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Positive relationship between passive muscle stiffness and rapid force production

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ABSTRACT

We aimed to examine the relationship among the muscle shear modulus at rest, maximal joint torque, and rate of torque development (RTD). Twenty-seven participants (28 ± 5 years, 13 women) were recruited in the study. The cross-sectional area (CSA) of the medial gastrocnemius (MG) muscle belly and shear modulus at an ankle joint angle of 0° were calculated using magnetic resonance imaging and ultrasound shear wave elastography, respectively. Subsequently, participants performed maximal isometric plantar flexion at 0° ankle joint angle [maximal voluntary contraction (MVC) test] as fast and hard as possible (RTD test). RTD was calculated from the time–torque curve over time intervals of 0–30, 0–50, 0–100, 0–150, and 0–200 ms from the onset of plantar flexion during the RTD test and was normalized by MVC torque to exclude muscle strength. MG CSA correlated significantly with MVC torque (r = 0.572), whereas MG shear modulus did not. In contrast, MG shear modulus correlated significantly with normalized RTD at all time intervals (r = 0.460–0.496). These results suggest that passive muscle stiffness is not associated with muscle force; however, higher passive muscle stiffness at a given joint angle may contribute to rapid force production.

1. Introduction

It is important to quantify muscle stiffness (which has a strong relationship with muscle hardness, but is essentially different) to prevent injury (Behm, Blazevich, Kay, & McHugh, 2016) and enhance sports performance (Kalkhoven & Watsford, 2018). Therefore, in an effort to understand muscle stiffness and its effects, some studies measured muscle stiffness as shear modulus using ultrasound shear wave elastography (Akagi & Takahashi, 2013, 2014; Ates et al., 2015; Hirata, Miyamoto-Mikami, Kimura, & Miyamoto, 2017; Hug, Tucker, Gennisson, Tanter, & Nordez, 2015; Lacourpaille et al., 2017; Shinohara, Sabra, Gennisson, Fink, & Tanter, 2010) and demonstrated its validity and reproducibility (Freitas, Andrade, Larcoupaille, Mil-homens, & Nordez, 2015; Hirata, Miyamoto-Mikami, Kanehisa, & Miyamoto, 2016; Hug et al., 2015; Miyamoto, Hirata, Kanehisa, & Yoshitake, 2015). Hence, ultrasound shear wave elastography is a useful tool for measuring muscle stiffness.

To date, it is not well understood whether muscle stiffness at rest (passive muscle stiffness) influences muscle functional characteristics, such as maximal isometric force and rapid force production. It is generally known that maximal isometric joint torque is closely associated with anatomical cross-sectional area (CSA) (Fukunaga et al., 2001). A couple of previous studies have reported on the relationship between muscle thickness (i.e., muscle size) and muscle stiffness (or hardness) (Akagi, Chino, Dohi, & Takahashi, 2012; Muraki, Fukumoto, & Fukuda, 2013); however, there are some contradictions to this finding. Akagi et al. (2012) showed a positive relationship between muscle thickness and muscle stiffness in calf muscles, but they used muscle thickness as an index of

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muscle size. Accordingly, it is possible that a difference in dimension, e.g., muscle thickness versus anatomical CSA, results in a contrasting relationship between the muscle size index and another parameter (e.g., shear modulus) (Sugisaki, Kobayashi, Tsuchie, & Kanehisa, 2018). Hirata et al. (2017) proved this when they found that the anatomical CSA of individual hamstrings was not significantly correlated with muscle shear modulus. Therefore, we expected that there should be no association between passive muscle stiffness and anatomical CSA or maximal joint torque in the calf muscles as well.

