ÓBUDAI EGYETEM
ÓBUDA UNIVERSITY

DOCTORAL (PhD) THESIS BOOKLET

FENGQIN FU

Enhancement of runners' performance and protection by alternative longitudinal bending stiffness of the shoes

Supervisor: Dr. habil. Gusztáv Fekete

Table of Contents

1 Summary in Hungarian Language

Napjainkban számos gyártó arra összpontosít, hogy javítsa a futóteljesítményt a futócipők hosszanti hajlítási merevségének (LBS) növelésével. Az LBS az a mechanikai jellemező, amelyet az atlétikai cipők metatarsophalangealis ízületi régiója körüli szükséges hajlítás kiszámításához használnak, amelyet az alapanyag tulajdonsága és a talp szerkezete befolyásol. Az LBS mechanizmusa azonban ma még nem ismert teljes mértékben, emiatt fontos, hogy jobban megértsük a mechanizmust és számszerűsítsük az LBS-t befolyásoló tényezőket. Ezen disszertáció célja, hogy ezeket a kérdéseket átfogó komplex módszerrel megválaszolja.

Első rész: A futócipők LBS-ének szénszál erősítésű betétekkel történő növeléséhez figyelembe kell venni a maratonsportok jellemzőit, mint például az elülső talp feszültségének problémáját a hosszú távú futás után. Ezért ennek a résznek az a célja, hogy megvizsgálja a középrészbe illesztett szénszálas lemezszerkezet független hatását az alsó végtagok biomechanikájára futás közben. Két különböző konstrukció nyomásváltozását hasonlítottam össze, a szegmentált lábfejlemez-konstrukciót (SFC) a teljes lábfejlemez-konstrukcióval (FFC) végeselem-szimuláció segítségével. A fő eredmények a középtalp maximális nyomásának csökkenését mutatták, miközben az LBS és az SFC energiavisszaadása nem változott jelentősen az FFC-hez képest. Ez jelezi, hogy a futócipők optimalizálhatók a szénlemezek alakjának megváltoztatásával.

Második rész: A futócipők LBS növelésére választott merev anyag szempontjából, különösen a női futócipők számára történő futócipők tervezésekor, figyelembe kellett venni fiziológiájukat, sportjellemzőiket és viselési szokásaikat. Ezért vizsgáltam az alsó végtag kinematikájában és kinetikájában tapasztalt (EW) és tapasztalatlan (IEW) közepes magassarkú viselők közötti különbségeket kocogás és futás közben. Az eredmények mutatják, hogy mind az EW, mind az IEW esetében nagy volt az ízületi sérülések kockázata, amikor közepesen magas sarkú cipőben futottak.

Harmadik rész: Olyan sportolók esetén, akik hozzászoktak a magas sarkú cipők viseléséhez, lényegesebb hogy tervezés során a futócipők párnázásának javítására összpontosítsunk a középrész vastagságának növelésével, különösen a láb hátsó területén.

A futócipő súlypontja a sarok vastagságának növekedésével magasabb lesz, ami befolyásolja a futás dinamikus stabilitását, ezért ennek a résznek a célja a női futócipőknek az alsó végtagok biomechanikájára és a női futók észlelési érzékenységére gyakorolt hatásainak vizsgálata volt. Az eredmények azt mutatták, hogy a 16 mm-es Heel-to-Toe Drop (HTD) és a három rétegnyi középrész (felső és alsó réteg párnázásra, középső réteg tartásra) kombinációja javítja a stabilitást és javítja a futási teljesítményt.

2 Antecedents of the Research

Studies had shown that increasing the LBS of shoes directly affected the performance of various sports such as running, jumping, sprinting, and multidirectional movements [1-4]. For example, the increased LBS of shoes improves fatigued athletes' reverse squat jump performance [6], increased LBS has been considered a treatment for these MTPJ injuries and a preventive method to reduce the risk of these injuries in athletes or reduce forefoot extension to treat injuries such as turf toe [7,8]. Roy et al. [5] and Stefanyshyn et al. [9] found that when the subjects ran on a stiffer midsole, there were approximately 1% energy savings compared to the control midsole.

