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Towards Biomechanical Digital Human Modeling of Elderly People for Simulations in Virtual Product Development

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This contribution illustrates a methodology to customize biomechanical digital human models to resemble people of different age and ability groups for the use in simulations to support user-centered design. Especially the conception of man models of elderly people holds potential for analyzing and optimizing products to yield more universal designs, due to the high heterogeneity of needs, wants and capabilities in this specific age group. The present approach considers age-related performance restrictions, but is also extendable to disease-related limitations. The conception process itself includes the scaling of anthropometry, muscle forces, range of motion as well as motion speed based on data from literature or manual measurements. The parameters are either selected by percentiles or the specific values itself.

HUMAN-CENTERED DESIGN

The purpose of the multidisciplinary field of human-centered design is to specify the products' characteristics to meet the requirements of its prospective users. The ever rising number of elderly people, especially in industrial nations, has great implications on how user-centered products are to be developed. The impact of the demographic change becomes even more significant for the industry as the distribution of wealth shifts more and more to the side of the older people. But this part of our population is not only important as customers. Especially old experts should be retained at work for longer to prevent information loss. Thus, the workplaces for these employees have to meet special needs related to ergonomics, too.

The issue of products focusing exclusively onto seniors is that these rapidly obtain a stigmatic character, which companies want to avoid. Therefore the so called Universal Design focuses onto the specification of products and services so that these are usable by as many people as possible including healthy and disabled people of any age group. Due to the high heterogeneity of their capabilities and needs, the elderly should serve as a magnifying glass for the development of user-centered products. To achieve this goal the products should comply with the seven principles of Universal Design: Equitable Use, Flexibility in Use, Simple and Intuitive Use, Perceptible Information, Tolerance for Error, Low Physical Effort, Size and Space for Approach and Use. (Story, Mueller & Mace, 1998)

According to Miehling, Krüger and Wartzack (2013), there are different methods to consider and evaluate user-product interactions in the product development process to fulfill the mentioned principles, ranging from the use of guidelines, experts' evaluations as well as simulations using physical prototypes, hybrid or purely virtual mock-ups.

Integrating Elderly Users into the Design Process

The most basic methods of considering the capabilities and needs resulting from age- and disease-related limitations of elderly people are experts' evaluations and guidelines. The use of these methods usually requires a specialized team of engineers, ergonomists, psychologists and gerontologists.

The commonly used concept of simulating user-product interactions is the evaluation of physical prototypes usually by prospective users supported by interviews or questionnaires. Thereby the physical mock-up has to represent the functions to be examined. The disadvantages of this approach are the costs for manufacturing the prototypes as well as the costs and time for conducting the user tests. If no representative old users or no users familiar with the use of the product to be tested are available, the application of an age simulation suit can be helpful. The wearing of these suits allows for gaining personal experience about how the user-product interaction feels like for elderly people and how common performance restrictions affect the products' usability.

These issues can also partly be addressed by the application of hybrid mock-ups, simulation systems containing physical and virtual components, emulating human-machine interfaces in a multimodal way. This approach enables real users to interact with a virtual prototype. Digital human models go even further, additionally putting the user into virtuality to generate a purely digital representation of the product as well as the human. (Miehling, Krüger & Wartzack, 2013)

The advantage of the virtual product development paradigm is that it is even applicable in the early stages of the product development process, where no physical prototype or even no geometry is available. To facilitate the virtual representation of user-product interfaces digital human models are needed, which represent a specific individual or user group as close as possible.

Digital Human Modeling

As already mentioned, digital human models should represent the behavior of real humans virtually. Due to the complex nature of the human body and mind, there is no model available which is able to incorporate all necessary domains to fully describe all the human abilities and properties. But there are models covering subdivisions enabling to perform for example anthropometric, anatomical, biomechanical or even cognitive analyses according to Bubb and Fritzsche (2009).

