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On the derivation of passive 3D material parameters from 1D stress–strain data of hydrostats

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A B S T R A C T

The present paper offers a novel equivalent-pressure approach to the derivation of isotropic passive muscle parameters from 1D stress–strain data sets. The approach aims specifically at the identification of material parameters in hydrostats, in which case the equivalent-force approach that is common for skeletal muscle generates suboptimal results. Instead, an equivalent-pressure hypothesis is formulated which provides more adequate boundary conditions for the concluding curve-fitting procedure.

The choice of an appropriate constitutive description is decisive for the quality of the deduced parameter sets. Here, a Yeoh material law is chosen for the model of a squid tentacle. Parameters derived by both, equivalent-force and equivalent-pressure algorithms, are compared, illustrating the applicability limits of either. They are implemented in a finite element model of the tentacle. A prey-capture strike is simulated and compared to data from literature. The hydrostat-specific interpretation of the equivalent-pressure hypothesis is shown to match the reference very well.

1. Introduction

In recent years several studies have been published in which finite element models were employed to investigate truly 3D behavior of muscles and muscle tissue. These models enable us to derive information regarding 3D strain and stress states, fiber course and pennation, transversal stiffness, and further properties which are in general not accessible through one-dimensional simulations. Previous 1D models were often complemented with geometric coupling constraints in order to account for specific 3D properties, such as incompressibility in case of hydrostats (Van Leeuwen and Kier, 1997). But these approaches cannot be regarded as thorough equivalent substitutes for 3D continuum descriptions.

Nonetheless it is common practice to utilize 1D data for calibration and verification of 3D models. This is due to the intricacy of an experimental determination of conclusive 3D data on the one hand, and due to the wealth and quality of readily available 1D data on the other hand.

Data from hydrostats are particularly expedient for verifications, as shown by Meier and Blickhan (2000), Liang et al. (2006), and Tang et al. (2009). Measurements on these structures reveal more about their passive properties than comparable data of skeletal muscles, in which fibers are roughly aligned with the external loads. But this special quality also requires a careful investigation of the model-specific differences. While muscle is frequently regarded as incompressible due to its high ratio of bulk to Young's modulus, its implementation into displacement based FE codes has to allow for dilatation. For hydrostat modeling, however, this is not only a necessity with respect to the algorithms, but also important for the validity of the model's energy balance.

The specification of a bulk modulus κ and the subsequent adaption to an existing force-stretch function do not suffice to optimally derive the passive material parameters of a hydrostat. An alternative pressure-consistent approach is proposed and assessed. The algorithm is illustrated using the example of a squid tentacle strike (Kier and Van Leeuwen, 1997). Specific material parameters were deduced and implemented in a FE model of the tentacle. Results are compared to the original model, which was optimized by Kier and van Leeuwen to match the experimental data.

2. On the constitutive modeling of muscle tissue

Most 3D muscle models (Johansson et al., 2000; Maenhout, 2002; Blemker et al., 2005; Ito et al., 2009) are based on the additive superposition of an unidirectional muscle fiber description and a hyperelastic description of the tissue matrix. The latter builds mostly on established isotropic hyperelastic material laws, for example Ogden or Mooney–Rivlin. Active fiber properties are

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