ÓBUDAI EGYETEM
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DOCTORAL (PhD) THESIS BOOKLET

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Biomechanical exploration on long-distance running forefoot injury mechanism and implication for footwear design optimization

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1 Summary in Hungarian Language

Annak ellenére, hogy hosszú ideje foglalkoznak a futás közbeni sérülések mechanizmusának felderítésével, kevés kutatás vizsgálta részletesebben a hosszú távú futás közben kialakuló többdimenziós lábfejdeformitásokat, illetve ennek következményeként a konkrét lábsérülések kezdeti kialakulási mechanizmusait. Látható módon a hagyományos vizsgálati módszerek korlátozottan alkalmazhatóak az élő láb szerkezetének mozgás közbeni vizsgálatára, ugyanakkor a véges elem technikák egyre inkább alkalmazottak biomechanikai struktúrák belső állapotainak vizsgálatára különböző terhelési körülmények között. A disszertáció témája ezeknek a kérdéseknek a részletes és pontos módszerrel történő vizsgálata.

A vizsgálatot azzal kezdődtem, hogy kísérleti módszerekkel mértem a lábfej többdimenziós változásait 5 és 10 km-es futás előtt és után azonnal majd feltártam a lábfej elülső része sérüléseinek (kék köröm (BT) és metatarsális stressz törések (MSF)) belső mechanizmusát. A kutatás eredményei azt mutatták, hogy a hosszú távú futás után csökkent a lábfej szélessége és a lábfej boltozatának magassága, miközben növekedett a lábfej bőrének hőmérséklete, ami a bütyksödés okozta kellemetlenséggel és túlzott lábfej-futócipő közötti súrlódó kölcsönhatással járt, növelve a BT sérülés kialakulásának kockázatát. A futócipő elégtelen ujjtér kialakítása korlátozza az ujjak járás funkcióját, ami további ismétlődő súrlódást okozhat a lábfej és a futócipő között, és ezzel tovább növelheti a BT sérülés kockázatát.

Az MSF sérülés mechanizmusával kapcsolatban kiderült, hogy a hosszú távú futás közben teljes talpi kontaktra utaló mintázatot okoz, a lábfej-alap érintkezés a lábfej külső élére koncentrálódik, a lábboltozat magassága csökken és az ujjak dinamikus funkciója is veszélyeztetetté válik, ennek következtében az elülső lábtalp terhelése részlegesen áttevődik a felső középső metatarsus felé, ezáltal növelve az előfordulási gyakoriságát a medial MSF-nek.

Ezt követően elkészítettem a lábfej-futócipő 3D modelljét, valamint a macskalábfej szintén 3D modelljét, majd elvégeztem az FE szimulációkat a lábfej-futócipő interakció futás közbeni vizsgálatára és a macskalábfej biomechanikai válaszának értékelésére, magaslatról történő leérkezés közben. A javasolt lábfej-futócipő modell érvényességének biztosítása érdekében mind a talp, mind a cipőtalp területeit négy részre osztottam összehasonlítás céljából, majd a Bland-Altman módszert alkalmaztam a módszerek közötti konzisztencia elemzésére. A futás szimulálásával meghatároztam a távolság változását a hüvelykujj és a futócipő elülső pontja között futás közben annak érdekében, hogy megfigyeljem a lábfej-futócipő interakciót a cipő felső részének eltávolítása nélkül.

Az eredmények jó egyezést mutattak a kísérletileg mért és a numerikusan kapott eredmények között. A macskalábfej nyugalmi állapotbeli és az állat leugrása szimulációjának eredményei azt mutatták, hogy a nagyobb feszültség a metacarpus szegmensre koncentrálódott, míg a kisebb feszültségek a phalangus részen, beleértve a proximális, középső és disztális szegmenseket. Az eredmények azt mutatták, hogy a megemelt MP szegmens az elsődleges feszültségi hely, és fontos szerepet játszik az MCP és a csuklóízület közötti merev csomópont létrehozásában, stabilizálva a distalis végtagot. Ezenkívül a mancspárnák segítenek optimalizálni a feszültségeloszlást a phalanx régióban.

