

A LONGITUDINAL ASSESSMENT OF RUNNING ECONOMY AND TENDON PROPERTIES IN LONG-DISTANCE RUNNERS

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ABSTRACT

Kubo, K, Tabata, T, Ikebukuro, T, Igarashi, K, and Tsunoda, N. A longitudinal assessment of running economy and tendon properties in long-distance runners. *J Strength Cond Res* 24(7): 1724–1731, 2010—The aim of this study was to investigate longitudinal changes in tendon properties and running economy of long-distance runners (LDRs) in the preparatory periods of track season (TS) and road season (RS). Eleven well-trained LDRs and 6 untrained subjects participated in the present study. In each period, muscle strength, neural activation level, and tendon elongation for both knee extensors and plantar flexors, jump performances, and oxygen consumption during submaximal running velocities were measured. No significant differences observed in any measured variables between the 2 seasons for untrained subjects. For LDRs, the total running distance during 1 month preceding RS (832 ± 95 km) was significantly longer than that during 1 month preceding TS (718 ± 80 km). No significant differences in the muscle strength, neural activation level, and jump performances were found between TS and RS. The stiffness of tendon structures in RS was significantly lower than those in TS for both knee extensors (-14.4% , $p = 0.023$) and plantar flexors (-16.6% , $p = 0.040$). At 3 running velocities, the oxygen consumptions in RS were significantly lower than those in TS. These results suggested that the lower oxygen consumption during submaximal running velocities observed in the preparatory period of RS may be attributable to the more compliant tendon structures but not in the neuromuscular characteristics.

KEY WORDS knee extensor, plantar flexor, tendon elongation, oxygen consumption

INTRODUCTION

Some previous studies indicated that running economy, defined as the steady-state oxygen consumption for a given running velocity, contributed to distance running performance among trained athletes (e.g., 5). According to some previous findings (4,27), there were no significant changes in running economy during 1-year training cycle. In contrast, other researchers reported an improvement in running economy and performance over a 1-year training cycle (24,25). However, a few studies have investigated the changes in running economy of the “well-trained” long distance runners (LDRs) among the different phases of training cycle (3). It is well known that the well-trained athletes change the training volume and intensity throughout training cycle for improving their performance of each event (e.g. (3)). Therefore, information on the changes in running economy among the different phases of training cycle is essential for improving the performance of LDRs.

Recent studies have used ultrasonography to investigate the effects of tendon properties on the performances during stretch-shortening cycle exercises (2,12,14,15,22). Staflidis and Arampatzis (22) reported that the tendon structures in knee extensors were more compliant in excellent sprinters than that in inferior sprinters. Therefore, it is likely that the running economy in long distance runners would be related to the tendon properties. Indeed, Arampatzis et al. (1) showed that the knee extensors of the most economical runners had a more compliant tendon and aponeurosis. Considering these previous findings, we hypothesized that if the running economy of well-trained LDRs changes among the different phases of training cycle, these changes would be related to the tendon properties in lower limbs.

In the present study, we investigated the tendon properties and running economy in the different phases of training cycle in terms of training volume and intensity, that is, preparatory phases of track season (TS) and road season (RS). The purpose of this study was to investigate longitudinal changes in tendon properties and running economy of well-trained LDRs in the different seasons.

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24(7)/1724–1731

Journal of Strength and Conditioning Research
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METHODS

Experimental Approach to the Problem

According to some previous findings (18,19,21,23), the running performance and economy of LDRs improved with resistance and plyometric training. However, the detail mechanisms of changes in running economy because of an additional resistance and/or plyometric training are unknown. On the other hand, recent studies demonstrated that the tendon properties affected the performances during stretch-shortening cycle exercises, that is, jump, sprint, and distance running (1,2,15,22). Considering these points, we examined the tendon properties and running economy of well-trained LDRs in the different phases of training cycle in terms of training volume and intensity. From these findings, we aimed to get the fundamental knowledge for planning of training to improve the performance of LDRs.

