STATIC PLANTAR PRESSURES IN THE ELITE TENNIS PLAYERS

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Abstract— The aim of the study was to investigate tennis players' plantar pressure characteristics and potential pain profiles in static standing through plantar pressure measurement. Research subjects included twenty-one elite tennis players (ET), twenty-eight subelite tennis players (ST) and twenty-eight non-athletes (controls). 'JC Mat', the optical plantar pressure measurement, was applied to examining the differences among three groups in the arch index (AI), three regional and six distinct sub-regional plantar pressure distributions (PPD) from the footprints. The tennis players' pain assessment and self-reported health status were examined for evaluating their common pain areas. Findings from the control group, the AI fell into the normal range. The ET group's arch type was classified as high-arched feet. PPD at the lateral longitudinal arch and the lateral heel of both feet, and the medial metatarsal bone of the right foot were significantly higher in the ET group. In the ST group, PPD were particularly concentrated in the medial metatarsal bone and the lateral heel of both feet. PPD exerted on the lateral longitudinal arch of both feet were significantly different between the ET and ST group. The lateral ankle and knee joints, the anterior cruciate ligament and the lateral ankle ligament were the most common musculoskeletal pain areas in tennis players. We conclude that the elite tennis players' AI was generally classified as high arches, and their PPD and pain profiles were categorized between the features of supinated foot and patellofemoral pain syndrome. The correlation between the experiences in tennis training and the development of the foot supination is worth further studies.

Keywords— Elite Tennis Players, Subelite Tennis Players, Arch Index, Plantar Pressure Distributions, Supinated Foot, Patellofemoral Pain Syndrome.

I. INTRODUCTION

Tennis is a high-intensity racket sport and characterized as quick starts and stops, rapid running and pivoting, instant lunging and jumping, sideward cutting movements followed by direction changes [1, 2]. These frequent movements in a tennis competition are generally treated as one of the main causes of the specific overuse injuries [3]. Most tennis injuries are chronic and mainly because of the repetitive nature of the specific movements [4]. Lower extremity injuries which occur to tennis players are reported to be nearly equal to or even more common than upper extremity injuries and spine problems [5]. Many lower limb injuries in tennis players are similar to those observed in runners because of the repetitive nature of their movements. Therefore, the specific musculoskeletal injuries in tennis players, including their plantar fascia, gastrocnemius, tendon and ligament, and knee and ankle joints, are under greater risk than most other athletes [3, 6]. Foot is one of the most commonly injured parts of the body. Hence, the excessive pressure on the foot may result in various problems, such as metatarsal stress fracture, plantar fascitis, tennis toe, and jamming injuries to the distal interphalangeal, proximal interphalangeal and metatarsophalangeal joints [3].

Medial longitudinal arch (MLA) is an important structure of the foot and is crucial for deformation of foot shapes. When jumping and running, the MLA provides adequate elastic forces and twisting forces for absorbing the ground reaction force, and this is helpful for attenuating the shock from movements, mitigating injuries and deferring fatigue [7, 8]. Abnormality in the structure of the MLA tends to be widely accepted as the key reason for sports injuries [8]. Previous studies showed that high-arched (supinated foot) individuals exhibited more laterally located bony injuries of the foot, ankle, knee, and lower extremity stress fractures [9]. Low-arched (pronated foot) individuals, however, had a higher risk of the medially soft tissue injuries [10, 11]. Undoubtedly, many methods can be used for defining and categorizing arch structures. Despite this, the researchers seemed to share the same view, confirming the arch index (AI) gained through the footprint measures as the valid approach to characterizing the MLA height and assessing the arch dynamically [8, 11-15]. Moreover, the AI can be used for understanding the foot growth and mature in morphology through showing arch changes in children from six to seventeen years old [16].

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 [17]. The measurements of static arch height and arch height ratio of the foot may assist clinicians in estimating foot postures during dynamic activities in the patients with lower-limb injuries [18]. Importantly, in order to assess the potential for several foot-specific pathologies and lower extremity dysfunction which may increase injury risks, clinicians usually infer dynamic foot function from static MLA postures [19, 20].

