

## Measurements of Foot Arch in Standing, Level Walking, Vertical Jump and Sprint Start

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### Abstract

Foot arch is important for force transfer and shock absorption in impact sports. The purposes of this study were to measure the height of foot arch in static standing and dynamic activities, and to compare the difference of foot arch between level walking, vertical jump and sprint start. Twenty-three healthy subjects were recruited in this study. Significant differences between non-weight bearing condition and standing were found on arch height, arch angle and arch index. Arch height was gradually decreased in loading phase but suddenly increased in push-off phase during level walking, vertical jump and sprint start. Vertical jump and sprint start required significantly greater ranges of arch height change than level walking. The information obtained from this study enhanced our understanding of the changes of the human foot arch in static standing and dynamic athletic activities. The findings of this study can be interpreted in the fields of orthopedics and sports footwear design.

**Keywords:** Medial longitudinal arch, Arch height, Arch angle, Arch index

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### Introduction

The foot is one of the most important interaction parts of the body with the ground in upright posture. The structure of the foot is critical to affect the load absorbed by the bones in the foot and the force transferred to proximal components of lower extremity when performing exercise with weight bearing on foot [1]. Medial longitudinal arch is the largest arch of the foot and the most important arch of the foot from a clinical point of view. The bony shape, the ligaments of the foot, and the muscular tones all play an important role in supporting the arches [2].

Based on the structure of the medial longitudinal arch, three types of the foot have been proposed: (1) normally aligned or normal foot, (2) low arched or pronated foot, or pes planus, and (3) high arched or supinated foot, or pes cavus [1, 3]. Normally aligned foot is defined as the foot in which the bisection of the posterior surface of the calcaneus is perpendicular to the ground and its arch height is within normal range. Pronated foot is defined as the foot in which the calcaneus is everted and its arch is low or absent. Supinated foot is defined as the foot in which the calcaneus is inverted and its arch is high. The supinated foot is more rigid with limited shock absorption ability, prone to higher stress underneath the heel and more force passing to the tibia and

femur. The pronated foot, with a greater ground contact area, is more flexible, leading to the load to be absorbed by the musculoskeletal structures of the foot. A higher plantar pressure on midfoot was observed for the people with pronated foot during walking [4]. The arch structure might be associated with different injury patterns. Williams et al. [5] reported that high-arched runners exhibited more bony, ankle and lateral injuries but low-arched runners revealed a higher risk of soft tissue, knee and medial injuries.

Several methods have been used to define and categorize arch structure. Visual observation has been proved to be unreliable [6]. Footprint measures could not describe the bony characteristics properly. However, they could be used to assess the arch dynamically [2] and have been used to provide the arch change in children from six to seventeen years old to understand the foot growth and mature in morphology [7]. Williams and McClay [8] indicated that most reliable and valid measurements of the foot arch may be the arch index, obtained by dividing dorsum height by truncated foot length, which could be measured by rulers or calipers. Another method to evaluate the arch was a specific designed mirrored foot photo box, which has been tested for the reliability and reproducibility of foot type measurements [9]. Foot arch measurements with these techniques proposed in previous studies were most in static standing.

Deformation of foot arch is crucial for force transfer and shock absorption, especially in impact sports, such as jump or sprint. There is also a specific association between arch type and sports injury. Measuring the change of foot arch during sport activities would be helpful to more understand the

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possible mechanism of sport injury. However, most of these techniques reported in literatures for measuring foot arch were limited to static standing condition and is not easy or allowed to measure arch height change during dynamic sport activities. Three-dimensional motion analysis with surface reflective marker placements has been widely used to estimate the joint motions in sports [10]. Therefore, the purposes of this study were to measure the foot arch changes in standing and dynamic sport activities with motion analysis system, and to compare the biomechanical differences of the foot arch between level walking, vertical jumping and sprint start.

### Methods

Twenty-three healthy subjects (17 males and 6 females) were recruited in this study. They had an average age of  $20.3 \pm 1.03$  years, average body height of  $169.4 \pm 6.5$  cm, and average body weight of  $61.5 \pm 7.8$  kg. All subjects volunteers from the university population and the surrounding communities. No subject had any neuromusculoskeletal deficit in lower extremity and trunk. Each subject's foot was screened by a certificated athletic trainer to exclude anyone with pes planus or pes cavus. Surface reflective markers were placed on navicular tuberosity, heel and the first metatarsal head on the left foot for each subject. Vicon motion analysis system (Oxford Metrics Limited., UK) with six high speed cameras was used to record the trajectories of the reflective surface markers. The sampling rate was 250 Hz. During the recording process, one AMTI force platform was simultaneously used to collect the ground reaction force data with a sampling rate of 1000 Hz. This experimental protocol has been approved by the ethical committee of National Taiwan College of Physical Education. Before data collection, the experimental procedure was clearly explained and the informed consent was signed for each subject.

