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Forefoot running requires shorter gastrocnemius fascicle length than rearfoot running

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ABSTRACT

This study aimed to investigate the influence of foot strike patterns on the behaviour of the triceps surae muscle-tendon unit, including the Achilles tendon whose length nearly corresponds to force of the triceps surae, and the medial gastrocnemius muscle (MG) during running. Seven male volunteers ran with forefoot and rearfoot strikes at 10, 14 and 18 km h^{-1} on a treadmill. The MG fascicle length was measured using ultrasonography. The *in vivo* length of the curved Achilles tendon was quantified by combining ultrasonography with optical motion capture of reflective markers on the right lower limb and an ultrasound probe. The forefoot strike resulted in a significantly shorter MG fascicle length at the initial contact, at Achilles tendon peak elongation, and at toe-off, than the rearfoot strike. The Achilles tendon length at initial contact was greater during the forefoot strike than during the rearfoot strike at 18 km h^{-1}, while its peak elongation was not significantly different during forefoot and rearfoot running. These results indicate that the MG, with a shorter length during forefoot running, manages to address demands for a similar peak force of the triceps surae than during rearfoot running.

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Introduction

Humans can select their foot strike pattern. Foot strike patterns are conventionally divided into subcategories according to the location of pressure (Cavanagh & Lafortune, 1980; Hatala, Dingwall, Wunderlich, & Richmond, 2013), or the visually identified location of the contact point (Hayes & Caplan, 2012; Kasmer, Liu, Roberts, & Valadao, 2013; Kasmer, Wren, & Hoffman, 2014; Kerr, Beauchamp, Fisher, & Neil, 1983; Larson et al., 2011; Nett, 1964; Ogueta-Alday, Rodríguez-Marroyo, & García-López, 2014), relative to the length of the foot at initial contact. In particular, according to whether initial contact is made around the ball of the foot or near the heel, the former and the latter strikes are termed forefoot strike and rearfoot strike, respectively. More than 70% of runners prefer a rearfoot strike for long-distance road races (Kasmer et al., 2013, 2014; Kerr et al., 1983; Larson et al., 2011). A rearfoot strike has been reported at the preferred speed of endurance running in 72% of habitually unshod Daasanach people (Hatala et al., 2013), as well as in habitually shod American athletes during both barefoot running (83%) and shod running (100%) (Lieberman et al., 2010). Laboratory studies have corroborated such empirical evidence suggesting the superiority of the rearfoot strike for endurance running. Although previous studies have found little difference in oxygen uptake between rear- and forefoot running at <15.1 km h^{-1} (Ardigo', Lafortuna, Minetti, Mognoni, & Saibene, 1995; Perl, Daoud, & Lieberman, 2012), others have reported that oxygen uptake is lower during rearfoot than during non-rearfoot running (Gruber, Umberger, Braun, & Hamill, 2013; Ogueta-Alday et al., 2014), suggesting that the rearfoot strike is spontaneously selected for endurance running to help minimize metabolic costs.

Some previous studies suggested that one of the potentially important mechanical factors that influence the running economy is the muscle-tendon unit (MTU) property (Arampatzis et al., 2006; Roberts, Marsh, Weyand, & Taylor, 1997). The MTU includes multiple elastic elements, which store and then release energy (Alexander & Bennet-Clark, 1977; Cavagna, Saibene, & Margaria, 1964; Ker, Bennett, Bibby, Kester, & Alexander, 1987). Among the elastic elements of various body parts, the Achilles tendon, which connects the soleus muscle proximally and the calcaneus distally, is believed to be the most important for human running (Bramble & Lieberman, 2004). In fact, a simulation study reported that the series elastic elements of the soleus and gastrocnemius muscles exhibited the greatest positive work among those of modelled lower limb muscles in running (Sasaki & Neptune, 2006). Previous studies have estimated the load on the Achilles tendon, which nearly corresponds to the Achilles tendon length (Magnusson, Aagaard, Rosager, Dyhre-Poulsen, & Kjaer, 2001), by dividing the plantar flexion torque calculated using inverse dynamics by the moment arm (Kulmala, Avela, Pasanen, & Parkkari, 2013; Perl et al., 2012). It was reported that the peak estimated force on the Achilles tendon during running at 14.4 km h^{-1} is higher in forefoot than in rearfoot runners (Kulmala et al., 2013). However, this technique has a drawback in that the estimated Achilles

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The supplemental data for this article can be accessed here.

tendon force includes the contribution of synergists and antagonists of the triceps surae. Computer simulations where these contributions are considered have shown inconsistent results for the difference in peak Achilles tendon force between rearfoot and non-rearfoot running (Almonroeder, Willson, & Kernozek, 2013; Lyght, Nockerts, Kernozek, & Ragan, 2016); this difference is partly due to a difference in modelling. Komi (1990) implanted a buckle containing a force transducer to the Achilles tendon directly and fitted one curve to integrated data on forefoot and rearfoot running to represent the relationship between running speed and peak Achilles tendon force. However, such an invasive technique may lead to unnatural behaviour by study volunteers because of the presence of pain and/or the use of local anaesthesia. Alternatively, the combination of a motion capture system and ultrasonography could measure the Achilles tendon length non-invasively (Fukutani, 2014; Lichtwark & Wilson, 2006). Therefore, this combination may provide a valuable insight into the differences in the natural behaviour of the Achilles tendon during forefoot and rearfoot running.

