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Review article

Finite element modelling for footwear design and evaluation: A systematic scoping review

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ABSTRACT

Finite element modelling has become an efficient tool for an in-depth understanding of the foot, footwear biomechanics and footwear optimization. The aim of this paper was to provide an updated overview in relation to the footwear finite element (FE) analysis published since 2000. The paper will attempt to outline the main challenges and research gaps that need confronting in the further development of realistic and accurate models for clinical and industrial applications. English databases of the Web of Science and PubMed were used to search ('finite element' OR 'FEA' OR 'computational model') AND ('shoe' OR 'footwear') until 16 December 2021. Articles that conducted FE analyses on the whole foot and footwear structures were included in this review. Twelve articles met the eligibility criteria, and were grouped into three categories for further analysis, (1) finite element modelling of the foot and high-heeled shoes; (2) finite element modelling of the foot and boot; (3) finite element modelling of the foot and sports shoe. Even though most of the existing foot-shoe FE analyses were performed under certain simplifications and assumptions, they have provided essential contributions in identifying the mechanical response of the foot in casual or athletic footwear. Further to this, the results have provided information in relation to optimizing footwear design to enhance functional performance. Nevertheless, further simulations still present several challenges, including reliable data information for geometry reconstruction, the balance between accurate details and computational cost, accurate representations of material properties, realistic boundary and loading conditions, and thorough model validation. In addition, some research gaps in terms of the coverage of footwear design, the consideration of insole/orthosis and socks, and the internal and external validity of the FE design should be fully covered.

1. Introduction

Footwear plays an essential role in most activities to fulfill urban society's aesthetic and cultural desires. High-heeled shoes (HHS), for example, continue to be an irresistible symbol of fashion among women for their sensuous attractiveness [1]. Meanwhile, footwear has also been designed to protect the foot from rough terrain, external intrusion, and many other foot abrasions during daily locomotion. During sports performance footwear design could help enhance athletic performance and decrease the risk of unexpected injuries through advanced shoe features such as the stiff plate, curved-shoe geometry, and lightweight resilient foam [2, 3, 4]. For instance, Nigg et al. [5,6] proposed in their studies that the excellent performance of the Nike Vaporfly 4% in improving the marathon running economy is highly related to its curved stiff carbon fibre plate and forefoot curvature. Nevertheless, it was also clarified that inappropriate or extraordinary footwear might increase the risk of foot or lower limb injuries [7, 8, 9]. The HHS has been widely reported to be associated with shoe discomfort, forefoot diseases, and knee joint osteoarthritis [10, 11]. Plantar fasciitis, foot fractures, and heel pain were all documented to be associated with abnormal plantar pressure concentration and overload during exercise, while the structure and material property of footwear plays a crucial role in this process [12, 13, 14].

Biomechanical evaluations of the influences of footwear features on foot variables and the interactions between foot and shoe could be helpful not only for injury prevention but also for footwear optimization [4, 15]. Laboratory-based experiments such as 3D motion capture

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analysis and in-shoe plantar pressure measurement can be applied to obtain information, but the detailed mechanical changes, such as internal stress and strain distribution of the foot structures and the joint contact pressure, are unmeasurable because of technological limitations. Under this scenario, researchers have turned to computational modelling such as finite element (FE) analysis for more in-depth analysis. FE analysis has the capability of modelling complicated geometry, diversified material properties, and complex boundary and loading conditions [16, 17, 18, 19, 20]. Accordingly, FE analysis has been widely conducted to give new insights for the footwear industry and clinical applications over the past decades. However, previous FE analyses mainly concentrated on the part of the foot and footwear models or the interaction only between foot, sole, and ground, while little research has incorporated the upper shoe in their assemblies [16, 21]. It should be noted that the shoe upper may reshape the biomechanics of the foot. In other words, the foot shape will deform especially wearing a tight shoe during dynamic simulation and the foot-shoe upper interaction could undoubtedly influence the internal stress and strain characteristics [22].

Although the foot and/or shoe FE models have been discussed in previous reviews [23, 24, 25, 26, 27], the current study restricted publications from the year 2000 onwards and focused on the previous papers that performed FE analyses on the whole foot and shoe structures, with the aims to provide updated information and more valuable insights and scope for further research in footwear design and optimization. The up-to-date methodologies and generalized workflow for computational modelling of the coupled foot and shoe models are also presented.

2. Methods

2.1. Data sources and search strategy

Two online databases (Web of Science and PubMed) were searched to identify current relevant studies until 16 December 2021. Each database was searched using the specific retrievable terms, and Medical Subject Headings (MeSH) were adopted in PubMed [28]. In general, the following keywords were used ('finite element' OR 'FEA' OR 'computational model') AND ('shoe' OR 'footwear'). Additionally, the authors further checked the reference lists of the eligible articles and retrieved reviews using the snowballing approach to ensure no paper has been potentially overlooked [29, 30, 31].

2.2. Eligibility criteria

To ensure a rigorous process, two authors independently assessed the retrieved records (Y.S. and E.S.), and the corresponding authors resolved any inclusion disagreements if they occurred (Y.G.). Articles were considered for this review if they met the eligibility criteria, (1) Original FE research articles published in English journals were included, while other types of articles (e.g., review, conference abstracts) were excluded; (2) the articles included should involve FE analyses of the entire foot and footwear, while analyses focused on parts of the foot or footwear were excluded; and (3) the articles included should present the methodological and results detail.

2.3. Methodological quality assessment

Methodological quality of all the included studies was assessed independently by two authors (Y.S. and E.S.) using the Methodological Quality Assessment of Subject-Specific Finite Element Analysis Used in Computational Orthopaedics (MQSSFE) [32], and the inconsistent results were resolved by the corresponding author (Y.G.). Since the MQSSFE instrument was mainly designed for clinical FE analysis, we eliminated two items that are not suitable for this review, which in total ended up with 35 items, covering 6 domains (① study design and presentation of findings; ② subject recruitment; ③ model reconstruction and configuration; ④ boundary and loading conditions, simulation; ⑤ model verification and validation; ⑥ model assumption and validity). The "+" scores one point while "−" scores zero point and a higher score implies greater FE quality.

2.4. Data extraction and management

For all articles that met the eligibility criteria, the following data were extracted and summarized into tables by one author (Y.S.) and further verified by another author (E.S.), (1) author characteristics (i.e., name of first author and publication year); (2) study purposes; (3) participant characteristics; (4) model characteristics (i.e., geometry design, material properties); (5) boundary and loading conditions; (6) validation; (7) primary findings. Any data disagreement occurring was resolved by the corresponding authors (Y.G.). Mendeley Desktop Reference Management Software (Mendeley Ltd., Netherlands) organized articles and generated citations.

3. Results

3.1. Search results

Figure 1 shows the review flow chart from databases searching for studies to be included. The search initially yielded 555 articles from the Web of Science database and 82 in the PubMed database. Ten eligible articles remained after removing duplicates and screening based on the eligibility criteria. By using the snowballing approach, two more papers were identified, which provided a total of 12 articles used in this review.

