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Influence of gender, limb dominance, training experience, and loading conditions on arch characteristics in badminton players

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Foot arch structure is critical in athletic performance, load absorption, and injury prevention, particularly in high-intensity sports such as badminton. However, little is known about how gender, limb dominance, and training experience influence foot arch function under different loading conditions. This cross-sectional study aimed to investigate the effects of gender, limb dominance, training experience, and varying loads on Arch Height Index (AHI), Arch Stiffness Index (ASI), and Arch Height Flexibility (AHF) in university-level badminton players. A total of 50 players (35 males, 15 females) were assessed using the AHI Measurement System under five loading conditions (10% body weight seated, 20 kg, 40 kg, 50% body weight standing, 90% body weight single-leg stance). Arch height, arch stiffness, and arch height flexibility were calculated to evaluate static and dynamic arch characteristics. Results indicated significant reductions in arch height, arch stiffness, and arch height flexibility with increasing load. Female players exhibited significantly lower arch height than males across all loads, and training experience was associated with increased arch height and arch stiffness, especially in females. No consistent differences were observed based on limb dominance. These findings highlight the importance of considering gender and training experience in functional foot assessments and the design of sport-specific footwear. Further research is warranted to examine long-term adaptations of the foot arch in response to athletic training and its implications for performance and injury prevention.

Keywords Badminton, Arch height index, Arch stiffness index, Arch height flexibility, Foot

Badminton is one of the most popular racket sports, attracting millions of participants around the globe[1]. As one of the fastest non-contact racket sports, badminton demands multi-joint coordination of the upper limbs, trunk, and lower limbs, as well as rapid bursts of body movement and high-intensity power output capabilities[2,3]. Given its high-intensity and intermittent nature, individuals engaging in long-term badminton training often exhibit higher overall levels of health and reduced proportions of health issues[4]. However, during badminton competitions, players frequently engage in repetitive strenuous movements, such as rapid acceleration, turning, sidestepping, cross-overstepping, lunging, jumping, high clears, and smashes. These frequent and strenuous movements may increase the risk of lower limb injuries[5–8].

In badminton, the foot is a crucial interface to bear loads. The human foot, with 26 bones, forms a complex structure and represents one of the most important functional parts of the body[9]. The bones, muscles, ligaments, and tendons of the foot play a pivotal role in maintaining the overall shape and posture under static or dynamic conditions, thereby ensuring optimal foot and ankle function[10]. The foot comprises the medial, lateral, and transverse arches, formed by multiple bones, ligaments, and muscles. The foot arch serves to cushion ground

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reaction forces, absorbing impact energy, transmitting propulsive forces to the ground, and recycling stored elastic energy[11,12]. Furthermore, the arch protects the joints and soft tissues of the foot and lower limbs while providing multi-segment stability and adaptability to different sporting surfaces and functional demands[13,14]. Considering the previous evidence that the arch morphology and function could be evaluated through variations in arch height, stiffness, and flexibility[15–22], the assessment of the arch's profile in badminton players is crucial for understanding the mechanism of athletic performance and sports injuries.

Arch height could be measured using the Arch Height Index (AHI), previously developed by Williams and McClay[23]. This index is defined as the ratio of the dorsal height of the foot to the length of the foot's dorsum, providing a quantifiable measure of arch height. A higher value reflects a higher arch, while a lower value indicates a flatter arch[24]. Arch height has been widely utilized to differentiate normal arches, flat feet (pes planus), and high arches (pes cavus)[24]. Arch height has been used further to define other indices of arch function. The stiffness of the arch could be quantified using the Arch Stiffness Index (ASI), introduced by Richards et al.[25], which is calculated as the ratio of arch height under weight-bearing conditions to that under non-weight-bearing conditions. A higher stiffness index suggests a more rigid arch with less deformation under load, whereas a lower index indicates greater deformability. Foot arch flexibility could be assessed using Arch Height Flexibility (AHF), developed by Rajshree Mootanah et al.[19], which represents the change in arch height from a sitting to a relaxed standing position. This flexibility metric reflects how much the arch deforms under loading, offering insights into the arch's dynamic response and plasticity.

Previous studies have demonstrated significant associations between foot arch characteristics—namely, arch height, stiffness, and flexibility—and individual factors such as gender, age, body weight, and external loading conditions[15,18,26,27]. Kubo et al. found that arch height decreased with increasing load conditions. Across all loading conditions, female participants have significantly lower arch height values than male participants[27]. Moreover, across varying load conditions, female participants consistently exhibited lower arch height values than their male counterparts, indicating a potential gender-related morphological difference in arch structure. In a study involving 120 university-aged females (18–25 years), Weimar et al. found that participants with longer, wider, and heavier feet tended to demonstrate lower arch heights, further supporting the influence of anthropometric variables on foot morphology[28].

Similarly, Zhao et al. employed a three-dimensional laser scanner to evaluate arch height and stiffness in 173 individuals. Their findings confirmed that females generally had lower arch heights than males; however, no significant gender differences were detected in terms of arch stiffness[18]. Notably, their study also revealed that while arch height remained relatively stable across different age groups, arch stiffness exhibited an increasing trend with age, possibly due to structural adaptations in ligamentous and fascial tissues. Additionally, BMI was found to significantly influence arch height—individuals with higher BMI values tended to have lower arches—yet no corresponding impact was observed on arch stiffness. From a functional perspective, Takabayashi et al. proposed that arch height flexibility (AHF) could serve as a clinically useful measure for evaluating plantar fascia tension during dynamic activities such as running[22]. Their findings emphasized that AHF captures the arch's deformation response to physiological loads more accurately than static metrics like arch height alone.

However, few studies have addressed how arch morphology and function respond to varied loading intensities in badminton players, especially when factoring in sport-specific attributes such as training experience and limb dominance. This gap in knowledge limits the generalizability of existing findings to high-performance athletic populations. Biomechanical investigations in badminton have primarily centered on plantar pressure distributions, fatigue mechanisms, and footwear-related factors[7,29–33]. However, there remains a gap in the literature regarding the influence of sport-specific variables—particularly gender, limb dominance, and training experience—on arch function across varied load conditions. Most previous studies have only evaluated one or two loading scenarios, limiting the ability to assess the foot arch's dynamic adaptability and functional integrity in athletic contexts. To address this gap, the current study systematically evaluated arch heigh, arch stiffness, and arch height flexibility in university-level badminton players under five distinct loading conditions: 10% body weight (seated), 20 kg and 40 kg (seated with external weights), 50% body weight (bipedal stance), and 90% body weight (single-leg stance). Arch metrics were measured bilaterally on dominant and non-dominant limbs in male and female players with varying training experience.

The objective of this study was to comprehensively evaluate the combined effects of gender, limb dominance, and training experience on three key arch indices (AHI, ASI, AHF) across a spectrum of load conditions in badminton players, thereby contributing new insights into sport-specific foot biomechanics. We hypothesized that: (1) female players would exhibit lower arch heigh, arch stiffness, and arch height flexibility values than males across all conditions; (2) the dominant foot would demonstrate lower values compared to the non-dominant foot; and (3) players with greater training experience would exhibit higher arch heigh, arch stiffness, and arch height flexibility values, reflecting adaptive structural responses to prolonged physical demand.

Methods
Participants
This study employed a cross-sectional observational design, following the STROBE guidelines for reporting observational studies. Ethical approval was obtained from the committee at Ningbo University (ty2022001), which was conducted following the Declaration of Helsinki. Informed consent was obtained from all participants regarding study objectives, procedures, and requirements. A priori power analysis was performed using G*Power 3.1 to estimate the required sample size for mixed ANOVA with a medium effect size ($f = 0.25$), $\alpha = 0.05$, and power = 0.80. The analysis indicated that a minimum of 44 participants would be required. Therefore, the final sample of 50 athletes was sufficient to detect significant effects with adequate statistical power.

Using participation in badminton for more than three years as the criterion for experience, individuals with more than three years of involvement are classified as Experienced (E), while those with less than three years are

	Experienced (n)	Novice (n)	Age (yr)	Height (cm)	Weight (kg)
Male (n = 35)	18	17	21.14 ± 1.81	176.46 ± 6.23	68.15 ± 8.33
Female (n = 15)	8	7	21.13 ± 1.85	164 ± 11.67	56.47 ± 8.06
All participants (n = 50)	26	24	21.14 ± 1.81	173.52 ± 7.30	64.65 ± 9.80

Table 1. Anthropometric information of all participants.