The operating range of the length of a muscle fibre is also important for locomotor performance because of the force–length relationship (Blix, 1894; Gordon, Huxley, & Julian, 1966). The force–length relationship has been described from isometric contractions; the force generation capacity of a muscle is maximum at an optimal length and decreases with both muscle shortening and stretching, corresponding to ascending and descending limbs of the force–length relationship, respectively (Gordon et al., 1966). Ultrasonographic measurements have revealed that the kinematics of a muscle fascicle do not always correspond to the kinematics of the MTU as a whole (Ishikawa, Pakaslahti, & Komi, 2007; Lichtwark & Wilson, 2006). Additionally, the estimated sarcomere length, which is calculated by dividing the muscle fascicle length by the average number of sarcomeres in series (Bobbert, Huijing, & van Ingen Schenau, 1986), of the medial gastrocnemius muscle (MG) (Ishikawa et al., 2007) and the fascicle length of the soleus muscle (Rubenson, Pires, Loi, Pinniger, & Shannon, 2012), during running, are maintained near the optimal length for optimal force output. If the foot strike pattern changes the length of the Achilles tendon, the operating range, with regard to the fibre length of the triceps surae muscle, will change. In addition, because the ankle, which is crossed by the MTU of the gastrocnemius muscle (Hawkins & Hull, 1990), is more plantarflexed during forefoot running than during rearfoot running (Kulmala et al., 2013; Landreneau, Watts, Heitzman, & Childers, 2014; Lyght et al., 2016; Shih, Lin, & Shiang, 2013), the length of this MTU would be influenced by the foot strike pattern. Consequently, it could be hypothesized that the forefoot strike leads to a more plantarflexed ankle and influences the knee joint angle and the elongation of the Achilles tendon, resulting in shorter gastrocnemius muscle fibres during running. To test this hypothesis, we directly measured the ankle and knee joint angles and the length of the Achilles tendon and the MG muscle fascicle, using motion capture and ultrasonography. These kinematic and musculotendinous data will provide mechanical and physiological insights regarding the reason for the difference in force generation between forefoot and rearfoot running.

Materials and methods

Participants

Seven healthy male volunteers participated in the experiment. The mean ± standard deviation values for age, height and body mass of the participants were 19.1 ± 0.4 years, 168.4 ± 4.4 cm and 61.1 ± 4.9 kg, respectively. All participants were habitually shod recreational runners. Four of the participants subjectively reported habitually running with a rearfoot strike pattern, while the remaining three reported a forefoot strike pattern. All participants provided written informed consent for participation in this study. The Human Research Ethics Committee at Kanagawa University approved all procedures used in the study that were performed according to the Declaration of Helsinki.

Experimental protocol

We set twofoot strike conditions (i.e., forefoot and rearfoot strikes), each at running speeds of 10, 14 and 18 km h^{-1}. The order of foot strike pattern and running speed was randomized for each participant. Participants spent as much time as they needed on a barefoot warm-up on a treadmill (N-Mill, Forcelink, Culemborg, the Netherlands). Prior to data collection, participants were also given time, as necessary, to familiarize themselves with running without shoes, which would interrupt the motion capture of the Achilles tendon, on the treadmill with the twofoot strike patterns. Participants were considered familiarized with each foot strike technique once they were able to produce consecutive cycles for each foot strike pattern for several seconds, at each of the three predefined running speeds, and confirmed their comfort with the running pattern to the experimenters. They ran barefoot at their self-selected stride frequency and length on the treadmill during all experimental trials. A trial for each combination of foot strike pattern and speed lasted >10 s, with a rest period of >1 min between consecutive trials. The foot strike pattern during each experimental trial was confirmed visually by the experimenters. When in doubt about a performed foot strike, the data for that trial were discarded, and the participant made another try.

Kinematic measurements

Kinematic data for all trials were recorded at 300 frames s^{-1} with a high-speed camera (EX-F1, Casio, Tokyo, Japan) (Figure 1). Small reflective markers were placed on the right side of each participant at the greater trochanter, head of the fibula, lateral malleolus, the head of the fifth metatarsal and superior calcaneal tuberosity, which was identified by an ultrasound apparatus (ProSound α7, Hitachi-Aloka Medical, Tokyo, Japan) prior to running. One marker was placed at the approximate midpoint between the distal edge of the apparatus' probe and the superior calcaneal tuberosity at rest. In addition, two reflective markers were also placed on both ends of the ultrasound-emitting surface. Each participant wore tight-fitting black running clothes to provide better visual contrast for video analysis and to help minimize marker movements.

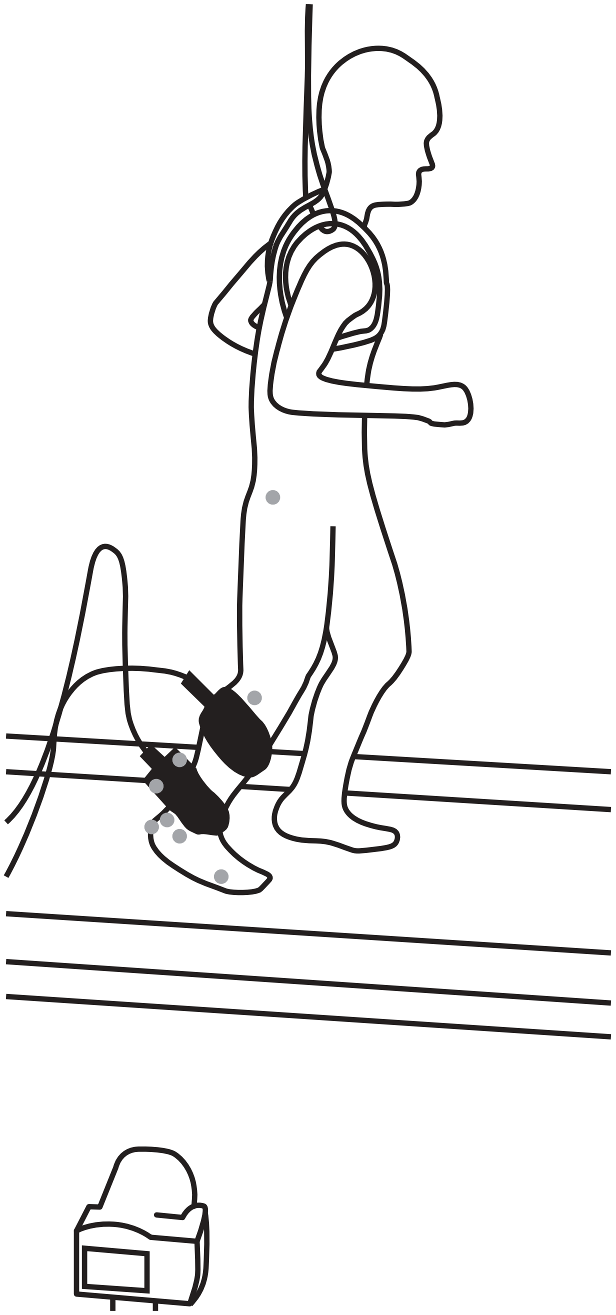

Figure 1. Experimental setup.

