

The Characteristics of Static Plantar Loading in the First-Division College Sprint Athletes

Tong-Hsien Chow

Abstract—Background: Plantar pressure measurement is an effective method for assessing plantar loading and can be applied to evaluating movement performance of the foot. The purpose of this study is to explore the sprint athletes' plantar loading characteristics and pain profiles in static standing.

Methods: Experiments were undertaken on 80 first-division college sprint athletes and 85 healthy non-sprinters. 'JC Mat', the optical plantar pressure measurement was applied to examining the differences between both groups in the arch index (AI), three regional and six distinct sub-regional plantar pressure distributions (PPD), and footprint characteristics. Pain assessment and self-reported health status in sprint athletes were examined for evaluating their common pain areas.

Results: Findings from the control group, the males' AI fell into the normal range. Yet, the females' AI was classified as the high-arch type. AI values of the sprint group were found to be significantly lower than the control group. PPD were higher at the medial metatarsal bone of both feet and the lateral heel of the right foot in the sprint group, the males in particular, whereas lower at the medial and lateral longitudinal arches of both feet. Footprint characteristics tended to support the results of the AI and PPD, and this reflected the corresponding pressure profiles. For the sprint athletes, the lateral knee joint and biceps femoris were the most common musculoskeletal pains.

Conclusions: The sprint athletes' AI were generally classified as high arches, and that their PPD were categorized between the features of runners and high-arched runners. These findings also correspond to the profiles of patellofemoral pain syndrome (PFPS)-related plantar pressure. The pain profiles appeared to correspond to the symptoms of high-arched runners and PFPS. The findings reflected upon the possible link between high arches and PFPS. The correlation between high-arched runners and PFPS development is worth further studies.

Keywords—Sprint athletes, arch index, plantar pressure distributions, high arches, patellofemoral pain syndrome.

I. INTRODUCTION

SPRINT, known as a short distance running race in track and field, is one of the high intensity and anaerobic activities and highly depends on the instantaneous force, muscle strength and speed of the lower limbs. The lengths of sprinting events are divided into 100, 200 and 400 meters. According to the previous studies, runners are more susceptible to excessive eversion of ankle joints than people engaging in other sports activities, and this is generally regarded as the result of the wear and tear on inner sides of runners' sole heels and their fast pace in running. [1] The most

common pain areas in runners are knee joints, ankle joints, the Achilles tendon and the forefoot region, coupled with fatigue fractures of the lower limbs. [2]

Foot arch, an anatomical structure of the foot, is constituted of ligaments, muscles and bones, and could be regarded as a shock absorber in the human body. [3] When walking and running, the medial longitudinal arch (MLA) provides adequate elastic forces and twisting forces for absorbing the ground reaction force, and this is helpful for attenuating the shock from movement, mitigating injuries and deferring fatigue. [4] Arch height of the MLA is generally treated as the influential and key determinant of the function of foot and lower limbs. [5] Abnormal arch height is ineffective in absorbing the ground reaction force, and thus, runners are prone to suffer from injuries. [6] High arch individuals have been associated with more laterally located bony injuries of the foot, ankle, knee, and lower extremity stress fractures while low arch subjects will show a greater incidence of medially soft tissue injuries such as patellar tendinitis, plantar fasciitis and knee pain. [7], [8] Apart from X-rays and ultrasonographic methods which provide direct measurements of MLA height, arch index (AI) from footprints could be considered a reliable and valid method to characterize the foot and MLA height. [9]-[14] Recently, it appears that assessment of static arch mobility, associated with lower extremities and footprint measures, is considered to be at the core of understanding the overall function of the foot and lower extremities during running. [15] Plantar pressure assessment from footprint is one of the effective methods to evaluate the plantar loading characteristics during functional activities such as running. [16] The parameters can be used to understand the variations in the plantar loading of different regions of the foot and assist in detecting the foot pathologies. [17], [18] In addition, the parameters have been widely used to provide the arch change in children from six to seventeen years old to understand the foot growth and mature in morphology. [19] The measurements of static arch height and arch height ratio of the foot may assist the clinician in estimating foot posture during dynamic activity in patients with lower-limb injuries. [20] Clinicians also commonly use static MLA posture to infer dynamic foot function in order to assess the potential for several foot-specific pathologies [21] and lower extremity dysfunction which may increase injury risk. [22] For example, greater regional plantar loadings have been associated with forefoot rheumatoid arthritis, hallux valgus deformity, [23] medial midfoot osteoarthritis, [24] and posterior tibialis tendon dysfunction leading to flatfoot deformity [21] although cause-effect relationships are not always clear. In addition, a