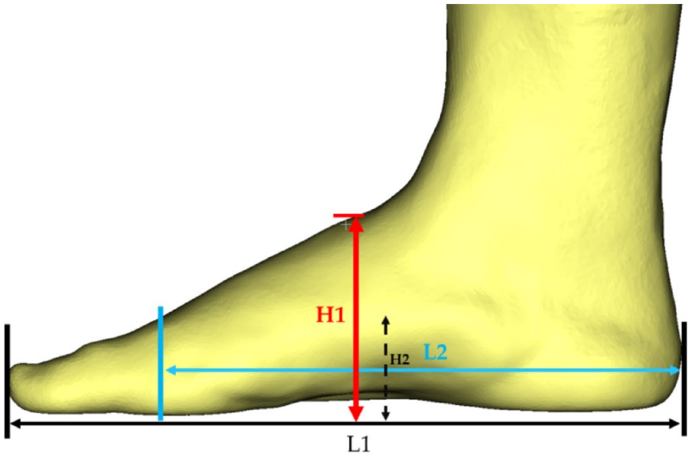

Fig. 1. Illustration of foot metric measurements.

classified as Novice (N)[34]. Specific inclusion criteria were as follows: (1) no lower limb injuries or abnormalities in the musculoskeletal system in the past six months; (2) engagement in badminton training or university-level competition at least three times per week; and (3) right-side dominance. A total of 50 university-level badminton players (35 males and 15 females) were recruited using convenience sampling from local university teams. Details of the participants' characteristics can be found in Table 1 below.

Experimental procedure

To ensure reliability, a single rater (YW) measured all foot structure parameters. Prior to foot anthropometric measurements, each participant's height was assessed using a wall-mounted stadiometer (YG-200; Yagami) accurate to 0.1 cm, and weight was measured using a digital scale (TBF-551; Tanita) accurate to 0.1 kg. The Arch Height Index Measurement System (AHIMS) was utilized to measure and calculate the foot characteristics required for arch height, arch stiffness, and arch height flexibility. The high reliability of the AHI measurement system (intra-class correlation coefficient > 0.94 for both intra- and inter-rater reliability) has been demonstrated in previous studies[19,22,35–37].

Participants wore lightweight clothing and were barefoot during the measurements. The 10% body weight (BW) condition was measured while participants were seated with their hips, knees, and ankles flexed at 90°. The 50% BW condition was measured while participants stood on both feet. The 90% BW condition was measured while participants stood on one leg, with the option to touch the table with their hands to maintain balance[27]. This was done to simulate the biomechanical effects of body weight on foot arches in different populations. The 20 kg and 40 kg load conditions involved placing fixed weights on the participants' thighs while seated, simulating the effects of fixed load weights on foot arch biomechanics in different populations.

Data processing

Measured parameters included foot length (L1), metatarsal length (L2), dorsal height (H1), and arch height (H2), with anatomical landmarks as shown in Fig. 1. AHI, ASI, and AHF were calculated as evaluation indices of foot function.

The AHI calculation method involves the ratio of dorsal height (H1) to metatarsal length (L2). Dorsal height is determined as the perpendicular distance from the midpoint (50%) of the participant's foot length to the dorsal surface of the foot (H1). According to a previous study[23], the AHI is calculated using the following Eq. (1):

$$\text{AHI}\,[\text{unitless}] = \frac{AH\ each\ load\ condition\,(\text{H1})}{Truncated\ foot\ length\,(\text{L2})} \tag{1}$$

The ASI calculation method used the ratio of AHI under load conditions to AHI under seated (10% load) conditions, with the AHI value under seated conditions serving as the AHI value under no-load conditions. ASI values under four different conditions, including 20 kg load, 40 kg load, 50% load, and 90% load, are calculated based on this ratio. According to a previous study[25], ASI is calculated using the following Eq. (2):

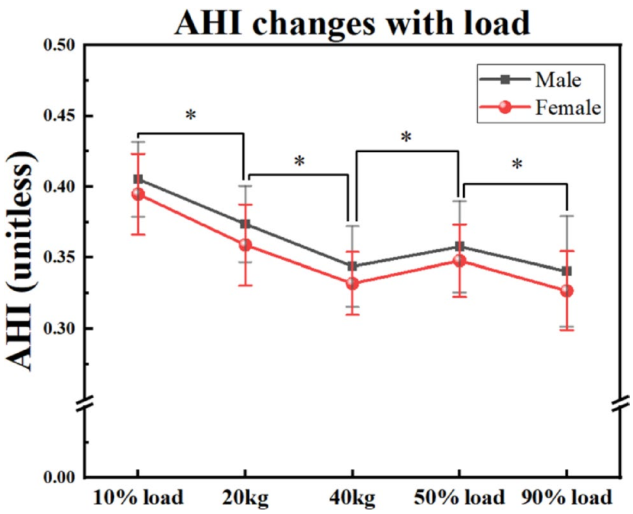

Fig. 2. AHI changes under the different loading conditions. Note: *indicates a significant difference ($p < 0.05$).

$$\text{ASI [unitless]} = \frac{AHI\ each\ load\ condition}{AHI\ sitting} \tag{2}$$

AHF was defined as the change in arch height from 10 to 50% of WB load (10–50% AHF) and 10–90% of WB load (10–90% AHF). According to previous studies[17,27], AHF was calculated using the following Eq. (3) and (4):

$$10\%{-}50\%\ \text{AHF [mm/kN]} = \frac{AH\ 10\%\ WB - AH\ 50\%\ WB}{0.4 \times body\ weight} * 100 \tag{3}$$

$$10\%{-}90\%\ \text{AHF [mm/kN]} = \frac{AH\ 10\%\ WB - AH\ 90\%\ WB}{0.8 \times body\ weight} * 100 \tag{4}$$

Statistical analysis

This study aimed to investigate the effects of gender, limb dominance, and training experience on the arch performance of badminton players under different load conditions. Statistical analyses were conducted using SPSS 27.0 (IBM Corp., Armonk, NY, USA) software. Before the hypothesis testing, the normality of data distribution for continuous variables was assessed using the Shapiro–Wilk test and visual inspections of Q-Q plots. Homogeneity of variances was tested using Levene's test. Outliers were identified using boxplots and z-scores ($|z| > 3.0$).

To account for the design structure of both within-subject factors (loading conditions) and between-subject factors (gender, limb dominance, training experience), a three-way mixed-design ANOVA was performed. Interaction effects and main effects were examined, and Greenhouse–Geisser corrections were applied when sphericity was violated (Mauchly's test). Tukey's HSD or Bonferroni-corrected post hoc comparisons were conducted to control Type I error when significant effects were found. Friedman tests with post hoc Wilcoxon tests (Bonferroni-adjusted) were used for non-normally distributed variables.

All significance levels were set at $p < 0.05$, and effect sizes were reported using partial eta-squared (η^2_p) for ANOVAs and Cohen's d for pairwise comparisons to indicate practical significance.

Results

Three of the 58 individuals initially screened were excluded due to musculoskeletal injury, and five declined to participate. Thus, 50 participants (35 males, 15 females) were included in the final analysis. There were no missing data for any of the measured variables.

The three-way mixed-design ANOVA revealed that load had a significant effect on arch heigh ($F = 111.837$, $p < 0.001$, $\eta^2_p = 0.70$), ARCH STIFFNESS ($F = 16.036$, $p < 0.001$, $\eta^2_p = 0.25$), and arch height flexibility ($F = 33.740$, $p < 0.001$, $\eta^2_p = 0.41$). Significant interactions were observed between load and experience for arch height ($F = 5.267$, $p < 0.001$, $\eta^2_p = 0.18$), arch stiffness ($F = 13.120$, $p < 0.001$, $\eta^2_p = 0.26$), and arch height flexibility ($F = 7.932$, $p = 0.006$, $\eta^2_p = 0.21$). Gender significantly affected arch height ($F = 6.882$, $p = 0.012$, $\eta^2_p = 0.13$), and experience significantly influenced both arch height ($F = 13.818$, $p < 0.001$, $\eta^2_p = 0.24$) and arch height flexibility ($F = 7.932$, $p = 0.006$, $\eta^2_p = 0.19$). Limb dominance did not show any significant main effect.

