©Journal of Sports Science and Medicine (2025) **24**, 370-387
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2025.370

Review article

A Systematic Review of Finite Element Analysis in Running Footwear Biomechanics: Insights for Running-Related Musculoskeletal Injuries

Yang Song [1†], Xuanzhen Cen [2†], Meizi Wang [1], Zixiang Gao [3], Qitao Tan [1], Dong Sun [2], Yaodong Gu [2], Yan Wang [1,4,5]✉ and Ming Zhang [1,5]

[1] Department of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China; [2] Faculty of Sports Science, Ningbo University, Ningbo, China; [3] Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, Canada; [4] The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China; [5] Research Institute for Sports Science and Technology, The Hong Kong Polytechnic University, Hong Kong SAR, China
[†]These authors have contributed equally to this work.

Abstract

This study presented a systematic review of recent advancements in the application of finite element (FE) methods to running and running shoe biomechanics. It focused on outlining the general approach to build foot-running shoe FE models, exploring their current applications and challenges, and providing directions for future research. The review also aimed to highlight the gap between theoretical mechanical responses in simulations and real-world manifestations of running-related musculoskeletal injuries (RRMI). A comprehensive search of electronic databases, including Web of Science, PubMed, and Scopus, identified 12 eligible articles for inclusion in this review. Current studies have examined the effects of various running shoe design features and conditions on the mechanical response of internal foot tissues using foot-running shoe FE models. These models have gradually evolved from simplified local representations to more realistic and comprehensive models, with the incorporation of experimental data enhancing simulation accuracy. However, to further improve simulation outcomes, key advancements are proposed to reduce development time and enhance model robustness. These include high-fidelity 3D model development, personalized shape transformation, AI-driven automated reconstruction, comprehensive dynamic running simulations, and improved validation methods. More importantly, future research needs to bridge the gap between FE simulations and RRMI risk by addressing the complexities of bone fracture criteria and conducting localized assessments of bone properties. Overall, this review provided valuable insights for biomedical engineers, medical professionals, and researchers, facilitating more accurate investigations of foot-running shoe FE models. Ultimately, these advancements aim to improve footwear design and training programs to reduce the risk of RRMI.

Key words: Computational simulation, footwear biomechanics, RRMI, running.

Introduction

Running is a popular and accessible sport enjoyed by people worldwide. Over recent decades, the number of runners and running events has increased significantly, driven by the sport's positive effects on both physical and mental health and the minimal equipment required (Hulteen et al., 2017; Nikolaidis and Knechtle, 2023). However, despite these benefits, running-related musculoskeletal injuries (RRMI) are common among runners. Studies have shown that the incidence of RRMI varies widely, ranging from 3.2% in cross-country runners to 84.9% in novice runners (Kluitenberg et al., 2015; Kakouris et al., 2021). Given this high injury rate, developing effective injury prevention programs is a priority. Among the various strategies, research on running shoes has received significant attention in both academia and the sports industry, as footwear represents the primary interface between the body and the ground (Hamill and Bates, 2023; Willwacher and Weir, 2023).

Since the introduction of the first commercial running shoe in the early 20th century, the footwear industry has undergone tremendous advancements. Today, advanced footwear technologies (AFT) such as stiff plates, curved-shoe geometry, and lightweight resilient foam are designed to improve performance and potentially reduce RRMI (Hébert-Losier and Pamment, 2023; Burns and Joubert, 2024). Mechanically, the onset of RRMI occurs when the stress on specific structures consistently exceeds their capacity without sufficient rest periods for tissue remodeling (Mai et al., 2023). However, directly determining the mechanical characteristics of internal body tissues, such as stress distribution in the bones and soft tissue, used to be challenging. In the complex puzzle of RRMI, biomechanical risk factors have been studied as surrogate variables that link running biomechanics to injury risk (Sun et al., 2020). For example, running shoes with thinner midsoles and lower heel-toe drops have been shown to reduce impact forces by influencing the stiffness of the body's impact attenuation system and decreasing deceleration (Shorten and Mientjes, 2011). Despite the findings, there is still no direct evidence clearly showing how these biomechanical factors affect tissue stress tolerance and, consequently, the risk of RRMI.

One of the most significant advancements in footwear biomechanics is the adaptation of finite element (FE) modeling, an engineering method that uses continuum mechanics to solve load-deformation problems (Tseng, 2021). This approach has been increasingly applied in the footwear industry, allowing researchers to quantitatively analyze how human tissues respond to different activities and shoe conditions (Song et al., 2022b; Cen et al., 2023). FE modeling provides more direct and measurable insights than traditional biomechanics studies, which often rely on

Received: 15 November 2024 / Accepted: 10 May 2025 / Published (online): 01 June 2025

qualitative assessments. This technique offers a promising opportunity to better understand the interaction between the musculoskeletal system and footwear, potentially leading to improvements in running technique and shoe design that reduce RRMI. Numerous FE models have already been developed (Song et al., 2022a; 2023; 2024; Li et al., 2024). For example, Song et al., (2023) studied different carbon-fiber plate (CFP) designs and found that thicker, low-loaded CFP resulted in more uniform plantar pressure and lower metatarsal stress during running, which may reduce the risk of metatarsal stress fractures. Zhou et al., (2024a) demonstrated that reducing the sole-ground contact angle during forefoot shod running could lower the risk of metatarsal stress fractures.

Given the growing use of FE methods to explore running and footwear biomechanics, synthesizing the available research is crucial. This is particularly important for both runners and shoe orthopedists seeking to apply these insights to reduce RRMI. At the same time, it is essential to recognize the limitations inherent in foot-running shoe FE models, such as subject-specific variability and model simplifications, which may limit the realism and generalizability of the simulations. These limitations raise questions about the extent to which FE simulation results can be directly linked to the onset of RRMI. Therefore, this review aimed to provide a systematic overview of the latest advancements in applying FE methods to running biomechanics and footwear design. By critically assessing the current research, we would outline the general approach to build foot-running shoe FE models, discuss their applications and challenges, and offer insights for future research. Additionally, we aim to reveal the gap between the mechanical responses predicted by FE models and the actual occurrence of RRMI in real-world scenarios, ultimately contributing to improved running shoe designs and injury prevention strategies.

Methods

The protocol of this systematic review was developed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement. The protocol for this systematic review was registered on INPLASY (registration number: INPLASY2024100089).

Data sources and search strategy

English-language searches of electronic databases, including Web of Science, PubMed, and Scopus, were conducted independently by two authors (Y.S. and X.C.) to identify relevant studies up to July 20, 2024. The corresponding author (Y.W.) rechecked the search results for accuracy. Reference lists of eligible articles and reviews were examined to ensure no relevant papers were overlooked. Each database was searched using specific retrieval terms, and Medical Subject Headings (MeSH) terms were employed in PubMed. Keywords from four categories (finite element analysis, biomechanics, running, and shoe) were utilized to identify pertinent studies. Boolean operators were applied to ensure that retrieved studies contained at least one keyword. The complete retrieval strategies are detailed in Supplementary Materials (Table 1). The study selection process was conducted using Rayyan QCRI. A flow diagram illustrating the review process from database searching to study inclusion is shown in Figure 1.

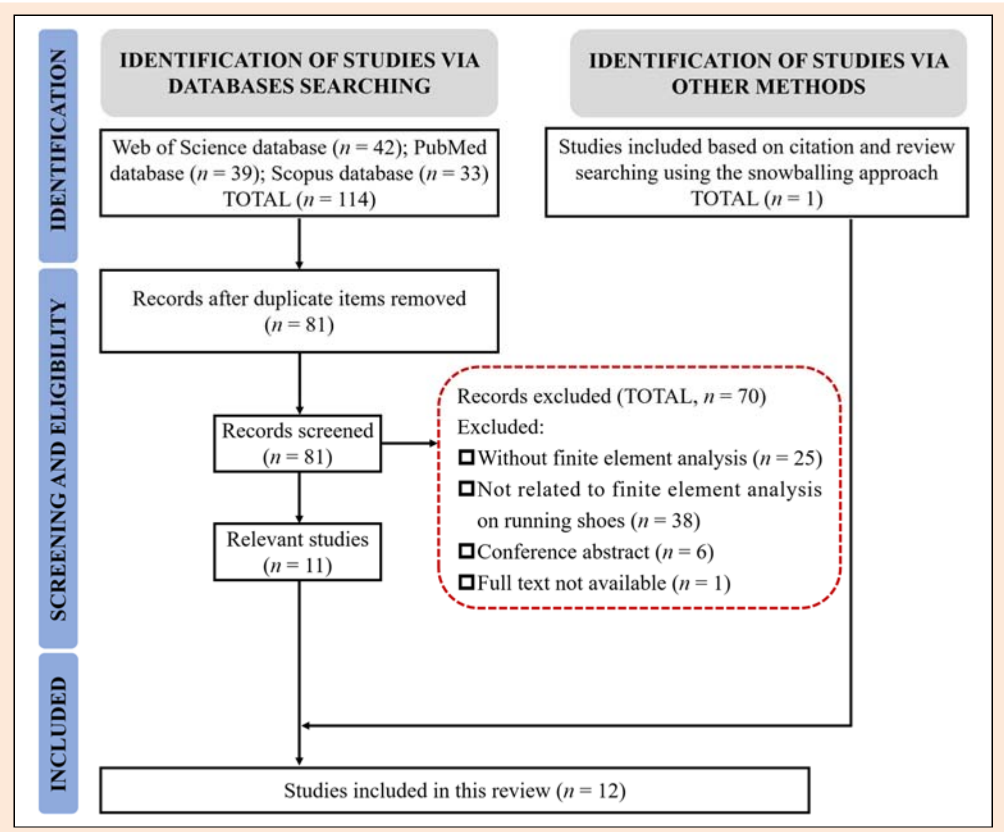

Figure 1. Preferred reporting items for systematic review and meta-analyses flow chart.

Table 1. Search strategies in each electronic database.