Marker position (grey circles) on a participant equipped with ultrasound probes (black objects on the lower limb) was captured using a high-speed camera located on the right side of the treadmill at a distance of approximately 2.0 m from the midpoint of the running lane. The camera lens was located parallel to the running direction.

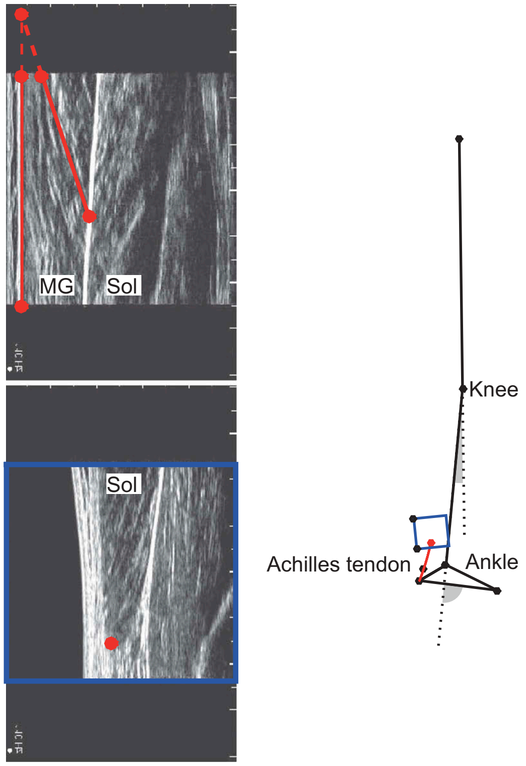

Figure 2. Oblique-sagittal ultrasound images of the medial gastrocnemius (MG) fascicle and the Achilles tendon.

Ultrasound images of the MG (left top) and the soleus (Sol) muscle (left bottom) are flipped and rotated to coordinate with the diagram of the right lower limb with an ultrasound probe (right). A probe surface is located at the left edge of the ultrasound image. To acquire the Achilles tendon images clearly, an attachable water bag was placed between the ultrasound probe for Sol myotendinous junction and the skin of the posterior surface of the lower limb. Hence, the superficial area of the ultrasound image at the left bottom appears black. MG fascicle length is calculated as the length of a muscle fascicle (thick red solid line) running between the superficial (thin red solid line) and deep aponeuroses along the line of collagenous tissue. When a fascicle extended out of the captured area in the ultrasound image, the fascicle length was calculated via linear extrapolation of a visible path of fascicle (thick red broken line) and a superficial aponeurosis (thin red broken line). The angle between a fascicle and superficial aponeurosis was also calculated for the estimation of the tendinous tissue length of the MG (Figure S1). The ultrasound image coordinate (i.e., local coordinate) position of the myotendinous junction of the Sol was detected and then the local coordinate position was transformed to the global coordinate position via a transformation expression with the global coordinate position of probe markers. Red dots and black dots represent points digitized from ultrasound images and camera images, respectively. A red curve on the right diagram represents the Achilles tendon interpolated based on the positions of the Sol myotendinous junction, one point of the skin on the Achilles tendon and the superior calcaneal tuberosity. Blue rectangles (left bottom and right) represent the area of the ultrasound image capturing the Sol myotendinous junction. Grey sectors between a black solid line and an auxiliary dotted line represent joint angles as defined according to Hawkins and Hull (1990).

Ultrasound measurements

Two ultrasound apparatuses were used to record oblique-sagittal image sequences of the MG and the Achilles tendon simultaneously (Figure 2). MG fascicles were targeted because the soleus muscle fascicle distribution is complex (Hodgson, Finni, Lai, Edgerton, & Sinha, 2006) and the distal portion of the gastrocnemius tendon forms a part of the Achilles tendon (Mellado, Rosenberg, & Beltran, 1998). A 6-cm width linear-array probe (7.5 MHz; UST-5712, Hitachi-Aloka Medical, Tokyo, Japan) was placed over the mid-belly of the MG and aligned with the midline of the muscle so that it was approximately in the same plane in which the muscle fascicles ran from the deep to the superficial aponeuroses. A 5-cm width linear-array probe (7.5 MHz; UST-567, Hitachi-Aloka Medical, Tokyo, Japan) with an attachable water bag option (WB-2463, Hitachi-Aloka Medical, Tokyo, Japan) and a scratch-built fixture was also attached to the Achilles tendon to image the myotendinous junction, which was identified as the most distal end of the soleus muscle. These probes were coated with a water-soluble transmission gel to provide acoustic contact and fixed with compressive bandages. Ultrasound images were acquired at a sampling rate of 110 Hz.

The collected ultrasound images and kinematic data were synchronized using pressure-sensitive sensors (DKH, Tokyo, Japan), which were attached to the recording buttons of ultrasound devices, and light-emitting diodes (LEDs), which were secured in front of the camera lens of a high-speed camera. The acquisition of the ultrasound image was started and ended at the same time when, via the pressure-sensitive sensors, the LEDs produced a flash signal on the upper and lower areas of the high-speed camera image for a short period of time. This signal allowed for time synchronization between the ultrasound and camera videos. According to a preliminary experiment in a similar setting, it was determined that the difference between the perceivable LED flash and the starting of the recording process for the ultrasound apparatus was 11 frames for the ultrasound video (0.1 s) in the subsequent analysis.

