# Digital human models in automotive engineering applications: a bibliometric analysis of research progress and prospects

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**Abstract:** Digital human models (DHMs) with high levels of customisation and realism have been widely employed in automotive engineering. Despite studies investigating the use of DHMs in specific domains, there is a lack of comprehensive analyses that evaluate the research trends of the field as a whole. This review proposes and employs a comprehensive, reproducible, and systematic bibliometric analysis approach, inspired by the PRISMA guidelines, to summarise the current state and challenges of DHMs in automotive engineering and to outline future directions. First, this review presents the general bibliometric distributions of publication and citation growth, research areas, keyword distribution, and thematic evolution. Furthermore, it offers an all-inclusive review of the development, validation, and application of DHMs in various fields of automotive engineering, including ergonomic design and safety evaluation. Finally, the prospects and challenges of DHMs are discussed to provide a novel perspective to promote the advancement of this field.

**Keywords:** DHMs; digital human models; automotive engineering; vehicle ergonomics; crash safety; bibliometric analysis.

**Reference** to this paper should be made as follows: Li, J., Li, P. and Hu, J. (xxxx) 'Digital human models in automotive engineering applications: a bibliometric analysis of research progress and prospects', *Int. J. Vehicle Design*, Vol. x, No. x, pp.xxx–xxx.

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Peijing Li is a fourth-year undergraduate student majoring in Computer Science with a minor in Civil Engineering at the College of Engineering of the University of Michigan in Ann Arbor, Michigan. He also served as a research assistant at the University of Michigan Transportation Research Institute in 2022. His research focus includes software simulation of platoons of connected and automated vehicles (CAV), as well as parametric digital human modelling and driver state modelling in the context of safety evaluation of CAVs.

Jingwen Hu, PhD, is the Associate Director of the University of Michigan Transportation Research Institute (UMTRI) and a Research Professor at the Institute's Biosciences Group. His research interests primarily focus on impact/injury biomechanics in motor-vehicle crashes by a multidisciplinary approach using a combination of experimental, computational, and epidemiological procedures.

## 1 Introduction

The investigation into digital human models (DHMs) began in the 1960s with the discovery and examination of their advanced visualisation and simulation properties. Since then, DHMs have gained significant importance across various fields, including social psychology, automotive safety, manufacturing industries, and ergonomics (Yin and Li, 2023, Wang et al., 2021, Thaneswer et al., 2013). In recent years, the application of DHMs in the automotive engineering field has gained considerable attention, particularly in vehicle crash safety and the cognitive domain (Debernard et al., 2016). DHMs are generally 2D or 3D digital manikins created by leveraging targeted populations' anthropometric, biomechanical, or physiological databases. These tools have been extensively utilised in numerical simulations, accident reconstructions, and evaluating ergonomic designs for vehicle interiors (Högberg et al., 2018, Parida et al., 2019, Stefania et al., 2016, Wirsching and Wagner, 2020). These methods are especially useful in cases where it is not feasible or ethical to conduct extensive testing with human subjects of a given population.

The demand for ergonomically sound products and systems has led to an increase in the need for DHMs. Over the last few decades, extensive research has explored the application of DHMs in automotive design and engineering. Previous studies have reported using DHMs in seat design (Gragg and Yang, 2011, Kim et al., 2010, Peng et al., 2017), the driver reaches, and ingress/egress assessment for vehicle crash safety (Causse et al., 2012, Chateauroux and Wang, 2010, Robert et al., 2014), human anthropometry (Fragos, 2020, Dong et al., 2010, Ma et al., 2011), injury biomechanics (Duprey et al., 2010, Wang et al., 2020, Golman et al., 2016, Liu et al., 2015), thermal comfort (Karthick et al., 2022, Ji et al., 2014), and mental health (Tao et al., 2016). Several commercially available software packages that import design environments, such as Transom Jack (Tao et al., 2016, Chaffin, 2007), SAMMIE (Summerskill et al., 2016, Chaffin, 2007), Human in CATIA (Li, 2014, Mohamad et al., 2013, Hong et al., 2014), SolidWorks (Zhang et al., 2015), RAMSIS (Peng et al., 2017, Hong et al., 2014, Chateauroux and Wang, 2010, Chaffin, 2007), and SANTOS (Santos et al., 2012, Yang et al., 2007), have been identified. These tools can visualise three-dimensional anthropometric data changes, better understanding human body shape and size variability. Research groups have developed different types of human body models (HBMs), including the Total Human Model for Safety (THUMS) (Lalwala et al., 2020, Li et al., 2013a) and the Global Human Body Models Consortium (GHBMC) (Mattos et al., 2015, Zheng et al., 2018, Meng et al., 2017). For example, HBMs are useful in impact biomechanics and accident analysis for vehicle safety assessment, accident reconstruction, safety gear designs, and more. Compared to experiments with live or postmortem human subjects, DHMs reduce the cost and time required for reworking and retrofitting physical Anthropomorphic Test Devices to specific populations while providing quantitative insights into the biomechanical and physiological responses of the human body under impact loading (Savin et al., 2016).

Recent advancements in DHMs and their growing use in automotive engineering have prompted a need for a comprehensive bibliometric analysis of the field. Although several narrative reviews (Yin and Li, 2023, Wang et al., 2021, Thaneswer et al., 2013, Wolf et al., 2020) have summarised the applications of DHMs, they tend to focus on specific models or applications, thus lacking a systematic overview of the field. Unlike a traditional review, bibliometric analysis has emerged as an effective tool for statistically analysing literature, allowing researchers to identify relevant characteristics and future trends (Chen et al., 2022, Pessin et al., 2022). This study used a bibliometric approach to conduct a detailed analysis of DHM-based automotive engineering research trends. Furthermore, given recent technological advancements in connected and automated vehicles, artificial intelligence, and virtual/mixed reality, we believe a standardised review protocol is urgently needed to uncover and summarise research trends from bibliometric statistics in DHMs and similar fields of automotive engineering.

Given the knowledge gap and the pressing need for state-of-the-art analysis, we have employed a bibliometric approach to synthesise the literature on DHMs, with a methodology that draws heavy inspiration from the PRISMA standard employed in the fields of medical research and meta-analysis – though it should be made clear that this review does not attempt to copy-and-paste the PRISMA reporting guidelines. However, we are impressed by PRISMA’s commitment to the following goals (Arya et al., 2021):

- improve the “quality of reporting and methodology for systematic reviews and meta-analyses”
- availability of “transparent, complete and reproducible methodology”
- quality demonstration of review to journals and readers.