	Finite element analysis	Biomechanics	Running	Shoe
PubMed	("Finite Element Analysis"[Mesh] OR "Computer Simulation"[Mesh] OR "Numerical Analysis, Computer-Assisted"[Mesh] OR "finite element*"[tw] OR FEA[tw] OR FEM[tw])	("Biomechanical Phenomena"[Mesh] OR "Kinetics"[Mesh] OR "Electromyography"[Mesh] OR biomechanic*[tw] OR kinematic*[tw] OR "plantar pressure"[tw] OR EMG[tw])	("Running"[Mesh] OR "Jogging"[Mesh] OR "Marathon Running"[Mesh] OR "Locomotion"[Mesh] OR "distance running"[tw] OR sprint*[tw])	("Shoes"[Mesh] OR Footwear[tw] OR "running shoe*"[tw] OR "running footwear"[tw] OR sneaker*[tw] OR "athletic shoe*"[tw])
Web of Science	("finite element*" OR "computer simulation" OR "numerical analysis, computer-assisted" OR FEA OR FEM)	(kinetic* OR electromyography OR biomechanic* OR kinematic* OR "plantar pressure" OR EMG)	(running OR jogging OR "marathon running" OR locomotion OR "distance running" OR sprint*)	(shoe* OR footwear OR "running shoe*" OR "running footwear" OR sneaker* OR "athletic shoe*")
Scopus	("finite element*" OR "computer simulation" OR "numerical analysis, computer-assisted" OR FEA OR FEM)	(kinetic* OR electromyography OR biomechanic* OR kinematic* OR "plantar pressure" OR EMG)	(running OR jogging OR "marathon running" OR locomotion OR "distance running" OR sprint*)	(shoe* OR footwear OR "running shoe*" OR "running footwear" OR sneaker* OR "athletic shoe*")

Eligibility criteria

The selection process was conducted independently by two authors (Y.S. and X.C.), with any disagreements resolved through discussion. If consensus could not be reached, the corresponding author (Y.W.) was consulted for a resolution. Studies were included in this review if they met the following criteria: 1) Original journal articles were included, while other types (e.g., reviews, conference abstracts) were excluded; 2) Biomechanical analyses of running shoes under running scenario using the FE method (including interactions with the lower limbs or feet) were essential for the inclusion of the study; and 3) The papers should provide methodological details and results.

Methodological quality assessment

The quality of all included studies was independently evaluated by two authors (Y.S. and X.C.) utilizing the Methodological Quality Assessment of Subject-Specific Finite Element Analysis Used in Computational Orthopaedics (MQSSFE) tool (Wong et al., 2021). This tool is especially relevant given the unique challenges and requirements associated with finite element analysis in biomechanics. The MQSSFE scale evaluates the methodological quality of single-subject FE studies across 37 items in 6 domains, focusing on study design (items 1 to 8), subject recruitment (items 9 to 12), model reconstruction (items 13 to 20), boundary and loading conditions (items 21 to 26), model verification and validation (items 27 to 31), and assumptions of the model (items 32 to 37). Two items (11 and 12) were excluded from this review because the MQSSFE tool is primarily designed for clinical FE analyses, resulting in a total of 35 assessed items. Each item can be addressed with a response of "Yes" or "No" corresponding to scores of 1 and 0 points, respectively. It has previously been shown to have sufficient reliability and validity (Wong et al., 2021). To ensure an objective quality assessment, scores were converted to a percentage scale (0% to 100%), with higher percentages indicating better adherence to criteria. The results were reviewed and confirmed by the corresponding author (Y.W.).

Data extraction and management

Data from the included studies were extracted and summarized in tables by one author (Y.S.) and subsequently verified by another author (Y.W.). The following information was collected: 1) author characteristics (first author and publication year); 2) study objectives; 3) participant characteristics; 4) model characteristics (geometry design and material properties); 5) boundary and loading conditions; 6) validation; and 7) primary findings. Mendeley Desktop Reference Management Software (Mendeley Ltd., Netherlands) was used for organizing articles and generating citations.

Results

Search results

Figure 1 illustrates the flow diagram for this systematic review, detailing the process from database searches to study inclusion. A total of 114 articles were identified from electronic database searches (Web of Science, n = 42; PubMed, n = 39; Scopus, n = 33). After removing 33 duplicate records, the titles, abstracts, and full texts of 81 articles were evaluated, resulting in the exclusion of 70 studies based on the eligibility criteria. The reasons for exclusion included 25 articles that did not utilize FE analysis, 38 that were unrelated to FE analysis of running/running shoes, 6 conference abstracts, and 1 article with an unavailable full text, which hindered the collection of study characteristics. An additional paper was identified through reference checking, resulting in a total of 12 articles included in this review (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Chen and Lee, 2015; Hannah et al., 2016; Li, Leong and Gu, 2019; NONOGAWA et al., 2021; Yang et al., 2022; Zhu et al., 2023; Song et al., 2023; 2024; Zhou et al., 2024a; 2024b).

Quality assessment

The methodological quality assessment of the 12 included studies, evaluated using the MQSSFE instrument, is summarized in Table 2. The mean total score was 26.7 out of 35 (76.2%), with scores ranging from 18 (51.4%) to 31 (88.6%). The overall fulfillment of the MQSSFE criteria across all studies was 76.2% out of 35 items.

All studies adequately presented their objectives and key findings (items 1 - 7), described material properties, interactions, boundary and loading conditions, and software settings (items 17, 19 - 21, 26), and conducted model validation while discussing potential implications (items 30, 31, and 37). They also performed well in detailing model subject characteristics and reconstruction modalities (items 9, 10, 13), addressing assumptions related to reconstruction, material properties, and boundary/loading conditions (items 32, 33). However, over half of the studies provided limited details on model reconstruction (items 14, 15, 16, 18) and did not apply boundary and loading conditions consistently from the same model subject (items 23, 25). Additionally, muscle forces were often neglected or oversimplified (item 24), and verification tests were generally overlooked (items 27, 28). The discussions on the limitations of model validation and the internal and external validity of the FE design were also insufficient (items 34, 35, 36).

Table 2. **Methodological quality assessment for the included studies.**

Studies	Chen et al.(2015)	Even-Tzur et al.(2006)	Hannah et al.(2016)	Li et al.(2019)	Nonogawa et al.(2021)	Song et al.(2023)	Song et al.(2024)	Verdejo et al.(2004)	Yang et al.(2022)	Zhou et al. (2024a)	Zhou et al.(2024b)	Zhu et al.(2023)	Criterion fulfilled in % of studies
Study Design and Presentation of Findings													
Item 1: Was the hypothesis/aim/objective of the study clearly described?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 2: Were all analyses planned at the outset of study?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 3: If data dredging (establish objectives, hypothesis and endpoint parameters without scientific reason) was used, was the spectrum of the data justified by any concepts?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 4: Were ALL the outcome measures and parameters (including all data reduction methods or derived parameters) clearly described and defined in the Objectives or Methods section?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 5: Were the time points or period for ALL the outcome measures clearly described?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 6: Were the main outcome measures appropriate to describe the targeted conditions?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 7: Were the key findings described clearly?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 8: Were ALL the contour plots that were used for comparison presented with the same colour scale?													
Score	0	1	1	0	1	1	1	1	1	1	1	1	83.3%
Subject Recruitment													
Item 9: Were the characteristics of the model subject clearly described?													
Score	1	0	0	1	1	1	1	0	1	1	1	1	75.0%
Item 10: Were the principal confounders of the model subject clearly described? (Age, sex, or body weight, and height)													
Score	1	0	0	1	1	1	1	0	1	1	1	1	75.0%
Item 11: Was the model subject participated in the study representative of the population with the targeted clinical conditions or demographic features?													
Score	/	/	/	/	/	/	/	/	/	/	/	/	/
Item 12: Were the targeted intervention or clinical condition clearly described? (with details in the severity, class, design/dimensions of implants, or details in surgical surgery)													
Score	/	/	/	/	/	/	/	/	/	/	/	/	/
Model Reconstruction and Configuration													
Item 13: Was the model reconstruction modality for the body parts and ALL other items, such as implants, clearly described (e.g. MRI, 3D-scanning, CAD)?													
Score	1	0	1	1	1	1	1	1	1	1	1	1	91.7%
Item 14: Were ALL important technical specifications (e.g. resolution) for the reconstruction modality clearly described?													
Score	0	1	0	0	0	0	0	1	1	1	0	1	41.7%

Table 2. Continue...

Studies	Chen et al.(2015)	Even-Tzur et al.(2006)	Hannah et al.(2016)	Li et al.(2019)	Nonogawa et al.(2021)	Song et al.(2023)	Song et al.(2024)	Verdejo et al.(2004)	Yang et al.(2022)	Zhou et al. (2024a)	Zhou et al.(2024b)	Zhu et al.(2023)	Criterion fulfilled in % of studies
Item 15: Was the posture or position of the body parts controlled during the acquisition process (e.g. MRI, CT) of the model reconstruction?													
Score	0	0	0	0	1	1	1	0	0	0	1	0	33.3%
Item 16: Were the model reconstruction methods for ALL components clearly described including those requiring additional procedures (e.g. connecting points for drawing ligaments from MRI)?													
Score	1	1	1	1	1	0	0	1	0	0	0	1	58.3%
Item 17: Were the orientation or relative position among the components of the model assembly (where appropriate) clearly described?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 18: Was the type of mesh for ALL components, including the order of magnitude of the elements, clearly described?													
Score	0	0	0	0	0	1	1	0	1	1	1	1	50.0%
Item 19: Were the material properties for ALL components clearly described and justified? (e.g. with reference)													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 20: Were ALL the contact or interaction behaviours in the model clearly described and justified?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Boundary and Loading Condition (Simulation)													
Item 21: Were the boundary and loading conditions clearly described?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 22: Was the boundary and loading condition sufficiently simulating the common activity/scenario of the conditions? (e.g. if the research or inference is targeted to ambulation or daily activities, simulations of balanced standing or pre-set compressive load are insufficient)													
Score	1	0	1	0	1	1	1	0	1	1	1	1	75.0%
Item 23: Was the model driven by the boundary condition acquired from the same model subject?													
Score	0	0	0	0	1	1	1	0	1	1	1	1	58.3%
Item 24: Was loading condition on the scenario sufficiently and appropriately considered in the simulation? (e.g. muscle force, boundary force, inertia force)													
Score	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Item 25: Was the loading condition acquired from the same model subject?													
Score	0	0	0	0	1	1	1	0	1	1	1	1	58.3%
Item 26: Were the software (e.g. Abaqus, Ansys), type of analysis (e.g. quasi-static, dynamic), AND solver (e.g. standard, explicit) clearly described? (solver can be regarded as clearly described if it is obvious to the type of analysis)													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Model Verification and Validation													
Item 27: Were the methods of mesh convergence or other verification tests conducted and clearly described?													
Score	1	0	1	0	0	1	1	0	1	1	1	0	58.3%
Item 28: Were the model verification conducted and results presented clearly; and that the model was justified acceptable?													
Score	1	0	1	0	0	1	1	0	1	1	1	0	58.3%
Item 29: Were direct model validation (with experiment) conducted and described clearly?													
Score	0	0	1	1	1	1	1	1	1	1	1	1	83.3%
Item 30: Were the model validation conducted and results presented clearly; and that the model was justified acceptable?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Item 31: Were the model prediction or validation findings compared to relevant studies?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%

Table 2. Continue...

