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Dependence of muscle and deep fascia stiffness on the contraction levels of the quadriceps: An *in vivo* supersonic shear-imaging study

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ABSTRACT

In the present study we investigated muscle contraction-driven changes in deep fascia mechanical property, to reveal mechanical interactions between them. Fourteen males (22–37 yr) performed isometric knee extension at 20, 40, 60% of the maximal voluntary contraction (MVC). During each contraction and at rest, shear wave velocities (SWV) of the rectus femoris (RF) and vastus lateralis (VL) and fascia lata were measured in both longitudinal and transverse ultrasound transducer directions relative to the thigh. Surface electromyogram was recorded from RF and VL and root mean square (RMS) values were determined. The slopes of the linear correlations between normalized SWV (%SWV: relative to rest) and RMS (%RMS_{EMG}: relative to MVC) were calculated for different sites and directions. Both muscles and fascia lata became stiffer as the muscle activation level increased to comparable degrees, with the slopes of those changes being 4–9 times higher in the longitudinal than transverse direction. The fascia lata showed lower slopes than those of muscles in the longitudinal direction while in the transverse direction neither parts showed significant differences. These results suggest that the force produced by the muscles partly transmitted to the fascia lata in the longitudinal and transverse directions, causing anisotropic changes in musculofascial entity.

1. Introduction

The deep fascia is a membranous tissue mainly composed of collagen fibers extending from head to toe (Kumka and Bonar, 2012). Deep fascia is connected to underlying muscles through loose connective tissues (Fig. 1) and to inter-muscular septa, tendons, and ligaments without any boundary in between (Stecco et al., 2008). Such an anatomical organization allows fascial tissues to bear forces produced by muscle contraction in an effect to transmit the forces to the neighboring muscles (Huijing et al., 2007), which is known as the epimuscular myofascial force transmission (Huijing, 2009; Maas and Sandercock, 2010; Yucesoy, 2010). There is some evidence from *in vivo* studies showing intra-limb (Huijing et al., 2011; Marinho et al., 2017; Yoshitake et al., 2018) and intra-muscle (Pamuk et al., 2016; Karakuzu et al., 2017) myofascial force transmissions in humans. These studies revealed that the myofascial force transmission could be induced by both passive joint angle change and active muscle contraction.

Previous studies reported that the fascia lata was thicker than the deep fascia at the pectoral region (Stecco et al., 2009), and was stiffer than the thoracolumbar fascia (Henderson et al., 2015). Not only inter-segment but also intra-segment differences of the elastic properties of deep fascia have been found in the lower leg and thigh regions (Stecco et al., 2014; Otsuka et al., 2018). It has also been noted that deep fascia has anisotropic mechanical properties being stiffer in the antero-posterior than medio-lateral direction (Stecco et al., 2014; Henderson et al., 2015; Otsuka et al., 2018). This may be due to the mechanical characteristics of the collagen fibers comprising deep fascia that run mainly along the direction of muscle contraction (Stecco et al., 2014). Because of these site- and direction-dependences in morphological and mechanical properties, deep fascia is considered to play a role to assist the force development of underlying muscles (Stecco et al., 2014; Otsuka et al., 2018).

One major issue when one aims to study the interaction between muscles and deep fascia is the limitations of *in vivo* studies. Most studies have used postmortem human or animal cadavers (Stecco et al., 2014; Otsuka et al., 2018; Henderson et al., 2015), and some *in vivo* studies showed inter- and intra-muscular mechanical interaction during contraction (Maas and Huijing, 2005; Finni et al., 2017; Karakuzu et al., 2017). However, they did not observe the interactions between muscle and deep fascia in voluntary motor performance. Supersonic shear wave elastography (SWE) is one of the latest and effective tools to measure elastic properties of the soft tissues *in vivo* non-invasively. The stiffness of the muscles has been examined using SWE in various conditions (e.g. at rest, during and after exercise) (Lacourpaille et al., 2012;

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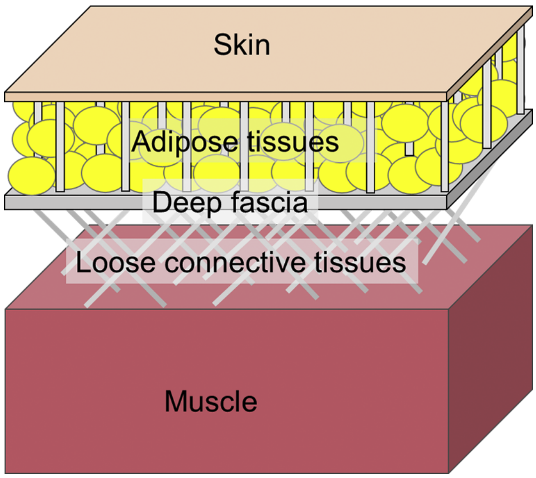

Fig. 1. The scheme showing the typical pattern of organization of subcutaneous tissues. The deep fascia connects to the underlying muscles via loose connective tissues.