Two static foot positions were measured in this study, non-weight bearing condition and static standing with the body weight even distributed on both feet. Three dynamic movements, level walking, vertical jump and sprint start, were tested in this study. Level walking was performed barefoot in the walkway with a self-selected speed while left foot stepping on force platform. During vertical jump with countermovement, the subjects were instructed to keep their hands across the chest and to jump as high as possible and the left foot was on force platform. During sprint start, the subjects were asked to run as fast as possible from a static preparing posture while left foot was the trailing foot on the force platform. Before data collection, each subject was instructed to perform three to five practice trials to be familiarized with these testing movements. Once the subject was comfortable with the tasks, five repetitions were measured for each testing condition and the average values were calculated. The testing order was random for each subject to maximally eliminate the possible sequential effect of data collection.

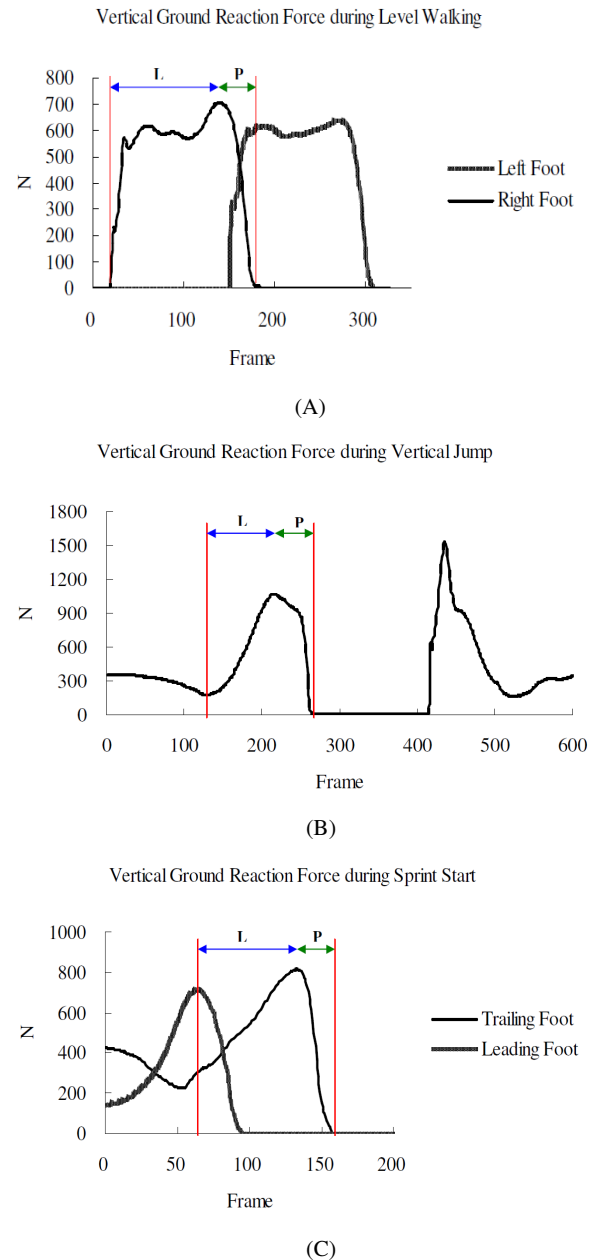


Figure 1: Loading phase (L) and push-off phase (P) during level walking (A), vertical jump (B) and sprint start (C).

Data in stance phase of level walking was analyzed. Data of the vertical jump and sprint start were analyzed in the acceleration phase which was defined as the duration from the vertical ground reaction force started to be increased to toe off. These three testing movements were divided into two phases, loading phase and push-off phase (Fig 1) and the data were normalized as 100% of a cycle. Vertical ground reaction force and three arch parameters, arch height, arch angle and arch index, were analyzed in this study. The navicular bone is the keystone of the medial longitudinal arch [11]. Arch height was then defined as the perpendicular distance from navicular tuberosity to the line connected between the heel and the first metatarsal head, representing the truncated foot length [12].

