Potential Relationship between Passive Plantar Flexor Stiffness and Running Performance

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ABSTRACT

The present study aimed to determine the relationship between passive stiffness of the plantar flexors and running performance in endurance runners. Forty-eight well-trained male endurance runners and 24 untrained male control subjects participated in this study. Plantar flexor stiffness during passive dorsiflexion was calculated from the slope of the linear portion of the torque-angle curve. Of the endurance runners included in the present study, running economy in 28 endurance runners was evaluated by measuring energy cost during three 4-min trials (14, 16, and 18 km/h) of submaximal treadmill running. Passive stiffness of the plantar flexors was significantly higher in endurance runners than in untrained subjects. Moreover, passive plantar flexor stiffness in endurance runners was significantly correlated with a personal best 5000-m race time. Furthermore, passive plantar flexor stiffness in endurance runners was significantly correlated with energy cost during submaximal running at 16 km/h and 18 km/h, and a trend towards such significance was observed at 14 km/h. The present findings suggest that stiffer plantar flexors may help achieve better running performance, with greater running economy, in endurance runners. Therefore, in the clinical setting, passive stiffness of the plantar flexors may be a potential parameter for assessing running performance.

Introduction

Running performance is determined by various factors, including biological, physiological, and biomechanical factors. Of those, especially running economy, which is defined as oxygen consumption (VO_2) during submaximal running, is a key component in determining running performance of endurance runners [25]. Furthermore, competitive performance has been suggested to be better predicted by running economy than VO_2 maximum in highly trained endurance runners [23]. The running economy is partially determined by biomechanical characteristics [25]. Superior running performance is achieved by large moments of the hip, knee, and ankle joints. Among these lower extremity joints, the role of the ankle plantar flexor moment as an energy source during running is relatively larger compared to other joint moments [22, 24], and the plantar flexor muscle strongly contributes to body support and propulsion during the contact phase [11, 24]. Thus, the properties of the plantar flexors may help achieve superior running performance, potentially by enhancing running economy, in endurance runners.

Range of motion (ROM) is a universal parameter for evaluating joint flexibility [2]. Previous studies have reported that running economy is related to the ROM of ankle joint dorsiflexion [7, 15], which indicates the flexibility of the ankle joint. In addition, previous studies have used passive stiffness, which is calculated from the slope of the liner portion of the torque-angle curve, as a flexibility parameter [6, 9, 10, 13, 17]. This passive stiffness has been frequently used to evaluate the mechanical properties of the muscle-tendon complex (MTC), even though this parameter includes the properties of other tissues, such as the skin, subcutaneous fat, fascia, ligament, joint capsule, and cartilage [16]. Kubo et al. [17] suggested that passive stiffness in the plantar flexors may reflect the properties of muscle tissue rather than tendon tissue. Recently, previous studies demonstrated that passive plantar flexor stiffness is correlated with muscle stiffness measured using shear wave elastography [6, 13]. These previous findings indicate that passive stiffness is better associated with the properties of muscle tissue than tendon tissue, and it is therefore suggested that passive stiffness may be useful for evaluating muscular flexibility.

Several previous studies examined the association between plantar flexor tendon stiffness and running performance [1, 8, 18, 21]. Arampatzis et al. [1] determined that greater plantar flexor tendon stiffness measured using ultrasonography is related to greater running economy. Moreover, Fletcher et al. [8] reported that, although stiffer plantar flexor tendon stiffness in women was correlated with greater running economy, no such significant correlation was observed in men, suggesting that plantar flexor tendon stiffness is insufficient for determining running economy. Furthermore, Kubo et al. [18, 21] reported that lower plantar flexor tendon stiffness was correlated with a faster personal best 5000-m race time, but running economy was not measured in this study. Thus, the relationship between plantar flexor tendon stiffness and running performance is unclear based on the findings in the previous studies [1, 7, 18, 21].

