Review Paper

Digital human modeling (DHM) for improving work environment for specially-abled and elderly

Charu M. Maurya[1] · Sougata Karmakar[1] · Amarendra Kumar Das[1]

Abstract
Digital human modeling (DHM), a technique of simulating human interaction with the product or workplace in a virtual environment is gaining popularity. This virtual evaluation process is useful in developing user-centered products by incorporating human factor principles at an early design phase, which reduces the design time and improves quality. Application of DHM has gained attention in the design process of the manufacturing industry, agriculture, healthcare sectors, transportation and aviation sectors, etc. However, the use of DHM for designing ergonomic products and work environment for the specially-abled and elderly is quite limited. This, otherwise, is more important as their real-life participation in experiments pertaining to the ergonomic evaluation of any product, workplace or public facility may cause discomfort to them. Moreover, improved products or workplace reduces their dependence on others and enables active involvement in work, communication, and social life. Therefore, an attempt has been made in this paper to explore the state of the art literature review on the applications of DHM based virtual ergonomic approaches to improve products and workplaces designs for specially-abled/elderly. The paper also proposes a way forward to continue research and developmental activities towards the betterment of the quality of life of the elderly and specially-abled persons through proactive and inclusive design strategies.

Keywords Digital human modeling (DHM) · Ergonomic design · Specially-abled · Elderly

1 Introduction

The ergonomic design of the work environment reduces postural stress, improves organizational productivity, enhances job satisfaction, and results in a better quality of work-life [1, 2]. With the advent of virtual ergonomics, user-centered workplaces and/or products are being developed and tested in a virtual environment at an early design phase. Human modeling software enables designers to simulate human –workplace interaction by inserting a digital human model in the CAD generated work environment. CAD-based virtual ergonomics evaluation process shortens design time, lowers development cost, improves quality and enhances productivity [3].

1.1 Digital human modeling (DHM) software

Digital human modeling software is a computer-aided design tool for the construction of 2D and 3D human models from anthropometric data of targeted users/population for ergonomic analysis of virtual human fit to virtual workstation components [4]. Any design or work environment can be evaluated from an ergonomics perspective using virtual simulation before making the real physical prototype [5]. The study of digital prototypes in virtual environment reduces the developmental cost and design time [6]. The correlation between the results of DHM simulation and real-life assessment is fairly high [7]. A few popular DHM software, which is commercially available include JACK, SAMMIE, RAMSIS, DELMIA, SANTOS, etc.

✉ Charu M. Maurya, mauryacm@iitg.ac.in | [1]Department of Design, Indian Institute of Technology, Guwahati, Assam, India.

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1.2 Application of DHM software for improving the work environment

Digital human modeling software has gained attention for proactive design and ergonomic evaluation of products and workplaces in diverse fields that include manufacturing industry, healthcare sectors, transportation, agriculture, defense research and development, aerospace-aviation sectors and so on. In industrial workplace, DHM has been applied for improving the designs of work cells in car manufacturing plants [8], designing of small fishing vessels to reduce work-related musculoskeletal disorders of fisherman [9], redesigning of work accessories for minimizing awkward postures in Indian shop floor workstation [10], workplace evaluation of coir industry, etc. [11].

The ergonomic analysis of refrigerated cabinets [12], shoe rack [13], adjustable walking cane [14], modified cycle rickshaw [15], improved load carrier for coolie [16] improved design of wearable load assisting device [17] etc. are few examples where DHM has been applied effectively. In the healthcare sector, DHM has been successfully utilized for improving laparoscopic surgery [18], evaluation of bathing system design for patients [19], patient lifting devices for healthcare personnel [20], etc.

DHM also finds its application in the field of transportation, aviation, and aerospace viz. vision analysis of pilots in jet aircraft [21], evaluation of cockpit design [22], vehicle interior design [23], evaluation of seat belt, driver posture and comfort in vehicles [24, 25]. Inclusion of DHM in the design process of the agricultural tools and machinery [26–28] is also gaining popularity.

