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Relationship between the length of the forefoot bones and performance in male sprinters

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Although recent studies have reported that the forefoot bones are longer in sprinters than in non-sprinters, these reports included a relatively small number of subjects. Moreover, while computer simulation suggested that longer forefoot bones may contribute to higher sprint performance by enhancing plantar flexor moment during sprinting, the correlation between forefoot bone length and sprint performance in humans has not been confirmed in observational studies. Thus, using a relatively large sample, we compared the length of the forefoot bones between sprinters and non-sprinters. We also examined the relationship between forefoot bone length and performance in sprinters. The length of forefoot bones of the big and second toes in 36 well-trained male sprinters and 36 male non-sprinters was measured using magnetic resonance imaging. The length of forefoot bones in the big and second toes was significantly longer in sprinters than in non-sprinters. After dividing the sprinters into faster and slower groups according to their personal best time in the 100-m sprint, it was found that the forefoot bone length of the second toe, but not that of the big toe, was significantly longer in faster group than in slower group. Furthermore, the forefoot bone length of the second toe correlated significantly with the personal best time in the 100-m sprint. This study supported evidence that the forefoot bones are longer in sprinters than in non-sprinters. In addition, this is the first study to show that longer forefoot bones may be advantageous for achieving superior sprint performance in humans.

KEYWORDS
bone metabolism, magnetic resonance imaging, metatarsophalangeal joint, moment arm, muscle cross-sectional area

1 | INTRODUCTION

It is well-known that superior sprint performance is achieved using the large moment generated from the hip, knee, and ankle joints. In contrast, the role of the metatarsophalangeal (MTP) joint in the forefoot during sprinting remains poorly understood. Previous studies reported that the MTP joint serves to absorb energy during stance phase while sprinting.[1-3] Moreover, it has been proposed that the elastic energy returned in the form of the MTP joint moment can partially utilize the enhancement of plantar flexor moment during push-off phase.[4-8] Thus, while the MTP joint is a relatively small joint, its moment during sprinting may be related to superior sprint performance.

A few recent studies have found that the forefoot is longer in sprinters than in non-sprinters.[4,5] Lee and Piazza[5] first reported that the distance from the first metatarsal head to the end of the toe was longer in sprinters than in non-sprinters.

Moreover, using computer simulation, the authors then showed that the magnitude of the plantar flexor moment achievable during the push-off phase while sprinting is enhanced concomitantly with the increase in forefoot length.[4,5] Taken together, these previous findings suggest that a longer forefoot may contribute to a higher sprint performance. This relationship between forefoot structure and performance in sprinters may be useful in explaining the important role of the MTP joint in sprinting performance. Specifically, the enhanced moment from the MTP joint may generate increased plantar flexor moment, most likely by changing the gear ratio, which is the ratio between the moment arm of the resultant ground reaction force and the moment arm of the muscle force.[9] However, this relationship has not been directly demonstrated in humans.

In a recent study using magnetic resonance imaging (MRI), Baxter et al.[4] demonstrated that the length of the forefoot bones of the big toe, which includes the distal phalanx, proximal phalanx, and metatarsal, is higher in sprinters than in non-sprinters. However, their study included a relatively small number of subjects (n=8 for each group of sprinters and non-sprinters). In addition, their study examined only the length of forefoot bones of the big toe, even though it is also common to have a longer second toe than the big toe,[10] indicating that the second toe may also be an important target for determining unique forefoot structures in sprinters. In fact, previous studies have reported that the loading of the second toe was greater than that of other toes during foot contact while running, although the measurement may not reflect loading while sprinting during maximal sprinting speed.[11,12] Moreover, loading on the longitudinal axis, which is known to be associated with bone formation,[13] may also be greater in the second toe than in other toes during the push-off phase of locomotion in humans.[14] Furthermore, toe loading increases with running speed[11] and with certain sprinting strike patterns, as runners with a toe strike pattern showed higher toe loading than that noted in runners with other strike patterns such as the rearfoot strike pattern.[12] Taken together, these observations suggest that longer forefoot bones in sprinters may be associated with the increased levels of mechanical stress applied to the bones during sprinting, which would enhance bone formation,[15] potentially by up-regulation of growth factors (eg, FGF, IGF, and TGF-β).[16] If the physiological response to sprinting-specific mechanical stress is indeed reflected in the length of the forefoot bones, this specific adaptation may be more pronounced in the second toe than in other toes, including the big toe. Therefore, the first hypothesis examined in this study was that the forefoot bone length of the second toe, in addition to that of the big toe, would be longer in sprinters than in non-sprinters. Moreover, previous studies have proposed that longer forefoot bones may contribute to higher sprint performance as observed by computer simulation.[4,5] Therefore, the second hypothesis examined in this study was that faster sprinters would have longer forefoot bones than those of slower sprinters, and this feature would be more pronounced in the second toe than in the big toe. To evaluate our hypotheses, we first compared the MRI-measured length of the forefoot bones of the big and second toes between sprinters and non-sprinters in a relatively large sample. Second, we compared the forefoot bone length of the big and second toes between faster and slower sprinters, identified based on their personal best time in the 100-m sprint. Finally, we examined the relationship between the forefoot bone length of the big and second toes and the personal best 100-m sprint time.