3.2. Study quality

The outcome of the methodological quality of 12 included studies is summarized in Table 1. The total score of each study was all above 20 (range from 20 to 28), and the mean value was 22.8. All 12 studies were awarded scores from the following items, including study objective clearly described (item 1), no unplanned analysis and data dredging (items 2 and 3), appropriate outcome measures and clear key findings (items 6 and 7), clear description of material properties, interaction, boundary and loading conditions, and software analysis setting (items 19, 20, 21, 26), and simplifications on model reconstruction and material properties, and potential implications of the research findings properly discussed (items 32 and 37). They also performed well in describing model reconstruction modality clearly and applying the proper boundary and loading conditions (items 13 and 22), conducting model validation and discussing its limitations (items 29, 30, 31, 34). However, over half of the papers included limited details about subjects (items 9 and 10) and model reconstruction (items 14, 15, 16, 18), and did not apply the boundary and loading conditions from the same model subject (items 23 and 25). Moreover, muscle forces were often neglected or simplified (item 24) while verification tests normally neglected (items 27 and 28). In addition, the internal and external validity of the FE design hasn't been widely discussed (items 35 and 36).

3.3. Overview of the coupled foot and shoe finite element modelling

With the rapid advancement of computational techniques, the coupled foot and shoe FE models were developed from two-dimensional (2D) to three-dimensional (3D), from partial structures to the representation of most complicated structure characteristics, aiming for a more delicate exploration of the foot-shoe interactions and shoe optimization.

The foot models were mainly reconstructed from high-resolution magnetic resonance images (MRI), while depending on the research emphasis they could also be built using a 3D laser scanner or CAD software. Meanwhile, the geometry of the footwear involved in this review were built using the CAD software or 3D laser, which could replicate the fundamental contours of the shoe segments, as shown in Figure 2. MRI segmentation can be conducted using the medical image

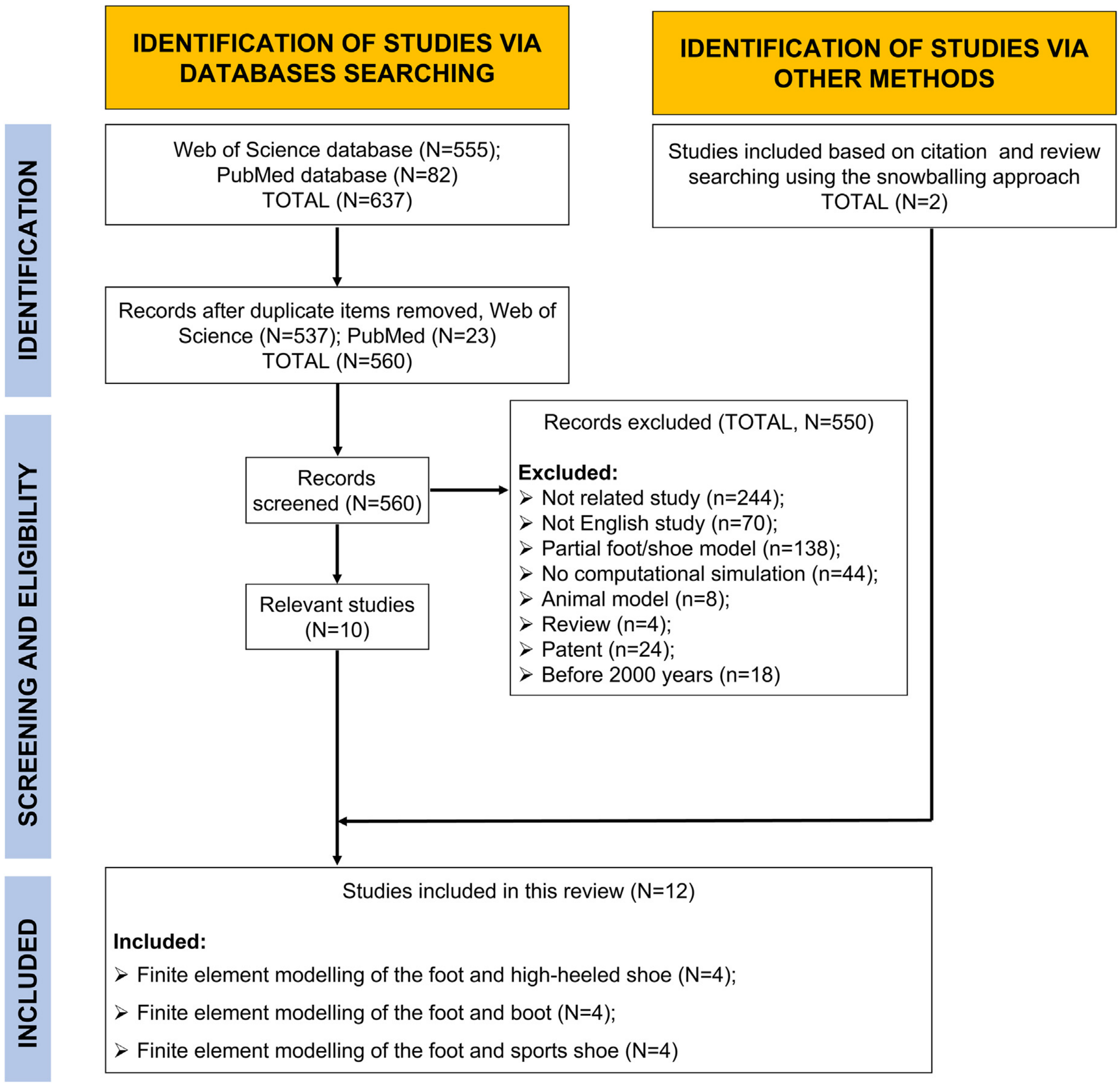

Figure 1. The review flow chart.

segmentation software (e.g., Mimics), and some components may be further fused or omitted. For surface smoothing and solid model creation, the reconstructed foot and shoe geometries can be imported into reverse engineering (RE) software (e.g., GEOMAGIC, SOLIDWORKS). Within the RE environment, some other basic structures such as cartilages can be further created based on the different levels of analytical definition. The foot connective components such as plantar fascia and ligaments were usually built by connecting the anatomical origins and terminations through the 2D tension-only truss, instead of reconstructing the 3D solid geometries. In addition, the coupled models can be established by directly aligning and assembling the foot and footwear structure or through the specified shoe fitting process using FE software such as ABAQUS. In terms of the material data, most of the material properties were acquired from existing literature while some material properties of the footwear were obtained through experiments using mechanical testing machines. Most components were idealized to be homogeneous, isotropic, and linearly elastic, except for soft tissue and outsole, which were commonly assumed hyper elastic in current models.

The boundary and loading conditions were determined experimentally for most of the simulations. For instance, the foot-plate system approach was commonly used to simulate the interaction between the foot, shoe, and ground. In this scenario, the proximal surfaces of the soft tissue, tibia, and fibula components or the underneath of the support plate were fixed, and the muscle forces and ground reaction forces (GRF) were estimated from the body weight (BW) of the subject (e.g., 50% BW for GRF and 50% GRF for the Achilles tendon (AT) force). For some dynamic movements, the subject-specific boundary and loading conditions were obtained from 3D motion analysis, including kinematics and kinetics variables, more accurately representing the conditions. The foot intrinsic and extrinsic muscle forces were further calculated from electromyography (EMG) and respective physiological cross-sectional areas (PCSA). For the interactions between the foot, shoe, ground plate etc., the connection types were commonly defined as the frictional contact surface with a coefficient of 0.5–0.6. Implicit or explicit formulations (quasi-static/dynamic simulation) were then applied to obtain the FE solution depending on the analysis setup. Lastly, the loading response of the foot, footwear, or other components such as plantar and outsole pressure were used for model validation. The methodologies extracted from the identified studies and generalized workflow for computational modelling of the foot and shoes are graphically presented in Figure 3.

Table 1. Methodological quality assessment for the included studies.