1.3 Need of DHM application for improving the work environment of the specially-abled and elderly

Following the literature review, it is evident that a large number of research and developmental activities have been carried out by applying DHM in product and workplace design for military personnel, automobile drivers, healthcare professionals and for general civilian populations. Researches on DHM applications in the design and development of products for specific population subgroups like elderly and specially-abled persons have received less attention. Thus, there is a scope for need-based design of products and support systems for such specific sub-populations by taking the advantages of DHM technologies. A user-centric work environment or ergonomic products is an utmost necessity for the specially-abled or elderly as they encounter various barriers like inadequate policies and standards, negative attitude, lack of provision of services and the problem with service delivery, etc. [29]. Specially-abled employees who work in uncomfortable workplaces have also complained of mobility trouble, problems associated with heart and blood circulation, depression, etc. [30]. They also face difficulties while traveling and using public transport [31], which prevents their participation in social and work life [29]. Apart from that, specially-abled persons also encounter other disparities like lower average pay, job insecurity, lack of training facilities, participation in decision-making, etc. [32]. Hence, convenient housing and adequate support services should be provided to the specially-abled or elderly people [33]. Moreover, planners, designers, and architects should adopt universal and inclusive designs approach to remove obstacles in accommodation, transportation and communication to empower the specially-abled to participate independently and comfortably in education, employment and social life [29]. In the scenario described above, virtual prototyping with DHM could enable the designer to evaluate the product and modify it by simulating the interaction of digital manikin with the CAD model of the product [34]. Digital manikin-based virtual testing of the product-user interface also reduces discomforts/troubles to the elderly and specially-abled persons by eliminating their actual participation in real experiments of physical compatibility evaluation.

2 Aim

The aim of the current paper is to explore the state of the art literature review on applications of DHM based virtual ergonomic approaches in improving the product and workplaces designs for specially-abled/elderly. The paper also proposes a way forward to continue research and developmental activities towards the betterment of the quality of life of the elderly and specially-abled persons through proactive and inclusive design strategies.

3 Results

The papers published in peer-reviewed English journals and conference proceedings using DHM for a product or workplace analysis and having the specially-abled or elderly as participants were considered for the present review. The studies pertaining to anthropometric databases of elderly and specially-abled for making their digital manikin were identified from the available literature. Areas such as industries, public places, sports, product design, healthcare, etc.

were also explored where DHM has been used for solving design related issues of specially-abled and elderly.

3.1 Anthropometric database of the specially-abled and elderly for DHM

Anthropometry is one of the important aspects of DHM based product/workplace design and evaluation. Different anthropometric databases are incorporated in DHM software to get the digital manikin for the targeted population in the simulation process [35]. Fourteen (14) studies dealing with the creation of anthropometric databases of elderly and specially-abled have been included in the present review. D'souza et al. [36] in their study created functional reach database of 320 users of wheel mobility devices using DMH software and applied it for calculating vertical reach ranges for forward and side-ways. A model to predict reach envelop of digital human model based on data collected from elderly subjects was also proposed [37]. Another human modeling software "HADRIAN" (human anthropometric data requirement investigation and analysis) was developed [38–43] where anthropometric data, range of motion data, reach range, data regarding the ability to do kitchen based activities in daily life were recorded from 102 respondents. The elderly having age-related impairments and specially-abled persons (covering a wide range of disability) were selected as respondents. The HADRIAN software was validated by comparing the results of HADRIAN manikins with the actual users while performing the task such as retrieving a ticket from the machine, using ATM to obtain cash or using the lift at the railway station [44]. Hogberg et al. [45] developed digital human models of the elderly by modifying the anthropometric and joint range of motion data. Anthropometric data of elderly and their caregiver was also collected [46] to develop 3 D digital interactive works environment through which movements of caregivers of elderly can be studied and improved through training. Chaffin [47] recorded 37,000 motions from people in the age group of 18–78 years for developing a database of human motion prediction models. The motions of the people while reaching and moving the light to moderate objects in either seated or in standing postures were recorded. The models can help to predict various motor behavioral strategies adopted by a different group of people within a virtual workplace. Motion capture technology to create digital human models of specially-abled people was also applied [48, 49].