2 | METHODS

2.1 | Subjects

Thirty-six well-trained male sprinters (age: 21.0±2.0 years) participated in this study. These sprinters were involved in regular sprint training and competition. Their best personal times of the 100-m sprint ranged from 10.21 to 11.90 seconds (11.07±0.45 seconds). On the basis of a preliminary study, 36 male non-sprinters (age: 20.9±2.2 years) matched to the sprinters for age, body height, and body weight were selected as a control group. The non-sprinters were recreationally active, but did not participate in any physical training program. In order to determine the impact of forefoot bone length on sprint performance, sprinters were further divided into two groups, one consisting of faster sprinters (n=18) and one consisting of slower groups (n=18), based on the personal best time in the 100-m sprint. The subjects were informed of the experimental procedures and provided written consent to participate in the study. None of the subjects had contraindications to MRI. All procedures were approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2011-009).

2.2 | MRI measurement

The length of each subject's right foot was measured in millimeters as the distance from the heel to the end of the big or second toe. The highest value in both toes was considered the maximum foot length, and this length was used to normalize the MRI-measured forefoot bone length.

The right ankle and forefoot structures of each subject were measured using a 1.5-T magnetic resonance system (Signa HDxt; GE Healthcare UK Ltd., Buckinghamshire). The subject was positioned supine on the scanner bed, with both knees fully extended. The subject's right ankle was carefully set at a neutral position (ie, 0°). The ankle and foot scans were acquired using a 4-channel foot ankle coil. Three-dimensional isotopic T_1-weighted images were obtained with a repetition time of 11.3 seconds, echo time of 5.1 ms, slice

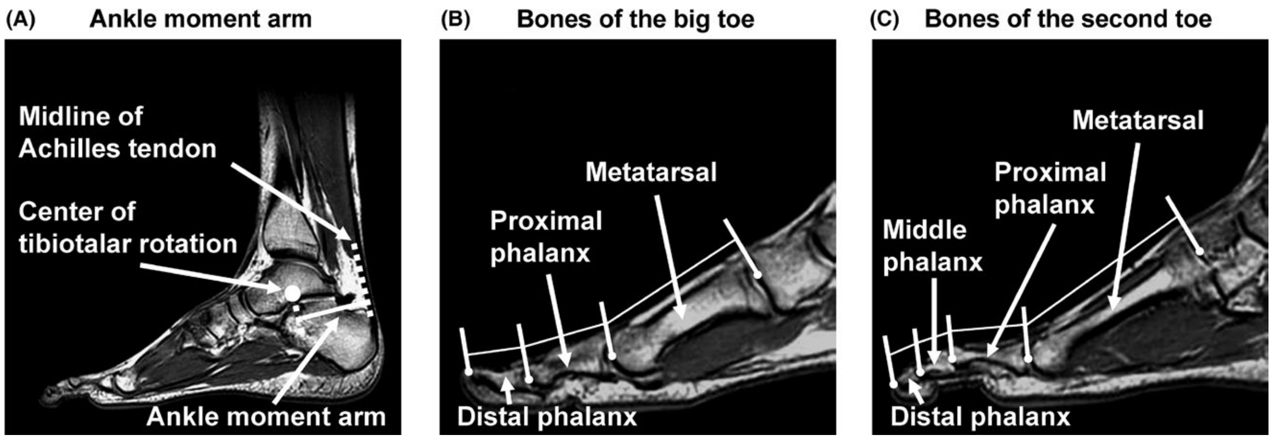

FIGURE 1 Representative magnetic resonance imaging scans used for measuring the length of the ankle moment arm (A) and forefoot bones of the big (B) and second (C) toes. Ankle moment arm length was measured as the distance between the center of tibiotalar rotation and the midline of the Achilles tendon. Forefoot bone length of the big toe included the distal phalanx, proximal phalanx, and metatarsal bones. Forefoot bone length of the second toe included the distal phalanx, middle phalanx, proximal phalanx, and metatarsal bones

