THESIS OF PHD DISSERTATION

Towards improved Understanding of Running Fatigue and Gait Asymmetry

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1. SCIENTIFIC BACKGROUND AND OBJECTIVES

1.1 Scientific Background

The popularity of long-distance running as an easily accessible and promoted sport has increased within the last four decades. However, the incidence of musculoskeletal injuries caused by running has also increased rapidly, especially in the lower extremities of amateur runner. It should, however, be noted that the etiology of running fatigue-induced injuries is multifactorial and complex. Fatigue-induced changes in the symmetry of the lower limbs may be one of the major causes of unilateral limb overloading.

The first research question of this thesis: Fatigue gait risk is associated with shifts in the distribution of bilateral plantar pressure. Therefore, human activity recognition (HAR) methods based on wearable sensors and deep learning algorithms have been widely developed in the last decade. Despite significant strides in gait and biomechanics analysis, research into automated fatigue gait recognition with data-driven models remains insufficient. Force plates or insoles with force transducers are easy to use relative to other biomechanical data collection methods, saving time in experimental setup data collection. Therefore, this study intends to use a deep learning algorithm based on bilateral plantar pressure data for the early identification of fatigue gait.

The first objective of this thesis: Detecting fatigue at the early stages of a run could aid training programs in making adjustments, thereby reducing the heightened risk of injuries from overuse. The study aimed to investigate the effects of running fatigue on plantar force distribution in the dominant and nondominant feet of amateur runners. The Convolutional Long Short-Term Memory Network (ConvLSTM) model will be used in this study on the ground that it transforms the structure of recurrent neural networks into a convolutional structure, thereby preserving the spatial and temporal information of plantar pressure.

The second research question of this thesis: Although many studies have investigated the acute effects of long-distance running on gait symmetry, they have mainly focused on exploring pre- and post-fatigue comparisons. One gap is the lack of understanding of how symmetry changes during various stages of long-distance running. In addition, researchers have utilized various techniques from chaos theory and information theory to enhance their understanding of the intricacies of gait behavior. Although nonlinear evaluation is important in the quantification of gait stability, there is a lack of research on gait asymmetry.

The second objective of this thesis: This part focuses on understanding the variations in gait symmetry during a prolonged running activity. Specifically, the question seeks to unravel how the dynamic stability of gait symmetry, as quantified by the Largest Lyapunov exponent (LyE), alters across different stages of a 10-kilometer run among amateur male runners. The results of present study could provide a towards improved understanding of the symmetry of long-distance running.

The third research question of this thesis: Understanding the internal load characteristics of the knee joint is essential for investigating unilateral knee injuries associated with running. previous studies on fatigue and differences in load between limbs haves not precisely addressed the distribution and extent of the load on the knee joint's internal tissues, potentially missing key insights into the causes of unilateral limb injuries.

The third objective of this thesis: The aim of this study is to determine whether there are differences in the location and magnitude of von Mises stress in the internal structures of both knee joints during the stance phase of gait, and to investigate the effects of running at the submaximal speed for 10 kilometers on these internal structures. The findings enhance our understanding of the impact of running-induced fatigue on bilateral knee joint loading. It provides a detailed analysis of factors leading to unilateral knee overload during extended running. These insights are essential in formulating targeted strategies to reduce injury risks.

