THESES OF PHD DISSERTATION

Effect of footwear drop on running biomechanics and finite element analysis in recreational runners

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Introduction

Long-distance running is a convenient sport that is popular with numerous runners around the world. With the increased number of runners, overuse of running injuries has increased. According to epidemiological investigations, the risk of running injuries increases by 79% yearly. It has been shown that recreational runners have a higher risk of lower limb running injuries than competitive runners. Many factors can cause running injuries, such as foot strike patterns, running experience, and fatigue. However, the running mechanisms involved in running fatigue, minimalist shoes, and running experience were still unclear. Therefore, this part first used the Partial Least Squares Algorithm (PLSR) to investigate if a linear relationship existed between the initial joint angle, ankle joint work, and knee joint work for female fatigue running. Secondly, to investigate the lower limb extremity muscle characteristics in minimalist shoes and normal shoes. Finally, utilize the FE model to identify the stress distribution of minimalist and normal shoes in the four different running stance phase conditions.

The first research question of this thesis is: Joint mechanics are permanently changed using different intensities and running durations. These variations in intensity and duration also influence fatigue during prolonged running. Little is known about the potential interactions between fatigue and joint mechanics in female recreational runners.

The first objective of this thesis is to describe and examine kinematic and joint mechanical parameters when female recreational runners are fatigued after long-distance running. The analysis used the Partial Least Square Algorithm (PLSR) to investigate if a linear relationship existed between the initial joint angle, ankle joint work, and knee joint work. The first hypothesis was that ankle work would decrease due to fatigue after prolonged running. The second hypothesis was that joint work would have a greater relationship with the initial angle of the ankle and knee.

The second research question of this thesis is: Previous studies always focus on the kinematics and kinetic variables of running in barefoot, minimalist shoes and conventional shoes. However, little work has investigated how negative heel-to-toe drop affects lower extremity muscle force variables during the running stance.

The second objective of this thesis: This section was to create musculoskeletal modeling and simulation techniques to compare the muscle force, kinematics, and kinetic variables of habitually rearfoot runners while wearing the heel-to-toe drop of negative 8mm shoes (minimalist shoes) and the heel-to-toe drop of positive 9mm shoes

(normal shoes) during the running stance phase. This section focused on the immediate effect of kinematic and kinetic variables during the running stance with different heel-to-toe drop shoe conditions.

The third research question of this thesis is: Previous studies have shown that the finite element model was considered an accurate approach to analyzing the foot stress distributions in the model of the foot and footwear under running stance phase conditions and in biomechanical investigations. However, few studies have focused on internal foot biomechanics while running with different heel-drop shoes during different running stances.

The third objective of this thesis is to investigate the internal stress in the metatarsals and midfoot with the different heel-drop shoes (normal and minimalist shoes) during the running stance phase. Two finite element models were developed from a reactional runner, and four conditions were simulated and compared: (1) initial contact, (2) midstance phase, (3) push off (4) toe-off.

Thesis points

1st Thesis point:

Based on my experiments, I could prove that a linear relationship can be found between the angle of the ankle at the initial contact and the joint work. This result demonstrates that the ankle angle at the initial contact decreases when fatigue arises due to prolonged running.

More importantly, I could deduce that an approximately 30% decrease in the angle of the ankle at the initial contact caused approximately 20% and 25% decrease in the positive work of the ankle and a 30% increase in the positive work of the hip joint when fatigue arose in case of female runners.

Since I detected no significant changes in the knee joint power, this result suggests that no proximal shift appears in knee joint mechanics in the case of female recreational runners following a prolonged run.

In conclusion, this experimental result proves that joint work redistribution takes place when fatigue arises due to prolonged running, slowly shifting more power to the hip joint to maintain equilibrium during running.

Related article to the 1st thesis point:

[1] **Wenjing Quan**, Ren Feng, Datao Xu, Gusztav, Julien S. BAKER, Yaodong Gu. (2021). Effects of Fatigue Running on Joint Mechanics in Female Runners: A Prediction Study Based on a Partial Least Squares Algorithm. Frontiers in Bioengineering and Biotechnology, 880. **Q1, IF = 5.890**

2nd Thesis point:

Based on my experiments on minimalist running shoes, I concluded that a decrease from 8 mm to -8 mm in the heel-to-toe drop resulted in a 12% increase in the soleus force, a 7% increase in Achilles tendon force and an 8% increase in the flexor hallucis longus force.