thickness of 1.2 mm, field of view of 28 cm, and matrix size of 256×256 pixels.

Representative MRI scans are shown in Figure 1. Ankle moment arm length was defined as the distance between the midline of the Achilles tendon and the center of tibiotalar rotation.[4,17] For the big toe, the length of the distal phalanx, proximal phalanx, and metatarsal was measured. For the second toe, the length of the distal phalanx, middle phalanx, proximal phalanx, and metatarsal was measured. In addition to the length of the forefoot bones, this study also determined the length of mid-foot bones, including the medial cuneiform, intermediate cuneiform, and navicular.

The bone length was measured along the long axis of the bone between the intersections of the long axis and the cortex at the distal and proximal ends.[4] These analyses were conducted using image analysis software (OsiriX version 5.6; OsiriX Foundation, Geneva, Switzerland). The measurements of the ankle moment arm, forefoot bones of the big and second toes, and mid-foot bones were performed twice, and the two values for each length were averaged. To assess the variability and repeatability of the MRI measurements obtained in this study, the coefficient of variation (CV) and intraclass correlation coefficient (ICC) were calculated. Additionally, we measured the ICC of the length of the ankle moment arm, forefoot bones in the big and second toes, and mid-foot bones on two separate days in 16 healthy males (age: 21.8±1.1 years, height: 171. 3±3.9 cm, weight: 66.5±6.4 kg).

2.3 | Statistical analysis

The data are presented as the mean±SD. The CV and ICC were calculated to assess the variability and repeatability of the MRI measurements obtained in this study. Comparisons of groups were performed using an unpaired *t*-test. The relationship between the forefoot bone length and sprint performance in sprinters was assessed using Pearson's product-moment correlation coefficient. The statistical significance level was defined at $P<.05$. All statistical analyses were conducted using IBM SPSS software (version 19.0; International Business Machines Corp, NY, USA).

3 | RESULTS

The CV of the two measurements in all the subjects was as follows: 1.1±0.9% for ankle moment arm; 1.6±1.2%, 1.5±1.2%, and 0.9±0.8%, respectively, for the distal phalanx, proximal phalanx, and metatarsal of the big toe; 2.1±1.5%, 2.2±1.6%, 1.7±1.4%, and 0.7±0.5%, respectively, for the distal phalanx, middle phalanx, proximal phalanx, and metatarsal of the second toe; and 1.8±1.1%, 2.3±1.4%, and 1.9±1.3%, respectively, for the medial cuneiform, intermediate cuneiform, and navicular of the mid-foot. The ICC of the two measurements in all subjects included in this study ranged from 0.919 to 0.987. The ICC for the measurements performed on two separate days in 16 healthy males was as follows: 0.970 for ankle moment arm; 0.956, 0.917, and 0.954, respectively, for the distal phalanx, proximal phalanx, and metatarsal of the big toe; 0.981, 0.988, 0.929, and 0.993, respectively, for the distal phalanx, middle phalanx, proximal phalanx, and metatarsal of the second toe; 0.952, 0.935, and 0.944, respectively, for the medial cuneiform, intermediate cuneiform, and navicular of the mid-foot.