From the biomechanics perspective, a stiffer shoe with natural flexion of the MTPJ was beneficial to a reduction in running energy loss [2]. Some domestic scholars also found that the MTPJ was constrained and could not walk as freely as usual in special hard-soled shoes, which showed a reduced range of motion. Still, to complete the walking movement, other joints would show corresponding compensatory signs, among which the ankle and knee joints contributed more to the adjustment of gait [10]. Nigg et al. [11] also demonstrated that increased the LBS of shoes induced an increased positive work at the MTPJ. It was similar to the findings of Toon et al. [12]. Willwacher et al. [13] emphasized that the net joint work was systematically shifted positively in the rigid condition compared to the control condition. These findings suggested that increasing the LBS of shoes induced some lower limb changes biomechanical, particularly in the MTPJ, enhancing running performance. In a study by Qiujie Li et al. [8], it was shown that the LBS of running shoes showed a significant "U" shaped relationship with the mechanical negative work at the MTPJ during jogging.

Also, in comparing different LBS of sports shoes, it was found that the center of pressure and the direction of pressure in the human body was shifted after the intervention with additional LBS of sports shoes. The reason for that was the degree of ankle valgus, hip adduction and pelvic tilt decreased as the LBS of the shoe sole increased. It was affected the internal load of the hip, knee, and ankle joints, and even caused injury [18]. As described, biomechanics characteristic of lower limbs about increasing the LBS has been widely investigated, mainly including kinematics and kinetics analysis of lower limbs' joints (MTPJ joint, ankle joint, and knee joint). Biomechanics and subjective feelings of runners were rarely combined in research.

Most studies had changed the LBS of running shoes by adding carbon fiber plates or adding other stiff materials to the midsole to improve LBS [14]. It was notable that the track shoes inserted with carbon fiber plates, such as the Nike Vaporfly 4% (VF) shoe combined both advances in midsole thickness and LBS to reduce energy loss by about 4% for runners, which was contributed to improving running performance [15, 16]. However, the role of carbon fibre plates embedded in running footwear midsoles on running injuries remains unclear. What's more, the LBS of the shoes may influence the occurrence of metatarsal stress fractures by modulating the peak pressure acting on various regions of the foot [17]. The midsole of race running shoes inserted carbon fiber plate increased the LBS of shoes and affected the strain force at the MTPJ. There was evidence that fatigue of the thumb muscles increased the pressure on the second metatarsal, which may lead to an increased risk of stress fractures [7,8]. Therefore, this thesis is focused on these undressed questions.

3 Objectives

In my thesis, I would like to draw up three research questions that have been unanswered so far in the relevant literature. Therefore, my objectives are the followings:

1st research question: Previous studies mainly focused on increasing the LBS of the shoe by embedding the full carbon fiber plate to midsole such as the Nike Vaporfly 4%. No study compared differences between full and segment carbon fiber plate.

1st objective: To investigate whether a forefoot carbon-fiber plate, inserted into the midsole, can alter physiological properties such as plantarflexion angular velocity, power, etc. in order to achieve higher running performance. It is also my question How much can the shape of the plate alter the running performance?

2nd research question: most studies on improving sports performance by increasing the LBS of running shoes had focused on male runners, But, gender differences in lower extremity structure and running models were obvious. What's more, over 60% of participants in the half marathon are female runners who have different wearing habits.

2nd objective: To identify those factors or parameters, which have the most influence on gait movement, and to implement them in our shoe design methodology. Carry out gait analysis on a group of people who regularly wear high-heel shoes and on another group who are inexperienced in these sorts of shoes.

3rd research question: It was twice to suffer specific running injuries in female runners than that of male runners, such as patellofemoral pain, Plantar fasciitis and so on which was related to cushioning of shoes. What kind of structure of midsole is benefit to motion control? how can combine reducing risk of injuries and running economic with the regard to shoe design?

