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Short communication

A method to characterize *in vivo* tendon force–strain relationship by combining ultrasonography, motion capture and loading rates

Pauline Gerus*, Guillaume Rao, Eric Berton

Institute of Movement Sciences E-J Marey, UMR CNRS 6233, Aix-Marseille Université, Parc Scientifique et Technologique de Luminy, 163, Avenue de Luminy,13288 Marseille, France

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ABSTRACT

The ultrasonography contributes to investigate *in vivo* tendon force–strain relationship during isometric contraction. In previous studies, different methods are available to estimate the tendon strain, using different loading rates and models to fit the tendon force–strain relationship. This study was aimed to propose a standard method to characterize the *in vivo* tendon force–strain relationship. We investigated the influence on the force–strain relationship for *medialis gastrocnemius* (MG) of (1) one method which takes into account probe and joint movements to estimate the instantaneous tendon length, (2) models used to fit the force–strain relationship for uniaxial test (polynomial vs. Ogden), and (3) the loading rate on tendon strain. Subjects performed ramp-up contraction during isometric contractions at two different target speeds: 1.5 s and minimal time with ultrasound probe fixed over the muscle–tendon junction of the MG muscle. The used method requires three markers on ultrasound probe and a marker on calcaneum to take into account all movements, and was compared to the strain estimated using ultrasound images only. The method using ultrasound image only overestimated the tendon strain from 40% of maximal force. The polynomial model showed similar fitting results than the Ogden model ($R^2=0.98$). A loading rate effect was found on tendon strain, showing a higher strain when loading rate decreases. The characterization of tendon force–strain relationship needs to be standardized by taking into account all movements to estimate tendon strain and controlling the loading rate. The polynomial model appears to be appropriate to represent the tendon force–strain relationship.

1. Introduction

Ultrasonography (US) associated with force measurements contributes to estimate the tendon force–strain relationship during muscle contraction (Maganaris, 2002) and allows to compare populations differing on age (Kubo et al., 2000) or sex (Burgess et al., 2008). Consequently, a method that accurately estimates the tendon force–strain relationship is essential.

During isometric contractions meaning that the muscle–tendon complex is held at constant length, firmly fixing the foot on plate does not prevent from movement of the body. Different methods were used to estimate *in vivo* muscle–tendon junction (MTJ) displacement while minimizing the measurement errors due to joint and probe movements. One method consists in using a skin marker and fixing the ultrasound probe (Burgess et al., 2008) on the leg but it leads to overestimation of the MTJ elongation (Muramatsu et al., 2001). Another method called passive correction (Maganaris, 2005) using additional measurements during passive task lead to inaccurate elongation value (Maganaris, 2005). An alternative method (Maganaris, 2005) requiring the use of two ultrasound probes over the MTJ and the calcaneum remains restrictive because of the second probe. These previous methods lead to either erroneous MTJ elongation or need additional tasks or US devices. A previous method combining motion capture and ultrasonography and providing an easy way to estimate the instantaneous tendon length has been used for dynamics tasks (Lichtwark and Wilson, 2005). However, this promising method has not been used during isometric contractions whereas this particular task is often used to characterize the tendon mechanical properties.

The tendon presents a non-linear behavior that could be represented in Finite Elements Modeling (FEM) by a hyperelastic mechanical model, such as Ogden formulation (Cheng et al., 2008; Shibata et al., 2006). *In vivo* force–strain relationships were also fitted using a second-order polynomial function (Burgess et al., 2008; Pearson et al., 2007) based on good fitting with experimental data. It is not known whether the use of a second-order polynomial fit is able to catch all the features of the force–strain relationship in comparison with an Ogden model.

The tendon force–strain relationship has been previously estimated during different loading rates meaning that different ramp-up

* Corresponding author. Tel.: +33 491 17 04 78; fax: +33 491 17 22 52.
E-mail address: pauline.gerus@univmed.fr (P. Gerus).

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