Összefoglalva, ez az értekezés egy komplex vizsgálati eljárást alkalmazott a kísérleti módszerek és a számítógépes szimulációk kombinálásával a futócipők optimalizálása és a lábfej elülső része sérüléseinek megelőzése érdekében.

2 Antecedents of the Research

As one of the convenient and low-cost forms of exercise, running has attracted extensive participation by people of all age groups around the world [1,2]. The possibility of obtaining multiple benefits such as weight loss, improved cardiovascular health, and stress relief makes it no surprise that the number of runners and running events has grown progressively during recent years [1,3,4]. More participants tend to run long distances in order to gain further benefits from a long-term perspective. It has been reported that the number of runners has doubled, and the number of marathon finishers has shown an exponential increase over the past decade [3]. For instance, at least 344,000 marathon runners finished the “New York City Marathon” from 2010 to 2017, which is more than 10 times compared to ~25,000 in 1970–1979 [5]. More recently, the 2021 New York City Marathon has seen 25,020 finishers among 30,000 people ran in this event even under the COVID-19 pandemic [6].

Wide participation in running, especially the prolonged distance, has been found to be associated with a higher injury rate of foot [7–14]. As the only interface that may be responsible for both the contact and propulsive motion during running based on the individual’s strike patterns, the forefoot has been previously demonstrated to be a high injury site due to the large loads and the repetitive nature of running [15]. The most common overuse injuries affecting the forefoot are pain across the metatarsal bones, metatarsal stress reactions and metatarsal stress fractures (MSF) [15]. Meanwhile, among other forefoot injury complaints, dermatologic issues are also frequently encountered particularly over longer distances [9,10,12,13]. Bruised toenail (BT), also known as Jogger’s toe, which appear as a collection of blood below the nail plate of the longest toe, is one of the most common types of forefoot dermatologic injuries that can bedevil runners after a race [16]. These common injuries can lead to significant pain due to the pressure forces that develop at the corresponding area and may cause temporary limitations of activities, which highlights the urgency to reveal the potential development mechanisms of these specific running injuries and propose the prevention strategies [17,18].

Running-related injuries (RRIs) can be caused from multiple aspects. Despite a longstanding interest in the running injury mechanism exploration, there has also been little research investigated more fully the multidimensional foot alterations (kinematics, kinetics, morphology, infrared thermography, etc.) during long-distance running, and subsequently the initial development mechanisms of specific foot injuries. For example, how forefoot kinematics during running might relate to foot structure and how this might further relate to forefoot injury (e.g., MSF) have not been fully analyzed. For the development of injury prevention strategies, a thorough understanding of foot biomechanics before and after running is prerequisite. In addition, to the author's knowledge, there is currently no study conducted quantitative analysis on dermatologic issues partly because of the fact that many of these dermatologic injuries are minor in nature. Most of the prior research were case studies or epidemiological studies based on questionnaires. However, experimental analysis can offer more accurate information in terms of injury mechanisms and protection strategies. Therefore, this dissertation mainly focuses on these undressed questions.

Not only alterations happened on foot might relate to forefoot injuries, but shoes may also play an important role during this process. It was previously demonstrated that wearing inappropriate shoes for a long-time exercise would add the odds and risk for foot injuries [19,20]. For example, the great toe might be more subject to toenail injury (e.g., BT) if the shoe has a shallow toebox [7]. Thus, developing a comprehensive approach to investigate the effects of shoe characteristics on foot variables could not only help to prevent injuries but also promote the optimization of footwear product design. Currently, traditional approaches are limited to investigating the in vivo structure of the foot during locomotion. While on the contrary, finite element (FE) methods have been increasingly applied for biomechanics analysis because of their capability of revealing the internal states within bony structures under different loading conditions, which offers an accurate alternative for fast and efficient footwear assessment [21–25]. Meanwhile, it is also worth noting that the animal bionic research has been increasingly conducted and applied for designing footwear or equipment [26–28]. For instance, the special morphological structure of the feline paw allows it to absorb two to three times of the body weight (BW) while landing from a height, which may provide an inspiration for the footwear cushioning feature. Based on the above findings in terms of forefoot injury mechanisms, this dissertation further aims to propose a completed workflow combining experiments and computational simulation for footwear optimization and forefoot injury prevention.

