

RESEARCH

The Plantar Pressure Analysis of Open Stance Forehand in Female Tennis Players

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Purpose: The aim of this study was to analyze plantar pressure during the open stance forehand (OSF) in female tennis players.

Methods: Seven female players executed the tennis forehand technique with open stance in the biomechanical laboratory. A portable pressure insole system was adopted to collect mean pressure (MP), peak pressure (PP), force (F), pressure-time integral (PTI) and contact area (CA) in 7 regions of the feet. Independent sample T-test was used to analyze the difference among these parameters.

Results: F, PP in the first phalangeal region (BT) and the remaining four toe regions (OT) of the right foot (RF) were both larger than the left foot (LF); F in the fourth and fifth metatarsophalangeal joint (M4-5), the middle foot region (MF), hind foot region (HF) and PP in M4-5 of LF were significantly greater than the same region in RF; MP in BT and OT of RF showed significantly higher pressure than LF. While MP among areas of M4-5 and HF of LF was significantly greater than RF; PTI, CA in OT, M4-5 and MF of RF were significantly higher than LF while M1, M2-3, M4-5 and MF of LF showed significant smaller.

Conclusion: RF role was to generate the power and LF role was to stabilize the balance of the body during the OFS. However, long-term and repeated open stance was likely to lead to the overuse injuries in the regions of M1 and HF of both feet.

Keywords: plantar pressure; tennis player; open forehands

1. Introduction

With the specialization and refinement of tennis training, Chinese female tennis players have achieved excellent results in the international top tennis events (Sterzing et al. 2014). Forehand shot (FS) is one of the most frequently used among various skills of Tennis. Plenty of researches show, because of its acceptable and practical characteristics, FS has become a crucial guarantee for offensive scoring. The open stance forehand, which was considered a useless skill, is now recommended by tennis experts. With the increasing speed in modern tennis, more players have been adopted with the open stance forehand skill compared to the traditional square stance skill. (Bahamonde and Knudson 2003). Johnson and McHugh (2006) carried out a study about the movement analysis of the world's elite tennis players by video observation, found that the forehand shot with open stance has the trait of large footstep movement range and fast return speed, which contributes significantly to high-intensity confrontation and large-angle save. Accordingly, the OFS has been used widely, even for professional tennis players.

Biomechanical method has been an effective means for the analysis of tennis movement skill (Elliott 2006). Girard et al. (2010) discussed the plantar pressure in two different positions of tennis serve and found that the type of position had a significant effect. The mean pressure (MP) and peak pressure (PP) in the lateral area of the forefoot was higher than the stationary serve, but MP in the medial forefoot and middle foot was lower. Girard et al. (2007) made a study about the influence of different tennis courts on plantar pressure, found that the contact time, MP in the medial metatarsophalangeal joint and the lateral side of the middle foot on the clay court were longer and higher compared with on the grass court. But MP in the lateral metatarsophalangeal joint was obviously lower. Although the research has proved that

biomechanical methods and theories have high reliability and validity in the fields of tennis movement analysis and injury prevention (Groppel 1986). However, there was no exactly research on how distribution of plantar pressure in OFS during the state of competition.

In the tennis competition, all kinds of commute, quick turns and stops, jumps and other actions need to be completed in the process of rapid movement, which can easily lead to the injuries of the ankle joint and foot (Sannicandro et al. 2014). Studies have indicated that Achilles tendinitis and bunion that were 9 times higher than male tennis players were the most common injuries to the feet of female players (Leach 1981). Medical and epidemiological studies have shown that the biomechanical abnormality of the foot is a key cause of foot injury and disease (Donatelli 1987, Xu et al. 2018). Burnfield et al. (2004) found that wearing shoes could reduce the peak pressure and average pressure in the heel and central metatarsal area after testing the plantar pressure of the healthy elderly at three different walking speeds. Praet et al. (2003) analyzed the plantar pressure of diabetic patients walking with three different sole structures and found that the curvature of the sole had an important effect on the pressure of the forefoot, and the pressure in the central metatarsal region was significantly reduced when patients walked with type C shoes with high sole curvature. Mickle et al. (2011) made a research on the gait, balance and plantar pressure of the elderly with toe deformity and found that with moderate or severe thumb eversion would have apparently different plantar pressure distribution characteristics when walking compared with the elderly with normal thumb; toe deformity has a direct cause-and-effect relationship with falls, which could affect the coordination and stability in the dynamic walking state.