Tong-Hsien Chow, PhD, is with the Department of Leisure Sport and Health Management, St. John's University, 499, Sec. 4, Tam King Road, Tamsui District, New Taipei City, 25135 Taiwan (Corresponding author, e-mail: thchow1122@mail.sju.edu.tw).

recent prospective study suggests the static characteristics of flatfoot, high-arched foot and rearfoot range of motion are risk factors for development of lower extremity overuse injuries in general. [25] When plantar pressure in each region of the foot is distributed evenly, sports injuries could be reduced effectively. [26] Even though the use of pressure assessment is beneficial, the reliability of the plantar pressure measurements can be affected by the characteristics of the subjects from a specific musculoskeletal fatigue. [27] Previous reliability studies confirmed the correlation between the variations in anatomical structure of the foot and pressure distributions. [9], [28], [29] The relationships between the plantar loading characteristics and patellofemoral pain syndrome (PFPS) in dynamic states were also discussed. [30]-[33] However, PFPS, also known as runners knee, is the most common overuse injury among runners.

Plantar pressure has been examined mostly during adult walking and running. [33]-[37] Nevertheless, limited information exists on the plantar loading characteristics of runners in static standing. To our knowledge, few studies are undertaken for exploring sprint athletes' static plantar loading characteristics and predicting their potential pain profile such as PFPS. Therefore, the purpose of this study was to generalize and explore the differences between sprint athletes and healthy non-sprinters in terms of their static plantar loading characteristics. Parameters including the arch index, three regional plantar pressure distributions (PPD) of the forefoot, midfoot and rearfoot, six distinct sub-regional PPD and the footprint characteristics of both feet were examined. Specifically, pain assessment and self-reported health status of the sprint athletes were examined and questioned for accurately evaluating the pain areas which occurred frequently in the body. We hypothesized that the sprint athletes are classified into high arch type and that the PPD were particularly concentrated in the forefoot and rearfoot regions. The plantar loading characteristics and pain profiles may correlate with the features of high-arched runners and PFPS.

II. METHODS

A. Subject Selection

The subjects participating in this study comprised two specific groups of college and university students in Taiwan. One of the groups, labelled as the 'sprint group', was constituted of 80 first-division college sprint athletes (42 males and 38 females) with specialties in the following sprint events: 100, 200 and 400 meters. For all subjects in the sprint group, the length of being the qualified first-division college sprint athletes was required to be above 4 successive years. They were mainly recruited from the sport university, school of kinesiology and three city sports centers in Taipei, Taiwan. The other group, the control group, was composed of 85 healthy non-sprinters (45 males and 40 females) who were the same age range (between 17 and 21 years old) as the sprint group. All subjects in the control group had neither specialties in sports nor regular time for exercise (the average time for exercise weekly was less than 2 days or 6 hours). Each

subject's age, gender, height, body weight and body mass index (BMI) were recorded in the research process. It has been widely accepted in many studies that people's arch shapes change when gaining weight in the process of growth and development, and that there seems to be a strong link between obesity and flatfeet. Considering the effect of the body weight on shape characteristics of the foot arch, each subject's BMI within this research was required to range between 18.5 and 24 and this particular range was defined by the World Health Organization (WHO) as healthy weight. A total of 165 subjects participated in this study, and their average age, height, weight and BMI value were shown in Table I. All subjects' pain and health assessments were conducted through self-reported health describes and the diagnoses made by a professional physiotherapist at the rehabilitation department. These health assessments were essential for this research to ensure that all subjects had no history of previous fracture and surgery, and that they had no injuries in their ankle joints, knee joints, hip joints, spine, and bones and muscles of their lower limbs within a year as this study was underway. Prior to the experiments, all subjects were required to sign the informed consent forms of participation in this study. The entire process of the experiments within this study followed the guidelines of the local Ethical Committee and the recommendations of the Declaration of Helsinki.

B. Instruments and Equipment

'JC Mat', provided by View Grand International Co., Ltd., Taiwan, was the optical plantar pressure instrument and served as the main research tool for the present studies. The measurement technology and principles of JC Mat were similar to the operation principles of Harris footprint measurement instrument. The key attributes of JC Mat were as follows: (1) the subtle characteristics of the foot were easily distinguished; (2) the plantar pressure distribution and footprints coincided with the weight calibration data (data not shown); (3) there were 25 sensors in each square centimeter for the plantar pressure measurement, and thus 13600 sensors were on each side (32*17 cm) of JC Mat; (4) the pressure sensing was sensitive and the scope of the sensor was large. A smooth and delicate plantar pressure image was shown in the form of round dots; (5) the static pressure profiles from footprints and barefoot images were captured instantly; and (6) the built-in FPDS-Pro software was competent for analyzing the following parameters: the arch index, plantar pressure values, balance of the center of gravity, toe angles and footprints.