We shall discuss how the PRISMA checklist can be adapted to a systematic review of the DHM application in the following “Methodology” section.

In the meantime, we also became aware of the tool of bibliometric mapping and its effectiveness for revealing trends, patterns, and relationships in research and visualising systematic literature reviews. In this review, we commence with a bibliometric analysis of the literature to provide an overview of the quantitative trends in the field. Using a cooccurrence network of keywords and research fields, we aim to extract meaningful insights by assessing the strength of the links between the nodes in the network. Subsequently, we present a detailed description and discussion of the identified hotspots, namely anthropometric, biomechanical, and physiological medical models, representing the main types of DHMs in the automotive engineering field. We provide representative examples of these hotspots to support our arguments. Lastly, we propose existing challenges and future perspectives of DHM research. Our review aims to provide an objective and comprehensive overview of DHMs in the automotive engineering field and, as such, is expected to serve as a reference and inspire novel ideas for future studies in this important field.

To our knowledge, a bibliometric analysis of the state of research on DHMs for automotive engineering applications has not been previously reported. A comprehensive understanding of the main application domains, the usage of theories, and the gaps between them are essential for identifying the areas of DHMs with sufficient evidence to justify implementation on a larger scale and the areas requiring further research. To address these research gaps, we have formulated the following questions:

**RQ1:** What are the advancements, categorisations, distribution, and evolution of the topics in peer-reviewed research papers or conferences on DHMs in automotive engineering in the recent two decades, according to our established criteria for inclusion?

**RQ2:** How was the research topic concerning DHMs in automotive engineering classification, validation, and application?

**RQ3:** What are the lacunae in knowledge, obstacles, and potential future avenues in the extant literature for researchers to explore further regarding the utilisation of DHMs in automotive engineering?

Answering these questions will enable researchers to identify evolving patterns, focal points, and potential priority directions in the domain of DHMs within automotive engineering studies. This process will, in turn, empower engineers to make well-informed choices concerning the development and design of DHMs, emphasising enhancing safety, ergonomics, and behavioural modifications.

## 2 Methods

### *2.1 Methodology declaration*

To attain the goals originally proposed by the PRISMA guidelines, our methodology heavily emphasises our systematic review process’s transparency, completeness, and reproducibility; we decided to adopt a subset of the 27-item PRISMA checklist

(Arya et al., 2021) to guide our literature review process of DHMs. The checklist items we omitted are more closely related to conventions in clinical studies and meta-analyses, particularly that there should be an established hypothesis about a clinical occurrence before proceeding with a meta-analysis study.

Meanwhile, the primary items in the PRISMA checklist that we decided were suitable to guide this study are mainly concerned with our methodology. Most notably, we are to specify our literature sources' eligibility criteria, information sources, and full search strategies. In terms of included studies, we are to provide information on the search and selection process, individual study characteristics, and the results of individual studies.

### *2.2 Methodology definition*

This review gathered all DHM-related data in automotive engineering using the advanced search capabilities of the Web of Science Core Collection (WoSCC), covering the period from 1 January, 2003, to 31 December, 2022, and confined to English language publications. The WoSCC, renowned for providing standardised and high-quality academic publication information, is extensively employed in the bibliometric analysis of the evolution of scientific topics. The data analysis was conducted using the Web of Science local function and the R-bibliometrix tool, a sophisticated bibliometric analysis instrument developed by K-Synth Srl, an academic spin-off from the University of Naples Federico II. The search queries were constructed as follows: "(Digital human model OR human numerical model OR DHM*) AND (vehicle OR automatic* OR virtual ergonomics OR vehicle collisions OR vehicle crash OR traffic accident OR car*)". We hope that by providing this detailed information, readers of this report can reproduce our search process.

Moreover, reference lists of retrieved studies were scrutinised, and expert opinions were sought to identify any further relevant publications or conferences not listed on WoSCC, including the International Research Council on the Biomechanics of Injury (IRCOBI). Duplicate and non-English language sources were omitted from the search outcomes.

The titles and abstracts of the remaining publications were screened based on the following criteria:

1 the publication must be a research paper that has been published in a peer-reviewed academic journal or conference

2 the publication must be final and either published or in press

3 the publication must involve the development or application of DHMs in the context of automobiles, with only papers satisfying this criterion being retained based on their titles, abstracts, and keywords

4 the publication (along with the institutions of its authors) can originate from any country or region.

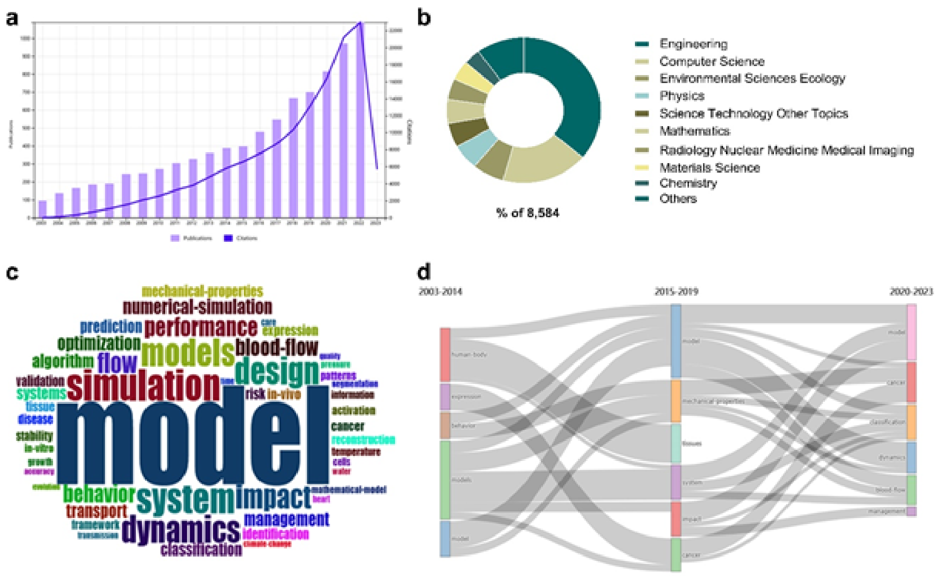
Two authors independently screened the queried publications according to these criteria, and any discrepancies regarding whether to include a publication were resolved through consensus or by a third reviewer. Full publications were obtained for all eligible publications, and those without full-text accessibility were excluded. Research ethics approval and informed consent were not required, as all data involving human subjects were obtained from electronic databases and search engines of research projects independently verified by research ethics boards.