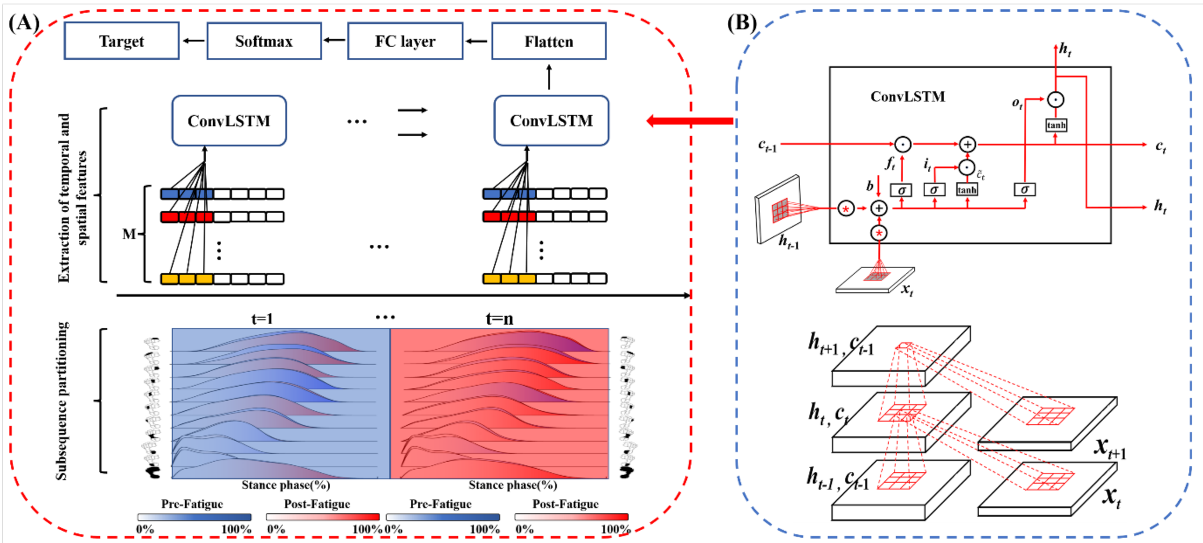
In summary, this study investigates the biomechanical implications of long-distance running, focusing on the potential relationship between running-induced fatigue and the risk of musculoskeletal injury in amateur runners. It delves into three key areas: using deep learning algorithms to detect fatigue gait through changes in bilateral plantar pressures, analyzing nonlinear changes in gait symmetry during long-distance running, and exploring internal knee loading characteristics to understand unilateral knee injury mechanisms. This study aims to provide new insights into the prevention and management of running-related injuries by comprehensively analyzing gait dynamics and joint loading at different stages of long-distance running.

2. Thesis points

1st Thesis point:

Based on experimental data, I divided the left and right plantar into 22 anatomic regions, where I have quantitatively allocated those time-intervals (contact durations) which can inflict overload on the feet. These findings, to my knowledge, have not yet published before. Furthermore, these results offer empirical data for evaluating risk factors associated with overuse injuries and assist in the early detection of fatigued gait.

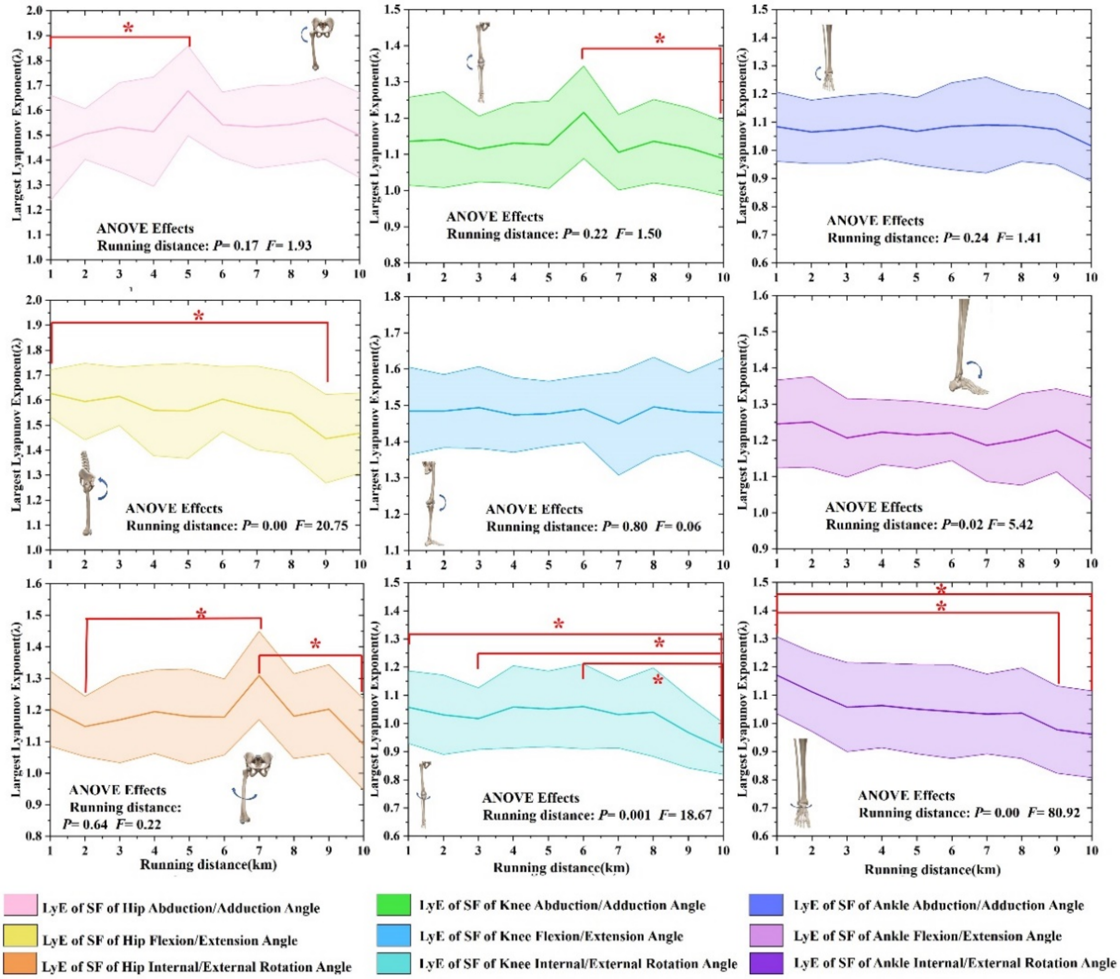
In addition, I created an augmented ConvLSTM model to recognize fatigue on running gait, from the perspective of deep learning, by the use of time-series planter pressure data. This data was based on high number of samples (thirty amateur runners). With this model, compared to the traditional CNN model, fatigue can be detected with higher accuracy (7%) and specificity (17%) as it is seen in the Table.



