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Research Paper

Viscoelastic properties of the human sternocleidomastoideus muscle of aged women in relaxation

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ABSTRACT

Improving the numerical models of the head and neck complex requires understanding the mechanical properties of the muscles; however, most of the data in existing literature have been obtained from studies on animal muscles. Muscle is hyper-elastic, but also viscoelastic. The hyper-elastic behaviour of the human sternocleidomastoideus muscle has been previously studied. The aim of this study is to propose a characterization of the viscoelastic properties of the same human muscle in relaxation. Ten muscles were tested *in vitro*. The viscoelastic behaviour was modelled with a generalized Maxwell's model studied at the first and second order, using an inverse approach with a subject-specific, finite-element model of each muscle. Based on these models, relaxation times τ (first order: 103 s; second order: 18 s and 395 s) and ratio moduli γ (first order: 0.33; second order: 0.20 and 0.19) were identified. The first-order model provided a good estimate of the relaxation curve (R^2: 0.82), but the second-order model was more representative of the experimental response (R^2: 0.97). Our results provide evidence that the viscoelastic behaviour of the human sternocleidomastoideus muscle can be described using a second-order Maxwell's model and that – combined with the previously identified hyper-elastic properties – the response of the muscle in tension and relaxation is fully characterized.

1. Introduction

Human body models are useful numerical tools in clinical, impact biomechanics or industrial applications. To be representative of the human body's response, these models require mechanical properties of the different tissues of the body, especially for the muscles. In order to assess these mechanical properties, the passive behaviour of the muscle has primarily been studied *in vitro*.

Mechanical tests such as compression tests (Aimedieu et al., 2003; Bosboom et al., 2001; Chawla et al., 2009; Dhaliwal et al., 2002; Gras et al., 2012a; McElhaney, 1966; Song et al., 2007; Takaza and Simms, 2012; Van Loocke et al., 2006, 2008, 2009; Untaroiu et al., 2005) or tensile tests (Anderson et al., 2001, 2002; Davis et al., 2003; Gottsauner-Wolf et al., 1995; Gras et al., 2012b, 2012c; Lin et al., 1999; Morrow et al., 2010; Myers et al., 1995, 1998; Noonan et al., 1993, 1994; Takaza et al., 2013; Yamada, 1970) have been

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conducted. However, most of these experiments were performed on animal muscles. Only Chawla et al. (2009), Dhaliwal et al. (2002) and Untaroiu et al. (2005) studied human muscles in compression, while Gras et al. (2012b) and Yamada (1970) studied them in tension.

The passive response of muscle is hyper-elastic and viscoelastic. The hyper-elastic behaviour is often described with constitutive laws derived from strain-energy functions (Bosboom et al., 2001; Hedenstierna et al., 2008; Johansson et al., 2000; Untaroiu et al., 2005; Weiss et al., 1996). The viscoelasticity of the muscle tissue can be studied in different ways, such as tests performed at various strain rates (Aimedieu et al., 2003; Best et al., 1994; Chawla et al., 2009; Gras et al., 2012c; Hawkins and Bey, 1997; McElhaney, 1966; Myers et al., 1995, 1998; Noonan et al., 1993, 1994; Song et al., 2007; Takaza and Simms, 2012; Taylor et al., 1990; Van Loocke et al., 2008; Sligtenhorst et al., 2006) or relaxation tests (Anderson et al., 2001, 2002; Bosboom et al., 2001; Myers et al., 1995; Van Loocke et al., 2008, 2009). The viscoelastic response of the model is then modelled with, for instance, the quasi-linear theory of viscoelasticity (Best et al., 1994; Myers et al., 1995, 1998; Van Loocke et al., 2008, 2009) or a simple rheological model, such as Kelvin–Voigt's or Maxwell's model (Aimedieu et al., 2003; Anderson et al., 2001, 2002; Chawla et al., 2009). The Maxwell's model can be considered at the first order (Anderson et al., 2001); however, the first-order model might not sufficiently describe a load relaxation of the muscle compared to a second-order model (Best et al., 1994).