The previous method for the evaluation of tendon stiffness involving ultrasonography is often technically difficult, and this might be related to discrepancies among previous findings [1, 7, 18, 21]. In contrast, the evaluation of simple passive stiffness is relatively easy, suggesting that this method can be widely applied in the clinical setting. If passive stiffness is related to running performance, its measurement may be useful for assessing running performance and evaluating the effects of training and/or rehabilitation. In a previous study, Spurrs et al. [26] reported that improved running economy by 6 weeks of plyometric training corresponded with enhanced passive stiffness in plantar flexors. Thus, their findings propose that passive plantar flexor stiffness may be related to running performance, including running economy; however, this direct relationship remains unknown. To determine the clinical efficacy of passive stiffness measurement of the plantar flexors, therefore, we first compared the passive plantar flexor stiffness between endurance runners and untrained subjects to gain a better understanding of the characteristics of passive plantar flexor stiffness in endurance runners. Thereafter, we compared the passive plantar flexor stiffness between the groups of faster and slower endurance runners based on their personal best 5000-m race time, and subsequently examined the relationship between passive plantar flexor stiffness and running performance, including running economy, in endurance runners.

Methods

Participants

Forty-eight well-trained male endurance runners (age: 20 ± 1 years, height: 171 ± 6 cm, weight: 56 ± 5 kg) participated in this study. These endurance runners were involved in regular training and competition. Their best personal times in a 5000-m race ranged from 858 to 967 s (mean 906 ± 27 s). On the basis of a preliminary study, 24 untrained subjects (age, 21 ± 2 years; height, 171 ± 4 cm; weight, 57 ± 4 kg) matched to the endurance runners for body height and weight were selected as a control group. The untrained control subjects were recreationally active but did not participate in any physical training program. Following comparison of passive plantar flexor stiffness between endurance runners and untrained subjects, the endurance runners were further divided into faster and slower groups (n = 24 in each group) based on their personal best 5000-m race time in order to examine the effect of passive plantar flexor stiffness on running performance. The subjects were informed of the experimental procedures and provided written consent to participate in the study. All procedures were approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2014-02) and met the ethical standards of the International Journal of Sports Medicine [12].

Passive stiffness

Passive stiffness of the plantar flexors in the subjects was measured using a BIODEX dynamometer system (BIODEX system 3; BIODEX Medical, Shirley, NY, USA). The subjects were instructed to refrain from performing stretching exercises for at least 2 h before measurement. The subjects were placed in the sitting position with full extension at the knee joint on a dynamometer, and the hip was securely fixed by seat belts. The subject's foot was tightly strapped to a footplate connected to the lever arm of a dynamometer. During the measurement, subjects were requested to maintain relaxation and not provide any voluntary resistance. To measure the passive stiffness, the baseline ankle joint was set at 20 ° dorsiflexion. Thereafter, passive dorsiflexion of the ankle joint was performed from 20 ° plantar flexion of the ankle joint with a slow constant velocity of 2 °/s. During dorsiflexion, torque was continuously sampled at 100 Hz and was used to calculate passive stiffness. Passive plantar flexor stiffness was calculated from the linear slope of the torque-angle curve between 10 ° and 20 ° dorsiflexion of the ankle joint. In a preliminary study, we measured passive stiffness of the plantar flexors on two separate days in 18 healthy men (age: 22 ± 1 years, height: 174 ± 5 cm, weight: 65 ± 8 kg). The coefficient of variation of two separate days was 8.0 ± 7.3 %. The intraclass correlation coefficient of two separate days was 0.962.

Running economy

Of the endurance runners included in the present study, 28 endurance runners were able to participate on the testing day and underwent measurement of running economy. Running economy was evaluated by calculating energy cost during three 4-min trials at submaximal running speeds of 14, 16, and 18 km/h on a treadmill (Valiant ultra; Lode BV, Groningen, The Netherlands) in endurance runners. A 4-min active rest at 6 km/h was incorporated between each 4-min running trial. The breath-by-breath VO_2 data were collected every 10 s throughout the treadmill testing using a gas analyzer (AE-310 S; Minato Medical Science, Osaka, Japan). The mean VO_2 value during the last 60 s of each 4-min running trial was converted to energy cost by using an energy equivalent of 20.1 J/ml of oxygen and dividing by submaximal speed (m/s) and body mass (kg) [4].