Subjects

Eleven well-trained male LDRs participated in this study. However, 3 subjects could not perform the measurements of jump performances and running economy in the preparatory phase of RS (see below). The reasons given were injury of left leg ($n = 2$) and lower-back pain ($n = 1$). Data are therefore presented for 8 subjects (jump performances and running economy) and 11 subjects (other measured variables). The duration of training experience ranged from 5.9 to 11.1 years (7.7 ± 1.5 years). The best official record of the LDR in a 5,000-m race within 1 year before these tests ranged from 14:11 to 14:53 and the average was 14:33 (minutes:seconds). Throughout 1 year, LDR ran from 150 to 200 km·wk⁻¹ on the average (at least 6 d·wk⁻¹, up to 4 h·d⁻¹). In addition, 6 untrained individuals whose age, body height, and limb lengths were similar to those of LDRs were selected as a control group (CRL). The physical characteristics of all the subjects (LDR and CRL) are shown in Table 1. All CRL subjects were either sedentary or mildly active, but none had been involved in any type of regular exercise program for at least 1 year before the test. All subjects were advised to maintain their usual dietary habits and not to make any

intentional changes such as increasing the amount of intake or number of meals per day, to avoid nutritional influence. This study was approved by the Faculty of Physical Education, Kokushikan University, and was consistent with their requirements for human experimentation. All subjects were fully informed about the experimental procedures to be used and the purpose of the study, and they gave their written informed consent before participating in the study.

Procedures

Experimental Design. The measurements of muscle function and tendon properties (see below) were performed on the right lower limb. Subjects had previously visited the laboratory on at least 1 occasion to familiarize with the procedures involved. The preparatory period of TS was characterized by decreasing training volume (i.e., running distance) and increasing training intensity (i.e., running speed). In the preparatory period of RS, the LDRs aimed to increase the running distance mainly. For LDR, the measurements were performed in the preparatory periods of “track season” (the first 10 days of May 2008) and “road season” (the first 10 days of September 2008). In the present study, we planned that for each subject a time slot of measurement for TS was consistent with that for RS. Long-distance runners recorded the distance of running per day and totaled the distance of running during 1 month preceding the measurement. For CRL, these measurements were performed in the same time.

Body Composition. Body mass was measured to the nearest 0.1 kg using a calibrated scale, and height was measured to the nearest 0.1 cm. Percent body fat was assessed using a segmental multifrequency bioelectrical impedance analysis performed with an in Body II machine (Biospace, Tokyo, Japan) according to the procedure described by Kiyama et al. (8).

Muscle Strength. Maximal voluntary isometric torque (MVIT) was measured by means of specially designed dynamometers (Applied Office, Tokyo, Japan) for knee extension and plantar flexion, respectively. Torque signals were amplified and

TABLE 1. Age and physical characteristics of the subjects (mean [SD]).*

	Age (y)	Height (cm)	Thigh length (cm)	Lower leg length (cm)
Long-distance runners ($n = 11$)	20.1 (1.2)	170.5 (5.0)	39.1 (1.8)	39.2 (1.8)
Control ($n = 6$)	21.2 (1.5)	170.7 (2.7)	40.3 (0.7)	40.3 (0.6)
	Body mass (kg)		Percent body fat (%)	
	TS	RS	TS	RS
Long-distance runners ($n = 11$)	55.7 (4.1)	55.4 (3.5)	9.8 (2.4)	9.7 (2.2)
Control ($n = 6$)	68.1 (10.4)	66.7 (8.5)	15.0 (6.6)	14.8 (6.9)

*TS = preparatory period of track season; RS = preparatory period of road season.

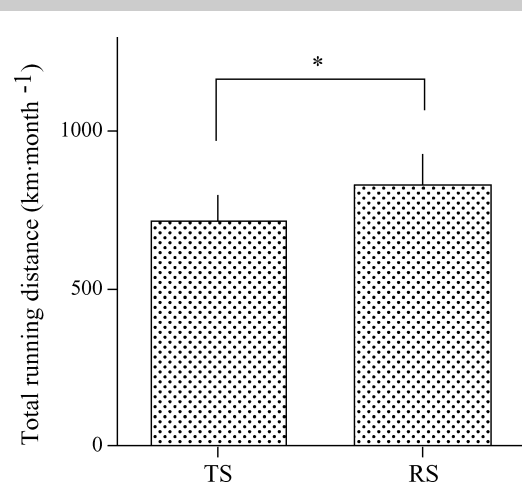


Figure 1. Total running distance during 1 month preceding the preparatory period of track season (TS) and of road season (RS).
*Significantly different between TS and RS ($p < 0.05$).