Model	Accuracy	Percentage difference	Sensitivity	Percentage difference	Specificity	Percentage difference
CNN	0.800	7%	0.874	0%	0.718	17%
aug. ConvLSTM	0.867		0.874		0.859	

2nd Thesis point:

I described the dynamic stability behaviour of nine major biomechanical parameters, namely abduction-adduction, flexion-extension and internal-external rotational angle of the hip-, knee-, and ankle joint by means of the Largest Lyapunov exponent (LLE) as a function of running distance.



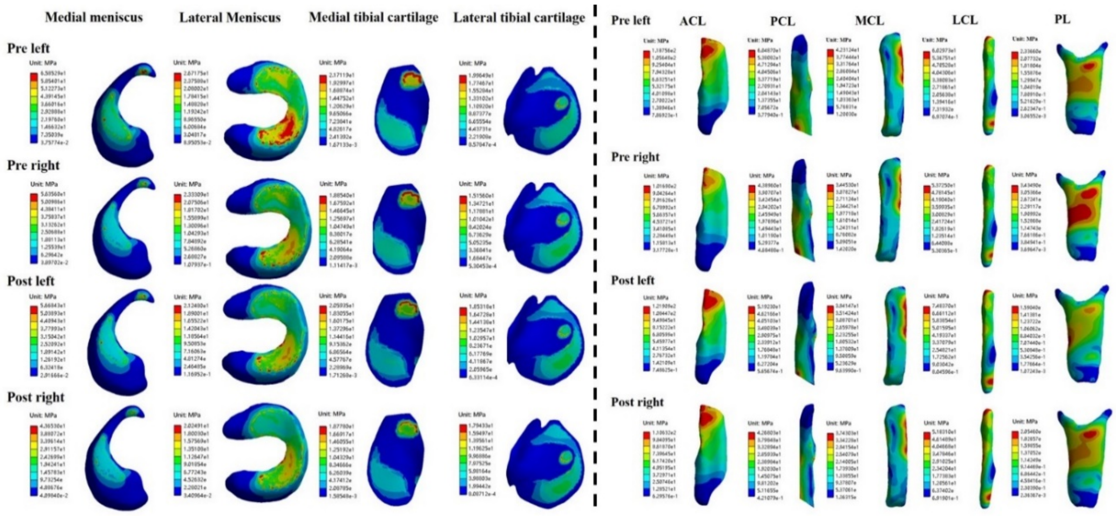
Based on my experiments (carried out on 17 male amateur runners) and calculations I could differentiate three groups for the biomechanical parameters such as *stable, continuously improving* and *fluctuating* and I could drew general conclusions. All angles were transformed into symmetry functions (SF).