Digital human models are in general used in industry, research as well as education. As anthropometric models provide the easiest operation and highest usefulness, these are the most prevalent in industry for the design of workplaces or the interior of vehicles. These man models are available inside predominant CAD (computer aided design) systems enabling the product designer to evaluate human-machine-interfaces according to comfort as well as ergonomic aspects. These systems are usually able to visualize reach spheres as well as the field of vision and evaluate static poses regarding their joint angle constellations. Jack (Siemens PLM), Human Builder (Dassault Systèmes) and RAMSIS (Human Solutions) which are shown in Figure 1 are examples for widely used anthropometric models, whereas RAMSIS additionally offers functionalities for seat and belt analyses. (Bubb & Fritzsche, 2009; Mühlstedt & Spanner-Ulmer, 2009)

Nevertheless it is the biomechanical models which hold the highest potential for future applications in product development and therefore gain more and more significance in research. Biomechanical models commonly contain a skeleton, modeled as multi-body system, as well as muscles acting as actuators. The underlying simulation systems are able to conduct dynamic analyses of the human musculoskeletal system considering muscle and joint loads which can be seen as the cause of a specific motion behavior. Due to the lack of usability and unsolved problems of simulating user-product interactions, biomechanical digital human simulation systems are still not widespread in industry. (Miehling et al., 2013)

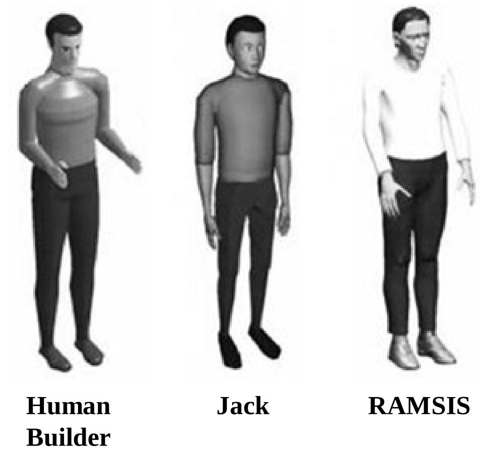

Figure 1. Anthropometric digital human models based on Mühlstedt and Spanner-Ulmer (2009)

Examples for biomechanical simulation environments are the AnyBody Modeling System (Aalborg University) or OpenSim (Stanford University) depicted in Figure 2. (Rasmussen, Dahlquist, Damsgaard, de Zee & Christensen, 2003; Delp et al., 2007)

The mentioned biomechanical models commonly specify an exemplary average individual. The associated simulation systems usually contain a scaling tool which usually allows for adjusting the individual's size and weight. However, this is not sufficient to model the wide variety of prospective users of potential products, especially when elderly people are to be considered due to the mentioned high heterogeneity of needs arising from age- and disease-related performance restrictions.

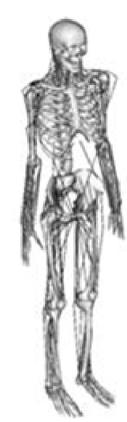

Figure 2. OpenSim model

The research question therefore is how these limitations can be modeled or considered in simulations of user-product interactions. Thereby it is important which data is needed, where the necessary data is stored, how it can be obtained and how it has to be represented to facilitate the generation of biomechanical digital human models of different age and ability groups.

AGE- AND DISEASE-RELATED PERFORMANCE RESTRICTIONS

There is a range of performance restrictions which can be acquired throughout human life. These can be divided into conditions arising from normal ageing processes affecting a large part of the elderly people and limitations originating from diseases concerning a smaller number of people. The approach presented in this paper focuses mainly onto the modeling of healthy elderly people taking the interpersonal statistical differences into account. But the outlined conception process is extendable to account for further impairments. The following sections give an overview of common limitations arising in the ageing process. According to Riemersma (2000), these are highly dependent on genetic differences, life-style, health history, exposure to contaminants, type of work and the overall physical and cultural environment.

Sensory capabilities. In this category especially visual and auditory abilities change over the life span. From around 40 years of age the sharpness and contrast of the visual system decrease (presbyopia) either due to the deteriorating accommodative capacity or to pathological conditions like macular degeneration and cataract. Hearing impairments already occur in the middle adulthood. 30% of the people over 60 years as well as 60% over 70 years of age report a decreased hearing ability. The same applies to smell, taste and vestibular functions. (Stöber, Williger, Meerkamm & Lang, 2012; Riemersma, 2000)

Motor skills. The umbrella term “motor skills” subsumes strength, endurance, speed of motion, coordination and mobility. As ageing progresses reaction times increase and the precision of movements decreases. The reaction time increases until the age of 65 years by about 25%. The task execution itself doesn’t slow down, rather the planning. Age-related conditions like Parkinson or Arthritis restrict the mobility even further. Parkinson’s disease for example is accompanied with the loss of coordination and fine motor skills, whereas Arthritis is accompanied with the deterioration of the range of motion due to the wear of joints and pain while moving. (Stöber et al., 2012)