sampled at 1 kHz using a 16-bit A/D converter (PowerLab/16SP, ADInstruments, Sydney, Australia). All measurements were performed on the right lower limb. During each task, subjects exerted isometric torque from zero (relax) to MVIT within 5 seconds. During the knee extension task, subjects sat in an adjustable chair with support for the back and the hip joint flexed at an angle of 80° (full extension = 0°) to standardize the measurements and localize the action to the appropriate muscle group. During torque measurements, the hips and back were held tightly in the seat using adjustable lap belts. The axis of the knee joint was aligned with the axis of the lever arm of the dynamometer. The right ankle was firmly attached to the lever arm of the dynamometer with a strap and fixed with a knee joint flexed at an angle of 90° (full extension = 0°). During the plantar flexion task, subjects lay prone on a test bench, and the waist and shoulders were

secured by adjustable lap belts and held in position. The ankle joint was set at 90° with the knee joint at full extension, and the foot was securely strapped to a footplate connected to the lever arm of the dynamometer. Before the test, subjects performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure. Each task was repeated 2 or 3 times per subject with at least 3 minutes between trials. The highest value among these trials was recorded as the muscle strength for each. We performed the measurements of all the items (strength, tendon properties, activation level; see below) for knee extensors first, and then for plantar flexions. At least a 10-minute rest period was inserted after the measurements for knee extensors.

Elongation and Stiffness of Tendon Structures. Elongations of the tendon structures in knee extensors and plantar flexors were also assessed during isometric knee extension and plantar flexion. The task was repeated 2 times per subject with at least 3 minutes between trials. The measured values shown below are the means of the 2 trials. An ultrasonic apparatus (SSD-2000, Aloka, Tokyo, Japan) with an electronic linear array probe (7.5-MHz wave frequency with 80-mm scanning length; UST 5047-5, Aloka) was used to obtain longitudinal ultrasonic images of vastus lateralis at the level of 50% of the thigh length, that is, distance between the greater trochanter and the lateral epicondyle of the femur and medial gastrocnemius muscles at the level of 30% of lower leg length, that is, the distance between the popliteal crease and the center of the lateral malleolus. The probe was longitudinally attached to the dermal surface with adhesive tape, which prevented the probe from sliding. The ultrasonic images were recorded on videotape at 30 Hz and synchronized with recordings of a clock timer for subsequent analyses. The point at which one fascicle was attached to the aponeurosis was visualized on the ultrasonic images. This point moved proximally during isometric torque development up to a maximum (see Figure 1 of Ref [8]). The

TABLE 2. Muscle strength, activation level, twitch properties, and tendon properties for long-distance runners (mean [SD]).*

	Knee extensors		Plantar flexors	
	TS	RS	TS	RS
MVC (N·m)	148.4 (20.0)	148.9 (19.1)	107.2 (20.8)	106.8 (20.3)
Neural activation level (%)	82.6 (11.4)	82.7 (11.8)	88.4 (7.5)	86.0 (11.9)
Twitch peak torque (N·m)	34.3 (5.2)	33.3 (4.2)	20.6 (4.6)	22.0 (2.7)
Time-to-peak torque (ms)	91.2 (12.0)	88.8 (9.1)	118.8 (11.9)	114.6 (8.8)
Half relaxation time (ms)	79.4 (9.2)	77.4 (8.1)	76.8 (8.4)	74.7 (4.5)
Maximal elongation of tendon structures (mm)	17.6 (5.2)	20.9 (4.5)†	15.2 (2.0)	17.0 (2.5)†
Stiffness of tendon structures (N·mm ⁻¹)	72.9 (26.7)	58.4 (12.5)‡	37.2 (7.2)	31.0 (12.4)‡

*TS = preparatory period of track season; RS = preparatory period of road season.

†Significantly different from TS.