Arch height index (AHI)

Figure 2 shows a significant decrease in arch height with increasing load among male and female players ($p < 0.05$). There were significant differences in arch height under all load conditions, with arch height significantly lower at 90% load compared to 50%, 20 kg, 40 kg, and 10% load conditions ($p < 0.05$).

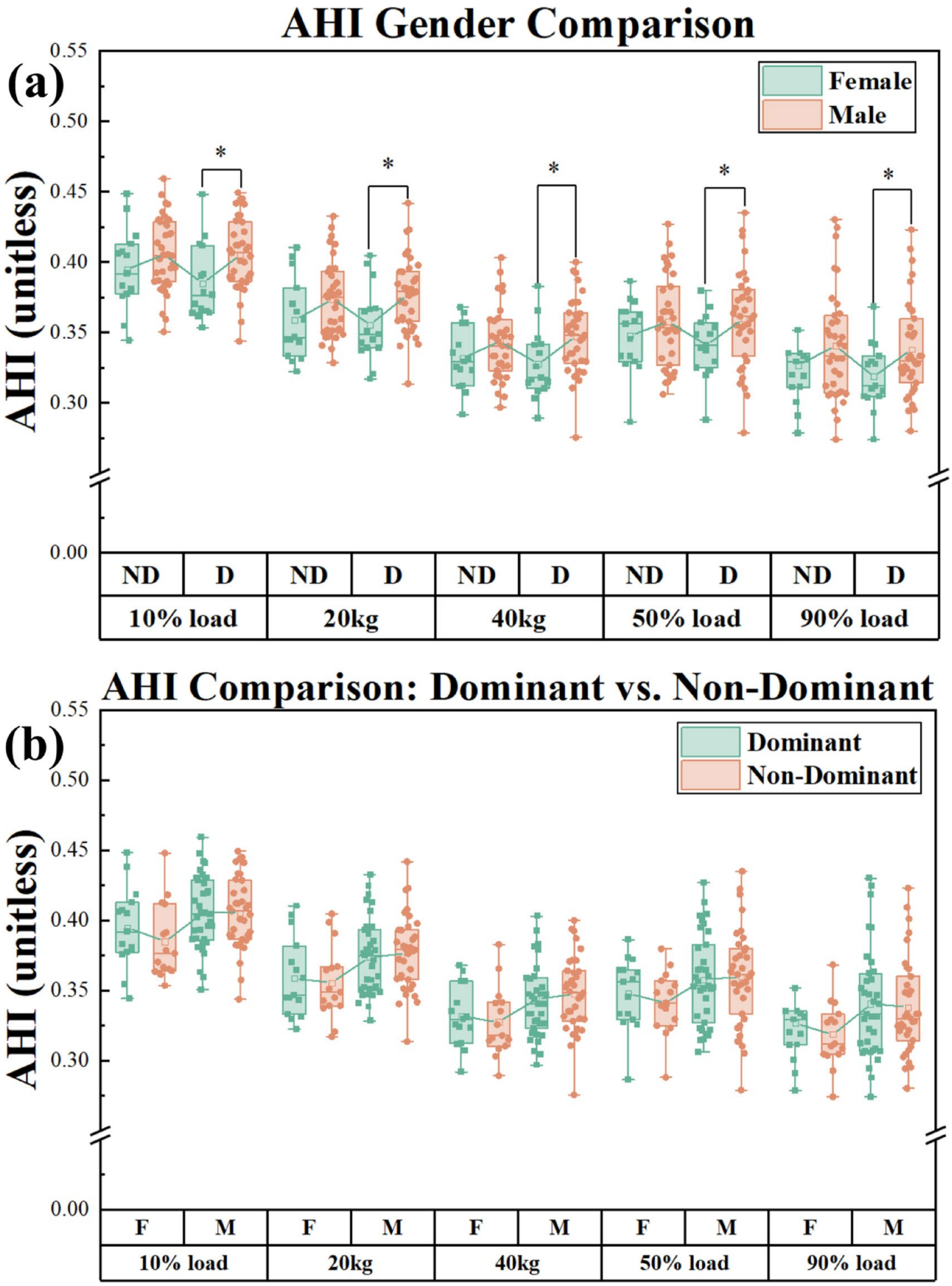

Fig. 3. Statistical comparison of AHI between gender (**a**) and limb dominance (**b**). *Note*: *indicates significant difference ($p < 0.05$); D—Dominant; ND—Non-Dominant; F—Female; M—Male.

As illustrated in Fig. 3 and detailed in Table 2, significant gender differences in arch height were observed for the dominant foot across all load levels. Female players consistently exhibited lower arch height than males ($p < 0.05$), with effect sizes ranging from moderate to large (Cohen's d = 1.00 at 10% load, 1.34 at 20 kg, 1.18 at 50% load, and 1.00 at 90% load).

No significant differences were found between the dominant and non-dominant feet in either male or female participants. However, clear differences emerged when comparing athletes with different levels of training experience. As shown in Fig. 4 and detailed in Table 3, experienced male players exhibited significantly higher arch height values than their novice counterparts under 50% body weight loading and 90% loading conditions,

Load	Gender	Non-dominant/dominant	Mean ± SD	95%CI	t	*p*	Cohen's d
10% load	M	ND	0.41 ± 0.03	[0.40,0.41]	1.23	0.21	–
	F	ND	0.39 ± 0.03	[0.38,0.41]			
	M	D	0.41 ± 0.03	[0.40,0.41]	2.51	**0.01***	**1.00**
	F	D	0.38 ± 0.03	[0.37,0.40]			
20 kg	M	ND	0.37 ± 0.03	[0.36,0.38]	1.71	0.09	–
	F	ND	0.36 ± 0.03	[0.34,0.37]			
	M	D	0.38 ± 0.03	[0.37,0.39]	2.61	**0.01***	**0.67**
	F	D	0.36 ± 0.03	[0.34,0.37]			
40 kg	M	ND	0.34 ± 0.03	[0.33,0.35]	1.61	0.1	–
	F	ND	0.33 ± 0.02	[0.32.0.34]			
	M	D	0.35 ± 0.03	[0.34,0.36]	2.53	**0.02***	**0.78**
	F	D	0.33 ± 0.02	[0.31,0.34]			
50% load	M	ND	0.36 ± 0.03	[0.35,0.37]	1.15	0.26	–
	F	ND	0.35 ± 0.03	[0.33,0.36]			
	M	D	0.36 ± 0.03	[0.35,0.37]	2.26	**0.03***	**0.78**
	F	D	0.34 ± 0.02	[0.33,0.35]			
90% load	M	ND	0.34 ± 0.04	[0.33,0.35]	1.41	0.17	–
	F	ND	0.33 ± 0.03	[0.31,0.34]			
	M	D	0.34 ± 0.03	[0.33,0.35]	2.32	**0.02***	**0.78**
	F	D	0.32 ± 0.02	[0.31,0.33]			

Table 2. Comparison of AHI between experienced and novice male badminton players. *Indicates significant difference ($p < 0.05$). The bold values were meant to highlight the statistics with significance.

indicating a moderate to large training-related enhancement in arch height. In female players, significant experience-based differences in arch height were observed across all loading conditions ($p < 0.05$), with consistently large effect sizes.

Arch stiffness index (ASI)

As shown in Fig. 5, the arch stiffness was reported a decrease with increasing load, with arch stiffness significantly lower in male and female players at 90% load compared to 50% and 40 kg load conditions ($p < 0.05$).

As shown in Fig. 5, arch stiffness decreased progressively with load. Significant reductions occurred at 90% load compared to 50% and 40 kg loads ($p < 0.05$). As illustrated in Fig. 6, no significant differences were found between the dominant and non-dominant feet. However, Table 4 shows that experienced male players had significantly higher ASI than novices under 20 kg load in both non-dominant ($p = 0.01$, d = 0.98) and dominant feet ($p = 0.00$, d = 1.37), and under 90% load for the non-dominant foot ($p = 0.006$, d = 0.66) (Fig. 7). No significant experience-based Arch Stiffness differences were found among female players.