3.2 DHM application for improving industrial workplace

Earlier researchers have reported few studies where DHM has been applied for improving the workplace of specially-abled and elderly. Aubry et al. proposed an approach for the ergonomic analysis of the specially-abled person's workplace. In this approach gesture-based description of the workplace, virtual environment and modeling of disability as motion constraints were utilized. Thus, motions of the specially-abled person affected by his/her disability were generated and ergonomic analysis of workplace (3D CAD model) was performed [50]. A discomfort model of the climbing task for a specially-abled worker with prosthesis limb was also developed. The model was validated by simulating ladder-climbing task with the model of digital under knee prosthesis wearer and the results were compared with statistical data from the observed experiment [51]. Kaklanis et al. introduced a new virtual modeling technique comprising virtual user models, task models, and simulation models as a core component of a simulation module, expressed in UsiXML format. Here, the virtual user model was described as a virtual user with disabilities, simulation model was described as the product/services to be tested, and a task model was described as the complex tasks of the user. The effectiveness of the proposed framework was evaluated virtually by examining the accessibility of a workplace to five virtual user models with different disabilities [52]. In a study, a digital manikin of the wheelchair user was developed and interfaced with the simulated workplace environment. The work environment was evaluated and all modifications were incorporated virtually [53]. In another study, immersive virtual reality technology was used to assess the modified workplace where a person with disability accessed virtual reality environment. The specific behavior of physically handicapped was studied in a virtual environment by integrating task and physical disability constraints. Their model considered three levels of constraints namely appearance (broken arm or amputation), kinematics (inaccurate pointing or less degree of freedom of joints) and physical (strength limits) that affect the motion and posture of physically handicapped in task performance [54]. An office environment for the elderly and disabled was evaluated using DHM software in a simulated environment and in a real scenario with actual users. Both evaluations gave similar results regarding accessibility features in office design [55]. Digital human modeling based inclusive design strategy was adopted in a study for evaluating furniture manufacturing assembly for an elderly worker having joint mobility constraints. A human model based on joint mobility data of elderly worker from HADRIAN database was developed. The posture adopted by workers in the furniture assembly environment was replicated virtually on a human model of the elderly worker to assess the acceptability of posture [56].

3.3 DHM application for public utilities

A few reported studies have illustrated the use of DHM for making public utilities comfortably accessible to the specially-abled. Li et al. examined the interaction behavior of wheelchair users with ATM machine in a virtual environment using DHM and immersive virtual reality technique. Comfort analysis of digital manikin was performed in DHM software. EMG measures of a person while using ATM with immersive virtual reality technique were also recorded. Both the results were compared with the subjective responses of real respondents [57]. In another study, the design of the ATM machine was also virtually evaluated and modified by studying its interaction with the digital human model of a wheelchair user from HADRIAN database [43].

A pedestrian simulation model to make the barrier-free environment for elderly and specially-abled at public buildings is being developed [58]. Such a simulation model at public places will be able to evaluate the visibility of the guidance system and reveal the areas not visible to the specially-abled [59].

3.4 DHM application in healthcare sectors

Healthcare sector is also taking benefit of DHM technology for designing prosthesis, exoskeleton and assistive aids. Morotti et al., Colombo et al. and Colombo et al. created two digital human models for transtibial amputee and transfemoral amputee. Its gait was simulated for analyzing causes of gait deviations related to prosthesis set up and socket modeling [60–62] (Fig. 1). A system for designing sockets for lower limb prosthesis was also developed. This system designs sockets based on the patient's weight, lifestyle, tonicity level and geometry of residuum [63]. A virtual prototype of intelligent bionic leg (IBL), an advanced trans-femoral prosthesis, was developed and virtually evaluated by Xie et al. [64].