Studies	Chen et al.(2015)	Even-Tzur et al.(2006)	Hannah et al.(2016)	Li et al.(2019)	Nonogawa et al.(2021)	Song et al.(2023)	Song et al.(2024)	Verdejo et al.(2004)	Yang et al.(2022)	Zhou et al. (2024a)	Zhou et al.(2024b)	Zhu et al.(2023)	Criterion fulfilled in % of studies
Model Assumption and Validity													
Item 32: Were the model assumptions or simplifications on model reconstruction/configuration AND material properties discussed?													
Score	1	0	1	1	1	1	1	0	1	1	1	1	83.3%
Item 33: Were the model assumptions or simplifications on the boundary and loading conditions discussed?													
Score	1	0	1	1	1	1	1	0	1	1	1	1	83.3%
Item 34: Were the limitations of model validation discussed? (e.g. differences in case scenario; differences between validation metric and primary outcome)													
Score	1	0	1	1	1	0	0	0	1	0	0	1	50.0%
Item 35: Was the limitation on external validity, single-subject, and subject-specific design discussed?													
Score	0	0	0	0	0	1	1	0	1	1	1	1	50.0%
Item 36: Were there any attempts to improve or discuss internal validity (such as mesh convergence test), uncertainty and variability in the study?													
Score	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Item 37: Was there any discussion, highlights or content on the implications or translation potential of the research findings?													
Score	1	1	1	1	1	1	1	1	1	1	1	1	100.0%
Sum	25	18	25	23	28	30	30	20	31	30	30	30	/
%	71.4%	51.4%	71.4%	65.7%	80.0%	85.7%	85.7%	57.1%	88.6%	85.7%	85.7%	85.7%	/

Study characteristics of data synthesis

The search yielded 12 articles published between 2004 and 2024, with a significant increase in studies over the last five years (7/12, 2020-2024). These studies presented various FE applications in running and running shoe biomechanics, employing different computational simulation strategies. All studies focused on constructing and analyzing FE models for foot-running shoes, with no research exploring interactions between footwear and other lower limb joints, such as the knee and hip joints. Detailed information regarding the simulation methods, including geometric design, material property assignment, boundary and loading definitions, model validation, as well as the FE software used and computational cost, is summarized in Table 3.

Table 3. The characteristics of the coupled foot-shoe models and their simulation details.

References	Model	Material properties	Boundary and loading conditions	Model validation	Software and computational cost
Chen et al.(2015)	▪ Foot: soft tissue, bone (only calcaneus); ▪ Shoe: insole, heel counter, midsole, outsole.	▪ Foot: hyperelastic for soft tissue and rigid body for calcaneus; ▪ Shoe: purely elastic for insole and midsole; linearly elastic for heel counter and outsole.	1) Fix the support plate; 2) Apply the landing impact force to the heel pad.	1) Impact force pattern; 2) Heel pad deformation; 3) Plantar pressure. (published literature data)	▪ ABAQUS 6.12 ▪ Two Intel Xeon processor, 5h 12min (3D model), 7min (2D model).
Even-Tzur et al.(2006)	▪ Foot: soft tissue, bone (only calcaneus); ▪ Shoe: midsole.	▪ Foot: linearly elastic for calcaneus, nonlinear viscoelastic for heel pad; ▪ Shoe: linear viscoelastic.	1) Fix the midsole or heel pad; 2) Apply sinusoidal force wave on the superior surface of the calcaneus.	NA	▪ COSMOSWorks 2005 ▪ NA
Hannah et al.(2016)	▪ Foot: soft tissue; ▪ Shoe: midsole, outsole.	▪ Foot: hyperelastic; ▪ Shoe: hyperelastic.	1) Introduce a homogeneous 3D structure of a foot prosthesis into the assembled model, connecting its plantar surface nodes to the calcaneal, metatarsal, and phalangeal plates; 2) Apply the 6 degrees of freedom foot segment kinematics to the three foot plates through rigid body reference points.	1) GRF; 2) Center of pressure.	▪ ABAQUS 6.12 ▪ NA

Table 3. Continue...

References	Model	Material properties	Boundary and loading conditions	Model validation	Software and computational cost
Li et al.(2019)	▪ Foot: soft tissue, bones, cartilage, Achilles tendon; ▪ Shoe: upper, insole, ▪ midsole, outsole.	▪ Foot: linearly elastic for all component except soft tissue (hyperelastic); ▪ Shoe: linearly elastic for all component except outsole (hyperelastic).	1) Fix the proximal surfaces of the soft tissue, tibia, and fibula; 2) Apply vertical concentrated forces in 100N increments under the support plate for each condition; 3) Apply the AT forces to the distal Achilles tendon through the muscle connectors.	1) Plantar pressure.	▪ ABAQUS 6.13 ▪ Four Intel Core i7-7700K processor, ▪ 6h 10min
Nonogawa et al.(2021)	▪ Foot: soft tissue, bones, plantar fascia; ▪ Shoe: sole.	▪ Foot: linearly elastic for all component except soft tissue (hyperelastic); ▪ Shoe: linearly elastic.	1) Fix the sole; 2) Apply the ankle joint force and moment at the independent node at the origin of the ankle joint coordinate system; 3) Apply the body force due to total body weight to all elements.	2) Plantar pressure; 3) Contact area.	▪ ABAQUS 2018 ▪ NA
Song et al.(2023)	▪ Foot: soft tissue, bones, ligaments (including plantar fascia); ▪ Shoe: upper, sole, carbon-fiber plate.	▪ Foot: linearly elastic; ▪ Shoe: linearly elastic.	1) Fix the proximal surfaces of the soft tissue, tibia, fibula, and shoe tongue; 2) Apply the AT force at the superior surface of the calcaneus through the muscle connectors; 3) Apply the MTP joint contact force on the top surface of the middle cuneiform; 4) Iterate the continuous displacement load under the plate until the simulated force reaches the GRF value.	1) Plantar pressure; 2) Outsole pressure.	▪ ANSYS 2021 R1 ▪ Four Intel Core i7-8565U processor, 8h 6min
Song et al.(2024)	▪ Foot: soft tissue, bones, ligaments (including plantar fascia); ▪ Shoe: upper, sole, carbon-fiber plate.	▪ Foot: linearly elastic; ▪ Shoe: linearly elastic.	1) Fix the proximal surfaces of the soft tissue, tibia, fibula, and shoe tongue; 2) Apply the AT force at the superior surface of the calcaneus through the muscle connectors; 3) Apply the MTP joint contact force on the top surface of the middle cuneiform; 4) Iterate the continuous displacement load under the plate until the simulated force reaches the GRF value.	1) Plantar pressure; 2) Outsole pressure.	▪ ANSYS 2021 R1 ▪ Four Intel Core i7-8565U processor, 8h 11min
Verdejo et al.(2004)	▪ Foot: soft tissue, bone (only calcaneus); ▪ Shoe: midsole.	▪ Foot: hyperelastic; ▪ Shoe: hyperelastic.	1) Fix the midsole; 2) Ramp down the upper calcaneus boundary by 20 mm (12 mm when no foam is present).	1) Plantar pressure.	▪ ABAQUS 6.3 ▪ NA
Yang et al.(2022)	▪ Foot: soft tissue, bones, cartilages, ligaments (including plantar fascia); ▪ Shoe: upper, heel cup, insole, midsole, outsole.	▪ Foot: linearly elastic; ▪ Shoe: linearly elastic for upper and outsole, hyperelastic for heel cup, insole, and midsole.	1) Fix the proximal surfaces of the soft tissue, tibia, fibula, and shoe tongue; 2) Apply the AT force at the superior surface of the calcaneus through the muscle connectors; 3) Apply the ankle joint contact force on the top surface of the talus; 4) Iterate the continuous displacement load under the plate until the simulated force reaches the GRF value.	1) Plantar pressure; 2) Outsole pressure.	▪ ANSYS 19.0 ▪ NA

Table 3. Continue...

References	Model	Material properties	Boundary and loading conditions	Model validation	Software and computational cost
Zhou et al.(2024a)	■ Foot: soft tissue, bones, cartilages, ligaments (including plantar fascia); ■ Shoe: insole, midsole, outsole.	■ Foot: linearly elastic for all component except soft tissue and skin (hyperelastic); ■ Shoe: linearly elastic.	1) Fix the support plate; 2) Add the initial landing velocity to the finite element model; 3) Apply the ankle joint moment and ankle joint reaction force to the slipring connectors and tibiotalar articular surface of the talus, respectively; 4) Apply the MPJ joint force on the top surface of the middle cuneiform bone.	1) Vertical displacement of the navicular bone.	■ ANSYS 2021 R1 ■ Fourteen Intel Core Ultra 5 processors, 4h 4min
Zhou et al.(2024b)	■ Foot: soft tissue, bones, cartilages, Achilles tendon, ligaments (including plantar fascia); ■ Shoe: insole, midsole, outsole.	■ Foot: linearly elastic for all component except soft tissue (hyperelastic); ■ Shoe: linearly elastic.	1) Fix the proximal surfaces of the soft tissue, tibia, and fibula; 2) Apply the five muscle force through the muscle connectors; 3) Apply the vertical GRF to the support plate.	1) Vertical displacement of the navicular bone.	■ ANSYS 2021 R1 ■ Fourteen Intel Core Ultra 5 processors, 4h 12min
Zhu et al.(2023)	■ Foot: soft tissue, bones, cartilages, ligaments (including plantar fascia); ■ Shoe: upper, midsole, outsole.	■ Foot: linearly elastic; ■ Shoe: linearly elastic for all component except midsole (hyperelastic).	1) Fix the ground support plate and the upper ends of the tibia and fibula; 2) Apply the net joint force to the middle part of the upper surface of the talus; 3) Apply the AT force to the attachment point of the Achilles tendon via the node force.	1) Plantar pressure; 2) Outsole pressure.	■ ANSYS 12.1 ■ Six Intel Core i7-8700k processor, 6h

Abbreviations: AT (Achilles tendon), GRF (Ground reaction force), MPJ (Metatarsophalangeal joint), NA (Not available).

As shown in Table 4, one study proposed a method to develop a dynamic foot-running shoe FE model using kinematic boundary conditions directly derived from motion capture data of experimental running trials (Hannah et al., 2016). Two studies investigated how different running conditions (e.g., foot touchdown velocities and sole-ground contact angles) influenced the mechanical characteristics of the foot based on FE models (Chen and Lee, 2015; Zhou et al., 2024a). Most studies examined the effects of various design features of running shoes on foot mechanical characteristics, including 4 studies on midsoles (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Nonogawa et al., 2021; Zhu et al., 2023), 2 on CFP (Song et al., 2023; 2024), 1 on outsoles (Zhou et al., 2024b), 1 on barefoot running shoes (Li et al., 2019), and 1 on multiple running shoe design features (heel cup, insole, midsole) (Yang et al., 2022).