Yoshitake et al., 2014, Ates et al., 2015; Andonian et al., 2016). Collagen-rich tissues like tendon, ligament, and plantar fascia have also been examined using SWE (Aubry et al., 2013; Brum et al., 2014; Wu et al., 2012; Wu et al., 2011). One study has suggested the applicability of SWE to deep fascia (Luomala et al., 2014). However, at present there is paucity of data on the contraction level dependence of the elastic properties of the deep fascia and its site differences *in vivo*, and the mechanical interaction between muscles and deep fascia during body movement still remains to be determined.

In the present study, we measured for the first time elastic properties of the fascia lata and underlying muscles using SWE. The aim was to investigate the inter-dependence in mechanical properties between fascia lata and neighboring muscles as well as site and direction differences, at different contraction intensities of isometric knee extension. We hypothesized that the fascia lata becomes stiffer at higher contraction levels that matches muscle belly stiffening, and that both fascia lata and muscles show anisotropic behavior in terms of directions as well as sites.

2. Material and methods

2.1. Participants

The present study was approved by the local ethical committee. Fourteen healthy males (age, 26 ± 4 years: height, 171.5 ± 6.2 cm: body mass 65.5 ± 11.0 kg; means ± SDs) gave their written informed consent before participating in this study.

2.2. Experimental design

The participants seated on an isometric dynamometer (VTE-002R, VINE, Japan). The locations of the ultrasound transducer were determined from B-mode images of the ultrasound (Aixplorer version 6.4, Supersonic Imagine, Aix-en-Provence, France), and markers were applied on the skin using a waterproof pen for the rectus femoris (RF) and vastus lateralis (VL) muscles in the longitudinal and transverse directions (Fig. 2). The shear wave velocity (SWV) of the muscles and fascia lata in the passive condition was measured twice at each site and direction in a random order using ultrasound shear wave elastography. The participant was orally instructed to stay completely relaxed and without any muscle contraction during the passive condition. After five sub-maximal contractions as a standardized warm-up, each participant performed the maximal voluntary contraction (MVC) of isometric knee extension for 3 s. More than two trials were performed if peak torques were substantially different (greater than10%). Following the MVC trials, the participants performed sub-maximal isometric knee extensions for 7 s at 20, 40, and 60% of the highest values of the MVC in a random order for two sets. The SWV was measured at two sites and two directions during contractions separately in a random order. More than 1 min of rest was taken between contractions. During contraction and at rest, knee extension torque and surface electromyography (EMG) from RF and VL were recorded.

2.3. Measurements

2.3.1. Shear wave elastography

The SWV of the RF and VL muscle bellies (midpoint of the greater trochanter and lateral condyle of the femur) on the right leg and fascia lata over these muscles was measured using an Aixplorer ultrasonic scanner with a linear array ultrasound transducer (L15–4, Supersonic Imagine, Aix-en-Provence, France) in the supersonic shear imaging (SSI) mode. We coupled the ultrasound transducer to the skin surface using an acoustic stand-off (Enraf-Nonius, France) (for fascia lata) and ultrasound gel (for muscle bellies), ensuring minimum pressure between the transducer and skin. Maps of the SWV were obtained at 12 Hz with a spatial resolution of 1 × 1 mm. RF and VL muscles and the fascia lata over these muscles were tested in the longitudinal (parallel to the muscle fascicle) and transverse (orthogonal to the longitudinal) probe directions (Fig. 3). The region of interest (ROI) for the muscles and fascia lata was set manually. In this study, the SWE device was operated by an experienced single examiner (S.O.).

2.3.2. Knee extension torque

The participants were seated on the dynamometer, with 80° and 70° of hip and knee joint angles, respectively (0° = full extension of hip and knee). The trunk of the participant was secured to the backrest of the dynamometer to restrict any upper body movement. The pad on the actuator arm of the dynamometer was securely fastened to the participant's right leg just above the medial malleolus. The torque data were amplified by a strain amplifier (DPM-711B, Kyowa, Japan). The data were recorded through an analogue to digital converter (Power Lab, AD Instruments, Australia) in a personal computer at a sampling frequency of 1,000 Hz after 10 Hz low-pass filtering.

2.3.3. Surface electromyogram

Surface electromyogram (EMG) was recorded through the test using a wireless EMG system (Trigno, Delsys, USA). After preparation of the skin (shaving, abrading, and cleansing with ethanol), EMG electrodes were placed over the belly of RF and VL muscles just above the location of the ultrasound transducer and parallel to the orientation of the muscle fibers. EMG signals were amplified and recorded through the analog-digital converter in a computer at a sampling frequency of 1000 Hz after bandpass-filtering (20–450 Hz).

