Eur J Appl Physiol (2017) 117:533–539
DOI 10.1007/s00421-017-3557-5

ORIGINAL ARTICLE

The knee extensor moment arm is associated with performance in male sprinters

Yuto Miyake[1] · Tadashi Suga[1] · Mitsuo Otsuka[1] · Takahiro Tanaka[1] · Jun Misaki[1] · Shoma Kudo[1] · Akinori Nagano[1] · Tadao Isaka[1]

Received: 20 June 2016 / Accepted: 21 January 2017 / Published online: 10 February 2017

Abstract
Purpose Although large knee extensor torque contributes to superior sprint performance, previous findings have indicated that the quadriceps cross-sectional area (CSA), a pivotal morphological regulator of knee extensor torque, is not correlated with performance in sprinters. We hypothesized that the knee extensor moment arm (MA), another main morphological regulator of knee extensor torque, may affect sprint performance. To test this hypothesis, we examined the relationship between knee extensor MA and sprint performance.
Methods The quadriceps CSA and knee extensor MA in 32 well-trained male sprinters and 32 male non-sprinters were measured using magnetic resonance imaging.
Results Knee extensor MA, but not quadriceps CSA, was greater in sprinters than in non-sprinters ($P = 0.013$). Moreover, knee extensor MA, but not the quadriceps CSA, was correlated with the personal best time in a 100-m race in sprinters ($r = -0.614$, $P < 0.001$). Furthermore, among 24 sprinters who participated in the 60-m sprint test, knee extensor MA was correlated with sprinting velocities in the acceleration ($r = 0.717$, $P < 0.001$) and maximum speed ($r = 0.697$, $P < 0.001$) phases.
Conclusion The present study demonstrates that the knee extensor MA is greater in sprinters than in non-sprinters, and this morphological structure in sprinters is associated with sprint performance. Therefore, for the first time, we provided evidence that a greater knee extensor MA in sprinters may be an advantageous for achieving superior sprint performance.

Keywords Magnetic resonance imaging · Muscle cross-sectional area · Joint torque · Muscle strength · Resistance training

Abbreviations

CSA	Cross-sectional area
MA	Moment arm
MRI	Magnetic resonance imaging
VGRF	Vertical ground reaction force

Introduction

Successful sprint performance is achieved through the generation of large torques by muscles crossing the hip, knee and ankle joints. Of these components, the knee extensor torque contributes to swing and stance phases during sprinting (Delecluse 1997). Moreover, previous studies have reported that maximal isokinetic knee extensor torque is positively correlated with sprint performance (Alexander 1989; Dowson et al. 1998). Maximal dynamic joint torque is strongly regulated by agonist muscle size (Kanehisa et al. 1994; Schantz et al. 1983). Thus, it can be speculated that knee extensor muscle size, as indicated by measures such as the quadriceps cross-sectional area (CSA), may be associated with sprint performance; however, to the best of our knowledge, this relationship has not been demonstrated in previous studies (Hoshikawa et al. 2006; Sugisaki et al. 2011). Based on these findings, it is proposed that morphological factors related to knee extensor torque production, other than muscle mass, may play an important role in sprint performance.

Communicated by Peter Krustrup.

✉ Tadashi Suga
t-suga@fc.ritsumei.ac.jp

[1] Faculty of Sport and Health Science, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan

Generally, because joint torque is expressed as the product of force and moment arm (MA), the magnitude of knee extensor torque is morphologically determined by the quadriceps size and knee extensor MA dimension. Recent studies have determined the relationship between maximal isokinetic torque and MA (Baxter and Piazza 2014; Blazevich et al. 2009; Sugisaki et al. 2010). Among these studies, Blazevich and et al. (2009) reported that the knee extensor MA was correlated ($r=0.50$) with maximal isokinetic knee extensor torque. Therefore, it has been proposed that the relationship between maximal knee extensor torque and sprint performance may explain why sprinters have a greater knee extensor MA rather than a greater quadriceps CSA. First, we hypothesized that if knee extensor MA is an important structure in sprinters, sprinters would have a greater knee extensor MA compared to non-sprinters. Moreover, although previous studies have reported a relationship between MA and the agonist muscle size in non-sprinters, the relationship between knee extensor MA and quadriceps CSA would not exist in sprinters, because knee extensor MA in sprinters would be independently associated with sprint performance. Second, we hypothesized that a greater knee extensor MA in sprinters would be an advantageous in sprinters. To test these hypotheses, we examined the difference in knee extensor MA between sprinters and non-sprinters. Then we examined the relationship between knee extensor MA and quadriceps CSA in sprinters. Finally, we examined the relationship between knee extensor MA and performance in sprinters.

Methods

Subjects

Thirty-two well-trained male sprinters (age: 21.0 ± 2.1 years, height: 175.2 ± 5.0 cm, body mass: 66.4 ± 4.9 kg) participated in this study. All participants experience in track-and-field sprinting for at least 5 years (9.1 ± 2.4), and they were involved in regular sprint training at least five times per week and competition. Their best personal time of a 100-m race ranged from 10.21 to 11.90 s (11.10 ± 0.44 s). All measurements for the sprinters in the present study were obtained during off-season. In addition, 32 non-sprinters (age: 21.6 ± 2.2 years, height: 173.6 ± 4.7 cm, body mass: 68.2 ± 8.5 kg) whose age, body height, and body mass were similar to those of the sprinters were selected as a control group. Control subjects were recreationally active, but were not involved in any physical training program. All subjects were instructed to avoid strenuous physical activity in the 24 h prior to each testing. The subjects were informed of the experimental procedures and provided written consent to participate in the study. This study was approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2011-009) and was performed in accordance with the Declaration of Helsinki.

Magnetic resonance imaging

Representative images of quadriceps CSA and knee extensor MA on magnetic resonance imaging (MRI) are shown in Fig. 1. The MRI measurement was performed using a 1.5-T magnetic resonance system (Signa HDxt; GE Medical Systems, WI, USA). To measure quadriceps CSA and knee extensor MA, we placed subjects in a supine position on the scanner bed, with both knees fully extended and both ankles set at the neutral position (i.e., 0°). In a measurement of the quadriceps CSA, axial T_1_weighted MRI scans of the thigh were acquired with a standard body coil. Axial scans were obtained in successive slices with an inter distance of 10 mm from the inferior aspect of the greater trochanter to the lower edge of the femur with a repetition time of 600 ms, echo time of 7.6 ms, field of view of 480 mm, and matrix size