From the above analysis of tennis motor skills and medical diagnosis, it can be realized that the method of plantar pressure can not only analyze players' motor skills, but also diagnose diseases of the body. From the perspective of these studies, using biomechanical method to explore the mechanics mechanism in sports state will make a positive effect on improving the performance of tennis players and preventing sports injuries. Based on this background, this study was aim to analyze the characteristics of the plantar pressure of female tennis players during forehand shot with open stance. We hypothesized that the bilateral feet of female tennis players would produce significantly different performance of pressure characteristics while female tennis players complete the forehand shot, which would further have an influence on the sports performance of tennis players.

2. Methods

2.1. Participants

This study recruits 7 women tennis players (age: 22 ± 2 year, height: 170 ± 5 cm, weight: 65 ± 8 kg) in the major of sports training from Ningbo University. The criterion of subject recruitment was that the training 9 ± 3 years, the right-handed in holding the racket, without any acute or chronic injuries of lower limb, foot and other injuries which had influence on sports performance. Prior to the experiment, the subjects were informed of the contents and voluntarily signed an informed consent.

2.2. Procedures

All of subjects were required to wear uniform tennis clothes, shoes, and to choose the suitable size of pressure insoles for flat shoes. After that, subjects were given enough time to get familiar with the experimental environment and equipment. Definitively, the whole process of the forehand with open stance will be completed in the laboratory.

During the execution of the experiment, players were required to hold the tennis racket of the same weight from the preparatory action, and move two steps to the right hand side for completing OFS. In this period, the acquisition data of plantar pressure during the whole movement process was transmitted to the computer simultaneously through the bluetooth receiver; each player was demanded to accomplish 15 times OFS, with 30s for rest after each shot for preventing fatigue.

2.3. Equipment and indicators

A portable sensory insoles pressure test system (Novel Pedar X, Munich, Germany) was used to collect the plantar pressure during OFS, the collection frequency was 50Hz. The collection areas were: the first phalangeal region (BT), the remaining four toe regions (OT), the first metatarsophalangeal joint (M1), the second and third metatarsophalangeal joint (M2-3), the fourth and fifth metatarsophalangeal joint (M4-5), the middle foot region (MF), and the hind foot region (HF) (**Figure 1**). The parameters of plantar pressure were: Force (F), Peak Pressure (PP), Mean Pressure (MP), Pressure-time Integral (PTI) and Contact Area (CA).

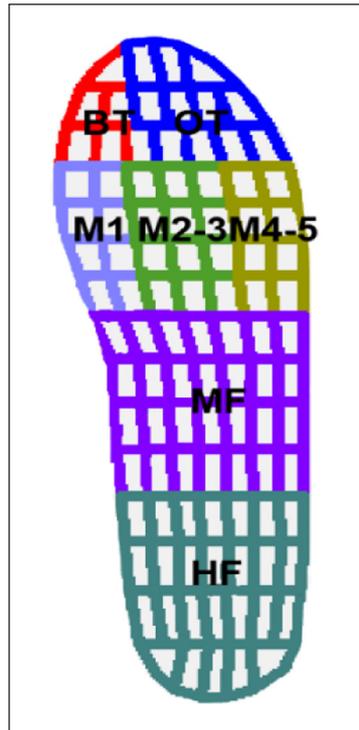


Figure 1: The distribution of the plantar district.