Arch height flexibility (AHF)

As shown in Fig. 8, it was found that arch height flexibility decreased with increasing load, showing significant differences ($p < 0.05$). Male and female players exhibited significantly lower arch height flexibility at 90% load compared to 50% load conditions ($p < 0.05$).

As shown in Fig. 9, no significant differences were observed in AHF between the dominant and non-dominant feet among male and female badminton players, and between the genders.

Figure 10 and Table 5 revealed that experienced male players showed significantly lower arch height flexibility than novices at 50% load. For the dominant foot, the difference was substantial ($p = 0.01$, d = − 1.03), and for the non-dominant foot ($p = 0.02$, d = − 0.73). These findings suggest decreased arch deformability in experienced male players under load. No significant differences in arch height flexibility were observed in female players by experience.

Discussion

In this study, we investigated the influence of gender, limb dominance, and training experience on the arch heigh, arch stiffness, and arch height flexibility of badminton players under different loading conditions. To date, several studies have separately examined the differences in arch heigh, arch stiffness, and arch height flexibility among normal individuals based on factors such as gender, age, bmi, dominant side, or various load conditions[15,18,20,27,28,37,38]. However, to the best of our knowledge, no investigations have explored the effects of gender, limb dominance, and experience on arch heigh, arch stiffness, and arch height flexibility among badminton players under different loading conditions. Therefore, this study represents the first attempt to investigate the combined influence of these variables in a sport-specific cohort under a multi-loading paradigm, offering a more comprehensive biomechanical profile of the foot arch in badminton athletes.

This study found that gender and experience impact the arch height, arch stiffness, or arch flexibility of badminton players under different loading conditions, while limb dominance did not significantly affect these

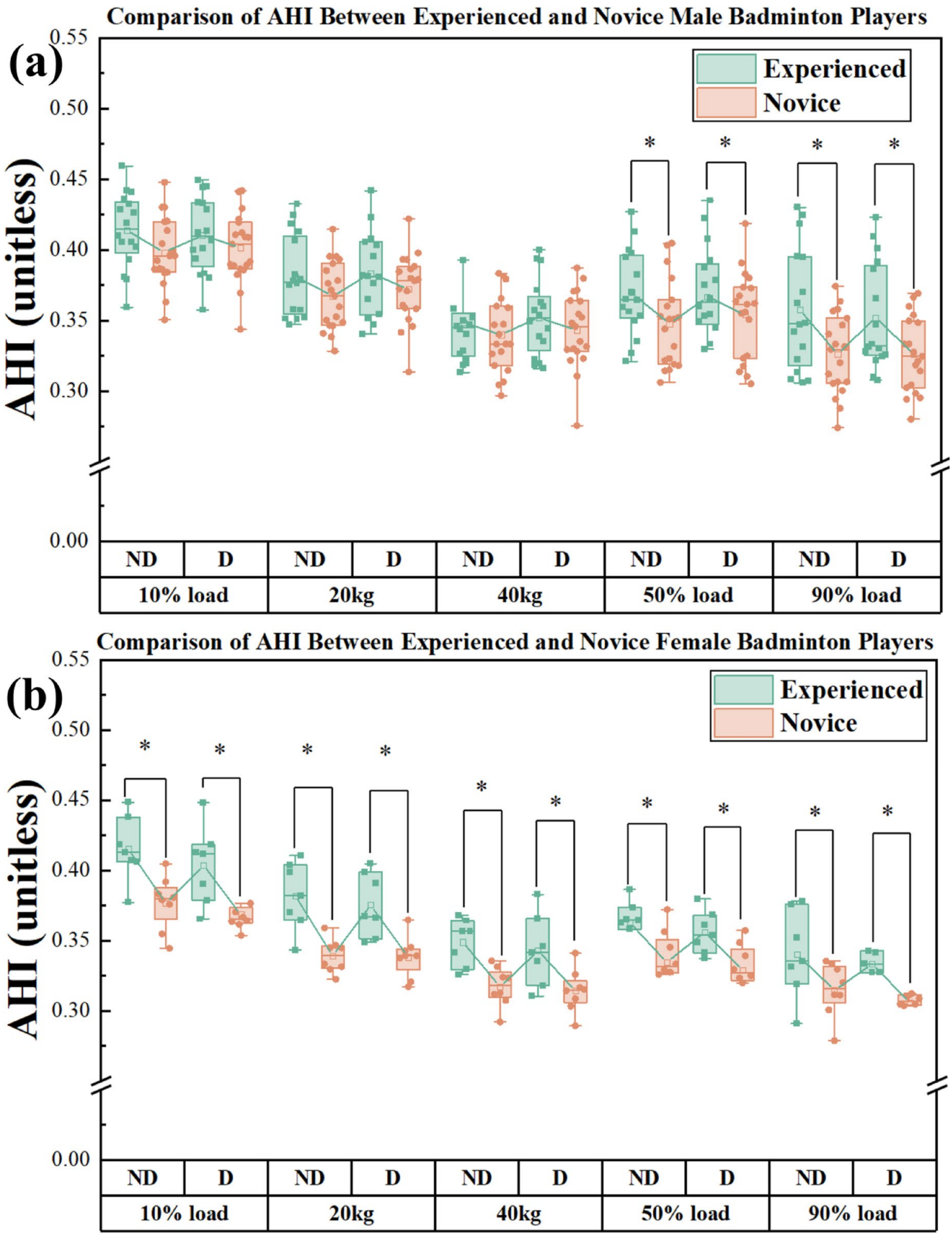

Fig. 4. Statistical comparison of AHI in males (**a**) and females (**b**) with different training experiences (Experience—Novice). Note: * indicates a significant difference ($p < 0.05$).

metrics. These results confirm some of our initial hypotheses which ones but also introduce nuanced deviations that reveal complex interactions between foot morphology, habitual use, and physical training adaptation. Specifically, arch heigh, arch stiffness, and arch height flexibility showed significant differences between males and females under different load conditions. Additionally, under all load conditions, the arch heigh of the dominant foot in female players was significantly lower than in male players. The stiffness of the non-dominant foot in female players was lower than in males under 90% BW conditions, but gender differences did not affect

Load	Experienced/novice	Non-dominant/dominant	Mean ± SD	95% CI	t	*p*	Cohen's d
10% load	E	ND	0.42 ± 0.02	[0.39,0.44]	3.49	**0.04***	**2.00**
	N	ND	0.38 ± 0.02	[0.36,0.39]			
	E	D	0.40 ± 0.03	[0.38,0.43]	3.12	**0.01***	**1.00**
	N	D	0.37 ± 0.01	[0.36,0.38]			
20 kg	E	ND	0.38 ± 0.02	[0.36,0.40]	4.26	**0.002***	**2.53**
	N	ND	0.34 ± 0.01	[0.33,0.35]			
	E	D	0.38 ± 0.01	[0.35,0.40]	3.70	**0.004***	**0.67**
	N	D	0.34 ± 0.01	[0.33,0.35]			
40 kg	E	ND	0.35 ± 0.02	[0.33,0.36]	3.92	**0.002***	**1.90**
	N	ND	0.32 ± 0.01	[0.31,0.33]			
	E	D	0.34 ± 0.03	[0.32,0.37]	2.59	**0.02***	**0.78**
	N	D	0.31 ± 0.02	[0.30,0.33]			
50% load	E	ND	0.36 ± 0.02	[0.35,0.38]	2.66	**0.02***	**1.18**
	N	ND	0.33 ± 0.03	[0.31,0.36]			
	E	D	0.36 ± 0.03	[0.34,0.35]	2.87	**0.01***	**0.78**
	N	D	0.33 ± 0.02	[0.31,0.37]			
90% load	E	ND	0.34 ± 0.02	[0.31,0.37]	1.87	**0.04***	**1.50**
	N	ND	0.31 ± 0.02	[0.30,0.33]			
	E	D	0.33 ± 0.02	[0.31,0.35]	2.70	**0.02***	**0.78**
	N	D	0.31 ± 0.02	[0.29,0.32]			

Table 3. Comparison of AHI between experienced and novice female badminton players. *Indicates significant difference ($p < 0.05$). The bold values were meant to highlight the statistics with significance.