3rd objective: To determine the structure and material of midsole, according to the characteristic of a group of people who regularly wear high-heel shoes. What kind of structure of midsole is benefit to motion control? Which material is better for improving running performance? Last but most important, how can combine reducing risk of injuries and running economic with the regard to shoe design?

4 Research Methods and Challenges

This dissertation relies on a multidisciplinary approach combining expertise in biomechanics, finite element simulation, mechanical testing and subjective perception. Through these methods, we can better understand the human movement characteristics, the correlation between people and shoes, and how to better quantify the improvement indicators of shoe products. The specific research methods are as follows:

Mechanical testing Data Collection: Mechanical impact measurement took the final five impacts from 30 repetitive im-pacts by an impact tester (Brentwood, NH, USA) on the experimental shoes with a drop height of 5.0 mm and a drop mass of 8.5 kg.

Mechanical flexion measurements fixed the forefoot area in the location of 70%-foot length (heel to toe) (Figure 22), then bending at 45 degrees was performed by applying a dynamic shoe flexor device (Brentwood, NH, USA) to measure the shoe LBS and energy return.

Finite Element Simulation: The outsole, midsole, and two kinds of carbon fiber plate had been modeled in 3D based on an industrial 2D shoe design drawing with Rhino 6 Computer-Aided Design (CAD) software (Robert McNeel & Assoc, Seattle, WA, USA). The carbon plate built-in midsole divides the midsole into two layers. The thickness of the upper midsole of the forefoot accounts for about 60%, and the thickness of the upper midsole of the heel accounts for about 36%. A meshing of the shoe has been done with ABAQUS software by this CAD model (Dassault Systemes Simulia Corp, Johnston, RI, USA) that the discretization was 2.7 mm. All of the solid parts were assembled into a whole sole model, then imported into the FE package ABAQUS (Dassault Systemes Simulia Corp, Johnston, RI, USA) to develop the numerical model. To simulate the flexion mechanical test, the sole model was first positioned on two rigid plates, corresponding to the virtual flexing machine: fixed and flexing one. The sole was camped to the fixed plate by applying a 900 N to toe clamp at a 70%-foot length (heel to toe) while the heel end was on the flexion plate (Figure 3), and the flex angle was 45 degrees. In this study, the midsole was made of Polyetherblockamide foam (Pebax®, UBESTA, Yubu Xingchan Co., Ltd, Yubu, Japan). Thus, to determine mechanical properties for finite element analysis, this material was tested at quasi-static rates by using a universal material test machine. Compression tests were performed according to the ASTM-575 standard using cylinder specimens (diameter: 28.6 mm. thickness: 12.5 mm) at a 10 mm/min speed. The specimen density was 0.12 g/cm3. Force-displacement data were obtained from the quasistatic tests and converted to stress-strain data using the sample dimensions. The Ogden hyper foam material model was chosen to represent the non-linear response of the Pebax® foam obtained from the experiments. This model describes a compressible and nonlinearly elastic behavior. The hyper foam material constants for Pebax® foam were $\mu = 0.28$, $\alpha = 5.177$, Poisson's ratio = 0.125. To determine the mechanical properties of the reinforced carbon fiber plate, a three-point bending test was carried out using the material testing machine with a speed of 1 mm/min. The test samples were prepared according to ASTM-D790: 1 mm thickness, 18 mm width, and 80 mm length strips were cut from an original plate with the help of an electrical power saw. The specimen density was 1.1 g/cm3. Young's modulus (E) was obtained from the mechanical test = 33,000 MPa and Poisson's ratio = 0.4. The sole, made of foam, was discretized using tetrahedral elements with an average size equal to 2.7 mm. The carbon fiber plate was also discretized, using tetrahedral elements with an average size equal to 1 mm. A convergence study has been performed to confirm if the mesh density was acceptable. Finally, the simulation was performed in Abaqus using the Dynamic Explicit solver.