Arch angle was defined as the angle between the line of heel-navicular tuberosity and the line of the first metatarsal head-navicular tuberosity [13]. Arch index was defined as the ratio of navicular height to the truncated foot length [8]. Vertical ground reaction force was represented as a percentage of body weight for each subject.

A paired-t test was performed to compare the differences for each parameter between static standing & non-weight bearing condition. One-way ANOVA with repeated measurements was performed to analyze the differences between level walking, vertical jump and sprint start. P-value less than 0.05 was considered statistically significant. All statistical analyses were performed with SPSS software (V13.0, Chicago, IL, USA). Data are presented as mean  $\pm$  standard deviation.

### Results

Significant differences between non-weight bearing and static standing conditions were found on arch height, arch angle and arch index (Table 1,  $p < 0.05$ ). The changes from non-weight bearing to standing in arch height, arch angle and arch index were 23% of reduction, 6% of increase and 20% of

reduction, respectively, indicating the body weight substantially deforms the structure of foot arch. The decreased arch height may partly absorb the transitional impact in lower extremity when transferring from non-weight bearing to weight bearing conditions.

The vertical ground reaction forces during level walking, vertical jump and sprint start were shown in Fig 2. There were double peaks on vertical ground reaction force during level walking while only one peak force occurred in vertical jump and sprint start. The peak vertical ground forces were 109%, 131% and 133% of body weight during level walking, vertical jump and sprint start, respectively. Peak force in level walking was significantly less than the vertical jump and sprint start ( $p < 0.05$ ). For timing difference, significant differences of vertical ground reaction force between these three movements were found in 0% – 32% and 38% – 100% of the cycle. Various ground reaction force patterns indicate distinct center of mass positions used with specific motor strategy to get optimum push-off force and superior performance in different activities.

Table 1: Arch height, angle and index in static conditions (nonWB = non-weight bearing; Ratio = Standing / NonWB)

	Height* (mm)	Angle* (°)	Arch Index*	Navicular Drop (mm)
NonWB	32.0 $\pm$ 4.2	144.1 $\pm$ 6.2	0.16 $\pm$ 0.03	7.38 $\pm$ 3.04
Standing	24.7 $\pm$ 3.8	151.9 $\pm$ 4.2	0.12 $\pm$ 0.02	—
Ratio	0.77 $\pm$ 0.09	1.06 $\pm$ 0.04	0.80 $\pm$ 0.24	—

\* $p < 0.05$ , paired t test.

Table 2: Range of arch height, arch angle, arch index and vertical ground reaction force during level walking, vertical jump and sprint start.

	Height* (mm)	Angle* (°)	Arch Index*	Force* (%BW)
Walk	7.63 $\pm$ 2.65	9.81 $\pm$ 3.39	0.046 $\pm$ 0.016	111 $\pm$ 5
Jump	12.23 $\pm$ 2.97	14.74 $\pm$ 3.59	0.070 $\pm$ 0.017	133 $\pm$ 19
Start	12.41 $\pm$ 3.04	15.15 $\pm$ 4.08	0.072 $\pm$ 0.018	135 $\pm$ 21

\* $p < 0.05$ , ANOVA with repeated measures.

The arch heights during level walking, vertical jump and sprint start were shown in Fig 3. Arch height was almost no change or minimally decreased in loading phase while the vertical ground reaction force was substantially increased. However, arch height was suddenly increased in push-off phase while the vertical ground reaction force was quickly decreased until the toe off. The timing differences on arch height curve were found in 0% – 50% and 86% – 100% of the cycle ( $p < 0.05$ ). Level walking had significantly greater arch height than vertical jump and sprint start in 0% – 50% of the cycle. Sprint start had significantly greater arch height than vertical jump in 86% – 100% of the cycle, the push off phase.

The arch angles during level walking, vertical jump and sprint start were shown in Fig 4. Arch angle was almost no change or minimally increased in loading phase and suddenly decreased in push-off phase. Arch angle pattern was almost opposite to the arch height pattern. Greater arch angle would lead to lesser arch height. The timing with significances on

arch angle were found in 0% – 45% and 84% – 100% of the cycle ( $p < 0.05$ ). Vertical jump and sprint start had significantly greater arch angle than level walking in 0% – 45% of the cycle. Vertical jump had significantly greater arch angle than sprint start in 84% – 100% of the cycle.

Arch index during level walking, vertical jump and sprint start were shown in Fig 5. Arch index, derived from the arch height divided by the truncated foot length, had the similar curve with arch height, showing almost no change or minimally decreased in loading phase and suddenly increased in push-off phase. The significant timing on arch index were found in 0% – 46% and 84% – 100% of the cycle ( $p < 0.05$ ). The pattern of arch index was very close to arch height's.