The ability of rapid force production is closely associated with the soft tissues, such as tendons, aponeuroses, muscles, and ligaments. Bojsen-Moller, Magnusson, Rasmussen, Kjaer, and Aagaard (2005) showed a positive relationship between rate of torque development (RTD) and the stiffness of vastus lateralis tendon-aponeurosis complex. Accordingly, one hypothesis that there is a relationship between passive muscle stiffness and RTD is considered. Schleip et al. (2006) suggested that an increase in perimysial thickness was associated with a higher passive muscle stiffness. Further, a positive relationship was observed between passive muscle stiffness and passive tension (Chino & Takahashi, 2016). de Ruiter, Buse-Pot, and de Haan (2008) confirmed that an increase in passive tension and in the length of the muscle-tendon complex was associated with the increase in the rate of force development. It is therefore assumed that muscles with a higher passive stiffness may be able to quickly produce a higher amount of joint torque. Furthermore, shear modulus in triceps surae increased at dorsiflexion (Chino & Takahashi, 2016), and there was a slack joint angle that corresponded to the muscles' slack length (Hirata, Kanehisa, Miyamoto-Mikami, & Miyamoto, 2015). Hirata et al. (2015) further demonstrated that this slack angle was different between participants, which suggests that shear modulus at a given joint angle (e.g., anatomical position) is also different between participants regardless perimysial thickness-related essential passive muscle stiffness. Therefore, we hypothesized that a higher passive muscle stiffness at a given joint angle enables rapid force generation, i.e., a higher RTD. To this effect, this study examined the relationships among muscle shear modulus at rest, maximal joint torque, and RTD.

2. Materials and methods

2.1. Participants

Twenty-seven healthy men and women (14 men and 13 women; age, 28 ± 5 years; height, 166.7 ± 7.5 cm; body mass, 62.1 ± 10.7 kg) volunteered for this study. Before proceeding with the experiment, the purpose, procedures, and risks associated with the study were explained, and a written informed consent was obtained from each participant. The experimental protocols were approved by the ethics committee of Japan Institute of Sports Sciences (No. 020). The study was completed in accordance with the rules and regulations outlined in the Declaration of Helsinki.

2.2. Magnetic resonance imaging

Participants lay in a supine position on a 3.0-T whole-body magnetic resonance imaging (MRI) scanner (MAGNETOM Verio, Siemens Healthcare Diagnostics K.K, Tokyo, Japan). T1-weighted spin-echo transaxial images of the preferred leg (kicking ball) were collected from the anterior border of tibia to the lateral malleolus, with the following parameters: repetition time = 500 ms, echo time = 8.2 ms, matrix = 256 × 256, field of view = 240 mm, slice thickness = 10 mm, and interslice gap = 5 mm.

We used Medical Image Processing, Analysis, and Visualization software (version 8.0.2; National Institutes of Health, Bethesda, MD, USA) to analyze the images on a personal computer. We assessed images that corresponded at 30% of the length from the anterior border of tibia to the lateral malleolus for each participant based on results of previous studies (Fukunaga et al., 1992; Hasson, Kent-Braun, & Caldwell, 2011), and this site was also used for shear modulus measurement (described below). This way, the medial gastrocnemius (MG) could be traced to calculate anatomical CSA.

2.3. Muscle shear modulus

The participants sat on an examination chair with the hip flexed to 70°, knee completely extended (0°), and ankle joint at 0°. The center of the ankle joint was visually aligned with the dynamometer's axis of rotation. The preferred leg was firmly secured to the footplate of an electrical dynamometer (Fig. 1) (Biodex System 4; Biodex Medical Systems, Shirley, NY, USA). An additional strap was used to fix the foot and backrest was adjusted to eliminate the space between the hip and backrest. Thus, heel lifting was minimized during maximal isometric plantar flexion. The room temperature was maintained at 23–25 °C to prevent changes in tissue elasticity (Chino & Takahashi, 2016; Mustalampi, Ylinen, Kautiainen, Weir, & Hakkinen, 2012; Point et al., 2017). An ultrasound scanner (Aixplorer; Supersonic Imagine, Aix-en-Provence, France) with a linear-array probe (SL 15-4; SuperSonic Imagine) and "MSK" preset was used to measure the shear modulus of MG (μ). The shear modulus (μ) was measured at 30% of the length from the lateral joint line of the knee to the lateral malleolus at the thickest point of MG (Akagi & Takahashi, 2013; Chino & Takahashi, 2016). The water-soluble gel was sufficiently applied to the head of the probe to obtain acoustic coupling without depressing the skin surface. A region of interest (ROI, 10 mm × 10 mm) was defined on the MG, and a 5-mm diameter ROI (Q-Box™) was identified in the center of the square-shaped ROI to quantify shear wave velocity (V). V was calculated and averaged for each image. It was then used to calculate μ using the following equation (Gennisson, Deffieux, Fink, & Tanter, 2013; Hug et al., 2015):

$$\mu = \rho V^2$$

where ρ is the density of the soft tissues (1000 kg/m^3). The measurements were performed five times, and the average value of three images excluding the minimum and maximum values were used for further analyses.