	Cho et al. [40]	Hladnik et al. [38]	Hladnik et al. [37]	Hladnik et al. [39]	Ishii et al. [42]	Karimi et al. [34]	Kim et al. [41]	Li et al. [43]	Milazzo et al. [35]	Qiu et al. [36]	Yu et al. [22]	Yu et al. [33]	Sum
Item 1	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 2	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 3	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 4	+	+	+	+	+	−	+	+	+	+	−	+	10
Item 5	+	+	+	+	+	+	+	+	+	+	−	+	11
Item 6	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 7	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 8	+	−	+	+	−	+	−	−	+	−	+	−	6
Item 9	−	−	−	−	+	+	−	+	+	−	+	+	6
Item 10	−	−	−	−	+	−	−	+	+	−	−	+	4
Item 11	/	/	/	/	/	/	/	/	/	/	/	/	/
Item 12	/	/	/	/	/	/	/	/	/	/	/	/	/
Item 13	+	+	+	+	+	+	−	+	+	+	+	+	11
Item 14	−	−	−	−	−	−	−	−	−	−	−	−	0
Item 15	−	−	−	−	+	+	−	−	+	−	+	−	4
Item 16	+	+	−	−	−	−	−	+	+	+	−	+	6
Item 17	−	−	−	−	−	−	−	−	−	−	−	−	0
Item 18	+	−	−	−	−	+	+	−	+	+	−	−	5
Item 19	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 20	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 21	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 22	+	+	+	+	+	+	+	−	+	+	+	+	11
Item 23	−	−	−	−	−	−	−	−	−	−	+	+	2
Item 24	−	−	−	−	−	−	−	−	−	+	+	+	3
Item 25	−	−	−	−	−	−	−	+	+	−	+	+	4
Item 26	+	+	+	+	+	+	+	+	+	+	+	+	12
Item 27	−	−	−	−	−	+	+	−	+	−	−	−	3
Item 28	−	−	−	−	−	+	−	−	+	−	−	−	2
Item 29	+	+	+	+	+	−	+	+	+	+	+	+	11
Item 30	+	+	+	+	+	−	+	+	+	+	+	+	11
Item 31	+	+	+	+	+	−	+	+	+	+	+	+	11
Item 32	+	+	+	+	+	+	+	+	+	+	+	+	12

(*continued on next page*)

Table 1 (*continued*)

	Cho et al. [40]	Hladnik et al. [38]	Hladnik et al. [37]	Hladnik et al. [39]	Ishii et al. [42]	Karimi et al. [34]	Kim et al. [41]	Li et al. [43]	Milazzo et al. [35]	Qiu et al. [36]	Yu et al. [22]	Yu et al. [33]	Sum
Item 33	+	+	+	+	+	+	+	+	–	+	+	+	11
Item 34	+	–	+	+	–	+	+	+	+	+	+	–	9
Item 35	–	–	–	–	–	–	–	–	–	–	–	+	1
Item 36	–	–	–	–	–	–	–	–	–	–	–	–	0
Item 37	+	+	+	+	+	+	+	+	+	+	+	+	12
Sum	23	20	21	21	22	22	21	23	28	23	24	26	

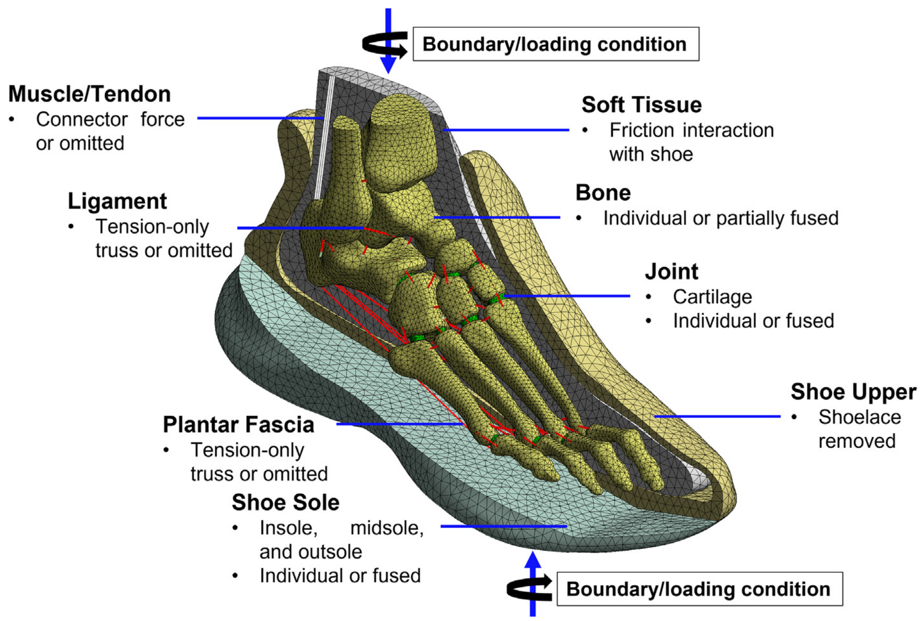

Figure 2. The main components of the coupled foot-shoe FE model and basic modelling methods.

3.4. Grouping

The included studies presented a wide range of applications in footwear biomechanics and conducted a variety of computational simulation strategies. Specifically, one-third of included articles simulated high-heel shoes, one third for boots, and the remaining one third for sports shoes. Forty-two percent (42%) were related to footwear design and optimization, while 58% focused on the interactions between the foot, footwear, and ground (or soccer ball). Detailed information of each included study and their primary findings are summarized in Table 2, and these studies were further grouped by footwear types to elaborate the simulation methods that were applied for geometric design, material property assignment, boundary and loading definition, and model validation (Table 3).

3.4.1. Finite element modelling of the foot and high-heeled shoe

The first group of articles studied the finite element modelling of the foot and HHS. Of these studies, the first two revealed the impact of HHS on internal foot biomechanics [22, 33], while the last two concentrated on HHS optimization [34, 35].

To explore the biomechanical response of high-heeled shod standing and walking, the first two studies reconstructed the most characteristics of the foot. While on the contrary, only bony structures and soft tissue were considered in the last two studies since shoe components were the main research focus. In terms of the HHS, custom shoe design software was applied for geometric development, and it divided the HSS into four components, including upper, sole, heel, and shankpiece. The shankpiece extending from the central heel to the forefoot regions was simulated to reinforce the HSS shank [22]. In the two HHS optimization studies, additional HHS shapes were introduced. Karimi et al.[34] proposed an adjustable HSS model which can manually switch from HSS to a flat-heeled shoe by the flexible heel, and Milazzo et al. [35] compared the influence of HHS with or without closed-shaped front side on the toe and footbed pressure. The material properties of the foot and HHS components were mostly selected from the literature, and only the soft tissue was assigned to be hyper elastic while others as linearly elastic. To ensure a higher realistic shoe model, Milazzo et al. [35] further conducted the tensile tests to determine the optimum Young's modulus.