C. Methods and Procedures

It took approximately six months to select the subjects and conduct the experiments for this study. Before the experiments were undertaken, all subjects were informed of the purpose and processes of this study and their consent to participate in this research was obtained. For the sake of consistency and trustworthiness of the experiments, time for each experiment was set between 3pm and 5pm. All subjects were required to measure their body weights and heights when the experiments

were conducted. This was helpful for recording the basic and accurate data of subjects' physiological conditions in terms of weights and heights. The subjects' weights and heights recorded during the experiments, associated with the given formula (body weight (kg)/height (m²)), served as the base for calculating the BMI values for this study. Apart from this, the subjects in the experimental processes were asked to follow the instructions listed below:

- (1) Roll both trouser legs up to above the knees if necessary, in order to prevent the clothing from limiting movements of the extremities.
- (2) Stand with bare feet on the sensing cushion with marks of the specific measuring range of JC Mat.
- (3) Relax the body; then, control and balance the center of gravity by standing with feet shoulder-width apart and with body weight evenly distributed on both feet.
- (4) Stampede for 6-8 steps, and then, stand still with a natural and comfortable posture and arms hanging straight down at sides.
- (5) Face the guide of the experiment, and look the guide straight in the eye. Keep the body stationary and balanced until there were no obvious changes in the pressure values of both feet measured by JC Mat.

When the condition above was met, the subjects' static pressure profiles were acquired immediately.

TABLE I
DEMOGRAPHIC CHARACTERISTICS

Demographics	Control			Sprint		
	Total	Male	Female	Total	Male	Female
Numbers	85	45	40	80	42	38
Age (years)	19.1 ± 0.7	19.1 ± 0.7	19.1 ± 0.8	18.9 ± 1.3	18.9 ± 1.6	18.9 ± 0.9
Height (cm)	165.5 ± 7.7	169.8 ± 7.3	160.7 ± 4.9	164.7 ± 6.1	167.3 ± 6.4	161.7 ± 4.2
Mass (kg)	60.8 ± 7.1	65.7 ± 5.6	55.4 ± 4.1	58.6 ± 3.7	61.1 ± 2.3	55.8 ± 2.6
BMI	22.1 ± 1.2	22.8 ± 0.8	21.4 ± 1.2	21.7 ± 1.7	21.9 ± 1.9	21.4 ± 1.5

Data are represented as mean ± SD. The control group: college and university students with neither specialties in sports nor regular time for exercise (the average time for exercise weekly was less than 2 days or 6 hours). The sprint group: the first-division college sprint athletes with specialties in the following sprint events: 100, 200 and 400 meters.

D. Pain Assessment and Self-Reported Health Status of the Subjects

The process of pain assessment and self-reported health status of the subjects was conducted through the assistance of a professional physiotherapist at the rehabilitation department. This process functioned as the basis for the subject selection criteria, the subject's physiological symptom assessment and confirmation of their pain locations. All subjects should subject to the skeleton arrangement and soft tissue pain assessment after the completion of plantar pressure measurement. Specifically, lower limb pain was defined as the musculoskeletal pain which occurred during the past month and originated from the structures of the foot, ankle, knee, lower leg and thigh. This definition excluded intermittent cramps, dermatological conditions, digital calluses and night-time paresthesia from analysis. A standardised protocol of the questioning and examination techniques was used within this research for determining the precise nature of the complaint (e.g., metatarsalgia and plantar fasciitis). The procedures for evaluating the pain areas which occurred frequently in the subjects' body were presented as:

- (1) The professional physiotherapist evaluated and documented the subjects' self-reported health status and pain areas which occurred frequently in the body.
- (2) The subjects were asked to stand with bare feet and roll both trouser legs up to above the knees if necessary.
- (3) Inspection of subjects' lower extremities by pressing their foot (including phalanges, metatarsal bones, navicular bone, cuboid bone and calcaneus), ankle joints, knee joints, hip joints, tibias, fibulas and femur, and then,

assessing the bones arrangement of their lower extremities.

The procedures for assessing the soft tissue pains were listed as:

- (1) The professional physiotherapist pressed the subjects' self-reported pain areas and re-checked the corresponding locations on the opposite side of pain areas.
- (2) Based on their clinical experiences, the professional physiotherapist pressed and examined the specific points in the subjects' common pains areas, including plantar metatarsal heads, plantar fascia, the inferior margin of navicular bones, the Achilles tendon, the medial and lateral sides of ankle joints, the medial and lateral fossas of knee joints, gastrocnemius, tibialis anterior and posterior, biceps and quadriceps femoris. This allowed the physiotherapist to definitely confirm the pain areas in the subjects' body.

