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Measurement of active muscle stiffness with and without the stretch reflex

Keitaro Kubo *, Tomonobu Ishigaki, Toshihiro Ikebukuro

Department of Life Science, University of Tokyo, Meguro, Tokyo, Japan

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ABSTRACT

The purpose of the present study was to evaluate active muscle stiffness with the stretch reflex according to changes (in 110-ms period after stretching) in torque and fascicle length during slower angular velocity (peak angular velocity of 100 deg·s^{-1}) in comparison with active muscle stiffness without the stretch reflex (in 60-ms period after stretching) during slower and faster (peak angular velocity of 250 deg·s^{-1}) angular velocities. Active muscle stiffness in the medial gastrocnemius muscle was calculated according to changes in estimated muscle force and fascicle length with slower and faster stretching during submaximal isometric contractions (10–90% maximal voluntary contractions). Active muscle stiffness significantly increased for both angular velocities and analyzed periods as torque levels exerted became higher. The effects of angular velocities and the interaction between angular velocities and torque levels were not significantly different between 250 deg·s^{-1} (in 60-ms period after stretching) and 100 deg·s^{-1} (in 110-ms period after stretching) conditions. The effects of the analyzed periods and the interaction between analyzed periods and torque levels were not significantly different between the analyzed periods (60-ms and 110-ms periods after stretching) for the 100 deg·s^{-1} condition. Furthermore, active muscle stiffness measured during the same angular velocity had significant correlations between those calculated in the different analyzed periods, whereas those under 250 deg·s^{-1} (60-ms period after stretching) did not correlate with those under 100 deg·s^{-1} (110-ms period after stretching). These results suggest that active muscle stiffness is not influenced by the stretch reflex.

1. Introduction

The mechanical properties of muscles as well as tendons play important roles during human movements. In the last two decades, previous studies have demonstrated the functional roles of human tendons on performance during stretch-shortening cycle exercises, e.g., jumping and running (Bojsen-Moller et al., 2005; Kubo et al., 2015a). We recently reported that the stiffness of human muscles under active conditions (i.e., active muscle stiffness) could be directly evaluated *in vivo* (Kubo, 2014). In a previous study (Kubo, 2014), we examined changes in torque and fascicle length in order to measure active muscle stiffness when the ankle joint commenced movement and then 60 ms thereafter. This time period was selected to avoid any potential neural effects, i.e., the stretch reflex (Allum and Mauritz, 1984; Blanpied and Smidt, 1992; Foure et al., 2010; Kubo, 2014). Using this technique, we found that active muscle stiffness was higher in long distance runners (who perform long-term running training) than in untrained subjects (Kubo et al., 2015b). Furthermore, we showed that active muscle stiffness significantly increased after 12 weeks of plyometric training (Kubo et al., 2017a).

However, no significant difference was observed in active muscle stiffness between sprinters and untrained subjects (Kubo et al., 2017b), whereas the leg and joint stiffness of sprinters was significantly higher than that of long distance runners (Harrison et al., 2004; Hobara et al., 2008). In addition, we found that the relative increase in active muscle stiffness after 12 weeks of plyometric training (as described above) was not related to that in joint stiffness during drop jumping (Kubo et al., 2017a). Although the reasons for these findings currently remain unknown, the effects of the stretch reflex on active muscle stiffness may be involved. As described earlier, active muscle stiffness measured by our method did not include the effects of the stretch reflex (Kubo, 2014). Performance and efficiency during stretch-shortening cycle exercises may be affected by the stretch reflex (Horita et al., 1996; Ishikawa and Komi, 2007). Furthermore, Hobara et al. (2007) showed that leg stiffness was regulated by a change in the stretch reflex response of the plantar flexor muscles. Based on these find-

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* Corresponding author at: Department of Life Science (Sports Sciences), The University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan.

E-mail address: kubo@idaten.c.u-tokyo.ac.jp (K. Kubo).

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ings, the higher joint stiffness for sprinters and plyometric training-induced increase in joint stiffness appear to be related to active muscle stiffness including the stretch reflex, but not to that without the stretch reflex.

According to previous findings (Allum and Mauritz, 1984; Blanpied and Smidt, 1992; Foure et al., 2010; Kubo, 2014), the measured torque (corresponding to muscle force) and joint angle (corresponding to muscle length) in the first 60 ms after the onset of stretching was attributed to the intrinsic stiffness of active muscles. Furthermore, force recruited by the stretch reflex contributed to the force between 65 and 120 ms (Allum and Mauritz, 1984). In our method (Kubo, 2014), difficulties are associated with evaluating active muscle stiffness appropriately 100 ms after the onset of stretching, because the ankle joint angle reaches 85 deg (i.e., the 5-deg dorsi-flexed position) and angular velocity begins to decrease at this time (Fig. 1A and B). On the other hand, we may be able to evaluate active muscle stiffness 100 ms after the onset of stretching (i.e., active muscle stiffness including the stretch reflex) if we adopt a lower stretch velocity.