Furthermore, it has been widely accepted that there is a correlation between the variations in anatomical structures of the foot and plantar pressure distributions (PPD) [11, 21, 22]. Plantar pressure assessment from the footprint can be regarded as one of the effective methods to evaluate the plantar loading characteristics during functional activities such as running [23]. The parameters can be used for understanding the variations in PPD in different regions of the foot, and assist in detecting the foot pathologies [24, 25]. High PPD is thought to be the potential factor for sports-related injuries in the lower extremity [26]. When plantar pressure in each region of the foot is distributed evenly, sports injuries could be reduced effectively [27]. A recent prospective study suggests that the static characteristics of the flatfoot, high-arched foot and rearfoot range of motion as the risk factors for developing lower extremity overuse injuries in general [28]. On this basis, the assessment of standing plantar pressure seems to be useful for exploring the relationships between PPD and lower-extremity posture [29]. The pressure distribution measurement may be significant for understanding the biomechanics of human feet in bipedal standing [29].

Although many studies have been conducted for understating people's plantar pressures during walking and running [30-34], little research examines plantar pressures in static standing. Despite the fact that the studies concerning athletes' plantar pressures highlighted the effect of the specific athletic movements on plantar loading [35, 36], they did not consider the impact of athletes' foot types on their plantar pressures. Apart from this, the studies involving tennis players' plantar pressures tended to center on the effect of tennis serve and court surfaces on players' plantar loading and their potential injuries [37-40]. These studies, however, are unable to fully reflect tennis players' original PPD in a static state in their career of training and competition.

Given the above context, the purpose of this study was to explore the differences between elite tennis players (ET), subelite tennis players (ST) and healthy non-athletes in terms of their static plantar pressure characteristics. The parameters which were examined within this study are listed below: the AI, three regional and six distinct sub-regional PPD, and footprint characteristics of both feet. Apart from this, data gained from the pain assessments and tennis players' self-reported health status within this study were used for evaluating the pain locations which occurred frequently in the body. We hypothesized that the tennis players in this study were classified into high arch type, and that their PPD were particularly concentrated in the lateral regions of midfoot and rearfoot. Moreover, the plantar pressure characteristics and pain profiles may correlate with the features of the supinated foot.

II. DETAILS EXPERIMENTAL

2.1. Subject Selection

The subjects participating in this study comprised three specific groups of college and university students in Taiwan. One of the groups, labeled as the 'elite tennis group', was composed of 21 right-handed first-division male tennis players. For the elite tennis group, the length of being the qualified first-division players was to have more than successive six-year experiences in tennis competitions. All subjects within the elite tennis group in this study were recruited from the sport university, school of kinesiology and three city sports centers in Taipei. The 'subelite tennis group' was constituted of 28 right-handed male tennis players who were the same age range (between 18 and 22 years old) as the elite tennis group. All subjects in the subelite tennis group were single-sport university athletes and participated only in team-based tennis training. They were playing tennis at least once a week at sports centers in Taipei. The control group within this study included 28 healthy age-matched male university students who 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. 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 77 subjects participated in this study, and their average age, height, weight and BMI value were shown in **Table 1**. All subjects' pain and health assessments were based on the self-reported health status and measurements which were diagnosed by the professional physiotherapist at the rehabilitation department. The pain and health assessments were essential for this research to ensure that all subjects had no history of previous fracture and surgery, and that they were free from 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 participants were informed of the purpose of the present study. Each participant was asked to read and sign the informed consent form approved by the institutional review board. 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.

2.2 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 study. 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.

2.3. Methods and Procedures

It took approximately six months to select the qualified 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 which were 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.