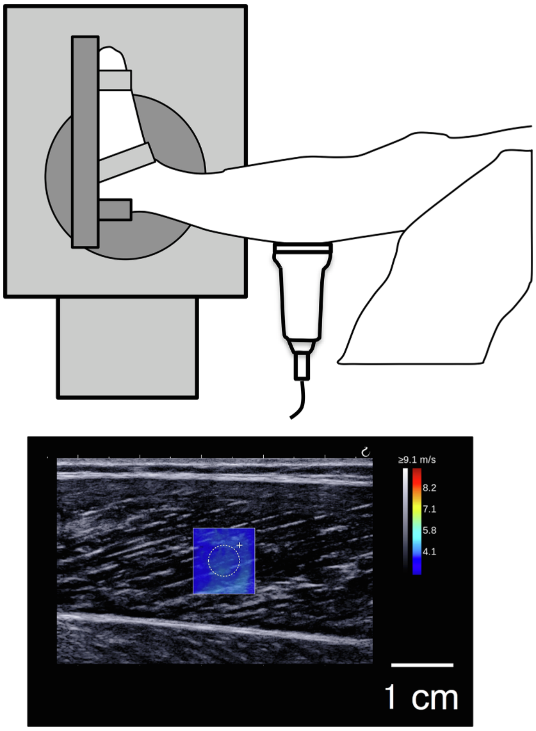

Fig. 1. Experimental setup for ultrasound shear wave elastography of the medial gastrocnemius.

2.4. Plantar flexion task

Participants performed isometric plantar flexion in the neutral position (i.e., 0° ankle joint angle) after ultrasound shear wave elastography measurements were taken. They performed several submaximal (30%, 50%, 70%, and 90% of perceived maximal effort) isometric contractions as warm-up. Two maximal voluntary isometric contractions (MVCs) were performed, and an additional trial was performed if peak torque values differed by > 5% between two trials. The MVC test consisted of loading (1 s), sustained (≥ 2 s), and relaxation (≤ 1 s) phases. Following this, the participants performed two maximal isometric plantar flexions as fast and hard as possible and sustained the maximal effort for about 1 s (RTD test).

Signals from the Biodex system were sampled at 2 kHz using an analog-to-digital converter (PowerLab; ADInstruments, Melbourne, Victoria, Australia) and were recorded on a personal computer using Chart 7.2.5 software (ADInstruments). The torque signal was sampled over 1 s during the sustained phase of the MVC test to calculate the MVC torque. The higher one was used as the representative value for further analyses. We calculated the normalized RTD based on previous studies (Blazevich, Horne, Cannavan, Coleman, & Aagaard, 2008; Ema et al., 2016). First, the onset of plantar flexion was determined as the point at which the torque exceeded the baseline by 2.5% of the MVC torque. To eliminate the effect of counter movement on RTD values, trials wherein > 0.5 Nm of dorsiflexion was observed before onset were excluded in accordance with the previous studies (Balshaw, Massey, Maden-Wilkinson, Tillin, & Folland, 2016; Ema, Saito, & Akagi, 2018). The RTD was then calculated as the slope of the time–torque curve over time intervals of 0–30, 0–50, 0–100, 0–150, and 0–200 ms from the onset of the plantar flexion. These RTD values were normalized by MVC torque to exclude the effect of muscle strength. We calculated normalized RTD values at several time intervals because the mechanical properties and physiological determinants of RTD depend on the time intervals (de Ruiter et al., 2008; Folland, Buckthorpe, & Hannah, 2014). The average value of two RTD trials was used for further analyses.

2.5. Additional plantar flexion task

From among 27 subjects, we examined change in ankle joint angle during the MVC task in 6 subjects. The ankle joint angle was assessed using an electrogoniometer (SG150, Biometrics Ltd., Gwent, UK). The signals from an electrogoniometer was synchronized with torque signals using an analog-to-digital converter. The signals were sampled over 1 s at rest and during the sustained phase of the MVC. The difference in the ankle joint angle at rest and during the MVC was calculated.

2.6. Statistical analyses

All data were presented as mean ± standard deviation (SD). Coefficient variations (CVs) of shear modulus among three scans and normalized RTD values between two trials were calculated. The relationships among muscle shear modulus, CSA, MVC torque, and

Table 1
Cross-sectional area (CSA), shear modulus of medial gastrocnemius, maximal voluntary contraction (MVC) torque, and normalized rate of torque development (normalized RTD) and coefficient variation (CV) of those measurements.