Data analysis

Initial contact with the ground was determined from video data by visual inspection, and a running cycle was defined as a period ranging from initial contact of the right lower limb to the time just before the next one. Five running cycles in which the ultrasound image data sequence was clearly distinguished were extracted for data analysis at each combination of foot strike pattern and running speed. Marker positions were digitized with unit conversion based on the placement of two reference tapes attached at a 1-m interval apart from each other on the treadmill and filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz, using MOVIAS Neo software (NAC Image Technology, Tokyo, Japan).

The fascicle attachment points on the superficial and deep aponeuroses for the MG muscle (Figure 2, left top) and the soleus myotendinous junction (Figure 2, left bottom) were manually tracked using in-house MATLAB-based scripts (The MathWorks, Natick, MA). After the manually tracked data were acquired, linear interpolation was applied to adjust the sampling rate of the ultrasound image data sequences, which was then changed to 300 Hz. The fascicle length was defined as the length of the attachment points of the fascicle lying between superficial and deep aponeuroses. When the point of attachment of the fascicle to the superficial aponeurosis extended outside the ultrasound image, this point was estimated using the intersection of a line through the endpoints of the visible fascicle path and a line through the endpoints of the superficial aponeurosis in the image (Blazevich, Cannavan, Coleman, & Horne, 2007). The use of shoes (i.e., barefoot or shod) and running surface mobility (i.e., treadmill or ground) have little influence on the behaviour of muscle fascicles (Cronin & Finni, 2013). Therefore, using barefoot running on a treadmill was expected to capture the general behaviour of the MG fascicles.

Prior to the Achilles tendon length calculation, the position of the soleus myotendinous junction in the ultrasound image was mapped into the global coordinate system, based on the global coordinates of two markers on the ultrasound probe (Figure 2). To replicate the curvature of the Achilles tendon (Arampatzis et al., 2006; Fukutani, 2014), the positions of three measured points in the Achilles tendon (i.e., soleus myotendinous junction, approximate midpoint of the Achilles tendon and superior calcaneal tuberosity) were fitted by a quadratic curve. Before the quadratic fitting, the position data were rotated in such a manner that the soleus myotendinous junction point and the superior calcaneal tuberosity were aligned horizontally. Subsequently, the length of the quadratic curve was analytically derived as the Achilles tendon length. This procedure is based on the sagittal assumption of the Achilles tendon, which is almost identical to the sagittal or oblique-sagittal assumption of muscle fascicles that has been implicitly set in various previous studies (Cronin & Finni, 2013; Fukunaga et al., 2001; Ishikawa et al., 2007; Lichtwark & Wilson, 2006; Maganaris, 2003; Rubenson et al., 2012).

MG MTU length was estimated via characteristics of the knee and ankle joint angles and shank length using an estimation equation (Hawkins & Hull, 1990) which defines the knee joint angle as the angle between shank and thigh and the ankle joint angle as the angle between the shank and the bottom of the foot (Figure 2). The MG tendinous tissue length was estimated from MTU length minus muscle fascicle length resolved along the long axis of MG MTU by multiplication of the fascicle length of the MG by the cosine of the fascicle angle (Figure S1), based on the model of Fukunaga et al. (2001).

The analysed data (MG fascicle length, length of the Achilles tendon, knee and ankle joint angles and the estimated length of the MTU and tendinous tissue) during five cycles were ensemble-averaged for each participant under each foot strike condition and each running speed. We divided the running cycle into the stance and swing phases for analysis, according to toe-off, which was defined as when the height of the head of the fifth metatarsal from the backward reference tape exceeded a threshold, which was determined with respect to each participant by visual inspection (25.3 ± 0.7 cm). The stance phase was defined as a period ranging from initial contact of the right lower limb to the point just before the toe-off. The swing phase was defined as the period ranging from toe-off to the time just before the next right lower limb contact. Moreover, the toe-off time relative to initial contact under each foot strike condition at each running speed for each participant was averaged to determine the representative value for the five-cycle data. We selected three time points (initial contact, the time of Achilles tendon peak elongation and toe-off) to analyse the time course data of MG fascicle length, Achilles tendon length, knee and ankle joint angles and estimated MG MTU length.

Statistical analysis

A two-way analysis of variance with repeated measures (twofoot strike patterns × three running speeds) was performed to test for differences in the duration of the stance phase, swing phase and running cycle. Tests were also conducted for differences in MG fascicle length, Achilles tendon length, knee and ankle joint angles, estimated MG MTU length at initial contact, and the time of Achilles tendon peak elongation and toe-off. Ultrasound images did not completely capture the distal end of the soleus muscle for one participant, which was needed for the detection of the Achilles tendon peak elongation; therefore, values at the time of Achilles tendon peak elongation were tested only in six participants. The Greenhouse-Geisser degrees of freedom correction (ε) was used to correct for any violations of the sphericity assumption. In cases in which the interaction between the foot strike pattern and running speed was statistically significant, simple effects were tested. Analysis of variance and simple effects tests were performed using statistical software

(SPSS Statistics 21, IBM Japan, Tokyo, Japan). The level of statistical significance for all comparisons was set at $P < 0.05$.

Results

Figure 3(a) shows that the MG fascicle length, especially during the stance phase, appeared to be shorter in forefoot running than in rearfoot running. In Figure 3(b), the foot strike pattern seemed to have a different effect on the Achilles tendon length at initial contact, depending on running speed; in particular, the length at initial contact appeared to be longer in the case of the forefoot strike than during the rearfoot strike at 18 km h^{-1}. In addition, the length of the Achilles tendon from the time of its peak elongation to toe-off appeared to be similar between forefoot and rearfoot running at any running speed. These observations were confirmed in the subsequent analysis.