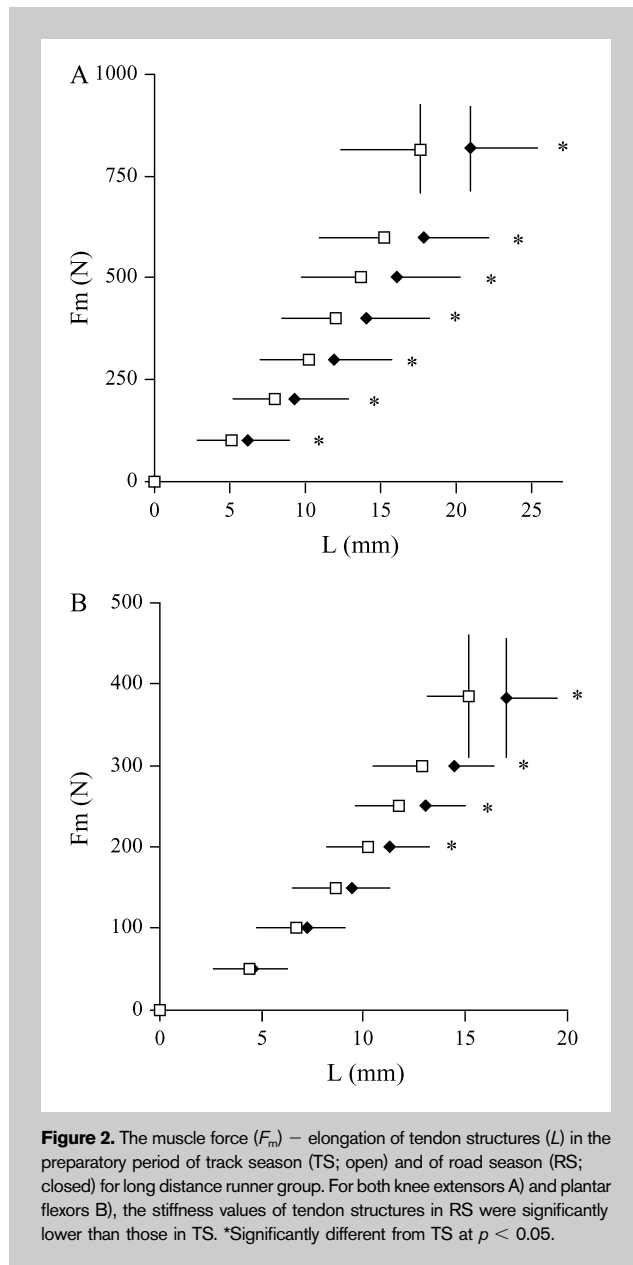


Figure 2. The muscle force (F_m) – elongation of tendon structures (L) in the preparatory period of track season (TS; open) and of road season (RS; closed) for long distance runner group. For both knee extensors A) and plantar flexors B), the stiffness values of tendon structures in RS were significantly lower than those in TS. *Significantly different from TS at $p < 0.05$.

displacement of this point is considered to indicate the lengthening of the deep aponeurosis and the distal tendon.

The displacements of tendon and aponeurosis will be attributed to both angular rotation and contractile tension, because any angular joint rotation occurs in the direction of knee extension and plantar flexion during an “isometric” contraction. Thus, angular joint rotation needs to be accounted for to avoid an overestimation of tendon displacement during an isometric contraction. To correct the measurements taken for the tendon and aponeurosis elongation, additional measurements were taken under passive conditions. To monitor joint angular rotation, an electrical goniometer (Penny and Giles, Biomechanics Ltd., Gwent, United Kingdom) was placed on the lateral aspect of each