2.4. Data analysis

Knee extension torque was normalized to the value during MVC. The SWV of muscles and fascia lata was measured by the ultrasound device. The muscle bellies and boundaries of the fascia lata were chosen manually as the ROI in the shear wave map, avoiding hypoechoic and saturated regions (Fig. 3). A spatial average value of the SWV over the selected ROI at each image was calculated using the SSI software (Q-Box™ Trace). Taking into account the mechanical delay of the SWV mapping (Sasaki et al., 2014), five images (every one second from 2 to 6 within 7 s contraction) in each condition were analyzed and the average value was used as representative of the condition. Average torque and root mean square (RMS) values of EMG over the same time window as of SWV (average value of the 4 s) were normalized to MVC (average of 0.5 s around the highest torque) (Yoshitake et al., 2014). The slope of the regression line over the relationship between normalized SWV (%

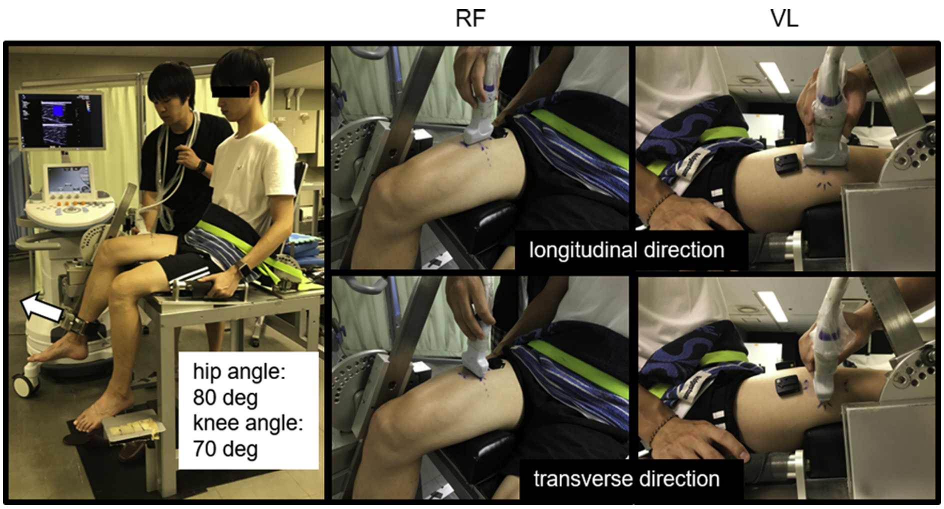

Fig. 2. The posture of the participant during the test and measurement sites of surface electromyography (EMG) and ultrasound shear wave elastography (SWE). The transducer of SWE was placed on the skin over the mid-belly of the rectus femoris (RF) and vastus lateralis (VL) both in longitudinal and transverse directions. The EMG was measured from RF and VL just superior to the SWE transducer for each muscle.

SWV; normalized to the value at rest) and normalized RMS (%RMS_{EMG}; normalized to MVC) values at different contraction levels was determined as the degree of stiffness change of each tissue.

2.5. Statistics

To examine whether the exerted torque was kept as instructed, one sample *t*-test was performed for the torques (normalized to MVC) and target levels (20, 40, 60%MVC). A paired *t*-test was performed to compare the %RMS_{EMG} values between RF and VL at each contraction level. For the intra-session reliability, the coefficient of variation (CV), standard error of measurement (SEM), and intraclass correlation coefficient (ICC) were calculated. The SWV of the muscles and fascia lata at each site was compared by a two-way analysis of variance (ANOVA) (probe directions × muscle activation levels) followed by a paired *t*-test and a one-way ANOVA with Bonferroni corrected post-hoc test. Pearson product-moment correlations were performed to %SWV-%RMS_{EMG} relationships at each site and direction. The slopes of %SWV-%RMS_{EMG} relationships of respective tissues were compared with a two-way ANOVA (sites × probe directions) followed by a paired *t*-test. To compare the slopes between muscle and fascia lata, a paired *t*-test was performed. Microsoft Excel (Excel 2016, Microsoft, USA) and SPSS statistical software (SPSS Statistics 24, IBM Corporation, USA) were used to perform these statistics. The significance level was set at