Physical characteristics and foot structures in sprinters and non-sprinters are listed in Table 1. The physical characteristics and foot length parameters did not differ significantly between sprinters and non-sprinters. Moreover, the ankle moment arm length did not differ significantly between the two groups. In contrast, for the big toe, the distal phalanx and

TABLE 1 Physical characteristics and foot structures in sprinters and non-sprinters

	Sprinters (n=36)	Non-sprinters (n=36)	*P* value
Height, cm	175.5±4.9	174.3±4.9	.318
Weight, kg	67.0±4.8	66.8±6.4	.930
Body mass index, kg/m^2	21.7± 1.3	22.0±1.8	.509
Heel to big toe, cm	26.1±0.7	26.1± 1.1	.860
Heel to second toe, cm	25.9±0.8	25.9±1.0	.939
Maximum foot length, cm	26.2±0.7	26.2± 1.1	.817
Ankle moment arm, mm	48.7±2.2	48.8±2.9	.862
Bones of the big toe			
Distal phalanx, mm	24.7±1.7	23.7±1.9	**.023**
Proximal phalanx, mm	33.6±1.7	32.5±2.3	**.032**
Metatarsal, mm	65.9±2.6	64.6±3.3	.062
Total bone length, mm	124.1±4.2	120.8±5.9	**.008**
Bones of the second toe			
Distal phalanx, mm	11.6±1.3	11.0±1.1	**.040**
Middle phalanx, mm	13.3±2.1	12.5±2.1	.096
Proximal phalanx, mm	31.3±1.9	30.1±1.8	**.008**
Metatarsal, mm	81.0±2.2	79.5±3.2	**.020**
Total bone length, mm	137.2±5.3	133.2±5.6	**.003**
Mid-foot bones			
Medial cuneiform, mm	25.1±1.9	24.7±1.5	.264
Intermediate cuneiform, mm	21.0±1.6	20.7±1.2	.322
Navicular, mm	18.8±1.3	19.0±1.3	.488

Values are presented as Mean±SD. Bold values indicate a significant difference between sprinters and non-sprinters.

proximal phalanx were significantly longer in sprinters than in non-sprinters ($P<.05$ for both). The metatarsal of the big toe tended to be longer in sprinters than in non-sprinters, but the difference did not reach statistical significance ($P=.062$). For the second toe, the distal phalanx, proximal phalanx, and metatarsal were significantly longer in sprinters than in non-sprinters ($P<.05$ for all), but no such trend was observed for the middle phalanx. The total length of the forefoot bones of both the big and second toes was significantly longer in sprinters than in non-sprinters ($P<.01$ for both). Moreover, the relative forefoot bone length, which represents the forefoot bone length normalized with the maximum foot length, was significantly longer in sprinters than in non-sprinters for both the big and second toes (Figure 2; $P\leq.001$ for both). On the other hand, for the mid-foot bones, the length of the medial cuneiform, intermediate cuneiform, and navicular did not differ between sprinters and non-sprinters.

Physical characteristics and foot structures in the groups of faster and slower sprinters are listed in Table 2. Although body weight was significantly heavier in faster than in slower groups ($P=.046$), body height and foot length did not differ significantly between the two groups. Moreover, ankle moment arm length did not differ between the two groups. In contrast, for the big toe, the distal phalanx was significantly longer in faster than in slower groups ($P=.036$), but this trend was not observed for the proximal phalanx or metatarsal. For the second toe, the distal phalanx was significantly longer in faster than in slower groups ($P=.004$), but this trend was not observed for the proximal phalanx, middle phalanx, or metatarsal. Although the total forefoot bone length of the big toe did not differ significantly between the two groups, that of the second toe was significantly longer in faster than in slower groups ($P=.046$). The relative forefoot bone length of the second toe, but not that of the big toe, was also significantly longer in faster than in slower groups (Figure 3; $P=.001$). Furthermore, the relative forefoot bone length of the second toe correlated significantly with the best personal time in the 100-m sprint (Figure 4; $R=-.495$, $P=.002$). On the other hand, for the mid-foot bones, the length of the medial cuneiform, intermediate cuneiform, and navicular did not differ between faster and slower sprinters.