Table 4. **The basic information of the included studies and their primary findings.**

References	Purposes	Parameters of interest	Primary findings
Chen et al.(2015)	■ Examine how reduced touchdown velocity affects internal heel pad deformations and stress during rearfoot running impacts, considering the dynamics of body movement and footwear.	1) Impact force pattern; 2) Heel pad strain and stress of skin and fatty tissue.	■ A reduction in foot touchdown velocity resulted in a less severe running impact and stress relief inside the heel pad.
Even-Tzur et al.(2006)	■ Examine the stress distribution and peak stress in the heel pad during rearfoot running impacts, considering the viscoelastic and geometrical properties of the the EVA midsole.	1) Heel pad stresses and strain.	■ EVA wear consistently elevated heel pad stress, with reduced EVA thickness identified as the most significant factor.
Hannah et al.(2016)	■ Propose a dynamic model of a shod footstrike that employs kinematic boundary conditions based on motion capture data from experimental running trials.	1) Experimental HSV footage; 2) vertical GRF; 3) COP excursion.	■ The HSV footage showed good visual agreement, but notable discrepancies were observed between the model and experimental GRF and COP readings.
Li et al.(2019)	■ Examine the differences in peak plantar pressure during the weight-bearing phase of running between barefoot and barefoot running footwear conditions.	1) Plantar pressure.	■ Barefoot running footwear showed better pressure distribution and less peak plantar pressure.

Table 4. Continue...

References	Purposes	Parameters of interest	Primary findings
Nonogawa et al.(2021)	■ Examine the running shoe stability when the y-axis component of ground reaction force is at its minimum during running.	1) Plantar pressure; 2) Contact area; 3) Heel eversion angle.	■ A decrease in resin foam hardness adversely affected shoe stability by increasing the heel eversion angle.
Song et al.(2023)	■ Examine the effects of carbon-fiber plate thickness and placement in running shoes on plantar pressure, forefoot strain, and metatarsal stress during forefoot running impacts.	1) Plantar pressure; 2) Forefoot strain; 3) Metatarsal stress.	■ A thicker, low-loaded CFP achieved pressure-relief benefits in running shoes without increasing metatarsal stress.
Song et al.(2024)	■ Examine the effects of CFP stiffness and shoe shape on plantar pressure, metatarsal stress distribution, and MPJ force transmission during forefoot running impacts.	1) Plantar pressure; 2) Metatarsal stress; 3) MTP contact force transmission.	■ A curved CFP produces lower peak pressure under the metatarsal heads and does not worsen stress.
Verdejo et al.(2004)	■ Examine the mechanical interaction between the heel pad and running shoe midsoles, and estimate the magnitude of internal heel pad stresses during rearfoot running impacts.	1) Plantar pressure; 2) Heelpad stress.	■ A significantly lower peak heelpad pressure and stress was found in a shod heel-strike, compared with a bare heel-strike with the same force.
Yang et al.(2022)	■ Examine the effect of running shoe design parameters on peak plantar pressure during rearfoot running impacts, and identify the optimal combination to enhance cushioning.	1) Plantar pressure.	■ The design of the conforming heel cup and insole material significantly influenced peak plantar pressure during heel landing, making a custom conforming heel cup essential for relieving high plantar pressure in long-distance heel-strike runners.
Zhou et al.(2024a)	■ Examine the effects of varying sole-ground contact angles on mid- to forefoot bone stress during forefoot running impacts.	1) Mid- to forefoot bone stress.	■ A reduced sole-ground contact angle reduced the mid- to forefoot bone stress, potentially decrease the risk of metatarsal stress fractures.
Zhou et al.(2024b)	■ Examine the effects of running shoe types (bionic vs. normal shoes) on mid- to forefoot bone stress during rearfoot running impacts.	1) Proximal phalanx and metatarsal stress.	■ Bionic running shoes reduced the proximal phalanx and metatarsal stress stress, potentially decrease the risk of metatarsal stress fractures.
Zhu et al.(2023)	■ Examine the effects of running shoe midsole hardness on plantar fascia stress and strain during running push-off.	1) Plantar fascia stress and strain; 2) MPJ flexion angle; 3) arch descent height; 4) shoe outsole pressure.	■ Increasing midsole hardness in running shoes reduces plantar fascia stress and strain but also increases overall foot load.

Abbreviations: CFP (Carbon-fiber plate), COP (Centre of pressure), GRF (Ground reaction force), HSV (High-speed video), MPJ (Metatarsophalangeal joint).

Discussion

The primary objective of this study was to conduct a comprehensive review and synthesis of recent advancements in the application of FE methods to running and running shoe biomechanics. The discussion is organized into three main sections: 1) Overview of foot-running shoe FE modeling; 2) Current applications of foot-running shoe FE models in running biomechanics; and 3) Future development and applications of foot-running shoe FE models in running biomechanics. In this framework, we will further highlight the key challenges faced in developing and applying foot-running shoe FE models within running biomechanics and aim to reveal the gap between the structure-specific mechanical responses observed in theoretical simulations and their real-world manifestations in RRMI. Ultimately, the study seeks to guide future research and contribute to the optimization of running shoe design and injury prevention strategies.

Overview of foot-running shoe FE modeling

The creation of foot-running shoe FE models involves several key steps, beginning with the acquisition of reliable geometric data for model reconstruction. In early research, symmetrical geometric shapes were often used for model construction, representing only partial structures. For instance, Verdejo and Mills (2004) and Even-Tzur et al. (2006) employed simple geometric forms, such as cylinders and spheres, to represent different foot and shoe components. Specifically, the calcaneus was modeled as a combination of a cylinder and hemisphere to capture its overall shape and curvature, while the heel pad was approximated using a thicker cylinder with a spherical lower surface to simulate its cushioning properties. The midsole was represented as a vertical cylinder, emphasizing its height and radius to replicate cushioning and support functions. Although these simplifications allowed for quicker modeling and analysis, they failed to capture the complex anatomical structures and interactions during movement. This limitation affects the model's ability to accurately reflect the biomechanical behavior of different foot shapes and sizes, leading to potential inaccuracies in results. To address these issues, researchers have increasingly turned to data from CT and MRI scans to develop more detailed and individualized models, thereby enabling a finer exploration of running biomechanics. Medical DICOM images of the foot and shoe are usually obtained by scanning the participant's leg in a shod condition using CT or MRI. These images are then segmented using medical image segmentation software, such as MIMICS (Materialise, Leuven, Belgium), to delineate the boundaries of bones, soft tissues, and the shoe, and are then utilized to reconstruct the 3D geometry. The resulting geometric models of the foot and shoe can be imported into reverse engineering software, such as SOLIDWORKS (Dassault Systèmes, Paris, France), for surface smoothing and solid model creation, including cartilages. Finally, these models are aligned and assembled to establish the coupled foot-shoe FE models. Typically, foot modeling involves extracting only the bones and the outer layer of soft tissue from the acquired images, with some bones fused for simplification. Other structures, such as cartilage, muscles, and connective tissues (e.g., tendons and ligaments), are manually reconstructed based on anatomical features. In some cases, researchers also reconstruct the 3D physical geometry of the Achilles tendon, given its crucial role in force generation during running activities (Li et al., 2019). For running shoe modeling, nearly half of the included studies reconstructed the two primary components: the upper and the sole. In some cases, the sole was further divided into insole, midsole, and outsole, and additional elements, such as CFP and heel cups, were modeled to explore their effects on foot biomechanics (Chen and Lee, 2015; Li et al., 2019; Yang et al., 2022; Zhu et al., 2023; Zhou et al., 2024b; 2024a). Non-structural features like shoelaces were often excluded to simplify the model. Additionally, it is important to note that some studies focused solely on the sole structure, neglecting the upper (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Hannah et al., 2016; Nonogawa et al., 2021; Zhou et al., 2024a; 2024b). This omission can significantly affect the results, as foot deformation occurs when wearing shoes during dynamic simulations. The interaction between the foot and the shoe upper plays a critical role in influencing internal stress and strain patterns (Yu et al., 2013).

After creating the foot-running shoe model, the next step is to mesh the model components. Each component is meshed individually using appropriate element geometries. In general, researchers aim to develop an optimal mesh density that balances model accuracy with computational efficiency. Depending on the shape of each component, commonly reported element geometries include triangular or quadrilateral elements for 2D FE models and tetrahedral, hexahedral, and pentahedral elements for 3D models. Tetrahedral elements were found used in most studies probably due to the complexity of human bone geometry and running shoe structures. Hexahedral elements, however, are more accurate and efficient for dynamic simulations, while tetrahedrals are preferred for discretizing complex surfaces (Burkhart et al., 2013). Some studies using simplified geometric models opted for hexahedral elements to improve accuracy, particularly for shoe components (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Chen and Lee, 2015; Nonogawa et al., 2021). Additionally, localized mesh refinement is often applied in contact regions between the running shoe and the ground, as well as in areas with intricate geometries, to enhance mesh quality. Before running the simulation, several beams or axial 1D elements are incorporated into the mesh to represent the ligaments connecting different bones. This approach is widely regarded as one of the most efficient methods for simulating ligament behavior in the foot-ankle complex (Wang et al., 2016). Finally, the foot-running shoe model's mesh is typically refined through a detailed mesh convergence study, ensuring a balance between computational efficiency and solution accuracy. Criteria such as plantar pressure and maximum vertical GRF are used to assess convergence, with a tolerance of less than 5% set for the mesh sensitivity analysis.

Once the mesh is generated, various properties must be assigned to establish the simulation environment. These include material properties, contact interactions, constraints, boundary conditions, and loads. The accuracy of FE models for the foot-running shoe complex is highly dependent on the appropriate assignment of material properties to each component of the model, which mainly includes bones, muscles, ligaments, fascia, soft tissue, the shoe upper, and the shoe sole. These material properties would directly influence the model's response and, consequently, the validity of the simulation results (Phan et al., 2021). Typically, material parameters are derived from values reported in literature. For instance, bones are commonly represented as linear elastic materials, with a Young's modulus of 0.73GPa (Cen et al. 2023). Similarly, muscles, fascia, and ligaments are often modeled as one-dimensional truss elements connecting anatomical insertion points, with varying lengths and cross-sectional dimensions, and assigned linear elastic properties with Young's modulus of 0.45GPa, 0.35GPa, and 0.26GPa, respectively (Cen et al. 2023). Soft tissue and shoe soles, on the other hand, are frequently represented using non-linear hyperelastic models, such as the five-term Mooney-Rivlin model, to more accurately capture their rubber-like mechanical behavior (Li et al., 2019; Zhou et al., 2024a; 2024b). While many studies rely on literature-based material properties, some incorporate personalized material properties obtained from in vivo experiments (for foot tissues) and mechanical testing (for running shoes) into the models. For example, Yang et al. (2022) determined the mechanical properties of shoe midsoles and insoles through material testing of custom-sized EVA and Latex samples using a MicroTester and a push-pull tester, respectively. In general, despite the availability of more complex material models, linear elastic assumptions remain a common choice in FE modeling of the foot-shoe interaction due to their computational efficiency and feasibility for parametric studies. This simplification allows researchers to systematically examine variations in running mechanics, such as changes in contact angles and footwear features, without incurring excessive computational costs or significantly compromising result reliability. However, it is important to recognize that most studies employing this approach use a quasi-static modeling framework, either analyzing discrete time points within the stance phase or conducting multiple simulations at different instances of the stance phase (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Li et al., 2019; Nonogawa et al., 2021; Yang et al., 2022; Zhu et al., 2023; Song et al., 2023; 2024; Zhou et al., 2024a; 2024b). Under dynamic loading conditions, where deformations and stress distributions evolve continuously, non-linear hyperelastic material models would be required to capture the complex mechanical behavior of both foot tissues and shoe components, given the substantial deformations relative to their geometric dimensions.