	Mean	CV
CSA	15 ± 3 cm^2	–
Shear modulus	14.6 ± 3.7 kPa	5.4 ± 4.5%
MVC torque	139.9 ± 44.6 Nm	–
Normalized RTD-30	315 ± 82 %MVC/s	15 ± 14%
Normalized RTD-50	337 ± 94 %MVC/s	16 ± 16%
Normalized RTD-100	381 ± 88 %MVC/s	14 ± 13%
Normalized RTD-150	363 ± 67 %MVC/s	10 ± 11%
Normalized RTD-200	332 ± 52 %MVC/s	9 ± 10%

CV of shear modulus is that value among 3 scans, and CVs of Normalized RTD are those values between 2 trials.

normalized RTD were examined using Pearson's product-moment correlation coefficient. The level of significance was set at $P < 0.05$ for all analyses. Statistical analyses were performed using the IBM SPSS Statistics software (version 24.0; IBM Corp., Armonk, NY, USA).

3. Results

CSA, muscle shear modulus, MVC torque, and normalized RTD values are as well as CVs of muscle shear modulus and normalized RTD are presented in Table 1.

There was a significant correlation between CSA and MVC torque (r = 0.572, $P < 0.01$). In contrast, muscle shear modulus was not significantly correlated with CSA ($P = 0.413$) or MVC torque ($P = 0.733$). Fig. 2 shows the relationship between muscle shear modulus and normalized RTD for each time interval. There were significant correlations between muscle shear modulus and normalized RTD at all time intervals (r = 0.460–0.496).

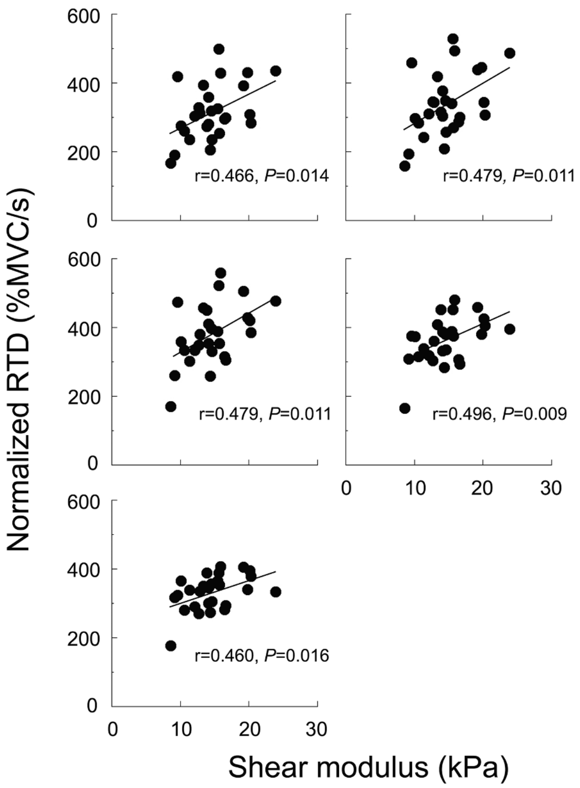

Fig. 2. Relationship between shear modulus of medial gastrocnemius and rate of torque development normalized by maximal voluntary contraction torque (normalized RTD) at time intervals of 30 (upper left), 50 (upper right), 100 (middle left), 150 (middle right), and 200 ms (lower left). Muscle shear modulus was significantly correlated with normalized RTD at all time intervals.

MVC torque was 125.8 ± 25.6 Nm in the additional plantar flexion task. The difference in the ankle joint angle at rest and during the MVC was 9.0 ± 2.3°.

4. Discussion

The present study examined the relationships among muscle shear modulus at rest, maximal joint torque, and RTD. The main findings were that MG shear modulus was not significantly correlated with MVC torque, although there was a significant correlation between shear modulus and normalized RTD, which supported our hypotheses.