Cognitive abilities. Cognitive faculties can be subdivided into mechanical and pragmatic capabilities of the human mind. Mechanical faculties are abilities needed in unknown or fast changing situations like processing speed, capacity of the working memory, attention and spatial orientation. These capabilities are negatively correlated to age and highly heterogeneous inside the age groups. The pragmatic faculties are defined by the knowledge of a person acquired throughout life and therefore enhance with age. Cognitive disorders like dementia, depression and delirium generally affect the cognitive abilities negatively. (Stöber et al., 2012)

Self-regulatory processes. Self-regulation controls emotions as well as actions. Research showed that elderly people usually exhibit the same or a better well-being as younger adults, despite deteriorating performance. (Stöber et al., 2012)

As biomechanical digital human models comprise just a skeleton as well as muscles, they are mainly used to model motor functions.

CONCEPTION OF BIOMECHANICAL DIGITAL HUMAN MODELS OF DIFFERENT AGE AND ABILITY GROUPS

To acquire the relevant data to consider age-related limitations in the conception process, a literature research was conducted. It focused on the changes in anthropometry, strength, mobility and motion speed with age. Figure 3 outlines the developed conception process.

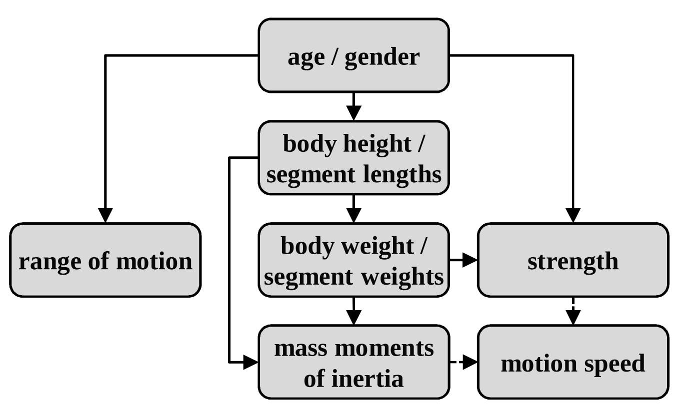

Figure 3. Overview of the conception process

First of all the gender and age of the model to be generated have to be chosen. In the consecutive steps of the outlined adaption process percentile values or the specific values themselves can be specified. Data from manual measurements of a specific person or user group to be considered can improve the models' accuracy even further.

Anthropometry. There are different methods to specify the body measures. The easiest way is to choose a body height and scale the individual body part dimensions accordingly. Another possibility is the choice of a percentile. The height and consequently the scaling factors for the body segments can then be computed using population data taking into account the specified age and gender. Body height data of one culture and gender can be presumed to follow a normal distribution. Most studies make the body height distribution of a specific age group available by specifying a mean value and the associated standard deviation. Thereof a normal distribution can be reconstructed easily. Figure 4 shows exemplary the height distribution of male and female Americans from 60 to 69 years of age collected in the "third national health and nutrition examination survey" (NHANES III). This publication reports the observations for nine percentile values. (McDowell, Fryar & Ogden, 2009)

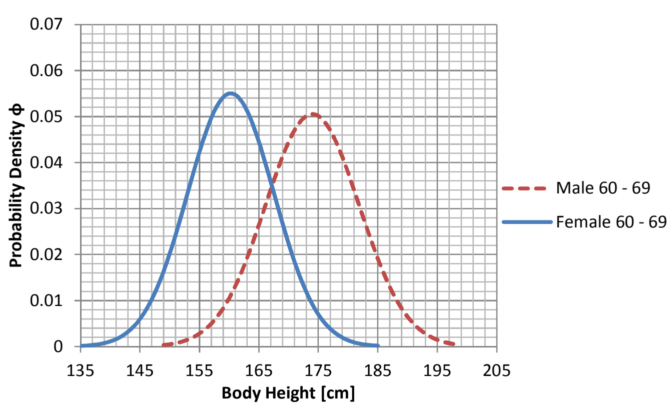

Figure 4. Probability density function of the body height of men and women at the age of 60 to 69 years based on McDowell, Fryar and Ogden (2009)

If the model to be generated should resemble a real person, manual measurements can be conducted to get the overall body height as well as values for the dimensions of the individual body parts. Subsequently scaling factors are calculated out of the individual body segments which are then used to scale the biomechanical digital human model. Another sophisticated method is to retrieve the segmental lengths through optical, marker-based or markerless measurement systems usually used for motion capture purposes. Krüger, Miehling and Wartzack (2012) for example developed a system for the markerless capture of motions as well as scaling of biomechanical digital human models based on the Microsoft Kinect sensor. This system automatically provides the scaling factors without the need for further calculations.

