Flexible multibody modeling of skeletal muscle considering the muscular bundle-fasciae coupling

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Summary

Complicated nonlocal interactions may occur between muscle bundles and muscular fasciae during the muscle contractions, while most existing biomechanical models simplified the muscle as a single force element and overlooked the nonlinear mechanical properties of muscular fasciae. This study established a flexible multibody model to demonstrate the change of force transmission caused by the muscular fasciae. Based on the Mortar contact method, the nonlinear coupling between the muscle bundles and muscular fasciae was regarded as mismatched one-dimensional beams embedded into three-dimensional solids. Here, reduced beam elements with a typical Hill-type model were developed using the absolute nodal coordinate formulation (ANCF). The muscular fasciae were discretized by tetrahedron elements with a hyperelastic constitutive relation. As a validation, a static simulation of muscle contraction was performed.

Introduction

The skeletal muscle is composed of active muscle fibers and muscle fasciae, which is a passive matrix of connective tissues surrounding fibers [1]. Muscle fasciae play a crucial role in muscle force transmission [2]. However, most existing models simplify the muscle as a spring, which cannot account for the three-dimensional mechanical behaviors. As an alternative, the detailed finite element model based on continuum mechanics lumped the passive and active properties of muscle in one finite element, which cannot explicitly distinguish the contributions of muscle fasciae and fiber bundles. To describe force transmission caused by the muscular fasciae, in this study, a flexible multibody muscle model based on the Mortar method is presented.

Methods

Both the muscle bundle and the muscular fasciae are discretized using ANCF elements. The muscle bundle is assumed to be a cable with tensile stress only and discretized by reduced beam elements. A typical Hill-type muscle constitutive model is adopted to simulate the muscle bundle contraction. The muscular fasciae is discretized by tetrahedron elements with a hyperelastic constitutive relation.

As shown in Figure 1(a), the muscle bundle represented by a beam is embedded inside the solid fascia. The constraint condition is described as the beam axis coupling with the solid volume. Based on the Mortar method [3], a Lagrange multiplier vector field, corresponding to the interaction force, is defined on the beam axis. The constraint condition can be expressed in a weak formulation as an integral over the Mortar space. Finally, the governing equations of the coupling system can be obtained according to the principle of virtual work and solved using Newton-Raphson iteration.

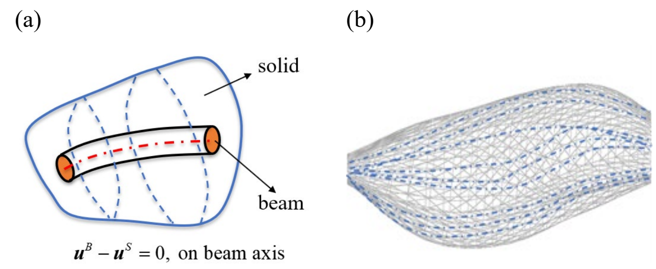

Figure.1: The muscle bundle-fascia coupling. (a) muscle bundle is embedded inside the fascia volume; (b) deformed configuration of biceps muscle belly.

Results and Discussion

As a validation, a static simulation of biceps muscle contraction was presented. Nine bundles of muscle fibers are arranged within the muscle belly. The initial geometrical arrangements of the muscle bundles were reconstructed by assuming the muscle belly to be non-compressible fluid [4]. The deformed configuration of the biceps muscle is presented in Figure 1(b).

Conclusions

A flexible multibody muscle model is presented based on the Mortar method. Numerical benchmarks proved that the established method provided an efficient tool to describe the coupling between muscle bundles and muscular fasciae.

Acknowledgments

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References

[1] Yucesoy CA et al.(2002). *J. Biomech*, **35**: 1253-1262.
[2] Huijing PA(1999). *Arch. Physiol. Biochem*. **107**: 292-311.
[3] Steinbrecher I(2020). *Comput. Mech*. **66**: 1377-1398.
[4] Choi HF et al.(2013). *PLOS One*. **8**: e77576