Statistical analysis

All data are expressed as mean ± SD. Groups were compared using an unpaired t-test. The relationship between passive stiffness of the plantar flexors and running performance (i. e., the best personal 5000-m race time and energy cost during submaximal treadmill running) in endurance runners was assessed using a Pearson's product moment correlation. The statistical significance level was defined at $P < 0.05$. All statistical analyses were conducted using IBM SPSS software (version 19.0; International Business Machines Corp, NY, USA).

Results

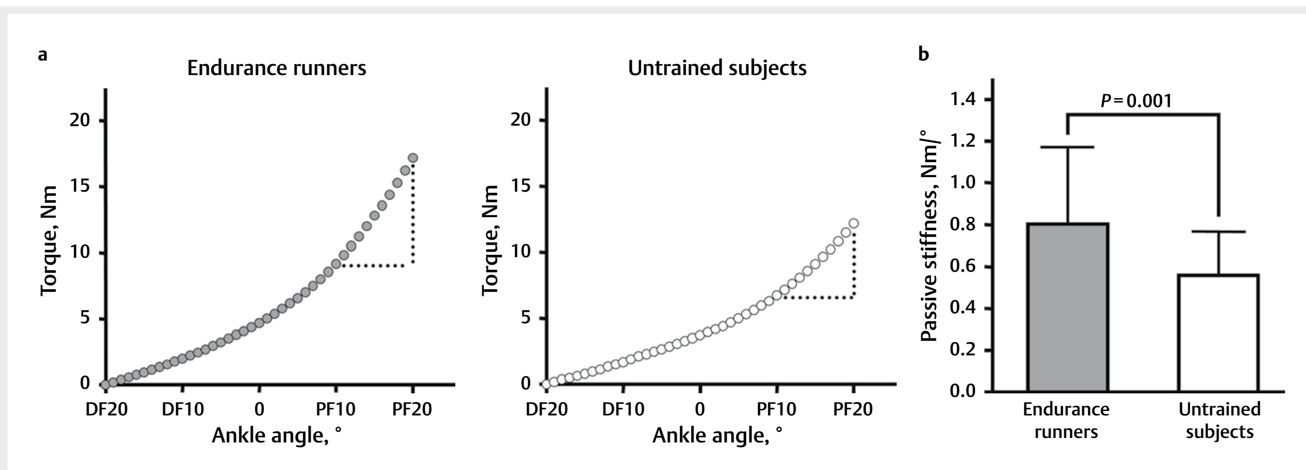
No significant difference was observed in body height and body weight between endurance runners and untrained subjects. In contrast, passive plantar flexor stiffness was significantly higher in endurance runners than in untrained subjects ($P = 0.001$; ▶ **Fig. 1**).

After dividing the endurance runners into faster and slower groups, passive plantar flexor stiffness was significantly higher in the faster group than in the slower group ($P < 0.01$; ▶ **Fig. 2**).Moreover, passive plantar flexor stiffness in endurance runners was significantly correlated with the personal best 5000-m race time ($r = -0.401$, $P < 0.01$; ▶ **Fig. 3**).