Following the assignment of material properties, appropriate boundary and loading conditions must be applied to the model. Most simulations in this review utilized data derived from motion analysis and musculoskeletal modeling of the subject (Hannah et al., 2016; Nonogawa et al., 2021; Yang et al., 2022; Song et al., 2023; 2024; Zhu et al., 2023; Zhou et al., 2024a; 2024b). Common constraints and loads include running kinematics and kinetics, such as foot-ground angle, joint moments, joint contact forces, foot muscle forces, and GRF. In these simulations, a stiff plate is often attached to the outsole of the shoe model to simulate ground support. The proximal surfaces of the soft tissue, tibia, fibula, and the shoe tongue loop are typically fixed in all directions. Various running postures are replicated by adjusting the plate angle. For load applications, researchers either apply direct loads to the dorsal surface or use force vectors connected to specific bone insertion points to simulate the forces exerted by relevant joints and muscles. To simulate the running stance phase, a quasi-static approach is commonly preferred. However, some studies have explored dynamic modeling to analyze the mechanical response of human structures under varying running conditions and footwear designs. For example, Chen and Lee, (2015) developed a computational model of a body-heel-shoe system to investigate the mechanical behavior of the heel pad under realistic impact loads during running. By applying different touchdown velocities of the foot prior to landing, they examined how these variations influenced internal deformations and stress distribution within the heel pad. Beyond boundary and loading conditions, a crucial factor in ensuring realistic simulation outcomes is the proper definition of contact interactions within the model. The accuracy of force transmission and mechanical behavior depends on how material properties interact and transfer loads across contact surfaces. Most studies in this review define the interactions between the foot, shoe, and ground plate as frictional surface-to-surface contact using the isotropic Coulomb friction model. The coefficient of friction, originally determined by Zhang and Mak, (1999), generally ranges from 0.5 to 0.6. For interactions within the shoe-such as between the insole, midsole, and outsole-a surface-to-surface tying method is commonly employed to ensure structural cohesion. Some studies adjust the friction coefficient between the shoe and ground plate based on surface conditions, with values ranging from 1.0 to 1.5 (Chen and Lee, 2015). An alternative approach was proposed by Hannah et al. (2016), who developed a dynamic FE model of a shod footstrike. Instead of defining frictional contact between the foot and the shoe, they constrained adjacent foot and footwear surfaces solely using foot segment kinematics data. However, their results failed to meet validation criteria, limiting the practical applicability of this method. This underscores the critical role of interface contact, particularly in dynamic simulation scenarios, where accurate force transmission is essential. To conduct FE simulations after defining boundary and loading conditions, researchers have extensively used commercial software such as ANSYS (ANSYS, Canonsburg, PA, USA) and ABAQUS (Simulia, Johnston, RI, USA) (Table 2). Earlier studies also employed other research software, such as COSMOSWorks (Dassault Systèmes, Paris, France) (Even-Tzur et al., 2006). The computational cost (simulation run time) is normally influenced by the processor configurations of the computing planforms used. However, as shown in Table 2, despite improvements in the number and power of processors, the overall simulation run time has not significantly decreased. This may be directly related to the increased complexity of the models. In general, researchers always strive to achieve an optimal balance between computational expense and accuracy, without assuming the necessity of acquiring high-performance computing hardware or costly commercial FE analysis software licenses.

Finally, the results of the FE simulation must be validated to ensure consistency with experimental findings. Most foot-running shoe FE models in this review were validated by comparing the distribution and peak values of plantar and outsole pressures with experimental data or published literature (Verdejo and Mills, 2004; Chen and Lee, 2015; Li et al., 2019; Nonogawa et al., 2021; Yang et al., 2022; Song et al., 2023; 2024; Zhu et al., 2023). Based on the findings of Zhang et al., (2007), an error of less than 10% is considerable between the computational and experimental data. For studies using dynamic modeling approaches, validation was achieved by comparing ground reaction forces, the center of pressure, and soft tissue deformation over time (Chen and Lee, 2015; Hannah et al., 2016). This is particularly effective as dynamic models simulate a portion of the stance phase during running, rather than just a single moment. Additionally, statistical methods are increasingly being used for validation (Song et al., 2023; 2024). Pearson correlation coefficients and intraclass correlation coefficients (ICC) are calculated to evaluate the agreement between simulation and experiment. The Bland-Altman plot is also employed to assess bias and establish limits of agreement between the two methods.

Current application of foot-running shoe FE models in running biomechanics

Repetitive and high-impact forces during running can lead to the gradual accumulation of tissue damage and degradation of material properties. If these issues are not addressed, they can result in RRMI and associated pain (Nigg et al., 2023). FE methods are valuable tools for identifying vulnerable skeletal and soft tissue components, aiding in injury prediction and prevention. Since the early 2000s, FE methods have gained prominence in running biomechanics. The studies included in this review broadly categorize current modeling and simulation efforts on running and running footwear into two primary groups. The majority of studies focused on the effects of various design parameters of running shoes on foot mechanics, with the goal of optimizing shoe design to lower the risk of RRMI (Verdejo and Mills, 2004; Even-Tzur et al., 2006; Li et al., 2019; Nonogawa et al., 2021; Yang et al., 2022; Song et al., 2023; 2024; Zhu et al., 2023; Zhou et al., 2024b).

Verdejo and Mills, (2004) pioneered the comparison between barefoot and shod heel conditions, analyzing internal loading in the heel pad during running strikes. As discussed earlier, they developed a simplified, local foot-running shoe FE model using basic geometric forms, consisting of only the heel structure and the EVA midsole. Their findings confirmed the shock-absorbing functions of both the heel pad and EVA foam, with the shod heel offering superior pressure relief compared to the barefoot heel during heel strikes. Building on this, Even-Tzur et al., (2006) extended the research by investigating the effects of EVA midsole wear on the protective performance of running shoes. By simulating the loss of EVA thickness and increased stiffness due to wear, they examined the resulting stress and strain on the heel pad during running strikes. Their results indicated that EVA wear consistently increased heel pad stress, with reduced EVA thickness being the most influential factor. Another study used a computationally simplified shoe model to examine the effect of midsole hardness on foot stability during running (Nonogawa et al., 2021). They found that reducing the hardness of the resin foam increased the heel eversion angle, compromising shoe stability. While these studies highlight the importance of midsole optimization, it is crucial to recognize the limitations of such simplified models, particularly in accurately representing sole layers. To address this, many researchers have undertaken more detailed FE studies of foot-running shoe models to explore running biomechanics in greater depth. Running FE shoe models were developed from partial structures to more complex representations of structural characteristics. For instance, Zhu et al. (2023) developed a coupled FE model of the foot and running shoe to investigate the effects of midsole hardness on plantar fascia stress and strain. Their model, constructed from CT scans, featured detailed representations of foot components such as bones, cartilage, ligaments, and soft tissues, as well as running shoe elements including the midsole, outsole, and upper. By varying the midsole stiffness from Shore A 10 to 50, the researchers found that increasing midsole hardness reduced plantar fascia stress and strain but increased the load on the foot. Similarly, Yang et al. (2022) reconstructed multiple shoe parameters, such as heel cup, insole material, midsole material, and insole thickness, using CT imaging. Their study aimed to determine the optimal combination of parameters to enhance the cushioning effect of running shoes. The results showed that a well-fitted heel cup and a softer insole significantly reduced peak plantar pressure during heel landings.

In recent years, specialized running shoe designs, such as CFP, five-finger shoes, and bionic outsoles, have gained attention due to their potential benefits for running training and performance (Fuller et al., 2019; Nigg et al., 2021; Zhou et al., 2022). However, few studies have directly focused on how these shoe features impact internal foot mechanics during running, which could reveal injury-inducing or injury-preventing effects of these structures. In two included studies by Song et al., (2023; 2024), the influence of various CFP designs on forefoot mechanical responses was investigated using FE methods. The researchers developed two FE foot models: one representing an intact foot in a running shoe and another incorporating a CFP with different placements, stiffness levels, and curvatures in the shoe midsole. By comparing plantar pressure, metatarsal stress, and joint contact forces across different CFP designs during running, the studies concluded that a low-loaded, thicker CFP could relieve pressure without significantly increasing metatarsal stress, and that curved CFP designs offered more benefits than flat plates. Li et al. (2019) developed a comprehensive foot-barefoot running shoe model to compare plantar pressure distribution between barefoot running and running in barefoot-style shoes. They reconstructed four key components of the barefoot running shoe: the upper, insole, midsole, and outsole. The upper and insole were designed to conform to the contours of the foot and ankle, while the midsole and outsole were modeled through extrusion and cutting of these contours. Their findings showed that barefoot running shoes provided better pressure distribution and lower peak plantar pressure compared to barefoot running. Lastly, Zhou et al. (2024b) modeled a 3D foot-bionic running shoe to analyze its effects on metatarsal stress during forefoot running strikes. Different from normal shoes, the outsole of the bionic running shoes was reconstructed based on the contours of the plantar foot, and they found that the metatarsal stress values in forefoot strike patterns with bionic running shoes were lower than with normal shoes. All these findings could provide valuable insights into the future design of running shoes in light of the best trade-off between greater running performance and lower foot injury risk.

