ROADMAP TO CONSIDER PHYSIOLOGICAL AND PSYCHOLOGICAL ASPECTS OF USER-PRODUCT INTERACTIONS IN VIRTUAL PRODUCT ENGINEERING

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ABSTRACT

To successfully facilitate user-centred design, a multitude of different aspects has to be considered, from purely physiological to psychological-emotional factors. The overall aim is to increase the customer satisfaction by enhancing the fit between products and their users in the respective context of use. Further virtualisation of user-centred design processes holds the potential to convey the concepts of frontloading and predictive engineering from classical product engineering. Our vision is to facilitate a comprehensive consideration of user-product interactions in virtual product engineering operationalised by the mission to develop methods and tools to assess and design user-product interactions according to physiological and psychological aspects. A variety of work has already been done to model musculoskeletal user groups, to configure, predict, simulate and optimise physical user-product interactions, to integrate such models into CAD or to map individual subjective values to product design. Nevertheless, there are still research areas to be addressed to enable a comprehensive implementation of the mentioned approach. These are discussed in the present contribution.

Keywords: User centred design, Simulation, Integrated product development, Affective Engineering, Biomechanical digital human models

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1 MOTIVATION

The shift from the seller's to the buyer's market along with increasing globalisation and prosperity requires a consistent user orientation from companies in order to survive in the market. In general, many different aspects from purely physiological to subjective factors influence the purchase decision. This includes comfort, usability and user experience as well as the aesthetics and perceived quality of products. Human beings as users are thus moving more and more into the focus of considerations in product development. Therefore, the aim is to increase long-term user satisfaction by enhancing the fit between products and their users' needs in the respective context of use. (Miehling, 2018) In this context, user-centred design processes may be used. They are characterised by an early focus on the user and the usage scenarios, the use of empirical measurements and highly iterative approaches (Gould and Lewis, 1985). This, however, makes such development processes very slow and costly. To overcome those challenges, extensive and continuous approaches like physical prototyping combined with user integration are needed.
Besides, in the field of classical product development, an increasing virtualization of engineering processes has already been successful for several decades. This ranges from mapping product geometry in CAD (computer-aided design) to CAE (computer-aided engineering) simulations in order to analyse and assure structural, multi-body, fluid dynamic or process behaviours of the envisioned product as early as possible. This frontloading approach (Thomke, 2000) is necessary not only to reduce development costs and time, but also to increase the products' quality by switching from physical prototypes to a virtual representation of the products and their usage processes.
Such a paradigm shift is also needed in user-centred design in order to master the mentioned challenges. This requires the facilitation of a comprehensive consideration of user-product interactions in virtual product engineering operationalised by the mission to develop methods and tools to assess and design user-product interactions according to physiological and psychological aspects. For the sake of applicability, a focus on the development of practicable solutions for product development is needed. Even though various approaches and methods have already been developed to virtualise user-centred design processes, there is still future research to be done in order to enable a comprehensive implementation of the mentioned vision.

2 STATE OF THE ART IN USER-CENTRED DESIGN

In the context of user-centred design, functional fulfilment and industrial design need to be considered equivalently (Vajna, 2014). Conventional methods of user-centred design like the Kano model, Quality Function Deployment (QFD) or requirement lists already support general user integration into the product development process. Hereby, QFD (Akao, 1990) aims for the transformation of the customer desires into corresponding product properties. The Kano model of customer satisfaction (Kano, 1984) helps analysing and prioritizing requirements. Those methods give a general idea about the user's requirements rather than focusing on the user's individual characteristics. To efficiently integrate the user into the product development process especially physiological and psychological aspects need to be considered.
Seeger (2005) attempted to formalise the user-product relationship. In this model of the user-product relationship (Figure 1), the user faces the product within his environment.