	Ankle	Knee	Hip	Dynamic stability
Stable parameters	ad/abduction, flexion-extension	flexion-extension	-	The stability of these parameters remain unaffected in the function of running distance.
Continuously improving parameters	internal-external rotation	internal-external rotation	flexion-extension	The stability of these parameters improve in the function of running distance.

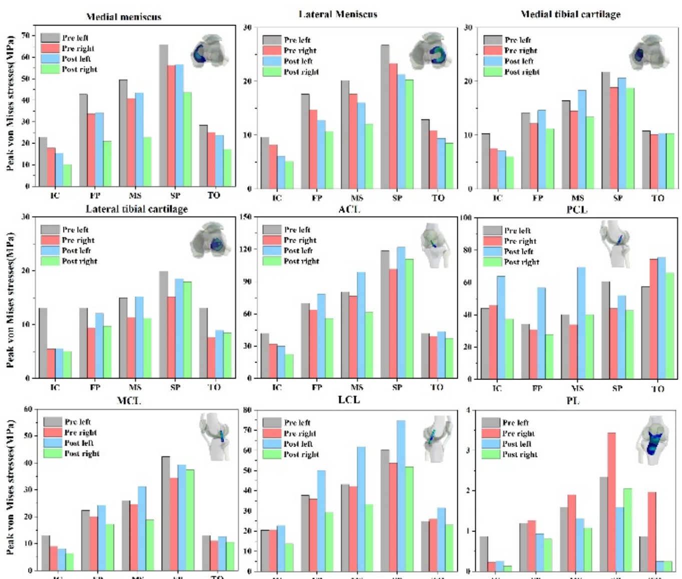
Fluctuating parameters	-	ad/abduction	ad/abduction, internal-external rotation	The stability of these parameters is decreased in the first part of the running distance. Approximately at the half of the distance a sudden peak can be observed, which is followed by a continuous improvement in stability.

3rd Thesis point:

I created a high accurate 3D Knee FE model. The joint reaction forces and joint reaction moments calculated from the musculoskeletal model simulation were used as boundary conditions to investigate the distribution and magnitude of loads on the meniscus, articular cartilage, and ligaments of the bilateral knee joints before and after a 10-kilometer run at this maximum intensity. I found similar load distribution in both knee joints regardless of the state. The left ACL was 17.07 MPa higher than the right side, and it increased by 3.15 MPa after fatigue. In post-fatigue states, it surpasses the right side by 11.28 MPa.



I propose a more comprehensive approach to load analysis by dividing the gait support period into five typical phases based on vGRF for comparison of organizational loads at the maximum moment. The results showed that the load on the meniscus and tibial cartilage were greater on the non-dominant side and greater in the pre-fatigue state. The load on the ACL, PCL, and LCL of non-dominant limb were increased after fatigue. However, they were decreased in the dominant side.



