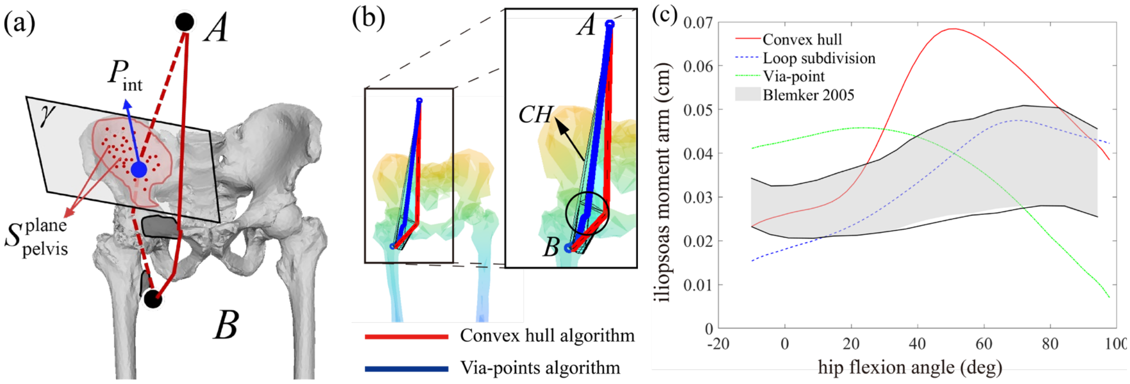

Figure 1: (a) Anti-penetration criterion; (b) Comparison between the proposed method and the via-point algorithm; (c) Comparison of the iliopsoas moment arm in relation to hip flexion [4]

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