Before establishing the load and boundary conditions, it should be mentioned that there is a shoe fitting/donning simulation for the HHS since the initial position of the foot normally does not match this type of shoe. Yu et al. [22,33] preloaded the major extrinsic muscles with BW, EMG data and PCSA to gradually manipulate the foot structure into plantarflexed position and match the shank profile of the HHS. Then, the overlapping surfaces between the dorsal foot and shoe upper were resolved using the interference fit contact simulation algorithm. On the contrary, Milazzo et al. [35] first acquired the foot model in its plantarflexion status and resolve the overclosure issue by applying the artificial

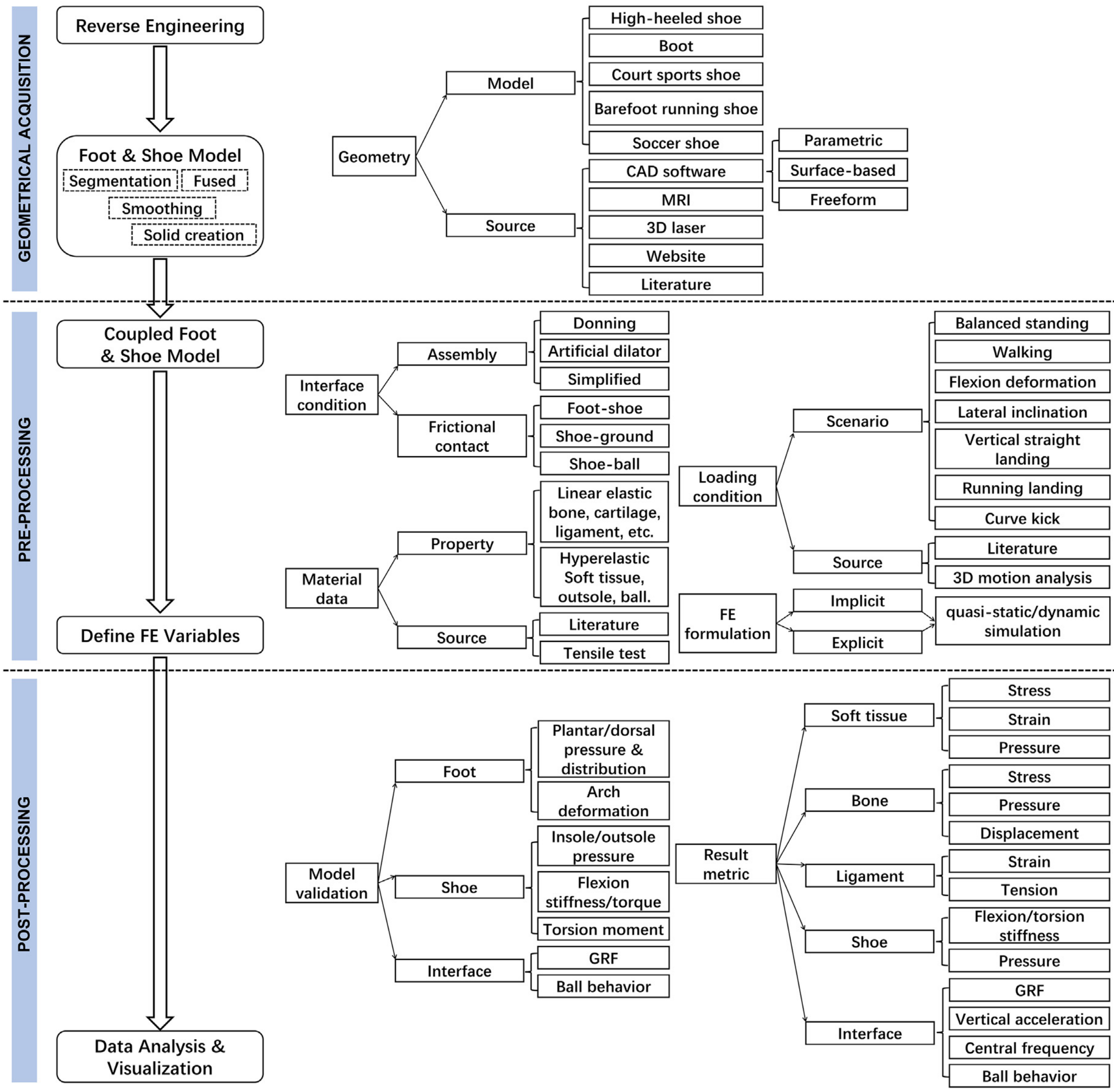

Figure 3. The methodologies and results extracted from the identified studies and generalized workflow for computational modelling of the foot and shoes.

dilator to the HHS model, which they demonstrated mimics the traditional procedure to adapt the foot into the shoe.

Both balanced standing and walking were simulated for the two studies focused on the interaction between the foot and HHS. Yu et al. [22] first investigated the biomechanical response of high-heeled shod walking. The foot-plate system approach was used, and by using the 3D motion analysis system and force platform simultaneously, they further determined the tibial inclination angle relative to the ground and the GRF during walking. In addition, the main extrinsic foot muscle forces were calculated based on the PCSA of each muscle and their EMG data during barefoot walking. In 2016, Yu et al. [33] further investigated the influence of HHS heel height on the strain and tension of ligamentous structures. Similar load and boundary conditions were used in their studies except for the balanced standing simulation, where the GRF assigned under the ground plate was estimated from BW. The last two studies only simulated the standing condition for HHS optimization using the similar boundary and loading setting of Yu et al. [33]. However, instead of assigning the GRF underneath the ground plate, Milazzo et al. [35] applied it on the proximal surfaces of the fibula and tibia while letting the ground plate be fixed in all directions. In the case of model validation, the predicted and experimental plantar pressure and distribution during motion were mostly used in the HHS simulation studies. Yu et al. [22,33] also calculated the maximum deviation of the center of pressure (COP) and arch deformation with different heel heights for further validation.

3.4.2. *Finite element modelling of the foot and boot*

The second set of identified studies proposed the finite element modelling of the foot and boot. The first research aimed to verify a coupled foot-boot FE model for further military parachute landing fall simulation [36]. The other three studies conducted a series of finite element simulations to optimize the structural characteristics of the racing cross-country ski boot [37, 38, 39].

In order to fully reveal the interaction between foot and boot for the subsequent injuries study during parachute landing, Qiu et al. [36] incorporated detailed foot geometries in their model. While in terms of boot modelling, a relatively different approach was taken compared to the HHS. Specifically, the boot model was built based on the foot and ankle contour. The contour surfaces of the upper and bottom of the foot and ankle model were first copied and enlarged to develop the four parts (i.e., upper, insole, midsole, and outsole) respectively, and then the boot was formed by assembling the four parts. In the boot optimization studies

Table 2. The basic information of the included studies and their primary findings.