E. Data Analysis

In order to examine the subjects' plantar pressure distributions in different regions and sub-regions of both feet, the images of the static footprint of both feet were digitized and imported into the specific computer program, FPDS-Pro software. The software allows the formation of a perpendicular line on images which extended from the tip of the second toe to the centre of the heel. A perpendicular line was then drawn tangential to the most anterior and posterior part of the footprint excluding the toes. The software automatically generates four parallel lines that perpendicular to the line and divide the outlined footprint into three equal parts. Three equal parts (region A, B and C) and six distinct sub-regions were appeared simultaneously among the

footprint (Fig. 1). In this study, 'regions A, B and C' of the footprint were defined, respectively, as the 'forefoot, midfoot and rearfoot regions'. As for the six sub-regions, 'sub-regions 1, 2, 3, 4, 5 and 6' were defined, respectively, as the 'lateral metatarsal bone (L.M.), lateral longitudinal arch (L.L.A.), lateral heel (L.H.), medial metatarsal bone (M.M.), medial longitudinal arch (M.L.A.) and medial heel (M.H.)'. The arch index ratio method developed by Cavanagh and Rodgers assumed that the arch index (AI) was calculated as the ratio of the area of the middle third of the footprint divided by the entire footprint area excluding the toes, i.e. $AI = B / (A + B + C)$. Based on Cavanagh and Rodgers' assertion, a normal arched foot was defined by the ratio between 0.21 and 0.26, a high-arched foot was defined by the ratio lower than 0.21, and a flat arched foot was defined by the ratio higher than 0.26.

F. Statistical Analysis

Descriptive statistics used for this study was to summarize all subjects' ages, heights, weights and BMI values. Numerical data gained in the research process was presented as mean and standard deviation (e.g. mean $\pm$ SD). The parameters gained from the plantar pressure measurement in terms of the arch index, three regional plantar pressure distributions of the forefoot, midfoot and rearfoot, six distinct sub-regional PPD were compared between groups using independent sample *t* test. Statistical significance was defined as $p < 0.05$ (marked as *) and $p < 0.01$ (marked as **). All of the statistics were calculated with the statistical software program (SPSS version 18; SPSS Inc, Chicago, Illinois).

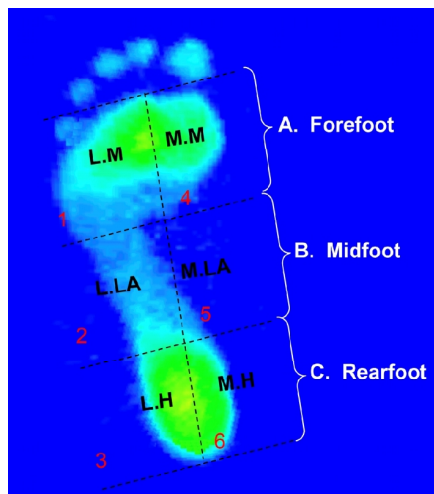


Fig. 1 Regions of interest at the foot were masked to the footprint of the 'JC Mat'. Illustration of the three regions and six distinct sub-regions used to assess the plantar loading. Three equal parts consisted of the following: (A) is forefoot region, (B) is midfoot region and (C) is rearfoot region. Six distinct sub-regions were divided from the three regions and defined as: L.M lateral metatarsal bone, L.L.A lateral longitudinal arch, L.H lateral heel, M.M medial metatarsal bone, M.L.A medial longitudinal arch and M.H medial heel

III. RESULTS

A. Arch Index

As Table II illustrates, the arch indices of the males' feet within the control group were 0.21 and the females fell into 0.19. Yet, the arch indices of both feet in the sprint group were significantly smaller than in the control group ($p < .01$). The results suggested that the arch type was higher in the sprint group than those in the control group.

B. Plantar Pressure Distributions of the Forefoot, Midfoot and Rearfoot Regions

The plantar pressure distributions were illustrated in the form of percentages of the relative load. The relative load in the forefoot region of both feet in the sprint group was higher, the males in particular, than in the control group ($p < .01$) (Table III). The relative load in the midfoot region of both feet was found to be significantly lower in the sprint group than in the control group ($p < .01$). The relative load in the rearfoot region of the right foot was higher in the sprint group, the males in particular, than in the control group ($p < .05$). Based on the findings from the sprint group, the relative load was low in the midfoot regions and was particularly concentrated in the forefoot region of both feet and rearfoot region of the right foot.

