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Systematic Review

Finite Element Modeling of Human–Seat Interaction and the Integration of 3D-Printed Foam in Enhancing Sitting Comfort: A Systematic Review

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Abstract

The aim of this systematic review is to summarize studies that apply the finite element method (FEM) to simulate human–seat interaction, while also evaluating the role of 3D-printed foam materials in enhancing sitting comfort. These studies employ a variety of human body models, ranging from basic to fully detailed representations including muscles, bones, and joints. Although simulation methods have continuously evolved, contact pressure remains the most commonly used evaluation metric. Additionally, 3D printing is a technology that enables the customization of material structures and has gained increasing attention due to its wide applicability in engineering. Recognizing the potential of 3D-printed foams in improving pressure distribution, this review systematically analyzed 42 full-text papers. The findings reveal a significant gap in the integration of 3D printing technology into foam design using FEM for the human–seat interface. This identifies a promising direction for future research.

Keywords: finite element method (FEM); sitting comfort; human–seat interaction; 3D-printed foam

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1. Introduction

Sitting is a common daily activity, occupying approximately 7–9 h per day [1–3] for tasks such as commuting, working, eating, or resting. For many, sitting is not a conscious act [4] but rather supports other primary goals. However, improper sitting posture can negatively affect health, leading to issues such as back pain, neck stiffness, or more severe spinal problems [5,6]. Therefore, researchers have focused on enhancing sitting comfort across various fields, including aerospace [7,8], transportation [9,10], and office environments [11,12], to improve work efficiency and user experience. Additionally, optimizing sitting posture helps wheelchair users feel more comfortable over extended periods, reducing physical strain and enhancing their quality of life [13,14]. To address these comfort-related challenges, researchers have adopted various approaches to study human–seat interaction, ranging from experimental setups to simulation-based methods.

Various approaches have been employed to simulate human–seat interaction and to conduct subsequent analysis and evaluation. These include experimental studies using specialized equipment [15], simulation-based analyses conducted in virtual environments [16], and hybrid methods that combine both approaches [17,18]. In addition to these methodological differences, studies have been conducted under varying test conditions, such as

static loading scenarios [18] and vibration environments [19], further contributing to the diversity and expansion of the research field. Among these approaches, the Finite Element Method (FEM) has emerged as a leading tool, offering unique advantages for analyzing human–seat interaction and contributing significantly to the development of ergonomic seating designs.

This paper focuses on finite element analysis of human–seat interaction. Compared to experimental approaches, virtual simulations offer several key advantages. For instance, they reduce the need for physical prototyping, allow easy adjustment of design parameters like material properties or seat tilt, and enable the testing of impractical real-world conditions, such as prolonged vibrations, without posing risks. Moreover, simulations provide detailed data on pressure distribution and internal stress, which are often difficult to obtain through physical experiments [20].

To further enhance seating performance, FEM can be combined with innovative materials, such as 3D-printed foams, which offer new possibilities for customized seat designs by enabling control over key properties like porosity, stiffness, and geometry to improve comfort [21]. Unlike traditional foams, 3D-printed foams allow for tailor-made designs to optimize pressure distribution and support, which some authors have successfully applied in related areas such as shoe soles and motorcycle seats [22,23]. However, its application in human–seat interaction, particularly when combined with FEM simulations, remains largely unexplored. This gap highlights the need for a systematic evaluation of current research to inform future seating design innovations.

Unlike previous reviews that focused only on FEM simulations, human–seat interaction [24,25] or on 3D printing in studies not related to seats [26,27], this review takes an interdisciplinary approach by combining FEM simulations with 3D-printed foams to study seating comfort. This combination not only shows the limits of current studies, such as the lack of work combining 3D-printed foams with FEM, but also makes this review a useful resource to guide future research in developing advanced, personalized seats.

To address this research gap, this systematic review synthesizes studies on FE based human–seat interaction modeling and assesses the role of 3D-printed foam in improving seating comfort. The review investigates three questions:

(1) To what extent have human–seat interaction models been investigated and simulated using the Finite Element Method (FEM)?

(2) Which FEM simulations have been employed to evaluate sitting comfort in human–seat interaction models?

(3) How effective is 3D-printed foam in enhancing seating comfort based on existing studies?

By answering these questions, the review provides recommendations and identifies opportunities for future research to advance the development of innovative, comfort-enhancing seating solutions.

2. Methods

This review was conducted following the 2020 PRISMA statement guidelines [28] and adhered to a pre-registered protocol in PROSPERO (number: CRD420251144659).

2.1. Literature Search Strategy

A comprehensive search was conducted to identify studies on FEM based human–seat interaction, pressure evaluation methods, and comfort-related research involving new materials such as 3D-printed foam, on electronic databases such as ScienceDirect, Scopus, SAE, Google Scholar, and Web of Science covering the period from 2015 to 2025. Keywords used included Finite Element Method, FEM, Human, Human body model,

HBM, Seat, Chair, Pressure, 3D-Printed, and 3D Printing. Keywords were combined using Boolean operators such as AND and OR to refine the search results. In order to ensure comprehensive retrieval, the author also searched and filtered papers that met the criteria from the references of previously screened and highly relevant papers.

2.2. Screening and Selecting Papers

The inclusion criteria were defined as follows: publications written in English from 2015 to 2025; journal or conference papers; all types of seats/chairs (e.g., automotive, aircraft, etc.); studies involving human–seat interface using the finite element method (FEM); and those addressing pressure-related aspects (including pressure variables, pressure distribution, interface pressure, etc.).

The exclusion criteria included: publications in languages other than English; studies that did not utilize FEM; studies that did not involve a human body model (HBM); and studies that did not focus on the human–seat interface.

2.3. Extracting Relevant Information

The extracted information focused on the study subject, body region, simulation methods, evaluation approaches, comfort enhancement strategies and their outcomes, as well as analyses related to cushioning and 3D-printed foam.

2.4. Literature Search and Selection Process

The screening process followed PRISMA guidelines [28]. Based on the databases, papers were identified. Then, titles and abstracts were screened using the Rayyan tool [29]. This was followed by a full-text assessment according to the eligibility criteria. Papers were excluded if they were irrelevant, did not use FEM, lacked HBM, or did not address human–seat interaction or 3D-printed foam applications.