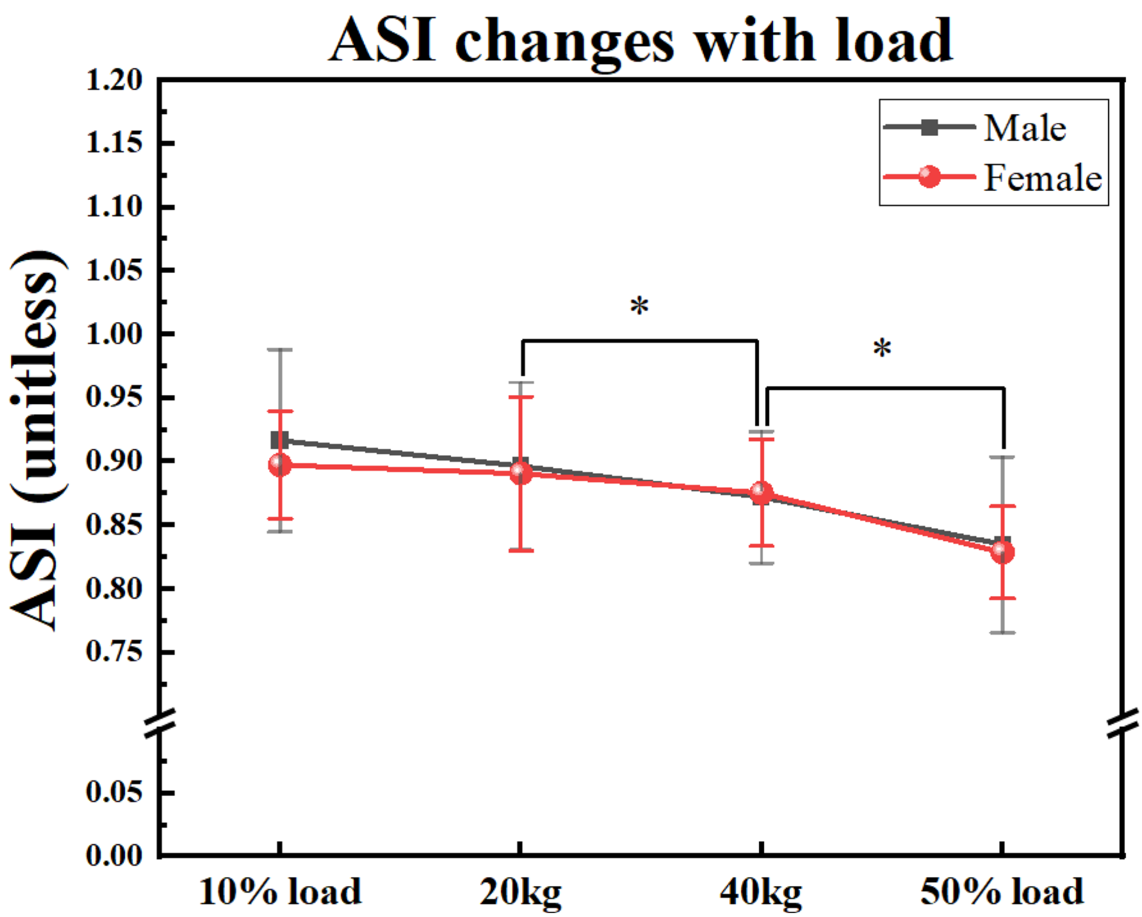

Fig. 5. ASI changes under different loading conditions. Note: *indicates a significant difference ($p < 0.05$).

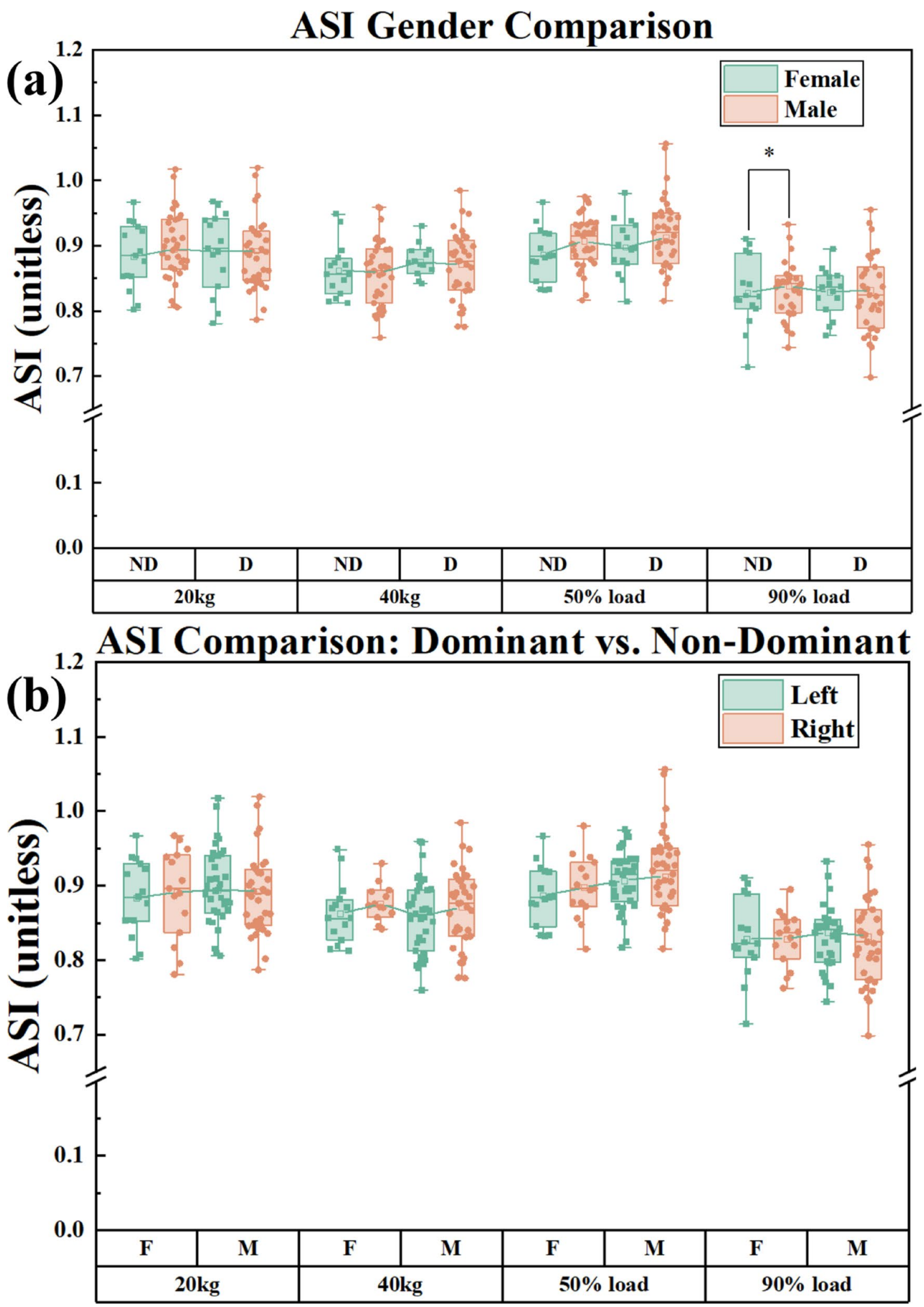

Fig. 6. Statistical comparison of ASI between genders (**a**) and limb dominance (**b**). *Note*: *indicates a significant difference ($p < 0.05$).