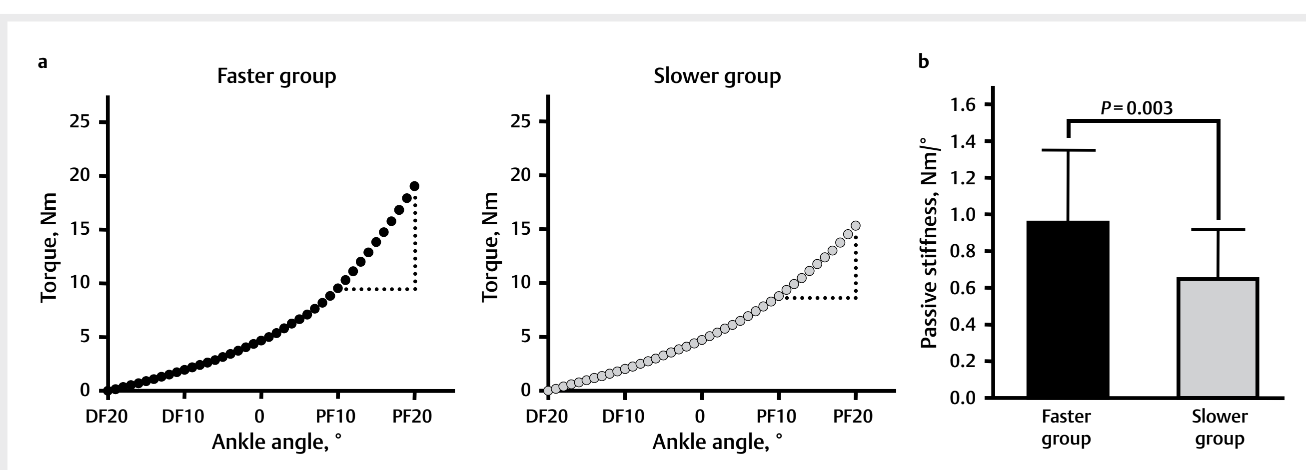
In the 28 endurance runners who participated in the measurement of running economy, the personal best 5000-m race time was significantly correlated with energy cost during submaximal running at all three speeds ($r = 0.720$ for 14 km, $r = 0.614$ for 16 km, $r = 0.519$ for 18 km, $P < 0.01$ for all). Passive plantar flexor stiffness was significantly correlated with energy cost during submaximal running at 16 km/h and 18 km/h ($r = -0.379$ and -0.445, respectively, $P < 0.05$ for both), and a trend towards such significance was observed at 14 km/h ($r = -0.337$, $P = 0.079$; ▶ **Fig. 4**).

Discussion

The major finding in the present study was that greater passive stiffness of the plantar flexors was related to better running perfor-



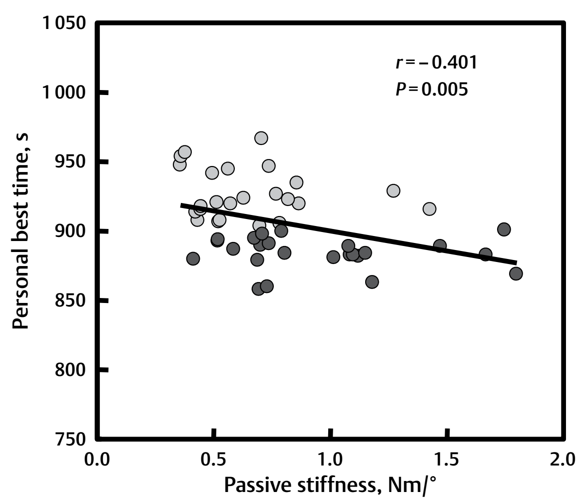
▶ **Fig. 1** Passive stiffness of the plantar flexors in endurance runners and untrained subjects. Panels show the mean changes in the torque-angle curve during passive dorsiflexion from 20° plantar flexion (PF) to 20° dorsiflexion (DF) **a** and the results of passive stiffness calculated from the slope of the linear portion of the curve **b** in endurance runners and untrained subjects.



▶ **Fig. 2** Passive stiffness of the plantar flexors in the faster and slower groups of endurance runners. The panels show the mean changes in the torque-angle curve during passive dorsiflexion (A) from 20° PF to 20° DF **a** and the results of passive stiffness calculated from the slope of the linear portion of the curve **b** in the faster and slower groups ($n = 24$ in each group) of endurance runners.

mance, including greater running economy, in endurance runners. Several previous studies reported that lower flexibility of the plantar flexors, as evaluated by the ROM, was related to greater submaximal running economy [7, 15]. Thus, the present study further confirmed the importance of the flexibility of the plantar flexors in running performance by showing the relationship between passive plantar flexor stiffness and running performance in well-trained endurance runners.