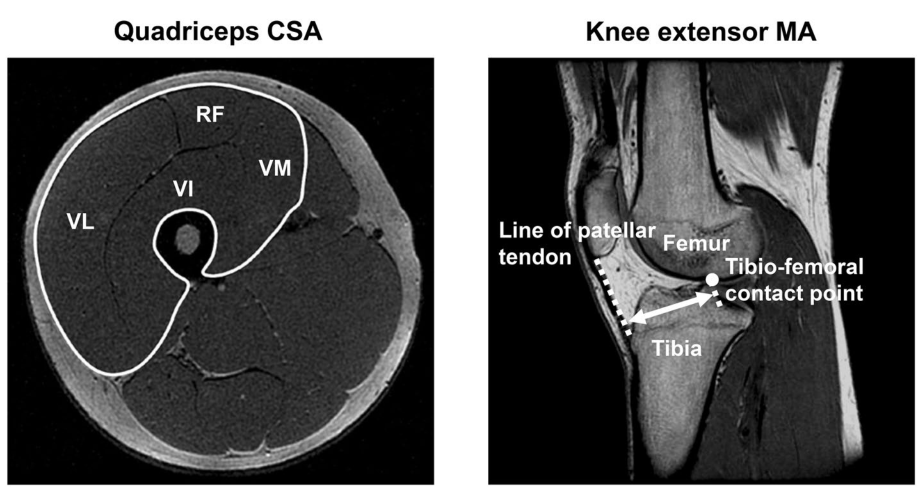

Fig. 1 Representative magnetic resonance imaging scans used for measuring quadriceps cross-sectional area (*CSA*) and knee extensor moment arm (*MA*). Quadriceps CSA, which included rectus femoris (*RF*), vastus intermedius (*VI*), vastus lateralis (*VL*), and vastus medialis (*VM*), was calculated at mid-thigh level. Knee extensor *MA* was calculated as the distance between tibio-femoral contact point and mid-line of the patellar tendon

of 512 × 256 pixels. Quadriceps CSA was calculated at 50% of thigh length (Hoshikawa et al. 2006; Sugisaki et al. 2011), which was defined as the distance between the great trochanter and the lower edge of the femur. The quadriceps CSA involved the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis. To exclude the difference in body size among subjects, a relative quadriceps CSA normalized to body weight to the two thirds power (Sugisaki et al. 2011) was used in the analysis in addition to the absolute CSA. In a measurement of the knee extensor MA, three-dimensional isotropic T_1-weighted MRI scans of knee joint were acquired with an eight channels coil. Sagittal scans were obtained in successive slices with an inter distance of 10 mm with a repetition time of 11.3 ms, echo time of 5.1 ms, slice thickness of 1.2 mm, field of view of 280 mm, and matrix size of 256 × 256 pixels. Knee extensor MA was calculated as the distance between the tibio-femoral contact point and the mid-line of the patellar tendon (Blazevich et al. 2009). To exclude the difference in body size among subjects, a relative knee extensor MA normalized to body weight to the one thirds powers was used in the analysis in addition to the absolute MA. The analyses for measuring quadriceps CSA and knee extensor MA were conducted using image analysis software (OsiriX Version 5.6, Switzerland). The measurements of quadriceps CSA and knee extensor MA were performed twice, and the mean of the two values was used. The coefficient of variations of the two measurements in quadriceps CSA and knee extensor MA were 0.3 ± 0.3 and 0.4 ± 0.2%, respectively. The intraclass correlation coefficients (ICC) of the two measurements ranged were 0.990 (95% CI: 0.984 to 0.994) and 0.996 (95% CI: 0.993 to 0.997), respectively. In an additional pilot study, we measured the quadriceps CSA and knee extensor MA on 2 separate days in 14 healthy males (age: 22.7 ± 1.0 years, height: 171. 6 ± 3.0 cm, body mass: 65.9 ± 7.2 kg). The ICC of the quadriceps CSA and knee extensor MA for the 2 days were 0.968 (95% CI: 0.903 to 0.990) and 0.997 (95% CI: 0.991 to 0.999), respectively.

60-m sprint testing

Of the sprinters included in the present study, 24 sprinters who were able to participate in the testing days underwent a 60-m sprint testing. The sprint test was performed using a starting block, and it was repeated two to three times to obtain successful sprints. The fastest trial was used to analyze the sprinting velocity. The sprinting time was recorded using photocell (E3G-R13; Omuron Inc, Kyoto, Japan) at 15 and 60 m. Intervals from 0 to 15 m and from 15 to 60 m were defined as the acceleration and maximum speed phases, respectively (Otsuka et al. 2015), and the sprinting velocities in each phase were calculated from distance and time.

Statistical analysis

The data are presented as the mean ± SD. Comparisons of groups were performed using unpaired *t*-testing. The relationship between variables was evaluated using a Pearson's product moment correlation. Statistical significance 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

Mid-thigh quadriceps CSA did not differ between sprinters and non-sprinters (Fig. 2). Similarly, the relative quadriceps CSA normalized with body mass$^{2/3}$ also did not differ between sprinters and non-sprinters ($P < 0.05$). In contrast, knee extensor MA was greater in sprinters