References	Objectives	Participants and motions	Parameters of interest	Primary results and findings
Finite element modelling of the foot and high-heeled shoe				
Karimi et al. [34]	Propose an adjustable HHS finite element model (HHS/FHS).	Participants: not appliable.	The von Mises stress in each region of the foot and shoe model.	①Lower von Mises stress in the soft tissue and bony structures of the foot when switching to FHS.
		Motions: balanced standing.		
Milazzo et al. [35]	Propose an integrated approach to design HHS and investigate the influence of HHS with or without closed-shaped front side on foot biomechanics during balanced standing.	Participants: one female.	Pressure distributions and peak pressure on the footbed and dorsal surface of the toes.	①Non-uniform pressures for both HHS models.
		Motions: balanced standing.		②Higher peak pressure on the footbed and the external toes for the closed-shaped HHS model.
Yu et al. [22]	Propose an HHS donning approach and reveal the biomechanical response of high-heeled shod walking.	Participants: not appliable.	The interfacial foot pressure, bone movement and stress.	①Maximum contact pressure at MTP joints at the push-off instant, with the largest magnitude at the first MTP.
		Motions: walking.		②Larger transverse movements during walking at the first and fifth MTP joints.
				③Four-time larger dorsal contact pressure at the first toe at push-off compared to heel strike instant.
Yu et al. [33]	Compare the effects of heel heights on strain and tension force of the ATL and plantar fascia during balance standing and investigate the change of strain and tension force during high-heeled shod walking.	Participants: one female.	The strain and tension force of the ATL and plantar fascia.	Balanced standing
		Motions: balanced standing and walking.		①Increased strain and tension force of the ATL with the elevated heel height.
				②Decreased strain and tension force of the plantar fascia at moderate heel height.
				Walking
				①Increased strain and tension force of the fascia while decreased ATL loading at push-off.
Finite element modelling of the foot and boot				
Hladnik et al. [38]	Propose a cross-country ski boot finite element model and determine the directions for torsion stiffness to mass contribution optimization of the boot middle region.	Participants: not applicable.	Torsion stiffness contribution, mass contribution, and torsion stiffness to mass contribution ratios.	①Shoe-upper, the most efficient region on torsion stiffness to mass contribution ratios.
		Motions: lateral inclination deformation of the boot.		②Soles, the highest potential region for boot torsion stiffness to mass contribution optimization.
				③Lower torsion stiffness to mass contribution ratios of the strengthening bands than expected.
Hladnik et al. [37]	Propose a cross-country ski boot finite element model and determine the directions for flexion stiffness to mass contribution optimization of the boot middle region.	Participants: not applicable.	Flexion stiffness contribution, mass contribution, and flexion stiffness to mass contribution ratios.	①Shoe-upper with strengthening bands and shoelaces, the most efficient region on flexion stiffness to mass contribution ratios.
		Motions: flexion deformation of the boot middle region.		②Midsole and sole, the highest potential region for the boot flexion stiffness to mass contribution optimization.
Hladnik et al. [39]	Propose a cross-country ski boot finite element model and determine the directions for flexion stiffness to mass contribution optimization of the boot front region.	Participants: not applicable.	Flexion stiffness contribution, mass contribution, and flexion stiffness to mass contribution ratios.	①Shoe-upper and shoe-cap, the most efficient region on flexion stiffness to mass contribution ratios.
		Motions: flexion deformation of the boot front region.		②Soles, the highest potential region for the boot flexion stiffness to mass contribution optimization.
Qiu et al. [36]	Propose a coupled foot-boot finite element model for further parachute landing fall simulation.	Participants: not applicable.	Plantar pressure distributions and the peak value.	①Good agreement with published experiment and predicted data in plantar pressure distributions and the peak value.
		Motions: balanced standing.		

(*continued on next page*)

Table 2 (*continued*)

References	Objectives	Participants and motions	Parameters of interest	Primary results and findings
Finite element modelling of the foot and sports shoe				
Cho et al. [40]	Propose a coupled foot-court sports shoe finite element model and reveal the landing impact characteristics of court sports shoes.	Participants: not mentioned.	GRF time curve, regional peak pressures at outsole, peak contact pressures at insole, equivalent stain distribution, time curve of the contact pressure and the vertical acceleration, and frequency response.	①Good agreement between predicted and experimental results in GRF time curve, regional peak pressures at outsole, and peak contact pressures at insole.
		Motions: vertical straight landing.		②Lower peak strain at soft tissue than that of the insole.
				③Severe fluctuation in the vertical acceleration with large amplitude at heel after the landing impact instant.
				④A wide frequency band with a relatively high center frequency at heel during the landing impact.
Ishii et al. [42]	Propose a couple foot-soccer shoe-ball finite element model and investigate the effects of soccer shoe upper on ball behavior after impact in a curve kick.	Participants: one male for model construction and five male soccer players for experiments.	Ball behavior: launch angle, ball velocity and ball rotation.	①Larger ball velocity and ball rotation as the foot velocity before impact increased.
		Motions: curve kick.		②Little effect of shoe upper material properties and friction coefficient between the shoe upper and the ball on ball behavior
Kim et al. [41]	Compare the effects of sports ground material properties on the impact force transfer characteristics during vertical straight landing.	Participants: 5 males and 5 females for the experiment.	GRF time curve, regional peak pressures at outsole, GRF, acceleration transfer and frequency response.	①Good agreement between predicted and experimental results in GRF time curve and regional peak pressures at outsole.
		Motions: vertical straight landing		②The highest GRF under asphalt ground while the lowest value under wood ground.
				③A decreasing trend for the peak vertical acceleration and the central frequency from asphalt to wood.
Li et al. [43]	Propose a coupled foot-barefoot running footwear finite element model and compare the peak plantar pressure differences during landing in the weight-bearing period between coupled model and barefoot model.	Participants: one female cadaver.	Peak plantar pressure and stress distributions in the metatarsals.	①Better pressure distribution and less peak plantar pressure in the coupled model than that of the barefoot model.
		Motions: running (landing in the weight-bearing period)		②An increasing trend for the peak von Mises stress in the five metatarsals as the loads increased.

Note: Anterior talofibular ligament (ATL); Ground reaction force (GRF); Metatarsophalangeal joints (MTP).

[37, 38, 39], only bony structures and soft tissue were considered, and the geometrical properties of bony structures were further simplified as a rod. The ski boot was reconstructed in detail based on its realistic counterpart. It is worth noting that shoelaces and strengthening bands were also considered in these studies in order to determine the flexion/torsion stiffness of the boot models with higher accuracy. Similar to the material property assignment of the HHS models, most components of the foot-boot model in Qiu et al.'s study [36] were assigned as linearly elastic except for the soft tissue. However, the material property assignment in Hladnik et al.'s studies [37, 38, 39] were slightly different. Firstly, the rod (which represents the lower part of the shank) was assigned with steel and soft tissue with silicone. Moreover, the material properties of the boot were first measured by tensile tests and then further verified based on the expected loading states during flexion/torsion stiffness measurements. For the textiles of some components (i.e., shoe upper, strengthening bands, and heel counter), a special material model intended for fabrics was applied.

The foot-plate system approach was used by Qiu et al. [36], and only balanced standing was simulated in their study. Both GRF and AT force were estimated from the BW, while no other foot muscle forces were further considered. In Hladnik et al.'s first study [38], the middle-front and back regions of the boot were fixed to the ground plate. The top of the steel rod was laterally inclined to a 10-degree twist angle with respect to the longitudinal boot axis to predict the torsion stiffness of the middle region of the boot. While in the remaining two studies [37, 39], the very front region or the middle-front region was fixed to the ground plate to determine the flexion stiffness of the front or middle region of the boot. During simulation, the top of the steel rod was displaced forward either for 180 mm or to a 17.8-degree flexion angle. In terms of model validation, the predicted plantar pressure and distribution during balanced standing were compared to previous experimental data in Qiu et al.'s study [36], while in Hladnik et al.'s studies [37, 38, 39], the numerically and experimentally acquired flexion/torsion stiffness curves were compared, and linear approximation function of the two curves was applied for further validation.

3.4.3. Finite element modelling of the foot and sports shoe

Studies included in the final category focused on the finite element modelling of the foot and sports shoe. Specifically, two studies investigated the landing impart characteristics of the court sports shoe [40, 41], one investigated the effects of soccer shoe on ball behavior during a curve kick [42], and the last one compared the biomechanical differences during running landing in the weight-bearing period between barefoot running shoe and barefoot [43].