3 Objectives

The first objective: To quantitatively reveal the intrinsic mechanism of BT injury development and verify the previously proposed injury mechanism of MSF during long-distance running. This aim is to be accomplished by investigating the multidimensional alterations happened to the forefoot segments during 10 km of running.

The second objective: To propose an efficient and accurate approach that can be used to realistically determine the foot-shoe interaction in case of running and further contribute to optimize the design of the shoe toebox in order to reduce the injury risk of BT. This aim is to be accomplished by establishing a fully coupled 3D foot-running shoe FE model, on which the experimental data will be applied for running simulation.

The third objective: To explore the buffering characteristics of the feline distal limb during landing and further apply it to optimize the design of the shoe insole in order to reduce the injury risk of MSF. This aim is to be accomplished by establishing a 3D feline paw FE model and investigating the internal stress distribution of the distal joint limb during landing from different jump height (0.6m, 0.8m, and 1.0m) respectively.

4 Research Methods and Challenges

Methods: This work combined experimental test and FE simulation to reveal the intrinsic mechanism of forefoot injury development (BT and MSF) during long-distance running and further contribute to optimize the design of the running shoe in order to reduce the corresponding forefoot injury risk.

The dissertation began with the experimental measurement to describe the multidimensional alterations of the foot before and immediately after 5 km and 10 km of running. An eight-camera Vicon motion capture system (Oxford Metrics Ltd., Oxford, United Kingdom) was used to capture the marker trajectory data through Oxford foot model (OFM), an in-ground AMTI force platform (AMTI, Watertown, MA, United States) was used to record the GRF data, a 3D foot scanner (Easy-Foot-Scan, OrthoBaltic, Kaunas, Lithuania) was used to collect the foot morphology data, an infrared camera (Magnity Electronics Co. Ltd., Shanghai, P.R. China) was used to measure the foot skin temperature data, the visual analogue scale (VAS) was used to calculate the subjective-perceived comfort, and a high-speed digital camera (Fastcam SA3, Photron, Japan) was used to collect the gap length between the hallux and toebox of the shoe. The same researcher conducted all procedures and data analyses to ensure consistency.

Regarding to the computational simulation, the reverse engineering technology was used to acquire geometrical data of foot, footwear, and distal forelimb structures of the cat and establish the corresponding 3D models. Firstly, the foot-shoe and distal limb geometries were reconstructed from the high-resolution CT image using Mimic (Materialise, Leuven, Belgium). Secondly, for surface smoothing and solid model creation, the reconstructed geometries were imported into reverse engineering software (Geomagic (3D Systems, South Carolina, United States) and Solidworks (Dassault Systèmes, Massachusetts, United States)). Within the reverse engineering environment, some other basic structures such as cartilages, plantar fascia and ligaments were further created based on the anatomical structure. Lastly, the coupled models were established by aligning and assembling the corresponding structures.

Moreover, the FE analysis through ANSYS (ANSYS, Pennsylvania, United States) was utilized to simulate the foot-shoe interaction and evaluate the biomechanical response of feline distal limb under landing condition. The boundary and loading conditions were determined by the data inputs from the experimental part, and the simulated pressure distribution of the foot, footwear, and forelimb was compared to the corresponding experimental data measured by Novel pressure measurement systems (Novel GmbH, Munich, Germany) for model validation.

Challenges: In order to reveal the potential development mechanism of running-related forefoot injuries (BT and MSF), this dissertation integrated several experimental measurements to describe the multidimensional alterations in the foot before and immediately after 5 km and 10 km of running, which includes subjective comfort, kinematics, kinetics, morphology, thermography. Currently, the challenges faced include the susceptibility of certain tests to uncontrollable factors. For instance, subjective comfort tests highly dependent on the participants' subjective judgment, while kinematic testing demands stringent experimental environment requirements, and infrared temperature testing is susceptible to indoor temperature variations. Therefore, these biomechanical results during long-distance running need to be further validated.

