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The association of muscle and tendon elasticity with passive joint stiffness: *In vivo* measurements using ultrasound shear wave elastography

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ABSTRACT

Background: Passive joint stiffness is associated with various tissues, including muscles, tendons, ligaments, and joint capsules. The specific elasticity of muscles or tendons can be measured using ultrasound shear wave elastography. To examine the association of muscle and tendon elasticity with passive joint stiffness, *in vivo* measurements of muscle and tendon elasticity were performed using ultrasound shear wave elastography.
Methods: In 25 subjects, passive ankle joint stiffness was determined using the joint angle–passive torque relationship. The stiffness index of the muscle belly of the medial gastrocnemius (MG)—influenced by the muscle fascicles, its aponeuroses, and the proximal tendon—was quantified by the displacement of the muscle-tendon junction, which was visualized using B-mode ultrasonography during passive dorsiflexion. The stiffness index of the Achilles tendon—influenced by the tendon and the ligaments and joint capsule of the ankle—was similarly determined. The MG and Achilles tendon elasticity was measured using ultrasound shear wave elastography.
Findings: Simple regression indicated a significant correlation between passive joint stiffness and stiffness index of the MG muscle belly ($r = 0.80$) and Achilles tendon ($r = 0.60$), but no correlation with elasticity of the MG ($r = -0.37$) or Achilles tendon ($r = -0.39$).
Interpretation: Individual variations in the elasticity of either the MG or Achilles tendon are not associated with variations in passive ankle joint stiffness; however, variations in the elasticity of other tissues, including MG aponeuroses or the ligaments and joint capsule of the ankle, would be associated with the variations in joint stiffness.

1. Introduction

Human movement requires a certain amount of the fitness component commonly called flexibility. Most exercise and sports programs therefore incorporate activities to develop the flexibility needed for safe and effective movement (Knudson et al., 2000). Many sports require vigorous joint rotations and often use extreme positions in the range of motion. Athletes must have sufficient flexibility to meet these sport-specific demands; otherwise, performance will be impaired and injury risks may increase (Knudson et al., 2000; The American Orthopaedic Society for Sports Medicine, 2008). Even among elderly individuals, a lower ankle flexibility in those with a history of falls compared with those without such history was reported in previous studies (Gehlsen and Whaley, 1990; Menz et al., 2006; Nitz and Low-Choy, 2004), implying that reduced ankle flexibility is an important risk factor for falls in the elderly. Fundamental research can further our understanding of the functional role of flexibility, and thereby will be helpful to further develop exercise and sports programs and to improve flexibility of athletes and elderly people.

Stiffness, which is a mechanical measure of a material's elasticity (Gleim and McHugh, 1997; Knudson et al., 2000), is an important measurement for evaluating flexibility. The passive stiffness of a joint can be quantified as the slope of the line relating the joint angle to the joint torque measured during passive movement of the joint. Thus, the measured passive stiffness includes contributions from all of the tissues located within and over the joint, including muscle, tendon, skin, subcutaneous tissue, fascia, ligament, joint capsule, and cartilage (Riemann et al., 2001). To investigate the relative association of the muscle and tendon with passive joint torque in humans, Kawakami et al. (Kawakami et al., 2008) devised muscle belly and tendon stiffness indices. The stiffness index of the medial gastrocnemius (MG) belly was estimated from the displacement of the distal muscle–tendon junction (MTJ) of the MG, which represents the change in the length of the muscle belly during passive dorsiflexion, using B-mode ultrasonography. In a similar way, the stiffness index of the Achilles tendon was estimated from the change in length of the muscle belly of the MG and the whole muscle–tendon unit (MTU). Using their methodology, Kawakami et al. (2008), demonstrated that the passive plantarflexion torque was more closely related to the stiffness

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index of the Achilles tendon than the MG muscle belly. These results also show the feasibility of the method to investigate the association of muscle and tendon elasticity with passive joint stiffness using B-mode ultrasonography.

Ultrasound shear wave elastography can quantitatively measure tissue elasticity *in vivo* (Bercoff et al., 2004; Gennisson et al., 2013). A focused ultrasound beam creates an acoustic radiation force, which induces a shear wave that propagates transversely to the radiation force. By capturing the propagation information from the shear wave, the shear wave propagation speed (c) can be acquired. The speed is used to calculate Young's modulus (E), one of the most relevant parameters used to quantify stiffness or elasticity of soft tissues (Shinohara et al., 2010), using the equation $E = 3\rho c$ (Arda et al., 2011), where ρ is density of the tissues (considered to be constant for soft tissues at 1000 kg/m^3). Elasticity measurements of the MG and Achilles tendon, using shear wave elastography, have previously been performed (Akagi and Takahashi, 2013; Arda et al., 2011; Hug et al., 2013; Maisetti et al., 2012). Hug et al. (2013) measured the elasticity of the MG and Achilles tendon during passive ankle dorsiflexion and reported that the shear elastic modulus for the MG increased at a less plantarflexed joint angle than the modulus of the Achilles tendon. Their study demonstrated that shear wave elastography, which measures tissue elasticity by capturing the shear wave that propagates within the specific tissue, can be used to measure the specific tissue elasticity of the MG or Achilles tendon. Therefore, to determine the associations between human muscle and tendon elasticity with passive stiffness of the ankle joint, we measured the specific tissue elasticities of the MG and the Achilles tendon *in vivo* using ultrasound shear wave elastography. In addition, we assessed the stiffness indices of the MG and the Achilles tendon using B-mode ultrasonography. We hypothesized that both the specific tissue elasticities and stiffness indices of the MG and Achilles tendon were associated with passive ankle joint stiffness.