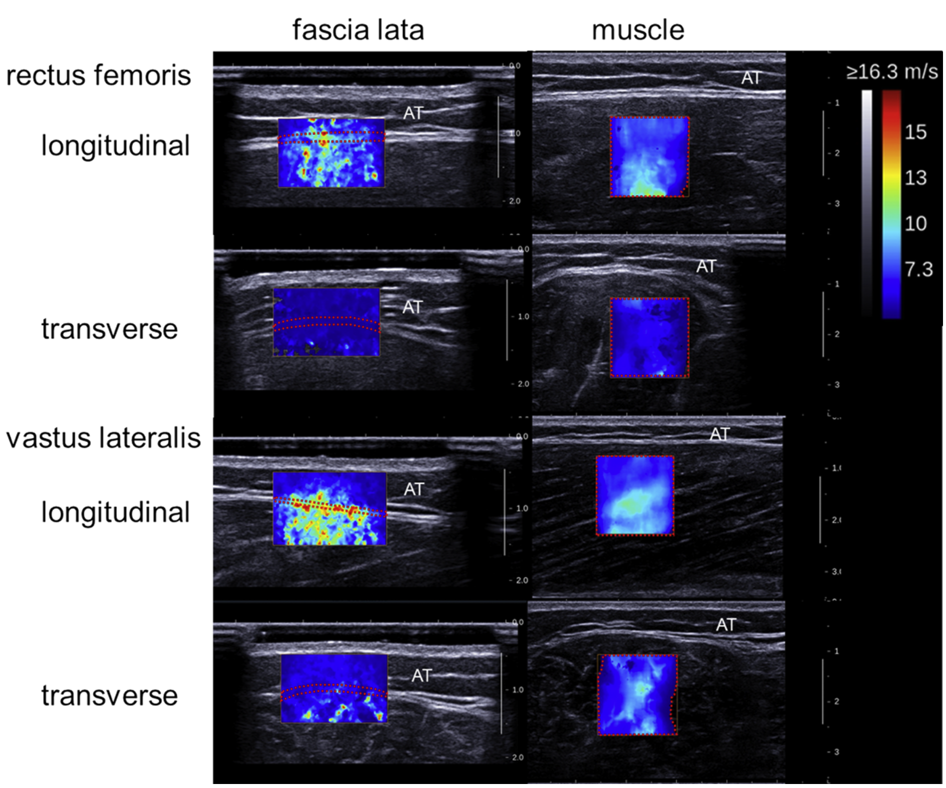

Fig. 3. Typical maps of the shear wave velocity (SWV) and regions of interest (ROIs) of the muscles and fascia lata during sub-maximal contraction in the longitudinal and transverse directions. RF: rectus femoris, VL: vastus lateralis, AT: adipose subcutaneous tissue.

Table 1
Repeatability of SWV measurements from two sets of sub-maximal contractions.

		Forces (%MVC)	At rest	20%	40%	60%
Fascia						
RF	Longitudinal	CV (%)	3.5	6.1	7.1	6.5
		SEM (m/s)	0.01	0.12	0.14	0.14
		ICC	0.97	0.79	0.85	0.88
	Transverse	CV (%)	1.4	7.2	4.9	5.6
		SEM (m/s)	0.004	0.14	0.09	0.15
		ICC	0.99	0.69	0.80	0.68
VL	Longitudinal	CV (%)	2.3	6.7	6.4	7.3
		SEM (m/s)	0.01	0.08	0.17	0.39
		ICC	0.99	0.97	0.91	0.70
	Transverse	CV (%)	3.3	5.7	5.8	9.1
		SEM (m/s)	0.04	0.12	0.15	0.41
		ICC	0.92	0.78	0.75	0.22
Muscle						
RF	Longitudinal	CV (%)	3.4	6.0	10.2	6.8
		SEM (m/s)	0.02	0.10	0.37	0.24
		ICC	0.95	0.91	0.62	0.75
	Transverse	CV (%)	4.2	8.8	9.3	6.7
		SEM (m/s)	0.04	0.12	0.15	0.41
		ICC	0.95	0.65	0.83	0.83
VL	Longitudinal	CV (%)	1.3	3.6	4.6	6.8
		SEM (m/s)	0.01	0.04	0.10	0.23
		ICC	0.86	0.97	0.93	0.85
	Transverse	CV (%)	4.0	8.4	9.2	9.0
		SEM (m/s)	0.04	0.25	0.29	0.31
		ICC	0.95	0.60	0.57	0.60

Values show coefficients of variation (CV), standard errors of measurement (SEM), and interclass correlation coefficients (ICC) of shear wave velocity of the rectus femoris (RF) and vastus lateralis (VL) and the fascia lata.

$p < 0.05$.