## 3 Results and discussion

### *3.1 Bibliometric analysis*

In a comprehensive assessment of 8584 publications, including 6248 papers and 2133 conference abstracts, the research contributions of over 7000 institutions across 128 countries or regions were analysed, focusing on the application of DHMs in automotive engineering (`ure 1(a)). The observed data showed a significant increase in published papers; however, while the publication rate continued to rise in recent years, the growth rate was more modest. Concurrently, the number of citations experienced annual growth, reflecting a heightened interest in DHMs within the automotive engineering domain. The top ten research area classifications were identified, with "engineering", "computer science", "environmental sciences ecology", "Physics", and "science technology other topics" emerging as the most frequent (Figure 1(b)).

**Figure 1** Analysis of DHMs in automotive engineering applications based on: (a) publication and citation growth; (b) research areas; (c) keyword distribution and (d) thematic evolution (see online version for colours)




To thoroughly investigate the advancements of DHMs in automotive engineering, R-bibliometrix was utilised to perform a keyword cooccurrence analysis. The resulting keyword cooccurrence network aided in pinpointing the principal research hotspots in this field. Figure 1(c) and (d) depict the aggregated prevalence of various keywords and research hotspots across all publications included in this review study. Figure 1(c) presents the most frequently employed keywords in the assessed studies, such as "model", "simulation", "design", "systems", and "impact". This analysis examined the temporal shifts in keyword usage to glean insights into the progress and trajectories within the automotive engineering landscape. Specifically, we evaluated the evolution of keyword trends based on DHMs and discerned the field's thematic organisation and transformation through a keyword cooccurrence examination. Visualising connections between distinct keywords across publications uncovered six clusters of keywords that typically converge during different periods: Figure 1(d) underscores various thematic evolutions, including "model", "cancer", "classification", "dynamic", "blood flow", and "management". Subsequently, we demarcate the review period into three distinct stages: "initial development", "aggressive expansion", and "stable development".

In the preliminary developmental phase, scholarly attention was predominantly devoted to employing DHMs for addressing ergonomic-oriented design challenges within automotive contexts, specifically for distinct population groups. Subsequently, during the vigorous expansion stage, investigators pursued innovative methodologies for applying DHMs across various automotive engineering facets, encompassing vehicle safety. Lastly, in the stable development phase, the research focused on ergonomic design, accident simulation, risk evaluation, and biomechanics, emphasising traffic collision safety. The progression of DHMs has transcended from illustrating rudimentary human geometry and anthropometry in the early 2000s to sophisticated finite-element biomechanical and physiological models. This advancement empowers researchers to examine vehicle safety and traffic incidents more effectively. Prospective DHM investigations indicate three substantial enhancements: size diversification to represent a more comprehensive population segment, dynamic motion simulation, and quantitative assessment of human-vehicle interaction. Anticipated advancements are poised to yield practical applications within vehicle safety and ergonomic design, catering to a heterogeneous population, encompassing individuals from diverse racial and ethnic origins, the elderly, those with disabilities, expectant women, and children. Consequently, DHMs are on the verge of establishing themselves as a potent design methodology for guaranteeing equitable access to safety and accessibility features in vehicular contexts.

### *3.2 Classifications of DHMs in automotive engineering*

Following a thorough bibliometric analysis, significant progress in research on the automotive industry has been observed, particularly in using DHMs. This research primarily centres on three distinct DHM categories: anthropometric, biomechanical, and physiological medical models. Both anthropometric and biomechanical DHMs assess ergonomic factors, encompassing spatial necessities, reach analysis, and manual handling tasks. Prevalent DHMs include Siemens Jack, RAMSIS, OpenSim, and the AnyBody Modelling System. Regarding study design, most research concentrates on the general adult population, with some studies delving into specific subgroups. Among an estimated 150 digital mannequin systems, Table 1 demonstrates the representative references. Within this section, we provide insight into the attributes, functionalities, and computational frameworks of DHMs, in addition to the prevalence and qualities of various commercially available models. DHM research aims to establish a holistic DHM that accurately depicts human anatomy, physics, physiology, and biochemical properties.