The obvious increment in these forces implies that the decrease in heel-to-toe drop potentially increases the risk of Achilles tendonitis and ankle flexor injuries in the case of running shoes.

In addition, since the strike index is significantly greater in the case of these minimalist shoes, I could prove that these shoes can change the foot strike pattern during running gait.

Furthermore, I also concluded that these minimalist running shoes decrease the knee flexion moment by 6% compared to normal shoes. Therefore, the knee joint loading is lower, resulting in less injury probability.

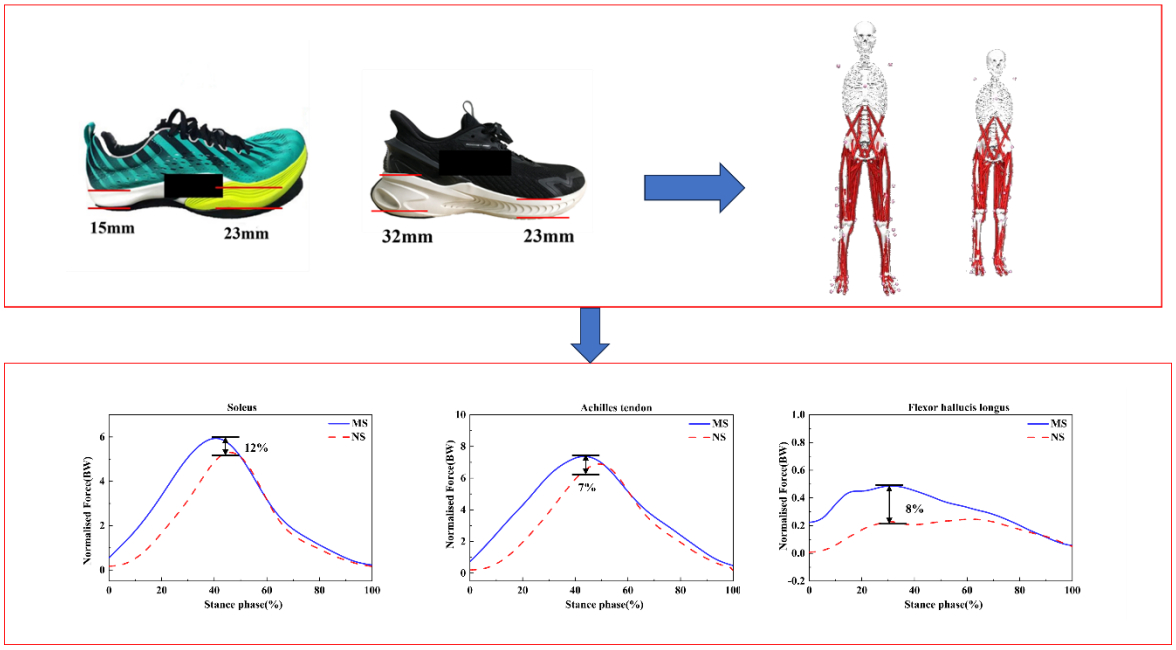

Figure 1 Muscle force changed between the MS and NS running.

Related article to the 2nd thesis point:

[1] **Wenjing Quan**, Linna Gao, Datao Xu, Huiyu Zhou, Tamás Korim, Shirui Shao, Julien S Baker, Yaodong Gu. 2023. Simulation of Lower Limb Muscle Activation Using Running Shoes with Different Heel-to-Toe Drops Using Opensim. Healthcare, 11(9), 1243,

Q2, IF = 3.160

3rd Thesis point:

I created a finite element model with different heel-drop shoes (normal and minimalist shoes) to study stress distribution during the four different running stance phases.

According to the numerical results, the minimalist shoes showed larger von Mises stresses in the metatarsal segment during the four running stance phases compared to normal shoes. This difference was the most significant in the push-off phase, where 12% higher von Mises stress was found compared to normal shoes.

Moreover, the highest von Mises stress was found in the 4th metatarsal when running in minimalist shoes. This result corresponds with the other authors' findings, who pointed out that lower-drop shoes might elevate the risk of metatarsal stress fracture.