Biomechanical Data Collection: For GRF and 3D kinematic measurements, participants ran across a set up of three consecutive and flush into the floor force plates (combined dimensions 270 × 60 cm, 1000 Hz (AMTI, Watertown, MA, USA)) in each shoe condition. The two-timing gates 8 m far from the middle force plate were used to record the running speed (Smart speed, Burbank, CA, USA) set 8 m apart, centering the middle force plate. Right leg kinematics were collected at 250 Hz and were collected using a 10-camera motion analysis system in a capture volume of 4.0 × 1.0 × 1.5 m (Vantage 5, Vicon, Metrics Ltd., Oxford, UK).. The right thigh, the right shank, the right foot (forefoot and rearfoot) were defined as segments by attaching retro-reflective markers of fourteen millimeters in diameter on the skin of the right and left anterior superior iliac spine (ASIS), the right and the left posterior superior iliac spine (PSIS), the right greater trochanter, the medial and lateral epicondyle of the femur, the medial and lateral malleolus, as well as attached to the shoe, representing the first and fifth metatarsal heads and second toe. Three marker tracking clusters were attached to the lateral side of the thigh and the lateral side of the lower leg. The extra reflective markers were added to the distal, proximal heel, and lateral rearfoot, respectively, and were defined as shoe-mounted tracking markers. A static trial was conducted before data collection. We used the Vicon Nexus 2.7 and Visual3D (C-Motion, Germantown, MD, USA) to process the collected experimental data. A fourth-order low pass Butterworth filter was used with a cut-off frequency of 100 Hz (kinetic) and 10 Hz (kinematic).

Subjective Perception: Testing took place simultaneously with biomechanical data collection, with participants filling in on the questionnaire immediately after completing the eight successful trials required for the respective shoe condition.

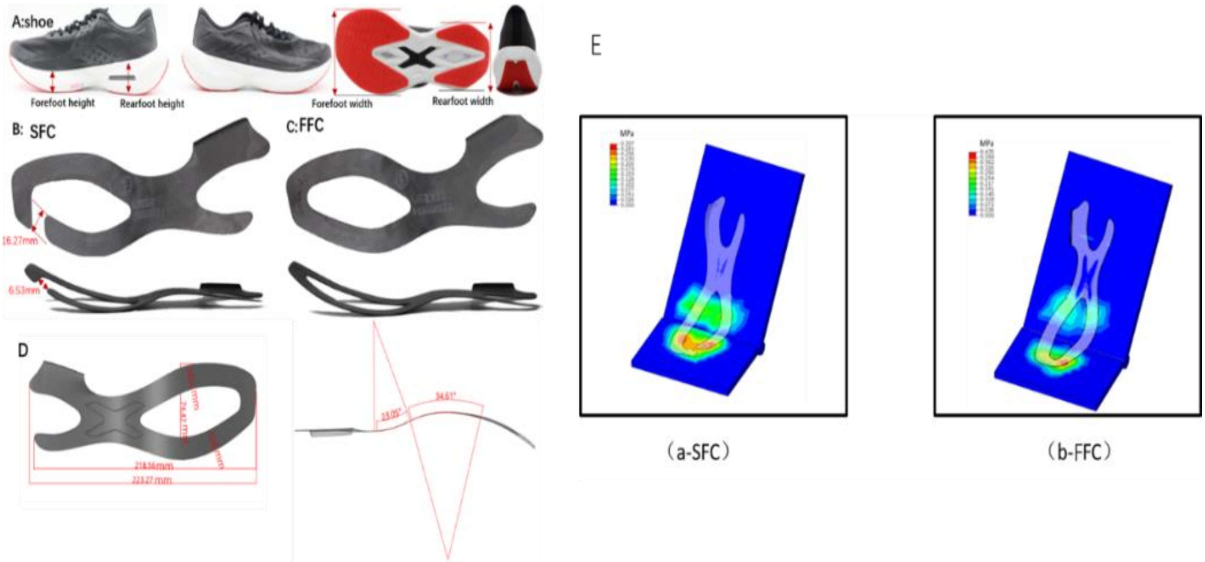
Runners assessed six perception variables (shoe weight, fit, arch support, cushioning, stability, over preference) on a questionnaire that had been repeatedly highlighted in some papers. Fifteen cm visual analogue scale (VAS) was carried out, these had been previously applied for running footwear assessment.