The earlier three studies did not compile a detailed segmentation and reconstruction of the anatomical structure of the foot. Cho et al. [40] and Kim et al. [41] used the same foot-shoe FE model in their studies. Most of the lower limb and foot skeleton were fused to one bony structure, which in total consists of two bone assemblies (i.e., the tibia and fibula were fused as a single bone and the other foot bones as another assembly) and one combined joint (ankle joint). Ishii et al. [42] also simplified the inner foot structures, such as bone shape and ligaments, and a generalized foot

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

References	Geometric acquisition		Model components			Material properties			Boundary conditions	Loading conditions	Experimental validation
	Foot	Shoe	Foot	Shoe	Others	Foot	Shoe	Others			
Finite element modelling of the foot and high-heeled shoe											
Karimi et al. [34]	Literature and in vivo MRI	CAD software design	① Soft tissue ② Bone (whole)	① Upper ② Heel ③ Sole	Support plate	Linearly elastic	Linearly elastic	Linearly elastic	Not mentioned	Vertical GRF (half bodyweight) under support plate.	Not mentioned
Milazzo et al. [35]	Literature, in vivo MRI, and 3D scanner	CAD software design	① Soft tissue ② Bones	① Upper ② Heel ③ Shankpiece ④ Sole	Support plate	Linearly elastic for bones. Hyperelastic for soft tissue.	Linearly elastic	Linearly elastic	Support plate fixed.	Half bodyweight on the proximal surfaces of the soft tissue, tibia, and fibula.	Pressure distributions and peak pressure on the footbed and dorsal surface of the toes.
Yu et al. [22]	Literature	CAD software design	① Soft tissue ② Bones ③ Cartilages ④ Plantar fascia ⑤ Ligaments	① Upper ② Heel ③ Shankpiece ④ Sole	Support plate	Linearly elastic for bones, cartilages, plantar fascia, and ligaments. Hyperelastic for soft tissue.	Linearly elastic	Linearly elastic	Proximal surfaces of the soft tissue, tibia, and fibula fixed.	Vertical GRF at heel strike, midstance, and push off instant under support plate. AT and foot extrinsic muscle forces.	Plantar pressure and distribution at heel strike, midstance, and push off instant.
Yu et al. [33]	In vivo MRI	CAD software design	① Soft tissue ② Bones ③ Cartilages ④ Plantar fascia ⑤ Ligaments	① Upper ② Heel ③ Shankpiece ④ Sole	Support plate	Linearly elastic for bones, cartilages, plantar fascia, and ligaments. Hyperelastic for soft tissue.	Linearly elastic	Linearly elastic	Proximal surfaces of the soft tissue, tibia, and fibula fixed.	Balanced standing Vertical GRF (half bodyweight) under support plate; AT and foot extrinsic muscle forces. Walking Vertical GRF at heel strike, midstance, and push off instant under support plate; AT and foot extrinsic muscle forces.	Plantar pressure and distribution and arch deformation.

(*continued on next page*)

Table 3 (*continued*)

References	Geometric acquisition		Model components			Material properties			Boundary conditions	Loading conditions	Experimental validation
	Foot	Shoe	Foot	Shoe	Others	Foot	Shoe	Others			
Finite element modelling of the foot and boot											
Hladnik et al. [38]	3D software design	CAD software design	① Soft tissue ② Foot strengthening (rod)	① Lacing part of shoe-upper ② Toe cap ③ Shoelaces ④ Strengthening bands ⑤ Ankle stabilizer ⑥ Heel counter ⑦ Heel pocket ⑧ Stabilizer fastener ⑨ Midsole ⑩ Glue layer 11 Sole	Support plate	Linearly elastic	Linearly elastic	Linearly elastic	Support plate and the whole foot-boot model fixed.	Displace the steel rod in the lateral boot axis direction.	Torsion moment with respect to the total twist angle.
Hladnik et al. [37]	3D software design	CAD software design	① Soft tissue ② Foot strengthening (rod)	① Lacing part of shoe-upper ② Toe cap ③ Shoelace ④ Strengthening bands ⑤ Heel counter ⑥ Heel pocket ⑦ Midsole ⑧ Glue layer ⑨ Sole	Support plate	Linearly elastic	Linearly elastic	Linearly elastic	Support plate and front region of the foot-boot model fixed.	Displace the steel rod in the longitudinal boot axis direction.	Flexion torque with respect to the total deformation angle.
Hladnik et al. [39]	3D software design	CAD software design	① Soft tissue ② Foot strengthening (rod)	① Shoe-upper ② Shoe-cap ③ Shoelace ④ Strengthening bands ⑤ Heel counter ⑥ Heel pocket ⑦ Midsole ⑧ Glue layer ⑨ Sole	Support plate	Linearly elastic	Linearly elastic	Linearly elastic	Support plate and outmost front part of the sole of the foot-boot model fixed.	Displace the steel rod in the longitudinal boot axis direction.	Flexion stiffness of the soles, artificial foot and coupled boot–foot model.

(*continued on next page*)

Table 3 (*continued*)

References	Geometric acquisition		Model components			Material properties			Boundary conditions	Loading conditions	Experimental validation
	Foot	Shoe	Foot	Shoe	Others	Foot	Shoe	Others			
Qiu et al. [36]	Website	CAD software design	① Soft tissue ② Bones ③ Cartilages ④ Plantar fascia ⑤ Ligaments	① Upper ② Insole ③ Midsole ④ Outsole	Support plate	Linearly elastic for bone, cartilage, plantar fascia, and ligaments. Hyperelastic for soft tissue.	Not mentioned	Linearly elastic	Proximal surfaces of the soft tissue, tibia, and fibula fixed.	Vertical GRF (half bodyweight) under support plate; AT forces (half of the body load).	Plantar pressure distributions and peak value.
Finite element modelling of the foot and sports shoe											
Cho et al. [40]	Not mentioned	CAD software design	① Soft tissue ② Bones ③ Cartilages ④ Ligaments	① Upper ② Insole ③ Midsole ④ Outsole	Support plate	Linearly elastic	Linearly elastic for upper, insole, midsole. Hyperelastic for outsole.	Linearly elastic	Support plate fixed	Bodyweight at the mass center of the coupled model; Initial vertical velocity; Acceleration of gravity.	GRF time curve, regional peak pressures at outsole, and peak contact pressures at insole.
Ishii et al. [42]	3D foot laser scanner	3D foot laser scanner	① Soft tissue ② Bones ③ Cartilages	① Upper ② Outsole	Ball (Outer panel, Bladder)	Linearly elastic	Linearly elastic	Hyperelastic	The coordinates of eight nodes (heel, lateral malleolus, three nodes on the lateral side of the foot, and three nodes on the ball surface).	3D joint reaction force and joint moment (constant loads) on the ankle joint centre node; Foot COM and angular velocities immediately before impact.	Ball behavior: launch angle, ball velocity and ball rotation.
Kim et al. [41]	Literature	Literature	① Soft tissue ② Bones ③ Cartilages ④ Ligaments	① Upper ② Insole ③ Midsole ④ Outsole	Support plate	Linearly elastic	Linearly elastic for upper, insole, midsole. Hyperelastic for outsole.	Linearly elastic	Support plate fixed	Bodyweight at the mass center of the coupled model; Initial vertical velocity; Acceleration of gravity.	GRF time curve and regional peak pressures at outsole.
Li et al. [43]	cadaver MRI	CAD software design	① Soft tissue ② Bones ③ Cartilages ④ Ligaments	① Upper ② Insole ③ Midsole ④ Outsole	Support plate	Linearly elastic	Linearly elastic for upper, insole, midsole. Hyperelastic for outsole.	Linearly elastic	Proximal surfaces of the soft tissue, tibia, and fibula fixed.	Vertical concentrated forces with 100N increments each condition under support plate; AT forces.	Plantar pressure and distribution during balanced standing and weight-bearing period.