This dissertation further integrated experimental measurements and computational simulation to propose two FE models with the aims to provide fast approach for running shoe design optimization and forefoot injury prevention. Foot modeling is a complex task that requires significant progress in various areas to achieve an integrated solution. Currently, no comprehensive foot model exists that can be directly applied to different scenarios. To develop such a model, several key challenges need to be addressed, including reliable data information for geometry reconstruction, the balance between accurate details and computational cost, accurate representations of material properties, realistic boundary and loading conditions, and thorough model validation. To ensure accurate simulations, mesh sensitivity testing is crucial for each component to determine the appropriate mesh size based on their material properties and size. Moreover, a significant number of simulations are required to obtain a reliable and convergent result. Therefore, further research and development are needed to address these challenges and create an integrated foot model that can be widely applicable.

5 New Scientific Results

1st Thesis point: I investigated the underlying mechanisms of forefoot injury development (BT and MSF) during 10km of running from multidimensional perspectives. Based on my experimental results, the injury development mechanisms of BT have been quantitatively deduced for the first time and the mechanisms of MSF injury have been further confirmed.

- The reduced ball width and arch height of the foot while increased foot skin temperature (increase in sweat) after long distance running were accompanied by hallux discomfort and excessive foot-shoe interaction (gap length between the hallux and toebox in sagittal plane), which could potentially be responsible for BT injury development (Figure 1A-D). In addition, the insufficient toebox space of the shoe limited the toe's ambulatory function and could lead to additional repetitive friction between foot and shoes (Figure 1E), which may further increase the BT injury risk.
- Long-distance running leaded to a relative midfoot strike pattern, more pronated foot posture, reduced arch height and loss of toe dynamic function (peak propulsive force) (Figure 2A-C), which further redistributed the forefoot plantar load with increased skin temperature under medial metatarsals (Figure 2D), causing an increased incidence of MSF injury development.