C. Plantar Pressure Distributions at the Six Sub-Regions

According to the present study, the relative load at the six distinct sub-regions was divided from the data gained from three regions. In the forefoot region, the relative load at the lateral metatarsal bone of the left foot was lower in the sprint group, the females in particular ($23.90 \pm 6.30\%$), than in the control group ($27.83 \pm 3.38\%$) ($p < .01$). The relative load at the medial metatarsal bone of both feet (left foot: $26.49 \pm 4.93\%$; right foot: $23.59 \pm 4.90\%$) was higher in the sprint group than in the control group (left foot: $19.26 \pm 3.76\%$; right foot: $19.24 \pm 4.37\%$) ($p < .05$). In the midfoot region, the relative load at the lateral longitudinal arch of both feet (left foot: $0.94 \pm 0.70\%$; right foot: $1.12 \pm 0.76\%$) was significantly lower in the sprint group, compared with the control group (left foot: $1.78 \pm 0.36\%$; right foot: $1.68 \pm 0.43\%$) ($p < .01$). Similarly, the relative load at the medial longitudinal arch of both feet (left foot: $1.47 \pm 0.66\%$; right foot: $0.76 \pm 0.48\%$) in the sprint group was significantly lower as compared with the control group (left foot: $1.76 \pm 0.93\%$; right foot: $1.47 \pm 2.61\%$) ($p < .05$). In the rearfoot region, the relative load at the lateral heel of the right foot was higher in the sprint group, the males in particular ($24.13 \pm 4.28\%$), than in the control group ($18.99 \pm 4.88\%$) ($p < .05$). The findings showed that plantar pressure distributions at the medial metatarsal bone of both feet and the lateral heel of the right foot were higher in the sprint group, the males in particular, whereas at the medial and lateral longitudinal arches of both feet were lower, compared with the control group (Figs. 2 and 3).

D. Footprint Characteristics

In Fig. 4, it can be found that footprints in the sprint group displayed the lower pressure profiles in the midfoot region of

both feet. The findings indicated that the arch type in the sprint group was higher than in the control group. Furthermore, the higher pressure profiles were found to be concentrated in

the forefoot region of both feet and rearfoot region of the right foot in the sprint group, particularly the males.

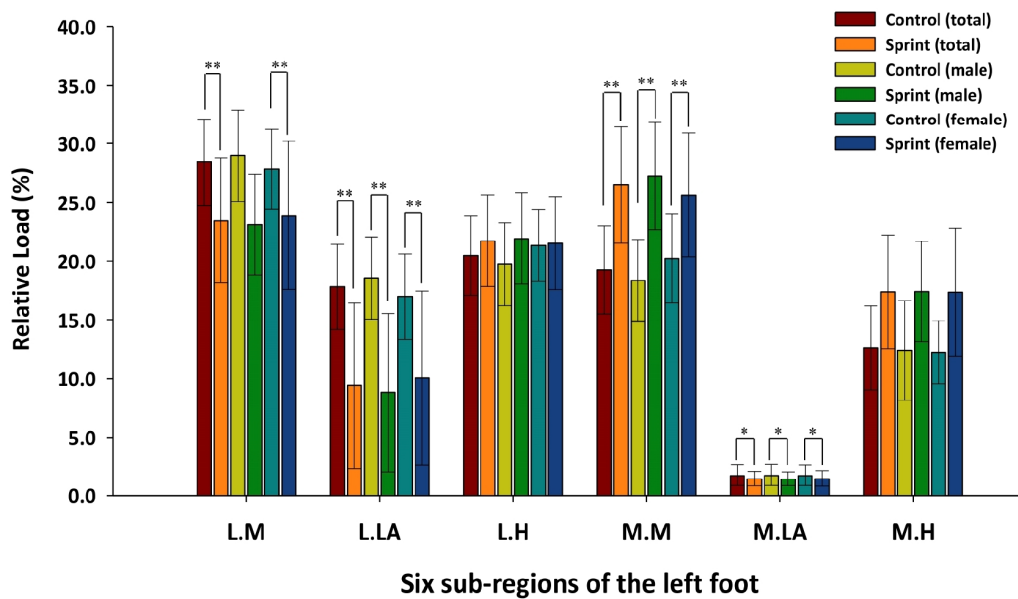


Fig. 2 Plantar pressure distributions of six sub-regions of the left foot in static standing. * $P < 0.05$ and ** $P < 0.01$ are significantly different between both groups by independent-samples T test