The studies were assessed according to the GRADE approach. A weighted score was assigned to each factor based on the relevance of the studies. The ratings were given as "Yes" (Y) [1], "Partial" (P) [0.5], and "No" (N) [0]. The highest possible quality rating was a weighted score of 10, corresponding to the ten listed factors. Criteria were established to analyze the strengths and weaknesses as well as the relevance of each study to the focus of this review. Based on the total scores, the studies were categorized into four quality levels: "Very Low" [1.0–2.9], "Low" [3.0–5.9], "Moderate" [6.0–8.4], and "High" [8.5–10].

3. Results

3.1. Search Results

The screening process followed the PRISMA flow chart guideline [28]. The initial search yielded 1218 papers, including 901 from Science Direct, 183 from SAE, and the remaining from sources such as Web of Science, Google Scholar, and Scopus. A total of 126 duplicate papers were removed. After screening titles and abstracts, 118 papers were selected for full-text evaluation. These papers were then reviewed in detail to determine whether they met the inclusion criteria, resulting in 32 papers selected for data extraction and analysis. In addition, 10 studies were searched from references of selected papers and manually searched. Figure 1 illustrates the screening process (PRISMA flow diagram) leading to the final selection of 42 papers. Research information of the papers is presented in Appendices A and B.

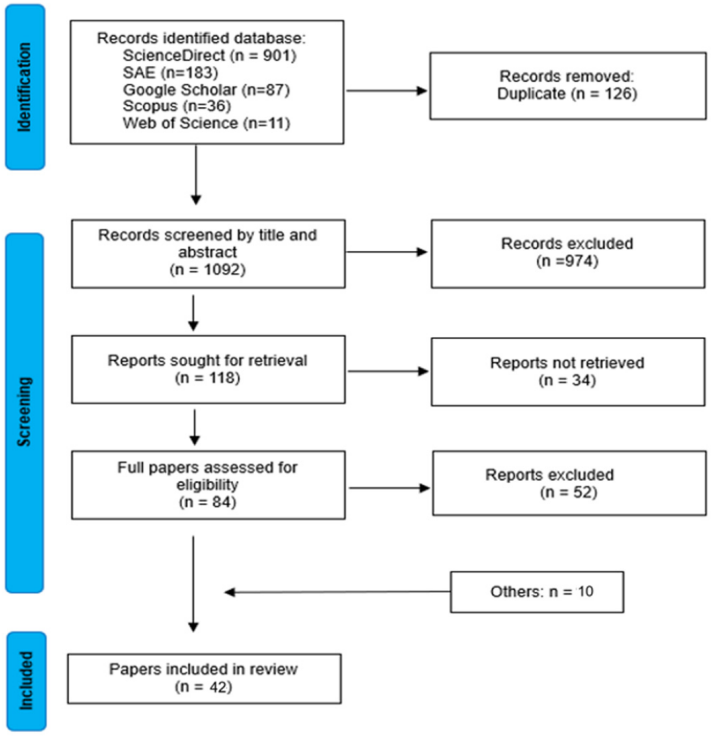


Figure 1. Search strategy (PRISMA flow diagram).

The quality assessment of the studies is closely related to the three research questions, covering aspects such as human body models, finite element simulations, pressure analysis or related measures, comfort evaluation, issues concerning 3D-printed products, and structural analysis. Results of the quality assessment of each selected and analyzed paper are presented in Appendix C. From the assessment, no study fell into the "Very Low" category; 4 studies were rated as "Low", 36 as "Moderate", and 2 as "High". However, most studies did not employ a combination of 3D printing and FEM, which limited their quality and prevented the majority from reaching the "High" category, thereby leaving a research gap that will be discussed in detail below.

Based on the GRADE ratings, this review is composed from three point of view as follows (Figure 2):

- Finite Element Human Body Models
  - Model variations.
  - Model posture determination process.
- Methods for Studying Sitting Comfort
  - Simulation conditions.
  - Evaluation methods.
- 3D-Printed Foam in Sitting Comfort

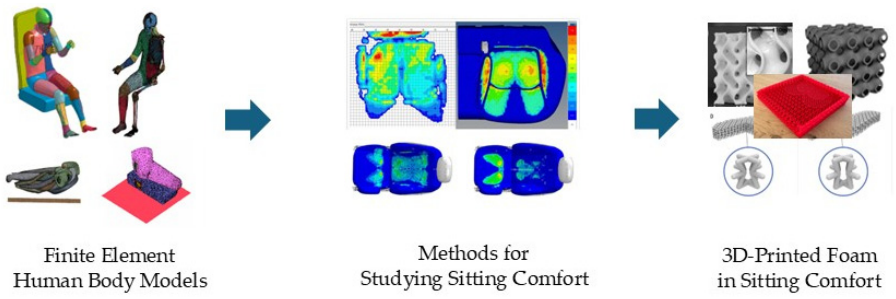


Figure 2. Three point of viewpoints for review.

3.2. Finite Element Human Body Models

3.2.1. Model Variations

Researchers have used several approaches to develop and apply finite element (FE) models of the human body. One common approach is to create models using 3D scanning [30–37]. These methods allow the model to closely match the size and shape of real participants, but they also raise challenges in simplifying the boundary conditions for simulation.

Another approach is to use existing human models available in simulation software, such as HYBRID III [38,39], MADYMO [40], POSER [41], GHBMC (Global Human Body Models Consortium) [42], THUMS [43], ANYBODY [44], and the Toyota dummy [45]. These models were originally developed for crash and safety studies, but they have also been used for ergonomic simulations. However, most of them do not fully represent muscles and ligaments, which limits their ability to simulate soft tissue behavior.

In contrast, the CASIMIR model [46–52] was specially designed for studying both static and dynamic seating comfort across different body sizes (Figure 3). Recently, the PIPER Adult model [18,20] has been developed based on the earlier PIPER Child Full Body model. This adult version includes detailed information on muscles, bones, and joints (Figure 3). According to the authors, the model aims to support personalized simulations, which can improve the accuracy of comfort analysis. It also helps to identify how factors such as bone shape, soft tissue thickness, and posture affect sitting comfort. These findings could be combined in the future to develop more general models that better represent a wide range of people [53].