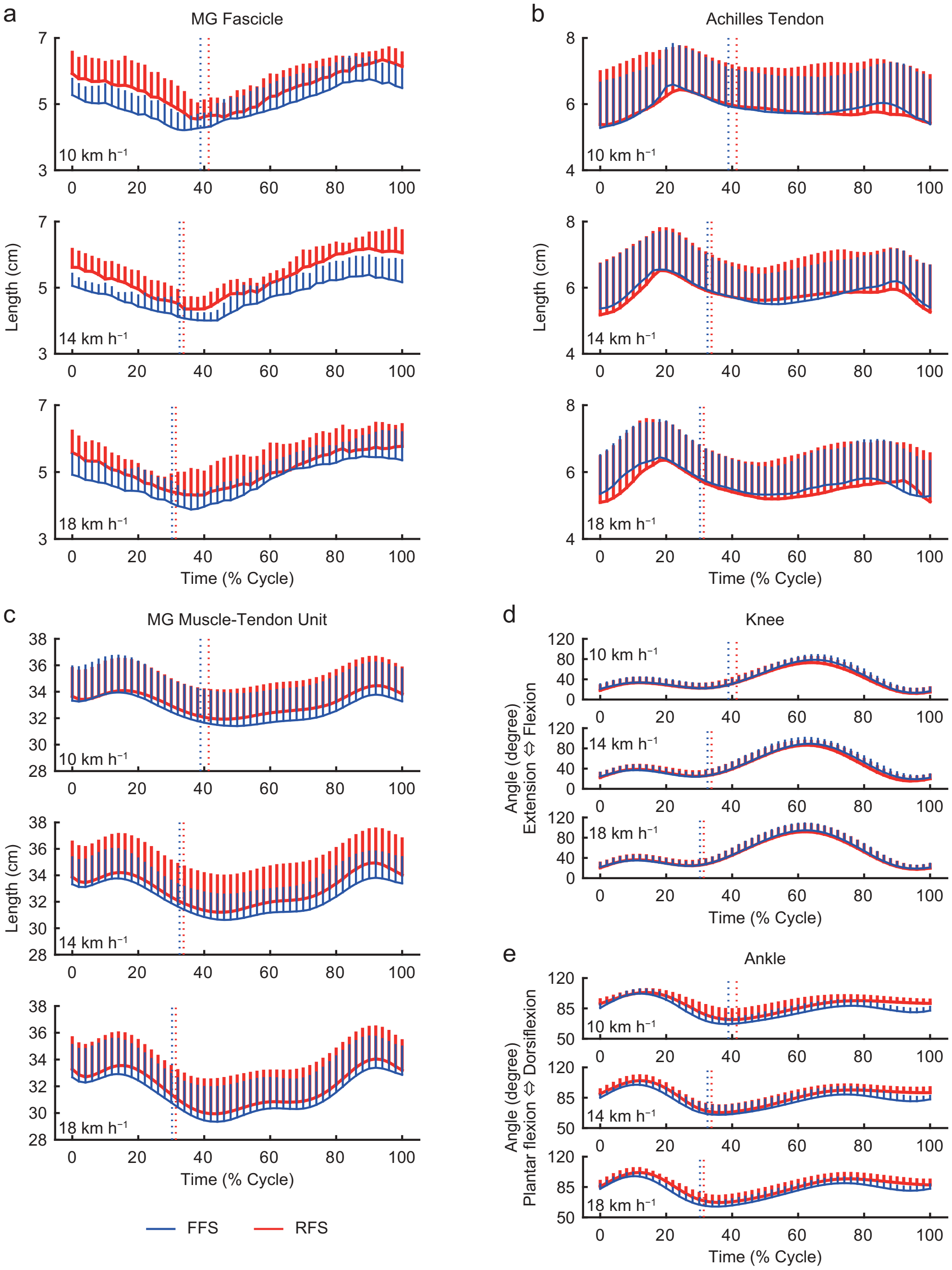

Figure 3. Ensemble-averaged time-series data during running with the forefoot strike (FFS) and rearfoot strike (RFS).

The fascicle length of the medial gastrocnemius muscle (MG) (a); the Achilles tendon length (b); the estimated length of the muscle-tendon unit of the MG (c), according to the estimated equation of Hawkins and Hull (1990); the knee joint angle (d); and the ankle joint angle (e) are illustrated. Each variable has three plots according to running speeds at 10, 14 and 18 km h^{-1} (top to bottom, respectively). Participants ran with FFS (blue) and RFS (red). Time is expressed as a percentage of the duration of one cycle. Data, per 2% of one cycle, is averaged across six participants whose distal end of the soleus muscle could be completely captured, and error bars represent standard deviation. Vertical broken lines represent toe-off, whose timing was averaged across six participants. Note that Figure 3 shows "overall pictures" and the values which were ensemble-averaged across six participants and are not equal to the means of statistically tested values because events (e.g., the Achilles tendon peak elongation) occurred at a different timing among participants.

At initial contact, time of Achilles peak elongation, and toe-off, there was a significant main effect of foot strike pattern on the MG fascicle length, but no significant main effect of running speed and no significant interaction on the MG fascicle length (Table 1 and Figure 3(a)).

At initial contact, there was no significant main effect of either foot strike pattern ($F_{1,6}$ = 2.23, ε = 1.00, P= 0.186) or running speed ($F_{2,12}$ = 0.58, ε = 0.99, P = 0.572) on the Achilles tendon length, but there was a significant interaction of the two factors on Achilles tendon length ($F_{2,12}$ = 10.99, ε = 0.66, P = 0.009; Figure 3(b)). Post-hoc testing indicated that the Achilles tendon length at initial contact with forefoot strike was significantly longer than that of the rearfoot strike at 18 km h^{-1} (P = 0.041) but was not significantly different at either 10 or 14 km h^{-1} (P = 0.686 and P = 0.086, respectively; Figure 4). At the time of Achilles tendon peak elongation and toe-off, there was no significant main effect of foot strike pattern or running speed, and there was no significant interaction effect on the Achilles tendon length (Table 2).

The knee joint was significantly more extended at toe-off during forefoot running (Table 1 and Figure 3(d)), and the ankle joint was significantly more plantarflexed at initial contact and toe-off during forefoot running, as compared with rearfoot running (Figure 3(e)). The estimated length of the MG MTU was significantly shorter at initial contact in forefoot strike compared to the rearfoot strike (Figure 3(c)). Although the stance phase was significantly shorter during forefoot running than during rearfoot running, the foot strike pattern had no significant main effect and no interaction with running speed on the entire running cycle time.