Another purpose of FE modeling in foot-running shoe studies is to examine how different running conditions-such as speed and running patterns-affect the mechanical characteristics of the foot. Several 2D and 3D FE models have been previously developed for this purpose (Li et al., 2017; Chen et al., 2019). However, most simulations focus solely on the interaction between the foot and the ground, often overlooking the influence of shoe features, which can significantly affect the stress and strain experienced by the foot during running. This limitation reduces the practical relevance of some studies, as most runners wear shoes while running. Two studies in our review addressed the effects of different running conditions using foot-running shoe FE models. Chen and Lee, (2015) developed a local foot-running shoe FE model to investigate how initial touchdown velocity during running affects internal heel pad mechanics. They reconstructed the posterior half of the foot, including the skin, subcutaneous fatty tissue, and bone, as well as the shoe components (insole, heel counter, midsole, and outsole) based on MRI images and 3D laser data. Their simulations revealed that reducing touchdown velocity led to a less severe impact and stress relief in the heel pad, with peak von Mises stress in the fatty tissue decreasing by 11.3%. More recently, Zhou et al., (2024a) developed a more complete FE model of the foot-running shoe and studied how different forefoot landing angles affect metatarsophalangeal joint stress. Their findings indicated that decreasing the sole-ground contact angle reduced peak von Mises stress on the metatarsals without causing additional damage to the ankle joint during forefoot running. Although the number of studies utilizing FE modeling to examine the effects of various running conditions is limited, such data would offer valuable insights for improving running techniques and reducing injury risks.

Future development and applications of foot-running shoe FE models in running biomechanics

Over the past few decades, significant progress has been made in the FE modeling of the foot-running shoe complex. However, there is still much room for improvement to fully harness the benefits of this approach in providing accurate analyses and more reliable results for both medical and biomechanical research, as well as the footwear industry. Currently, CT scans are commonly used as the reference source for reverse engineering FE models of foot and running shoes due to their low cost and accessibility. While CT scans offer detailed insights into bone structures, they are less effective at accurately capturing the locations and orientations of muscles, tendons, and ligaments in the human foot. In contrast, MRI excels at visualizing soft tissue and muscle structures, making it a more suitable tool for modeling the non-bony elements of the foot. Additionally, 3D laser scanning can enhance the modeling process by providing a rapid and precise geometric reconstruction of external surfaces (Li et al., 2020; Luximon and Luximon, 2021). This surface topography technique bypasses the need for delineating geometry boundaries in medical image segmentation software, thereby facilitating the remodeling of footwear characteristics. Therefore, a 3D model integrating data from CT, MRI, and 3D laser scans could yield a more biofidelic representation of the foot and running shoe, capturing both bony and soft tissue structures with enhanced accuracy (Figure 2). However, a key limitation of the current CT/MRI-based approach is its inability to generalize FE models beyond individual cases, restricting their applicability to larger populations. This constraint arises primarily from the substantial time and effort required to construct even a single FE model from CT/MRI images, contributing to the prevalence of single-subject and subject-specific foot-shoe models. To overcome this challenge, novel transformation methods are needed to adapt a reference foot model to match an individual's foot geometry. A promising solution has been proposed by Xiang et al. (2024) and Yu et al. (2025), who developed a framework that integrates statistical shape modeling (SSM) with free-form deformation (FFD) to generate a comprehensive 3D foot model. Specifically, this framework uses SSM and FFD to enable precise alignment of internal bone structures with personalized external foot geometries, leveraging only skin measurements for the SSM (Figure 2). Another promising direction involves the integration of AI-driven methodologies to automate and accelerate various stages of the model reconstruction process. In particular, deep learning techniques have demonstrated significant potential in several critical areas: (1) automating bone structure segmentation from medical imaging data, (2) optimizing mesh quality and density, and (3) directly predicting FE analysis outcomes (Nath et al. 2024). Nevertheless, further empirical studies are necessary to evaluate the accuracy, reliability, and feasibility of these SSM&FFD and AI-based methods across different populations and conditions.

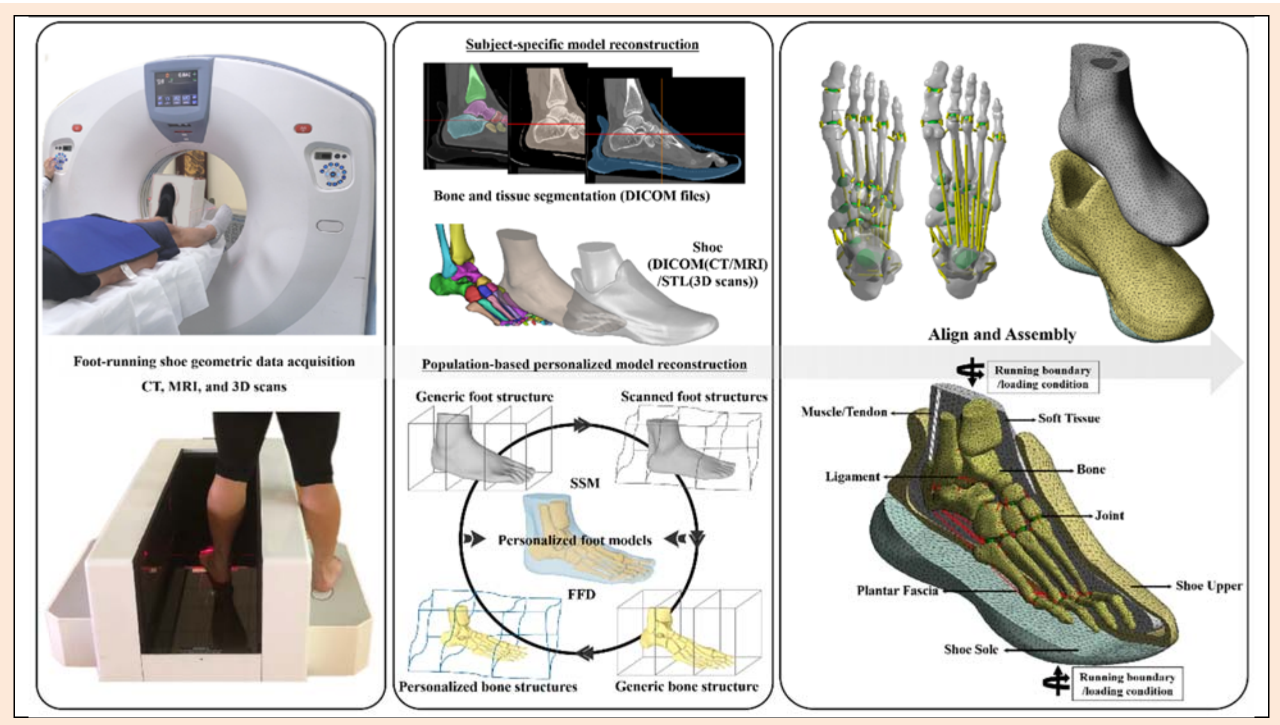

Figure 2. Finite element modeling process of the foot-running shoe.

To increase confidence in FE simulation results, it is crucial to determine accurate material properties and apply realistic boundary and loading conditions. Normally, biological tissues exhibit complex, nonlinear behavior, and many existing models account for this by incorporating nonlinear material properties for soft tissue and shoe soles to improve accuracy. However, constructing an FE model that assumes all components are nonlinear is currently impractical, as it would significantly increase the difficulty and computational time of the simulations. In this context, the material properties of foot tissues could be drawn from previous studies that have undergone extensive validation. For running shoes, the material properties can be determined through a combination of mechanical measurements and sensitivity tests, as shoe designs can vary widely in terms of material stiffness and damping. For overly simplified or local models, it is important to define the material properties of the reconstructed components, as ignoring these factors could have a significant impact on the overall model stiffness. Finally, it must be re-emphasized that under dynamic running conditions involving large deformations, future studies should aim to develop computational strategies that not only incorporate advanced nonlinear hyperelastic material models but also minimize simulation costs, thereby enabling the accurate capture of the complex mechanical interactions between the foot and footwear.

Regarding boundary and loading conditions, human motion analysis and musculoskeletal modeling have been widely used to replicate the foot-shoe system under running conditions. However, relying solely on a single biomechanical parameter, such as kinematics, may not yield the desired simulation outcomes (Hannah et al., 2016). Instead, multiple input parameters-such as joint angles, muscle forces, and ground reaction forces-must be integrated into the FE model to achieve more realistic results. Additionally, further validation of the models is essential. For example, previous case studies have investigated stress fractures of the navicular bone when running in CFP shoes (Tenforde et al., 2023). In such FE simulations, it is crucial to validate the navicular bone displacement during running between simulation and in-vivo experiments. Techniques such as dual-plane fluoroscopy and MR image-based measurements could be employed for real-time capture of the bone motion state (Akrami et al., 2018). Another aspect that should be mentioned is that while many foot-running shoe FE models have been proposed, most of these models focus solely on static loading boundary conditions. Since running is a dynamic activity, static models are limited in their ability to accurately represent the internal mechanical response of the foot. Instead, dynamic FE analysis should be proposed to model the foot-shoe interaction throughout the running stance phase, allowing for more complex structural, material, and contact modeling. Dynamic analysis can also facilitate iterative studies to further understand the intricate relationships between body dynamics and load distributions within foot soft tissues during running (Chen et al., 2019; 2021). However, it should be noted that in conducting dynamic simulations, further consideration of the contact modeling between the foot and the shoe is necessary, as different contact mechanics models can influence stress distribution, deformation patterns, and kinematics throughout the gait cycle in finite element simulations. Future research should investigate non-linear and deformable contact mechanics to better simulate dynamic interactions. Additionally, since insoles and socks are placed between the foot and footwear, future studies should also consider the impact of these structures on adjusting friction between the foot and shoes, which may also influence the biomechanical response of the foot in dynamic simulations.

Last but not least, while existing FE simulations of running shoes have provided valuable insights into the internal stress and strain characteristics of the foot and the load transfer mechanisms between the foot and footwear, a research gap remains regarding the relationship between these mechanical responses and the risk of RRMI. Specifically, it is still unclear whether the magnitude of mechanical changes observed in FE models significantly impacts RRMI injury risk. A key factor in RRMI risk assessment is the bone fracture criterion, yet there is no consensus across studies (Doblaré et al., 2004). For instance, the maximum stress criterion suggests that failure occurs when principal stress exceeds a material's ultimate strength. This approach is foundational in many engineering applications, providing a straightforward method to predict material failure under load. However, it oversimplifies the complexities of material behavior under different loading conditions, particularly in multi-axial stress states encountered during running. Another widely used measure is the principal strain criterion, often referred to as the Saint-Venant criterion. This standard emphasizes the material's response during deformation, especially under high-load conditions. By focusing on strain rather than stress, this approach offers valuable insights into how materials behave under significant forces, making it a useful tool in injury risk assessments. In the running FE simulation conducted by Wong et al., (2016), distortion energy criteria were applied, including the von Mises-Hencky criterion and the Tresca criterion. The findings indicated that the von Mises-Hencky criterion yields the most accurate results when assuming isotropic material properties. This criterion effectively predicts a material's yield behavior under multi-axial stress conditions, particularly in scenarios involving plastic deformation. However, its limitations regarding shear stress can lead to inaccuracies in predicting material failure in specific situations. Incorporating the Tresca criterion, which focuses more on shear performance, may help address these shortcomings, offering a more comprehensive understanding of material behavior.