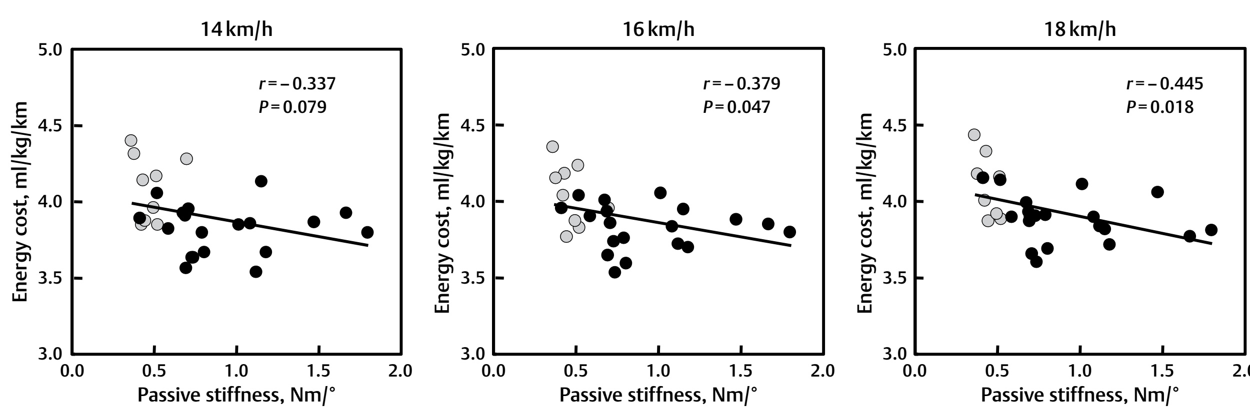
Hunter et al. [15] previously reported that the ROM of dorsiflexion was correlated with running economy in recreational endurance runners. Moreover, Crait et al. [7] showed a significant relationship between the ROM of dorsiflexion and running economy in well-trained endurance runners. In these previous studies, the flexibility of the plantar flexors was examined by determining the ROM; however, this parameter is generally considered as joint flexibility [2]. In contrast, in the present study, the flexibility of the plantar flexors was examined by determining passive stiffness, and this parameter has been previously employed for assessing MTC flexibility [6, 9, 10, 13, 17]. During running, muscle tissue in the plantar flexor MTC generates the large amount of force for isometrically supporting and concentrically pushing throughout the contact phase [11, 24]. Additionally, tendon tissue in the plantar flexor MTC stores and releases the elastic energy during this phase [3]. Thus, the plantar flexor MTC helps achieve superior running performance, including running economy. The relationship between the flexibility of the plantar flexor MTC and running economy in endurance runners was previously unclear. Therefore, the present study is the first to suggest that the flexibility of the plantar flexor MTC may be an important determinant of running performance in endurance runners.



▶ **Fig. 3** Relationship between passive stiffness of the plantar flexors and the personal best 5000-m race time in endurance runners. The faster and slower groups of endurance runners are subdivided by the dark and light grey circles, respectively.

In the present study, the correlation coefficient between passive plantar flexor stiffness and energy cost of submaximal running speed was relatively higher at 18 km than at 14 km/h or 16 km/h, suggesting that a stiffer MTC of the plantar flexors may play a more important role in improving running economy at faster speeds than at slower speeds. Because of the increased running velocity, a reduced contact time is required [5, 27]. The reduced contact time is associated with enhancement of vertical ground reaction force during the stance phase [27], which is partially due to increased plantar flexor force [22, 24]. A stiffer plantar flexor MTC may be useful to generate a larger force with a smaller angular change at the ankle joint during stance phase. Therefore, this property is beneficial for reducing contact times and improving running economy when running at a high speed.