For designing exoskeletons, musculoskeletal analysis of upper limb exoskeleton in a simulated environment was performed [65]. In this way, the designs of the exoskeleton can biomechanically be evaluated before making an actual prototype. To analyze the effect of the strap that connects the exoskeleton with the human body, a combined human exoskeleton model was developed and evaluated in a simulated environment [66]. Virtual prototyping of rehabilitation exoskeleton by merging computational musculoskeletal analysis with simulation was also proposed [67]. In the proposed framework an exoskeleton–limb musculoskeletal model is developed first and then its performance is assessed using biomechanical, morphological and controller parameters. These parameters are optimized for developing the virtual design. The virtual experiment is then carried out to generate a modification in the design if required. The application of such a framework was illustrated by developing the index finger exoskeleton prototype.

In the area of assistive aids, a modified DHM tool was applied for ergonomic evaluation of a bathing system design from caretakers' (elderly) and caregivers' point of view. Most suitable bathing posture was also defined. Anthropometrics, joint range of motion, description, and appearance were customized for developing manikins of the elderly. RULA and joint comfort values were used to evaluate bathing system design [19]. A walker with sit-stand assistance for the elderly was developed and virtually evaluated on the human model before experimenting on real users [68]. A sit to stand and mobility assistance

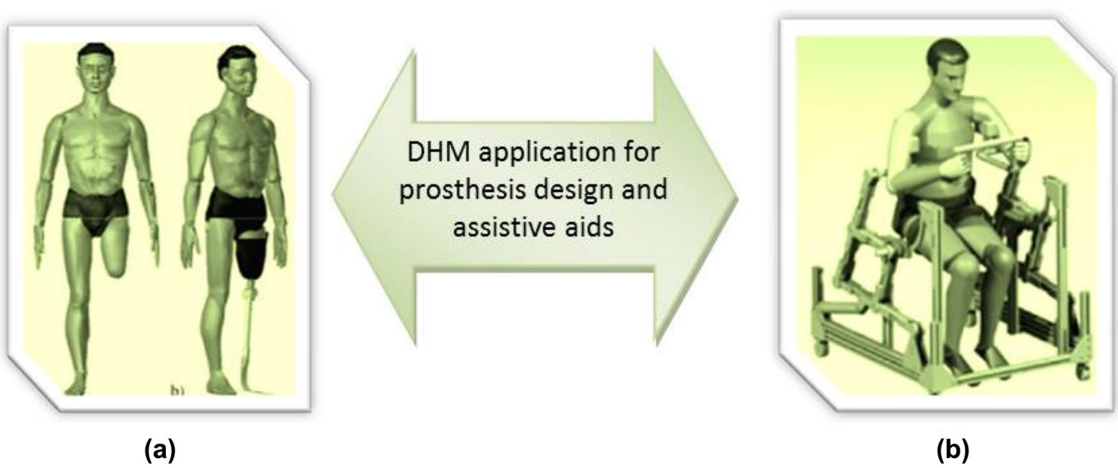

Fig. 1 DHM application in **a** prosthesis design from Colombo et al. [62] and **b** assistive aids for elderly and specially-abled from Khan et al. [69]

device for the elderly was also developed and virtually evaluated by Khan et al. [69]. Out of numerous case examples, two prominent usages of DHM in the design of prosthesis for the person with amputated leg and assistive aids for the elderly and specially-abled have been depicted in Fig. 1 for the easy understanding of the readers.

Application of virtual human for assisted healthcare is also evolving. The virtual human with characteristics like speech recognition, natural vision, and language allows a human user to interact with their computer in a more natural way. The virtual human monitor the type of user such as old age person or disable, record data from sensors and communicate the data to healthcare professionals. Currently, virtual patient technology has been applied for mental health diagnosis and clinical training [70]. Kakijaki et al. applied digital human modeling to physiotherapy education for 3D visualization and analysis of gait motion of the normal and hemiplegic patient [71].