2.4. Statistical methods

The data of F, PP, MP, PTI and CA in 7 regions of the plantar area were expressed by Excel and expressed by mean standard deviation ($M \pm SD$). The difference between these parameter among right and left feet was performed by the independent sample T-test using 17.0 SPSS (SPSSInc., Chicago, USA), and P was set as $P < 0.05$.

3. Results

3.1. Force

The F in 7 regions were displayed in **Table 1**. The F of M1 (left: 232.43 ± 75.27 , right: 212.36 ± 128.97 ; $p = 0.065$) and M2-3 (left: 116.00 ± 10.24 , right: 86.34 ± 47.00 ; $p = 0.065$) in the left foot were significantly higher compared with the right foot (**Figure 2**). Except M1 and M2-3, there were no significant differences in other rest regions. In addition, During OFS, the F of BT (left: 57.4 ± 16.45 , right: 107.79 ± 11.66 ; $P = 0.001$) and OT (left: 64.92 ± 9.94 , right: 81.38 ± 14.52 ; $P = 0.002$) in the right foot were significantly greater than the left foot. However, the M4-5 (left: 96.54 ± 29.2 , right: 62.34 ± 34.11 ; $P = 0.011$), MF (left: 268.07 ± 76.19 , right: 153.82 ± 59.37 ; $P = 0.000$) and HF (left: 549.28 ± 72.54 , right: 488.52 ± 69.53 ; $P = 0.045$) in the left foot were significantly higher than the right foot.

3.2. Peak pressure

There were some significant differences in PP among left and right feet (**Table 1, Figure 2**). The PP in the right foot showed significantly greater at BT (left: 119.29 ± 42.76 , right: 208.06 ± 79.33 ; $P = 0.001$), OT (left: 70.71 ± 9.27 , right: 90.23 ± 18.66 ; $P = 0.007$), M1 (left: 184.04 ± 62.97 , right: 265 ± 103.46 ; $P = 0.038$) than the left foot. The PP of the left foot in M4-5 (left: 114.83 ± 47.77 , right: 92.95 ± 23.21 ; $P = 0.011$) was significantly higher than the right foot.

3.3. Mean pressure

The MP of the right foot in BT (left: 62.12 ± 17.81 , right: 112.73 ± 38.35 ; $p = 0.001$) was higher than the left foot (**Table 1, Figure 2**). The MP of the left foot was significant higher in OT (left: 38.89 ± 7.34 , right: 48.07 ± 8.78 ; $p = 0.007$), M4-5 (left: 76.19 ± 23.05 , right: 49.74 ± 28.3 ; $p = 0.017$), MF (left: 62.72 ± 17.18 , right: 34.85 ± 13.45 ; $p = 0.000$) and HF (left: 138.50 ± 19.98 , right: 119.82 ± 17.05 ; $p = 0.018$) than the right. had significant differences in mean pressure (**Table 1, Figure 2**).

Table 1: The detail information of plantar pressure among left and right feet while player completes OFS.