3. SCIENTIFIC PUBLICATIONS

3.1 Referred articles related to this thesis:

1. **Gao, Z.,** Xiang, L., Fekete, G., Baker, J. S., Mao, Z., & Gu, Y. (2023). A Data-Driven Approach for Fatigue Detection during Running Using Pedobarographic Measurements. Applied Bionics and Biomechanics, 2023, 1-11. IF: 2.2, Q3
2. **Gao, Z.,** Zhu, Y., Fang, Y., Fekete, G., Kovács, A., Baker, J. S., ... & Gu, Y. (2023). Automated recognition of asymmetric gait and fatigue gait using ground reaction force data. Frontiers in Physiology, 14: 369-382. IF:4.000, Q2
3. **Gao, Z.,** Fekete, G., Baker, J. S., Liang, M., Xuan, R., & Gu, Y. (2022). Effects of running fatigue on lower extremity symmetry among amateur runners: From a biomechanical perspective. Frontiers in Physiology, 13: 899818-899830. IF: 4.000, Q2
4. **Gao, Z.,** Zhao, L., Fekete, G., Katona, G., Baker, J. S., & Gu, Y. (2022). Continuous time series analysis on the effects of induced running fatigue on leg symmetry using kinematics and kinetic variables: Implications for knee joint injury during a countermovement jump. Frontiers in Physiology, 13: 877394. IF: 4.000, Q2
5. Xiang, L., Gu, Y., Wang, A., Shim, V., **Gao, Z.,** & Fernandez, J. (2023). Foot Pronation Prediction with Inertial Sensors during Running: A Preliminary Application of Data-Driven Approaches. Journal of Human Kinetics, 87: 29-40. IF: 2.300, Q3
6. Xiang, L., Gu, Y., Rong, M., **Gao, Z.,** Yang, T., Wang, A., ... & Fernandez, J. (2022). Shock acceleration and attenuation during running with minimalist and maximalist shoes: a time-and frequency-domain analysis of tibial acceleration. Bioengineering, 9(7), 2-9. IF:5.046, Q2
7. Xiang, L., Gu, Y., **Gao, Z.,** Yu, P., Shim, V., Wang, A., & Fernandez, J. (2024). Integrating an LSTM framework for predicting ankle joint biomechanics during gait using inertial sensors. Computers in Biology and Medicine, 170, 1-12. IF: 7.700, Q2
8. Xiang, L#., **Gao, Z#.,** Wang, A., Shim, V., Fekete, G., Gu, Y., & Fernandez, J. (2024). Rethinking running biomechanics: a critical review of ground reaction forces, tibial bone loading, and the role of wearable sensors. Frontiers in Bioengineering and Biotechnology, 12, 1-13. IF: 5.700, Q2

3.2 International conference abstracts related to this thesis:

1. **Zixiang Gao,** Yuqi He, Gusztav Fekete and Yaodong Gu. The Effect of The of Running-Induced Fatigue on The Symmetry of Kinematics and Kinetic Variables of Knee Joints in a Countermovement Jump. 27th Congress of the European Society of Biomechanics, Portugal.2022
2. **Zixiang Gao,** Yuqi He, Gusztav Fekete and Yaodong Gu. Effects of Running Fatigue on Knee Joint Symmetry Among Amateur Runners. International Society of Biomechanics in Sports. Britain.2022
3. **Zixiang Gao,** Yuqi He, Liangliang Xiang, Gusztav Fekete, András Kovács and Yaodong Gu. Automatically Detecting Fatigue Gait Based on Time Series Bilateral Plantar Force Distribution Using Deep Learning Algorithms, 28th Congress of the European Society of Biomechanics, Netherlands, 2023