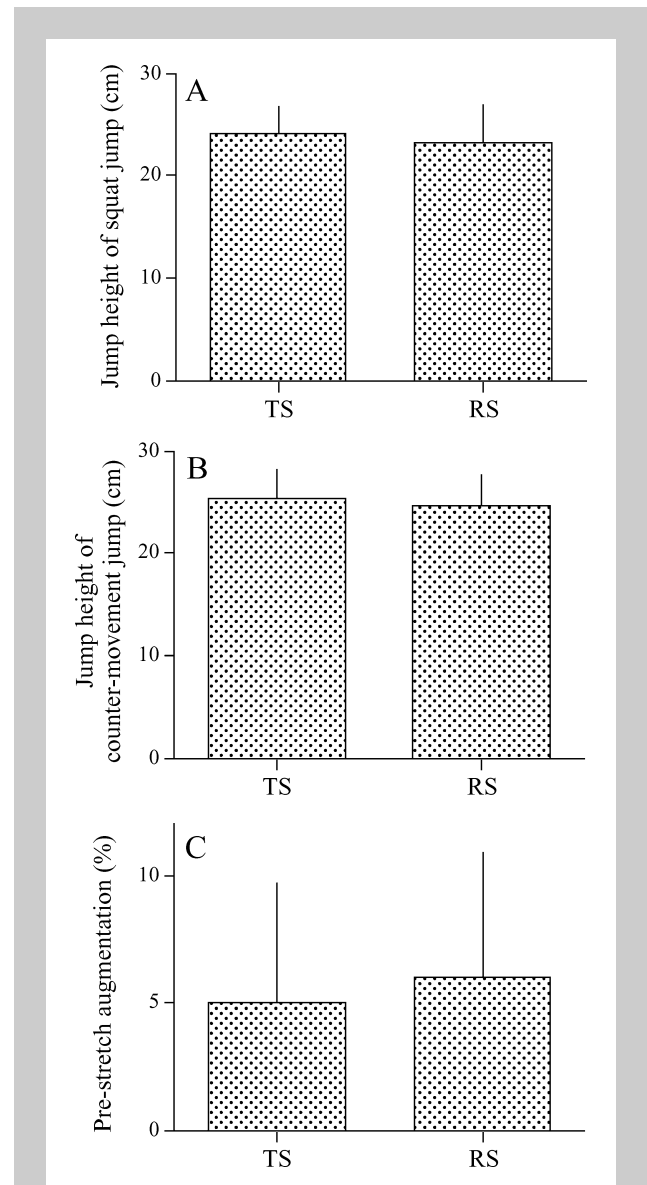


Figure 3. Jump heights of squat jump A) and counter-movement jump B), and prestretch augmentation C) in the preparatory period of track season (TS) and of road season (RS) for the long-distance runner group.

joint. The displacement of each site caused by rotating the knee and ankle from 110° to 70° was digitized in sonographs taken. Thus, for each subject, the displacement of each site obtained from the ultrasound images could be corrected for that attributed to joint rotation alone. In the present study, only values corrected for angular rotation are reported.

The measured torque (TQ) during isometric knee extension and plantar flexion was converted to muscle force (F_m) by the following equations (9,16):

$$F_m = k TQ M A^{-1},$$

where k is the relative contribution of the physiological cross-sectional area in each of vastus lateralis muscle within the

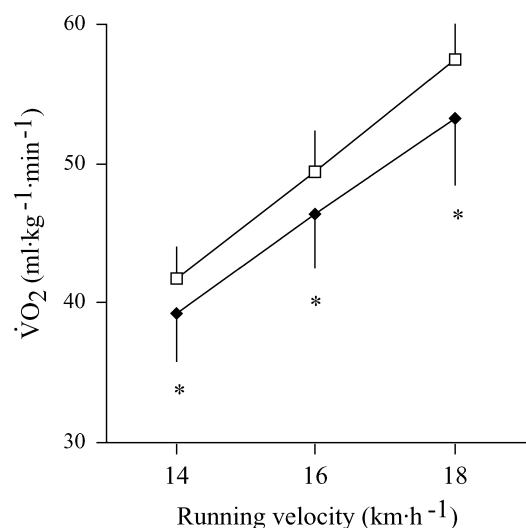


Figure 4. Oxygen consumption during submaximal running velocities (14, 16, and 18 km·h⁻¹) in the preparatory period of track season (TS; open) and of road season (RS; closed). *Significantly different from TS at $p < 0.05$.

knee extensors and medial gastrocnemius muscle within the plantar flexors, and MA is the moment arm length in each of quadriceps femoris muscles at 90° and triceps surae muscle at 90°, which was estimated from the limb length of each subject. In the present study, the F_m and the tendon elongation values above 50% of MVIT were fitted to a linear regression equation, the slope of which was adopted as stiffness (e.g. [14]). Intraclass correlation coefficient (ICC) and mean coefficient of variation (CV) of the 2 measurements were 0.89 and 6.9% for knee extensors and 0.91 and 7.4%, respectively.

Resting Twitch Properties and Neural Activation Level. The posture of the subject and setup were the same as those for the