Parameter	District	Left		Right		Different	T-value	p
		M	SD	M	SD			
F	BT	57.40	16.45	107.79	11.66	-50.39	-4.043	0.001*
	OT	64.92	9.94	81.38	14.52	-16.45	-3.413	0.002*
	M1	232.43	75.27	212.36	128.97	20.08	0.475	0.640
	M2-3	116.00	10.24	86.34	47.00	29.67	2.056	0.065
	M4-5	96.54	29.20	62.34	34.11	34.20	2.749	0.011*
	MF	268.07	76.19	153.82	59.37	114.25	4.202	0.000*
PF	HF	549.28	72.54	488.52	69.53	60.76	2.117	0.045*
	BT	119.29	42.76	208.06	79.33	-88.77	-3.625	0.001*
	OT	70.71	9.27	90.23	18.66	-19.51	-3.174	0.007*
	M1	184.04	62.97	265	103.46	-80.96	-2.265	0.038*
	M2-3	131.5	17.24	131.14	23.51	0.36	.046	0.964
	M4-5	114.83	47.77	92.95	23.21	21.88	1.543	0.011*
MP	MF	127.5	58.18	105.25	23.08	22.25	1.332	0.198
	HF	245.5	36.56	241.25	32.02	4.25	.299	0.768
	BT	62.12	17.81	112.73	38.35	-50.61	-4.2	0.001*
	OT	38.89	7.34	48.07	8.78	-9.17	-2.939	0.007*
	M1	122.34	39.62	111.77	67.88	10.57	.455	0.655
	M2-3	90.43	8.92	68.14	37.10	22.29	1.952	0.077
PTI	M4-5	76.19	23.05	49.74	28.31	26.46	2.567	0.017*
	MF	62.72	17.18	34.85	13.45	27.87	4.681	0.000*
	HF	138.50	18.98	119.82	17.05	18.67	2.551	0.018*
	BT	59.80	18.81	183.95	123.44	-124.15	-3.152	0.011*
	OT	36.13	10.51	78.14	22.93	-42.00	-5.630	0.011*
	M1	82.75	20.55	213.30	129.18	-130.55	-3.316	0.007*
CA	M2-3	54.74	15.04	92.43	25.18	-37.69	-4.350	0.001*
	M4-5	53.40	19.78	65.12	31.68	-12.16	-1.070	0.303
	MF	33.72	19.48	54.50	44.87	-20.77	-1.374	0.196
	HF	31.12	12.07	128.94	85.85	-97.82	-3.576	0.006*
	BT	8.96	.61	9.24	.0014	-.2757	-1.854	0.082
	OT	14.85	1.56	16.58	.6621	-1.73	-3.402	0.003*
CA	M1	19	.00	12.40	4.58	6.605	6.155	0.000*
	M2-3	12.67	.00	8.26	3.06	4.41	6.155	0.000*
	M4-5	12.67	.00	8.26	3.06	4.41	6.155	0.000*
	MF	42.95	1.33	34.81	7.93	8.142	3.376	0.007*
	HF	39.37	1.076	39.93	1.38	-.5592	-1.27	0.214

Note: * Demonstrated the significantly different level among left and right feet in tennis player while execute OFS, $p < 0.05$.

3.4. Pressure time integral

The overall PTI of players were showed in **Figure 2** and **Table 1**; the right foot of subject in BT(left: 59.8 ± 18.81 , right: 183.95 ± 123.44 ; $P = 0.011$), OT (left: 36.13 ± 10.51 , right: 78.14 ± 22.93 ; $P = 0.011$), M1

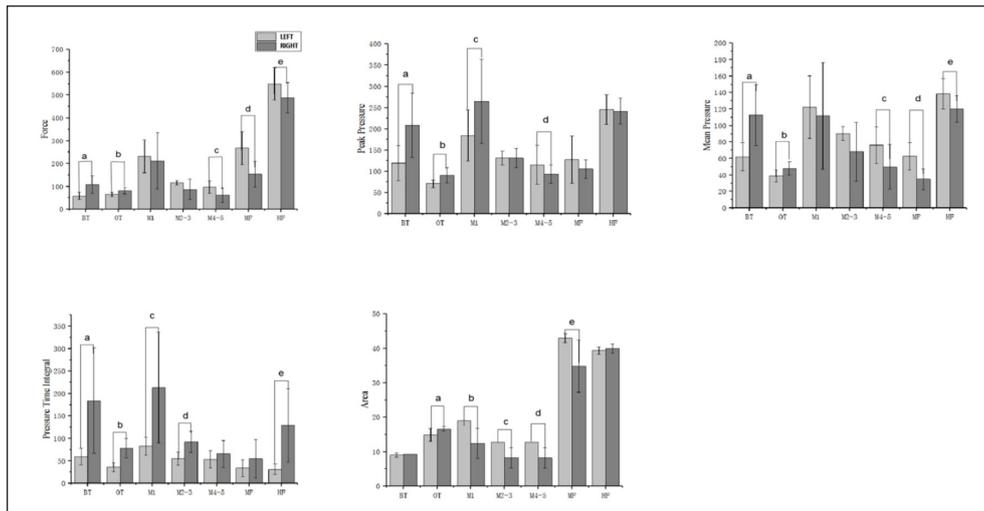


Figure 2: The comparison of plantar pressure among left and right feet.