Arch heights at toe off were 30.4 $\pm$ 4.1, 33.7 $\pm$ 3.3, and 34.0 $\pm$ 3.9 mm during level walking, vertical jump and sprint start, respectively. Vertical jump and sprint start showed significantly greater arch heights at toe off than level walking ( $p < 0.05$ ). Arch angles at toe off were 143.8 $\pm$ 4.4, 140.3 $\pm$ 3.7, and

139.5±4.3 degrees during level walking, vertical jump and sprint start, respectively. Vertical jump and sprint start showed significantly lesser arch angles at toe off than level walking ( $p<.05$ ). Arch indices at toe off were  $0.16\pm0.02$ ,  $0.18\pm0.02$ , and  $0.18\pm0.02$  during level walking, vertical jump and sprint start, respectively. Vertical jump and sprint start showed greater arch indices at toe off than level walking ( $p<.05$ ).

Ranges of arch parameters were defined as the maximum value subtracted by minimum value during whole movement cycle. Sprint start had the greatest range of arch height (12.41 mm) compared to level walking (7.63 mm), which was only approximately 60% of the range needed in sprint start (Table 2,  $p<.05$ ). Greater arch height change might be beneficial to provide a greater spring effect on foot to generate a more powerful push off force and a faster starting speed in sprint.

**Discussion**

Abnormality in structure of the medial longitudinal arch of the foot is commonly considered to be a predisposing factor to sports injury. Foot arch measurements were widely used for the reasons of orthotic prescription and to assist in finding out

possible risk factors or causes of sport-related injuries [14]. This study provided the dynamic data of arch height, arch angle and arch index in level walking and two common sports activities, vertical jump and sprint start. Powerful muscle strength in lower extremity is usually considered to be required for excellent performances in vertical jump or sprint start, and foot arch would then be functionally changed for compensation. Understanding the needed ranges of arch height in walking and sports activities would be valuable to assist in the fields of orthopedics and sports industry. The information would be beneficial in preventive therapy with suggestion for orthotics and ergonomic uses for sport footwear production.

There have been several researches to evaluate foot arch heights with different techniques, such as lateral foot radiology [15-17], calipers [8], footprint [18], masked millimeter scale [19], photography [20] and ruler [21] in different groups of people (Table 3 [8, 15-22]). Their ranges for the navicular height were from 30.2 mm to 43.2 mm in even standing. With the use of surface reflective markers on foot, the arch height estimated in our study was calculated by the perpendicular distance from navicular tuberosity to the baseline connected

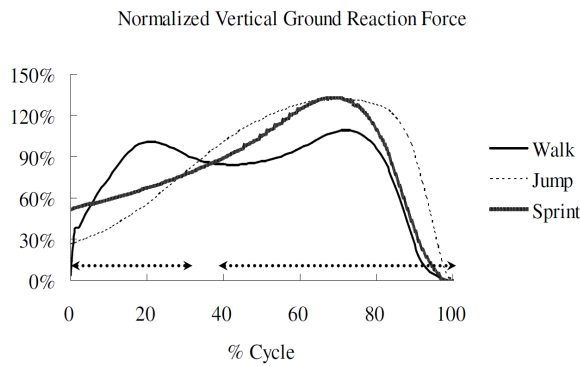


Figure 2: Vertical ground reaction forces during level walking, vertical jump and sprint start (dash line: significant difference,  $p<.05$ , ANOVA).

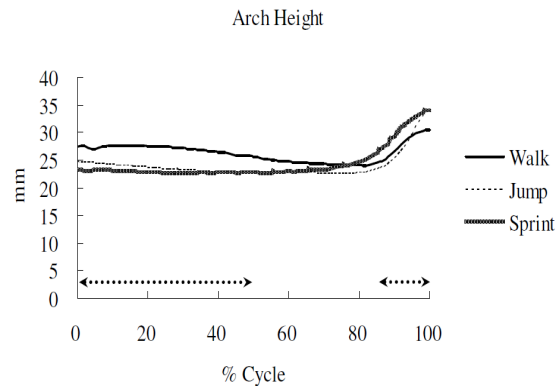


Figure 3: Arch heights during level walking, vertical jump and sprint start (dash line: significant difference,  $p<.05$ , ANOVA).