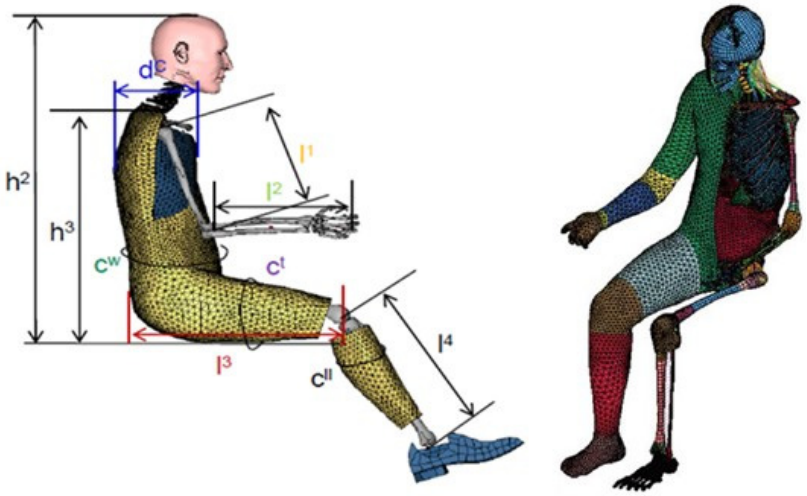


Figure 3. CASIMIR model (**left**) [49] and PIPER Adult model (**right**) [53].

In addition, not all authors use full-body models to study human–seat interaction. Many studies focus only on a specific body region (Figure 4), such as the buttocks alone [54–57], or the buttocks combined with elements like bones and muscles [30–33,36,37,42,44,58]. This approach offers advantages in terms of reducing computational load and simplifying the simulation process. However, it also presents major challenges regarding accuracy and generalizability, as such models are often overly simplified and rely on multiple assumptions.

Most studies use models representing the 50th percentile, which is considered to reflect the average human body [32,34,35,37,39–42,45,50,52]. Some studies also examine the 5th percentile [34,35,52] and the 95th percentile [34,35,38,48,51,52] to account for body size variation.

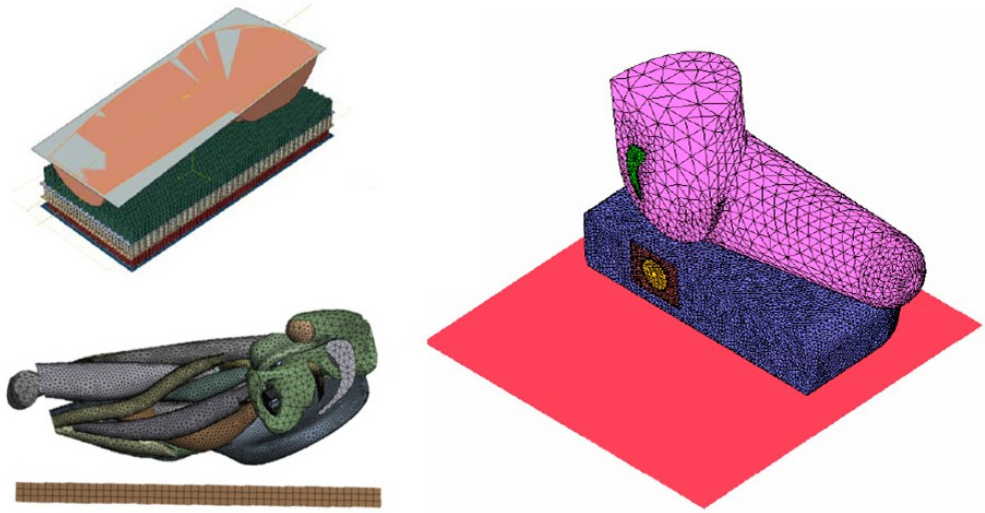


Figure 4. Buttock—Thigh model in [31,54,58].

3.2.2. Model Posture Determination Process

The sitting action usually occurs in a very short time, from the moment the body first contacts the seat until a stable posture is achieved. In most studies, this is treated as a free-fall process starting with zero initial velocity and ending in a static equilibrium between the body and the seat. This setup is often referred to as "static seating" or "static loading".

For this type of simulation, the human body model is placed very close to the seat surface (Figure 5). In some cases, the distance between the body and the seat is specified as 0.1 mm [58], while other studies simply state that the body lightly contacts the cushion surface [48,54,55], or that the body and seat are positioned very close together without specifying the exact gap [18,20,38,43,46].

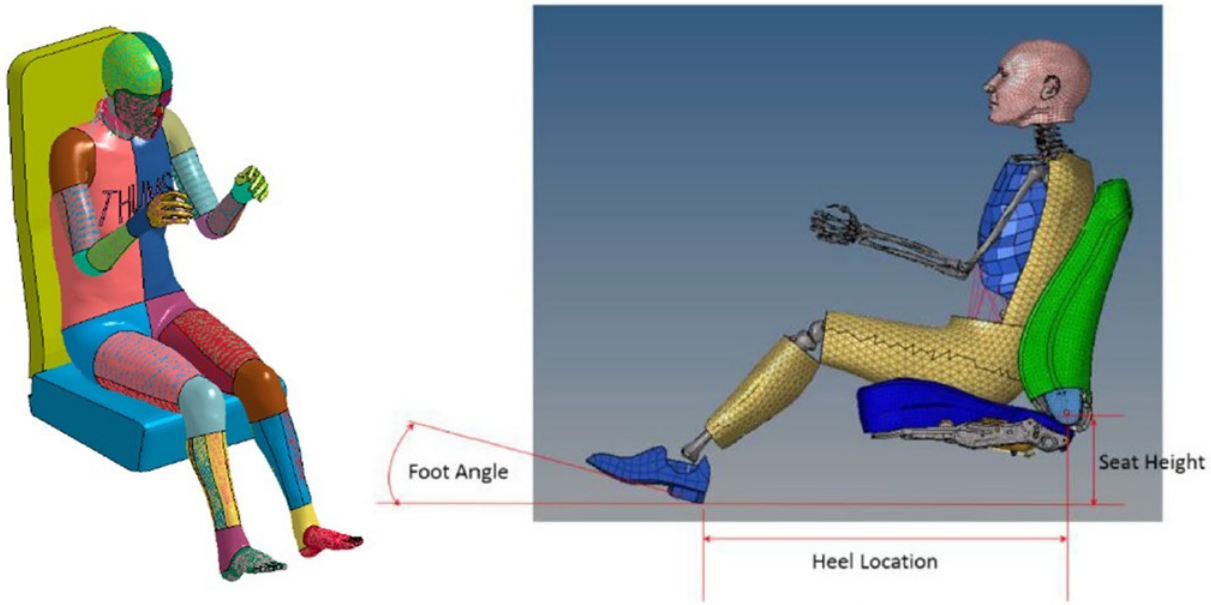


Figure 5. The human body model is very close to the seat model [43,49].