measurement of the muscle strength and tendon properties as mentioned above. At least a 5-minute rest period was given after measurement of the tendon properties. Resting twitch properties were assessed by supramaximal electrical stimulations. The task was repeated 2 times per subject with at least 2 minutes between trials. The measured values shown below are the means of the 2 trials. The stimulating lead electrodes were placed on the skin over the femoral nerve at the inguinal region and the midbelly of the quadriceps femoris muscle for knee extensors and on the skin of the right popliteal fossa and oriented longitudinal to the estimated path of the tibial nerve with the anode distal for plantar flexors, respectively. A high-voltage stimulator (SEN-3301, having a specially modified isolator SS-1963, Nihon-Koden, Tokyo, Japan) generated rectangular pulses (triple stimuli with a 500-microsecond duration for 1 stimulus and an interstimulus interval of 10 milliseconds). Maximal twitch contractions were evoked in the resting muscle by progressively increasing the stimulation intensity until increases failed to elevate twitch torque further. The stimulus intensity that elicited peak twitch torque was used throughout the duration of the measurements. Peak torque, time to peak torque, and half-relaxation time were measured as the twitch properties. When the voluntary torque peaked, a superimposed maximal triple twitch was applied to assess the activation level of muscles. The difference between peak twitch torque and MVIT (twitch torque) was measured. Shortly (within 1–2 seconds) after MVIT, the same stimulation was given to the muscle at rest (control twitch torque). The measured values shown below are the means of 2 trials. The neural activation level (%) of the knee extensor muscles was calculated as $\{1 - (\text{twitch torque during MVIT} / \text{control twitch torque})\} \times 100$ as previously reported (9,16). Intraclass correlation coefficient and CV of the 2 measurements were 0.89 and 2.3% for peak torque, 0.91 and 2.1% for time to peak torque, 0.87 and 2.5% for half-relaxation time, and 0.85 and 3.2% for neural activation level, respectively.

Jump Performances. Each subject performed 2 kinds of maximal vertical jumps on the force plate (Kistler, 9281B,

TABLE 3. Muscle strength, activation level, twitch properties, and tendon properties for control group (mean [SD]).*

	Knee extensors		Plantar flexors	
	TS	RS	TS	RS
MVC (N·m)	201.5 (38.2)	194.4 (40.9)	120.9 (23.8)	122.7 (21.6)
Neural activation level (%)	90.7 (7.1)	90.2 (3.9)	91.6 (11.1)	90.9 (9.7)
Twitch peak torque (N·m)	44.0 (10.0)	43.3 (8.7)	23.0 (5.4)	23.3 (4.8)
Time to peak torque (ms)	86.9 (10.1)	88.6 (9.8)	111.9 (11.8)	113.8 (12.2)
Half relaxation time (ms)	89.8 (14.5)	91.0 (13.1)	96.4 (14.3)	97.0 (13.9)
Maximal elongation of tendon structures (mm)	25.4 (6.6)	26.8 (7.2)	17.8 (4.2)	18.3 (5.0)
Stiffness of tendon structures (N·mm ⁻¹)	78.6 (16.8)	82.4 (10.3)	34.9 (12.4)	34.5 (10.8)

*TS = preparatory period of track season; RS = preparatory period of road season.

TABLE 4. Jump performances and running economy for control group (mean [SD]).*

	TS	RS
Squat jump (cm)	32.2 (3.7)	33.0 (3.8)
Countermovement jump (cm)	36.6 (2.9)	37.6 (3.7)
Prestretch augmentation (%)	14.4 (7.2)	14.5 (5.5)
Oxygen consumption at 8 km·h ⁻¹ (ml·kg ⁻¹ ·min ⁻¹)	27.2 (2.0)	28.7 (2.2)
Oxygen consumption at 10 km·h ⁻¹ (ml·kg ⁻¹ ·min ⁻¹)	33.9 (2.3)	34.8 (1.9)
Oxygen consumption at 12 km·h ⁻¹ (ml·kg ⁻¹ ·min ⁻¹)	40.3 (2.0)	41.1 (1.9)

*TS = preparatory period of track season; RS = preparatory period of road season.

Winterthur, Switzerland) with and without countermovement, that is, the countermovement jump (CMJ) and squat jump (SJ), respectively. Subjects retained the “hands on hips” position until the final phase of jumps. For the SJ, subjects were positioned on the force plate with a knee angle of 90°. For the CMJ, subjects stood erect, and countermoved until the knee was flexed to 90°, before jumping. For all trials, subjects were instructed to jump as quickly as possible to a maximum height. These angles were accurately controlled by the use of an electrogoniometer (Penny and Giles). We excluded the trials in which the extra dip saw just before jumping of SJ and the knee angle differed by $\pm 5^\circ$ for the lowest position of CMJ. By measuring the flight time (T_{air}) from the force record, the vertical take-off velocity (V_v) of the center of gravity and jump height (H) of the center of gravity were calculated as follows:

$$V_v = \frac{1}{2} T_{\text{air}} g,$$

$$H = V_v^2 (2g)^{-1},$$

where g is the acceleration of gravity (9.81 m·s⁻²).