Challenges: There are some challenges for it. First, long distance running will cause runners to sweat a lot, which will affect the accuracy of the data collected by the equipment. Then there is no experimental evidence supporting this idea and future studies will need to investigate the influence of racing running shoes with a stiff plate on long-distance running performance for female runners, because most female runners can't run a long distance when running with a pair of shoes inserted high stiff carbon plate. Last, some innovative structural ideas cannot be realized quickly by existing processes.

5 New Scientific Results

1st Thesis point: I investigated the independent effect of forefoot carbon-fiber plate, inserted into the midsole, and I deduced the following scientific results:

- By inserting the carbon-fiber plate, I could increase the peak plantarflexion angular velocity on the metatarsophalangeal joint by 20% with fast speed. This increased angular velocity will be benefit to propulsion phase during running for runner.
- I deducted that if a carbon-fiber plate is used only in the midsole, not a full forefoot plate, then this configuration will result in increased positive work at the knee joint by 9%, and a reduction of maximum pressure on the midsole by 29%. It could reduce the risk of injuries such as metatarsal stress fractures and plantar fasciitis by decreasing stress on the metatarsal region, especially the second metatarsal region.
- Based on my numerical and experimental results, I concluded that changing the shape of the carbon plate does not affect the running performance (the difference is less than 1%). Therefore, the simplest shape can be chosen for use since the biomechanical parameters will not be affected while the manufacturers can inexpensively produce these plates.



Related articles to the 1st thesis point:

[1]**Fu, F**., Levadnyi, I., Wang, J., Xie, Z., Fekete, G., Cai, Y., & Gu Y. (2021). Effect of the Construction of Carbon Fiber Plate Insert to Midsole on Running Performance. MDPI: Materials, 14, 51-56. **IF: 2.623, Q2**

[1]**Fu, F.Q**., Wang, S., Shu, Y., et al., A Comparative Biomechanical Analysis the Vertical Jump Between Flatfoot and Normal Foot. Journal of Biomimetics, Biomaterials and Biomedical Engineering. Trans Tech Publications, 2016. 28, 26-35. **Q4**

2[nd] Thesis point: I investigated the biomechanical differences of people who are experienced and inexperienced (IEW) in wearing high-heel shoes. The main reason was to identify the most influencing common parameters and those which are different between the two groups.

I experimentally deduced that both groups, experienced moderate high-heel wearers and inexperienced moderate high-heel wearers, regulate their stride speed through stride length. This is the common parameter.

I also experimentally deduced that the experienced moderate high-heel wearers group had higher GRF results by 11%, which means that these people are subjected to 31% higher vertical average loading rate than the inexperienced moderate high-heel wearers group. Due to this fact, this group is more exposed to the risk of injury in the musculoskeletal system of the lower limbs. This is a different parameter.

Furthermore, I also experimentally deduced that the inexperienced moderate high-heel wearers group use 12% higher stride frequency to regulate the stride speed. This is a different parameter, which helps to compensate for the reduced balance.

As a conclusion, in the design of running shoes for EW should pay more attention to the cushioning of rearfoot while enhancing the stability of shoes during running for IEW was a curial point for manufacturers.