Discussion

The main findings of the present study were that MG fascicle length at initial contact, at the time of Achilles tendon peak

Table 1. Temporal, musculotendinous and kinematic data during running with the forefoot strike (FFS) and rearfoot strike (RFS).

			Mean ± SD		Analysis of variance					
Variable	Occasion	Speed (km h^{-1})	FFS	RFS	N	Factor	F	dfn	dfd	ε	P
Duration (s)	Stance phase	10	0.25 ± 0.01	0.26 ± 0.02	7	Foot	26.12	1	6	1.00	0.003*
		14	0.19 ± 0.02	0.21 ± 0.02		Speed	433.28	2	12	0.94	<0.001*
		18	0.16 ± 0.01	0.17 ± 0.01		Foot × Speed	1.37	2	12	0.88	0.292
	Swing phase	10	0.39 ± 0.04	0.38 ± 0.05	7	Foot	1.52	1	6	1.00	0.265
		14	0.40 ± 0.06	0.41 ± 0.04		Speed	7.12	2	12	0.72	0.020*
		18	0.39 ± 0.05	0.38 ± 0.05		Foot × Speed	0.69	2	12	0.55	0.449
	Cycle	10	0.64 ± 0.05	0.64 ± 0.06	7	Foot	1.92	1	6	1.00	0.216
		14	0.60 ± 0.07	0.62 ± 0.04		Speed	88.03	2	12	0.63	<0.001*
		18	0.55 ± 0.06	0.55 ± 0.06		Foot × Speed	0.72	2	12	0.53	0.437
MG fascicle length (cm)	Initial contact	10	5.3 ± 0.5	5.9 ± 0.6	7	Foot	8.92	1	6	1.00	0.025*
		14	5.1 ± 0.3	5.7 ± 0.5		Speed	2.53	2	12	0.59	0.156
		18	5.0 ± 0.6	5.7 ± 0.6		Foot × Speed	0.10	2	12	0.99	0.907
	AT peak elongation	10	4.7 ± 0.4	5.3 ± 0.7	6	Foot	10.20	1	5	1.00	0.025*
		14	4.6 ± 0.3	5.0 ± 0.4		Speed	1.61	2	10	0.57	0.260
		18	4.5 ± 0.5	4.9 ± 0.4		Foot × Speed	0.50	2	10	0.77	0.576
	Toe-off	10	4.4 ± 0.5	4.7 ± 0.5	7	Foot	12.50	1	6	1.00	0.013*
		14	4.1 ± 0.3	4.6 ± 0.7		Speed	1.83	2	12	0.79	0.214
		18	4.1 ± 0.5	4.4 ± 0.5		Foot × Speed	0.37	2	12	0.60	0.599
Knee joint angle (degree)	Initial contact	10	22.1 ± 8.9	19.6 ± 8.9	7	Foot	3.58	1	6	1.00	0.108
		14	25.5 ± 7.2	23.1 ± 7.8		Speed	1.41	2	12	0.98	0.282
		18	23.2 ± 8.2	22.0 ± 9.2		Foot × Speed	0.56	2	12	0.60	0.511
	AT peak elongation	10	28.7 ± 8.5	26.0 ± 9.9	6	Foot	0.57	1	5	1.00	0.484
		14	33.2 ± 7.5	33.4 ± 8.3		Speed	6.13	2	10	0.65	0.040*
		18	32.8 ± 8.7	33.0 ± 7.9		Foot × Speed	0.97	2	10	0.72	0.395
	Toe-off	10	29.3 ± 7.8	33.7 ± 9.9	7	Foot	8.73	1	6	1.00	0.026*
		14	25.9 ± 7.4	26.7 ± 8.3		Speed	19.95	2	12	0.80	<0.001*
		18	25.4 ± 6.0	26.9 ± 7.6		Foot × Speed	3.96	2	12	0.61	0.081
Ankle joint angle (degree)	Initial contact	10	84.3 ± 4.9	90.3 ± 4.1	7	Foot	15.62	1	6	1.00	0.008*
		14	84.3 ± 3.7	89.2 ± 4.3		Speed	7.86	2	12	0.67	0.018*
		18	82.7 ± 4.7	85.8 ± 5.4		Foot × Speed	1.34	2	12	0.87	0.299
	AT peak elongation	10	93.0 ± 8.6	93.2 ± 10.7	6	Foot	3.87	1	5	1.00	0.107
		14	94.2 ± 7.5	98.7 ± 8.0		Speed	0.65	2	10	0.62	0.484
		18	92.6 ± 7.1	97.4 ± 6.8		Foot × Speed	0.58	2	10	0.57	0.500
	Toe-off	10	66.3 ± 6.1	71.7 ± 10.8	7	Foot	10.48	1	6	1.00	0.018*
		14	64.6 ± 10.2	68.1 ± 5.9		Speed	3.19	2	12	0.78	0.097
		18	63.4 ± 5.1	68.9 ± 5.2		Foot × Speed	0.47	2	12	0.53	0.530
Estimated MTU length (cm)	Initial contact	10	33.8 ± 2.6	34.3 ± 2.5	7	Foot	6.12	1	6	1.00	0.049*
		14	33.6 ± 2.0	34.2 ± 2.6		Speed	1.84	2	12	0.87	0.208
		18	33.0 ± 2.3	33.8 ± 2.5		Foot × Speed	0.19	2	12	0.57	0.713
	AT peak elongation	10	33.5 ± 2.5	33.6 ± 2.1	6	Foot	2.12	1	5	1.00	0.205
		14	33.6 ± 2.1	34.0 ± 2.9		Speed	2.09	2	10	0.74	0.192
		18	32.7 ± 2.3	33.5 ± 2.4		Foot × Speed	0.38	2	10	0.62	0.606
	Toe-off	10	32.2 ± 2.6	32.5 ± 2.4	7	Foot	4.77	1	6	1.00	0.072
		14	31.8 ± 1.9	32.3 ± 2.6		Speed	3.93	2	12	0.92	0.055
		18	31.1 ± 2.4	31.7 ± 2.6		Foot × Speed	0.13	2	12	0.58	0.765

Data are presented as mean ± standard deviation (SD). MG: medial gastrocnemius muscle; MTU: MG muscle-tendon unit; AT: Achilles tendon; dfn: degrees of freedom for numerator; dfd: degrees of freedom for denominator; ε: Greenhouse-Geisser degrees of freedom correction; Foot: foot strike pattern factor; Speed: speed factor; Foot × Speed: interaction of foot strike pattern factor and speed factor. *P < 0.05, indicating a significant main effect.