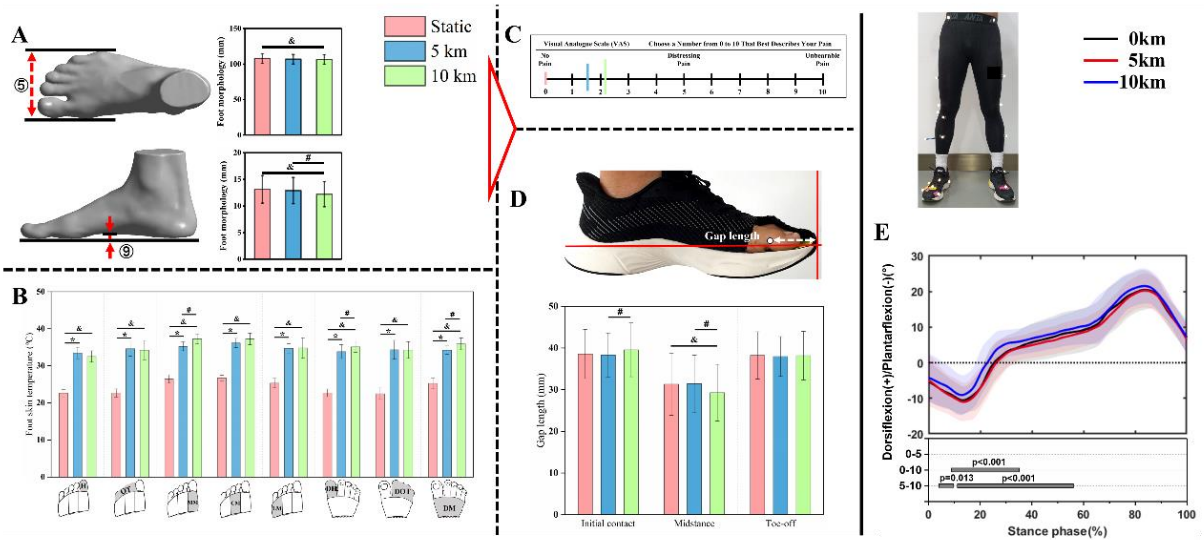

Figure 1 The injury development mechanisms of BT

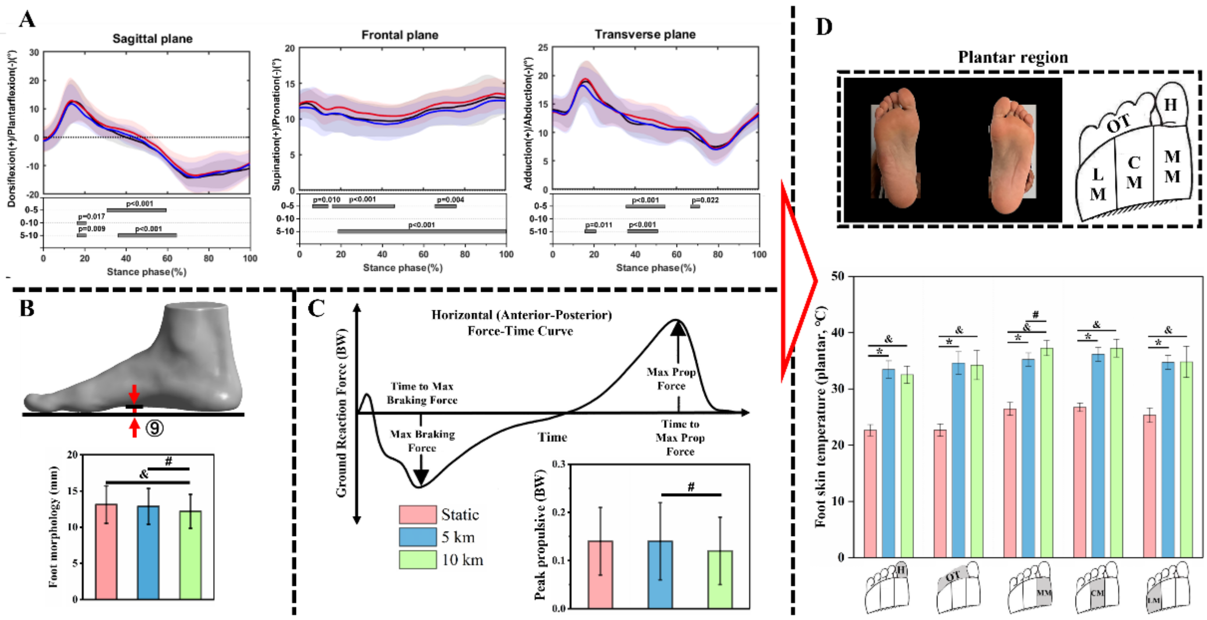

Figure 2 The injury development mechanisms of MSF

[8.1 Scientific Publications related to the Thesis Points, P4 & P5]

2nd Thesis point: Based on my experiments on the potential mechanisms of BT injury development, I proposed a high accurate 3D frictional-coupling foot-shoe FE model to provide an alternative tool for accurately observing the foot-shoe interaction without destroying the upper structure of the shoe and it could be further applied for fast evaluation and optimization of the footwear structure in order to reduce the incidence of BT injury with a simultaneous reduction of the production batches and costs(Figure 2A).

- I proposed a more comprehensive approach to model validation by dividing the plantar and shoe outsole regions into four parts for pressure comparison and further applied the Bland-Altman method for consistency analysis. The results demonstrated a good agreement between the experimentally measured and numerically predicted difference (MD: 0.008MPa, 96% scattered between ±1.96SD)(Figure 2B).
- I further simulated the dynamic running scenario using the boundary conditions derived from motion capture analyses of the participant's gait, which can reproduce the running motion more realistically than the foot-plate system approach. Based on the calculation, the relatively small difference (<10%) in terms of the experimental and predicted gap length between the hallux and toebox during running demonstrated the effectiveness of the model for dynamic simulations(Figure 2C).