After collecting the data for the segmental lengths, the body weight of the model to be generated has to be specified. Most surveys report the weight as average values with standard deviations. Due to the problem that body weight tends to increase with body size, the body weight cannot be computed by using this representation. It just specifies the distribution of weight for people of average height. In the present approach body weight can therefore either be chosen directly or by the body mass index (BMI). Keys, Fidanza, Karvonen, Kimura and Taylor (1972) advised the body mass index as a measure for the physical constitution of populations. BMI is body weight in kilograms divided by body height in meters squared. The BMI removes the dependency of height and weight and is a good predictor for body fat percentage. The NHANES III study again specifies the BMI values for nine percentiles. Intermediate values can be interpolated. As the height has already been determined in the preceding step, the body weight can be calculated from the BMI. The body's mass distribution respectively individual body segment weights are then computed considering the scaling factors for the body part dimensions. If the man model's dimensions are scaled just considering the overall change in body height, the mass distribution stays unaffected.

Mass moments of inertia. The mass moments of inertia of the individual body parts are especially important in dynamic simulations of multi-body systems like the human body. If the changes of the segments' mass as well as dimensions are known, the inertia tensors can be calculated.

Strength. The maximum isometric forces generated by skeletal muscles largely depend on age, but body weight and size play a role, too. A taller, heavier person tends to be able of generating bigger muscle forces in comparison to a shorter, lighter person of the same age, gender and ethnicity. From around 30 years of age the maximum muscle forces decrease steadily. Women are generally less strong than their male counterparts. The scaling factors for the muscle strength are displayed in Table 1. Intermediate values can again be interpolated. (van den Berg & Wulf, 2007)

Age	20	30	40	50	60	70	75
Female	0.58	0.57	0.52	0.47	0.42	0.30	0.22
Male	0.92	1.00	0.95	0.87	0.79	0.67	0.60

Table 1. Factors for the maximum muscle strength with age based on van den Berg and Wulf (2007)

Range of motion. Unlike with body measures, weight and strength, there is no clear correlation between the mobility and the age of a person. The distributions in this respect coincide largely, given that diseases like arthritis are ignored. Due to the just stated aspects the range of motion is scaled using percentile values without regarding the affiliation to a specific age group. (Greil, Voigt & Scheffler, 2008)

Motion speed. The maximum speed of movement does not directly depend on body weight and size. The execution of movements decelerates just a small portion due to physiological changes in the skeletal muscles, but largely due to the smaller maximum forces resulting from the progressing muscular dystrophy with age. Additionally as weight increases, the segments' mass moments of inertia rise and therefore the same muscle forces yield lower angular accelerations and in turn angular velocities.

CONCLUSION AND OUTLOOK

In this contribution a methodology for the conception of biomechanical digital human models of people of different age and ability groups considering age-related performance restrictions was shown. It allows for the derivation of parameters like anthropometry, body weight, strength and range of motion which are necessary for the adaption of the biomechanical digital human models to match the specified individual as close as possible. The general methodology is based on surveys found in literature. Thereby percentile values or values for the parameters itself can be specified. Manual measurements can support this process for further refinement and thus yield better results in subsequent simulations.

The use of the NHANES III survey helped to address issues due to the varying data quality and representation in the other relevant publications. Moreover most of the studies examined people of different cultural origin and the majority is based upon small populations. Furthermore the age ranges mostly lack consistency.

The next step towards increasing the usability of this approach is the implementation of a software tool, which allows for the automatic derivation of the necessary parameters and adjusts the biomechanical digital human model accordingly.

After the implementation of the tool, the generated man models have to be validated by comparing simulations performed with customized models to norms, guidelines or empirical data before these can be successfully applied for analyzing, optimizing and validating new product designs.

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