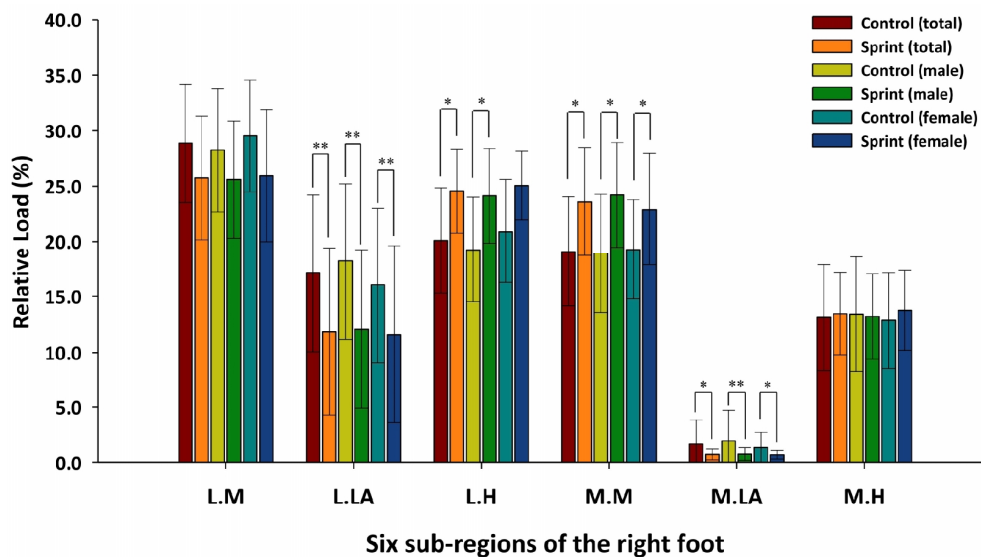


Fig. 3 Plantar pressure distributions of six sub-regions of the right foot in static standing. * $P < 0.05$ and ** $P < 0.01$ are significantly different between both groups by independent-samples T test

TABLE II
ARCH INDEX OF THE FOOT

	Left foot			Right foot		
	Control	Sprint	P-value	Control	Sprint	P-value
Total	0.20 ± 0.03	0.12 ± 0.08	< 0.01	0.20 ± 0.04	0.13 ± 0.08	< 0.01
Male	0.21 ± 0.03	0.11 ± 0.08	< 0.01	0.21 ± 0.05	0.14 ± 0.08	< 0.01
Female	0.19 ± 0.03	0.12 ± 0.08	< 0.01	0.19 ± 0.03	0.13 ± 0.08	< 0.01

The arch indices of both feet are represented as mean ± SD during the static standing. P values of arch index were determined by independent-samples T test between the sprint (n=80 for male=42, female=38) and control (n=85 for male=45, female=40) group.

TABLE III
RELATIVE LOAD OF THE FOREFOOT, MIDFOOT AND REARFOOT REGIONS

Region	Control			Sprint		
	Total	Male	Female	Total	Male	Female
Left foot						
Forefoot (%)	23.86 ± 5.93	23.69 ± 6.51	24.04 ± 5.23	24.99 ± 5.33*	25.18 ± 4.86**	24.78 ± 5.83
Midfoot (%)	9.60 ± 8.67	9.97 ± 9.02	9.18 ± 8.30	5.43 ± 6.38**	5.13 ± 6.02**	5.77 ± 6.77**
Rearfoot (%)	16.55 ± 5.28	16.34 ± 5.17	16.78 ± 5.42	19.58 ± 4.91	19.69 ± 4.67	19.45 ± 5.19
Right foot						
Forefoot (%)	24.14 ± 6.76	24.00 ± 6.99	24.31 ± 6.54	24.66 ± 5.34**	24.88 ± 5.03**	24.42 ± 5.69*
Midfoot (%)	9.16 ± 8.48	9.63 ± 8.61	8.63 ± 8.35	6.31 ± 7.72**	6.44 ± 7.62**	6.16 ± 7.87*
Rearfoot (%)	16.71 ± 5.95	16.37 ± 5.53	17.09 ± 6.41	19.02 ± 6.69*	18.67 ± 6.81*	19.41 ± 6.58

The percentage of relative load are represented as mean ± SD for each foot region during the static standing. * $p < 0.05$, ** $p < 0.01$, significant difference between the sprint ($n=80$ for male=42, female=38) and control ($n=85$ for male=45, female=40) group.

TABLE IV
PAIN ASSESSMENT AND THE SELF-REPORTED HEALTH STATUS IN THE SPRINT GROUP

Pain areas/bone	Proportion	Subjects	Pain areas/bone	Proportion	Subjects
Lateral knee joint	40.0%	32/80	Biceps femoris	53.8%	43/80
Plantar metatarsal bone	35.0%	28/80	Gastrocnemius	47.5%	38/80
Lateral ankle joint	28.8%	23/80	Achilles tendon	43.8%	35/80
Tibia	21.3%	17/80	Quadriceps femoris	37.5%	30/80
Calcaneus	21.3%	17/80	Plantar fascia	27.5%	22/80
Medial ankle joint	20.0%	16/80	Tibialis anterior	22.5%	18/80
Medial knee joint	20.0%	16/80	Lower back	22.5%	18/80
Femur	18.8%	15/80	Fibula	13.8%	11/80
Hip joint	16.3%	13/80	Others	6.3%	5/80
Fibula	7.5%	6/80			