**Table 1** Typical types of various DHMs for automotive engineering applications

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Ahmed et al. (2021) | Ergonomics | Surrogate Modelling | Not specified | Full-body | Compare performance measures between DHM simulations and surrogate model optimisation results | √ | | |
| Arun et al. (2016) | Model proposition and validation | FEA | 50%-tile male | Full-body | PMHS sledge experiment, correlational analysis | | √ | |
| Asgharpour et al. (2014) | Model validation | FEA | Not specified | Head and neck | Compare model simulation results with published experimental results | | √ | |
| Baker et al. (2018) | Model proposition and validation | FEA | 50%-tile male | Limbs (upper and lower limb) | Compare accident reconstruction results with actual reports | | √ | |
| Belwadi et al. (2019) | Model proposition | FEA | 18–48mo child | Full-body | Not reported | | √ | |
| Bourdet and Willinger (2006) | Model proposition and validation | FEA+MBS | Not specified | Head, neck, torso | Compare the mechanical behaviour of the model with that reported in the literature | | √ | |
| Carter et al. (2009) | Accident reconstruction | FEA+MBS | 15yo female | Full-body | Compare accident reconstruction results with actual reports | | √ | √ |
| Causse et al. (2012) | Ergonomics | DHM | Dist. of 5%-tile female to 95%-tile male | Full-body | Not reported | √ | | |
| Chaffin (2005) | Meta-methodology | DHM | Not reported | Not reported | Not reported | √ | | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Chaffin (2007) | Meta-methodology | Motion Sim | Not specified | Full-body | Not reported | √ | | |
| Xianghai et al. (2011) | Model proposition and validation, accident reconstruction | FEA | Not specified | Head | Compare accident reconstruction results with actual crash data | | √ | √ |
| Chang and Wang (2007) | Ergonomics | Motion Sim | Not specified | Full-body | Dynamic simulation and ergonomics evaluation | √ | √ | |
| Chateauroux et al. (2010) | Ergonomics | DHM | Younger (20–35yo) and older(63–92yo) drivers | Legs, hands | Not reported | √ | | |
| Choi (2015) | Model proposition and validation | FEA | Elderly Korean driver | Chest | Sledge impact test with Hybrid-III dummy | | √ | √ |
| Cloutier et al. (2015) | Ergonomics | MBS | 50%-tile US female | Shoulder, elbow joint, hip, knee, and ankle joint | Not reported | √ | | |
| Costa et al. (2020) | Accident reconstruction | FEA | 46yo male pedestrian | Leg, hip | Compare simulation results with other published simulation data | | √ | √ |
| Danelson and Stitzel (2015) | Accident reconstruction | FEA | 50%-tile male | Lungs | Compare accident reconstruction results with published PMHS test results | | √ | √ |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Dawson et al. (2020) | Accident reconstruction | FEA | 11 Children, 10 Adolescents, 11 Adults | Head | Compare MADYMO simulation with Hybrid III dummy impact experiments | | √ | |
| Decker et al. (2019) | Model validation | FEA | 50%-tile male, 6yo, 5%-tile female, 95%-tile male | Head, 12th thoracic vertebrae, and aceta-bulum | Compare model simulation results with published baseline values | | √ | |
| Du et al. (2016) | Model proposition and validation | FEA | 50%-tile Chinese male | Liver, simplified thoracoabdominal organ, and human skeleton | PMHS test | | √ | √ |
| Fahlstedt et al. (2015) | Accident reconstruction | FEA | Three (2m1f) injured bicyclists | Head and neck | Overlap and relative location of reconstruction compared with actual medical imaging | | √ | √ |
| Faraway and Reed (2007) | Ergonomics, model proposition | MBS | Truck driver | Head, hand, and torso | Not reported | √ | | |
| Fernandes et al. (2018) | Model proposition and validation | FEA | 460 CT scans and 182 MRI scans of adults | Head and neck | Compare model simulation results with cadaver test results | √ | √ | √ |
| Fritzsche (2010) | Ergonomics | DHM | 20 car assembly tasks by 50%-tile male workers | Full-body | Compare DHM simulation results with real-life ergonomics data | √ | | |
| Gaewsky et al. (2015) | Accident reconstruction | FEA | Drivers | Full-body | Compare model simulation results with published baseline values | | √ | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Gilad and Byran (2015) | Ergonomics | DHM | Three tractor operators | Full-body | Not reported | √ | | |
| Golman et al. (2014) | Accident reconstruction | FEA | 50th-percentile male | Full-body | Compare model simulation results with published baseline values | | √ | √ |
| Golman et al. (2015) | Model validation | FEA | 50th-percentile male | Chest | Compare model simulation results with published PMHS test results | | √ | √ |
| Golman et al. (2016) | Model proposition and validation, accident reconstruction | FEA | 50th-percentile male | Full-body | Compare accident reconstruction results with actual crash data | | √ | |
| Gragg and Yang (2011) | Ergonomics | DHM | Non-obese and obese adults | Full-body | Not reported | √ | | |
| Gragg and Yang (2011) | Ergonomics | DHM | 95%-tile male and 5%-tile female | Full-body | Not reported | √ | | |
| Gragg et al. (2012) | Ergonomics | DHM | 95%-tile male and 5%-tile female | Full-body | Compare model simulation results with published seat adjustment ranges | √ | | |
| Gu (2012) | Model proposition, accident reconstruction | MBS | Driver | Full-body | Not Reported | | √ | |
| Lei et al. (2008) | Accident reconstruction | MBS | Motorcyclists | Full-body | Compare reconstructed and actual accidents | | √ | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Han et al. (2011) | Accident reconstruction | FEA | Pedestrians | Full-body | Compare model simulation results with cadaver test results | | √ | √ |
| Hanson et al. (2006) | Meta-methodology | Participatory ergonomics | University and industry users, manager | Not reported | Ratings of the system prototype's usability evaluation | | | |
| Hanson et al. (2012) | Meta-methodology | DHM | Assembly personnel | Full-body | Comparison with other DHMs on the market | √ | | |
| Högberg (2009) | Ergonomics | DHM | Families of adult manikins | Full-body | Not reported | √ | | |
| Hong et al. (2014) | Model proposition and validation | DHM | 5%, 50%, 95%-tile Korean male adults | Full-body | Compare model anthropometry with published datasets and that of other DHMs | √ | | |
| Hsiao et al. (2005) | Ergonomics | DHM | 88m and 12f agriculture workers | Full-body | Compare model anthropometry with published datasets | √ | | |
| Hu et al. (2012) | Model proposition and validation | FEA+MBS | Young school-aged children | Full-body | Compare model simulation with Hybrid-III dummy impact experiments | | √ | |
| Hu et al. (2019) | Accident reconstruction | FEA | Older, obese, and/or female occupants | Full-body | Not reported (validated in previous publication of same authors) | √ | √ | √ |
| Huang et al. (2018) | Model proposition and validation | FEA | 50th percentile male pedestrian | Lower Extremity | Compare model simulation results with cadaver test results | | √ | √ |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Hwang et al. (2020) | Model proposition and validation | FEA | Post-mortem human subjects | Full-body | PMHS test | | √ | |
| Ji et al. (2014) | Model proposition and application | FEA | Driver and passenger | Full-body | Compare model simulation results with experimental results | | √ | |
| John et al. (2022) | Model proposition and validation | FEA | Average female and male | Full-body | Compare model simulation with blunt impact experiments | | √ | |
| Jones et al. (2018) | Model proposition and validation | MBS | Children aged 12–58 months | Full-body | Compare physical measurement and predicted body shape from model | √ | | |
| Jung et al. (2009a) | Model proposition, ergonomics | Generation method | US Army anthropometry | Full-body | Compare physical measurement and predicted body shape from model | √ | | |
| Jung et al. (2009b) | Model proposition | Integrated Framework | Korean skeletons | Full-body | Not reported | | √ | |
| Karthick et al. (2022) | Ergonomics | DHM | Not reported | Full-body | Not reported | | | √ |
| Kerrigan et al. (2009) | Accident reconstruction | FEA+MBS | 50th-percentile male | Lower limbs | Compare model simulation with PMHS test results | | √ | |
| Kim et al. (2010) | Model proposition and validation | FEA | SizeUSA anthropometric database | Full-body | Compare model simulation results with experimental results | | √ | |