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

The process of the subjects' pain assessment and self-reported health status was conducted through the assistance of the professional physiotherapist at the rehabilitation department. This process functioned as the basis for the subject selection criteria, the subjects' physiological symptom assessment and confirmation of the pain location. After the plantar pressure measurement, all subjects were asked to undergo the skeleton arrangement and soft tissue pain assessment. The term 'lower limb pain' used in this study 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 standardized protocol for 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 location which occurred frequently in the subjects were presented as follows:

1. The professional physiotherapist evaluated and documented the subjects' self-reported health status and pain location 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 follows:

1. The professional physiotherapist pressed the subjects' self-reported pain location and re-checked the corresponding location on the opposite side of the pain location.
2. Based on their clinical experiences, the professional physiotherapist pressed and examined the specific points in the subjects' common pain locations, 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 subjects' common pain locations.

2.5. 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 allowed the footprint to be divided into three equal regions (region A, B and C) and six sub-regions (sub-region 1, 2, 3, 4, 5 and 6) via the following techniques: firstly, the software formed a nearly vertical line on the footprint image. The nearly vertical line extended from the tip of the second toe to the center of the heel, and was drawn tangent to the most anterior and posterior parts of the footprint excluding the toes. Secondly, the software generated a set of four parallel lines which were perpendicular to the nearly vertical line and divide the footprint into three equal parts. In this study, 'regions A, B and C' of the footprint were defined, respectively, as the 'forefoot, midfoot and rearfoot'. 'Sub-regions 1, 2, 3, 4, 5 and 6' were defined, respectively, as the 'lateral metatarsal bone (L.M.), lateral longitudinal arch (L.LA.), lateral heel (L.H.), medial metatarsal bone (M.M.), medial longitudinal arch (M.LA.) 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.

2.6. Statistical Analysis

Descriptive statistics used for this study was to summarize all subjects' ages, heights, weights, BMI values and experience. Numerical data gained in the research process was presented as mean ± SD. One-way ANOVA was used for distinguishing the differences among three groups in terms of their arch index, three regional and six sub-regional plantar pressure distributions. Post-ANOVA, associated with t-test and Scheffe correction, was used for dealing with the between-group comparisons. All statistics were calculated with the Statistical Package for the Social Sciences for Windows (Version 17.0; SPSS Inc., Chicago, IL). Statistical significance were defined as $P < 0.05$ (marked as *) and $P < 0.01$ (marked as **) between the elite tennis players (ET) and control group, $P < 0.05$ (marked as †) and $P < 0.01$ (marked as ††) between the subelite tennis players (ST) and control group, and $P < 0.05$ (marked as #) and $P < 0.01$ (marked as ##) between the ET and ST groups.

Table 1. Demographic characteristics and training experience in elite tennis (ET), subelite tennis (ST) players, and controls.

Demographics	Control	ET	ST
Numbers	28	21	28
Age (years)	19.1 ± 0.7	20.0 ± 2.1	19.5 ± 1.1
Height (cm)	170.2 ± 8.4	171.5 ± 8.3	169.1 ±
Mass (kg)	66.2 ± 6.4	63.1 ± 6.4	66.5 ± 7.0
BMI	22.8 ± 0.7	21.4 ± 1.4	23.2 ± 0.7
Experience (years)	---	9.3 ± 2.9	3.3 ± 1.1

Data are represented as mean ± SD. The control group: male university students who had neither specialties in sports nor regular time for exercise (the average time for exercise weekly was less than 2 days or 6 hours). The elite tennis group: right-handed first-division male tennis players. The subelite tennis group: single-sport university athletes and participated only in team-based tennis training (playing tennis at least once a week).

Table 2. Pain assessment and self-reported health status in the tennis players

Pain areas	ET(*n*=21)	Proporti	ST(*n*=28)	Proporti
Bone				
Lateral ankle joint	15/21	71.4%	15/28	53.6%
Lateral knee joint	13/21	61.9%	12/28	42.9%
Patella	10/21	47.6%	12/28	42.9%
Femur	9/21	42.9%	13/28	46.4%
Metatarsal heads (1st~3rd)	6/21	28.6%	6/28	21.4%
Tibia	6/21	28.6%	5/28	17.9%
Calcaneus	4/21	19.0%	2/28	7.1%
Soft tissue				
Anterior cruciate ligament	15/21	71.4%	12/28	42.9%
Lateral ankle ligament	14/21	66.6%	10/28	35.7%
Quadriceps femoris ligament	10/21	47.6%	10/28	35.7%
Biceps femoris	8/21	38.1%	9/28	32.1%
Gastrocnemius	8/21	38.1%	7/28	25%
Achilles tendon	5/21	23.8%	7/28	25%

Pain assessment and self-reported health status of the elite tennis players (ET) and subelite tennis players (ST) was conducted though the assistance of the professional physiotherapist at the rehabilitation department.

