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Biomechanical Optimization**

ABSTRACT BOOKLET

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1. Summary of the Context of the Research

The human foot constitutes a pivotal component of the lower-limb kinetic chain, fulfilling multiple biomechanical functions throughout the gait cycle, including load bearing, impact attenuation, stability maintenance, and propulsion generation. During locomotion, the rearfoot primarily dissipates ground reaction forces at heel strike; the midfoot preserves the integrity of the longitudinal arch, thereby facilitating load transfer and energy transformation; and the forefoot generates the principal propulsive force during push-off. Consequently, the mechanical coupling between the foot and footwear exerts a direct influence on plantar pressure distribution, joint loading patterns, gait stability, and the risk of musculoskeletal injury. Footwear design, therefore, extends beyond conventional materials engineering and must be regarded as an integrated systems-level challenge encompassing structural optimization and biomechanical regulation.

Conventional footwear design has largely relied on homogeneous foam materials and empirically driven geometric modifications to achieve cushioning and support. Although such approaches can enhance perceived comfort or attenuate impact forces to a certain extent, their regulatory mechanism predominantly depends on altering bulk material stiffness, thereby limiting the capacity for region-specific mechanical modulation. Given the pronounced functional heterogeneity of plantar regions throughout the gait cycle, a uniform structural configuration is inherently constrained in its ability to simultaneously accommodate rearfoot cushioning, midfoot stabilization, and forefoot propulsion. Moreover, substantial inter-individual variability in foot morphology, gait patterns, and load distribution further undermines the efficacy of standardized design paradigms, rendering truly personalized biomechanical matching difficult to achieve.

Recent advances in additive manufacturing have opened new technological avenues for structural innovation in footwear design. Three-dimensional printing enables the high-precision fabrication of complex internal architectures, thereby rendering the integration of lattice structures into midsole systems technically feasible. By modulating lattice unit topology, porosity, strut thickness, and spatial arrangement, it becomes possible to tailor global mechanical behavior through geometric variation while maintaining constant material composition. This paradigm of structurally programmable design establishes a robust theoretical and technological foundation for region-specific functional regulation and individualized customization.

Although prior investigations have explored lattice-based insoles or localized cushioning components, several critical limitations remain. Much of the existing work has focused on a single or narrowly defined set of lattice topologies, lacking a systematic construction of a multidimensional geometric parameter space and, more importantly, a quantitative mapping between geometric descriptors and macroscopic mechanical performance. In addition, performance evaluation has frequently relied on static compression tests or simplified loading scenarios, which fail to capture the multi-phase, dynamically evolving load characteristics inherent to real gait.

Moreover, finite element analysis, machine learning-based optimization, and subject-specific gait data have yet to be integrated into a coherent closed-loop design framework. As a result, structural generation continues to depend substantially on empirical tuning rather than data-driven automated optimization. Compounding this challenge, functional requirements vary markedly across application contexts. For athletic performance enhancement, design priorities center on maximizing propulsion efficiency and energy return, whereas clinical or orthotic applications place greater emphasis on controlling arch collapse and alleviating localized pressure concentrations. Such

heterogeneous demands underscore the necessity of establishing a scalable, predictive, and optimizable structural design framework capable of accommodating diverse biomechanical objectives.

It is therefore imperative to establish a systematic design methodology that integrates parametric lattice modelling, foot–shoe coupled finite element analysis, dynamic gait data incorporation, and multi-objective optimization within a unified framework. Such an approach should enable the construction of explicit mappings between geometric parameters and macroscopic mechanical performance across high-dimensional design spaces, while subjecting computational predictions to rigorous experimental validation to ensure engineering feasibility. By doing so, footwear design can transition from a paradigm dominated by material selection and empirical iteration toward one characterized by structurally programmable architectures and data-driven optimization. Situated within this context, the present study seeks to provide a coherent theoretical foundation and methodological framework for personalized lattice-based footwear design.

2. The Aims

In response to the foregoing research context and unresolved challenges, this dissertation seeks to develop an integrated design framework that unifies parametric modelling, finite element analysis, and machine learning–driven optimization to enable programmable control of footwear structural performance and gait-informed dynamic optimization.