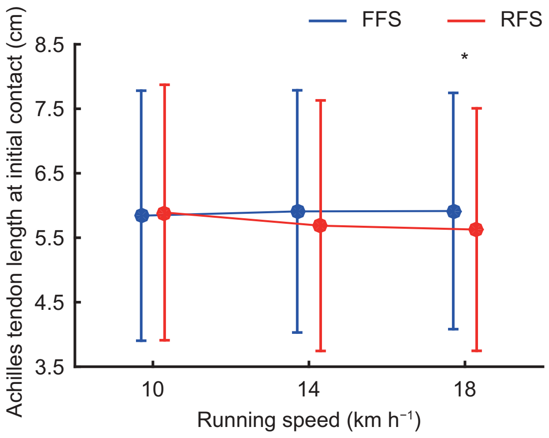

Figure 4. Group average data (*N*= 7) of Achilles tendon length at initial contact with the forefoot strike (FFS) and rearfoot strike (RFS).

Participants ran at 10, 14 or 18 km h^{-1} with the FFS (blue) and RFS (red). Error bars represent standard deviation. *$P < 0.05$, indicating a significant simple effect of foot strike pattern at 18 km h^{-1}.

elongation and at toe-off was significantly shorter during forefoot running than during rearfoot running, while peak elongation of the Achilles tendon was similar between forefoot and rearfoot running (Tables 1–2). These findings suggest that the MG during forefoot running responds to demands for a similar peak triceps surae force at a shorter fibre length than that during rearfoot running.

To our knowledge, this is the first attempt to directly measure the entire length of the Achilles tendon during forefoot and rearfoot running. The results indicate that the Achilles tendon peak length is similar between forefoot and rearfoot running (Table 2 and Figure 3(b)). This finding is compatible with the results of a previous study based on *in vivo* human running using a buckle transducer (Komi, 1990). In addition to peak elongation, the Achilles tendon length at toe-off was also similar in both foot strike conditions (Table 2 and Figure 3(b)). Although some researchers have assumed that the Achilles tendon during forefoot running stores and returns more elastic energy than in rearfoot running (Perl et al., 2012), the Achilles tendon length at the time of its peak elongation (i.e., store) and at toe-off (i.e., return) in the present study indicate this assumption does not hold.

In this study, MG fascicle length was shorter during forefoot running than during rearfoot running at initial contact, at the time of Achilles tendon peak elongation, and at toe-off. The shortened MG length during forefoot running at initial contact could be influenced by joint angles. The forefoot strike leads to a more plantarflexed ankle (Kulmala et al., 2013; Lyght et al., 2016; Shih et al., 2013) upon initial contact than the rearfoot strike (Table 1 and Figure 3(e) and 5); thus, the length of the MG MTU, which is calculated by the ankle and knee joint angles through the estimation equation (Hawkins & Hull, 1990), was shorter at initial contact during forefoot running than during the rearfoot strike (Table 1 and Figure 3(c)). Therefore, this suggests that a shortened MG MTU at initial contact kinematically constrains the MG muscle fibre to be shorter during the forefoot strike than the rearfoot strike. On the contrary, the estimated length of the MG MTU was similar at the time of Achilles tendon peak elongation and toe-off between forefoot and rearfoot running. In these cases, considering that the distal portion (i.e., a part of the Achilles tendon) of the gastrocnemius tendon seems to differ in elongation from its more proximal portion during plantar flexor contraction (Finni, Hodgson, Lai, Edgerton, & Sinha, 2003), tendinous tissues other than a part of the Achilles tendon within the MG MTU may compensate for a shorter fascicle length, possibly as a result of changes in the force contribution ratio between the MG and other portions of the triceps surae.

A shorter muscle fibre length of the MG during forefoot running through the stance phase leads to a disadvantageous force output. The estimated sarcomere length of the MG during running locates in the middle of the shallow ascending limb of the force–length relationship (Ishikawa et al., 2007) as stated by Walker and Schrodt (1974). Although a simulation study largely depending on estimation equations speculated that the MG fibre length during running reaches deep into the descending limb of the force–length relationship (Dorn, Schache, & Pandy, 2012), MG fibre length could not greatly exceed optimal length because the force-generation capacities of the MG and lateral gastrocnemius muscles are maximum with the fully extended knee and nearly fully dorsiflexed ankle (Maganaris, 2003), leading to a practically maximum lengthening of the gastrocnemius MTU. MG muscle fascicles during running are located nearly in the middle of the ascending limb of the force–length relationship, causing their shortening to lead to a decrease in their force generation capacity. Thus, a higher activation is needed to generate the same force. In fact, it was reported that MG activity during forefoot running is higher than during rearfoot running (Landreneau et al., 2014, see also Shih et al., 2013). In addition, the minimal fascicle length of the soleus muscle, which is a synergist of the MG during running, reaches to the steep ascending limb of the force–length relationship that is specifically predetermined for each participant using a dynamometer, and its peak

Table 2. Length of the Achilles tendon (AT) during running with the forefoot strike (FFS) and rearfoot strike (RFS).

