Flexible Multibody Modeling of Muscle Wrapping Based on ANCF and Its Applications in Human-Machine Interactions

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1 Introduction

The muscles wrap around their underlying bone segments in human musculoskeletal system, and the obtained curved muscle paths strongly influence their nonlinear dynamic responses [1]. Researchers often simplify muscle wrapping as the shortest path problem without considering time-dependent muscle-bone contact [2]. In comparison, conventional finite element method (FEM) of skeletal muscles introduces expensive computational costs [3]. To describe nonlinear muscle-bone wrapping with acceptable computational cost, a flexible multibody modeling of the skeletal muscle was established based on absolute nodal coordinate formulation (ANCF). It was further utilized in evaluating the human-machine interactions of wearing a space suit based on forward dynamics simulations.

2 ANCF muscle element with variable cross-section

The full-parameterized ANCF element is established to simultaneously consider the fusiform geometry, distributed mass, and muscle activations of skeletal muscles. The cross-sectional geometry perpendicular to the beam axis can be expressed as a category of superellipse curves, and the radius of the curves is assumed to be described by a quartic polynomial [4] (Figure 1). The skeletal muscle consists of contractile fiber bundles and soft tissue matrix, and its volume almost remains unchanged during contraction. The stress within the muscle belly $\boldsymbol{\sigma}^{\mathrm{mus}}$ is described as the sum of the Hill-type fiber stress $\boldsymbol{\sigma}^{\mathrm{f}}$, the hyperelastic matrix stress $\boldsymbol{\sigma}^{\mathrm{m}}$, and the bulk stress $\boldsymbol{\sigma}^{\mathrm{b}}$ denoting its constant volume characteristics:

$$\boldsymbol{\sigma}^{\mathrm{mus}} = \boldsymbol{\sigma}^{\mathrm{f}} + \boldsymbol{\sigma}^{\mathrm{m}} + \boldsymbol{\sigma}^{\mathrm{b}} \tag{1}$$

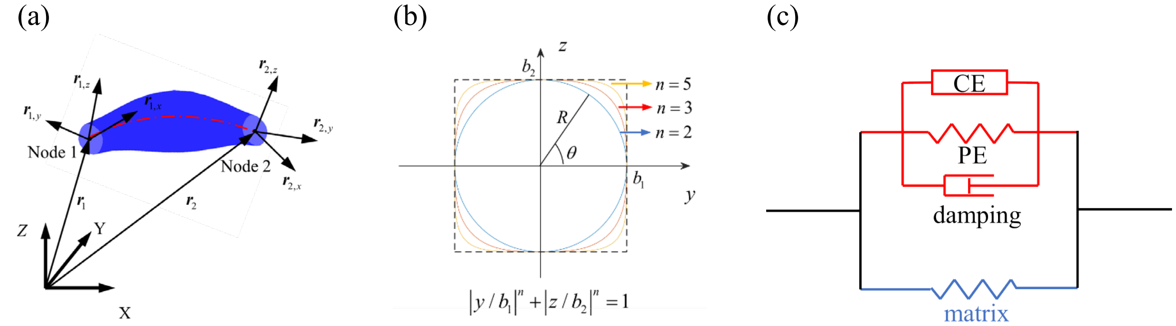

Figure.1: ANCF muscle element. (a) The element and its corresponding generalized coordinates; (b) the super-ellipse description of the elemental cross section; (c) Hill-type muscle model in parallel connection with the passive stiffness of the interfiber matrix and a linear damping;

3 Muscle wrapping description based on beam-to-beam contact

A surface-to-surface beam contact formulation is presented to describe muscle wrapping based on the proposed ANCF muscle element. The minimal distance criterion is used to find the closest points between the two beams and to determine whether two beams contact. The master-slave method is then adopted to search the contact zone. The shape and position of the contact zone can be accurately captured due to the solid element-like feature of the full-parameterized element. The pointwise contact force is calculated based on the penalty method, and the generalized contact force of the contact zone can be obtained numerically using double Gauss quadrature.