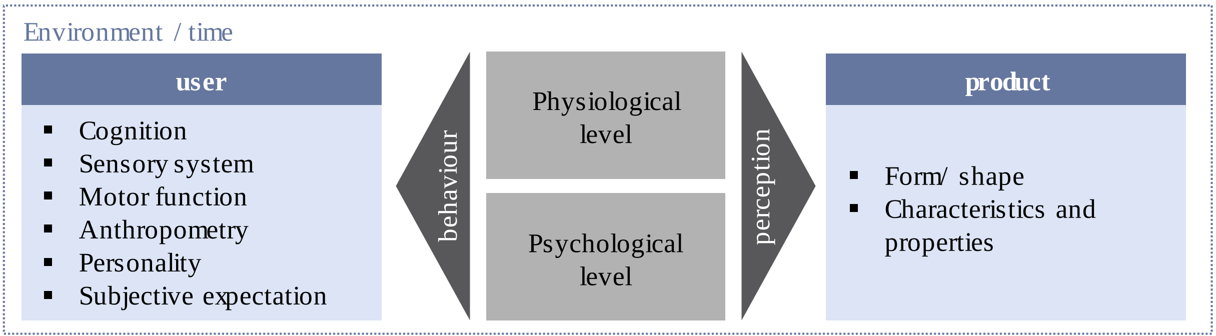

Figure 1. Model of user-product interaction based on (Seeger, 2005; Freudenthal, 1999; Glende, 2010)

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This interaction process is a feedback loop between the product and human behaviour, containing a physiological and psychological level (Glende, 2010). The product is described by its characteristics leading to its properties as well as form and shape, which are perceived by the user. The user is also characterised physiologically and psychologically (Freudenthal, 1999). Depending on the interaction, only specific product and user characteristics are relevant and thus need to be considered during the product development process.
The main challenge herby is the heterogeneity of the users as well as the variety of different usage scenarios. For example, there are different strategies when grasping objects or ingressing/egressing on a vehicle (Bichler, 2015). Even the same user will not choose the same movement behaviour at each repetition. Therefore, product design needs to address an optimal fit of the user's characteristics and product properties. Currently, user tests are preferably used in conjunction with physical mock-ups or predecessor products. These methods do not allow a verification in the early phases of product development. Moreover, iterations performed on physical prototypes are demanding and expensive due to a high manufacturing and testing effort. To overcome these challenges the interaction between user and product needs to be virtually modelled to enable the utilisation of predictive engineering (Wartzack, 2001). Hence, this allows the frontloading of information from the later stages of the product lifecycle into early product development phases.
Therefore, the aim is to model the user-product interaction virtually. This requires approaches to physiologically and psychologically describe the user, the product as well as the interaction itself. On the one hand, physiological aspects of the user-product interaction can be assessed and designed using digital human models. Anthropometric models enable accessibility and visibility analyses as well as occupational risk analyses (e.g. EAWS, RULA, REBA, NIOSH lifting equations) based on empirical data. Musculoskeletal simulation environments, such as OpenSim (Seth *et al.*, 2018) or the AnyBody Modeling System (Damsgaard *et al.*, 2006) enable dynamic simulations of the human locomotor apparatus. Gößling *et al.* (2014) performed a virtual comparison of the commonly used fatigue-reducing activation strategy with a strategy minimizing bending in the bone. Both strategies led to similar results. This fact emphasises the integrity of such simulation results.
Bichler (2015), for instance, developed methods for the virtual assessment of ingress and egress on a car using biomechanical digital human models. Besides such exemplary applications, Krüger and Wartzack (2014) integrated musculoskeletal simulations into CAD. Furthermore, Krüger and Wartzack (2017) developed a contact model in order to simulate user-product interactions with regard to force optimization. Miehling (2018) developed methods for musculoskeletal modelling of user groups based on empirical population data. This enables a configuration, prediction, simulation and optimization of the respective user-product interactions containing parametric musculoskeletal simulation (Miehling *et al.*, 2015). Musculoskeletal modelling is done throughout various modelling domains based on empirical population data (Miehling *et al.*, 2013) also containing a sophisticated strength mapping algorithm (Miehling and Wartzack).
In addition to physiologically oriented approaches, numerous other methods focus on the consideration of subjective factors in product development. For example, Hassenzahl *et al.* (2003) introduced an open access online tool to subjectively evaluate the usability and appearance of products. Furthermore, Kansei Engineering Systems link such subjective assessments directly to a products' Gestalt (eng. form or shape) (Nagamachi and Lokman, 2011). ACADE (Approach of Computer Aided Design of Emotional impressions) is a more quantitative method trying to connect the user's personal attitudes to specific product properties and thus better address the user's subjective needs (Zöller and Wartzack, 2017).