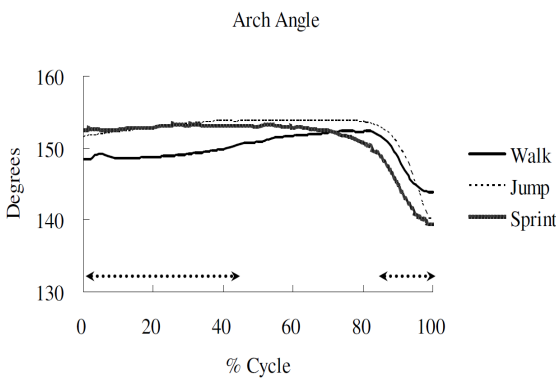


Figure 4: Arch angles during level walking, vertical jump and sprint start (dash line: significant difference,  $p<.05$ , ANOVA).

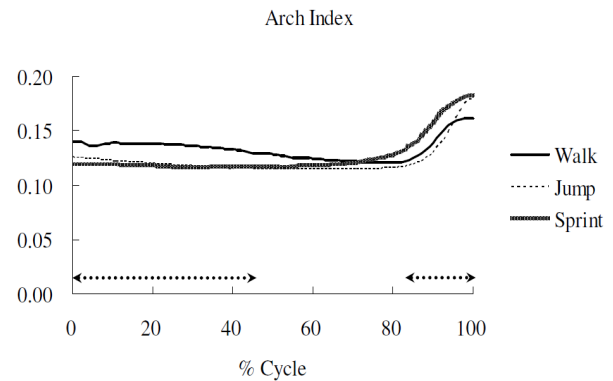


Figure 5: Arch index during level walking, vertical jump and sprint start (dash line: significant difference,  $p<.05$ , ANOVA).

Table 3: Arch heights reported in literatures (M: male; F: female)

Research	Subjects	Age (years)	Testing condition	Method	Navicular height (mm)
Cowan [20]	189 arm trainees	20.3 (range, 17-35)	One-leg standing	Photography	46±6.1
Saltzman [15]	100 orthopedic patients with wide range of diagnoses (31 M; 69 F)	46±16	Standing	Lateral foot radiology	33.1±9.4
Chu [18]	51 subjects (102 feet) (37 M, 14 F)	23.4 (M); 22.9 (F)	Standing	Calipers	37.3±5.9
McPoil [19]	27 subjects (9 M, 18 F)	26.1±4.8	Standing	Masked millimeter scale	43.2±7.1 (relaxed); 49.4±5.2 (neutral subtalar)
Cavanagh [17]	50 subjects	63.1±13.1	Standing	Radiology	40.2±8.2
Williams [8]	51 subjects (102 feet) (23 M, 28 F)	27.1±6.1	10% weight bearing	Calipers mounted to Plexiglas plate	39.7±5.6
Williams [8]	51 subjects (102 feet) (23 M, 28 F)	27.1±6.1	90% weight bearing	Calipers mounted to Plexiglas plate	34.6 ±5.6
Rossi [22]	8 subjects with navicular drop > 10 mm (3 M, 5 F)	18-26	N/A	N/A	34 – 36
Menz [16]	216 people (76 M, 140 F) with plantar calcaneal spur	75.9±6.6 (range, 62-94)	Standing	Lateral foot radiology	30.2±5.2 (spur absent), 30.9±6.3 (spur present)
Bandholm [21]	15 medial tibial stress syndrome (MTSS) (6 M, 9 F), 15 healthy (6 M, 9 F)	20-32	Unload; full load	Ruler (1 mm resolution)	MTSS: 49.8±4.6 (unload), 42.8±5.8 (load); Healthy: 50.0±6.6 (unload), 45.0±8.0 (load)
This study	23 subjects (17 M, 6 F)	20.3±1.03	Unload; standing	Surface markers	42.0 (unload); 34.7 (standing)

between the heel and the first metatarsal head. The diameter of surface maker was 20 mm. Then a 10-mm offset distance from the ground to the baseline would be made. The arch height in our study was 32.0 mm in non-weight bearing condition and 24.7 mm in standing. With the adding up the 10-mm offset distance, the modified arch height in our study were 42.0 mm in non-weight bearing condition and 34.7 mm in standing, which was very close to the navicular heights measured by the methods of radiology and calipers (Table 3).

In addition to arch height, there were several researches measuring the navicular drop, the difference between weight bearing and non-weight bearing conditions. The range of the navicular drop reported in literatures was from 5.3 mm to 7.4 mm (Table 4 [21, 23-25]). The navicular drop measured in our study was 7.38±3.04 mm, indicating a good agreement with the previous researches in literatures.