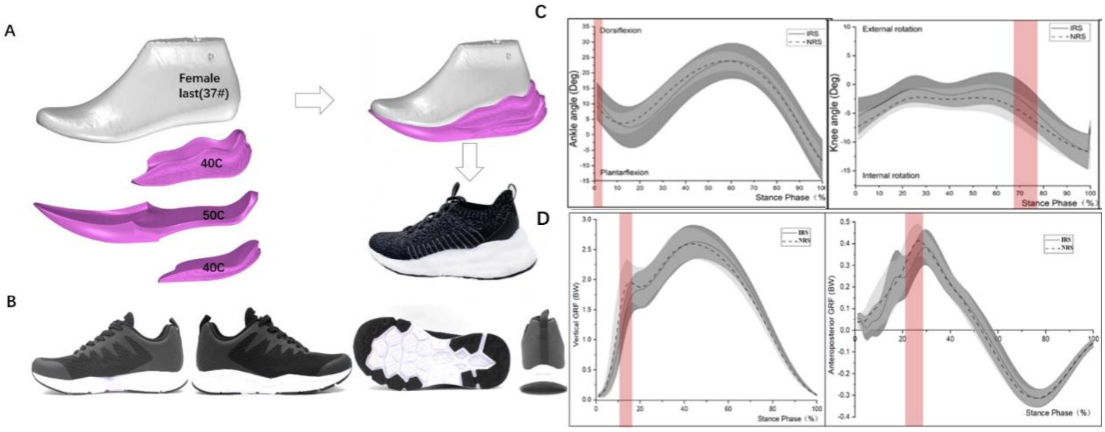
Related articles to the 2[nd] thesis point:

Fu, F., Zhang, Y., Shu, Y., Gu, Y. (2016). Lower-limb mechanics during moderate high-heel jogging and running in different experienced wearers. Human movement science, 48, 15-27. **IF:1.955, Q2**

3rd Thesis point: I investigated the effects of innovative running shoes (high heel-to-toe drop and special structure of midsole) on the biomechanics, and I deduced the following scientific results:

- By choosing the stiff material to increase the longitudinal bending stiffness of innovative running shoes, I could decrease the metatarsophalangeal joint range of motion by 9%, and peak metatarsophalangeal plantarflexion moment by 13%. These biomechanical changes will be benefit to greatly reduce the work by metatarsophalangeal joints and improve the economy of running.
- I deducted that increasing the height of the rearfoot to 32mm and offset to 16mm, then this configuration will result in a reduced peak braking force by 9%, average vertical force transient by 22%, peak vertical force transient by 37%, and peak vertical force by 9% during running. It could be benefit to release ground impact force on musculoskeletal tissue which is related to reduce risks of running injuries.
- Adjusting the hardness composition of the midsole in innovative running shoes into three layers of the midsole (up and lower layers were for cushioning: 40Asker C, the middle layer was for support: 50Asker C), induced 23% smaller knee internal rotation angle while it did not cause significant changes (difference is less than 1%) at the joint (knee and ankle) torques.

Based on my numerical and experimental results, I concluded that innovative running shoes would benefit the industrial utilization of shoe producers in the light of reducing the ground impact force and strengthening the running economy by decreasing the metatarsophalangeal joint work for experienced moderate high-heel wearers.



Related articles to the 3rd thesis point:

[1]**Fu, F.Q.,** Guo, L.M., Tang, X.F., Wang, J.Y., Xie, Z.H., Fekete, G., Cai, Y.H., Hu, Q.L., Gu, Y.D., Effect of the innovative running shoes with the special midsole structure on the female runners' lower limb biomechanics. Frontiers in Bioengineering and Biotechnology, 2022, 10, 866321. **IF: 5.48, Q1**

Isherwood, J., Rimmer, E., [3]**Fu, F.Q.**, et al. Biomechanical and Perceptual Cushioning Sensitivity based on Mechanical Running Shoe Properties. Footwear Science, 2021. (5), 221-231. **IF：0.6, Q3**