3 THE UCD HOUSE AS A ROADMAP

Despite the mentioned existing research, in order to consider a wide range of the multitude of relevant aspects of user-product interactions in virtual product engineering processes, there are some more areas to be addressed, which are summarised in the **UCD house** (Figure 2).
Foundation of the **UCD house** forms the current state of the art. The identified pillars depict the gap between the state of the art and the mentioned vision respectively the mission derived thereof. The pillars on the far left focus primarily on physical aspects of the user-centred design, the pillars on the far right focus on psychological aspects. The pillars in between compose of both aspects in different proportions. In the following sections, the individual pillars of the **UCD house** are explained separately, even though they are interconnected with each other.

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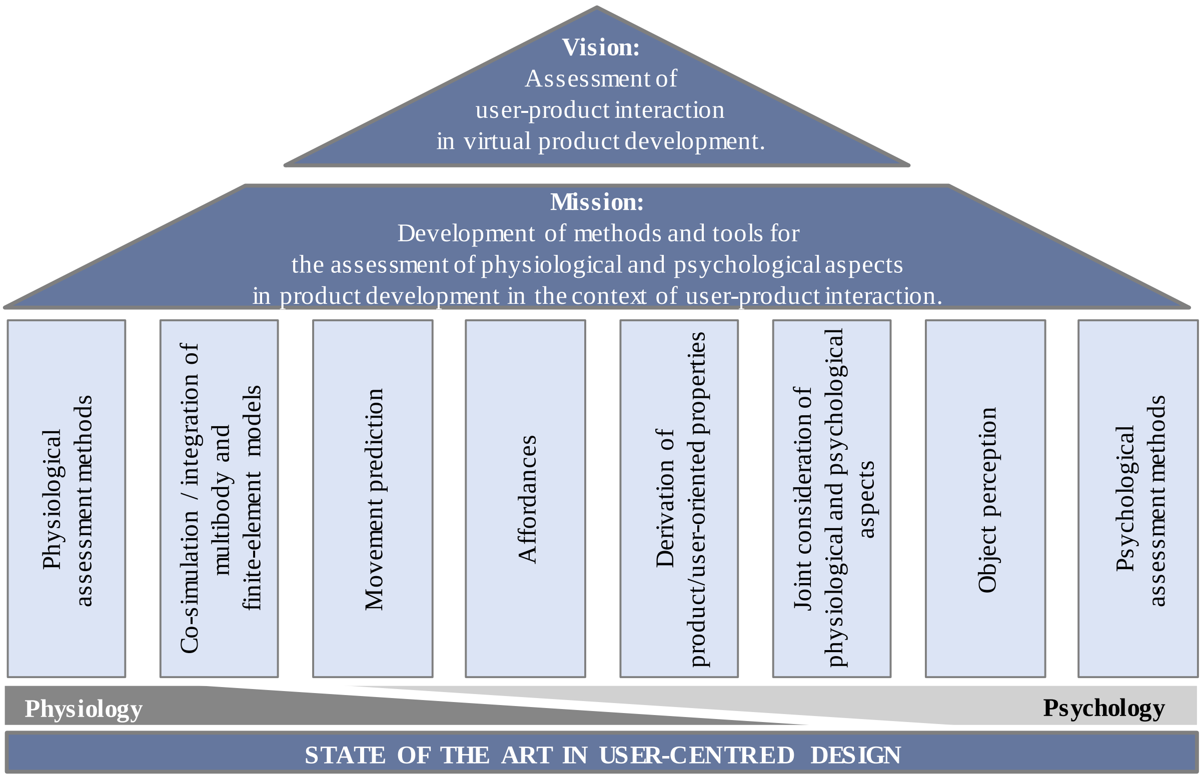

Figure 2. Graphical outline of the UCD house

3.1 Physiological assessment methods

The analysis of the physiological user-product interaction with suitable digital (human) models results in physiological quantities that are related to a specific design. For instance, joint reaction forces or muscle activations, resulting from a user-product interaction, can be computed with musculoskeletal simulation approaches. These physiological values describe the inner body strain during an interaction but are difficult to interpret for a product designer. Physiological criterions, like discomfort, comfort (Bubb, 2015; Rasmussen, 2005) or ergonomics, offer the possibility to express and assess physiological quantities in the context of product development. However, it is widely unknown, which physiological quantities (e.g. muscle forces or joint angles) lead to discomfort or an ergonomic product use. Therefore, the physiological results are currently evaluated with regard to a reference. An absolute assessment, which would allow statements about whether a product use is comfortable or ergonomic, is currently lacking. In order to fill this gap, empirical studies are necessary, whereof assessment models and criterions must be derived that enable the product developer to trace absolute physiological results to product characteristics.