3. Results

3.1. Shear wave elastography

The CV, SEM, and ICC of SWV values for each tissue, site, probe direction, and contraction level are shown in Table 1. The ICC of the muscles (0.62–0.99) and fascia lata (0.68–0.99) showed that the SWV was kept "almost perfectly (0.81–1.00)" and "substantially (0.61–0.80)" same in the two cycles of the measurements, except for the fascia lata over VL in the transverse direction at 60%MVC (0.217; "fair") and VL muscle in the transverse direction at 20, 40, and 60% MVC (0.60, 0.57, 0.60, respectively; "moderate") (Landis and Koch, 1977).

Table 2 shows the SWV of the muscles and fascia lata at each site, probe direction, and contraction level. Significant interactions between probe directions and muscle activation levels were found at each site of fascia lata and muscle both for RF and VL ($p < 0.01$). In both directions, the SWV of the fascia lata increased with higher contraction levels. In every contraction level, the fascia lata over VL showed significantly higher SWV than that of RF ($p < 0.01$). At all levels of contraction, the SWV of the fascia lata in the longitudinal direction was significantly higher than that of the transverse direction ($p < 0.01$). For both muscles, the SWV in the longitudinal direction was lower than that of the transverse direction at rest ($p < 0.01$), but was higher during contraction ($p < 0.01$) except for that of RF at 20%MVC ($p = 0.09$). The SWV of the muscles in the longitudinal direction increased with higher levels of contraction ($p < 0.05$). In the transverse direction, the SWV of the muscles was higher at 20, 40, 60%MVC than at rest ($p < 0.05$).

3.2. Slope of the relationship between %SWV and %RMS_{EMG}

%SWV and %RMS_{EMG} of both the fascia lata and muscles showed significant and positive correlation at every site and direction ($p < 0.05$) (Fig. 4). A significant main effect of the direction was shown at each site of the fascia lata and muscles. The slopes of those changes of the fascia lata and muscles were higher in the longitudinal than transverse direction ($p < 0.01$) (Table 3).

3.3. Torque exertion and muscle activation

Average values of the %RMS_{EMG} of each muscle and %SWV of the fascia lata and muscles at each contraction level are shown in Fig. 5. Knee extension torques were sustained at 20.8 ± 1.6%, 40.7 ± 1.9%, and 60.8 ± 1.8%MVC, which were not significantly different from the target levels (20, 40, and 60%MVC). Muscle activation levels were not significantly different between RF and VL except for 20%MVC which showed higher %RMS_{EMG} in VL (21.7 ± 5.8%) than in RF (14.8 ± 4.9%).

4. Discussion

The present study showed dependence of the fascia lata and quadriceps muscles stiffness on the level of knee extension torque exertion. To the best of our knowledge, this is the first study that delineated deep fascia's mechanical behavior associated with underlying muscle contractions.

The stiffness of RF and VL muscle bellies in the longitudinal direction increased with increasing contraction levels, which is in line with several previous studies (Nordez and Hug, 2010; Yoshitake et al., 2014; Ates et al., 2015). Regardless of the ultrasound probe's direction, the stiffness of RF and VL was similar at rest and during sub-maximal contractions in most cases. In addition, the slopes of the relationships between %SWV and %RMS_{EMG}, i.e., the degrees of stiffening, of RF and

Table 2
The SWV values of the fascia lata and muscle belly at each site and direction.

		Shear-wave velocity (m/s)			
		Rectus femoris		Vastus lateralis	
	Contraction level	Longitudinal	Transverse	Longitudinal	Transverse
Fascia lata	At rest	$2.5 \pm 0.5^{*20,40,60,\dagger,\$}$	$3.2 \pm 0.5^{*40,60,\$,\#}$	$4.2 \pm 0.8^{*20,40,60,\dagger,\#}$	$3.9 \pm 0.5^{*20,40,60}$
	20%	$4.1 \pm 0.6^{*40,60,\dagger,\$,\#}$	$3.6 \pm 0.3^{*40,60,\$,\#}$	$7.5 \pm 2.2^{*40,60,\dagger}$	$4.4 \pm 0.5^{*40,60,\#}$
	40%	$5.0 \pm 0.8^{*60,\dagger,\$,\#}$	$4.1 \pm 0.4^{*60,\$,\#}$	$8.8 \pm 1.7^{*60,\dagger}$	$4.9 \pm 0.6^{*60}$
	60%	$5.9 \pm 1.0^{\dagger,\$,\#}$	$4.5 \pm 0.4^{\$}$	$9.9 \pm 1.2^{\dagger,\#}$	5.1 ± 0.5
Muscle	At rest	$2.4 \pm 0.3^{*20,40,60,\dagger}$	$3.6 \pm 0.7^{*20,40,60}$	$2.6 \pm 0.3^{*20,40,60,\dagger}$	$3.7 \pm 0.6^{*20,40,60}$
	20%	$5.2 \pm 1.0^{*40,60,\$}$	4.6 ± 0.6	$6.5 \pm 1.0^{*40,60,\dagger}$	4.8 ± 0.6
	40%	$9.1 \pm 2.2^{*60,\dagger,\$}$	4.6 ± 0.8	$8.1 \pm 1.2^{*60,\dagger}$	4.8 ± 0.6
	60%	$10.4 \pm 3.7^{\dagger}$	4.7 ± 0.7	$9.1 \pm 1.4^{\dagger}$	5.2 ± 0.8