6 Possibility to utilize the Results

The Contemporary Good Design Award (CGD) was an international design award organized by the German Red Dot Award organization. In contrast, the red dot design museum Essen was the primary support of the red dot product design award and the red dot brand and communication design award, the red dot design museum Singapore was the primary support of the red dot design concept award, and the red dot design museum Xiamen was the primary support of the recent good design award. In 2015, the German Red Dot Award organization and Xiamen Media Group launched the Contemporary Good Design Award. Red Dot was responsible for the organization of the international jury and the selection of works, using more than 60 years of experience in operating top international design awards and design resources to ensure the professionalism, seriousness, and authority of the Contemporary Good Design Award. The products that stand out would be honored to recognize their outstanding design achievements and receive professional services from the winners. The product with a 16mm HTD and three layers of the midsole won the Contemporary Good Design Award in 2020. The product can become one of the preferred running shoes for female runners

7 References

1. Lam, W.K., Lee, W., Lee, W.M., et al., Segmented forefoot plate in basketball footwear - Does it influence performance and foot joint kinematics and kinetics? J Appl Biomech, 2017. 34(1), 1.
2. Worobets, J., Wannop, J.W., Influence of basketball shoe mass, outsole traction, and forefoot bending stiffness on three athletic movements Sports Biomech, 2015. 14(3), 351-360.
3. Tinoco, N., Bourgit, D., Morin J.B., Influence of midsole metatarsophalangeal stiffness on jumping and cutting movement abilities. P I Mech Eng P-J Spo, 2010. 224(209-217).
4. Toon, D., Vinet, A., Pain, M., et al., A Methodology to Investigate the Relationship between Lower-Limb Dynamics and Shoe Stiffness Using Custom-Built Footwear. P I Mech Eng P-J Spo, 2011. 225(1), 32-37.
5. Leardini, A., Benedetti, M.G., Catani F., et al., An anatomically based protocol for the description of foot segment kinematics during gait. Clinical Biomechanics, 1999. 14(8), 528-536.
6. Krell, J.B., Stefanyshyn, D.J., The relationship between extension of the metatarsophalangeal joint and sprint time for 100m Olympic athletes. Journal of Sports Sciences, 2006. 24(2), 175-180.
7. Stefanyshyn, D.J., Wannop, J.W., The influence of forefoot bending stiffness of footwear on athletic injury and performance. Footwear Science, 2016. 8(2), 51-63.
8. Yan, P., Effect of sneaker shoe sole design on biomechanical characteristics of lower extremity. China Leather, 2017.
9. Lemont, H., Ammirati, K.M., Usen, N., Plantar fasciitis: a degenerative process (fasciosis) without inflammation. Journal of the American Podiatric Medical Association, 2003. 93(3), 234-237.
10. Mizrahi, J., Verbitsky, O., Isakov, E., et al., Effect of fatigue on leg kinematics and impact acceleration in long-distance running. Hum Movement Sci, 2000. 19(2), 139-151.
11. Nigg, B.M., Segesser, B., Biomechanical and orthopedic concepts in sports shoe construction. Med Sci Sports Exerc, 1992. 24(5), 595-602.
12. Hasegawa, H., Yamauchi, T., Kraemer, W.J., Foot strike patterns of runners at the 15-km point during an elite-level half marathon. Journal of Strength and Conditioning Research, 2007. 21(3), 888-893.
13. Willwacher, S., Koenig, M., Potthast, W., et al., Does specific footwear facilitate energy storage and return at the metatarsophalangeal joint in running? J Appl Biomech, 2013. 27(5), 583-592.

14. Stefanyshyn, D., Fusco, C., Increased shoe bending stiffness increases sprint performance. Sports Biomech, 2004. 3(1), 55.
15. Willwacher, S., Nigg, K.M., Braunstein, B., et al., The gearing function of running shoe longitudinal bending stiffness. Gait Posture, 2014. 40(3), 386-390.
16. Hébert-Losier, K., Finlayson, S.J., Driller, M.W., Metabolic and performance responses of male runners wearing 3 types of footwear: Nike vaporfly 4%, saucony endorphin racing flats, and their own shoes. J. Sport Health Sci, 2020.
17. Arum, T., Finite element modeling of the human foot and footwear. In Proceedings of the ABAQUS Users' Conference, Bos-ton, MA, USA, 2006. 23–25 May.
18. Parker, K.R., The effects of a rigid shoe midsole on plantar fasciitis in runners. University of Ottawa, 2006.