4 | DISCUSSION

The present study determined that the forefoot bones of the big and second toes are longer in sprinters than in non-sprinters. Moreover, we found that, in sprinters, a longer

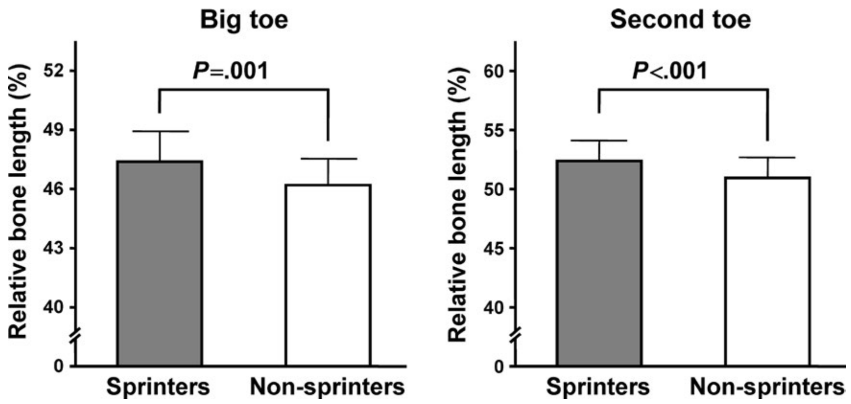

FIGURE 2 Relative forefoot bone length of the big and second toes in sprinters and non-sprinters. The relative forefoot bone length of the big and second toes was normalized with the maximum foot length, expressed as a percentage, and presented as mean±SD

TABLE 2 Physical characteristics and foot structures in faster and slower groups of sprinters

	Faster group (n=18)	Slower group (n=18)	*P* value
Height, cm	176.3±5.0	174.6±4.7	.309
Weight, kg	68.6±4.6	65.4±4.6	**.046**
Body mass index, kg/m^2	22.1± 1.3	21.4±1.2	.127
Heel to big toe, cm	25.9±0.8	26.3±0.7	.144
Heel to second toe, cm	25.9±0.7	26.0±0.9	.871
Maximum foot length, cm	26.1±0.7	26.3±0.7	.265
Ankle moment arm, mm	49.3±2.3	48.1±2.0	.094
Bones of the big toe			
Distal phalanx, mm	25.3±1.6	24.1±1.6	**.036**
Proximal phalanx, mm	33.5±1.7	33.7±1.6	.685
Metatarsal, mm	65.5±2.7	66.3±2.4	.368
Total bone length, mm	124.2±4.4	124.0±4.2	.902
Bones of the second toe			
Distal phalanx, mm	12.2±1.1	11.0±1.2	**.004**
Middle phalanx, mm	13.6±1.6	13.0±2.4	.348
Proximal phalanx, mm	31.6±1.6	30.9±2.1	.294
Metatarsal, mm	81.5±2.4	80.6±2.0	.211
Total bone length, mm	141.1±4.0	133.5±5.4	**.046**
Mid-foot bones			
Medial cuneiform, mm	25.3±2.1	24.9±1.7	.559
Intermediate cuneiform, mm	21.2±1.4	20.9±1.7	.680
Navicular, mm	18.7±1.4	18.9±1.3	.599

Values are presented as Mean±SD. The sprinters were divided into faster and slower groups based on their personal best time in a 100-m race. Bold values indicate a significant difference between faster group and slower group.

forefoot bone length of the second toe, but not that of the big toe, was correlated with a higher personal best time in the 100-m sprint. Taken together, these findings indicate the importance of the forefoot structure as a determinant of performance in sprinters.

In a series of studies by Piazza et al.,[4,5] forefoot bones were found to be longer in sprinters than in non-sprinters. However, these studies included a relatively small number of sprinters and non-sprinters. In the present study, we re-examined the relevance of the length of the forefoot bones using a relatively large number of subjects and confirmed that forefoot bones of both the big and second toes are longer in sprinters than in non-sprinters. In addition, the present study found that forefoot bone length of the second toe, but not that of the big toe, was longer in faster sprinters than in slower sprinters. Importantly, we obtained evidence that a longer forefoot bone length in the second toe correlated with a higher sprint performance in humans. Using computer simulation, previous studies proposed that a longer forefoot produces a larger plantar flexor moment during the push-off phase while sprinting;[4,5]

