Physically motivated strain energy for an architecturally detailed muscle model

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INTRODUCTION

The deformation of the muscle-tendon complex in response to forces depends on architectural design, tissue properties and architecture. In this study we derive a mathematical model of muscle which is amenable to finite element simulation, and which allows for flexible prescription of constitutive laws that encapsulate many of the known material properties of muscle. These include isotropic behaviour along directions transversely oriented to the local fibre direction, as well as the ability to independently vary the activation states of different regions of the muscle. We incorporate different incompressible, transversely isotropic hyperelasticity. We assume the local stresses arise purely in response to the local changes in configuration and neglect, for the current study, the history-dependent contributions. The stresses can be derived from a strain-energy function that must be invariant under changes of the observer's frame of reference, and that must also possess the transverse symmetry associated with muscle fibres. We explicitly include the fibre direction into this strain energy function. The invariants of the Cauchy-Green deformation tensor provide other contributions to the strain energy, and encode information on the local muscle properties.

We are then able to construct a suitable model of strain energy, which can be used to calculate deformations of the muscle-tendon complex under different loading conditions.

METHODS

Starting from a continuum description of a nearly-incompressible fibre-reinforced material, we derive constitutive laws that encapsulate many of the known properties of muscle. These include isotropic behaviour along directions transversely oriented to the local fibre direction, as well as the ability to independently vary the activation states of different regions of the muscle. We incorporate different tissues in the muscle-tendon complex by appropriate choices of material properties.

There are many studies that have modeled muscle responses in different loading conditions. In many earlier works simpler elements (i.e. spring-damper) and formulations were used. In order to have a muscle model with detailed architecture and be able to replicate many loading conditions a finite element study seems to be more practical. Among the strain energy functions that have been used for modeling soft tissues (including muscle) there are two distinct approaches. The first approach (i.e. Weiss et al. 1996) had its strain energy based on invariants of a Cauchy-Green deformation tensor (classic formulation). The benefit of this formulation is that it is much easier to solve for the elasticity equation, and avoids higher levels of nonlinearity when compared to formulations from the second approach (i.e. Criscione et al. 2001). However, the second approach defined physically-based invariants and allows a faster and more understandable way in defining material constants using experimentally measured material properties.

In this study we introduce a new strain energy function, derived from both these previous approaches, to model muscle tissue elasticity.

DISCUSSION & CONCLUSIONS

The physically based invariants introduced by Criscione et al. (2001), beside developing a higher degree of nonlinearity, seem to depend on the order that consecutive loadings are evaluated (i.e. cross-fiber shear, along-fiber stretch and along-fiber shear). This makes the formulation unreliable for some situations such as dynamic loading.

In analogy with prior work (see i.e. Blemker et al. 2005 or Criscione et al. 2001), we also describe invariants of motion which can be related to experimentally-measurable quantities. These in turn enable the measurement of elasticity parameters in the model. However, the strategy to solve the finite element solution will be based on classical hyperelasticity strategies, using the constitutive laws for muscle.

REFERENCES