Because of this close contact, air friction is usually ignored, and studies focus only on the friction coefficient between the human body and the seat [30,31,35,42,46,54,55]. One study found that the friction coefficient significantly affects the simulation results [20], suggesting that this parameter plays an important role in static seating simulations.

Static sitting is commonly assessed in general research on seating. In addition, many studies investigate human–seat interaction in specific contexts such as vehicles and equipment, including automobiles [34,41,42,46–48,59], wheelchairs [33,54–56], high-speed trains [43], and excavators [45]. Therefore, researchers often combine the analysis with vibration problems, using dynamic loads applied from below the seat to simulate forces transmitted to the seated person [39,45,46,52,59,60]. In one wheelchair-related study [33], the authors simulated straight-line movement at a constant speed (i.e., pushing the wheelchair) to predict stress beneath the skin of the buttocks.

In a recent study published in 2024 [20], a new loading method called "Drop and Rotate" (D&R) was proposed. The study demonstrated that adding a rotational load, which mimics the action of rotating the hips to lean back against the seat, made the simulation more realistic. This rotational motion was applied for a certain period and then removed to allow the human–seat system to reach a static equilibrium. The force and pressure results obtained using this method showed better agreement with experimental data compared to the traditional free-fall approach. This was seen as a promising improvement, encouraging other researchers to explore new simulation directions for improving accuracy.

3.3. Methods for Studying Sitting Comfort

3.3.1. Simulation Conditions

In addition to defining static and dynamic boundary conditions, several studies also explored different sitting postures and analyzed the seat cushion materials.

Regarding posture, studies [20,49,61] evaluated the backrest angle, including conditions with and without back support. Meanwhile, studies [34,43,49] focused on the tilt angle of the seat surface or cushion. Study [61] also considered arm support and foot placement in order to thoroughly analyze the influence of posture on user comfort.

Studies that only used buttock models (or models including the pelvis and surrounding muscles) focused on the effects of the seat pan on the seated user.

In terms of seat cushions, most studies analyzed the seat area that comes into contact with the buttocks, which is considered the region experiencing the highest pressure during sitting. Researchers examined various aspects of seat cushion design [34], structure [54], shape [37,50], and stiffness distribution [45,50]. To enhance comfort, some authors [58] also investigated the integration of pneumatic springs into the cushion.

3.4. Evaluation Methods

In the study of the human–seat interface, the evaluation of results plays an important role in ensuring comfort, safety, and the effectiveness of the design.

The validation of simulation results using experimental models is a critical step carried out in most studies [20,30,33,35–38,42–46,48,53,54,56,58,60]. Another approach is to compare the results with previously published data [31,34,40,41,54] or with results from a different research method [60].

Most authors focus on evaluating contact pressure (Figure 6), which is considered a key factor in determining sitting comfort. Studies have shown that lower contact pressure generally corresponds to higher comfort. Additionally, a more even pressure distribution is often associated with greater comfort for the seated person.

Some authors analyze more factors in their studies. In [31,33,38,41,42,46], the authors mention stress. In other studies [20,39,60], the authors address shear forces at the contact surface, while study [56] combines thermal simulations in the human–seat interaction.

For each parameter analyzed, the simulation results were considered acceptable if the error was within a 20% range. For example, study [31] reports a 13% error, ref. [33] reports a peak pressure error of 4.09%, ref. [38] reports an error of less than 10%, ref. [43]

shows an error for peak pressure, average pressure, and contact area ranging from 3.5% to 14.43%, ref. [44] shows a peak pressure error of 14 ± 11%, ref. [58] reports a peak pressure difference of 20%, and many other studies report simulation results that closely match experimental results with errors less than 5%.

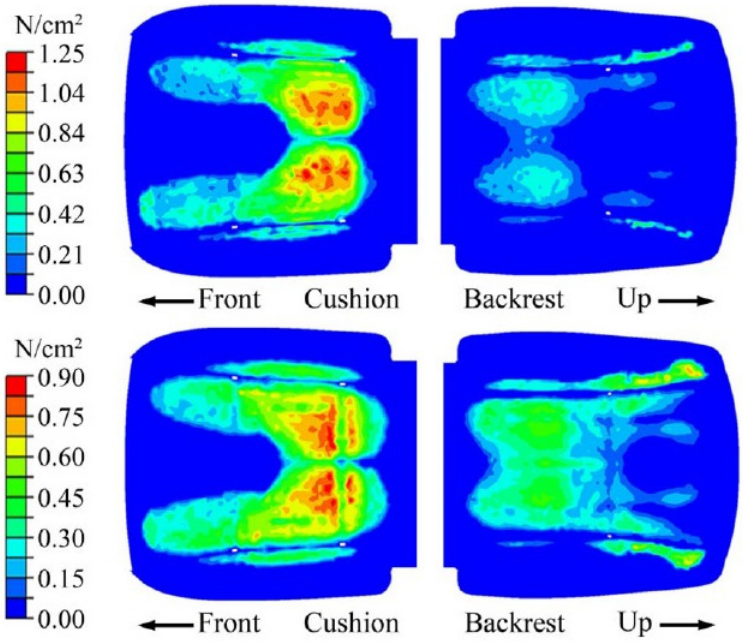


Figure 6. A case of Pressure distribution [30].

Overall, the main goal of these studies is to improve comfort, reduce pressure, and prevent pressure sores for users by evaluating the human–seat interface and various parameters.