		Mean ± SD (cm)		Analysis of variance						
Occasion	Speed (km h^{-1})	FFS	RFS	*N*	Factor	*F*	dfn	dfd	ε	*P*
AT peak elongation	10	6.7 ± 1.2	6.5 ± 1.3	6	Foot	1.15	1	5	1.00	0.333
	14	6.7 ± 1.1	6.6 ± 1.3		Speed	0.88	2	10	0.70	0.417
	18	6.6 ± 1.1	6.4 ± 1.1		Foot × Speed	0.66	2	10	0.76	0.507
Toe-off	10	6.5 ± 1.8	6.4 ± 1.7	7	Foot	0.03	1	6	1.00	0.860
	14	6.4 ± 1.5	6.4 ± 1.7		Speed	1.03	2	12	0.66	0.368
	18	6.3 ± 1.6	6.3 ± 1.7		Foot × Speed	0.05	2	12	0.88	0.938

Data are presented as mean ± standard deviation (SD). dfn: degrees of freedom for numerator; dfd: degrees of freedom for denominator; ε: Greenhouse-Geisser degrees of freedom correction; Foot: foot strike pattern factor; Speed: speed factor; Foot × Speed: interaction of foot strike pattern factor and speed factor.

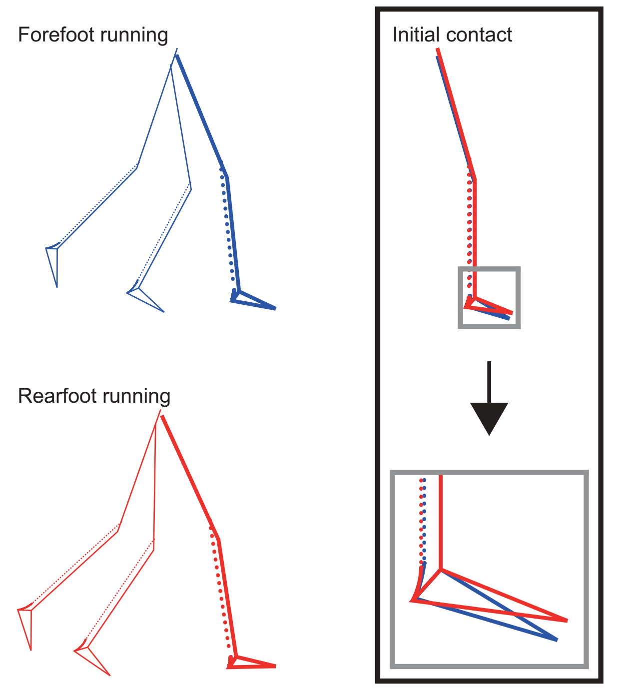

Figure 5. Typical example of diagram representing the right lower limb and the Achilles tendon during forefoot and rearfoot running.

The right lower limb (solid line) and the Achilles tendon (solid curve) at initial contact (right; thick diagram), the time of Achilles tendon peak elongation (middle), and toe-off (left) during running with the forefoot (top; blue) and rearfoot (bottom; red) strikes at 18 km h^{-1} are shown in the left panel. Because the muscle-tendon unit length of the medial gastrocnemius muscle was calculated from an estimation equation based on knee and ankle joint angles, the corresponding muscle-tendon unit cannot be drawn. Alternatively, a parallel line (dotted line) to the shank is drawn from the soleus myotendinous junction as a virtual line of the muscle-tendon unit of the medial gastrocnemius muscle, not involving the Achilles tendon. The diagrams at initial contact with the forefoot and rearfoot strikes are rotated to set the shank vertically and then superimposed at the ankle in the right panel. The superimposed diagrams around the ankle are expanded at the bottom of the right panel.

length is close to the optimal length (Rubenson et al., 2012). Since plantarflexing the ankle during forefoot running (Kulmala et al., 2013; Landreneau et al., 2014; Lyght et al., 2016; Shih et al., 2013) results in the shortening of the soleus MTU, the soleus fascicle length, which was not measured in the present study because of its complex muscle fascicle distribution (Hodgson et al., 2006), would also be shorter in the case of the forefoot strike. Consequently, the fibre length of the triceps surae is shortened during forefoot running, leading to a relatively low force-generation capacity.

It should be noted that the influence of the foot strike pattern on the Achilles tendon depends on the running speed. In this study, the Achilles tendon length at initial contact was longer during forefoot running at the highest examined running speed (18 km h^{-1}), in contrast to lower speeds (Figure 4). As empirical evidence, it was reported that forefoot strikers ranked relatively high in a marathon (Kasmer et al., 2013). In addition, a majority (barefoot running: 91%; shod running: 54%) of athletes of Kalenjin, from where many elite Kenyan distance runners originate (Onywera, Scott, Boit, & Pitsiladis, 2006), run with the forefoot strike at a preferred endurance running speed (approximately 21 km h^{-1}) (Lieberman et al., 2010), which is higher than the speeds examined in the present study and in previous studies reporting the superiority of the rearfoot strike in running economy (Gruber et al., 2013; Ogueta-Alday et al., 2014). For example, rearfoot strikers consumed 5.4% and 9.3% less oxygen than non-rearfoot strikers during running at 11 and 13 km h^{-1}, respectively (Ogueta-Alday et al., 2014), and rearfoot running led to approximately 2% lower oxygen consumption across forefoot and rearfoot strikers at 14.4 km h^{-1} (Gruber et al., 2013). Interestingly, it has been observed that some experienced runners changed their foot strike pattern from the rearfoot to forefoot strike at speeds of >18.5 km h^{-1} (Dorn et al., 2012). Therefore, forefoot strike during running at speeds of elite marathoners would have a different effect on the behaviour of MTU compared with running at lower speeds and might be preferable over rearfoot strike. Future studies are warranted to investigate the effect of foot strike pattern on the behaviour of MTU and running economy at >18 km h^{-1}.

In conclusion, the present study revealed that MG fascicle length at initial contact, at the time of Achilles tendon peak elongation, and at toe-off is shorter during forefoot running than during rearfoot running. Although the Achilles tendon length at initial contact with the forefoot strike was longer than that at the rearfoot strike at 18 km h^{-1}, the length at the time of its peak elongation and at toe-off was identical between forefoot and rearfoot running, regardless of running speed. These findings suggest that during forefoot running, the MG manages to address demands for a similar peak force of the triceps surae muscle with a shorter fibre length, as compared with rearfoot running.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data that support the findings of this study are available from the corresponding author, R. K., upon reasonable request.

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