Note: Achilles tendon (AT); Center of mass (COM); Ground reaction force (GRF); Magnetic resonance images (MRI).

shape was finally adapted in their study. On the other hand, Li et al. [43] incorporated most of the inner structures of the foot in their study, aiming to reveal the forefoot stress changes with different loading underneath the ground plate. In terms of the sports shoe models, all of them were built based on the contour of the foot and ankle and included four main components (upper, insole, midsole, and outsole), except for the soccer shoe, which was reconstructed through a 3D foot laser scanner and only included shoe upper and outsole. A soccer ball model was also built in Ishii et al.'s study [42], and it consisted of two layers, the outer panel and the internal latex bladder. The material properties of the foot and sports shoe were mostly chosen from previous studies, and all the components were assigned to be linearly elastic except for the soft tissue and shoe outsole, which were defined as hyper elastic. In addition, the soccer ball was also described as a hyper elastic model.

The foot-plate system approach was used by Li et al. [43], and vertical concentrated forces with 100N increments were applied under the ground plate to simulate weight-bearing and other ascending loading conditions. AT force estimated from the BW was also applied simultaneously with the changing foot loadings. In Cho et al.'s and Kim et al.'s studies [40, 41], the total BW was added to the mass center of the coupled model, and a vertical downward initial velocity with the acceleration of gravity was further applied to simulate the vertical straight landing scenario. For the kick impact event [42], the coupled model was first adjusted to the posture immediately before kick impact. At the same time, the constant 3D joint reaction force and joint moment were applied on the ankle joint center node, and the velocity of the center of mass of the foot and foot angular velocity immediately before impact was also added. Moreover, the initial foot velocity, the material properties of the shoe upper, and the friction coefficient between the shoe upper and the ball were stepwise increased to determine the main factor that would affect the ball behavior during curve kick. In terms of model validation, the predicted foot or shoe pressure and its distribution were compared to the experimental data for the barefoot running shoe and court sports shoe. Moreover, Cho et al. and Kim et al. [40,41] also compared the predicted and experimental GRF history time curve after the initial ground contact for further validation. The model validation for soccer shoe was slightly different as Ishii et al. [42] aimed to reveal the interaction between the shoe and ball. In their study, the predicted results for ball behaviors, including launch angle, ball velocity and ball rotation immediately after the curve kick impact, were applied to evaluate the model validity.

4. Discussion

The primary purpose of the present study was to critically review and summarize previous literature investigating foot-shoe biomechanics from a FE simulation perspective. Unlike past reviews, this study concentrated on the more comprehensive assembled footwear models that included both upper and sole shoe structures. In general, most of these modelling developments have no doubt laid fundamental groundwork and improved our understanding of the foot-shoe biomechanics. However, it must be emphasized that many coupled foot-shoe FE analyses were performed under certain simplifications and assumptions, such as simplified geometrical structures and linear assumption of material properties, highlighting several strong challenges and gaps confronted in the further development of more realistic and accurate models for clinical and industrial applications. The major challenges of existing foot-shoe FE models in terms of model design, material property assignment, boundary and loading condition, and model validation are discussed below, and the possible advancements, application on footwear and research gap are further proposed.

4.1. Model design

The first main challenge is to obtain reliable data information for geometry reconstruction. Based on these included studies, it is obvious that MRI is currently the most used imaging modality that can provide high-resolution images for accurate reconstruction of soft tissue and bony structures [33, 34, 35, 43]. Besides that, the 3D foot laser scanner has also been applied to support foot modelling [35, 36, 37, 38, 39, 40, 41, 42]. However, although this surface topography method can offer a relatively quick and accurate geometry reconstruction of the foot external surfaces, the limitation is that it cannot provide any information about the foot internal structure, and this restricts its further usage for modelling purposes [24]. On the other hand, CAD software design appears to be the dominant option for the reconstruction of shoe geometries. The virtual shoe models were either made based on the structure of their realistic counterparts [22, 33, 34, 35, 37, 38, 39] or the contour of the foot models [36, 40, 43]. However, two issues may arise during the shoe modelling process. First, since the shoe models were built separately, an extra shoe fitting simulation is needed to resolve the surface overclosure between the dorsal foot and shoe upper. Second, the accuracy and reliability of the shoe models, especially the shoe upper, need further verification if they were designed based on the profile of the foot and ankle. It is proposed that using MRI or computed tomography (CT) to obtain the shod medical image could be a more effective alternative for reliable foot and shoe modelling.

A geometrically detailed FE model involving all major foot and shoe structures is necessary for realistic evaluation of the foot-shoe biomechanics and footwear optimization [44]. However, only the major ligaments were included in many of the existing models, and some that fused distal bones were also considered. Besides that, many non-structural shoe features such as shoelaces were often removed during the shoe modelling process. The ignorance of these structures would lead to the inaccurate representation of model integrity, which may further affect the simulation accuracy and limit its further usage. Recent barefoot FE simulations have focused on developing realistic structural modellings such as tendons, skin, and fat tissue of the foot, which indicates that there is potential for further improvement of the existing foot-shoe FE models [45, 46, 47].

The above drawback also brings another critical challenge in terms of model design, which is the balance between accurate details and computational cost. Regardless of the analysis complexity, it is generally assumed that the computational time increases with the model size, which in turn is associated with the types and the total number of the model elements [24, 27]. Thus, it is obvious that a detailed foot-shoe FE model will include a greater number of model elements and consequently the computational cost would significantly increase. However, it should be re-iterated that model accuracy is crucial, especially for special-shaped footwear analyses and for clinical applicability [24, 27]. Future research on this topic should focus on methods that could help achieve the minimum simulation cost with industrial and/or clinically satisfied model accuracy.

4.2. Material property assignment

The main issue on material property assignment is that most of the included studies assumed linearly elasticity for both foot and footwear structures based on previous literature, which is certainly an approximated situation for biological tissue. Normally, all biological tissues present complex nonlinear behavior [24]. Several existing models have considered nonlinear material for the soft tissue of the foot and the shoe outsole to increase accuracy [22, 33, 35, 36, 40, 41, 43]. However, it is currently not practical to build a foot-shoe FE model assuming all components are nonlinear, as this would make the simulation significantly difficult and time-consuming. Besides that, it is also worth mentioning that in some studies the bone structures were further simplified or even not included [34, 35, 37, 38, 39, 42]. In these cases, the material properties of the model should be further calculated since the ignorance of bone structures may in turn have significant influences on the model stiffness. To achieve that, a combination of mechanical measurements and sensitivity tests of material property is proposed. In addition, although this review did not involve any patient-specific foot-shoe models, it is suggested that material properties adopted for foot problems and orthotic footwear design should also be determined via the above methods since they may be highly associated with clinical outcomes.

4.3. Boundary and loading condition

The main direct challenge for implementing accurate FE analyses is defining a realistic boundary and loading condition. For some FE analyses such as balanced standing, a certain number of existing models in this review considered only the GRF or vertical concentrated forces estimated from the BW, with all foot muscle forces ignored or only the simplified AT force included [34, 35, 36, 43]. Moreover, it was found that the boundary and loading conditions were not always determined from the same model subjects. According to the literature, it may be acceptable in some cases where subject-specified characteristics were restricted or not the study focus, while on the other hand obtaining relevant loading data through biomechanical and computational tests on the involved subjects is critical, especially for clinical-related scenario where model accuracy is the prerequisite [44].

Currently, human motion analysis and musculoskeletal modelling have been widely used in barefoot and foot-insole FE simulations to accurately determine the subject-specific boundary and loading conditions for motions like walking and running [16, 21, 48]. However, only a limited number of existing foot-shoe models have incorporated the above methods to improve accuracy, and in these studies foot muscle forces were estimated by EMG data and PCSA [22, 33]. It has been previously clarified that musculoskeletal analysis may be a more computationally efficient approach in muscle force estimation compared to the EMG approach [44]. More attempts for foot-shoe analysis, including motion analysis and multi-body models, could add further verifications. In addition, for some specific motion simulations, such as the boot flexion deformation [37, 38, 39], it is proposed that a motion-based loading conditions may further help to optimize the flexion/torsion stiffness of the boots with more practical significance.