3.5. 3D-Printed Foam in Sitting Comfort

3.5.1. Overview

3D printing, also known as additive manufacturing, is a process of creating objects layer by layer from digital models. This technology allows precise control of complex geometries and material distribution. With the advancement of 3D printing technology, this technique has been studied and applied in various fields [62], such as aerospace, automotive and healthcare. In ergonomic research, particularly concerning human comfort, the application of 3D printing is considered highly feasible. Several studies have explored its use in foot cushioning design [63], shoe soles [64,65], and foam seat designs for motorcycles [23] and airplanes [21]. In the field of cushioning, 3D printing enables the fabrication of foam structures with customized internal shapes and patterns, improving comfort and performance in many products.

3.5.2. Structural Characteristics

In additive manufacturing, there are various structural networks such as Honeycomb, Cubic, Triply Periodic Minimal Surfaces (TPMS), Random Porous Structures, and more. Among these, TPMS has been frequently used as an alternative to conventional foams due to its comparable compression properties; However, not every TPMS structure can fully replace conventional foams. David et al. (2022) studied six types of structures designed with two different materials, resulting in a total of 12 test samples (Figure 7A(a)), to experiment and compare with three types of traditional foam in order to determine the most suitable structure [66].

In another study [67], the authors used a Schwarz structure (a type of TPMS) to design a wheelchair cushion instead of using a Gyroid structure (Figure 7A(b)).

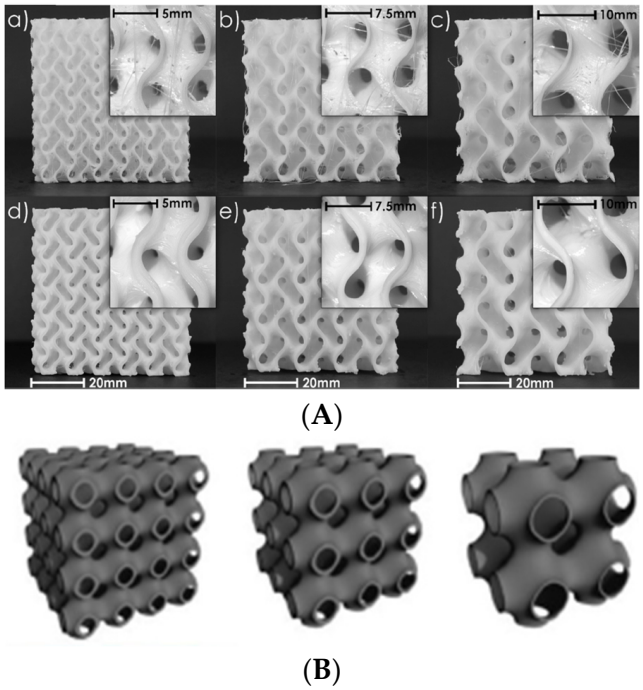


Figure 7. Gyroid (**A**) [66] and Schwarz (**B**) [67] printed samples.

In addition, some studies have also used honeycomb structures [68] to design cushions that help attenuate vibrations transmitted from the road surface and the car floor to the seated person. The authors also evaluated this structure as a form of negative Poisson's ratio (NPR) structure, which expands in the perpendicular direction when subjected to force. As a result, the contact area increases, and the applied forces are distributed more evenly and over a wider surface. Similarly, Random Porous Structures [23] have been designed for motorcycle seats to enhance sitting comfort.

Beyond modifying individual structures or parameters to determine a suitable replacement shape or even to increase comfort compared to conventional foams [64–66], another approach widely adopted by researchers is to fabricate a product that contains multiple structures or varying parameters [21,67]. Such customized designs allow 3D-printed cushions to have position-dependent stiffness: areas under high pressure exhibit lower stiffness, while areas under lower pressure are stiffer. This results in more uniform pressure distribution and greater sitting comfort.

3.5.3. Three-Dimensional Printing Technology Combined with Finite Element Simulation

Literature on 3D printing has been reviewed; however, the integration of 3D-printed structural models into simulations of human–seat interaction has not yet been identified within the scope of this systematic review.

Other related studies include [63,64], which highlighted simulations using 3D-printed materials, but these were focused on interactions between the foot and footrests or shoe soles (Figure 8). These studies also concluded that there was a reduction in pressure distribution and prevention of foot ulcers, suggesting that similar methods may improve comfort in seating applications.

The study [69] combined Design, Finite Element Analysis, and 3D printing to evaluate bioprinted scaffolds, providing design and fabrication strategies for tissue-specific scaffolding systems in tissue engineering applications.

Study on 3D-printed cushions was conducted for airplane seats, but no simulation methods were applied in this research [21]. The study concluded that 3D-printed cushions are fully feasible (Figure 9). The study [67] designed cushions based on pressure mapping and experiments without the use of simulations, which may result in repeated cycles of design and product optimization. However, this limitation was not explicitly discussed by the authors. The studies are detailed in Appendix B.

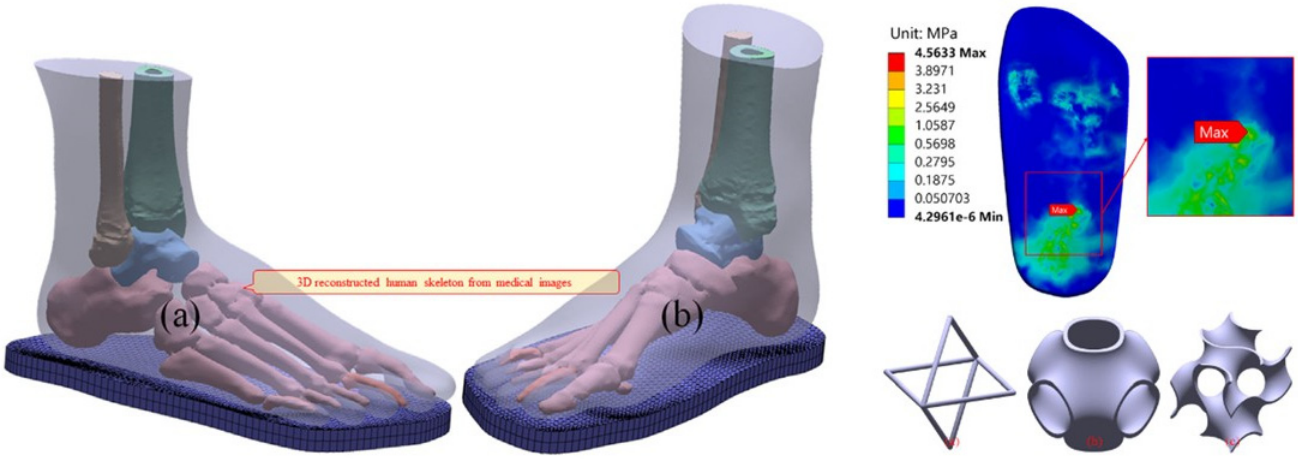


Figure 8. 3D-printed cushion for insole [64].