III. RESULTS AND DISCUSSION

3.1. Arch Index

The arch indices of both feet in the control group were 0.21. Yet, the arch indices of both feet in the elite tennis players were significantly smaller than those in the subelite tennis players and control group ($p < .05$), respectively. The results suggested that the arch type was higher in the elite tennis players among three groups.

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

The plantar pressure distributions in the forefoot, midfoot and rearfoot regions of both feet were found to have no significant difference among the ET, ST and control groups. The results suggested that three regional plantar pressures were similar in three groups.

3.3. Plantar Pressure Distributions at the Six Distinct Sub-Regions

The calculation of plantar pressure at the six distinct sub-regions was based on the data gained from the forefoot, midfoot and rearfoot. In the forefoot region, the plantar pressures at the lateral metatarsal bone of both feet were significantly lower in the ET (left: 22.77 ± 4.25%, right: 22.84 ± 4.20%) and ST (left: 23.15 ± 3.74%, right: 24.88 ± 3.32%) groups than in the control group (left: 29.22 ± 3.93%, right: 30.88 ± 3.67%) ($p < .01$). Yet, the plantar pressures at the medial metatarsal bone of both feet were higher in the ST (left: 20.95 ± 5.66%, right: 20.34 ± 4.24%) group and the right foot in the ET (20.75± 5.32%) group than in the control group (left: 17.85 ± 3.45%, right: 17.36 ± 2.85%) ($p < .05$). In the midfoot region, the plantar pressures at the lateral longitudinal arch of both feet were significantly higher in the ET (left: 22.55 ± 3.41%, right: 22.46 ± 4.84%) group than in the control group (left: 19.29 ± 3.56%, right: 18.46 ± 2.68%) ($p < .01$). In the rearfoot region, the plantar pressures at the lateral heel of both feet were higher in the ET (left: 24.92 ± 3.39%, right: 24.88 ± 5.54%) and ST (left: 23.98 ± 3.65%, right: 24.26 ± 4.12%) groups compared with the control group (left: 21.47 ± 2.89%, right: 21.46 ± 2.21%) ($p < .05$). Compared with the ST group, the ET group's plantar pressures were higher at the lateral longitudinal arch of both feet, but lower at the medial heel of both feet. The findings showed that the ET group's plantar pressures were higher at the medial metatarsal bone of the right foot, the lateral longitudinal arch and the lateral heel of both feet. Moreover, the ST group's plantar pressures were higher at the medial metatarsal bone and the lateral heel of both feet (**Fig. 1 and 2**).

3.4. Footprint Characteristics

Based on the findings presented in **Fig. 3**, the ET group's footprints displayed the pressure profiles and their plantar pressures tended to be concentrated in the lateral regions of the midfoot and rearfoot of both feet. In addition, the pressure profiles from the ST group's footprints seemed to be particularly located in the medial region of the forefoot and the lateral region of the rearfoot.

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

As can be seen in **Table 2** which illustrates the findings from the pain assessment and the self-reported health status of the ET and ST groups, the seven most common pain locations in bones are presented as follows: the lateral ankle joint (71.4-53.6%), the lateral knee joint (61.9-42.9%), the patella (47.6-42.9%), the femur (46.4-42.9%), the first to the third metatarsal heads (28.6-21.4%), the tibia (28.6-17.9%) and the calcaneus (19.0-7.1%). The six most common pain locations in soft tissues are listed below: the anterior cruciate ligament (71.4-42.9%), the lateral ankle ligament (66.7-35.7%), the quadriceps femoris (47.6-35.7%), the biceps femoris (38.1-32.1%), the gastrocnemius (38.1-25.0%) and the Achilles tendon (25.0-23.8%).