8 Publications

8.1 Scientific Publications related to the Thesis Points

1. **Fu, F.Q**., Guo, L.M., Tang, X.F., Wang, J.Y., Xie, Z.H., Fekete, G., Cai, Y.H., Hu, Q.L., Gu, Y.D., Effect of the innovative running shoes with the special midsole structure on the female runners'lower limb biomechanics. Frontiers in Bioengineering and Biotechnology, 2022, 11. **IF: 5.48 Q1**
2. **Fu, F.,** Levadnyi, I., Wang, J., Xie, Z., Fekete, G., Cai, Y., & Gu Y., Effect of the Construction of Carbon Fiber Plate Insert to Midsole on Running Performance. MDPI: Materials, 2021. 14, 51-56. **IF: 2.623 Q2**
3. Isherwood, J., Rimmer, E., **Fu, F.Q.,** et al. Biomechanical and Perceptual Cushioning Sensitivity based on Mechanical Running Shoe Properties. Footwear Science, 2021. (5), 221-231. **IF: 0.6 Q3**
4. **Fu, F.Q.**, Wang, S., Shu, Y., et al., A Comparative Biomechanical Analysis the Vertical Jump between Flatfoot and Normal Foot. Journal of Biomimetics, Biomaterials and Biomedical Engineering. Trans Tech Publications, 2016. 28, 26-35. **Q4**

5. **Fu, F.**, Zhang, Y., Shu, Y., et al., Lower limb mechanics during moderate high-heel jogging and running in different experienced wearers. Human movement science, 2016. 48, 15-27. **IF: 1.955 Q2**

8.2 Additional Scientific Publications (optional)

1. Wang, M., Fu, L., Gu, Y., Mei, Q., **Fu, F**., Fernandez, J. (2018). Comparative study of kinematics and muscle activity between elite and amateur table tennis players during topspin loop against backspin movements. Journal of Human Kinetics, 64, 25-33. **IF: 2.932 Q3**

2. **Fu, F**., Zhang, Y., Shao, S., et al., Comparison of center of pressure trajectory characteristics in table tennis during topspin forehand loop between superior and intermediate players. International journal of Sports Science & Coaching, 2016. 11(4), 559-565. **IF: 0.519 Q3**

3. Mei, Q., Gu Y., **Fu, F.**, et al., A biomechanical investigation of right-forward lunging step among badminton players. Journal of sports sciences, 2016. 1-6. **IF: 2.713 Q1**

Additional Scientific Publications in conferential proceedings

1. Fu Fengqin, Comparative study of kinematics between superior and amateur football players during playing football in situ. The 4th International Science and Football Conference (ISAFA) 2017. At: Ningbo, China.

2. FENGQIN FU, YANG SHU, Yaodong Gu. A comparative biomechanical analysis of vertical jump between flatfoot and normal foot. The 6th Asian Society of Sports Biomechanics Conference (ASSB) 2016. At: Ningbo, China.

Scientific Research Projects Related to the Thesis

1. Research and development of personal professional marathon running shoes for Dong Guojian (First place record of Marathon track and field in China)
2. Comparative study on running technique between top-elite and sub-elite marathon runners in China.
3. Research and development of professional sprint spikes shoes.
4. Research and development of professional 5000m-10000m long distance running spikes shoes.
5. Research and application of key techniques in 110m of Xie wen jun (Men's 110th Birmingham International Diamond League in 2019).
6. Research on optimization of key technical parameters for Provincial track and field team （Yunnan, Ningxia, Qinghai and Jiang xi Provinces).
7. Research and development of sprint characteristics based for track running shoes.