Level walking is one of the most important activities of

daily living, in which partial weight bearing occurs in push-off phase (double support in gait). Maintaining rhythmic steps and stable center of mass trajectory is the prerequisite for level walking. On the other hand, double-leg stance occurs in push-off phase of vertical jump and single-leg stance in trailing leg occurs in sprint start. To reach optimum sports performance, producing a higher vertical speed in vertical jump or a faster forward speed in sprint start is essential. Since foot arch is crucial for shock absorption during athletic impact motion, the changes of foot arch in vertical jump and sprint start were revealed in this study and their changes of foot arch were substantially greater than level walking. Most significant differences between level walking and these two sport movements were found at the initial load phase (0-50%) and final push-off phase (85-100%). This would present a quantitative assessment of foot motion in sports and provide new insight into the foot kinematics in athletic training.

Table 4: Navicular drop reported in literatures (M: male; F: female)

Research	Subjects	Age (years)	Testing condition	Method	Navicular drop (mm)
Nygaard [23]	47 college female athletes	N/A	Single limb standing	Digital caliper	8.94±0.08% (incontinent) 13.7±0.09% (continent)
Fiolkowski [24]	10 subjects (9 M, 1 F)	28±6.8 (21 – 35)	Standing; unload	Ruler	6±2 (normal) 9±3 (anesthesia of tibial nerve)
Nakhaee [25]	30 professional runners (30 healthy, 17 injured)	21.33	Standing; unload	Cardboard card	5.3±2 (healthy); 7.4±2.5 (injured)
Bandholm [21]	15 medial tibial stress syndrome (MTSS) (6 M, 9 F), 15 healthy (6 M, 9 F)	20-32	Standing; unload	Ruler (1 mm resolution)	MTSS: 7.7±3.1; 5.0±2.2 (healthy)
This study	23 subjects (17 M, 6 F)	20.3±1.03	Standing; unload	Surface markers	7.38±3.04

Leardini et al. [13] used surface markers on foot to record foot segments during the stance phase of gait as well as the medial longitudinal arch. Trajectories of the markers were collected by a motion analysis system. The angle of medial longitudinal arch was determined by three markers on first metatarsal head on dorsal aspect of the first metatarso-phalangeal joint, heel, and apex of sustentaculum tali. Foot arch angle was found as 60 degrees at toe off in Leardini's study. Yet 144 degrees of foot arch was found in our study. Arch angle difference between these two studies might be due to one marker attachment was different. They used apex of sustentaculum tali as keystone of foot arch but the navicular tuberosity was used in our study. Bandholm et al. [21] used reflective markers and Vicon motion analysis system, and measured the foot arch angle during stance phase of gait. They found 152 degrees of arch angle at heel strike and 159 degrees at toe off. Based on our findings of arch angle, 148 degrees at heel strike and 144 degrees at toe off were found. The little distinction between Bandholm's and our studies was because different marker location at heel was used. Marker was attached on medial heel in Bandholm's study but on posterior heel in our study. The various definitions of arch angle in different studies might lead to a more than 10-degree difference for arch angle estimation.

The patterns of arch height and arch angle in gait were investigated by Cashmere et al. [12]. They found arch height during stance phase of gait was a little decreased after heel strike, immediately increased at foot flat, and then gradually reduced in mid-stance phase. In push off phase, a sudden increase of arch height occurred until toe off. They also noted that the pattern of arch angle curve was just opposite to arch height's curve. These findings from Cashmere's study were in good agreement with our findings. Both studies had similar observation of arch angle in stance phase of gait. In addition to investigating the arch change during level walking, however, there were very little literatures exploring the arch height or arch angle change in other dynamic activities or sports. Considering the grand variation at foot complex and specific footwear requirements in different sports, measuring arch height or arch angle in different sports would be beneficial on prevention of sports injury, modification of the sports footwear and finally on enhancement of sports performance.

### Conclusion

With the use of motion analysis system, this study measured the arch height, arch angle, arch index and vertical ground reaction forces with surface reflective markers during static standing, level walking, vertical jump and sprint start. Our arch height data in standing were quite consistent with previous researches. The patterns and range in arch heights during level walking and two sports activities were also found in this study. The information obtained from this study enhanced our understanding of the dynamic change of the human foot arch not only in static standing but also dynamic athletic activities. The findings of this study can be interpreted in the fields of orthopedics and sports industry. The implication may enable to

come up with recommendations for the orthopedic practice and ergonomic use in the footwear production.

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