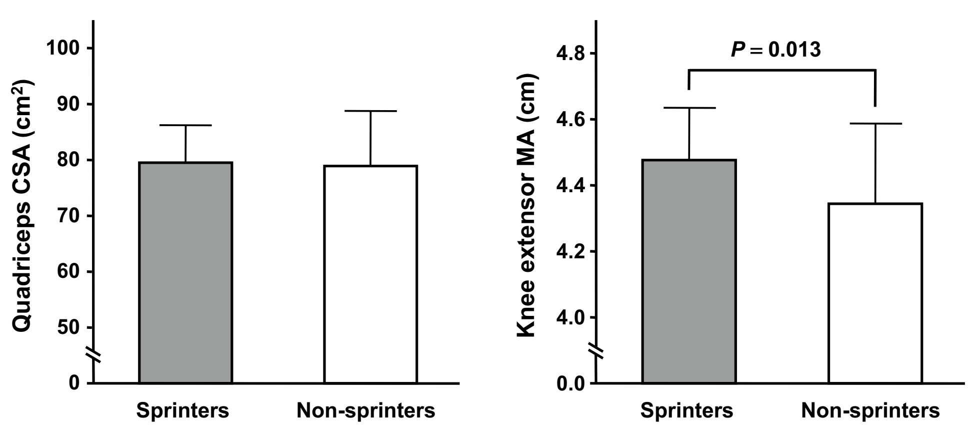

Fig. 2 Differences in quadriceps CSA and knee extensor MA between sprinters and non-sprinters. Values are presented as Mean ± SD

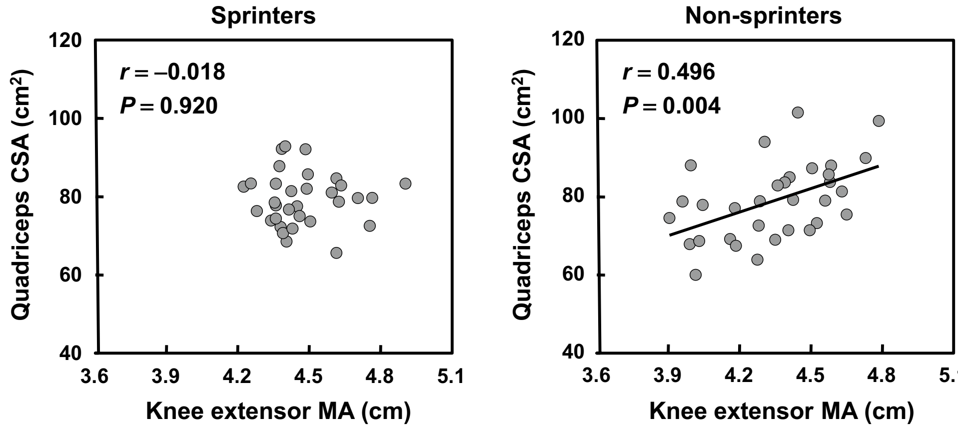

Fig. 3 Relationships between quadriceps CSA and knee extensor MA in sprinters and non-sprinters

than in non-sprinters. Additionally, relative knee extensor MA normalized with body mass$^{1/3}$ was also greater in sprinters than in non-sprinters ($P < 0.05$). Furthermore, although knee extensor MA in non-sprinters was correlated with quadriceps CSA ($r = 0.496$, $P = 0.004$), no such relationship was observed in sprinters (Fig. 3).

In sprinters, there was no relationship between quadriceps CSA and personal best 100-m race time. Similarly, no relationship was observed using the quadriceps CSA relative to body mass$^{2/3}$. In contrast, knee extensor MA was inversely correlated with the personal best 100-m race time (Fig. 4; $r = -0.614$, $P < 0.001$). Such a relationship was also observed using knee extensor MA relative to body mass$^{1/3}$ ($r = -0.371$, $P = 0.036$). Furthermore, knee extensor MA, but not quadriceps CSA, was correlated with the sprinting velocities recorded during the acceleration ($r = -0.717$, $P < 0.001$) and maximum speed ($r = -0.697$, $P < 0.001$) phases in the 60-m sprint testing (Fig. 5). Additionally, after normalized with body mass, knee extensor MA, not the quadriceps CSA, was also correlated with sprinting velocities recorded during acceleration ($r = 0.512$, $P = 0.010$) and the maximum speed ($r = 0.562$, $P = 0.004$) in this testing.