The central objective is to establish a closed-loop engineering workflow spanning foot morphology acquisition, structural parameter generation, mechanical performance prediction, and physical prototype validation. Within this framework, lattice architectures are adaptively configured according to individual gait characteristics and functional demands, and their engineering feasibility and biomechanical effectiveness are rigorously verified through experimental evaluation. The specific research objectives are as follows:

First, to establish a multidimensional parametric lattice modelling framework and to derive a quantitative mapping between lattice geometric descriptors and macroscopic mechanical performance. By systematically defining key variables—including unit-cell topology, porosity, strut thickness, and orientation—a scalable high-dimensional design space is constructed. Finite element analysis is subsequently employed to evaluate the influence of diverse parameter combinations on effective stiffness, stress distribution, and deformation patterns, thereby enabling predictive characterization of structure–property relationships.

Second, to develop a regionally differentiated lattice midsole design strategy guided by functional demands across the gait cycle. In accordance with the distinct biomechanical roles of rearfoot cushioning, midfoot stabilization, and forefoot propulsion, a partitioned structural modulation scheme is formulated. The mechanistic effects of region-specific parameter variations on impact attenuation capacity, arch control, and propulsive efficiency are systematically examined, thereby establishing a functional correspondence between structural design variables and phase-dependent gait requirements.

Third, to construct a dynamic gait–driven multi-objective optimization framework. Subject-specific gait data are incorporated directly into the objective functions, enabling the formulation of a multi-objective model that simultaneously accounts for impact attenuation, structural stability, and propulsive performance. By integrating surrogate modelling with Bayesian optimization, efficient exploration and accelerated convergence within a high-dimensional design space are achieved, thereby enhancing the level of automation and data-centric intelligence in the generation of personalized lattice architectures.

Fourth, to fabricate optimized lattice prototypes using additive manufacturing and to conduct multi-subject gait experiments alongside mechanical performance testing for systematic validation of model predictions. Through comprehensive analysis of biomechanical responses under realistic locomotor conditions, the study evaluates both the *in vivo* performance and the practical engineering feasibility of the optimized structures.

Through the systematic realization of these research objectives, this dissertation seeks to establish a scalable and generalizable framework for structural design and optimization. The proposed methodology provides a coherent technological pathway and rigorous theoretical underpinning for the advancement of personalized footwear engineering and related intelligent wearable systems.

3. The Methods Used During the Research

To achieve the defined research objectives, this study establishes a systematic technical framework that integrates parametric modelling, finite element analysis, machine learning–based optimization, and experimental validation. Guided by a closed-loop engineering logic, the overall methodology coherently unifies data acquisition, structural generation, numerical simulation, algorithmic optimization, and physical prototype verification into an integrated workflow encompassing modelling, simulation, optimization, fabrication, and validation.

At the data acquisition stage, three-dimensional foot scanning and gait capture systems were employed to obtain subject-specific foot geometry and dynamic locomotor parameters. The collected dataset encompassed external morphological contours, plantar pressure distributions, and kinematic as well as kinetic variables throughout the gait cycle. These measurements not only enabled the reconstruction of individualized geometric foot models but also provided quantitative foundations for defining structural regulation objectives and establishing performance evaluation metrics in subsequent optimization procedures.

Within the structural generation stage, a multidimensional parametric lattice modelling framework was developed. By formally defining critical geometric variables—including unit-cell topology, strut thickness, porosity, and spatial configuration scalable high-dimensional design space was constructed, enabling controlled and systematic generation of lattice architectures. Concurrently, the midsole was functionally partitioned in accordance with phase-specific gait demands, allowing regionally differentiated structural expression within a unified parametric schema and thereby establishing a foundation for function-oriented structural modulation.

In the mechanical analysis phase, a coupled foot–shoe finite element model was established to numerically simulate stress distributions, deformation characteristics, and effective stiffness under dynamic loading conditions across diverse lattice parameter combinations. Model predictions were rigorously validated through comparison with experimental measurements, thereby ensuring computational reliability. On this basis, an explicit mapping between lattice geometric parameters and macroscopic mechanical performance was derived, providing the computational foundation for subsequent optimization procedures.

With respect to the optimization strategy, surrogate modelling was integrated with multi-objective Bayesian optimization to enable iterative exploration of the high-dimensional design space. The objective functions concurrently incorporated key biomechanical performance metrics—including impact attenuation, arch stability, and propulsive efficiency—while embedding subject-specific gait data directly into the optimization formulation. In this manner, structural generation was explicitly anchored to individualized biomechanical demands. Through successive iterations and convergence analysis, personalized combinations of structural parameters satisfying multiple performance constraints were systematically identified.