Note: * Represented the significant difference between the peak pressure of the both feet ($p < 0.05$); **(a)** Represented the significant difference between left and right feet force values in BT ($p < 0.05$); **(b)** Represented the significant difference between left and right feet force values in OT ($p < 0.05$); **(c)** Represented the significant difference between left and right feet force values in M4-5 ($p < 0.05$); **(d)** Represented the significant difference between left and right feet force values in MF ($p < 0.05$); **(e)** Represented the significant difference between left and right feet force values in HF ($p < 0.05$).

(left: 82.75 ± 20.55 , right: 213.3 ± 129.18 ; $P = 0.007$), M2-3 (left: 54.7 ± 15.04 , right: 92.43 ± 25.18 ; $P = 0.001$) and HF (left: 31.12 ± 12.07 , right: 128.94 ± 85.85 ; $P = 0.006$) were greater than the left foot.

3.5. Contact area

During OFS, CA illustrated some significant differences in **Figure 2** and **Table 1**. The CA in the left foot was significantly larger in M1 (left: 19 ± 0.00 , right: 12.40 ± 4.58 ; $p = 0.000$), M2-3 (left: 12.67 ± 0.00 , right: 8.26 ± 3.06 ; $p = 0.000$), M4-5 (left: 12.67 ± 0.00 , right: 8.26 ± 3.06 ; $p = 0.000$), MF (left: 42.95 ± 1.33 , right: 34.81 ± 7.93 ; $p = 0.007$) than the right foot. However, the CA of the right foot in BT (left: 8.96 ± 0.61 , right: 9.24 ± 0.0014) and OT (left: 14.85 ± 1.56 , right: 16.58 ± 0.6621 ; $p = 0.003$) were significantly larger than the left foot.

4. Discussion

The purpose of this study was to analyze the changes of plantar pressure among left and right feet of female tennis players during the process of forehand shot with open stance, in order to provided data reference for the injury prevention and the improvement of sports performance of tennis players. Through the experimental test, it was found that there were significant differences between right and the left feet; (1) the F, PP and MP of the right foot in BT and OT were greater than the left foot, while the F, PP and MP of the left foot in M4-5, MF and HF were greater than the right foot; (2) the CA of the right foot was larger in OT than the left foot, while the CA of the left foot in M1, M2-3, M4-5 and MF were larger than the right foot.

When female tennis players finished OFS, there was a significant difference in F on the bottom of left and right feet. The F, PP and MP of right foot were greater in BT, OT and M1 than the left foot; while the left foot was greater in M4-5, MF and HF than the right foot. The result of F showed the difference of motion mechanisms of players' left and right feet (Gu et al. 2019). The right foot mainly relies on the forefoot to generate power and cushion during OFS, while the left foot primarily relies on the rear foot. This difference in F may be caused by the characteristics of specific movement skills (Liang et al. 2019), because the lateral movement of the open gait required the right foot to push off the ground and transfer the center of mass (COM) through the forefoot, while the left foot needed to be used as the supporting foot to keep the body's COM stable during the swing (Xu et al. 2018). Ridola and Palma (2001) showed that the foot of human body was principally in contact with the ground by three fulcrum of root bone trochanter, first metatarsal bone and fifth metatarsal bone. Based on this theory, plantar pressure was also mainly borne by the three regions. However, the fifth metatarsal bone was significantly smaller in physiological structure than the root bone trochanter and the first metatarsal bone, it borne a smaller force load during movement (Wright et al.