In addition, to effectively assess the risk of bone fractures, determining the yielding thresholds for specific bone segments is crucial. While overall yielding thresholds, such as the compressive yielding stress of trabecular calcaneus (1.8 MPa) (Mittra et al., 2008) and shear yielding stress (0.792 MPa) (Sanyal et al., 2012), provide general guidelines, individual bone segments may exhibit varying mechanical properties due to differences in geometry, density, and loading conditions. Localized assessments should be conducted to measure the mechanical properties of different regions within the bone. Additionally, anatomical variability among individuals must be considered, as this can influence fracture thresholds. Utilizing advanced imaging techniques such as micro-CT or MRI can help visualize and analyze the internal structure and density of the bone, allowing for more precise threshold determination. Furthermore, evaluating how different loading scenarios, such as impact or repetitive stress, affect fracture thresholds in specific bone areas is essential. Future research should prioritize investigating localized yielding thresholds for specific bone segments and soft tissue injury parameters, considering various running shoe designs and loading conditions. This comprehensive approach will provide deeper insights into effective injury prevention strategies. Addressing the gap between FE simulations and RRMI risk assessment is vital for advancing our understanding of injury mechanisms in runners. Ultimately, this holistic methodology could enhance the design of footwear and training programs aimed at reducing the risk of RRMI.

Limitations of this review

Several potential limitations of this review should be noted here. First, we included only English-language sources, which may have introduced language and selection bias. Second, our search was confined to prominent databases and specific publication types, such as journal articles, potentially overlooking relevant studies in other formats or less mainstream sources. Additionally, the MQSSFE, designed specifically for quality assessment in computational orthopaedics, was used in our review of FE analysis in running footwear biomechanics. Certain aspects of this instrument were not heavily weighted, which could affect the overall reliability and validity of the included studies. Future research should aim to expand the MQSSFE to evaluate FE studies across a broader range of applications. Lastly, a significant limitation was the small number of studies included and the limited number of running footwear simulated. Given the heterogeneity of the studies and the use of models not typically derived from representative cases, caution must be taken when interpreting and generalizing the biomechanical findings.

Conclusion

The use of 3D computational FE models for the simulation of foot and running shoes has started to emerge as an adjuvant method for studies on running and running shoe biomechanics. This review provided a systematic overview of the current practice and trends on this topic. Current studies have explored the impact of various design characteristics of running shoes and different running conditions on the mechanical response of internal foot tissues using foot-running shoe FE models. Additionally, the models have gradually transitioned from simplified local representations to more realistic and comprehensive models, with the integration of experimental results further enhancing the accuracy of the simulations. Nevertheless, to effectively enhance the simulation results, we propose integrating some key improvements to shorten the development time and increase the robustness of the model: developing high-biofidelic 3D foot and running shoe models using MRI, CT, and 3D laser scans, employing SSM&FFD-based shape transformation methods for personalized adaptations and AI-driven techniques for automated model reconstruction, creating a dynamic running simulation with appropriate material properties and multiple loading parameters from musculoskeletal analysis, and validating the model in-depth through dual-plane fluoroscopy or MR image-based measurements of internal foot movements. More importantly, although existing FE simulations have improved our understanding of the mechanical responses of the foot and footwear during running, yet a significant research gap remains in connecting these responses to the risk of RRMI. Addressing the complexities of bone fracture criteria and incorporating localized assessments of bone properties will enhance injury risk assessments and inform better footwear design and training strategies. By delving deeper into each of these critical points, we can gain a better understanding of the topic at hand and its significance.

Acknowledgements

This study was sponsored by the Research Grants Council (RGC #15211322), Shenzhen Research Fund (JCYJ20230807140414029) and the Research Institute for Sports Science and Technology (RISports) in the Hong Kong Polytechnic University. The experiments comply with the current laws of the country where they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who organized the study.

References

Akrami, M., Qian, Z., Zou, Z., Howard, D., Nester, C.J. and Ren, L. (2018) Subject-specific finite element modelling of the human foot complex during walking: sensitivity analysis of material properties, boundary and loading conditions. *Biomechanics and Modeling in Mechanobiology* **17**, 559-576. https://doi.org/10.1007/s10237-017-0978-3

Burkhart, T.A., Andrews, D.M. and Dunning, C.E. (2013) Finite element modeling mesh quality, energy balance and validation methods: A review with recommendations associated with the modeling of bone tissue. *Journal of Biomechanics* **46**, 1477-1488. https://doi.org/10.1016/j.jbiomech.2013.03.022

Burns, G.T. and Joubert, D.P. (2024) Running Shoes of the Postmodern Footwear Era: A Narrative Overview of Advanced Footwear Technology. *International Journal of Sports Physiology and Performance* **1**, 1-12. https://doi.org/10.1123/ijspp.2023-0446

Cen, X., Song, Y., Sun, D., Bíró, I. and Gu, Y. (2023) Applications of Finite Element Modeling in Biomechanical Analysis of Foot Arch Deformation: a Scoping Review. *Journal of Biomechanical Engineering*, 1-28. https://doi.org/10.1115/1.4062311

Chen, W.M. and Lee, P.V.S. (2015) Explicit finite element modelling of heel pad mechanics in running: inclusion of body dynamics and application of physiological impact loads. *Computer Methods in Biomechanics and Biomedical Engineering* **18**, 1582-1595. https://doi.org/10.1080/10255842.2014.930447

Chen, T.L.W., Wong, D.W.C., Wang, Y., Lin, J. and Zhang, M. (2019) Foot arch deformation and plantar fascia loading during running with rearfoot strike and forefoot strike: A dynamic finite element analysis. *Journal of Biomechanics* **83**, 260-272. https://doi.org/10.1016/j.jbiomech.2018.12.007

Chen, T.L.W., Wong, D.W.C., Wang, Y. and Zhang, M. (2021) Plantar fascia loading at different running speed: a dynamic finite element model prediction. *HKIE Transactions* **28**, 14-21. https://doi.org/10.33430/V28N1THIE-2020-0011

Doblaré, M., Garcıa, J.M. and Gómez, M.J. (2004) Modelling bone tissue fracture and healing: a review. *Engineering Fracture Mechanics* **71**, 1809-1840. https://doi.org/10.1016/j.engfracmech.2003.08.003

Even-Tzur, N., Weisz, E., Hirsch-Falk, Y. and Gefen, A. (2006) Role of EVA viscoelastic properties in the protective performance of a sport shoe: Computational studies. *Bio-medical Materials and Engineering* **16**, 289-299.

Fuller, J.T., Thewlis, D., Tsiros, M.D., Brown, N.A.T., Hamill, J. and Buckley, J.D. (2019) Longer-term effects of minimalist shoes on running performance, strength and bone density: a 20-week follow-up study. *European Journal of Sport Science* **19**, 402-412.