3.5 DHM application in sports

DHM was applied by Holmberg et al. for understanding the effect of the impairment on sport's performance [72]. In their study musculoskeletal simulation for skiing sport was carried out on digital manikin with lower leg prosthesis. The influence of technique, fitness, and training was taken as negligible. Two full-body simulation models with identical anthropometric data were created having similar kinematics and external kinetics. In order to assess the impact of prosthesis on muscular work, one model was composed of full muscle setup and the other without muscle setup in right lower leg and foot. Biomechanical simulation of cross-country skiing was performed on both manikins. The output was used for computing metabolic muscle work and skiing efficiency. The results indicated that without muscles in leg and foot, skiing demanded more muscular efforts in total.

3.6 DHM for vehicle design and assessment

DHM has also gained the attention of researchers for designing and analyzing vehicles, which can be comfortable to specially-abled and elderly. A humanoid model was used for analyzing techniques adopted by the elderly in getting into a car [73]. Vehicle egress strategies and constraints faced by the elderly were also evaluated using RAMSIS bodybuilder [74]. A virtual modeling technique was used for evaluating car designs for hand brake and storage compartment use with a virtual model of the elderly having spinal cord injury by Kaklanis et al. [75]. Erdelyi et al. virtually evaluated the vibrational comfort level of the motorcycle ride with human models of able-bodied riders and people with different disabilities using root mean square (RMS) and vibration dose value (VDV) [76]. The suitability of a bus design for elderly and disabled people was also analyzed by Marshall et al. using digital manikin of specially-abled and elderly from HADRIAN database [77]. To provide the glimpse of application of DHM software in vehicle design and evaluation targeting for elderly and specially-abled people as the users, current researchers have compiled images from various pieces of literature and presented in Fig. 2.

3.7 DHM application in other areas

A model for simulating motion according to age by incorporating age-related changes in gait pattern, kinematics, and kinetic values has also been developed [78]. The model can be used for analyzing crowd behavior in the virtual environment. Wyk [79] worked on a methodology which can help to set up an open framework where a virtual human can be animated for visualizing sign language. In this method, any verbal language can be translated into a sign language in a machine translation system.

4 Future work

The participation of specially-abled or elderly in the real-life design development and evaluation process might cause discomfort to them. However, ergonomic design that suits their needs is very much required for minimizing the effects of constraints caused by their disability. The review presents the holistic knowledge base regarding the applications of DHM technology by various researchers in improving the quality of life of the elderly and specially-abled people. It is hoped that it would encourage researchers to develop and modify designs of products of everyday use for the aforesaid targeted users. DHM based virtual ergonomics evaluations in the field of transport, public utilities like hospital environment, markets, parks, temples, etc. are needed for modifying existing design towards more inclusive considering the specific requirements of the elderly and specially-abled persons as these public places are frequently accessed by them. In the living environment, designs of the bathroom, toilets, furniture, etc. can also be evaluated and accordingly design modifications can be performed to address ergonomic issues if any. DHM can also be applied to design and evaluate assistive aids and prosthesis to make them more user-friendly.

5 Discussion and conclusion

The present paper explores the areas where DHM has been applied for ergonomic evaluations and improving the work environment of elderly and specially-abled persons. The paper highlights the efforts done by researchers for