In the present study, we determined that passive stiffness of the plantar flexors was significantly higher in endurance runners than in untrained subjects. Hobara et al. [14] previously reported that ankle joint stiffness during hopping exercise was significantly higher in endurance runners than in untrained subjects. Ankle joint stiffness during such a jump exercise has been shown to be related to



▶ **Fig. 4** Relationships between passive stiffness of the plantar flexors and running economy at submaximal treadmill speeds in endurance runners. The faster (n = 19) and slower (n = 9) groups based on personal best 5000-m race time are subdivided by the dark and light grey circles, respectively.

the properties of muscle tissue rather than tendon tissue [20]. Moreover, Kubo et al. [19] recently reported that passive plantar flexor muscle stiffness, but not tendon stiffness, is higher in endurance runners than in untrained subjects. Furthermore, passive plantar flexor stiffness measured in the present study may reflect the properties of muscle tissue rather than tendon tissue [6, 13, 17]. Therefore, in the present study, the difference in passive plantar flexor stiffness between endurance runners and untrained subjects may be explained by the muscle tissue that was stiffer in endurance runners than in untrained subjects. The present study also showed that passive stiffness of the plantar flexors was significantly higher in the faster group than in the slower group among endurance runners, indicating that muscle tissue is stiffer in faster runners than in slower runners. Thus, the present findings suggest that stiff plantar flexor muscles may be necessary to achieve better running performance in endurance runners.

As a limitation of the present study, although we determined the relationship between passive stiffness of the plantar flexors and running performance in endurance runners, there were relatively low correlations between passive plantar flexor stiffness and running performance, including the personal best 5000-m race time and running economy, in endurance runners. Running performance is determined by various factors, including biological, physiological, morphological, and biomechanical factors [25]. Thus, a higher stiffness of the plantar flexor MTC is only one of the factors that determine running performance in endurance runners. In addition, we could not clarify the contribution of muscle and tendon tissues to passive stiffness of the plantar flexor MTC. Nevertheless, based on the aforementioned discussion, we believe that the stiffness of muscle tissue may play a more important role than that of tendon tissue in endurance runners. Another limitation is that the present study did not perform kinetic and kinematic analyses during running. This information may further clarify the importance of higher stiffness of the plantar flexor MTC in running performance among endurance runners. Therefore, further studies are needed to determine the relationship between passive plantar flexor stiffness and kinetic and kinematic variables during running, such as ankle joint moment and stride frequency and length, in endurance runners.

Conclusion

The present study showed that passive stiffness of the plantar flexors was associated with running performance, including running economy, in endurance runners. Thus, we suggest that stiffer plantar flexors, especially muscle tissue, may help achieve better running performance in endurance runners. Furthermore, we propose that, in clinical settings, simple passive stiffness of the plantar flexors may be a potential parameter for assessing running performance and evaluating the effects of training and/or rehabilitation.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Arampatzis A, De Monte G, Karamanidis K, Morey-Klapsing G, Stafilidis S, Brüggemann GP. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. J Exp Biol 2006; 209: 3345–3357

[2] Boone DC, Azen SP. Normal range of motion of joints in male subjects. J Bone Joint Surg Am 1979; 61: 756–759

[3] Bramble DM, Lieberman DE. Endurance running and the evolution of Homo. Nature 2004; 432: 345–352

[4] Chang YH, Kram R. (1999) Metabolic cost of generating horizontal forces during human running. J Appl Physiol 1999; 86: 1657–1662

[5] Chapman RF, Laymon AS, Wilhite DP, McKenzie JM, Tanner DA, Stager JM. (2012) Ground contact time as an indicator of metabolic cost in elite distance runners. Med Sci Sports Exerc 2012; 44: 917–925