Discussion

In the present study, we found that knee extensor MA was greater in sprinters than in non-sprinters. Moreover, a greater knee extensor MA in sprinters was significantly correlated with a higher sprint performance. These findings were also maintained when knee extensor MA and the quadriceps CSA was normalized by body size. Therefore, the present findings demonstrated that knee extensor MA may be associated with performance in sprinters.

Recent studies have demonstrated that MA in several joints is correlated with muscle size, including anatomical CSA (Baxter et al. 2012; Blazevich et al. 2009; Sugisaki et al. 2010), suggesting that the magnitude of MA is mediated by muscle size. In the present study, we also observed a positive correlation between knee extensor MA and quadriceps CSA in non-sprinters. In contrast, no such correlation was observed in sprinters, indicating that knee extensor MA in sprinters is unaffected by muscle mass. Interestingly, when matching the physical characteristics, quadriceps CSA was similar between sprinters and non-sprinters, although the knee extensor MA was greater in sprinters than in non-sprinters. To the best of our

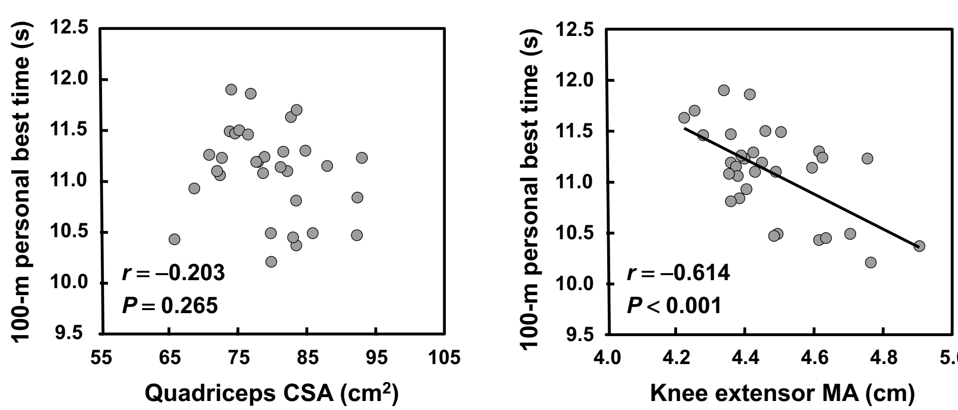

Fig. 4 Relationships between knee extensor MA and personal best 100-m race time in sprinters