The test was repeated 5 times per subject, except for the trials in which knee angle differed by more than $\pm 5^\circ$, with at least 3 minutes between trials. Three data, excluding the largest and smallest values, were averaged. Coefficient of variation of the 3 measurements were 5.3% for SJ and 4.7% for CMJ, respectively.

The performance during stretch-shortening cycle exercise was evaluated from the relative difference in jump height between SJ and CMJ as an augmentation by a prior stretch (14,15):

$$\text{Prestretch augmentation (\%)} = \{(\text{CMJ} - \text{SJ})/\text{SJ} - 1\} \times 100.$$

Running Economy. Running economy was determined by measuring oxygen consumption (ml·kg⁻¹·min⁻¹) at 3 different velocities on a treadmill (AR-100, Minato Medical Science, Osaka, Japan). For LDR, after a warm-up period of 4 minutes at a running velocity of 10 km·h⁻¹, the subjects ran at 3 submaximal velocities (14, 16, and 18 km·h⁻¹) for 4 minutes. For CRL, after a warm-up period of 4 minutes at

a running velocity of 6 km·h⁻¹, the subjects ran at 3 submaximal velocities (8, 10, and 12 km·h⁻¹) for 4 minutes. Oxygen consumption was measured during 4 minutes of each running velocity using a breath-by-breath spirometer (AE-3005, Minato Medical Science, Osaka, Japan), and the average value of the oxygen consumption was calculated during the last minute of each running velocity.

The repeatability of the running economy (oxygen consumption at 3 different velocities) measurements was investigated on 2 separate days in a preliminary study with 5 young men. Intraclass correlation coefficient and CV of the 2 measurements were 0.84 and 5.1% for 8 km·h⁻¹, 0.87 and 4.7% for 10 km·h⁻¹, 0.83 and 6.5% for 12 km·h⁻¹, respectively.

Statistical Analyses

Values are reported as means $\pm$ SD. A 2-way analysis of variance with repeated measures (2 (groups) $\times$ 2 (test times)) was used to detect the significant differences in the measured variables between TS and RS. The level of significance was set at $p \leq 0.05$. Power calculations (statistical power) were performed using G*power computer software. Statistical power of >0.8 was obtained in the main significant changes, for example, stiffness, etc.

RESULTS

The total running distance during 1 month preceding RS (832 $\pm$ 95 km) was significantly longer than that during 1 month preceding TS (718 $\pm$ 80 km) (+12.7%, $p = 0.005$, Effect of Size [ES] = 1.31; Figure 1). There were no differences in body mass and percent body fat between TS and RS (Table 1). For both knee extensors and plantar flexors, MVIT, activation level, and twitch properties (peak torque, time to peak torque, and half-relaxation time) did not show any change between TS and RS (Table 2).

For both knee extensors and plantar flexors, the elongation values of tendon structures in RS were significantly greater than those in TS (Figure 2). The maximal elongation values of tendon structure in RS were significantly greater than those in TS (knee extensors; +23.1% $p = 0.008$, ES = 0.69, plantar flexors; +12.8% $p = 0.005$, ES = 0.82) (Figure 2, Table 2). The stiffness of tendon structures in RS was significantly lower than that in TS for knee extensors (-14.4%, $p = 0.023$, ES = 0.76) and plantar flexors (-16.6%, $p = 0.040$, ES = 0.65) (Figure 2, Table 2).

Both SJ and CMJ heights tended to be lower in RS (SJ; 23.3 $\pm$ 3.6 cm, CMJ; 24.6 $\pm$ 3.0 cm) than in TS (SJ; 24.1 $\pm$ 2.6 cm, CMJ; 25.3 $\pm$ 2.8 cm) (SJ; $p = 0.150$, CMJ; $p = 0.061$) (Figure 3). There were no difference in the prestretch

augmentation between TS ($5.0 \pm 4.7\%$) and RS ($6.0 \pm 4.9\%$) ($p = 0.493$). At 3 running velocities, the oxygen consumptions in RS were significantly lower than those in TS (Figure 4).

The measured variables for CRL were presented in Tables 1, 3, and 4. No significant changes in all the measured variables were found between TS and RS.