| Kim et al. (2020) | Model proposition and validation | FEA | 50th-percentile male | Full-body | Calculating Modal Assurance Criterion between simulated and measured data | | √ | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Klein et al. (2017) | Model validation | FEA | Adults of ages 17–89yrs and BMI 15–48 kg/$m^2$ | Femur | Compare model simulation with PMHS test results | | √ | |
| Kleinbach and Fehr (2017) | Model validation | FEA+MBS | Not reported | Shoulder, thorax, abdomen and pelvis | Compare simulation results of different models | | √ | |
| Kuo and Chu (2005) | Dev environment proposition | DHM | Not reported | Not reported | Not reported | √ | | |
| Kyung and Nussbaum (2009) | Ergonomics | Not reported | 38 volunteer drivers | Full-body | Subjective ratings | √ | √ | |
| Kyung et al. (2010) | Ergonomics | Not reported | 38 volunteer drivers | Full-body | Not reported | √ | √ | |
| Lalwala et al. (2020) | Accident reconstruction | FEA | Pedestrians | Lower extremity | Compare accident reconstruction results with actual crash data | | √ | √ |
| Lämkull et al. (2009) | Ergonomics | DHM | Assembly personnel | Full-body | Compare model simulation results with observed behaviour | √ | | |
| Larsson et al. (2022) | Model morphing and validation | FEA | 22 Post Mortem Human Subjects | Full-body | Compare model simulation with PMHS test results | √ | √ | |
| Leledakis et al. (2021) | Accident reconstruction | FEA | Midsize male car passenger | Lower and upper extremities, torso, and head | Not reported | | √ | |
| Li and Yang (2010) | Accident reconstruction | MBS | Pedestrian | Head–brain | Compare model output with observation | | √ | √ |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Li et al. (2011) | Model proposition and validation | FEA | 11 CT scans of 3-month children | Head | Compare model simulation results with cadaver test results | | √ | √ |
| Li et al. (2013a) | Accident reconstruction | FEA | Pedestrian | Upper Limb | PMHS test | | √ | √ |
| Li et al. (2013b) | Accident reconstruction | FEA | Adult female pedestrian | Lower limb | PMHS test | | √ | √ |
| Liu et al. (2015) | Accident reconstruction | FEA | Pedestrians | Thorax | Not reported | | √ | √ |
| Ma et al. (2011) | Ergonomics | MBS | Korean adults | Full-body | Not reported | √ | | |
| Ma et al. (2020) | Model proposition and validation, accident reconstruction | FEA | 50th-percentile Chinese male | Lower limb | Compare simulation results between isolated lower limb model and full-body model | | √ | |
| Maheshwari et al. (2020) | Accident reconstruction | FEA | 6yo and 10yo vehicle occupant | Head and thorax | Not reported | | √ | |
| Marshall et al. (2013) | Ergonomics | MBS | Dutch male driver | Not reported | Compare model simulation results with experimental results | | | √ |
| Mavrikios et al. (2006) | Ergonomics | DHM | 23 adults | Full-body | Compare model simulated motion with real motion | √ | √ | |
| Meng et al. (2017) | Model proposition and validation | FEA | Six-year child | Full-body | Compare model simulation with PMHS test results | | √ | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Milanowicz and Kędzior (2016) | Model proposition | MBS | 50th percentile male | Upper extremity | Not reported | | √ | √ |
| Mizuno et al. (2005) | Model proposition and validation | FEA | Three-Year Child | Full-body | Compare model simulation with Hybrid-III dummy impact experiments | | √ | |
| Mo et al. (2014) | Accident reconstruction | FEA | Adult pedestrian | Lower Limb | Compare model-simulated injury thresholds with those from isolated lower limb tests | | √ | √ |
| Newell et al. (2016) | Model proposition and validation, accident reconstruction | FEA | Military vehicle occupant | Lower limb | Compare model simulation results with experimental results | | √ | |
| Ozsoy et al. (2015) | Ergonomics | MBS | Normally distributed adult driver population | Upper and lower limbs, torso | Comparing with available literature results by simulation | | √ | |
| Park et al. (2017) | Model proposition and validation | FEA | Children age 3–11 | Full-body | Compare simulated anthropometry to that of the reference ATD | √ | | |
| Park et al. (2019) | Model proposition and validation | MBS | Korean drivers | Hip location, eye location, and joint angles | Leave-one-out cross-validation of anthropometric measurements | √ | | |
| Peng et al. (2017) | Ergonomics | DHM | Chinese and French drivers | Full-body | Compare anthropometric measurements of different ethnic backgrounds | √ | | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Pradhan and Samantaray (2018) | Model proposition and validation | MBS | Not reported | Full-body | Compare model simulation data with published ISO thresholds | | √ | |
| Pramudita et al. (2014) | Model proposition and validation | MBS | 50th percentile Japanese male | Full-body | Rear impact test from volunteers | √ | √ | |
| Putnam et al. (2014) | Model proposition and validation | FEA | Not reported | Thorax (chest and neck) | Calibrate upper body model with results from frontal crash tests | | √ | |
| Reed et al. (2019) | Ergonomics | 3D body scan | Male and female vehicle occupants | Full-body | Not reported | √ | √ | √ |
| Rim et al. (2008) | Ergonomics, meta-methodology | MBS | Workflow for ergonomic and biomechanical analysis using DHMs | Upper body | Not reported | √ | √ | |
| Robert et al. (2014) | Ergonomics | MBS | Driver | Full-body | Not reported | √ | | |
| Roth et al. (2010) | Model proposition and validation | FEA | 0–6mo newborns | Head and neck | Compare model simulation results with experimental results | √ | √ | |
| Roth et al. (2013) | Model proposition and validation | FEA | 50th-percentile male | Thorax, Abdomen, Pelvis | Compare model simulation results with experimental results | | √ | |
| Rugh et al. (2004) | Model proposition | FEA | Not reported | Torso together with neck and head | Not reported | | | √ |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Sahoo et al. (2013) | Accident reconstruction | FEA | 15 car-pedestrian accidents | Head | Not reported | | √ | √ |
| Santos et al. (2012) | Ergonomics | 3D body scan | Public transit users | Full-body | Not reported | √ | | |
| Shimamoto et al. (2015) | Ergonomics, electromagnetics | FEA | Adult male | Full-body | Comparing simulated and measured magnetic field distributions | | √ | |
| Song et al. (2014) | Ergonomics | Not reported | Not reported | Full-body | Not reported | | | |
| Spada et al. (2012) | Ergonomics | Not reported | Not reported | Not reported | Not reported | | | |
| Summerskill et al. (2015) | Ergonomics | DHM | Driver of large goods vehicles | Full-body | Compare model simulation results with experimental results | √ | | |
| Tang et al. (2020) | Accident reconstruction | FEA | Adult males with BMIs of 25,30,35,40 $kg/m^2$ | Full-body | Not reported | | √ | √ |
| Tao et al. (2016) | Model proposition and validation | MBS | Not reported | Full-body | Compare model simulation results with experimental results | √ | | |
| Taskin et al. (2019)) | Model validation | Lumped-parameter human body biodynamic models | Adult passengers | Head, upper torso and lower torso | Compare model simulation results with experimental results | | | √ |
| Untaroiu et al. (2013) | Model proposition and validation | FEA | 50-percentile male | Lower limbs | PMHS test | | √ | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Untaroiu et al. (2017) | Model proposition and validation | FEA | Adult male | Lower extremity | PMHS test | | √ | |
| Wang and Trasbot (2011) | Ergonomics | MBS | Adults of different statures | Full-body | Not reported | | √ | |
| Wang et al. (2014) | Accident reconstruction | FEA + MBS | Two car-pedestrian crashes | Lower extremity | Compare accident reconstruction results with actual crash data | | √ | |
| Wang et al. (2020) | Accident reconstruction | FEA + MBS | 56yo male pedestrian | Head | Compare accident reconstruction results with actual crash data | | √ | √ |
| Wang et al. (2022b) | Model proposition and validation | FEA + MBS | Two-wheeled vehicle operator and passenger car occupants | Full-body | Compare model simulation with published PMHS test results | | √ | |
| Wang et al. (2022a) | Model comparison and validation | MBS | European and Chinese pedestrians | Full-body | Compare accident reconstruction results from different models | √ | √ | |
| Xiao et al. (2018) | Accident reconstruction | FEA | Motorcyclists | Head | Compare MADYMO simulation with PC-Crash simulation as benchmark | | √ | |
| Xu et al. (2016) | Accident reconstruction | MBS | 50-percentile male | Full-body | Not reported | | √ | √ |
| Yang et al. (2007) | Model proposition | MBS | Caterpillar cab operator | Full-body | Not reported | √ | | |