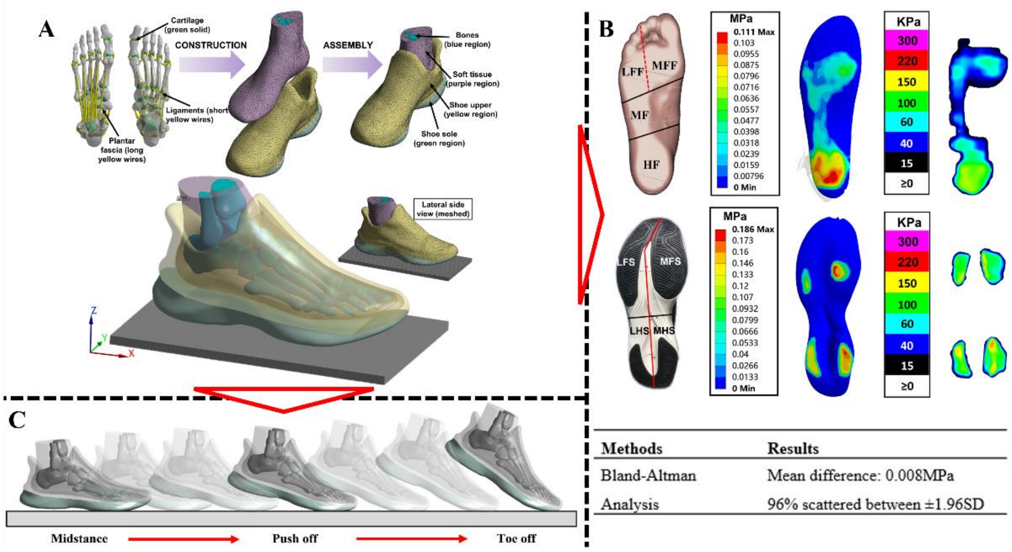

Figure 2 The proposed high accurate 3D frictional-coupling foot-shoe FE model

[8.1 Scientific Publications related to the Thesis Points, P1 & P2]

3rd Thesis point: I proposed a high accurate 3D feline fore-left paw FE model to investigate the GRF distribution and internal stress distribution of the distal joint limb both under static standing and landing with different height (0.6m, 0.8m, 1.0m) and reveal how a cat's paw absorbs and transmits large impact forces to avoid musculoskeletal injuries during movement (Figure 3A).

- For the validation of the feline paw model, the predicted paw pressure presented a good consistency with the experimental pressure data (Figure 3B). The paw pressure concentrated mainly on the metapodial pad and minimal stress was found in phalange region even through it is the main supporter of the body, which indicated the thick substrate tissue (paw pad) under the distal joint effectively decrease the GRF and optimize its distribution.
- In terms of force transmission mechanism, larger stress was concentrated on the MP segment and its growth rate increased with landing height, indicating that the raised MP segment contributes to create a stiff junction between the MCP and wrist joint, transmit impact force and stabilizing the distal joint (Figure 3C).