DISCUSSION

Main finding of this study was that the oxygen consumption during 3 running velocities decreased significantly in RS compared to TS. This result implied that when the training volume (total running distance) increased, the running economy improved for the well-trained LDRs. Recent studies demonstrated that the running performance and economy improved because of an additional resistance and/or plyometric training (18,19,21,23). Up to now, however, the detail mechanisms of changes in running economy because of an additional training are unknown. Paavolainen et al. (18) reported that simultaneous explosive-strength and endurance training produced a significant improvement in 5-km running performance in LDRs. In addition, they stated that these improvements were because of improved neuromuscular characteristics that were transferred into enhanced muscle power and running economy. In the present study, however, no significant changes in muscle strength, activation level, and twitch characteristics between TS and RS. Therefore, we may say that the improved running economy in RS was not related to the neuromuscular characteristics as stated by Paavolainen et al. (18).

Other interesting finding of this study was that the tendon structures for both knee extensors and plantar flexors were more compliant in the preparatory period of RS than in the preparatory period of TS. Our previous studies demonstrated that the human tendon structures did not change after the repeated ballistic exercises (e.g., drop jump) temporarily (11,13). Furthermore, De Zee et al. (6) showed that the tendon of pig hardly changed during the dynamic loading such as running (referred to as dynamic creep). Therefore, the present result conflicted with these previous findings concerning acute changes in the tendon properties in vivo and in vitro (6,11,13). On the other hand, fatigue leads to failure after repeated applications of stress, which may be much lower than the ultimate stress. Some previous studies showed that mean extension of tendons increased slowly during the fatigue test but much faster just before rupture (20,26). Wang et al. (26) implied that this failure would result from cumulative damage. In the present study, the difference in the total running distance was almost 100 km (about 13%) between TS and RS. Assuming that the stride length of 1 step is 1.5 m (7,17), we can say that the repeated numbers of step in the RS increased about "67,000 steps" compared to in the TS. This amount of increase in steps would be considerably greater than that of De Zee et al. (6) (corresponding to the running for 20 minutes with a speed of $19 \text{ km} \cdot \text{h}^{-1}$; 3% strain

1,600 cycles). Certainly, the differences in the materials of surface (track vs. road) would affect the tendon properties in lower limbs. However, it is very difficult to mention this point, because LDR in the present study ran on both track and road in TS and RS indeed. In the present study, we would like to pay attention to the difference in the total running distance. Considering these points, it may be that the observed increase in the tendon elongation is related to the cumulative damage of tendon structures because of the increase of training volume (i.e., running distance).

Recent studies using ultrasonography demonstrated that the performances during stretch-shortening cycle exercises were related to the tendon properties (2,12,14,15,22). As mentioned above, the maximal elongation of tendon structures for both sites in RS (increase in total running distance) was longer than in TS. Apart from the fatigue of tendon structures, it is likely that the increment of tendon extensibility in RS is related to the improvement of performance during stretch-shortening cycle exercises. Indeed, Kubo et al. (12) and Staflidis and Arampatzis (22) reported that the tendon structures in knee extensors were more compliant in excellent sprinters than that in inferior sprinters. Moreover, Arampatzis et al. (1) showed that the knee extensors of the most economical LDRs had a more compliant tendon and aponeurosis. Therefore, the present results support the above previous findings. Considering these points, the changes in tendon properties would contribute to the improvement of running economy in the preparatory period of RS. These discussions are speculative and require additional data for clarification.

PRACTICAL APPLICATIONS

We investigated longitudinal changes in muscle and tendon properties, jump performances, and running economy of LDRs in the preparatory periods of TS and RS. The present results indicated that the lower oxygen consumption during submaximal running velocities observed in the preparatory period of RS may be attributable to the changes in tendon properties but not in the neuromuscular characteristics. Furthermore, because the jump and running exercises included "stretch-shortening cycle" of lower limb muscles, we expected that the changes in jump heights were linked with the changes in oxygen consumption during submaximal velocities (running economy). However, there were no differences in jump performances between the 2 seasons. Taken together, these results implied that for LDRs it should be adopt "running" exercise, but not "jump" exercise to evaluate abilities of stretch-shortening cycle exercises certainly.

ACKNOWLEDGMENTS

This study was supported by the Grant-in-Aid for Exploratory Research (19650168 to K. Kubo) from Japan Society for Promotion of Science. The authors would like to thank all the subjects who participated in this study for volunteering their time and energy.

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