**Table 1** Typical types of various DHMs for automotive engineering applications (continued)

| *References* | *Methodology* | *Model construction* | *Subjects* | *Body parts* | *Validation* | *Anthropometry* | *Biomechanics* | *Physiological medical* |
|---|---|---|---|---|---|---|---|---|
| Yao et al. (2011) | Model proposition | FEA | Pedestrian | Head, neck, thorax, pelvic, thighs, legs, feet and shoes | Compare model simulation results with experimental results | | √ | |
| Yu et al. (2020) | Model proposition and validation | FEA + MBS | Male pedestrians | Head, neck | Compare model simulation with published cadaver test results | | √ | √ |
| Zhang et al. (2017) | Model proposition | FEA | Mid-size male model morphed into diverse anthropometries | Full-body | Apply pendulum chest impact condition and compare responses between morphed models and traditionally scaled models | √ | √ | |
| Zhang et al. (2017b) | Model proposition and validation | FEA | Not reported | Full-body | Compare model simulation with PMHS test results | | √ | |
| Zheng et al. (2018) | Model proposition and validation | FEA | Not reported | Lumbar spine | Compare model simulation with published cadaver tests | | √ | |
| Zhu et al. (2016) | Model proposition and validation, accident reconstruction | FEA | 10yo Child | Full-body | Compare accident reconstruction results with actual crash data | | √ | √ |
| Zou et al. (2019) | Accident reconstruction | MBS | Scooter riders | Full-body | Compare accident reconstruction results with actual crash data | | √ | √ |

DHM: digital human model; FEM: finite element analysis; MBS: multi-body system; PMHS: post-mortem human subject.3.2.1. DHMs classified by human body properties.

### 3.2.1 DHMs classified by human body properties

Anthropometry, biomechanics, and human physiology are the three major modelling components reviewed in this paper. Anthropometry models utilise physical measurements like 3D scanning to study population morphological variations, including race, age, sex, and body type (Dong et al., 2010, Fragos, 2020, John et al., 2022). Biomechanical models, such as THUMS, simulate injury responses in vehicle collisions resulting from human biomechanics (Lalwala et al., 2020, Li et al., 2013a). Human physiological models (Rugh et al., 2004) aim to replicate and predict the physiological responses of vehicle occupants under various external stimuli, such as thermal comfort or field of view. It is important to note that a specific model may encompass more than one of these features.

The accurate representation of human body size and biomechanical parameters is essential for designing mannequins for various applications. Anthropometry provides critical information about human size and dimensions, but designing products based on individual sizes is not recommended due to significant variations between individuals (Hogberg, 2009). Instead, product design should consider the statistical characteristics of specific groups. Non-contact measurement technologies, like whole-body scanners, have improved the collection of body size data, which is crucial for designing products that can accommodate a target population's variability fatigue (Dong et al., 2010, Savin et al., 2016). Digital human models are often used in automotive crash simulation studies to simplify the description of human motion. Biomechanics models (Dawson et al., 2020, Zou et al., 2019, Carter and Neal-Sturgess, 2009), such as 3DSSPP, Ergowatch, and MADYMO, are developed for specific purposes. Positioning digital human limbs under known conditions is often necessary to improve digital human assembly operation simulation and human factor analysis. Standard manikin anthropometry inputs standardise measurements and reduce approximation in DHMs, facilitating the transition of user-defined standard manikins between software packages. To ensure accurate mannequin design, the DHM community requires a comprehensive global standard anthropometry database, or a more limited one, along with suitable methods for creating specific anthropometry using scaling algorithms. These methods should consider the geographical region, age, and special conditions such as pregnancy (Gragg et al., 2012, Ma et al., 2020).

### 3.2.2 DHMs classified by model construction heuristics

Meanwhile, we also classify different DHMs by how they are digitally constructed and computed, with two general types being finite element and multibody models. Finite element models involve constructing a mesh with finite elements to accurately represent the human body's geometries. Although more computationally expensive, these models can represent the accurate size and shape of specific body parts, such as the lower (Savin et al., 2016, Ma et al., 2020, Baker et al., 2018) and upper limbs (Mohamad et al., 2013, Li et al., 2013a) or the head and neck (Ruan et al., 2008, Mattos et al., 2015, Yu et al., 2020, Putnam et al., 2014, Fraga et al., 2009). Thus, FE models can be found in anthropometric and physiological studies where the accuracy of modelling the geometry and measurements of such body parts are essential. Conversely, multivariate models approximate entire body parts with rigid bodies represented by simple 3D geometry (e.g., spheres, planes, ellipsoids) and model the dynamic interactions between different body parts. These less geometrically accurate models are less computationally expensive and thus are often employed in larger parametric studies analysing the biomechanical response of the entire human body under specific load scenarios.