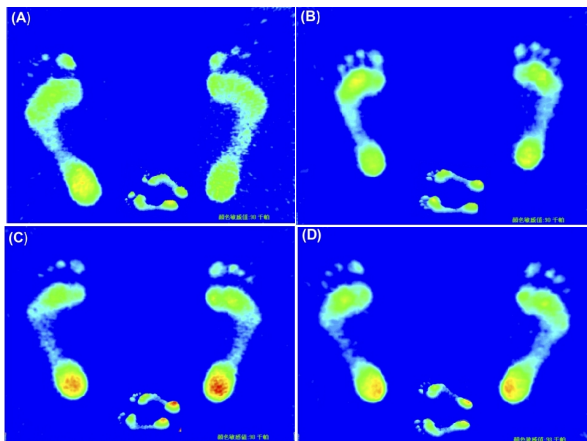


Fig. 4 Footprints of both feet between the (A) male control group, (B) female control group, (C) male sprint group and (D) female sprint group

E. Pain Assessment and Self-Reported Health Status of the Subjects

As can be seen in Table IV which illustrates the findings from the pain assessment and the self-reported health status of the sprint group, the ten most common areas in which pains occurred are presented as follows: the lateral knee joint (40.0%), the plantar metatarsal bone, particularly the first to the third metatarsal heads (35.0%), the lateral ankle joint (28.8%), the tibia (21.3%), the calcaneus (21.3%), the medial ankle joint (20.0%), the medial knee joint (20.0%), the femur (18.8%), the hip joint (16.3%) and the fibula (7.5%).

The eight most common pains which occurred in soft tissues are listed below: the biceps femoris (53.8%), the gastrocnemius (47.5%), the Achilles tendon (43.8%), the quadriceps femoris (37.5%), the plantar fascia (27.5%), the tibialis anterior (22.5%), the lower back (22.5%), the neck and shoulder (13.8%).

IV. DISCUSSION

The purpose of this study was to examine the differences between the sprint and control groups, by focusing particularly on the arch index, three regional and six distinct sub-regional plantar pressure distributions, footprint characteristics and pain profiles in the static standing posture. The results revealed that the static arch index of both feet was considerably close to each other in the sprint and control group, respectively. The arch index of both feet in the sprint group was lower than in the control group. According to the previous studies, the arch index of the footprints could be considered as a predictor of the arch height [9]-[14] while the normal values of the arch index ranged between 0.21 and 0.26. [11] On this basis, the males' foot arches in the control group could be classified into the normal range, whereas the females in the control group may be categorized into the high-arched foot. Differences in the findings from the control group could be attributed to the differences in the subjects' genders and BMI values. As evidenced in many studies, arch types are usually considered to be correlated with genders. [38] Body weight is also thought to be one of the key causes of the flatfoot. [10] Similar to these assertions, other researchers

agree that ages, genders, BMI values function as the influential determinants of the arch index. [12], [39], [40] Furthermore, both males and females in the sprint group generally fell into the high arch type. It is well known that a high-arched individual with an increased height of the MLA often experiences the supinated foot and decreased pronation during the stance phase. [37] An over-supinated foot was defined as increased calcaneal inversion and may provide an advantage in reducing contact time when running. [41] Hasegawa et al. indicated that runners who had the greatest degree heel inversion at foot strike also had the shortest contact time. [41] A shorter contact time and a higher frequency of inversion at the foot contact might contribute to higher running economy. [41] Therefore, deformation of foot arch appeared to be crucial for force transfer and shock absorption, especially in impact sports, such as jump and sprint. [42]

With regard to the results of plantar pressure distributions in the forefoot, midfoot and rearfoot regions, three regional plantar pressure distributions were found to be consistent with the AI. The relative load in the midfoot region of both feet in the sprint group was smaller than that in the control group. In addition, the regional plantar loading of the sprint group, the males in particular, was mainly concentrated in the forefoot region of both feet and rearfoot region of the right foot. The results tended to coincide with the previous studies which verified that the young male runners' peak plantar pressure, associated with the related impulse, was lower in the midfoot region but higher in the forefoot region after a 30-minute intense run. [27] The studies by Willems et al. went further, arguing that after a long-distance fatigue running, runners' plantar pressure was found to be concentrated in the forefoot and inside of the foot. [33] Stolwijk et al. maintained that after the long-distance walking, people's plantar pressure was mainly concentrated in the inside of toes and heels. [34] Supporting these findings from Fourchet et al., on the one hand, highlighted the increase in the relative load under the medial and central forefoot regions while jogging. They also revealed that the relative load under the lesser toes was reduced. [35]