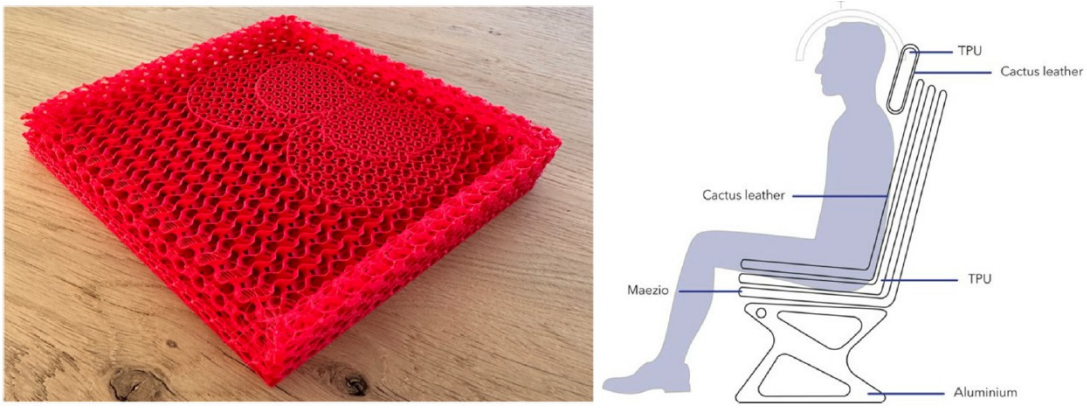


Figure 9. 3D-printed cushion for seat [21].

From the studies, it can be concluded that simulating 3D-printed structures in the human–seat interaction is feasible, and the application of 3D printing in seat cushion design is also viable. However, no such studies have been found to date, which presents a significant gap that could be explored to develop new directions in human–seat interaction research.

4. Discussion

This study aims to synthesize knowledge related to finite element modeling of the human body, as well as summarize findings regarding the human–seat interaction interface, simulation methods, and identify future research gaps. Understanding and comparing different human body models and simulation approaches offers opportunities to shape future research directions in this field.

Some studies have directly applied FEM to the lattice structures of 3D printed shoe sole models, and a similar application is entirely feasible for seat foam. Moreover, the homogenization method can be considered by replacing the original 3D printed block with

an equivalent homogeneous model. Such substitute models match in terms of Young's modulus, Poisson's ratio, shear or compressive properties, or strain energy, etc. This approach simplifies the simulation and is suitable for investigating stiffness, overall pressure, and ability to carry a load, but it cannot capture local effects or 3D printing defects. The choice of method depends on each researcher's objectives and research conditions.

In addition, this study focused on the results of simulation using commercial software. This means users cannot modify calculation logic or formulas. Recently, enhancement of finite element (FE) mathematical expression proposed [70], it may enhance capabilities of FE simulation software in the future. This can make the simulation process more detailed and further optimized.

The moderate quality of the studies reflects limitations in study design and data availability. The customized criteria indicated a moderate to high risk of bias in FEM and 3D printing studies, with inaccuracy being particularly evident in 3D printing due to the limited number of studies. Future research should standardize reporting and strengthen 3D printing studies with FEM validation.

The reviewed studies reveal that the process of building simulation models varies among researchers, often conducted independently without inheritance from previous works. Most authors develop their own models tailored to specific research conditions. Over time, through their own series of studies, some level of inheritance has emerged. Studies using scanned data as input are considered to generate simpler human body models compared to pre-built models available in software (such as HYBRID III or THUMS), which are mainly used for crash analysis. More advanced models have been developed for studying human–seat interaction, including CASIMIR and PIPER Adult.

Human body models are typically applied in two main simulation types: static and dynamic. Among them, static simulations with pelvic rotation are regarded as more complex but more optimized than traditional static studies. In combination with static and dynamic simulations, many authors conduct design evaluations of seat structures and foam materials with the goal of improving comfort, reducing stress, fatigue, or pressure-related injuries caused by prolonged sitting.

From the screened studies, the use of 3D printing technology in comfort enhancing design has been investigated by many authors, including applications in seat cushions. However, the integration of human body finite element models with 3D-printed structural models in simulations for optimizing the seat cushion design process has not yet been identified.

This study highlights a research gap in the use of 3D-printed materials and their application in simulating human–seat interaction. Besides its research potential, the issue of computer hardware requirements must be considered, as translating the detailed structure of 3D-printed foam into finite element models results in a very large number of elements. When combined with full human body models, this poses a challenge due to the enormous element count.

The study was also acknowledged by the authors to have certain limitations. Because the number of studies with controlled experiments comparing human body models and 3D printing is still limited, the limited availability of experimental validation restricts the ability to confirm the accuracy of simulations, especially when integrating 3D-printed structures with human body models. Moreover, most available studies are based on controlled simulations, while experimental investigations involving diverse user groups such as different ages, genders, or health conditions remain limited. This raises challenges in generalizing the findings to populations.

As stated in the three questions, this review focused on simulations of the mechanical inter-action between seats and occupants, so thermal comfort was out of focus. This was a

de-liberate limitation of scope. The papers found only addressed short-term simulations. Long-term comfort is primarily evaluated experimentally, not through simulation. This aspect, while not intentionally limited in the review, resulted in outcome that there is a lack of simulation studies using human body models to analyze the effects of long-term sitting on comfort. Static Finite Element simulations and short-term sitting simulation do not account for changes in material properties due to thermal effects caused by human seating.

5. Conclusions

This study reviewed a total of 42 research papers. Among them, 35 studies addressed Research Questions 1 and 2, which focus on human body models and simulation methods; 9 studies related to 3D printing were used to answer Research Question 3.

No studies were found that addressed all three research questions simultaneously, revealing a potential research gap. This gap presents both opportunities and challenges in terms of equipment requirements, modeling methods, and simulation techniques, especially when using full-body models such as CASIMIR or PIPER Adult, which involve a high number of elements, complex boundary conditions, and constraints.