### *3.2.3 Adaptation of commercial DHMs*

In the realm of ergonomic design, DHMs have experienced a surge in prevalence, prompting many investigators to employ commercially obtainable solid-body DHM software as a substitute for developing their representations de novo. Prominent software utilised for DHM purposes includes Jack, RAMSIS, and Delmia (Ariffin et al., 2021, Summerskill et al., 2016). RAMSIS has been acclaimed as an efficacious instrument for conducting human factors engineering analyses and appraisals of automotive interiors, furnishing designers with intricate DHMs to simulate assorted operational behaviours of vehicle occupants (Chaffin, 2007). Similarly, via simulation, Jack and Delmia facilitate human factors engineering evaluations during vehicular design and manufacturing phases (Ariffin et al., 2021).

Although commercial DHM products have demonstrated their dependability and effectiveness, investigations incorporating these models require comprehensive data on their composition, appropriateness for the specific use case under examination, and validation methodologies. We believe that leaving out such vital information – even for tried-and-true DHM products – may compromise the quality and integrity of a DHM-related study and introduce unwanted bias.

## *3.3 Validation of DHMs in automotive engineering*

The validation procedure of DHMs designed for automotive engineering applications primarily involves juxtaposing a model's simulation outcomes with real-world data sources. As such, the kind of data sources that a validation study of DHMs draws upon is of paramount importance to the soundness of the validation attempt. However, there also have been alternative means of designing and validating DHMs based on or in conjunction with crash test dummies gaining traction over recent years (Baker et al., 2018, Choi, 2015, Hu et al., 2012, Yao et al., 2011).

It can be observed that a plurality of validation studies for DHMs involve collecting data from real-life test subjects or their analogues. Previous biomechanical tests employed volunteer, animal, and human cadaver tests to examine biomechanical responses (Savin et al., 2016, Fernandes et al., 2018, Han et al., 2012, Huang et al., 2018, Li et al., 2011, Yu et al., 2020, Zheng et al., 2018). While volunteer tests yield invaluable data on human body acceleration tolerance, they prove unsuitable for scrutinising biomechanics under high-speed and heavy-load conditions. Living animals have also been utilised in experiments; however, their morphological traits and body mass distribution diverge significantly from humans, curbing the applicability of the results. Fresh human cadavers serve as superior substitutes for biomechanical investigations, enabling researchers to examine the response of distinct body parts for models that focus on such parts instead of the entire body (e.g., abdomen) (Savin et al., 2016). Generally, studies that employ such forms of live experiments would attempt to repeat similar procedures on their DHM and directly compare the results from the experiment versus the simulation, providing the most direct approach to evaluating the performance of models under specific, predetermined scenarios. Nonetheless, cadaveric tests present substantial limitations, including experimental risks, physical disparities, and ethical concerns, underscoring the urgent necessity to devise a novel human surrogate for vehicular impact injury biomechanics research (Roth et al., 2010).

Ethical considerations and public sentiment have negatively impacted DHM validation tests involving live human subjects, while PMHS tests face obstacles due to sample scarcity and elevated costs. As a result, most DHM validation entails comparison with extant literature (Savin et al., 2016, Fernandes et al., 2018, Han et al., 2012, Huang et al., 2018, Li et al., 2011, Yu et al., 2020, Zheng et al., 2018). Researchers may also attempt to corroborate simulation results from their models with data published in other pieces of literature, including but not limited to validation datasets of similar models and real-world traffic crash results. Moreover, while most rigid-flexible coupling DHMs undergo validation through these methods, verifying the rigid-flexible coupling connection component is seldom addressed (Wang et al., 2021).

Crash test dummies, composed of diverse materials such as steel, aluminium, rubber, and polymers, are outfitted with numerous sensors and extensively employed to document responses. These devices, already verified by industrial and/or governmental regulatory bodies with extensive testing data, are becoming more common in validating DHMs when researchers lack the resources for real-life testing and are unsatisfied with rigid, published datasets (Baker et al., 2018, Choi, 2015, Hu et al., 2012, Yao et al., 2011). For instance, the WorldSID, a side impact dummy, assesses the fidelity of various body parts, while the BioRID, a rear impact dummy, has been validated by contrasting responses with PMHS and volunteer data, rendering it a sensitive instrument for rear impacts. Crash test dummies, an essential instrument for automotive safety tests, exhibit limitations in predicting damages in regions beyond Europe and US due to their design focus on these areas. There has also been a rise in the simultaneous development of physical crash test dummies and DHMs for marginal or vulnerable populations (Hu et al., 2012). To enhance vehicle safety performance, developing dummies tailored for vulnerable populations, such as the elderly and obese, is imperative. Further investigation into crash test dummies mandates the involvement of multiple nations to develop a dummy that aligns with each country's unique conditions.

### *3.4 Applications of DHMs in automotive engineering*

Table 1 discloses the two principal domains of DHM application within the automotive sector: ergonomic design and accident collision analysis. The current investigation endeavours to examine these domains independently. The automotive industry represents a mature and emblematic manufacturing sector that embraces and fosters cutting-edge technologies, with virtual manufacturing gaining traction in industrial facilities. Essential research areas within the automotive and transportation sectors encompass comfort and discomfort, wherein DHMs have supplanted test panels for comfort assessments. Furthermore, modelling motor behaviour and motion sequences constitutes a vital research area addressing ingress/egress (Causse et al., 2012, Robert et al., 2014), driving motions (Park et al., 2019), accessibility (Chateauroux and Wang, 2010, Mavrikios et al., 2006), step motions (Gu, 2012, Panicker et al., 2020), and sitting behaviour (Leledakis et al., 2021, Tao et al., 2016).

This review concentrates on the initial domain of DHM application: ergonomic evaluation and design. DHMs provide an economical means of estimating human body motion during the early phases of vehicle design and assembly process development before testing or deployment involving actual human subjects. DHMs have evolved into an indispensable instrument during the conceptual design stage of vehicles, particularly in the analysis of visual field performance, empowering designers to develop products that accurately embody the individual body shapes of consumers (Case, 2013). Additionally, DHMs are crucial for enhancing the efficiency and quality of automotive interior design by evaluating cabin and seat configurations. While standard anthropometric data and mannequins are significant, they cannot satisfy diverse personal needs, rendering DHMs essential. It is noteworthy that numerous papers emphasise automotive interior assessment (Högberg et al., 2018, Wirsching and Wagner, 2020).