In crash loadings, the head and neck complex can be highly stretched at strain rates depending on the acceleration level of the crash. Several head and neck models have recently been developed (Brolin et al., 2005; Frechede et al., 2005, 2006; Hedenstierna et al., 2009; Fice and Cronin, 2012). However, the mechanical properties of the muscles are based on animal muscle data. In Gras et al. (2012b), the hyper-elasticity of the human sternocleidomastoideus muscle in tension has been characterized using an inverse approach with a subject-specific finite-element model. However, its viscoelastic properties were not evaluated.

Therefore, in order to get the full characterization of the human sternocleidomastoideus muscle (i.e., hyper-elasticity and viscoelasticity), this study proposes a simple viscoelastic model based on the generalized Maxwell's model to characterize the response of the muscle in relaxation.

2. Material and methods

2.1. Experimental protocol

The tested specimens and the experimental protocol applied in this study were partially described in Gras et al. (2012b). Ten human sternocleidomastoideus muscles were tested. The mean age of the donors was 58 years old (min: 50 years old; max: 66 years old). After dissection, the muscles were frozen at −20 °C. Before the test, the muscles were thawed for 12 h in a saline bath at 4 °C and then brought to room temperature for 2 h (Gottsauner-Wolf et al., 1995; Van Ee et al., 2000).

After the acquisition of the muscle's geometry to create a subject-specific finite-element model of the muscle and after a pre-cycling phase to stabilize its mechanical properties, a tensile test was performed at a velocity of 10 mm min^{-1} and with an amplitude of 20 mm. This maximum displacement was then maintained for 14 min in order to observe the load relaxation. This final step was used to analyse the muscle's viscoelastic behaviour. Load F (N), displacement d (m) and time t (s) were recorded. The muscle was regularly moistened with saline solution to avoid dehydration.

2.2. Viscoelastic behaviour: Finite-element method

Subject-specific finite-element models of each muscle were used to identify the viscoelastic mechanical properties of each muscle. These finite-element models were based on the 3D reconstructions of the muscles acquired before the tests (Gras et al., 2012b). Each model was composed of 2010 nodes and 1508 8-node elements.

The simulations to reproduce the muscle behaviour in tension and relaxation were performed using RADIOSS (Altair HyperWorks®), with an implicit formulation. In order to represent the experimentation, the lower nodes of the model were blocked in translation and rotation to simulate the embedding of the muscle's lower extremity; the upper nodes were submitted to 20 mm displacement along the vertical axis at 10 mm min^{-1}. This displacement was then maintained for 14 min. The load was calculated in the top layer of the elements.

The material was modelled as homogeneous to simplify the approach and because the objective was to assess the mechanical properties of the entire muscle structure. The constitutive law was hyper-elastic, as described in Gras et al. (2012b), as well as viscoelastic.

The hyper-elastic behaviour is based on Ogden's law (Ogden, 1972) and defined with a strain energy per unit volume W (J m^{-3}) (Simo, 1987; Simo and Hughes, 1998) (1):

$$W = 2\mu\alpha^{-2}[\lambda_1^{\alpha} + \lambda_2^{\alpha} + \lambda_3^{\alpha} - 3 + \beta^{-1}(J^{-\alpha\beta} - 1)] \tag{1}$$

The λ_i are the principal stretches (dimensionless). J is the volumetric strain (dimensionless). The parameter μ (Pa) is a shear modulus, and α (dimensionless) is a curvature parameter. The parameter β (dimensionless) is related to Poisson's ratio ν (2).

$$\beta = \nu/(1-2\nu) \tag{2}$$

The material was considered to be almost incompressible, and Poisson's ratio was fixed at 0.495 (Behr et al., 2006; Blemker et al., 2005; Blemker and Delp, 2006; Bosboom et al., 2001; Johansson et al., 2000; Weiss et al., 1996). The μ and α parameters were identified with the tensile phase (Gras et al., 2012b) and then used in the material definition proposed here.

The viscoelastic model was based on the generalized Maxwell's model. The rheological model was composed of a non-linear spring whose behaviour was defined by the hyper-elastic law, in parallel with two spring-damper systems. Each of the model's spring-damper systems were described by two parameters: relaxation time (3) and ratio of elastic moduli (4).

$$\tau_k = \eta_k/E_k \tag{3}$$

$$\gamma_k = E_k/(E_0 + \Sigma E_k) \tag{4}$$