[6] Chino K, Takahashi H. Measurement of gastrocnemius muscle elasticity by shear wave elastography: association with passive ankle joint stiffness and sex differences. Eur J Appl Physiol 2016; 116: 823–830

[7] Craib MW, Mitchell VA, Fields KB, Cooper TR, Hopewell R, Morgan DW. The association between flexibility and running economy in sub-elite male distance runners. Med Sci Sports Exerc 1996; 28: 737–743

[8] Fletcher JR, Pfister TR, Macintosh BR. Energy cost of running and Achilles tendon stiffness in man and woman trained runners. Physiol Rep 2013; 1: e00178

[9] Gajdosik RL, Vander Linden DW, Williams AK. Influence of age on length and passive elastic stiffness characteristics of the calf muscle-tendon unit of women. Phys Ther 1999; 79: 827–838

[10] Guissard N, Duchateau J. Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. Muscle Nerve 2004; 29: 248–255

[11] Hamner SR, Seth A, Delp SL. Muscle contributions to propulsion and support during running. J Biomech 2010; 43: 2709–2716

[12] Harriss DJ, Macsween A, Atkinson G. Standards for Ethics in Sport and Exercise Science Research: 2018 Update. Int J Sports Med 2017; 38: 1126–1131

[13] Hirata K, Miyamoto-Mikami E, Kanehisa H, Miyamoto N. Muscle-specific acute changes in passive stiffness of human triceps surae after stretching. Eur J Appl Physiol 2016; 116: 911–918

[14] Hobara H, Kimura K, Omuro K, Gomi K, Muraoka T, Sakamoto M, Kanosue K. Differences in lower extremity stiffness between endurance-trained athletes and untrained subjects. J Sci Med Sport 2010; 13: 106–111

[15] Hunter GR, Katsoulis K, McCarthy JP, Ogard WK, Bamman MM, Wood DS, Den Hollander JA, Blaudeau TE, Newcomer BR. Tendon length and joint flexibility are related to running economy. Med Sci Sports Exerc 2011; 43: 1492–1499

[16] Johns RJ, Wright V. Relative importance of various tissues in joint stiffness. J Appl Physiol 1962; 17: 824–828

[17] Kubo K, Kanehisa H, Fukunaga T. Is passive stiffness in human muscles related to the elasticity of tendon structures? Eur J Appl Physiol 2001; 85: 226–232

[18] Kubo K, Miyazaki D, Shimoju S, Tsunoda N. Relationship between elastic properties of tendon structures and performance in long distance runners. Eur J Appl Physiol 2015; 115: 1725–1733

[19] Kubo K, Miyazaki D, Yamada K, Yata H, Shimoju S, Tsunoda N. Passive and active muscle stiffness in plantar flexors of long distance runners. J Biomech 2015; 48: 1937–1943

[20] Kubo K, Morimoto M, Komuro T, Tsunoda N, Kanehisa H, Fukunaga T. Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint. Eur J Appl Physiol 2007; 99: 235–243

[21] Kubo K, Tabata T, Ikebukuro T, Igarashi K, Yata H, Tsunoda N. Effects of mechanical properties of muscle and tendon on performance in long distance runners. Eur J Appl Physiol 2010; 110: 507–514

[22] Kulmala JP, Korhonen MT, Ruggiero L, Kuitunen S, Suominen H, Heinonen A, Mikkola A, Avela J. Walking and running require greater effort from the ankle than the knee extensor muscles. Med Sci Sports Exerc 2016; 48: 2181–2189

[23] Morgan DW, Baldini FD, Martin PE, Kohrt WM. Ten kilometer performance and predicted velocity at VO_2 max among well-trained male runners. Med Sci Sports Exerc 1989; 21: 78–83

[24] Novacheck TF. The biomechanics of running. Gait Posture 1998; 7: 77–95

[25] Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Med 2004; 34: 465–485

[26] Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. Eur J Appl Physiol 2003; 89: 1–7

[27] Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. (2000) Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol 2000; 89: 1991–1999