2011). Own to the difference of anatomical structure, M1 and HF in the feet of female tennis players in this experiment showed large CA, which higher than F, PP and MP.

The results showed that the PP refers to the maximum ground reaction force in a certain area, which could be used as an important indicator to analysis damage of relevant plantar tissues (Veves 1992). The greater PP in the plantar region demonstrated the stronger force on this region increased the possibility of injuries (Burns 2005). In this experiment, it was found that BT and OT in the right foot were significantly greater than the left foot. This indicated that female tennis players had a greater risk of foot injury, especially in the forefoot area. And this results of the study support Bylak and Hutchinson (1998) that the main foot injury of female tennis players was bunions (inflammation of the medial process of the first metatarsal), which was mainly caused by the friction between BT and M1 or shoes which affected by external forces for a long time.

In addition, the MP of left and right foot M1 and HF were relatively high when players finished OFS. Related research showed that unbalanced plantar pressure was the one of the important causes of ankle joint injury (Wong et al. 2007). Morrison and Kaminski (2007) found that the stress time of the forefoot was longer than the rear foot; with the increase of the load on the medial forefoot, the load on the lateral hind foot also began to increase. Based on this study, it can be speculated that when female tennis players complete OFS, the feet and ankle joints may have the high risk of injuries due to the imbalance of the pressure distribution of the left and right feet. In addition, PTI in this study also showed the higher in the right foot compared to the left foot while the players completed OFS. Biomechanical studies showed that the PTI was the cumulative effect of time and pressure on a certain area of the plantar region, and it could be used to judge the cumulative degree of fatigue (García-Pérez et al. 2013), which had a great significance for the prevention of plantar injury (Wong et al. 2007). In this study, the pressure on the right foot of female tennis players during OFS were higher than the left foot, that could be inferred (1) The right foot was more prone to injuries due to fatigue; (2) players mainly completed COM transfer by from the BT, OT, M1 of right foot to M4-5 and HF of the left foot. Some studies found that the impulse in the arch area of the right foot was higher than the left foot in the state of motion. The feet arch, as the elastic structure system, not merely has the function of protecting the nerves and blood vessels of the feet, but also has the function of distributing the stress of the feet evenly (Cavanagh et al. 1997). It was important to have the complete arch for the feet function, because of tennis players' right foot was the power generating foot in OFS, which needed to accomplish the power accumulation through the arch (Nigg et al. 1993, Llana et al. 2002). Therefore, the impulse of each region of the right plantar was higher than the left foot, and long-term repeated use may easily lead to deformation of the foot arch.

In this experiment, the CA of the left foot in M1, M2-3, M4-5 and MF were larger than that right foot, which can be found from the CA of the player's plantar. On the other hand, the CA of the forefoot in the right and the rear foot in left were also greatly. This trend was consist with the F of the left and right feet, and the higher F was accompanied by the larger CA.

5. Limitations

This study used biomechanical method to analyze the plantar pressure of female tennis players' during OFS. The results of this study can provide theoretical support for players' performance and plantar injuries. However, the limitations in this study were also worth paying attention to: (1) Compared with the real tennis court, the experimental environment was different. (2) The subjects recruited were second-level, and there were no more tennis players from other sports grades, so the number of the experimental samples was small. (3) The plantar division of the middle foot area and the posterior foot area were too large to analyze accurately the pressure situation of the middle foot area and the plantar lateral of the posterior foot area.

6. Conclusions

There were different mechanical mechanisms in the left and right feet while female tennis player having OFS. During the OFS, the right foot was the dominant foot and the left foot was used for supporting. It was suggested that female tennis players should pay attention to the stress of their right foot M1, HF. At the same time, the trainer should emphasis on the feet muscle strength exercise for female tennis players in order to further improve the body function and prevent the occurrence of strain and disease.

Competing Interests

The authors have no competing interests to declare.

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