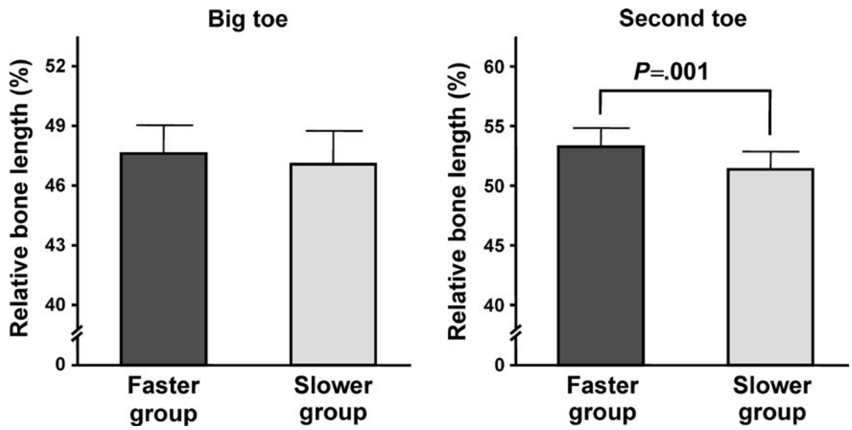

FIGURE 3 Relative forefoot bone length in the big and second toes in the groups of faster and slower sprinters. The relative forefoot bone length of the big and second toes was normalized with the maximum foot length, expressed as a percentage, and presented as mean±SD. The sprinters were divided into two groups: one consisting of faster sprinters (n=18) and one of consisting of slower sprinters (n=18), based on the personal best time in the 100-m sprint

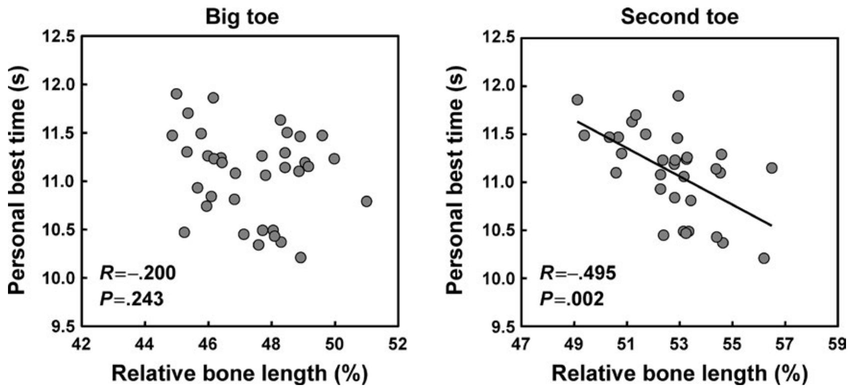

FIGURE 4 Relationship between relative forefoot length and personal best time in the 100-m sprint in sprinters

as larger plantar flexor moment correlates with higher sprint performance,[18,19] the results of the computer simulations suggest that a longer forefoot can contribute to achieving a higher sprint performance. Moreover, several previous studies have proposed that, despite being a relatively small joint, the MTP joint in the forefoot contributes to sprint performance.[1–3] It is speculated that a longer forefoot is associated with an enhanced MTP joint moment because of the change in gear ratio during sprinting.[9] Krell and Stefanyshyn[2] reported that, in sprinters, a greater maximal MTP joint extension velocity correlated with a faster sprint time in a 100-m sprint, indicating that the increase in the maximal velocity, which is a result of enhanced plantar flexor moment induced by greater MTP moment, may originate from the foot structure involving longer forefoot bones. In this regard, the present finding may support previous conclusions regarding the important role of the MTP joint in efficient sprint performance, as suggested by the positive relationship found between forefoot bone length and performance in sprinters.

Baxter et al.[4] determined that ankle moment arm length was shorter in sprinters than in non-sprinters. In contrast, we did not find any difference in ankle moment arm length between sprinters and non-sprinters. The discrepancy may partly originate from the fact that our study included a larger study sample than that analyzed by Baxter et al.[4] Moreover, previous studies have reported that the size of the plantar flexor muscle is greater in sprinters than in untrained subjects.[20,21] Furthermore, Baxter and Piazza[17] reported that the length of the ankle moment arm increased with the volume of the plantar flexor muscle. Based on the findings of previous investigations and those of the present study, we propose that ankle moment arm length is at least the same size in sprinters and non-sprinters, and not shorter in sprinters than in non-sprinters, as previously reported by Baxter et al.[4] However, this discrepancy between the findings of Baxter et al.[4] and those of the present study might also be related to differences in ethnicity, athletic level, and sprint type, although a complete and clear explanation is yet to be found. In addition, the size of the plantar flexor muscle may account for part of the discrepancies, but this hypothesis cannot be verified, as such measurements were not performed in either the study by Baxter et al.[4] or the present study. Thus, in the future studies, clarifying the relationship between ankle moment arm length and plantar flexor muscle size in sprinters may be useful for explaining the discrepancy between the findings of Baxter et al.[4] and those of the present study.