Load	Experienced/novice	Non-dominant/dominant foot	Mean ± SD	95%CI	t	*p*	Cohen's d
20 kg	E	ND	0.92 ± 0.04	[0.90,0.94]	2.56	**0.01***	**0.98**
	N	ND	0.87 ± 0.06	[0.85,0.90]			
	E	D	0.93 ± 0.06	[0.89,0.96]	3.76	**0.00***	**1.37**
	N	D	0.86 ± 0.04	[0.84,0.88]			
40 kg	E	ND	0.85 ± 0.06	[0.82,0.88]	− 1.19	0.24	–
	N	ND	0.87 ± 0.04	[0.85,0.89]			
	E	D	0.87 ± 0.06	[0.84,0.90]	− 0.56	0.58	–
	N	D	0.88 ± 0.05	[0.85,0.90]			
50% load	E	ND	0.90 ± 0.04	[0.87,0.92]	− 1.55	0.13	–
	N	ND	0.92 ± 0.04	[0.90,0.93]			
	E	D	0.89 ± 0.09	[0.84,0.94]	− 1.58	0.12	–
	N	D	0.93 ± 0.05	[0.91,0.95]			
90% load	E	ND	0.86 ± 0.07	[0.82,0.89]	1.92	**0.006***	**0.66**
	N	ND	0.82 ± 0.05	[0.80,0.85]			
	E	D	0.86 ± 0.08	[0.81,0.90]	1.69	0.1	–
	N	D	0.81 ± 0.05	[0.79,0.84]			

Table 4. Comparison of ASI between experienced and novice male badminton players. *Indicates significant difference ($p < 0.05$). The bold values were meant to highlight the statistics with significance.

arch stiffness under other load conditions. Regarding experience, we found that experience influenced the arch height of both feet in male players under 50% BW and 90% BW conditions, while it affected the arch height of both feet in female players under different load conditions.

From a gender perspective, this study found significant differences in arch heigh of the dominant foot between genders under different load conditions, as expected, with females exhibiting smaller arch heigh compared to males. This may be related to physiological differences between genders, such as muscle mass, skeletal structure, and hormone levels[39,40]. Female ankle muscles tend to be weaker, and ligaments are relatively Less stiff compared to males[41]. During static and dynamic loading processes, the feet of females tend to be more flexible than those of males, leading to greater arch flexibility in females and, thus, a larger range of arch height variations. Our data further confirmed large effect sizes for these differences, especially under high load conditions, which suggests that these gender-related structural differences may have important implications for footwear design and injury prevention strategies.

The dominant side typically refers to the side of the body that is more frequently used in motor tasks. In this study, foot dominance was determined by identifying the foot the participant preferred to use when kicking a ball, which is a widely accepted method in biomechanical research to define lower limb dominance. For instance, right-handed individuals usually have a dominant right foot. Research indicates that the dominant side often endures greater load and higher frequency of movement, which may lead to structural adaptations[42]. Over time, the repetitive load and usage can cause the arch of the dominant foot to become more developed or undergo morphological adjustments to better meet functional demands. However, arch stiffness did not show significant differences between genders, suggesting that the arch's stiffness characteristics are similar. Previous studies have indicated that arch stiffness is higher in females compared to males[15], but in this study, there were no differences in arch stiffness between genders under various load conditions. Our findings are similar to the conclusions drawn by Zhao et al.[13], which suggests that this discrepancy in results may be due to ethnic differences among the participants. Arch height flexibility did not show any gender differences in this study, consistent with previous research findings[27,36].

From the perspective of the dominant side, previous research has found that the standing arch heigh of the dominant foot is significantly higher than that of the non-dominant foot[15]. However, our study found no significant differences in arch heigh between the dominant and non-dominant feet of male and female badminton players under different load conditions. This discrepancy may be related to the characteristics of the participants. The participants selected for our study were university badminton players. In badminton matches and training sessions, players typically rely more on their dominant foot for support, propulsion, jumping, and changes of direction. The lunge, which accounts for over 15% of all movements, is one of the most typical movements in badminton[43,44]. During a lunge, the non-dominant foot pushes off the ground, while the dominant foot in different directions to complete the lunge. These biomechanical demands may have led to adaptations in both feet, thus equalizing any dominance-related asymmetry typically observed in non-athlete populations[45–47].

From the perspective of experience, long-term engagement in badminton training may lead to adaptive changes in foot structure. As the experience increases, arch heigh significantly increases under 50% and 90% load conditions among male players. Similarly, female players significantly increase arch heigh under all testing load conditions. This may reflect the positive effects of badminton training on foot arch structure, as long-term engagement in badminton training can strengthen the muscles inside the foot, thereby increasing arch height[47,48]. Additionally, compared to males, females generally have weaker muscle strength, making the impact of badminton training on female foot arch height more pronounced. The effect of experience on arch stiffness is significant in male players, which may be related to adaptive changes in foot structure due to long-term training.

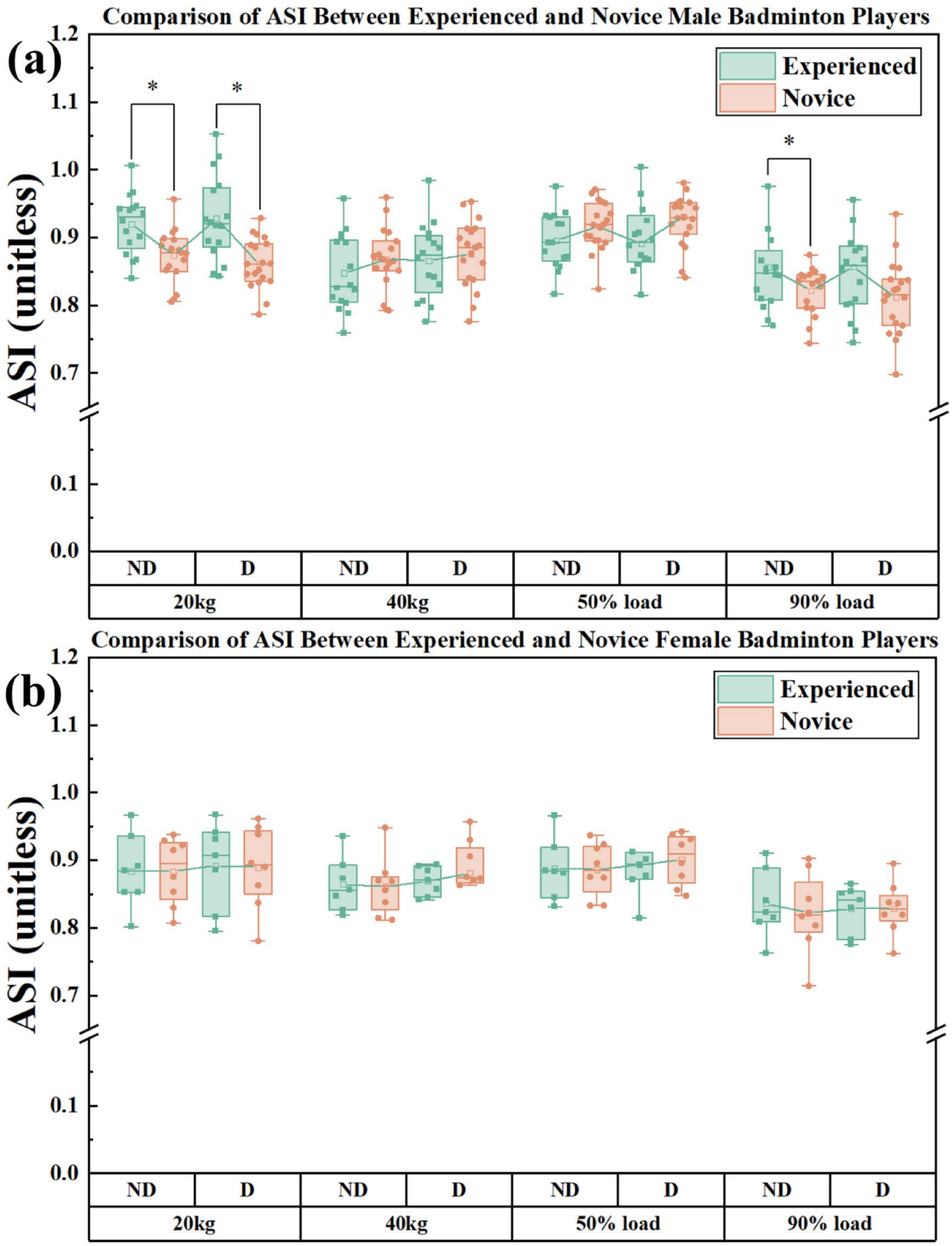

Fig. 7. Statistical comparison of ASI in male players (**a**) and female players (**b**) ASI with different training experiences. *Note*: *Indicates a significant difference ($p < 0.05$).