The secondary domain investigated in this study pertains to vehicle safety, injury analysis, and crash reconstruction. DHMs simulate and reconstruct vehicle occupants' biomechanical and injury responses during collisions. The most researched injury among human-affected body regions is head/brain injury, succeeded by lower extremities (Li et al., 2013b, Ma et al., 2020, Newell et al., 2016, Tang et al., 2020, Untaroiu et al., 2013) and other areas (Chang et al., 2009, Ruan et al., 2008, Li and Yang, 2010, Mattos et al., 2015, Putnam et al., 2014). DHMs are primarily developed to examine the correlation between human injury and load to safeguard individuals during vehicular collisions. Human injury biomechanics is integral to traffic safety research and offers insights for forensic identification and accident management by traffic police. Injury biomechanics data amassed over the past 40 years are indispensable for establishing pedestrian protection detection standards, test procedures, and evaluation methods, and these parameters can inform the safety design and performance evaluation of front vehicle structures. Nevertheless, some human injuries, such as chest injuries, warrant further exploration.

Comfortable posture and joint angles are critical determinants of driver and passenger fatigue levels (Savin et al., 2016, Cloutier et al., 2015, Mavrikios et al., 2006, Park et al., 2019, Ruan et al., 2008). 3D digital mannequins can be positioned according to comfortable joint angles, facilitating the evaluation of the visual field, reach, and comfort for various body shapes. However, extant posture prediction models neglect the influence of posture variables, relying exclusively on body size, which proves crucial in failing to capture the characteristics of target driver populations (Panicker et al., 2020). The integration of digital mannequins with layout tools remains limited.

## 4 Limitations

This review provides a concise examination of the potential constraints of DHMs in the context of their application to automotive engineering. It is well-known that DHM tools exhibit advantages and disadvantages; the former materialises in identifying geometrical issues, while the latter arises from potential challenges in detecting problems related to tactile sensations. Furthermore, DHM experiences are not uniform among users, leading to the risk of inappropriate usage. Despite the advantages of rapid evaluations and early feedback offered by DHM, its limitations in accurately assessing ergonomics and predicting cognitive and perceptual factors, as highlighted by Chaffin's summary, should not be disregarded (Brischetto et al., 2018). Mixed prototyping, such as virtual reality, may alleviate some of these constraints. However, it remains necessary to enhance the automated task evaluation capabilities of DHMs, particularly for complex industrial activities like manual assembly operations. Additionally, DHMs face difficulties in precisely evaluating ergonomics and predicting cognitive and perceptual factors, especially when simulating intricate tasks (Massolino et al., 2017, Stefania et al., 2016). Cognitive tools and methodologies within the DHM domain are still in the developmental phase, in contrast to their physical counterparts.

The review also emphasises the constraints of anthropometric datasets for DHMs in accounting for a wide range of age, BMI, and overall body shape in segment parameter calculations. Most existing human models are based on European and American men, limiting their predictive capacity for car crash injuries among individuals of diverse genders, countries, and physical attributes. The development and validation process of mechanical dummies, relevant finite element models, and human models focusing on injury biomechanics are presented to address this issue. The review accentuates the necessity for country-specific crash test dummies that represent the general human characteristics of various populations and the importance of considering the diversity of people's types, sizes, and ages when developing DHMs to protect occupants' safety better (Panicker et al., 2020).

In summary, the authors recognise the limitations inherent in their literature review, specifically the restriction to English-language publications, which may have excluded relevant research from other nations with significant contributions to automobile safety research. Nonetheless, the authors argue that the English-language publications examined in this study offer a reasonably representative portrayal of DHMs application trends in automotive engineering research.

## 5 Conclusion and perspectives

This comprehensive review presents an in-depth analysis of DHMs development, validation, and application in automotive design and engineering. The paper introduces a novel, transparent, and reproducible methodology for conducting systematic reviews in automotive engineering, offering a more adaptable approach based on bibliometric analysis. The study begins by delineating the current state of DHM research, encompassing publication and citation growth, research areas, keyword distribution, and thematic evolution. Furthermore, a bibliometric analysis identifies contemporary research trends and DHM applications in automotive engineering, including developing, validating, and investigating human biomechanical injuries resulting from collisions. The paper also presents the three primary DHMs employed in automotive engineering, namely anthropometric, biomechanics, and physiological medical models, in Table 1. Although the field shows promising results, it remains in its infancy with numerous opportunities for exploration. DHMs have the potential to promote inclusive design in automotive engineering applications, with recent advancements in computer and bioscience technologies providing avenues for further research. However, challenges persist in this domain.

1 Developing anatomically, geometrically, and biomechanically accurate finite element models representing diverse populations will contribute to more equitable vehicle designs. These parametric finite element human models will address safety discrepancies in motor vehicle crashes among various population segments. Additionally, the emergence of automated driving calls for more sophisticated physiological models portraying muscle dynamics, blood circulation, and internal

organ injuries under pre-crash and crash loadings. Model validation remains a central research focus, with techniques and validation data expected to diversify, leading to enhanced instrumentation and documentation.

2 As computational power expands, DHMs are projected to become increasingly prevalent in vehicle design optimisations requiring hundreds or thousands of simulations. Stochastic sampling and machine learning methodologies utilising DHM-predicted outcomes as training data will be extensively employed in such applications. In the early stages, complex HDMs will be used to evaluate innovative vehicle interior or safety designs. Nonetheless, future research should focus on developing a rigid-flexible coupling modular DHM to address efficiency and accuracy concerns in numerical simulations. This model will utilise a finite element model to simulate fracture and brain injury biomechanics in the body's collision region and multi-rigid bodies for other areas. However, validating the rigid-flexible coupling DHM will prove challenging and necessitate further investigation, particularly in validating the rigid-flexible coupling joints of the human body.

3 While most research on human injury biomechanics based on collisions has concentrated on brain and limb injuries, other regions and complex biomechanical phenomena have received less attention. As a result, future research should prioritise muscle activity and blood flow mechanisms, injury mechanisms of internal organs and other regions, and the properties of human tissue materials, especially under dynamic conditions. Moreover, augmented reality and DHMs can be used for human factors engineering analysis in cases where 3D models are unavailable, or modelling is challenging. However, existing DHMs are static and demonstrate limited interactions with physical environments. Consequently, future research should concentrate on intelligent interactions between DHMs and physical environments, allowing DHMs to automatically generate postures and movements to accommodate various requirements while supporting human factors engineering analysis and evaluation. This integration can also be applied to automated engineering industries.

In conclusion, DHMs hold significant potential for ergonomic design and safety assessment in automotive engineering. Despite ongoing challenges, the transition from fundamental research to practical application necessitates additional research and development efforts to design user-friendly tools and equipment for anthropometric and biomechanical data. The collaborative efforts of ergonomics scientists, designers, engineers, and physicians will ultimately lay the foundation for DHMs to serve the population in automotive engineering.

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