Journal of Biomechanics 44 (2011) 2106–2112

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short range stiffness elastic limit depends on joint velocity

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ARTICLE INFO

Article history:
Accepted 17 May 2011

Keywords:
Short range stiffness
Joint stiffness
Muscle
Cross-bridges
Elastic limit
Model
Identification

ABSTRACT

Muscles behave as elastic springs during the initial strain phase, indicated as short range stiffness (SRS). Beyond a certain amount of strain the muscle demonstrates a more viscous behavior. The strain at which the muscle transits from elastic- to viscous-like behavior is called the elastic limit and is believed to be the result of breakage of cross-bridges between the contractile filaments. The aim of this study was to test whether the elastic limit, measured in vivo at the wrist joint, depended on the speed of lengthening. Brief extension rotations were imposed to the wrist joint ($n=8$) at four different speeds and at three different levels of voluntary torque using a servo controlled electrical motor. Using a recently published identification scheme, we quantified the elastic limit from measured joint angle and torque. The results showed that the elastic limit significantly increased with speed in a linear way, indicating to a constant time of approximately 30 ms before cross-bridges break. The implications for movement control of the joint are discussed.

1. Introduction

Muscles exhibit a relatively high stiffness over a short time interval just after an imposed length change, referred to as the short range stiffness, or SRS (Kirsch et al., 1994; Lin and Rymer, 1993; Morgan, 1977; Rack and Westbury, 1974; Walmsley and Proske, 1981). When lengthening or shortening continues, the stiffness drops and the muscle starts to act more like a viscous damper (Rack and Westbury, 1974). The length change or strain at which transition from high to low stiffness occurs is known as the elastic limit (Campbell and Lakie, 1998). For movement control, in particular the maintenance of body posture, regulation of joint stiffness is important for minimization of joint displacement in the presence of (external) disturbing forces. In particular, the response to the first part of an unexpected movement must largely be determined by the muscle properties since some time is required before any form of reflex response can develop (Grillner, 1972). In that respect it is important to determine the elastic limit under various loading conditions. The elastic limit has been studied extensively from single muscle fibers or muscles in animal preparations (Cui et al., 2007; Kirsch et al., 1994; Lin and Rymer, 1993; Morgan, 1977; Walmsley and Proske, 1981). From these studies it can be concluded that the elastic limit increases with the velocity of lengthening (Campbell and Lakie, 1998). However, a systematic study on the effect of joint angular velocity on the elastic limit in humans is lacking. Past studies on the in vivo human joint that focused on SRS were limited to passive conditions and slow movements to avoid additional torque changes from stretch reflexes (Axelson and Hagbarth, 2001; Lakie et al., 1984; Loram et al., 2007). Using an identification procedure we were able to estimate SRS and its concomitant elastic limit in vivo at different levels of muscle activation and fast rotations (van Eesbeek et al., 2010).

The main goal of the present study was to test the dependency of SRS and the elastic limit on wrist joint rotation velocity and voluntary torque. The results are important for future studies on neuromuscular control and disorders of joint impedance.

2. Methods

Essential aspects of the used method for estimation of short range stiffness (SRS) are provided but for a full description of the method the reader is referred to a previous study (van Eesbeek et al., 2010).

2.1. Instrumentation

Ramp-and-Hold (RaH) extension rotations were imposed to the wrist joint by an electric motor, controlled as a stiff (1000 N m/rad) servo. The wrist flexion-extension axis was aligned to the motor axis. The forearm was immobilized with respect to the hand using clamps at distal and proximal radius and ulna such that

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doi:10.1016/j.jbiomech.2011.05.022