Regarding the relationship between ankle moment arm length and sprint performance, previous studies using computer simulation have shown that a greater plantar flexion moment may be generated from the toe under a higher contractile speed because of a shorter ankle moment arm (ie, rearfoot) and longer forefoot.[4,17] Unexpectedly, Baxter and Piazza[17] found a positive relationship between ankle moment arm length and maximal dynamic plantar flexor strength at a high isokinetic angular velocity, indicating that a relatively longer moment arm might contribute to generate greater moment, despite higher contractile shortening. A larger plantar flexor moment contributes to higher sprint performance by shortening the contact time during the stance phase.[18] Moreover, Dowson et al.[19] have reported that a larger isokinetic strength of plantar flexion correlated with higher sprint performance. Taken together, these reports clearly suggest that a longer, rather than shorter, ankle moment arm seems to contribute to a higher sprint performance.

The present study has several limitations. First, we determined that the forefoot bones in the big and second toes were significantly longer in sprinters than in non-sprinters, but it is unclear whether this result is derived from genetic or long-term training effects. Regarding long-term training effects, previous studies have determined that mechanical stress applied to the bone may enhance bone formation,[15] likely via up-regulation of growth factors.[16] Thus, we speculate that mechanical stress on the toe during sprinting, potentially through years of sprint training, may induce specific bone formation. Nevertheless, further longitudinal studies are needed to investigate the specific changes in the forefoot structure in both junior and senior sprinters. Second, the present study showed that ankle moment arm, which reflects rearfoot bone length, did not differ between sprinters and non-sprinters. Moreover, the length of the mid-foot bones, including the medial cuneiform, intermediate cuneiform, and navicular, was also comparable between the two groups. Thus, we could not provide strong data to support the present findings that forefoot bone length was significantly longer in sprinters than in non-sprinters, although other morphological dimensions of the foot structure, not assessed in the present study, may represent contributing factors. For example, whereas muscle size was not assessed in the present study, lower limb muscle size is known to be greater in sprinters than in non-sprinters,[20,21] and subsequent foot remodeling caused by muscle hypertrophy may explain the discrepancy between the findings of previous investigations and those of the present study. For example, muscle hypertrophy in the foot may induce modifications of foot arch height, which may help store the elastic energy absorbed by the MTP joint during the stance phase of sprinting, and subsequently enhance the plantar flexor moment via increasing MTP joint moment using the returned energy during push-off phase.[6,7,22] Thus, further studies are needed to examine the relationships among the length of the forefoot bones, size of the foot muscles, and foot proportions such as foot arch height. Finally, we determined that, in sprinters, the forefoot bone length is related to sprint performance, with faster sprinters having longer forefoot bones than slower sprinters. However, we did not obtain direct evidence linking forefoot bone length to kinetic or kinematic data (eg, ground reaction force and contact time) during sprinting; this relationships should be elucidated in the future studies. Furthermore, the present study found that sprint performance is related to the forefoot bone length of the second toe, but not to that of the big toe. However, we could not conclude that the second toe rather than the big toe plays an important role in sprint performance. Nevertheless, because most sprinters use a toe strike pattern,[2] it is expected that, during contact, the strike pattern caused greater peak pressure and impulse in the second toe than in the other toes.[12] Thus, understanding the mechanisms underlying the toe strike sprinting pattern may be useful to explain the present findings. In the future studies, it may be interesting to compare the performance of athletes with differing foot strike pattern (eg, forefoot vs rearfoot strike patterns), especially among endurance runners.

5 | CONCLUSION AND PERSPECTIVES

The present study proposed that a longer forefoot in sprinters may be advantageous for achieving higher sprint performance by enhancing plantar flexor moment during sprinting. In contrast, a shorter forefoot in sprinters may be disadvantageous for sprint performance. With a shorter forefoot, a greater plantar flexor muscle may be required to compensate for the decreased plantar flexion moment. Further studies are needed to examine the functional relationship between lower leg muscularity and forefoot structures. Clarifying this relationship may be useful in understanding individual features and outlining corresponding programs for training and rehabilitation of sprinters, to improve outcome and performance.

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