Concerning stress distribution, 74% higher von Mises stress was found in the midfoot when running in minimalist shoes compared to normal shoes during the mid-stance phase. This suggests that the design of minimalist shoes should consider midfoot support and cushioning to reduce the pressure distribution during running.

Therefore, I could generally conclude that shoes with lower drop increase stress levels in the metatarsal and midfoot, particularly during the push-off phase.

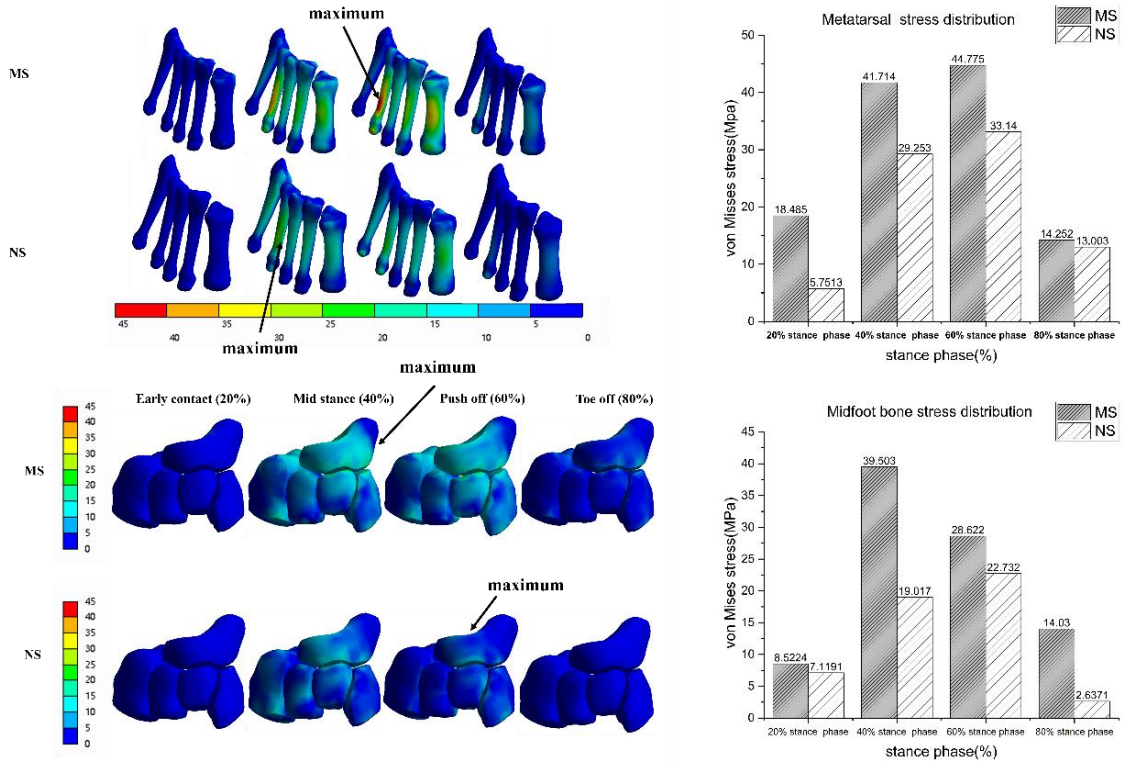

Figure 2 3D-footwear Finite Element model analysis.

Related articles to the 3rd thesis point:

[1] **Wenjing Quan**, Huiyu Zhou, Datao Xu, Shudong Li, Julien S. BAKER, Yaodong Gu. (2021, October). Competitive and Recreational Running Kinematics Examined Using Principal Components Analysis. In Healthcare (Vol. 9, No. 10, p. 1321). **Q2, IF = 2.645**

[2] **Wenjing Quan**, Feng Ren, Dong Sun, Gusztáv Fekete,Yuhuan He. (2021). Do Novice Runners Show Greater Changes in Biomechanical Parameters? Applied Bionics and Biomechanics, 2021. **Q3, IF = 1.781**