4.4. Model validation

The validation of a FE model is a direct challenge that is highly associated with the model practicality. Currently, existing foot-shoe FE models are mainly validated against the distribution and peak values of experiment-measured plantar pressure data [22, 33, 35, 36, 43]. However, it is proposed that comparing the pressure characteristics of the specific anatomical sites and the shoe outsole are also necessary for further model validation. In addition, for some specific footwear types, such as HHS, the pressure validation of the dorsal surface of the foot should also be conducted since the foot would experience large deformation during high-heeled motions. Moreover, some experimental validations were performed by comparing the GRF-time curves during the movement [40, 41]. In these cases, using statistical analyses such as Goodness of Fit could further help to evaluate the method consistency. Lastly, since contact modelling was generally applied on all the bony segments and foot-shoe interfaces, internal joint movements, soft tissue deformations, as well as relative movements between foot and shoe could all be experimentally validated by dual-plane fluoroscopy and MR image-based measurements [44, 49].

4.5. Application on footwear

The computational simulation of the foot-shoe FE model has gradually become an essential tool for footwear industrial field. In this review, three types of footwear (HHS, boot, and sports shoe) were mainly taken into consideration. Researchers have proposed several key features that should be considered for design and optimization of footwear and footwear components. In terms of HHS, recent efforts have mainly focused on the shoe donning simulation, shoe upper (especially the toe box), and heel height. Normally, the foot shape of women does not always match properly with the HHS, which may further lead to foot pain and more forefoot deformities. The shoe donning procedure established by Yu et al. [22] could help to reveal this issue. By realizing the realistic simulation of complex foot shape and HHS structure, this method can determine the shoe fit performance both for neutral and deformed foot shape. For shoe upper, because of its wrapping effect on the top of the foot, the dorsal contact pressure of hallux and fifth toe was found increased considerably during high-heeled shod walking [22]. However, it was also found that HHS with an opened upper front side contributed to lower loads on the external toes than the closed-shaped specimen [35]. The heel height of HHS was also found to be associated with foot biomechanics [33]. Specifically, it was demonstrated that an appropriate heel height can add help to reduce fascia strain. In general, it is proposed that the information of these two unique HHS features on dorsal pressure or fascia strain should be fully considered and the shoe donning simulation could be widely applied to facilitate better HHS design.

In terms of boot, most of the included simulations were conducted on cross-country ski boot models and the contribution of the boot stiffness and mass to energy efficiency was further highlighted. When determine the mass optimization while considering its flexion and torsion stiffness, it was found that the shoe upper is the most efficient region and shoe sole has the highest potential [37, 38, 39]. As a result, it is suggested that the footwear manufacturer should consider calculating the corresponding flexion/torsion stiffness to mass contribution ratios of these regions for ski boot design. For sports shoe, it is currently still under preliminary simulations without taking any specific shoe features into consideration. Li et al. [43] investigated the effects of barefoot running shoe on plantar pressure, but they didn't simulate the unique design of this type of footwear and neither did they make further comparison with normal running shoes. Ishii et al. [42] focused more on the ball behavior than the soccer shoe itself. Nevertheless, based on previous laboratory-based experiments on footwear, it should be highlighted that the FE simulation on different upper and sole features of sports shoe are highly required for footwear optimization.

4.6. Research gap

The existing foot-shoe FE simulations have shown their contributions to understand the foot and footwear biomechanics. However, the benefit has been limited since only few types of shoes were investigated so far. Currently, there is increasing numbers of studies that focused on the comparison of gait biomechanics between different features and/or types of shoes, such as flip-flops, ballet shoes, and minimalist shoes [50, 51, 52, 53]. Footwear can reshape the biomechanics of human lower limb, and thus it is definite that these analyses would contribute to understand the footwear functionality. Nevertheless, there is still a clear research gap between the lower limb biomechanics and footwear design, while the FE analysis may serve as the connection between them since it could offer additional insights into the internal stress and strain characteristics of the foot as well as the load transfer mechanism between foot and footwear. For instance, the metatarsal loading can be directly determined through the FE simulation to investigate the probability of stress fracture when running in minimalist footwear, which could in turn provide evidence for footwear optimization. The unique structure of flip-flops can be rebuilt and its influence on interphalangeal joints could be further revealed to help optimize design. Since footwear industry is currently being modernized by emerging computer technologies, it is therefore proposed that more comprehensive FE models considering both foot and major types of shoes are expected to be simulated to accelerate the process of footwear design and optimization.

Another research gap confronting the foot-shoe FE models is the consideration of insole/orthosis and socks in the footwear. Both insole/orthosis and socks are placed between the foot and footwear, and it has been previously demonstrated that these structures play important roles in adjusting friction between foot and shoes, modulating the biomechanical response of the foot, and may also in implicating injury prevention [21, 54, 55, 56]. Moreover, it was also found that some specified insoles/orthoses would further influence the biomechanics of proximal joints [57]. Nevertheless, to the authors' knowledge, there has been little or no research in relation to the foot-shoe FE analysis which takes these structures under consideration. Researchers should start to bring together the insole/orthosis and socks with shoes for FE analysis in order to create a more representative model for understanding foot and footwear interaction and provide accurate guidance to the functional design of footwear.

Based on the results of the methodological quality assessment, there are also two additional research gaps that should be highlighted here. First, in this review, most of the existing foot-shoe simulations neglected the model verification process. In this case, the accuracy of the mathematical model and its solutions may not be guaranteed since it is normally justified the model verification tests [58]. Thus, it is proposed that research on complicated FE models, such as foot-shoe complex, should conduct model verification using mesh convergence test to further ensure the internal accuracy. The second research gap is related to the external validity issue of the FE studies. It has been demonstrated that the inherent research design of FE analysis (i.e., single-subject/subject-specific design) can further hinder the external validity or the generalizability of the findings [32]. Although some population-based models or statistical models were adopted to address this issue [59, 60], no consensus has been currently reached, which indicates that there are still plenty of rooms for further work to cover this gap.

4.7. Limitations

Despite the strengths of this systematic scoping review, two potential limitations should be noted here. First, our study may prone to several bias in light of the following reasons, (1) only FE research published in English journal were included, which may lead to language and publication bias since some FE analysis were written with non-English and published in conference abstract/proceedings, book chapters, and preprints; (2) only two databases were searched and the snowballing approach was used during literature search, while these two issues may result in selection bias; and (3) the selective reporting bias may also exist as some articles may involve comparisons between different designs or different levels of parameters that were not detailed in the review analysis. A further limitation of this review was that a direction comparison between the findings of FE models were difficult because there was large heterogeneity in their configurations and outcome measures.

5. Conclusion

To summarize, although numerical modelling of the entire foot-shoe complex has received less attention than other conditions, it has shown essential contributions to further understanding the foot and footwear biomechanics. This is specifically the case where the FE model was applied for identifying mechanical properties of the foot in casual or athletic footwear and for optimizing footwear design to enhance its functional performance. Nevertheless, this study highlights the need for improvement in several aspects, including geometry, material, boundary and loading properties, and validation of the foot and footwear. Moreover, it also stressed the importance to cover some research gaps in terms of the coverage of footwear design, the consideration of insole/orthosis and socks, and the internal and external validity of the FE design.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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