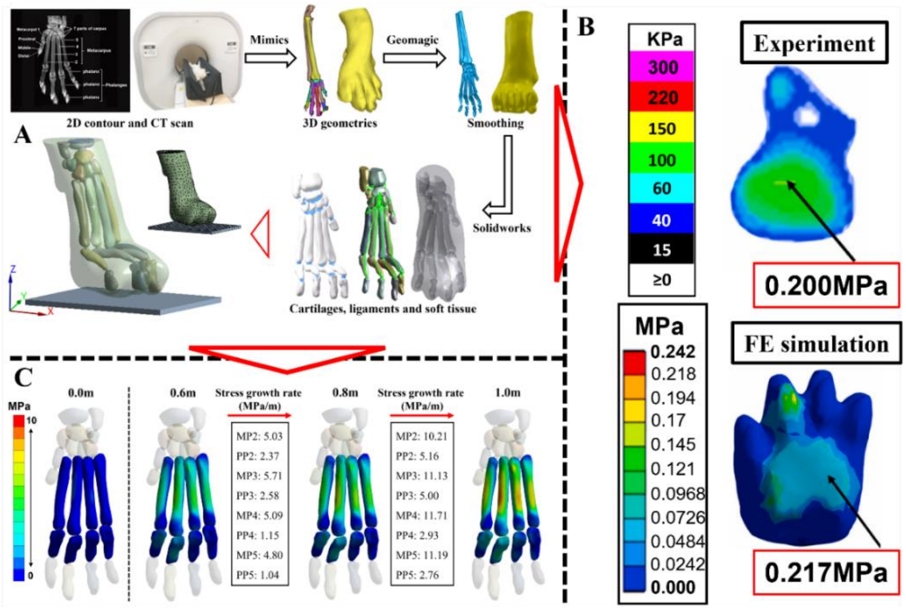

Figure 3 The proposed high accurate 3D feline fore-left paw FE model

[8.1 Scientific Publications related to the Thesis Points, P3]

6 Possibility to utilize the Results

In this dissertation, a comprehensive method combining experimental tests and FE simulations were applied to reveal the potential mechanism of forefoot injury development (BT and MSF) during long-distance running. This dissertation further introduced a 3D frictional-coupling foot-shoe FE model aiming to observe the foot-shoe interaction without destroying the upper structure of the shoe and also created a feline paw model to understand its buffering mechanism during landing. The findings of this study can provide comprehensive biomechanical details and alternative approach for clinicians and researchers to evaluate and optimize footwear design so as to reduce running-related forefoot injury risk.

7 References

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8 Publications

8.1 Scientific Publications related to the Thesis Points

1. **Song, Y.,** Shao, E., Bíró, I., Baker, J. S., Gu, Y. (2022). Finite element modelling for footwear design and evaluation: A systematic scoping review. Heliyon, 8(10), e10940. **IF: 3.776, Q1**

2. **Song, Y.,** Cen, X., Zhang, Y., Bíró, I., Ji, Y., & Gu, Y. (2022). Development and validation of a subject-specific coupled model for foot and sports shoe complex: A pilot computational study. Bioengineering, 9(10), 553. **IF: 5.046, Q2**

3. Wang, M., **Song, Y.,** Baker, J. S., Fekete, G., Ugbolue, U. C., Li, S., Gu, Y. (2021). The biomechanical characteristics of a feline distal forelimb: a finite element analysis study. Computers in Biology and Medicine, 129, 104174. **IF: 6.698, Q1**

4. Li, J., **Song, Y.,** Xuan, R., Sun, D., Teo, E. C., Bíró, I., Gu, Y. (2022). Effect of long-distance running on inter-segment foot kinematics and ground reaction forces: A preliminary study. Frontiers in Bioengineering and Biotechnology, 10, 833774. **IF: 6.064, Q2**

5. Chen, H., **Song, Y.,** Liu, Q., Ren, F., Bíró, I., Gu, Y. (2022). Gender effects on lower limb biomechanics of novice runners before and after a 5 km run. Journal of Men's Health. 18(8), 176. **IF: 0.789, Q3**

8.2 Additional Scientific Publications

1. **Song, Y.,** Li, J., István, B., Xuan, R., Wei, S., Zhong, G., Gu, Y. (2021). Current evidence on traditional Chinese exercises for quality of life in patients with essential hypertension: a systematic review and meta-analysis. Frontiers in Cardiovascular Medicine, 7, 627518. **IF: 5.846, Q1**
2. Sun, D., **Song, Y.,** Cen, X., Wang, M., Baker, J. S., Gu, Y. (2022). Workflow assessing the effect of Achilles tendon rupture on gait function and metatarsal stress: Combined musculoskeletal modeling and finite element analysis. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 236(5), 676-685. **IF: 1.763, Q2**
3. Lin, S., **Song, Y.,** Cen, X., Bálint, K., Fekete, G., & Sun, D. (2022). The implications of sports biomechanics studies on the research and development of running shoes: A systematic review. Bioengineering, 9(10), 497. **IF: 5.046, Q2**

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