[3] Huiyu Zhou, Datao Xu, **Wenjing Quan**, Ukadike Chris Ugbolue, Zhanyi Zhou, Yaodong Gu. Journal: Journal of Human Kinetics. 2023(accept). Can the entire function of the foot be concentrated in the forefoot area during the running stance phase? A finite element study of different shoe soles.**Q1, IF = 2.3**

List of publications

Referred articles related to this thesis:

1. **Wenjing Quan**, Ren Feng, Datao Xu, Gusztav, Julien S. BAKER, Yaodong Gu. (2021). Effects of Fatigue Running on Joint Mechanics in Female Runners: A Prediction Study Based on a Partial Least Squares Algorithm. Frontiers in Bioengineering and Biotechnology, 880. **Q1 IF=5.890**
2. **Wenjing Quan**, Linna Gao, Datao Xu, Huiyu Zhou, Tamás Korim, Shirui Shao, Julien S Baker, Yaodong Gu. 2023. Simulation of Lower Limb Muscle Activation Using Running Shoes with Different Heel-to-Toe Drops Using Opensim. Healthcare **Q2 IF=3.160**
3. **Wenjing Quan**, Huiyu Zhou, Datao Xu, Shudong Li, Julien S. BAKER, Yaodong Gu. (2021, October). Competitive and Recreational Running Kinematics Examined Using Principal Components Analysis. In Healthcare (Vol. 9, No. 10, p. 1321). **Q2 IF=2.645**
4. **Wenjing Quan**, Feng Ren, Dong Sun, Gusztáv Fekete,Yuhuan He. (2021). Do Novice Runners Show Greater Changes in Biomechanical Parameters? Applied Bionics and Biomechanics, 2021. **Q3 IF=1.781**
5. Huiyu Zhou, Datao Xu, **Wenjing Quan**, Ukadike Chris Ugbolue, Zhanyi Zhou, Yaodong Gu. Journal: Journal of Human Kinetics. 2023(accept). Can the entire function of the foot be concentrated in the forefoot area during the running stance phase? A finite element study of different shoe soles. **Q1 IF=2.3**

International conference abstracts related to this thesis:

1. **Wenjing Quan,** Datao Xu, Xinyan Jiang, Yanan Huang. 2021. Lower limb biomechanical analysis of heel shock absorption and stability in running shoes with different midsole stiffness. The 21st National Sports Biomechanics Academic Exchange Conference. At: Taiyuan, China.

2. **Wenjing Quan,** Datao Xu, Yaodong Gu, Gusztáv Fekete. 2021. Effects of a Triple Density Midsole with Lateral Windows on Lower Limb Kinematics and Kinetics of runners in Comparison to a Conventional Running. The 8th Asian Sport Biomechanics Conference. At: Taiwan, China.
3. **Wenjing Quan,** Huiyu Zhou, Yaodong Gu, Gusztáv Fekete. 2021. Running shoe effects on knee and ankle loading during running in Male Recreational Runner. The 8th Asian Sport Biomechanics Conference. At: Taiwan, China

Other publications:

1. **Wenjing Quan,** Meizi Wang, Gongju Liu, Gusztáv Fekete, Julien S. BAKER, Feng Ren, Yaodong Gu. (2020). Comparative Analysis of Lower Limb Kinematics between the Initial and Terminal Phase of 5km Treadmill Running. *JoVE (Journal of Visualized Experiments)*, (161), e61192. **Q2 IF=1.26**
2. Meizi Wang, Julien S. BAKER. Siqin Shen, **Wenjing Quan,** Gusztáv Fekete, Yaodong Gu. (2020). A preventive role of exercise across the coronavirus 2 (SARS-CoV-2) pandemic. Frontiers in Physiology, 1139. **Q2 IF=4.566**
3. Huiyu Zhou, Datao Xu, **Wenjing Quan,** Minjun Liang, Ukadike Chris Ugbolue, Julien S. BAKER, Yaodong Gu. (2021, October). A Pilot Study of Muscle Force between Normal Shoes and Bionic Shoes during Men Walking and Running Stance Phase Using Opensim. In Actuators (Vol. 10, No. 10, p. 274). **Q2 IF=1.994**
4. Xinyan Jiang, Huiyu Zhou, **Wenjing Quan,** Qiuli Hu, Julien S. BAKER, Yaodong Gu. (2021). Ground Reaction Force Differences between Bionic Shoes and Neutral Running Shoes in Recreational Male Runners before and after a 5 km Run. International Journal of Environmental Research and Public Health, 18(18), 9787. **Q2 IF=3.390**
5. Datao Xu, **Wenjing Quan,** Huiyu Zhou, Dong Sun, Julien S. BAKER, Yaodong Gu. (2022). Explaining the differences of gait patterns between high and low-mileage runners with machine learning. Scientific Reports, 12(1), 1-12. **Q1 IF=4.379**
6. **Wenjing Quan,** Qichang Mei, Yaodong Gu, Feng Ren, Sterzing, T., & Fernandez, J. (2018). Biomechanical Variations in Female Runner's Pre and Post Treadmill Running. In Journal of Biomimetics, Biomaterials and Biomedical Engineering (Vol. 37, pp. 1-11). **Q4 IF=0.64**
7. Jingying Lu, Datao Xu, **Wenjing Quan,** Julien S. Baker, Yaodong Gu. (2022) Effects of Forefoot Shoe on Knee and Ankle Loading during Running in Male Recreational Runners (Vol. 19, No.2). **Q4 IF=0.338**
8. Huiyu Zhou , Datao Xu , **Wenjing Quan** , Ukadike Chris Ugbolue , Nicholas F. Sculthorpe , Julien S. Baker , Yaodong Gu.(2022) A foot joint and muscle

force assessment of the running stance phase whilst wearing normal shoes and bionic shoes. Acta of Bioengineering and Biomechanics. **Q3 IF=1.265**

9. Dong Sun, Yang Song, **Wenjing Quan,** Jianshe Li, Yaodong Gu, 2022.The effect of running shoes bending stiffness alteration on lower extremity biomechanical performance and running economy. China Sport Science and Technology.
10. Jinpeng Zhang, **Wenjing Quan,** Yuhuan He. 2022 The effect of running surface on the lower limb biomechanical. Zhejiang Sport Science.
11. Datao Xu, **Wenjing Quan**, Huiyu Zhou, Dong Sun, Julien S. BAKER, Yaodong Gu. 2022. Exploring the gait pattern of "high-low" mileage runners based on deep neural network and layer-by-layer correlation propagation technology difference. Journal of Medical Biomechanics. Vol.37, No.5.
12. Datao Xu, Huiyu Zhou, **Wenjing Quan**, Fekete Gusztav, Meizi Wang, Julien S Baker, Yaodong Gu.2023. Accurately and effectively predict the ACL force: Utilizing biomechanical landing pattern before and after-fatigue. Computer Methods and Programs in Biomedicine. **Q1 IF=6.1**
13. Huiyu Zhou, Datao Xu, **Wenjing Quan**, Ukadike Chris Ugbolue, Zhanyi Zhou, Yaodong Gu. Journal: Journal of Human Kinetics. 2023(accept). Can the entire function of the foot be concentrated in the forefoot area during the running stance phase? A finite element study of different shoe soles.**Q1 IF=2.3**
14. Datao Xu, Huiyu Zhou, **Wenjing Quan**, Fekete Gusztav, Julien S Baker, Yaodong Gu. 2023. Adaptive Neuro-Fuzzy Inference System model driven by the Non-Negative Matrix Factorization-extracted muscle synergy patterns to estimate lower limb joint movements. Computer Methods and Programs in Biomedicine. **Q1 IF=6.1**
15. Datao Xu, Huiyu Zhou, **Wenjing Quan**, Xinyan Jianga, Minjun Liang, Shudong Li, Ukadike Chris Ugbolue, Julien S. Baker, Fekete Gusztav, Xin Mag, Li Chen, Yaodong Gu. 2023. A new method proposed for realizing human gait pattern recognition: Inspirations for the application of sports and clinical gait analysis. Gait poster.**Q1 IF=2.4**

Reviewer for international journal articles:

1. BMC Musculoskeletal Disorders
2. Physical Activity and Health
3.PLOS One

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Total independent citations (Scopus): 58
(https://www.scopus.com/authid/detail.uri?authorId=57202351906)
Independent Hirsch index: 3
Total Impact Factor (Web of Science): 50.508