Values are means ± SD. *20, *40, *60: vs. 20, 40, 60%, respectively. †: vs. transverse direction. $^{\$}$: vs. vastus lateralis. $^{\#}$: vs. muscle, $p < 0.05$.

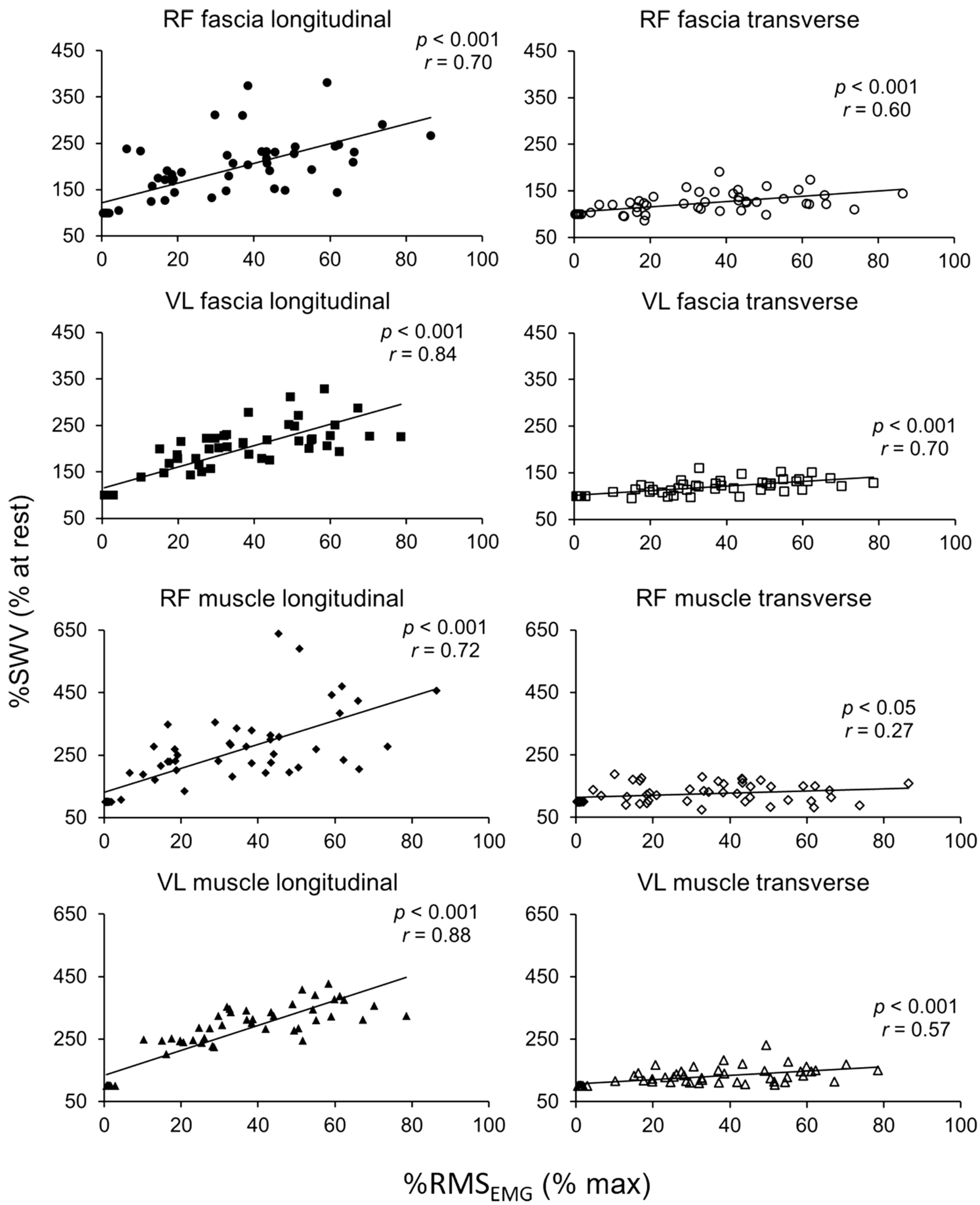

Fig. 4. Relationships between relative values of SWV (%SWV) and EMG RMS (%RMS_{EMG}) over and within muscles (fascia lata: RF; circle, VL; square, muscle: RF; diamond, VL; triangle) in the longitudinal (shaded) and transverse (unshaded) directions.