During the physical validation phase, optimized lattice midsole prototypes were fabricated using additive manufacturing, followed by multi-subject gait experiments and mechanical performance assessments. Systematic comparisons of plantar pressure distributions, joint kinematics, and kinetic parameters were conducted to evaluate the biomechanical performance of the optimized structures under realistic locomotor conditions. This process further enabled rigorous examination of the agreement between numerical predictions and empirical measurements.

4. Scientific Results

Based on the systematic investigations conducted in this dissertation, the following innovative scientific contributions have been achieved:

(1) A multidimensional parametric lattice modelling framework was developed, enabling the systematic definition and scalable generation of key geometric descriptors, including unit-cell topology, porosity, strut thickness, and spatial configuration. This unified parametric representation establishes a methodological foundation for structurally programmable midsole design.

(2) A quantitative mapping between lattice geometric parameters and macroscopic mechanical performance was established. Through coupled foot–shoe finite element analysis, the relationships governing effective stiffness evolution, stress distribution characteristics, and deformation modes across diverse parameter combinations were elucidated, thereby enabling predictive structure–property characterization driven by geometric design variables.

(3) A functionally partitioned lattice midsole design methodology was proposed. Guided by the phase-specific biomechanical demands of rearfoot cushioning, midfoot support, and forefoot propulsion during the gait cycle, a regionally differentiated lattice modulation strategy was formulated. Numerical simulations and experimental evaluations demonstrated that the partitioned architecture exhibits superior impact attenuation and stability control compared with homogeneous configurations.

(4) A dynamic gait–driven multi-objective optimization framework was constructed, embedding subject-specific kinetic data directly into the objective functions. By concurrently addressing impact mitigation, structural stability, and propulsive efficiency, automated exploration and structural generation within a high-dimensional design space were achieved, thereby enhancing the scientific rigor and personalization capacity of the design process.

(5) An efficient parameter optimization strategy was introduced by integrating finite element simulations with surrogate modelling and Bayesian optimization. This approach substantially reduced the computational burden associated with high-dimensional searches while improving convergence efficiency and robustness.

(6) A closed-loop engineering workflow encompassing modelling, simulation, optimization, additive manufacturing, and experimental validation was established. Multi-subject gait experiments systematically confirmed the biomechanical efficacy and engineering feasibility of the optimized structures under realistic application conditions, providing a replicable technological pathway for the scalable implementation of personalized footwear structural design.

5. List of Publications Related to the Thesis

Referred articles related to this thesis:

1. **Z Lu**, X Li, D Sun, Y Song, G Fekete, A Kovács, Z Gao, J Zheng, L Xiang, Y Gu. (2025). Computationally tuned dual-layer lattice pads adapted to gait-induced pressure distribution. *npj Advanced Manufacturing*, 2(1), 43. Nature Portfolio journal.
2. **Z Lu**, X Li, D Sun, Y Song, G Fekete, A Kovács, K András, Y Gu. (2025). Parametric cushioning lattice insole based on finite element method and machine learning: A preliminary computational analysis. *Journal of Biomechanics*, 184, 112674. IF: 2.4, Q1.
3. **Z Lu**, X Li, D Sun, Y Song, G Fekete, A Kovács, Y Gu. (2025). Will this be the next step? A systematic review of 3D printing in footwear biomechanics. *Footwear Science*, 17(2), 127-142. IF: 3.8, Q2.
4. **Z Lu**, D Sun, B Kovács, Z Radák, Y Gu. (2023). Case study: The influence of Achilles tendon rupture on knee joint stress during counter-movement jump—Combining musculoskeletal modeling and finite element analysis. *Heliyon*, 9(8). IF: 3.4, Q1.
5. **Z Lu**, X Li, M Rong, JS Baker, Y Gu. (2022). Effect of rearfoot valgus on biomechanics during barbell squatting: A study based on OpenSim musculoskeletal modeling. *Frontiers in neurorobotics*, 16, 832005. IF: 2.8, Q2.
6. **Z Lu**, X Li, R Xuan, Y Song, I Bíró, M Liang, Y Gu. (2022). Effect of heel lift insoles on lower extremity muscle activation and joint work during barbell squats. *Bioengineering*, 9(7), 301. IF: 3.7, Q2.
7. **Z Lu**, D Sun, D Xu, X Li, JS Baker, Y Gu. (2021). Gait characteristics and fatigue profiles when standing on surfaces with different hardness: Gait analysis and machine learning algorithms. *Biology*, 10(11), 1083. IF: 3.5, Q2.
8. C Hu, Y Song, D Sun, **Z Lu**, H Chen, X Cen, D Janićijević, Z Radak, Z Gao, JS Baker, Y Gu. (2025, January). Sedentary Duration and Systemic Health Burden: Nonlinear Associations with Muscle, Fat, and Vascular Phenotypes in a US Population-Based Study. *Healthcare*. IF: 2.4, Q2.
9. C Zhu, D Sun, Y Xu, **Z Lu**, C Hu, X Cen, Y Song, Z Gao, Y Gu. (2025). Integrating footwear features into fatigue prediction models for marathon runners: A hybrid CNN-LSTM approach. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 17543371251356133. IF: 1.1, Q2.
10. C Hu, X Cen, D Sun, **Z Lu**, Y Xu, C Zhu, Y Xu, Y Gu. (2025). Biomechanical effects of asymmetric backpack shoulder straps on the unilateral flatfoot: a finite element analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 1-11. IF: 2.4, Q2.
11. S Gao, Y Song, D Sun, X Cen, M Wang, **Z Lu**, Y Gu. (2025). Impact of Becker muscular dystrophy on gait patterns: Insights from biomechanical analysis. *Gait & Posture*. IF: , Q1.
12. Y Xu, C Zhu, Y Fang, **Z Lu**, Y Song, C Hu, D Sun, Y Gu. (2025). The effects of different carbon-fiber plate shapes in shoes on lower limb biomechanics following running-induced fatigue. *Frontiers in Bioengineering and Biotechnology*, 13, 1539976. IF: 4.8, Q1.
13. L Shen, **Z Lu**, X Li, D Sun, Y Song, G Fekete, A Kovács, F Li, X Cen. (Forthcoming Articles). Advances and Future Directions of Foetal Finite Element Modelling in Childbirth: from Biomechanical Interactions to Clinical Implications. *International Journal of Biomedical Engineering and Technology*. IF: 0.6, Q4.
14. X Li, **Z Lu**, Y Song, M Liang, Y Yuan, G Fekete, A Kovács, D Sun, Y Gu. (2024). Pregnancy-

induced gait alterations: meta-regression evidence of spatiotemporal adjustments. *Frontiers in bioengineering and biotechnology*, 12, 1506002. IF: 4.8, Q1.

15. D Wang, F Li, JS Baker, P Zhang, **Z Lu**, J Yu, M Liang. (2024). The effect of simulated basketball game load on patellar tendon load during stop-jump movement. *Molecular & Cellular Biomechanics*, 21(2), 292-292.

16. X Li, **Z Lu**, X Cen, Y Zhou, R Xuan, D Sun, Y Gu. (2023). Effect of pregnancy on female gait characteristics: A pilot study based on portable gait analyzer and induced acceleration analysis. *Frontiers in Physiology*, 14, 1034132. IF: 3.4, Q1.

17. X Li, **Z Lu**, D Sun, R Xuan, Z Zheng, Y Gu. (2022). The influence of a shoe's heel-toe drop on gait parameters during the third trimester of pregnancy. *Bioengineering*, 9(6), 241. IF: 3.7, Q2.

International conference abstracts related to this thesis:

1. The 17th Biennial Footwear Biomechanics Symposium. Title: Personalised footwear design method based on machine learning and finite element analysis. 2025. Norway (Oral presentation).

2. The 29th Annual Congress of the European College of Sport Science. Title: Stepping into the Future: Unveiling Biomechanical Innovations in 3D Printed Footwear Design. 2024. Scotland, UK (Oral presentation).

3. 2024 international Competitive Sports Biomechanics Forum 23rd National Sports Biomechanics Conference. Title: Customized 3D-Printed Insoles for Diabetic Foot Care: Finite Element Analysis and Machine Learning Approach. 2024. China (Oral presentation).

4. The 7th International Conference on Material Strength and Applied Mechanics (MSAM 2024). Title: Customized 3D-Printed Insoles for Diabetic Foot Care: Finite Element Analysis and Machine Learning Approach. 2024. Hungary (Oral presentation).