https://doi.org/10.1080/17461391.2018.1505958
Hamill, J. and Bates, B.T. (2023) Biomechanics and footwear research 1970-2000. *Footwear Science* **15**, 123-131. https://doi.org/10.1080/19424280.2023.2209045
Hannah, I., Harland, A., Price, D., Schlarb, H. and Lucas, T. (2016) Evaluation of a kinematically-driven finite element footstrike model. *Journal of Applied Biomechanics* **32**, 301-305. https://doi.org/10.1123/jab.2015-0002
Hébert-Losier, K. and Pamment, M. (2023) Advancements in running shoe technology and their effects on running economy and performance-a current concepts overview. *Sports Biomechanics* **22**, 335-350. https://doi.org/10.1080/14763141.2022.2110512
Hulteen, R.M., Smith, J.J., Morgan, P.J., Barnett, L.M., Hallal, P.C., Colyvas, K. and Lubans, D.R. (2017) Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis. *Preventive Medicine* **95**, 14-25. https://doi.org/10.1016/j.ypmed.2016.11.027
Kakouris, N., Yener, N. and Fong, D.T.P. (2021) A systematic review of running-related musculoskeletal injuries in runners. *Journal of Sport and Health Science* **10**, 513-522. https://doi.org/10.1016/j.jshs.2021.04.001
Kluitenberg, B., van Middelkoop, M., Diercks, R. and van der Worp, H. (2015) What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. *Sports Medicine* **45**, 1143-1161. https://doi.org/10.1007/s40279-015-0331-x
Li, Y., Leong, K.F. and Gu, Y. (2019) Construction and finite element analysis of a coupled finite element model of foot and barefoot running footwear. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology* **233**, 101-109. https://doi.org/10.1177/1754337118803540
Li, J.C., Shu, W.H., Yang, Y.N. and Yan, R. (2020) Parametric modeling and performance analysis of a personalized insole based on 3D scanning and selective laser sintering. *International Journal of Computer Integrated Manufacturing* **33**, 936-945. https://doi.org/10.1080/0951192X.2020.1815849
Li, F., Sun, D., Zhu, C., Zhang, Q., Song, Y., Cen, X., Xu, Y., Zheng, Z. and Gu, Y. (2024) The impact of toe spring and foot strike angle on forefoot running biomechanics: a finite element analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 1-11. https://doi.org/10.1080/10255842.2024.2321991
Li, S., Zhang, Y., Gu, Y. and Ren, J. (2017) Stress distribution of metatarsals during forefoot strike versus rearfoot strike: A finite element study. *Computers in Biology and Medicine* **91**, 38-46. https://doi.org/10.1016/j.compbiomed.2017.09.018
Luximon, A. and Luximon, Y. (2021) New technologies - 3D scanning, 3D design, and 3D printing. In: *Handbook of Footwear Design and Manufacture*. Elsevier. 477-503. https://doi.org/10.1016/B978-0-12-821606-4.00019-3
Mai, P., Robertz, L., Robbin, J., Bill, K., Weir, G., Kurz, M., Trudeau, M.B., Hollander, K., Hamill, J. and Willwacher, S. (2023) Towards functionally individualised designed footwear recommendation for overuse injury prevention: a scoping review. *BMC Sports Science, Medicine and Rehabilitation* **15**, 152. https://doi.org/10.1186/s13102-023-00760-x
Mittra, E., Rubin, C., Gruber, B. and Qin, Y.X. (2008) Evaluation of trabecular mechanical and microstructural properties in human calcaneal bone of advanced age using mechanical testing, µCT, and DXA. *Journal of Biomechanics* **41**, 368-375. https://doi.org/10.1016/j.jbiomech.2007.09.003
Nath, D., Ankit, Neog, D.R. and Gautam, S. S. (2024) Application of machine learning and deep learning in finite element analysis: a comprehensive review. *Archives of Computational Methods in Engineering* **31**, 2945-2984. https://doi.org/10.1007/s11831-024-10063-0
Nigg, B.M., Cigoja, S. and Nigg, S.R. (2021) Teeter-totter effect: A new mechanism to understand shoe-related improvements in long-distance running. *British Journal of Sports Medicine* **55**, 462-463. https://doi.org/10.1136/bjsports-2020-102550
Nigg, B.M., Nigg, S., Hoitz, F., Subramanium, A., Vienneau, J., Wannop, J.W., Khassetarasha, A., Alizadeh, S., Matijevich, E., Honert, E.C., Edwards, W.B. and Mohr, M. (2023) Highlighting the present state of biomechanics in shoe research (2000-2023). *Footwear Science* 1-11. https://doi.org/10.1080/19424280.2023.2209044
Nikolaidis, P.T. and Knechtle, B. (2023) Participation and performance characteristics in half-marathon run: a brief narrative review. *Journal of Muscle Research and Cell Motility* **44**, 115-122. https://doi.org/10.1007/s10974-022-09633-1
Nonogawa, M., Nakaya, S., Isobe, M., Takeuchi, K. and Azegami, H. (2021) Developing a three-dimensional numerical foot model and identifying the loading condition for designing a stable sole for running shoes. *Mechanical Engineering Journal* **8**, 21-200. https://doi.org/10.1299/mej.21-00200
Phan, P.K., Vo, A.T.N., Bakhtiarydavijani, A., Burch, R., Smith, B., Ball, J.E., Chander, H., Knight, A. and Prabhu R.K. (2021) In silico finite element analysis of the foot ankle complex biomechanics: A literature review. *Journal of Biomechanical Engineering* **143**, 090802. https://doi.org/10.1115/1.4050667
Sanyal, A., Gupta, A., Bayraktar, H.H., Kwon, R.Y. and Keaveny, T.M. (2012) Shear strength behavior of human trabecular bone. *Journal of Biomechanics* **45**, 2513-2519. https://doi.org/10.1016/j.jbiomech.2012.07.023
Shorten, M. and Mientjes, M.I.V. (2011) The “heel impact” force peak during running is neither “heel” nor “impact” and does not quantify shoe cushioning effects. *Footwear Science* **3**, 41-58. https://doi.org/10.1080/19424280.2010.542186
Song, Y., Cen, X., Chen, H., Sun, D., Munivrana, G., Bálint, K., Bíró, I. and Gu, Y. (2023) The influence of running shoe with different carbon-fiber plate designs on internal foot mechanics: A pilot computational analysis. *Journal of Biomechanics* **153**, 111597. https://doi.org/10.1016/j.jbiomech.2023.111597
Song, Y., Cen, X., Sun, D., Bálint, K., Wang, Y., Chen, H., Gao, S., Bíró, I., Zhang, M. and Gu, Y. (2024) Curved carbon-plated shoe may further reduce forefoot loads compared to flat plate during running. *Scientific Reports* **14**, 13215. https://doi.org/10.1038/s41598-024-64177-3
Song, Y., Cen, X., Zhang, Y., Bíró, I., Ji, Y. and Gu, Y. (2022a) Development and validation of a subject-specific coupled model for foot and sports shoe complex: A pilot computational study. *Bioengineering* **9**, 553. https://doi.org/10.3390/bioengineering9100553
Song, Y., Shao, E., Bíró, I., Baker, J.S. and Gu, Y. (2022b) Finite element modelling for footwear design and evaluation: A systematic scoping review. *Heliyon* **8**, e10940. https://doi.org/10.1016/j.heliyon.2022.e10940
Sun, X., Lam, W.-K., Zhang, X., Wang, J. and Fu, W. (2020) Systematic review of the role of footwear constructions in running biomechanics: Implications for running-related injury and performance. *Journal of Sports Science and Medicine* **19**, 20-37. https://pubmed.ncbi.nlm.nih.gov/32132824/
Tenforde, A., Hoenig, T., Saxena, A. and Hollander, K. (2023) Bone stress injuries in runners using carbon fiber plate footwear. *Sports Medicine* **53**, 1499-1505. https://doi.org/10.1007/s40279-023-01818-z
Tseng, Z.J. (2021) Rethinking the use of finite element simulations in comparative biomechanics research. *PeerJ* **9**, e11178. https://doi.org/10.7717/peerj.11178
Verdejo, R. and Mills, N.J. (2004) Heel-shoe interactions and the durability of EVA foam running-shoe midsoles. *Journal of Biomechanics* **37**, 1379-1386. https://doi.org/10.1016/j.jbiomech.2003.12.022
Wang, Y., Wong, D.W.C. and Zhang, M. (2016) Computational models of the foot and ankle for pathomechanics and clinical applications: A review. *Annals of Biomedical Engineering* **44**, 213-221. https://doi.org/10.1007/s10439-015-1359-7
Willwacher, S. and Weir, G. (2023) The future of footwear biomechanics research. *Footwear Science* **15**, 145-154. https://doi.org/10.1080/19424280.2023.2199011
Wong, D.W. C., Chen, T.L.W., Peng, Y., Lam, W.K., Wang, Y., Ni, M., Niu, W. and Zhang, M. (2021) An instrument for methodological quality assessment of single-subject finite element analysis used in computational orthopaedics. *Medicine in Novel Technology and Devices* **11**, 100067. https://doi.org/10.1016/j.medntd.2021.100067
Wong, D.W.-C., Niu, W., Wang, Y. and Zhang, M. (2016) Finite element analysis of foot and ankle impact injury: risk evaluation of calcaneus and talus fracture. *Plos One* **11**, e0154435. https://doi.org/10.1371/journal.pone.0154435
Xiang, L., Gu, Y., Shim, V., Yeung, T., Wang, A. and Fernandez, J. (2024) A hybrid statistical morphometry free-form deformation approach to 3D personalized foot-ankle models. *Journal of Biomechanics* **168**, 112120. https://doi.org/10.1016/j.jbiomech.2024.112120
Yang, Z., Cui, C., Wan, X., Zheng, Z., Yan, S., Liu, H., Qu, F. and Zhang, K. (2022) Design feature combinations effects of running shoe on

plantar pressure during heel landing: A finite element analysis with Taguchi optimization approach. *Frontiers in Bioengineering and Biotechnology* **10**, 1-13. https://doi.org/10.3389/fbioe.2022.959842

Yu, J., Cheung, J.T.-M., Wong, D.W.-C., Cong, Y. and Zhang, M. (2013) Biomechanical simulation of high-heeled shoe donning and walking. *Journal of Biomechanics* **46**, 2067-2074. https://doi.org/10.1016/j.jbiomech.2013.05.009

Yu, P., Cen, X., Xiang, L., Wang, A., Gu, Y. and Fernandez, J. (2025) Foot tissue stress in chronic ankle instability during the stance phase of cutting. *Medical & Biological Engineering & Computing*, 1-13. https://doi.org/10.1007/s11517-024-03276-9

Zhang, M. and Mak, A.F.T. (1999) In vivo skin frictional properties. *Prosthetics and Orthotics International* **23**, 135-141. https://doi.org/10.3109/03093649909071625

Zhang, Z., Zhang, W., Zhai, Z.J. and Chen, Q.Y. (2007) Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part 2-Comparison with experimental data from literature. *Hvac&R Research* **13**, 871-886. https://doi.org/10.1080/10789669.2007.10391460

Zhou, H., Xu, D., Quan, W., Ugbolue, U.C. and Gu, Y. (2024a) Effects of different contact angles during forefoot running on the stresses of the foot bones: a finite element simulation study. *Frontiers in Bioengineering and Biotechnology* **12**, 1337540. https://doi.org/10.3389/fbioe.2024.1337540

Zhou, H., Xu, D., Quan, W., Ugbolue, U.C., Zhou, Z. and Gu, Y. (2024b) 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. *Journal of Human Kinetics* **92**, 5. https://doi.org/10.5114/jhk/174311

Zhou, H., Xu, D., Quan, W., Ugbolue, U.C., Sculthorpe, N.F., Baker, J.S. and Gu, Y. (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* **24**. https://doi.org/10.37190/ABB-02022-2022-03

Zhu, X., Liu, J., Liu, H., Liu, J., Yang, Y. and Wang, H. (2023) Effects of midsole hardness on the mechanical response characteristics of the plantar fascia during running. *Bioengineering* **10**, 533. https://doi.org/10.3390/bioengineering10050533

Key points

- Previous FE studies have focused on how running shoe design parameters affect foot mechanics, aiming to optimize shoe design and reduce RRMI risk.
- Future work should consider applying personalized shape transformation and AI-driven techniques for rapid large-scale FE modeling and dynamic running simulations.
- Addressing bone fracture criteria and localized bone assessments is key to bridging the gap between FE simulations and RRMI risk.

AUTHOR BIOGRAPHY

Yang SONG
Employment
Postdoctoral researcher, Depart. of Biomedical Engineering, The Hong Kong Polytechnic Univ., Hong Kong, China
Degree
PhD
Research interests
Footwear biomechanics; computational simulation
E-mail: yangsong@polyu.edu.hk

Xuanzhen CEN
Employment
Lecturer, Faculty of Sports Science, Ningbo University, Ningbo, China
Degree
PhD
Research interests
Running biomechanics; computational simulation
E-mail: cenxuanzhen@outlook.com

Meizi WANG
Employment
Postdoctoral researcher, Depart. of Biomedical Engineering, The Hong Kong Polytechnic Univ., Hong Kong, China
Degree
PhD
Research interests
Footwear biomechanics; computational simulation
E-mail: meiziwang@polyu.edu.hk

Zixiang GAO
Employment
Postdoctoral researcher, Human Performance Lab., Faculty of Kinesiology, University of Calgary, Calgary, Canada
Degree
PhD
Research interests
Running biomechanics; musculoskeletal injury prevention
E-mail: zixiang.gao@ucalgary.ca

Qitao TAN
Employment
Research assistant professor, Department of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
Degree
PhD
Research interests
Biomedical engineering; running biomechanics
E-mail: qitao.tan@polyu.edu.hk

Dong SUN
Employment
Associate professor, Faculty of Sports Science, Ningbo University, Ningbo, China
Degree
PhD
Research interests
Running biomechanics; musculoskeletal injury prevention
E-mail: sundong@nbu.edu.cn

Yaodong GU
Employment
Professor, Faculty of Sports Science, Ningbo University, Ningbo, China
Degree
PhD
Research interests
Sports biomechanics
E-mail: guyaodong@nbu.edu.cn

Yan WANG
Employment
Research assistant professor, Department of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
Degree
PhD
Research interests
Biomedical engineering; running biomechanics
E-mail: annie.y.wang@polyu.edu.hk

Ming ZHANG
Employment
Professor, Department of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
Degree
PhD
Research interests
Biomedical engineering
E-mail: ming.zhang@polyu.edu.hk

✉ **Prof. Yan Wang, PhD**
Department of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, 999077, China