Table 3
The slopes of the relationships between %SWV and %RMS_{EMG}.

	Site			
	Rectus femoris		Vastus lateralis	
	Longitudinal	Transverse	Longitudinal	Transverse
Fascia lata	$2.6 \pm 1.4^{\dagger,\$}$	0.8 ± 0.6	$2.5 \pm 1.0^{\dagger,\$}$	0.5 ± 0.2
Muscle	$4.8 \pm 2.7^{\dagger}$	0.5 ± 0.5	$4.2 \pm 1.0^{\dagger}$	0.7 ± 0.6

Values are means ± SD. †: vs. transverse direction. $: vs. muscle, $p < 0.05$.

VL, were almost identical for longitudinal and transverse directions. No studies have ever examined changes in the stiffness of the quadriceps muscles during contraction, and the present study indicates that RF and VL muscles become stiffer with similar degrees under the same intensity of isometric contraction in the present knee and hip joint configuration.

Regarding the fascia lata, the SWV over VL was higher than that over RF at rest and during contraction in both transducer directions. In a human cadaver study, we have found that the fascia lata over VL is thicker and stiffer than that over RF (Otsuka et al., 2018). Such *ex situ* findings suggest that morphological differences (e.g. thickness, collagen fibers direction, and tissue composition) also affect fascia lata stiffness

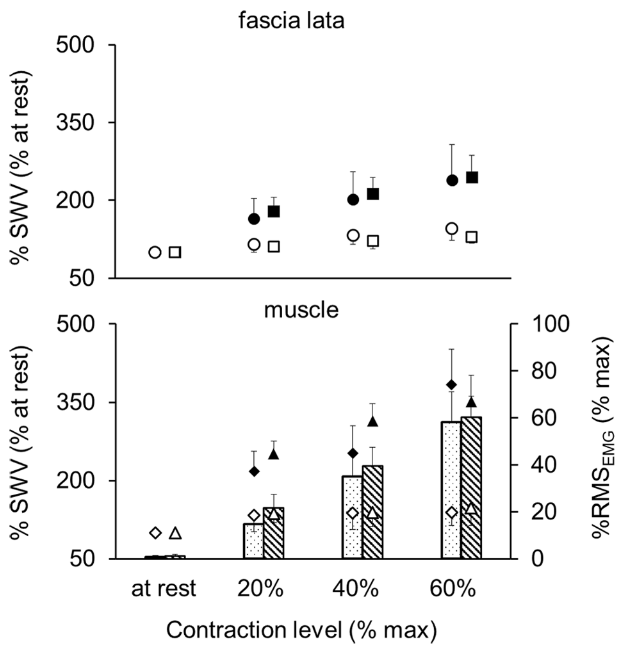

Fig. 5. Average values of %SWV of the fascia lata (RF: circle, VL: square) and muscles (RF: diamond, VL: triangle) in the longitudinal (shaded) and transverse (unshaded) directions at rest and each contraction level. The bar graph shows the $\%RMS_{EMG}$ of the muscles (RF: dots, VL: stripe).

in vivo. Interestingly, the degree of stiffening of the fascia lata as a function of contraction intensity was comparable for the two sites. This suggests that the degree of stiffening in the present study is a function predominantly of contraction intensity of the underlying muscles, regardless of the morphological differences in the fascia lata. The degree of stiffening of the fascia lata, however, was lower than that of the muscles especially in the longitudinal direction. Anatomical observation has shown that muscle fibers insert directly into the deep fascia and/or are connected to it via the epimysium (Stecco et al., 2014). Due to such connections, a large amount of the forces, generated by the muscle fibers can be transmitted to the adjacent connective tissues that surround the muscles (Rijkelijkhuizen et al., 2007). It is therefore likely that the fascia lata becomes stiffer according to the passive mechanical stress from underlying muscles' contraction through the myofascial network, and that the relative amounts of stiffness changes are not identical between muscles and fascia lata. Additionally, those connective tissues transmit forces not only serially but also laterally to the neighboring muscles (Maas and Sandercock, 2010). In the present study, knee extension torque was kept at the target level in spite of different muscle activation levels between RF and VL at 20%MVC, which may affect epimuscular myofascial force transmission between synergist muscles.

Although the SWV of each tissue in the longitudinal direction was lower than that of the transverse direction at rest except for the fascia lata over VL, it became significantly higher during contractions. Our previous study on *ex situ* fascia lata revealed a higher stiffness in longitudinal than in transverse direction (Otsuka et al., 2018). The result of the present study supports this cadaveric finding and further adds to a notion that the fascia lata becomes stiffer as increasing contraction levels which is prominent in the longitudinal direction compared to the transverse direction. It is generally known that the tendons which are in series with muscles play an important role in elastic energy storage during counter movement exercise (Kawakami et al., 2002).