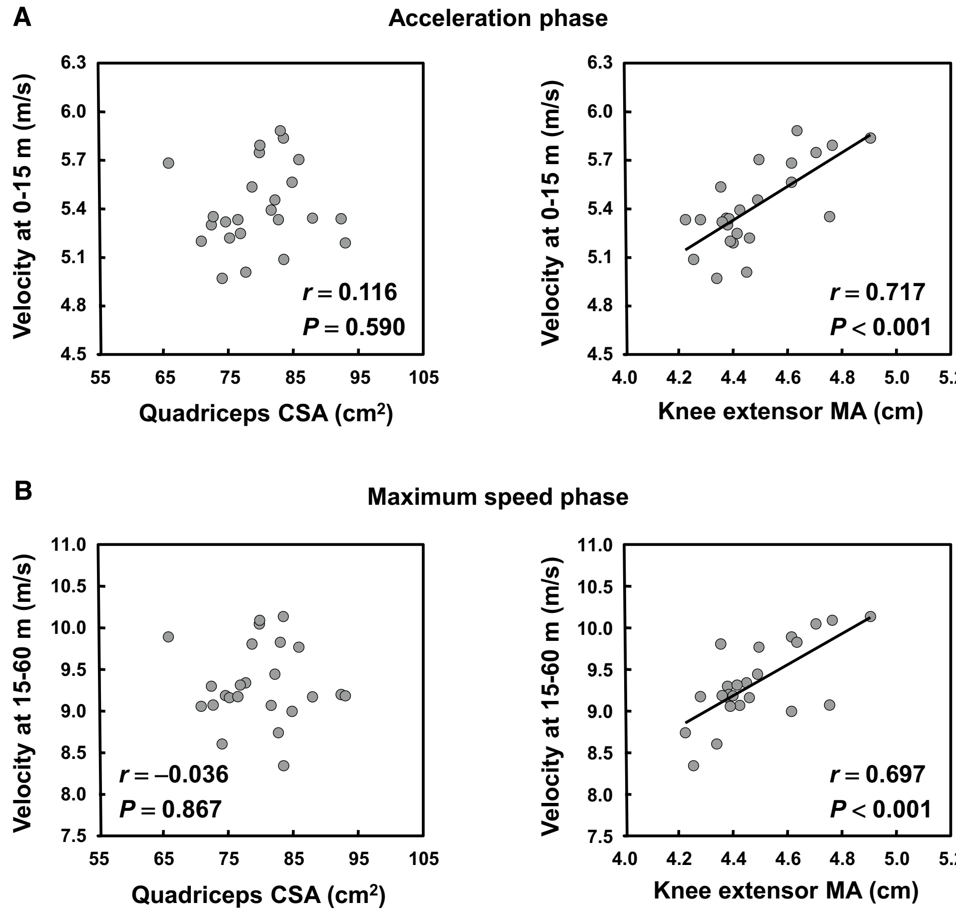

Fig. 5 Relationships between knee extensor MA and sprinting velocities of the acceleration (**a**) and maximum speed (**b**) phases in 60-m sprint testing in sprinters

knowledge, this is the first study to provide evidence that sprinters' knee joint is characterized by a greater extensor MA independent of muscle size.

The present study showed that knee extensor MA is greater in sprinters than in non-sprinters; however, this difference was minimal (3.0%). Nevertheless, because joint torque is related to muscle size and MA dimension, we propose that a greater MA may be able to enhance the intrinsic torque-producing capacity, despite an equal muscle size. In fact, although this capacity is often associated with physiological and neurological factors (Klein et al. 2001; Morse et al. 2004), a greater knee extensor MA may contribute to generating a higher knee extensor torque per muscle size in sprinters than in non-sprinters (Häkkinen and Keskinen 1989; Maughan et al. 1983). Taken together, although knee extensor MA was slightly different between sprinters and non-sprinters, a knee joint with a greater MA may be useful for generating higher knee extensor torque.

In the present study, no correlation was observed between quadriceps CSA and personal best time in a 100-m race in sprinters, consistent with the results of previous studies (Hoshikawa et al. 2006; Sugisaki et al. 2011). In contrast, the present study found that the knee extensor MA was correlated ($r = -0.614$) with the personal best time in a 100-m race in sprinters. Previous studies have indicated that maximal isokinetic knee extensor torque was correlated ($r = -0.58$ to -0.71) with 100-m sprint time (Alexander 1989; Dowson et al. 1998), suggesting that knee extensor torque plays an important role in achieving a successful sprint performance. In a recent study, Blazevich et al. (2009) reported that knee extensor MA was positively correlated ($r = 0.50$) with maximal isokinetic knee extensor torque. Thus, the present findings suggest that elite sprint performance may be associated with the production of large knee extensor torque as a result of a greater knee extensor MA.