No significant correlation between MG shear modulus and MVC torque suggests that passive muscle stiffness is not associated with maximal joint torque, which supports previous findings (Akagi, Shikiba, Tanaka, & Takahashi, 2016; Chino, Ohya, Kato, & Suzuki, 2018; Hirata et al., 2017). For example, Akagi et al. (2016) demonstrated that an increase in the muscle thickness of the triceps brachii after a 6-week resistance training program did not show changes in muscle shear modulus. Conversely, a couple of studies suggested that muscle hardness is related to muscle force or the index of muscle size in knee extensors (Muraki et al., 2013), triceps brachii (Akagi, Tanaka, Shikiba, & Takahashi, 2015), and triceps surae (Akagi et al., 2012). Only one previous study (Hirata et al., 2017) has examined the relationship between muscle stiffness and anatomical CSA as the index of muscle size in individual hamstring muscles. Hirata et al. (2017) found no significant associations between them in each muscle in 71 healthy young males. As we also evaluated anatomical CSA, the difference in the relationship could be attributed to difference in the dimensions, i.e., muscle thickness versus anatomical CSA. Muscle thickness is associated with anatomical CSA; however, these two indices of muscle size sometimes show opposite relationships with other parameters. For example, a negative association was observed between muscle thickness and the 100-m sprint time (Kubo, Ikebukuro, Yata, Tomita, & Okada, 2011) while a positive association was reported between anatomical CSA and the 100-m sprint time (Hoshikawa et al., 2006). Further studies should be conducted to clarify the relationship between passive muscle stiffness and muscle size.

There were significant correlations between shear modulus and normalized RTD at all time intervals (Fig. 2). To the best of our knowledge, this is the first study to show significant relationships between muscle shear modulus and normalized RTD. We consider that there are a couple of reasons for associations between passive muscle stiffness and normalized RTD, such as essential muscle stiffness and length-related muscle stiffness. Schleip et al. (2006) suggested that an increase in perimysial thickness was associated with a higher passive muscle stiffness. Further, a positive relationship has been reported between passive muscle stiffness and passive tension (Chino & Takahashi, 2016). de Ruiter et al. (2008) confirmed that an increase in passive tension and in the length of the muscle-tendon complex was associated with the increase in the rate of force development. Therefore, muscles with a higher passive stiffness (e.g., thicker perimysium) may generate force much faster.

We interpreted that length-related passive muscle stiffness would also be related to normalized RTD in the present study. Hirata et al. (2015) reported on the slack angle of the ankle joint that corresponds to the muscles' slack length, and this slack angle varies between participants. This indicates that the muscle (sarcomere) length at a given joint angle is different between participants. Thus, the relationship between passive tension in individual muscles and at joint angles may also be different between participants. As mentioned above, a higher passive tension positively correlated with rapid force production (de Ruiter et al., 2008). Therefore, there is a possibility that normalized RTD is associated with muscle length-related passive muscle stiffness in the present study.

The series elastic components of muscle-tendon unit affect rapid force production. Waugh, Korff, Fath, and Blazevich (2013, 2014) indicated that tendon stiffness positively affected rapid force production. These relationships are elaborated in a review article on rate of force development, which states that the speed of force transmission through a material is influenced by the material's stiffness (Maffiuletti et al., 2016). One concern is that tendon stiffness may be related to passive muscle stiffness. Thus, correlations between MG shear modulus and normalized RTD presented in our study are spurious. However, Kubo, Kanehisa, and Fukunaga (2001) reported that passive muscle stiffness was not related to tendon stiffness. Therefore, it is considered that passive muscle stiffness and tendon stiffness affect rapid force production differently.

It may be considered that the higher the RTD, the better the sports performance, such as sprinting (Townsend et al., 2017) and ability to change direction (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2014). Ema et al. (2016) also suggested that a higher RTD positively contributes to balance in older people. Thus, our results will contribute to future studies focusing on creating efficient training regimens for athletes and/or older people.

One limitation of this study is that the relationship between shear modulus and normalized RTD was only examined in MG. It is assumed that the MG muscle contributes approximately 25% and the soleus muscle contributes approximately 60% to the ankle joint torque when considering the physiological CSA of individual muscles in the triceps surae (Ward, Eng, Smallwood, & Lieber, 2009). Furthermore, it has been suggested that the tension of the deep muscles is effectively transmitted to the bone in the early phase of muscle contraction in the quadriceps femoris (Zhang, Wang, Nuber, Press, & Koh, 2003). Taken together, because the soleus muscle may contribute more to the RTD during plantar flexion, the relationship between the soleus muscle shear modulus and RTD should be examined in future studies.

5. Conclusions

We demonstrated that muscle shear modulus of MG did not correlate with maximal isometric joint torque but with normalized RTD. These results suggest that passive muscle stiffness is not related to muscle force in triceps surae, but a higher passive muscle stiffness may contribute to more rapid force production. Our work will be helpful in understanding the relationship between a muscle's properties and function.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.05.002.

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