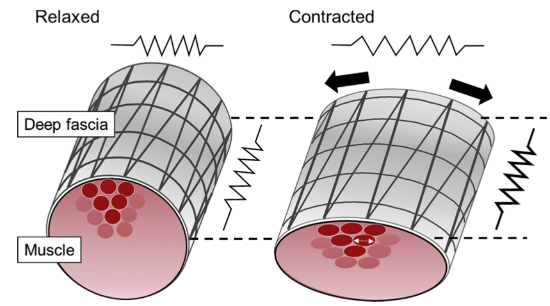

Fig. 6. Schematic illustrations of the changes in fascia lata with muscle contraction. The fascia lata can act as a spring with its elasticity showing anisotropic changes by contraction.

Aponeuroses covering muscle belly can contribute to elastic energy storage and recovery by being stretched in the longitudinal direction and increasing its longitudinal stiffness during contraction (Azizi and Roberts, 2009). In this study, the fascia lata also became stiffer in the longitudinal direction during contraction. This suggests that the fascia lata can act as a spring, contributing to elastic energy storage, myofascial force transmission, and limb stability (Eng and Roberts, 2018; Wilke et al., 2018). The epimuscular myofascial force transmission could occur not only in the direction parallel to muscles but also radially (Findley et al., 2015), and this could be due to the radial expansion of the contracting muscle fibers (Eng and Roberts, 2018). Such a radial expansion may involve lateral stretch and hence stiffening of the fascia lata in the transverse direction. Less stiffness of the fascial tissues in the transverse direction could contribute to maintaining intramuscular pressure (Garfin et al., 1981) and allow for underlying muscle's radial expansion (Eng and Roberts, 2018). It is speculated that such deformations of the fascia lata in both longitudinal and transverse directions match and optimize underlying muscles' contractions, thereby comprising a myofascial functional entity (Fig. 6).

We should mention limitations to the present study including our methodology. We found high reliability of the SWE measurements in the longitudinal direction (ICC: 0.618–0.989), but ICC values of SWV were lower in the transverse direction at sub-maximal contraction levels (e.g., ICC: 0.217; fascia lata over VL at 60%MVC). Several SWE studies mentioned about the lower reliability in the transverse probe direction than in the longitudinal direction for tendons (Brum et al., 2014). We found larger individual differences (SD) of the SWV than intra operator differences (SEM) at each contraction level, implying that the measurement error is not so large as to affect data analysis in the present study. However, this should be carefully taken into consideration when one measures the soft tissues in the transverse direction using SWE. In addition, we could only measure up to 60%MVC of the isometric knee extension because of the limit of SWE machine to measure SWV (~16.3 m/s). In our daily life, thigh muscles are activated by ~20%MVC at most (Kern et al., 2001; Sawai et al., 2006). Thus, the present contraction levels cover a large amount of daily motor tasks and our results indicate that the fascia lata contributes to optimizing underlying muscles functions during daily activities. However, in this study, muscle activation level of RF and VL was not identical at 20%MVC, which is in line with the previous finding (Alkner et al., 2000). Differences of activation levels between muscles might be due to difference in size and recruitment patterns of those muscles (Alkner et al., 2000). Besides, we measured the muscle activation level only from two synergist muscles, although epimuscular myofascial force transmission could also occur between antagonistic muscles and across the joints (Huijing et al., 2007; Cruz-Montecinos et al., 2016). Further studies are warranted to investigate the stiffness changes of the deep fascia at different sites including synergist and antagonist muscles with lower muscle activation levels (~20%MVC).

In conclusion, our study showed that not only the quadriceps muscles but also the fascia lata become stiffer when increasing the level of isometric knee extension torque. There is anisotropy in the elastic properties of the muscles and fascia lata during muscle contractions as well as the way they change as a function of contraction levels. These results further imply that the deformations of the fascia lata in both longitudinal and transverse directions match and optimize underlying muscles' contractions.

Conflicts of interests

The authors declare that there are no conflicts of interest.

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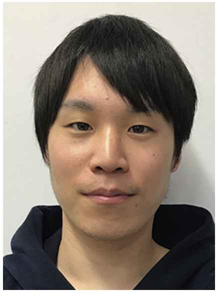

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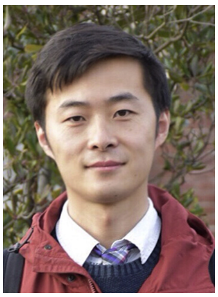

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