Simulation software and the finite element method are powerful tools for reducing costs in research and product development. However, it also presents challenges for researchers, particularly in integrating modern modeling tools and software to meet increasingly demanding requirements.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Research information of the FEM papers.

Ref.	Model Acquirement Method	Simulation Method and Analyzed Aspects	Confirm Results
[18]	PIPER Adult	Static simulation • Pressure distribution • Contact area • Peak pressure • Soft tissue thickness below ITs. Variable: seat cushion angle (SPA: 0–15°, 5° step).	Comparison with experimental results • Contact force: Average error < 22.3 N (horizontal) and <15.5 N (vertical), small compared to body weight (784.8 N). • Pressure: Simulated contact area is 5.8% higher • Soft tissue thickness: Simulation compression ratio (49.1–58.5%) was lower than MRI (60.2–74.7%), but the trend was consistent

Table A1. *Cont.*

Ref.	Model Acquirement Method	Simulation Method and Analyzed Aspects	Confirm Results
[20]	PIPER Adult	Static simulation: Drop and Rotate • Pressure distribution • Contact force • Total horizontal force Variables: Seat cushion angle (SPA: 0°, 5°), coefficient of friction (COF1, COF2, COF3), torso-thigh angle (T2T: 93°, 95°, 97°, 100°).	Comparison with experimental results • With COF1, the pad shear force has low error: DROP (1.7%, 1 N), D&R (4%, 2.4 N) compared to actual measurement (59.2 N). • With COF2, COF3, the simulated cutting force is higher: DROP (47.8%, 28.3 N; 47.3%, 28 N), D&R (15.9%, 9.4 N; 12.3%, 7.3 N). • D&R is less sensitive to high COF, cutting forces are closer to experimental than DROP.
[30]	Scan	Static simulation • Comparison with and without seat covers	Comparison with experimental results • Using pressure gauges on actual car seats
[31]	MRI Scan	Static simulation • Pressure distribution • Pressure ratio in areas • Seat surface hardness • Seat deformation	Comparison with previous research papers • 65% error below 5 mm and less than 13% error above 10 mm
[32]	CT Scan (Male 50th percentile)	Static simulation • Pressure distribution	Comparison with experimental results
[33]	MRI Scan	Static and dynamic simulation (push wheelchair) • Pressure distribution • Contact Pressure and Internal Stress of Muscle and Fat	Comparison with experimental results • Error 4.09% of peak pressure
[34]	Scan (geometric template and point-clouds)	Static simulation • Pressure distribution • Shear force • Variation in cushion angle and thickness	Comparison with experimental results • High consistency
[35]	Scan (body surface point cloud scan)	Static simulation • Pressure distribution • Seat surface stiffness influenced by seat cover	Comparison with experimental results • High consistency
[36]	Scan (low-dose biplanar X-ray, B-mode ultrasound and optical scanner)	Static simulation • Pressure distribution • Pelvic deflection	Comparison with experimental results • Less than 1 kPa
[37]	Scan (medical scanning 3D reconstruction)	Static simulation • Pressure distribution	Comparison with experimental results • Maximum pressure deviation from 0.13% to 15.28%, average pressure from 3.00% to 39.89%

Table A1. *Cont.*

Ref.	Model Acquirement Method	Simulation Method and Analyzed Aspects	Confirm Results
[38]	Hybrid III 95th Percentile	Static simulation • Pressure distribution • Soft tissue deformation • Shear stress at the contact surface. • Von Mises stress in soft tissue	Comparison with experimental results • Error below 10%
[39]	Hybrid III	Dynamic simulation • Compressive force • Shear force • Intradiscal pressure • Von-Mises stress	Comparison with experimental results in vivo. • consistent with clinical observations.
[40]	MADYMO 50th	Static simulation • Pressure distribution	Comparison with previous research papers
[41]	POSER 50th	Static simulation • Pressure distribution • Lumbar support thickness • Contact area • Force on the backrest • Von Mises stress	Comparison with previous research papers
[42]	GHBMC 50th	Static simulation • Effects of 10 PU foams with different stiffness on surface pressure, stress and deformation. • Pressure distribution • Intrinsic soft tissue stress and strain.	Comparison with experimental results • The CORA scores in the present study are 66.8% and 75.8%, respectively.
[43]	THUMS	Static simulation • Pressure distribution • Effects of 4 types of polyurethane foam and 3 seat tilt angles	Comparison with experimental results • The relative errors of pressure characteristics between simulation and experiment ranged from 3.5% to 14.43%.
[44]	ANYBODY	Static simulation and Inverse dynamics for bones • Pressure distribution • Soft tissue deformation • Contact area, spinal compression force	Comparison with experimental results • Peak pressure error 14 $\pm$ 11%
[45]	Dummy Toyota (50th percentile)	Static simulation • Pressure distribution Dynamic simulation • Vibration under rock crushing conditions	Comparison with experimental results • Pressure: Overall accuracy > 85%. • Vibration: Frequency accuracy > 98%, total > 90%.
[46]	CASIMIR	Static and Dynamic simulation • Pressure distribution • Directional displacement of cushion and backrest	Comparison with experimental results • Error 0–10%