However, female players did not show significant differences in arch stiffness, suggesting the need for further research to explore the reasons behind this. The influence of experience on arch height flexibility in male players is significant. Takabayashi found that arch height flexibility can effectively assess changes in plantar fascia tension, indicating that long-term badminton training may lead to changes in plantar fascia tension in male players[22].

This study found significant differences in arch heigh, arch stiffness, and arch height flexibility among badminton players under different loading conditions. Specifically, arch height, stiffness, and flexibility decreased with increasing load, which may be attributed to the foot arch's ability to adjust its shape and function automatically, as well as the biomechanical characteristics of the foot arch. The interaction among various

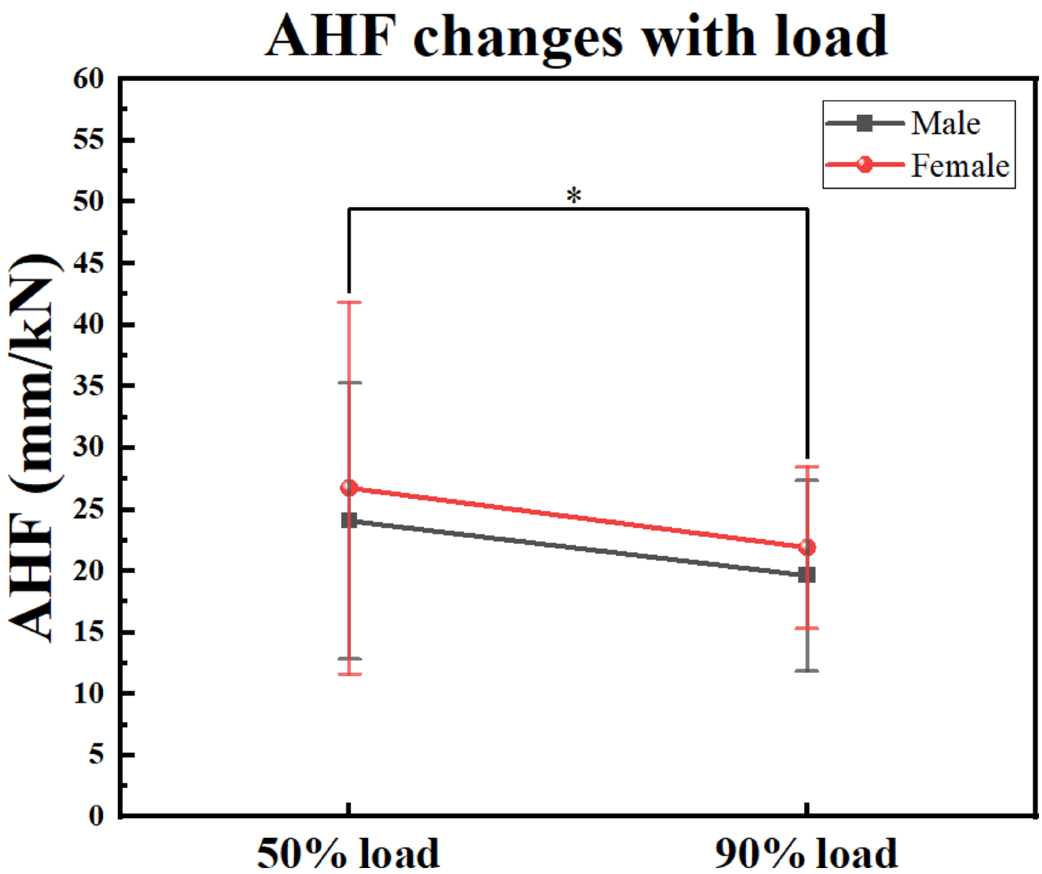

Fig. 8. AHF changes under different load conditions. Note: *indicates a significant difference ($p < 0.05$).

tissues, such as bones, muscles, ligaments, and fascia in the foot, determines the morphology and function of the foot arch. These tissues exhibited complex interplay and regulatory mechanisms, allowing the foot arch to adapt and adjust its height under different loading and movement conditions to maintain stability and flexibility[20,27,35]. Biomechanical characteristics of the foot arch refer to elastic potential and shock-absorbing properties during movement, which could deform and recover to absorb and release kinetic energy, reducing energy loss and improving movement efficiency[42,49,50]. Therefore, the foot arch experiences greater pressure and tension as the load increases. The foot arch's elastic potential and shock-absorbing properties become more pronounced, resulting in greater deformation and recovery. Consequently, the height and curvature of the foot arch decrease, while the length and width of the foot increase, and the contact area expands to distribute and balance the load and impact[51].

From a practical standpoint, these results suggest that foot arch structure evaluation under varied load conditions may serve as a useful diagnostic for assessing training status or injury risk in badminton players. Insights from this study can support the development of gender- and experience-specific insoles and footwear designs, which may enhance movement efficiency, injury prevention, and comfort in high-performance sports settings.

Several limitations in the study should be considered. Firstly, this study mainly focused on Chinese University badminton players, and foot morphology and arch stiffness may be influenced by age and ethnicity[18,52]. The arch height, arch stiffness, and arch height flexibility data obtained in this study may not be generalizable to other age groups and population ethnicities. Secondly, different sports activities involve different types and magnitudes of foot impact, which may result in variations of foot structure or morphology among players from different sports[53]. Therefore, the arch heigh, arch stiffness, and arch height flexibility data from this study may not be applicable to players from other sports and physical activities. Lastly, foot arch height may exhibit ethnic and regional variations[36]. Therefore, the results of this study may differ if applied to other ethnic groups. These limitations need to be addressed in future research endeavors.

Although this study provides valuable information regarding the foot arch structure of badminton players, many questions still require further investigation. For example, the potential effects of long-term changes in foot arch structure on athletic performance and injury risk remain unclear. In addition, the role of training or equipment interventions in optimizing foot arch function warrants further investigation. Future research should adopt longitudinal and interventional designs to examine foot arch plasticity over time, and incorporate dynamic testing protocols (e.g., lunge, jump landings) to complement static load assessments. Furthermore, studies targeting broader athlete groups and using wearable sensor-based gait assessments could provide deeper insights into in-game foot biomechanics and performance linkage.

