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Viscous elements have little impact on measured passive length–tension properties of human gastrocnemius muscle–tendon units *in vivo*

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ABSTRACT

Several studies have measured the elastic properties of a single human muscle–tendon unit *in vivo*. However the viscoelastic behavior of single human muscles has not been characterized. In this study, we adapted QLV theory to model the viscoelastic behavior of human gastrocnemius muscle–tendon units *in vivo*. We also determined the influence of viscoelasticity on passive length–tension properties of human gastrocnemius muscle–tendon units. Eight subjects participated in the experiment, which consisted of two parts. First, the stress relaxation response of human gastrocnemius muscle–tendon units was determined at a range of knee and ankle angles. Subsequently, passive ankle torque and ankle angle were collected during cyclic dorsiflexion and plantarflexion at a range of knee angles. Viscous parameters were determined by fitting the stress relaxation experiment data with a two-term exponential function, and elastic parameters were estimated by fitting the QLV model and viscous parameters to the cyclic experiment data. The model fitted the experimental data well at slow speeds (RMSE: 1.7 ± 0.5 N) and at fast speeds (RMSE: 1.9 ± 0.2 N). Muscle–tendon units demonstrated a large amount of stress relaxation. Nonetheless, viscoelastic passive length–tension curves estimated with the QLV model were similar to elastic passive length–tension curves obtained using a model that ignored viscosity. There was little difference in the elastic passive length–tension curves at different loading rates. We conclude that (a) the QLV model can be used to quantify viscoelastic behaviors of relaxed human gastrocnemius muscle–tendon units *in vivo*, and (b) over the range of velocities we examined, the velocity of loading has little effect on the passive length–tension properties of human gastrocnemius muscle–tendon units.

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1. Introduction

Hoang et al. (2005) developed a non-invasive method to measure the elastic passive length–tension properties of a single human muscle *in vivo*. The method, which was based on a method originally described by Herzog and ter Keurs (1988), involves measuring passive ankle torques at a range of knee angles and using optimization to identify parameters of the elastic passive length–tension curve from the torque–angle data. The method was later combined with ultrasonographic measures of muscle fascicle length to determine the elastic passive length–tension properties of the gastrocnemius muscle fascicles and tendon (Hoang et al., 2007). More recently, Nordez et al. (2009a) further refined the method by reducing the number of parameters in the model used to analyze the data.

Several studies on animal muscles have shown that skeletal muscles do not act as elastic springs. Instead, the force response of skeletal muscles is dependent on the rate of elongation. That is, muscles behave viscoelastically (Buchthal et al., 1951; Best et al., 1994; Bagni et al., 1999). Nordez et al. (2009b) implemented and validated a rheological model in human ankles. This model accounted for both velocity dependence and dissipative properties of the passive ankle, but did not determine the properties of individual muscle–tendon units. The existing studies on the properties of a single human muscle–tendon unit (e.g. Hoang et al., 2005; Nordez et al., 2009a) have only examined elastic behavior. To our knowledge, loading rate dependence and other viscoelastic behaviors have not been examined in single muscle–tendon units in human subjects.

It may be possible to characterize viscoelastic behaviors of muscle–tendon units using quasi-linear viscoelastic (QLV) theory (Fung, 1993). Best et al. (1994) measured the viscoelastic responses of live rabbit tibialis anterior and extensor digitorum longus muscles and successfully modeled hysteresis and force responses to constant velocity deformation using QLV theory.

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