Previous studies have reported that a larger vertical ground reaction force (VGRF) during stance phase is correlated with higher sprint velocity in sprinters (Morin et al. 2012; Weyand et al. 2000). Knee extensor torque contributes to enhancing the VGRF during stance phase (Dorn et al. 2012), indicating that a greater knee extensor MA may be useful for producing a large VGRF. In the present study, we identified that a correlation between a greater knee extensor MA and the velocities of the acceleration and maximum speed phases. In sprinting, the knee extensor torque contributes in accelerating the body center of mass, and subsequently, maintains a quasi-uniform height of the body center of mass over the maximum speed phase (Delecluse 1997). According to the roles of knee extensor torque in sprinting, the VGRF contributes to accelerating the body center of mass and maintaining height of the body center of mass (Hunter et al. 2005; Morin et al. 2012; Weyand et al. 2000). Thus, we propose that a greater knee extensor MA in sprinters may cause the development of large VGRF during the stance phase by potentially contributing to a higher rate of acceleration and maximum attained speed. In addition, a greater knee extensor MA may enable sprinters to achieve higher knee extensor torque for a given level of quadriceps muscle mass. In sprinting, having a smaller quadriceps may be beneficial, because this will make the leg moment of inertia smaller, which results in quicker hip flexion motions. Thus, in addition to providing a mechanical advantage over the stance phase, a greater knee extensor MA may further facilitate rapid hip flexion during the swing phase because it enables a reduced quadriceps mass for a given magnitude of knee extensor torque produced.

The present study has a couple of limitations. Although we measured the anatomical quadriceps CSA in the mid-thigh level and found that it was similar in size between sprinters and body size-matched non-sprinters, Abe et al. (2000) reported that muscle fascicles in the vastus lateralis were longer in sprinters than in non-sprinters. Hence, it is suggested that even the anatomical CSA is similar between the two groups, whereas the physiological CSA is greater in sprinters than in non-sprinters. Moreover, we showed that the anatomical quadriceps CSA was not correlated with performance in sprinters, which is in accordance with previous findings (Hoshikawa et al. 2006; Sugisaki et al. 2011). However, Kumagai et al. (2000) reported that vastus lateralis muscle fascicles were longer in faster groups with a personal best 100-m race time of less than 11 s than in the slower group with a personal best 100-m race time of less than 12 s in sprinters. Hence, faster sprinters in the present study may have a greater physiological CSA compared to slower sprinters. Thus, further studies are needed to examine the relationship between physiological knee extensor CSA and performance in sprinters.

Another limitation of our study was that although we measured knee extensor MA with both knees fully extended and we showed the relationship between knee extensor MA and performance in sprinters, the joint angle (i.e., 180°) measured in the present study was not reached during sprinting (Kuitunen et al. 2002). Hence, knee extensor MA at full knee extension measured in the present study may not reflect knee extensor MA during sprinting. Nevertheless, we considered that the difference in knee extensor MA at full knee extension among sprinters may remain in joint angles from knee extension to flexion (Tsaopoulos et al. 2006), and if so, it may contribute in achieving superior sprint performance by potentially increasing the superiority of knee extensor torque production during sprinting. Further studies are needed to measure knee extensor MA at several joint angles in sprinters. Additionally, because the present study did not perform a detailed analysis of kinematic and kinetic data during sprinting, further studies are also needed to examine the relationships between knee extensor MA and various sprint variables.

In conclusion, present study showed that the knee extensor MA was greater in sprinters than in non-sprinters, independent of the quadriceps CSA. Furthermore, the knee extensor MA in sprinters was correlated with sprint performance, potentially because it enhances the velocities of the acceleration and maximum speed phases. Therefore, for the first time, we provided evidence that a greater knee extensor MA in sprinters may be an advantage for achieving superior sprint performance.

Acknowledgements We are grateful to all subjects who gave of their time and effort to participate in this study. This study was supported by Grant-in-Aid for Scientific Research (#15K16497 to T.S; #16H03238 to A.N; #26560361 and #15H03077 to T.I).