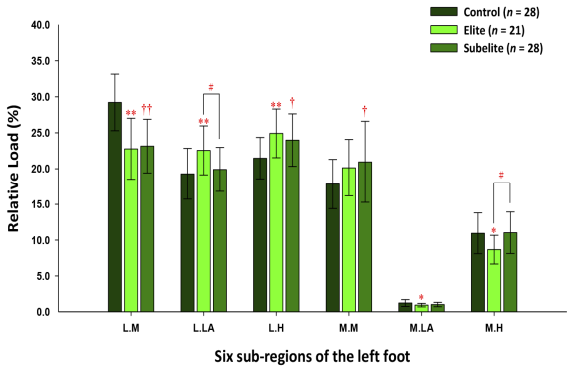


Fig.1. Plantar pressure distributions of six sub-regions of the left foot in static standing. Data are expressed as mean ± SD. *$P < 0.05$, **$P < 0.01$, significant differences between the ET and control group. †$P < 0.05$, ††$P < 0.01$, significant differences between the ST and control group. $^{\#}P < 0.05$, $^{\#\#}P < 0.01$, significant differences between ET and ST group.

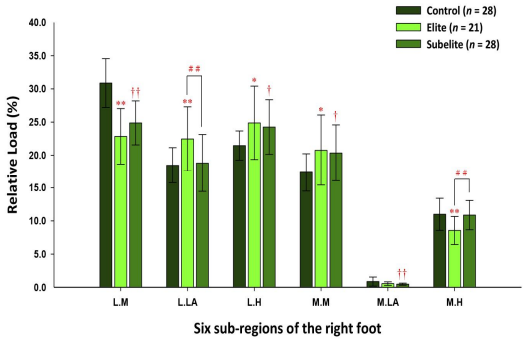


Fig.2. Plantar pressure distributions of six sub-regions of the right foot in static standing. Data are expressed as mean ± SD. *$P < 0.05$, **$P < 0.01$, significant differences between the ET and control group. †$P < 0.05$, ††$P < 0.01$, significant differences between the ST and control group. $^{\#}P < 0.05$, $^{\#\#}P < 0.01$, significant differences between ET and ST group.

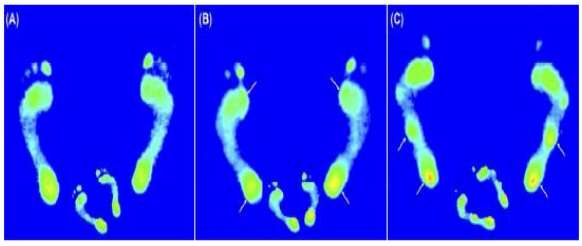


Fig.3. Footprints of both feet among the (A) control group, (B) subelite tennis group and (C) elite tennis group. White arrows indicate the higher pressure profiles.

CONCLUSIONS

On this basis, it could be argued that the elite tennis players' arch index was generally classified as the high-arched foot, and that their plantar pressure characteristics were categorized as the supinated foot. Nevertheless, findings from the present study showed that both groups of tennis players' pressure profiles somewhat corresponded to 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. Pain assessment and the self-reported health status confirmed that the most common musculoskeletal pains in tennis players tended to coincide with the symptoms of foot supination and PFPS. Notably, plantar pressures exerted on the lateral longitudinal arch of the foot appeared to be crucial for the difference between the elite and subelite tennis players. Therefore, findings from this research confirmed the link between tennis players and PFPS. The correlation between the experiences in tennis training and the development of the foot supination is worth further studies.

ACKNOWLEDGMENTS

We sincerely appreciate St. John's University for supporting this study with the research funding and equipment. We also gratefully acknowledge the funding from the Ministry of Science and Technology, Taipei, Taiwan under Grant MOST 104-2622-H-129-001-CC3.

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