Table A1. *Cont.*

Ref.	Model Acquirement Method	Simulation Method and Analyzed Aspects	Confirm Results
[47]	CASIMIR, ANYBODY	Static simulation • Pressure distribution • Joint angle and moment • Muscle activity and fatigue	Comparison with experimental values in previous studies • High consistency
[48]	CASIMIR (Male 95th percentile)	Static simulation • Pressure distribution	Comparison with experimental results • High consistency
[49]	CASIMIR (Male 95th percentile)	Static simulation • Pressure distribution, maximum pressure, average pressure • Variables: leg angle, heel position, seat height, cushion angle, backrest angle, arm position.	Comparison with experimental values in previous studies • Consistent with the experimental trend
[50]	CASIMIR (Male 50th percentile)	Static simulation • Pressure distribution, cushion/backrest load, pressure gradient. • Variables: heel position, foot angle, arm position, torso angle, thigh angle, seat height.	Comparison with the test and check with previous experiments • Not perfectly correlated due to difficulty in finding a real person who exactly matches the manikin (in height, weight, body size) and limitations of the Body Pressure Distribution plate
[51]	CASIMIR (NAM95—North American Male 95th percentile)	Static simulation • Pressure distribution • Contact area	The simulation results are indirectly compared with previous experimental studies.
[52]	CASIMIR (F05—Female 5th percentile, Male M50—50th percentile, M95—Male 95th percentile)	Static simulation • Pressure distribution Dynamic simulation • Seat transfer function • Variables: excitation frequency (1–20 Hz), amplitude (1–4 mm)	Comparison with experimental results • The curve-progressions of simulation and experiment are very well correlated
[54]	Zygote Human Factors	Static simulation • Pressure distribution • Shear stress at the tissue-stroma interface. • Von Mises stress at the surface and inside of the thigh-gluteal tissue.	Comparison with experimental results • Compare contact pressure (175.8 kPa) and shear stress (5.7 kPa) with previous study (187.7 kPa, 2 kPa). • Compare von Mises stress (36.44 kPa) with other 2D (180 kPa) and 3D (40–50 kPa) models.
[55]	Zygote Human Factors	Static simulation • Pressure distribution • von Mises stress at the thigh-buttock tissue interface	Comparison with previous research papers
[56]	Self-built	Static simulation • Pressure distribution • Stress in thigh-buttock • Temperature distribution at the tissue-cushion interface	Comparison with experimental results • Contact pressure: Simulation 36 kPa, experiment 34.45 kPa, error ~4.3%.

Table A1. *Cont.*

Ref.	Model Acquirement Method	Simulation Method and Analyzed Aspects	Confirm Results
[57]	Self-built	Static simulation • Pressure distribution • Contact force variance. • Contact area.	Comparison with previous research papers
[58]	Self-built	Static simulation • Pressure distribution Peak pressure	Comparison with experimental results • Peak pressure difference ~3.5 kPa (20%) when gas spring pressure increases from 0 to 25 kPa.
[59]	Self-built	Static simulation • Pressure distribution • Dynamic simulation vertical excitation or road profile excitation	Comparison with experimental results • Low error; matching accuracy of 97.45% and 81.85–89.94% in other results
[60]	Virtual Human Driver	Static simulation • Pressure distribution • Dynamic simulation • Dynamic excitation based on test track data.	Compare Modelica simulation results with finite element models (FEM) through: • Indentation Load Deflection (ILD) to evaluate PU foam stiffness. • The H-point displacement error between Modelica and FEM is 6% (65.3 mm vs. 61.4 mm).
[61]	Self-built	Static simulation • Pressure distribution • Peak pressure.	Paired T-test showed no significant difference between CAD and Tekscan (p-value = 0.958 > 0.05), correlation 98%
[63]	Self-built	Static simulation • Pressure distribution • Peak equivalent stress	Consistent with physical measured diagram from previous studies
[64]	Self-built	Static simulation • Pressure distribution • Peak pressure Contact area	Comparison with experimental results using the Pedar-X pressure measurement system High consistency

Appendix B

Table A2. Research information of the 3D printing papers.

Ref.	Lattice Structure	Application Product	Design Method	FEM Combination
[21]	TPMS (Gyroid)	Aircraft seat	Customized structure	–
[22]	Auxetic	Sports shoe Midsoles	Design and comparison of various structures	Static Analysis without Human body models
[23]	Random Porous Structures	Motorcycle seats	Design and comparison of various structures	–
[63]	TPMS (Gyroid and Schwarz)	Shoes and insoles	Customized structure	Static Analysis with foot models

Table A2. *Cont.*

Ref.	Lattice Structure	Application Product	Design Method	FEM Combination
[64]	Auxetic	Shoe midsole	Design and comparison of various structures	Static Analysis with soft tissues and bones of the foot
[65]	Auxetic	Shoe sole	Design and comparison of various structures	–
[67]	TPMS (Schwarz)	Wheelchair cushion	Customized structure	–
[68]	Honeycomb	Seat cushion	Optimize for vibration isolation efficiency	–
[69]	Lattice, wavy, hexagonal, and shifted	Tissue-engineered scaffolds	Design and comparison of various structures	Static Analysis without Human body models

Appendix C

Table A3. Quality assessments of selected papers.

Ref.	HBM Used	Human–Seat Interaction	FEM Simulation Details	Pressure/Force Analysis	Comfort Assessment	Comparison with Experiments/Literature	3D-Printed Structure	3D Printing and FEM Integration	Effectiveness of Printed Foam	Scope, Coverage and Depth	Quality Level
[18]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[20]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[21]	N	P	N	P	Y	P	Y	N	Y	P	L
[22]	N	N	P	Y	Y	Y	Y	P	Y	Y	M
[23]	N	N	N	Y	Y	Y	Y	N	Y	P	L
[30]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[31]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[32]	P	Y	Y	Y	Y	P	N	N	N	Y	M
[33]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[34]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[35]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[36]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[37]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[38]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[39]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[40]	Y	Y	Y	P	Y	P	N	N	N	P	L
[41]	Y	Y	Y	Y	Y	P	N	N	N	Y	M
[42]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[43]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[44]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[45]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[46]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[47]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[48]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[49]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[50]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[51]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M

Table A3. *Cont.*

Ref.	HBM Used	Human–Seat Interaction	FEM Simulation Details	Pressure/Force Analysis	Comfort Assessment	Comparison with Experiments/Literature	3D-Printed Structure	3D Printing and FEM Integration	Effectiveness of Printed Foam	Scope, Coverage and Depth	Quality Level
[52]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[54]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[55]	Y	Y	Y	Y	Y	P	N	N	N	Y	M
[56]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[57]	P	Y	Y	Y	Y	P	N	N	N	Y	M
[58]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[59]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[60]	Y	Y	Y	Y	Y	Y	N	N	N	Y	M
[61]	P	Y	Y	Y	Y	Y	N	N	N	Y	M
[63]	P	N	Y	Y	Y	Y	Y	Y	Y	Y	H
[64]	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	H
[65]	N	N	N	Y	Y	Y	Y	N	Y	Y	M
[67]	N	Y	N	Y	Y	Y	Y	N	Y	Y	M
[68]	N	Y	N	Y	Y	Y	Y	N	Y	Y	M
[69]	N	N	P	P	N	Y	Y	Y	Y	P	L

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