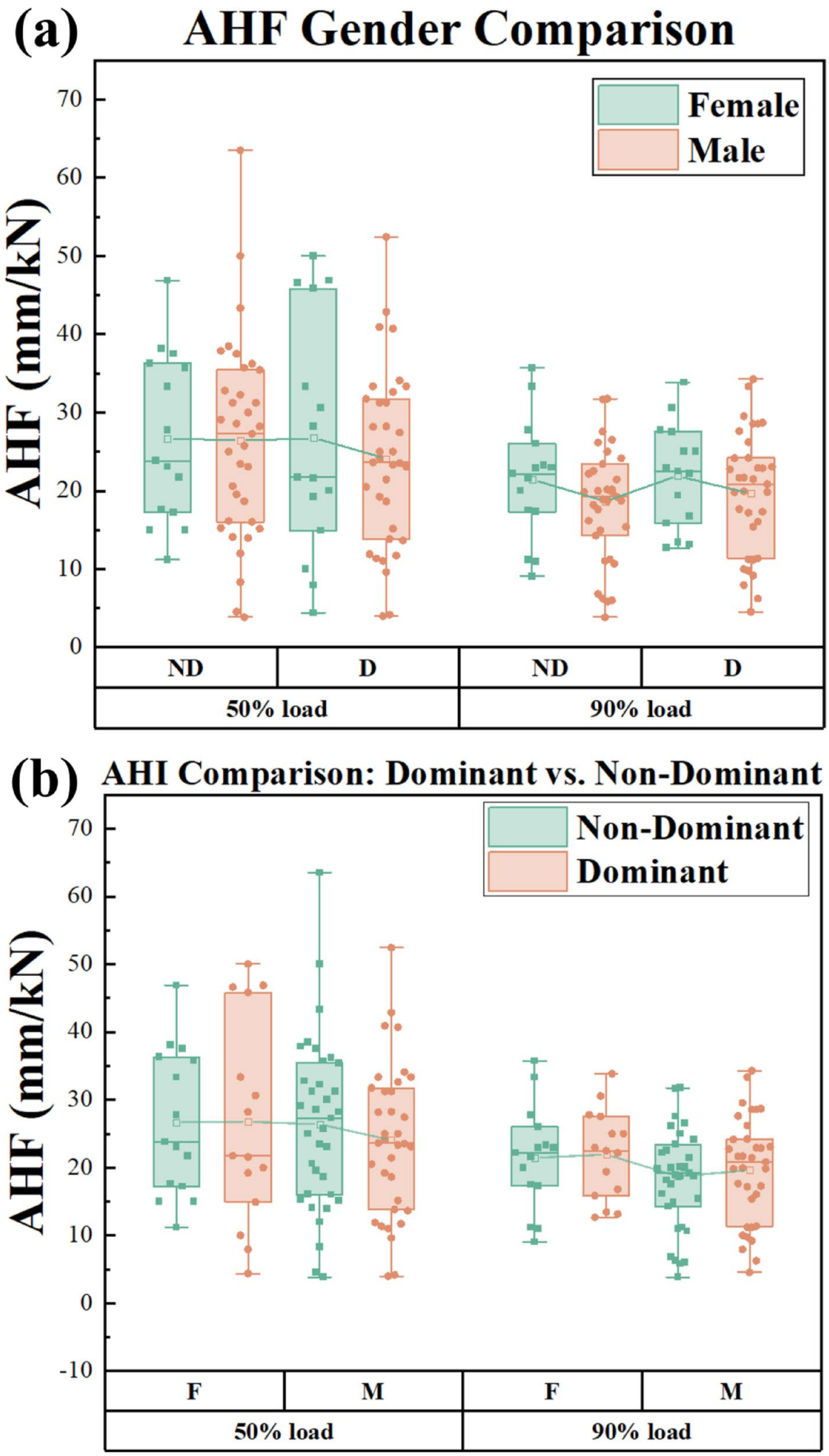

Fig. 9. Statistical comparison of AHF between genders (**a**) and limb dominance (**b**). *Note*: *indicates a significant difference ($p < 0.05$).

Conclusion

This study systematically investigated the effects of gender, training experience, and limb dominance on foot arch characteristics in badminton players under five different loading conditions using AHI, ASI, and AHF

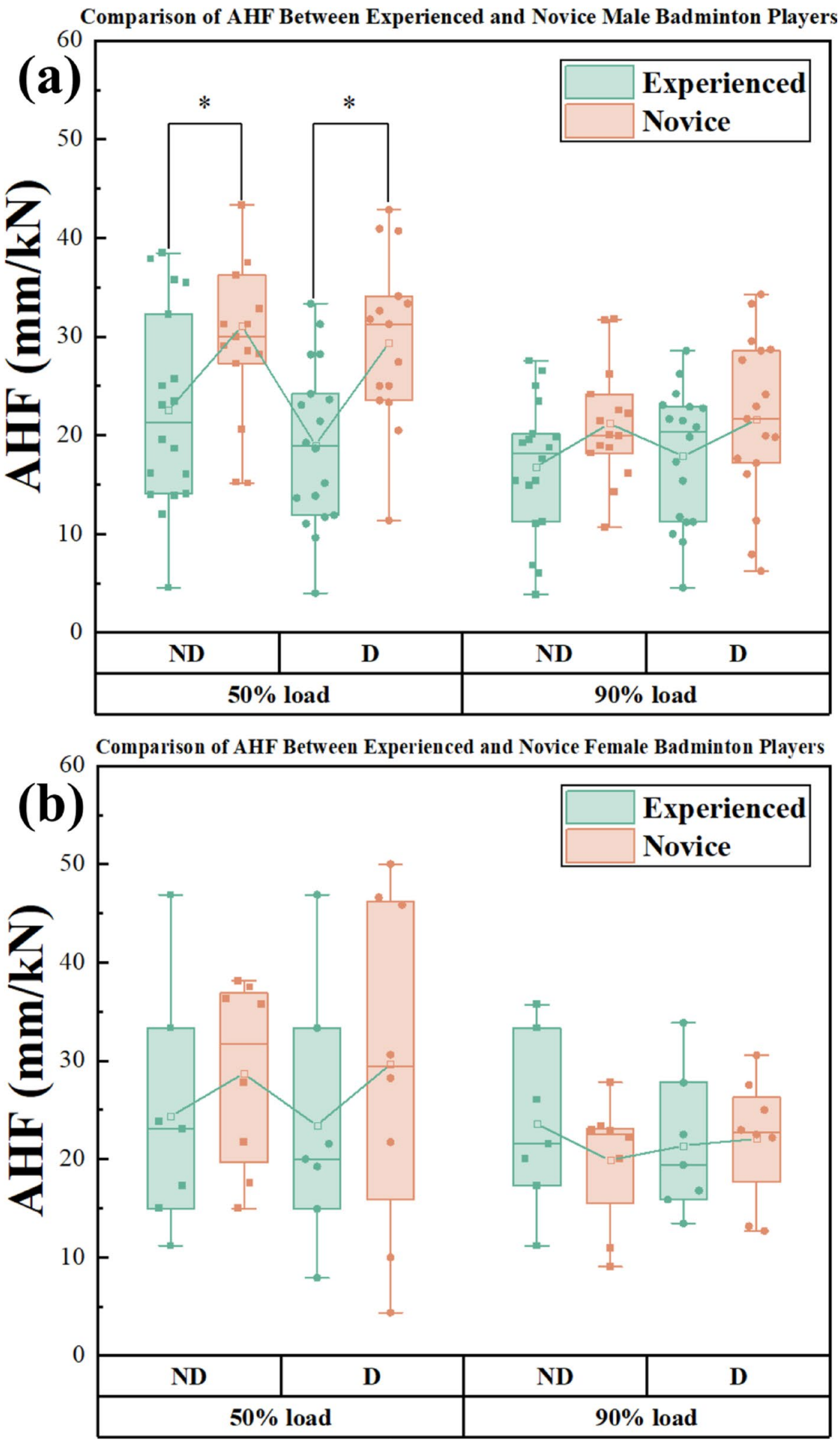

Fig. 10. Statistical comparison of AHF in male players (**a**) and female players (**b**) with different training experiences. *Note*: *indicates a significant difference ($p < 0.05$).

as primary indicators. The findings revealed that gender and experience significantly influenced arch height, stiffness, and flexibility, while limb dominance did not produce consistent effects. Notably, females showed lower arch heigh values across all conditions, and experienced athletes demonstrated higher arch heigh and arch stiffness, suggesting training-related adaptations in foot structure. These results underscore the importance of incorporating gender- and experience-specific considerations into functional foot assessments, footwear design,

Load	Experienced/novice	Non-dominant/dominant foot	Mean ± SD	95%CI	t	*p*	Cohen's d
50% load	E	ND	22.54 ± 10.01	[17.56,27.52]	− 2.52	**0.02***	**− 0.73**
	N	ND	31.07 ± 13.21	[24.28,37.87]			
	E	D	19.00 ± 8.20	[14.92,23.08]	− 2.82	**0.01***	**− 1.03**
	N	D	29.42 ± 11.68	[23.42,35.43]			
90% load	E	ND	16.79 ± 6.92	[13.34,20.23]	− 1.97	0.06	–
	N	ND	21.21 ± 7.71	[17.24,25.17]			
	E	D	17.89 ± 6.80	[14.50,21.27]	− 1.30	0.20	–
	N	D	21.59 ± 8.30	[17.32,25.86]			

Table 5. Comparison of AHF between experienced and novice male badminton players (unit: mm/KN). *Indicates a significant difference ($p < 0.05$). The bold values were meant to highlight the statistics with significance.

and training protocols for badminton players. Future research should expand on these findings by including more diverse athletic populations and adopting dynamic and longitudinal methodologies to further explore foot arch adaptability and its implications for performance and injury prevention.

Data availability
Raw data are available upon reasonable request from the corresponding author.

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Author contributions
Y.W., Q.M., J.Z. and F.Y. designed the study, conducted the measurement and data analysis. Y.W., J.Z. contributed to the original draft of the manuscript. Q.M. and BXWL. validated the results. Q.M., B.X.W.L. F.Y., J.F., and Y.G. proofread, reviewed, and finalized the manuscript. All authors read and approved the final version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information

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