2. Methods

2.1. Participants

Twenty-five healthy subjects, 13 males and 12 females, without apparent neurological, orthopedic, or neuromuscular problems, participated in this study. Mean (SD) age, height, and weight were 22.0 (4.3) years, 170.3 (8.3) cm, and 64.0 (11.8) kg for the male group, respectively, and 25.6 (5.6) years, 160.6 (5.5) cm, 53.5 (6.4) kg for the female group, respectively. All participants were informed of the purpose of the study and of the experimental protocol, including the possible risk and discomfort associated with the experimental procedures, before giving their written informed consent to participate. The study was approved by the Ethics Committee of the Japan Institute of Sports Sciences.

2.2. Determination of passive ankle joint stiffness

Based on the methods of previous studies (Chesworth and Vandervoort, 1989; Riemann et al., 2001), passive stiffness of the ankle joint was determined by the relationship between joint angle and passive torque. Subjects lay prone on a flat bed with their right knee fully extended and their right foot secured to the footplate of an electrical dynamometer (Biodex System 4; Biodex Medical Systems, Shirley, NY, USA) (Fig. 1). The footplate was adjusted to align the rotational axes of the ankle joint and of the dynamometer as closely as possible. To prevent the heel from lifting from the footplate during dorsiflexion, the foot was firmly secured to the footplate by two straps. An additional strap was placed over the right calf to prevent the body from moving forward during dorsiflexion. To demonstrate that this strap did not interfere with passive dorsiflexion, a preliminary study was conducted. No significant effect of the strap was found on the torque measured during passive dorsiflexion. The footplate angle changed from 30° of plantarflexion (+30°) to 10° of dorsiflexion (−10°), and back, at a constant velocity of 5°/s. Throughout the joint movement cycles, subjects were asked to completely relax their lower limb muscles and not to offer any voluntary resistance. After two cycles of preconditioning, data were collected during the dorsiflexion phase of the third cycle. To correct for the gravitational torque caused by the weight of the footplate, the torque magnitude generated by the empty ankle footplate was subtracted from the torque measured during the passive joint movement (Muraoka et al., 2002; Salsich et al., 2000). The joint angle–passive torque relationship was generated by fitting the data with a fourth-order polynomial equation ($y = ax^4 + bx^3 + cx^2 + dx + e$, where y is the passive torque, x is the joint angle, and a–e are constants) as well as its first derivative equation ($dy/dx = 4ax^3 + 3bx^2 + 2cx + d$) at the neutral anatomical position (0°), in order to determine the passive ankle joint stiffness.

2.3. Determination of the MG muscle belly and Achilles tendon stiffness indices

The stiffness indices of the MG muscle belly and the Achilles tendon were determined using B-mode ultrasonography, as described by Kawakami et al. (2008). The displacement of the MTJ with dorsiflexion was visualized using B-mode ultrasonography (Aixplorer; SuperSonic Imagine, Aix-en-Provence, France) with a 4 − 15-MHz linear array transducer (SL 15-4; SuperSonic Imagine) (Fig. 1). The transducer was oriented longitudinally along the belly of the MG and secured to the skin with double-sided adhesive tape to prevent slippage over the skin during measurement. Subjects lay prone with their right foot secured to a dynamometer footplate (Biodex System 4; Biodex Medical Systems), and the ankle was moved to fixed angular positions for measurement, including +30°, +20°, +10°, 0°, and −10°, in that order. Between each test position, a rest period of 60 s or more was provided at the +30° ankle position, where the passive torque of the ankle joint has been shown to be near zero (Kawakami et al., 1998; Muraoka et al., 2002; Riener and Edrich, 1999). This rest period ensured the restoration of the original musculotendinous viscoelastic properties prior to each measurment (Kawakami et al., 2008). Measurements at all ankle positions were repeated twice, and the average of the two measurements was used for analysis. The displacement of the MTJ during dorsiflexion was quantified using a caliper program (ImageJ v1.47; National Institutes of Health, Bethesda, MD, USA) to determine the displacement with elongation of the MG muscle belly. The elongation of the MTU with dorsiflexion was estimated using the following two-step procedure. (i) Based on a previously reported equation for predicting change in the MTU length from joint angle that used 0° as the reference (Grieve et al., 1978), here the MTU length change (ΔL, as a percent of the lower leg length) from the +30° position to each ankle joint position ($\theta = +30°, +20°, +10°, 0°$, and $-10°$) was calculated as $\Delta L = -0.00061 \bullet [(90 - \theta)^2 - 60^2] + 0.30141 \bullet (30 - \theta)$. (ii) The MTU elongation of each subject was calculated by multiplying the MTU length change by the lower leg length, which was measured as the distance from the lateral joint line of the knee to the center of the lateral malleolus. The elongation of the Achilles tendon was then calculated by subtracting the elongation of the MG muscle belly from the MTU elongation. The locations of the MTJ and the calcaneal tuberosity (insertion point of the Achilles tendon), with the ankle in anatomical neutral (0°) position, were confirmed using B-mode ultrasonography and were marked with a felt tip pen. The distance between these two points was measured over the dermal surface using a tape measure, and was used as the tendon length at 0° ankle position. The tendon length with the ankle at +30°, defined as the initial tendon length, was determined by subtracting the tendon elongation that occurred when the ankle position changed from +30° to 0° from the tendon length at 0°. The initial MG muscle belly length was estimated by