In the present study, we attempted to evaluate active muscle stiffness including the stretch reflex according to changes (the duration analyzed was more than 100 ms) in torque and fascicle length during slower stretch velocity (peak angular velocity of 100 deg·s^{-1}) in comparison with the data obtained (the duration analyzed was 60 ms) during slower (peak angular velocity of 100 deg·s^{-1}) and faster angular velocities (peak angular velocity of 250 deg·s^{-1}; Kubo, 2014). We hypothesized that active muscle stiffness with the stretch reflex (measured in the first 100 ms during slower angular velocity) was higher than that without the stretch reflex (measured in the first 60 ms after the onset of stretching during slower and faster angular velocities). Previous studies demonstrated that the contribution of the stretch reflex to exerted torque and joint stiffness was enhanced when the exerted torque increased to intermediate levels (Mrachacz-Kersting and Sinkjaer 2003; Sinkjaer et al. 1988; Toft et al. 1989). For example, Mrachacz-Kersting and Sinkjaer (2003) reported that the contribution of reflex-mediated torque was initially low and peaked at a background torque of 20–40% of the maximal volun-

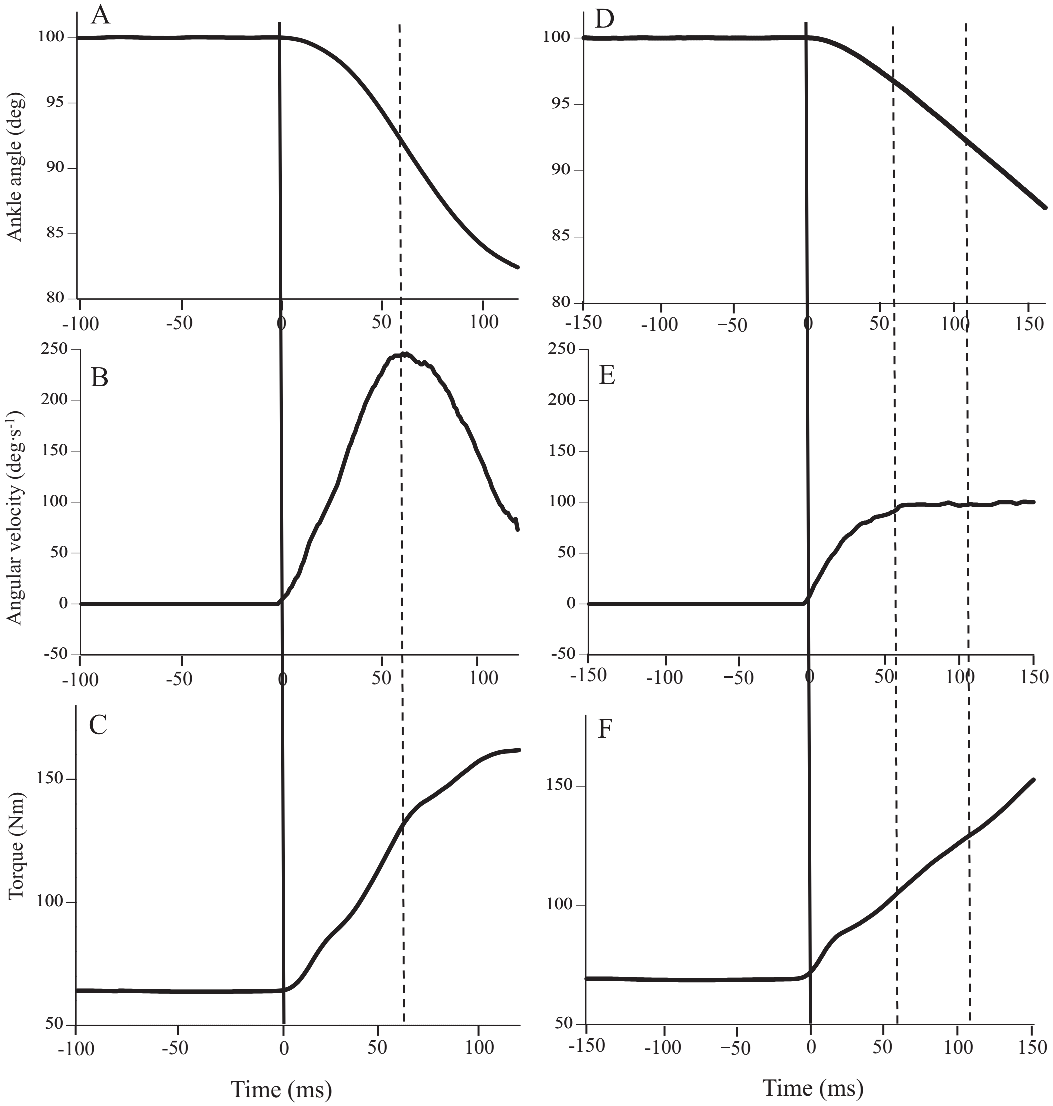

Fig. 1. Typical examples of changes in the ankle joint angle (A and D), angular velocity (B and E), and torque (C and F) during 250 deg·s^{-1} (left) and 100 deg·s^{-1} (right) conditions. The vertical solid line represents stretch onset. The first 60 ms for 250 deg·s^{-1} and 60 ms and 110 ms for 100 deg·s^{-1} (right vertical dotted lines) of the stretch were used to calculate active muscle stiffness.

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