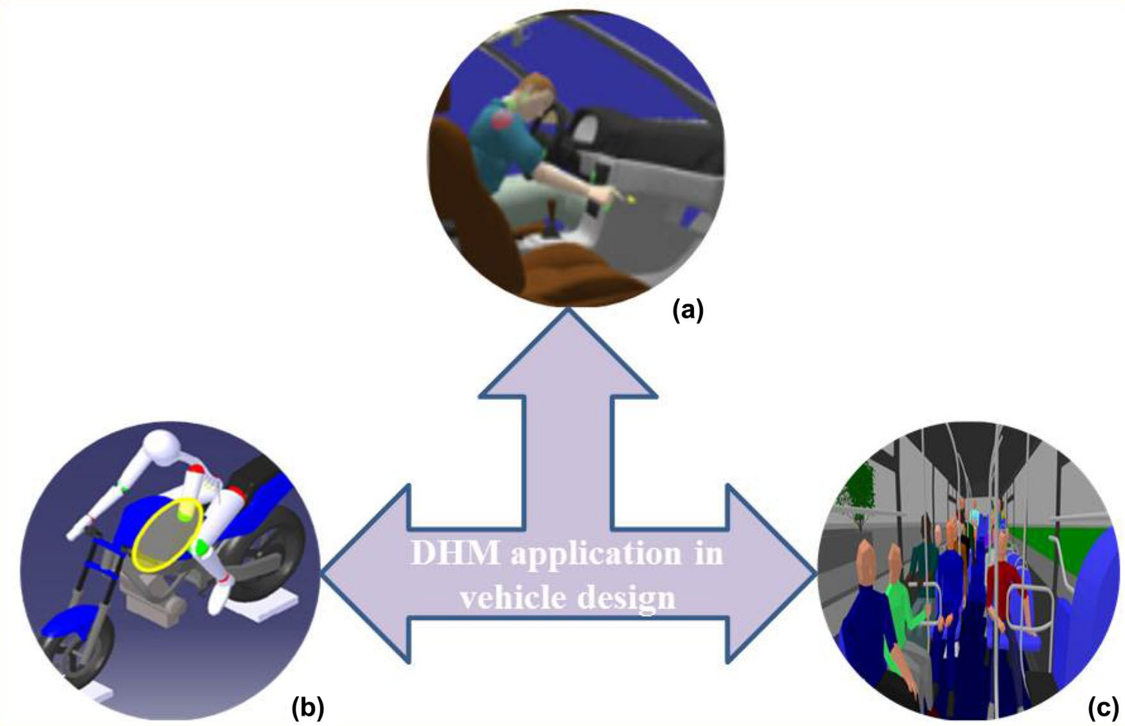

Fig. 2 DHM application in vehicle design and evaluation for elderly and specially-abled. Images adopted from **a** Kaklanis et al. [75], **b** Erdelyi et al. [76] and **c** Marshall et al. [77]

recording anthropometric and biomechanical data of specially-abled and elderly people and developing software such as HADRIAN. DHM has been applied for evaluating and modifying the workplaces viz. industrial workplace, public utilities, vehicle design, prosthesis design, etc. to make it compatible with elderly and specially-abled. Specially-abled employees often encounter problems viz. trouble in mobility, blood circulation, and depression in the industrial workplace. DHM can be of immense help in solving the workplace-related problems of the specially-abled as done in case of office design [55] and furniture assembly [56]. Physical disability often hampers the movement of specially-abled and elderly and absence of appropriate physical infrastructures discourages their interaction in the social environment. DHM can be effectively used for virtual evaluation and improvement of the infrastructural facility of public places like ATM, railway station, bus-stop and public transportations. The current paper also highlights the research and development activities carried out by the researchers for designing assistive aids, prosthesis, and exoskeleton with the help of DHM and its successful evaluation in a simulated environment. In the automotive industry, suitable modifications in the design of hand brake, storage compartment has been undertaken using DHM in order to make it comfortable for specially-abled and elderly.

Though limited, DHM has now been applied by researchers in the design process for making the work environment suitable for the specially-abled and elderly people. The major bottleneck for application of digital human modeling for product and facility design for elderly and specially-abled is the unavailability of anthropometric and biomechanical (total range of motion and comfort range of motion of body joints) databases of the aforesaid populations. This is true for most of the countries all over the world. Hence, the need of the hour is to develop such databases for effective use of DHM software to provide a better quality of life to these targeted users. It is envisaged that the body of literature presented in the current review would encourage designers and engineers to use DHM based ergonomic evaluation as an inclusive design approach for ensuring a barrier-free environment for the specially-abled and the elderly persons. The future research pertaining to applications of DHM software in developing manikins (with anthropometric and biomechanical data of elderly and specially-abled population) for ergonomic design and development of various products and facilities as described in current review would facilitate the quality of life of the elderly and specially-abled persons.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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