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A mass–length scaling law for modeling muscle strength in the lower limb

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ABSTRACT

Musculoskeletal computer models are often used to study muscle function in children with and without impaired mobility. Calculations of muscle forces depend in part on the assumed strength of each muscle, represented by the peak isometric force parameter, which is usually based on measurements obtained from cadavers of adult donors. The aim of the present study was twofold: first, to develop a method for scaling lower-limb peak isometric muscle forces in typically-developing children; and second, to determine the effect of this scaling method on model calculations of muscle forces obtained for normal gait. Muscle volumes were determined from magnetic resonance (MR) images obtained from ten children aged from 7 to 13 yr. A new mass–length scaling law was developed based on the assumption that muscle volume and body mass are linearly related, which was confirmed by the obtained volume and body mass data. Two musculoskeletal models were developed for each subject: one in which peak isometric muscle forces were estimated using the mass–length scaling law; and another in which these parameters were determined directly from the MR-derived muscle volumes. Musculoskeletal modeling and quantitative gait analysis were then used to calculate lower-limb muscle forces in normal walking. The patterns of muscle forces predicted by the model with scaled peak isometric force values were similar to those predicted by the MR-based model, implying that assessments of muscle function obtained from these two methods are practically equivalent. These results support the use of mass–length scaling in the development of subject-specific musculoskeletal models of children.

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1. Introduction

Musculoskeletal models are often used to study the gait patterns of adults and children with and without impaired mobility (Liu et al., 2008; Fox et al., 2009; Steele et al., 2010; Correa et al., 2011). These models commonly describe the force-generating properties of muscle using a five-parameter 'Hill-type' muscle-tendon unit (Zajac, 1989). The parameter that represents strength is peak isometric muscle force, which is defined as the contractile force produced by a fully-activated muscle when the muscle is held at its optimum fiber length (Zajac, 1989; Kaufman et al., 1991). Most modeling studies have employed generic values of peak isometric force based on muscle size measurements obtained from cadavers of adult donors (e.g., Amis et al., 1979; Wickiewicz et al., 1983; Friederich and Brand, 1990). It is clear, however, that peak isometric forces ought to be determined on a subject-specific basis, particularly in studies involving children.

Muscle strength can be estimated *in vivo* using several approaches. The maximum isometric torque developed about a joint can be measured during a maximum voluntary contraction (e.g., Knapik et al., 1983). Unfortunately, the strength of an individual muscle cannot be determined by this method because dynamometer measurements yield only the net torque developed by all the muscles spanning a joint. In addition, maximum voluntary contractions are difficult to elicit even from healthy subjects, let alone those affected by neurological conditions such as cerebral palsy and stroke. Peak isometric force may be estimated for an individual muscle on the basis of muscle size (Bamman et al., 2000), which can be measured using magnetic resonance (MR) imaging (e.g., Narici et al., 1988; Tate et al., 2006). This is commonly done by multiplying the muscle's physiological cross-sectional area (PCSA) by a nominal value of maximum muscle stress, often referred to as specific tension (Zajac, 1989; Delp et al., 1990; Garner and Pandy, 2003). Since PCSA is defined as the cross-sectional area of a muscle when measured perpendicular to the direction of the muscle fibers (Roy and Edgerton, 1992), peak isometric muscle force may be estimated as follows:

$$F_{max} = PCSA \times \sigma = \frac{Vol \times \cos(\alpha)}{l_0} \times \sigma \quad (1)$$

where σ denotes muscle specific tension; Vol is the muscle volume; and α and l_0 are muscle pennation angle and optimal

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