Findings from the six distinct sub-regional plantar pressure distributions can be summarized as follows: these plantar loadings in the sprint group, particularly the males, were mainly exerted on the medial metatarsal bone of both feet and the lateral heel of the right foot. Yet, they were found to be relative low on the medial and lateral longitudinal arches of both feet. These findings seem to be consistent with the previous studies. As many studies have pointed out, runners' peak plantar pressure and the related impulse were generally concentrated more at the metatarsal and less at the lateral regions of the toes. [36] Keller et al. pointing out the fact that the plantar pressure on the toes and heel increased when walking at a higher speed (faster than 80 m·min⁻¹). [43] Ho et al. went further, revealed that the plantar pressure on the heel, medial and central metatarsals, and toes were significantly higher when walking speed increased from 57 m·min⁻¹ to 80 m·min⁻¹. [44] In addition, higher peak forces usually occur

underneath the second and third metatarsal particularly after a fatiguing race. [33] Bisiaux and Moretto observed significant decreases in peak pressure and relative impulse under the medial heel 30 min after a fatiguing run. [27] Moreover, people with high arches tend to suffer from over supination, and this results not only in a decrease in pronation throughout the stance phase but also in an increase in supination in the forefoot and rearfoot regions of foot during exercise. [37] Therefore, the plantar pressure and the integration of pressure over time are usually higher in the metatarsal and calcaneal regions. This could lead to a high risk of injuries on the lateral sides of their knees and ankle joints. [7]

Plantar pressure and impact forces on the foot have been widely accepted as one of the main causes of running injuries. [7], [8] As regards findings from the present research, the common bony pains in sprint athletes were found in sequence are the lateral knee joint, the first to the third metatarsal heads, the lateral ankle joint, the tibia and calcaneus etc. The common pains which occurred frequently in soft tissues by the order are the biceps femoris, the gastrocnemius, the Achilles tendon and the quadriceps femoris etc. The results seemed to be consistent with the previous studies which revealed the high-arched runners were prone to have high loads on the lateral foot, and this may result in problems with the lateral foot (fifth metatarsal stress syndromes) and lower extremities (lateral knees and ankle). [3], [7] Molgaard et al. reported that high-arched runners had a high probability of ankle injuries, heel pain and stress fractures. [45] These injuries may be the result of runners' high-arched feet moving with a stiffer lower extremity and higher loading rates during running. [15] Moreover, high-arched runners are found to have the lower eversion-to-tibial internal-rotation (EV:TIR) ratio than low-arched runners. A lower EV:TIR as the key in increasing the stress on the knee in high-arched runners. [46] To some degree, these arguments were inconsistent with our findings which showed that even with high arches, the sprint athletes' relative load and pain areas were at the medial metatarsal. Interestingly, however, although there was no statistically significant increase in the relative load at the lateral heel of the left foot, plantar pressure in this region in the sprint group was found to be higher than in the control group. These findings somewhat supported the previous studies which verified that high peak forces considerably increased underneath the second and third metatarsal after a fatiguing race, [33] and that the loading decreased at the medial heel [27] and at the lateral toes [36] in running. The pressure exerted on the medial side of the pronated foot were found to be the main reason for runner's heel eversion, and this may result in the anterior knee pain and tibialis anterior pain. However, the pressure exerted on the forefoot region may cause the Achilles tendonitis. [33] Runners' calcaneal valgus in the stance phase of the gait cycle makes them prone to suffer from fatigued calf muscles, such as fatigued gastrocnemius and fatigued soleus, and this may make their ankles and feet unstable. [47] On this basis, it could be argued that the sprint athletes' arch index and plantar loading characteristics were generally classified as high-arched foot, and that their PPD were categorized between

the features of the calcaneal valgus (pronated foot) of runners and the calcaneal varus (supinated foot) of high-arched runners. Notably, findings from the present research, on the one hand, corresponded to the previous studies which revealed that runners with PFPS exerted a significantly higher vertical peak force underneath the lateral heel and underneath the second and third metatarsal during running. The results from pain assessment and the self-reported health status appeared the lateral knee joint and biceps femoris were the most common musculoskeletal pains in sprint athletes. The results were also consistent with the symptoms in high-arched runners. Although many studies have stressed the link between PFPS and running, little research has been conducted for exploring the relationships between PFPS and high arches. Nevertheless, findings from this research reflected upon the possible link between high arches and PFPS. Therefore, the correlation between high-arched runners and PFPS development is worth further studies.

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