The dynamic equations of the whole system can be expressed as:

$$\begin{cases} \boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{F}(\boldsymbol{q},\dot{\boldsymbol{q}},\boldsymbol{a},t) + \boldsymbol{C}_{\boldsymbol{q}}^{\mathrm{T}}\boldsymbol{\lambda} = \boldsymbol{0}, \\ \boldsymbol{C}(\boldsymbol{q},t) = \boldsymbol{0}, \end{cases} \tag{2}$$

where $\boldsymbol{M}$ is the mass matrix of the system, $\boldsymbol{q}$ is the vector of generalized coordinates, $\boldsymbol{F}$ is the generalized force vector including muscle force, muscle-bone contact force, and the external force applied to the system. $\boldsymbol{C}$ represents the system constraint conditions, $\boldsymbol{C}_{\boldsymbol{q}}$ is the constraints Jacobian matrix corresponding to $\boldsymbol{q}$, and $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers. The generalized-α method is utilized to solve the index-3 differential algebraic equations [5].

4 Applications in human-machine interaction analysis

A forward dynamics simulation of the sagittal elbow flexion considering the inflation pressure of space suit was presented. A simplified musculoskeletal model of upper limb was established; see Figure 2(a). The model consisted of three rigid bones and five muscle fibers representing the biceps and triceps brachii. Their parameters were obtained from Gfrerer and Simeon [4]. The upper arm was assumed to be fixed to the ground, and the humerus bone only had the flexion/extension DOF. A wrapping surface with cylindrical shape was also introduced to force the triceps fibers to wrap around the elbow. The sagittal arm movements were driven by the prescribed muscle activation curves . For simplicity, we neglected the time-dependent contact behavior between the suit and the underlying muscle tissues. The inflation pressure acting on the muscle surface $\boldsymbol{p}$ was transformed to the distributed nodal loads according to the virtual work principle:

$$\oint_S \boldsymbol{p}\delta\boldsymbol{r}\mathrm{d}S = \sum_{i=1}^{N}\boldsymbol{P}_i\delta\boldsymbol{e}_i, \tag{3}$$

where $\boldsymbol{p}$ is the inflation pressure, $\boldsymbol{r}$ is the position vector, $\boldsymbol{P}_i$ is the vector of generalized distributed nodal force, $\boldsymbol{e}_i$ is the vector of nodal generalized coordinates.

The simulation results are shown in Figure 2(b). During elbow flexion movements, the muscle paths of the biceps brachii are adjusted due to the inflation pressure, resulting in the change of the elbow range of motions and the muscle stress distributions.

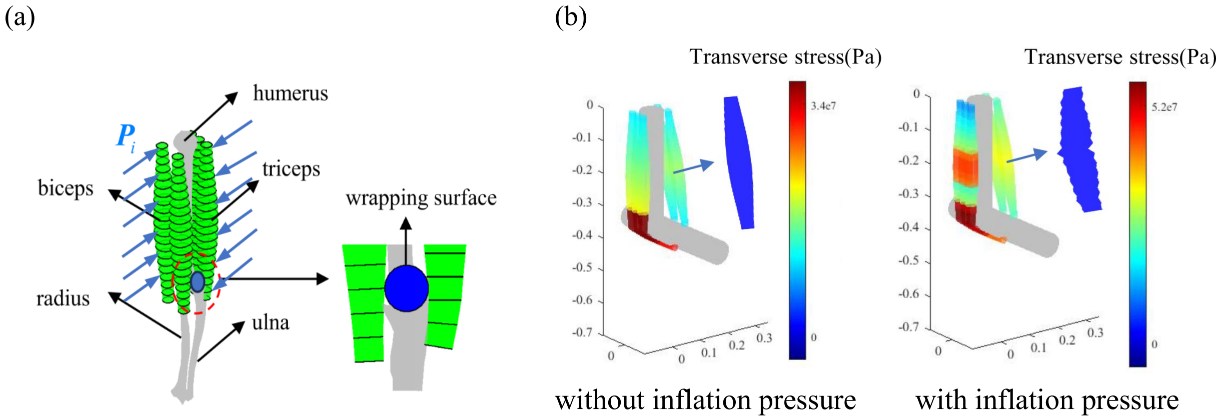

Figure 2: The sagittal elbow flexion. (a) simplified musculoskeletal model of upper limb; (b) comparison of muscle stress distribution

5 Summary and conclusion

The proposed ANCF muscle element successfully considered the fusiform geometry and the cross-sectional changes during muscle wrapping. The surface-to-surface contact model captures the stress distributions within the muscle belly. The inclusion of a Hill-type muscle model further realizes muscle-driven forward dynamics simulation with gas-pressurized space suit. The established numerical method provides an efficient analysis tool to describe muscle-bone force transmissions, highlighting its potential in evaluating the biomechanical responses of dynamic human-machine interactions.

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