3.3 Other publications:

1. **Gao, Z.** (2022). The Effect of Application of Asymmetry Evaluation in Competitive Sports: A Systematic Review. Physical Activity and Health, 6(1).CS: 3.9(Scopus), Q1
2. **Gao, Z.,** Mei, Q., Fekete, G., Baker, J.S. and Gu, Y., (2020). The Effect of Prolonged Running on the Symmetry of Biomechanical Variables of the Lower Limb Joints. Symmetry, 12(5),1-11. IF: 2.713, Q2
3. **Gao, Z.,** Mei, Q., Xiang, L., Gu, Y., (2020). Difference of walking plantar loadings in experienced and novice long-distance runners. Acta of bioengineering and biomechanics, 22(3), 127-147. IF: 1.281, Q4
4. **Gao, Z.,** Mei, Q., Xiang, L., Baker, J.S., Fernandez, J., & Gu, Y. (2020). Effects of limb dominance on the symmetrical distribution of plantar loading during walking and running. Proceedings of the Institution of Mechanical Engineers Part P-Journal of Sports Engineering and Technology, 1-7. IF: 1.238, Q4
5. **Gao, Z.,** Song, Y., Yu, P. M., Zhang, Y., & Li, S. D. (2019). Acute Effects of Different Stretching Techniques on Lower Limb Kinematics, Kinetics and Muscle Activities during Vertical Jump. In Journal of Biomimetics, Biomaterials and Biomedical Engineering 40, 1-15. EI (Scopus), EI (Scopus) IF: 0.70, Q3
6. Zhou, Z., Li, S., Yang, L., **Gao, Z.,** Lin, Y., Radak, Z., & Gu, Y. (2023). Inter-Segmental Coordination of the Swimming Start among Paralympic Swimmers: A Comparative Study between S9, S10, and S12 Swimmers. Applied Sciences, 13(16), 1-12, 9097. IF: 2.700, Q1
7. Wang, Y., Jiang, H., Yu, L., **Gao, Z.,** Liu, W., Mei, Q., & Gu, Y. (202). Understanding the Role of Children’s Footwear on Children’s Feet and Gait Development: A Systematic Scoping Review. Healthcare, 11 (10), 1-14. IF: 2.800, Q2
8. Mei, Q., Gu, Y., Xiang, L., Yu, P., **Gao, Z.,** Shim, V. and Fernandez, J., (2019). Foot shape and plantar pressure relationships in shod and barefoot populations. Biomechanics and Modeling in Mechanobiology, pp.1-14. IF:2.527, Q3
9. Liu W, Mei Q, Yu P, **Gao, Z.,** Biomechanical Characteristics of the Typically Developing Toddler Gait: A Narrative Review (2022). Children, 9(3): 2-16. IF:2.400, Q3
10. Yu, L., Yu, P., Liu, W., **Gao, Z.,** Sun, D., Mei, Q., Gu, Y. (2022). Understanding Foot Loading and Balance Behavior of Children with Motor Sensory Processing Disorder. Children, 9(3): 1-19. IF:2.863, Q2
11. Xiang, L., Deng, K., Mei, Q., **Gao, Z.,** Yang, T., Wang, A., ... & Gu, Y. (2021). Population and Age-Based Cardiorespiratory Fitness Level Investigation and Automatic Prediction. Frontiers in Cardiovascular Medicine, 8: 1-9. IF:6.050, Q1
12. Zhang, Y., Xu, Y., **Gao, Z.,** Yan, H., Li, J., & Lu, Y. (2022). The Effect of Standing Mats on Biomechanical Characteristics of Lower Limbs and Perceived Exertion for Healthy Individuals during Prolonged Standing. Applied Bionics and Biomechanics, 2022: 1-11. IF: 2.2, Q3
13. Mei, Q., Fernandez, J., Xiang, L., **Gao, Z.,** Yu, P., Baker, J. S., & Gu, Y. (2022). Dataset of lower

extremity joint angles, moments and forces in distance running. Heliyon, 8(11), e11517. IF:4.000, Q3

14. Cen, X., Liang, Z., **Gao, Z.,** Lian, W., & Wang, Z. (2019). The Influence of the Improvement of Calf Strength on Barefoot Loading. In Journal of Biomimetics, Biomaterials and Biomedical Engineering, 40, 16-25. EI (Scopus), EI (Scopus) IF: 0.70, Q3.

15. Mei, Q., **Gao, Z.,** Fernandez, J., & Gu, Y. (2019). 3D Foot Shape Modelling Based on Statistical Shape Model. Journal of Medical Biomechanics. CSSCI, IF: 0.964

16. Mei, Q., Gu, Y., Xiang, L., Yu, P., **Gao, Z.,** Shim, V. and Fernandez, J., (2019). Foot shape and plantar pressure relationships in shod and barefoot populations. Biomechanics and Modeling in Mechanobiology, 19: 1211-1224. IF: 2.527, Q3

Reviewer for international journal articles:

1. Plos One
2. Frontiers in Physiology
3. Frontiers in Bioengineering and Biotechnology
4. BMC Musculoskeletal Disorders
5. Int. J. of Biomedical Engineering and Technology
6. Ergonomics
7. Frontiers in Sports and Active Living
8. BMC Sports Science, Medicine and Rehabilitation
9. Journal of Orthopaedic Surgery and Research
10. Physical Activity and Health Journal
11. Scientific Report

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Total independent citations:

Scopus Database: 24 (https://www.scopus.com/authid/detail.uri?authorId=57207686220)

Independent citations: 133

Independent Hirsch index: 7

Total Impact Factor: 67.379 (Web of Science)