References

Abe T, Kumagai K, Brechue WF (2000) Fascicle length of leg muscles is greater in sprinters than distance runners. Med Sci Sports Exerc 32:1125–1129

Alexander MJ (1989) The relationship between muscle strength and sprint kinematics in elite sprinters. Can J Sport Sci 14:148–157

Baxter JR, Piazza SJ (2014) Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men. J Appl Physiol 116:538–544

Baxter JR, Novack TA, Van Werkhoven H, Pennell DR, Piazza SJ (2012) Ankle joint mechanics and foot proportions differ between human sprinters and non-sprinters. Proc Biol Sci 279:2018–2024

Blazevich AJ, Coleman DR, Horne S, Cannavan D (2009) Anatomical predictors of maximum isometric and concentric knee extensor moment. Eur J Appl Physiol 105:869–878

Delecluse C (1997) Influence of strength training on sprint running performance. Current findings and implications for training. Sports Med 24:147–156

Dorn TW, Schache AG, Pandy MG (2012) Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. J Exp Biol 215:1944–1956

Dowson MN, Nevill ME, Lakomy HK, Nevill AM, Hazeldine RJ (1998) Modelling the relationship between isokinetic muscle strength and sprint running performance. J Sports Sci 16:257–265

Häkkinen K, Keskinen KL (1989) Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. Eur J Appl Physiol Occup Physiol 59:215–220

Hoshikawa Y, Muramatsu M, Iida T, Uchiyama A, Nakajima Y, Kanehisa H, Fukunaga T (2006) Influence of the psoas major and thigh muscularity on 100-m times in junior sprinters. Med Sci Sports Exerc 38:2138–2143

Hunter JP, Marshall RN, McNair PJ (2005) Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomech 21:31–43

Kanehisa H, Ikegawa S, Fukunaga T (1994) Comparison of muscle cross-sectional area and strength between untrained women and men. Eur J Appl Physiol Occup Physiol 68:148–154

Klein CS, Rice CL, Marsh GD (2001) Normalized force, activation, and coactivation in the arm muscles of young and old men. J Appl Physiol 91:1341–1349

Kuitunen S, Komi PV, Kyröläinen H (2002) Knee and ankle joint stiffness in sprint running. Med Sci Sports Exerc 34:166–173

Kumagai K, Abe T, Brechue WF, Ryushi T, Takano S, Mizuno M (2000) Sprint performance is related to muscle fascicle length in male 100-m sprinters. J Appl Physiol 88:811–816

Maughan RJ, Watson JS, Weir J (1983) Relationships between muscle strength and muscle cross-sectional area in male sprinters and endurance runners. Eur J Appl Physiol Occup Physiol 50:309–318

Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR (2012) Mechanical determinants of 100-m sprint running performance. Eur J Appl Physiol 112:3921–3930

Morse CI, Thom JM, Davis MG, Fox KR, Birch KM, Narici MV (2004) Reduced plantarflexor specific torque in the elderly is associated with a lower activation capacity. Eur J Appl Physiol 92:219–226

Otsuka M, Kurihara T, Isaka T (2015) Effect of a wide stance on block start performance in sprint running. PLoS ONE 10:e0142230

Schantz P, Randall-Fox E, Hutchison W, Tydén A, Astrand PO (1983) Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. Acta Physiol Scand 117:219–226

Sugisaki N, Wakahara T, Miyamoto N, Murata K, Kanehisa H, Kawakami Y, Fukunaga T (2010) Influence of muscle anatomical cross-sectional area on the moment arm length of the triceps brachii muscle at the elbow joint. J Biomech 43:2844–2847

Sugisaki N, Kanehisa H, Tauchi K, Okazaki S, Iso S, Okada J (2011) The relationship between 30-m sprint running time and muscle cross-sectional areas of the psoas major and lower limb muscles in male college short and middle distance runners. Int J Sports Health Sci 9:1–7

Tsaopoulos DE, Baltzopoulos V, Maganaris CN (2006) Human patellar tendon moment arm length: measurement considerations and clinical implications for joint loading assessment. Clin Biomech 21:657–667

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 89:1991–1999