3.2 Movement prediction

A key element of the physical user-product interaction is the user's movement performed during product usage. Thus, movement analysis is necessary in order to asses this element of user-product-interaction. To do so, the movement that a user will perform to use a product must be known a priori. Current movement analysis methods utilise experimental data, which is usually acquired with motion capture systems. For the virtual assessment of a movement in early product development phases, however, experimental data is usually not available, since no physical mock-up exists for motion capturing nor a final product design that can be analysed. Therefore, a movement prediction approach is necessary. In order to describe a realistic interaction behaviour the movement prediction approach should predict movements based on product properties, user properties and the environment (compare Figure 1). As an example, Figure depicts the user-product interaction for a bicycle. The way the movement is performed by a user depends on the individual characteristics of the user (e.g. described by anthropometry, strength or age parameters) and on product characteristics (e.g. geometric dimensions or actuation forces). A sufficient movement prediction approach has to consider these dependencies.

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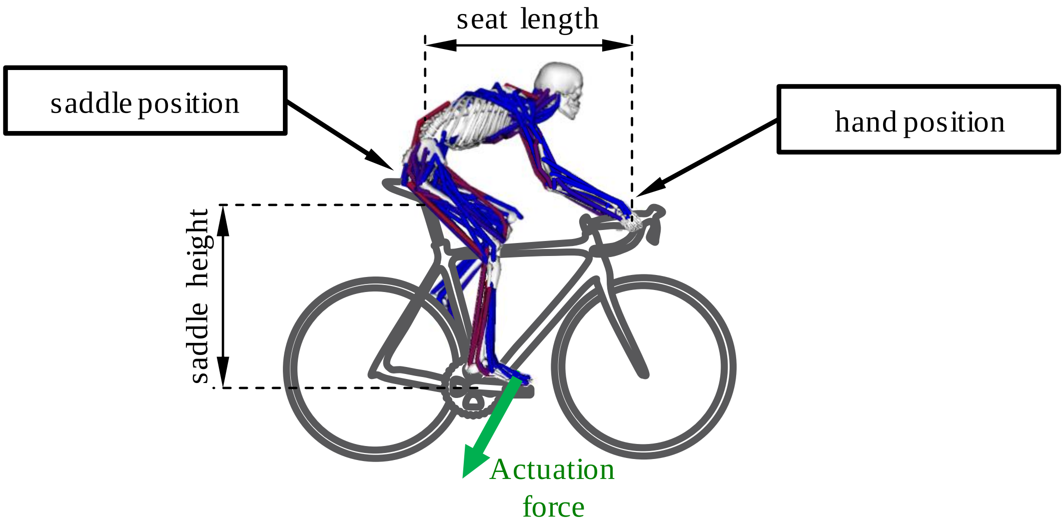

Figure 3. User-product interaction for a bicycle

For the purpose of character animation data-driven movement prediction approaches, using reinforcement learning and artificial neural networks show promising results (Holden *et al.*, 2016; Peng *et al.*, 2018). The aim of these approaches is the synthesis of realistic appearing movements. These models are very well suited to learn and describe movement manifolds (possibilities to execute a movement task). Still, the resulting movements often lack dynamic consistency and physiological validity, which is necessary for a reliable dynamic movement analysis. For the purpose of biomechanical analysis, optimization problems (Wolf and Wartzack, 2018), highly iterative approaches (Farahani *et al.*, 2016) and optimal control algorithms (Ackermann and van den Bogert, 2010) are utilised to predict dynamically consistent and physiological movements. These approaches enable an accurate prediction of specific movements, but do seldom address a movement's manifold.

For product development, movement prediction approaches need to be developed that address these challenges, depending on the purpose. The development of products that have a high interaction level with the user, like exoskeletons (Miehling *et al.*, 2018), demands movement prediction approaches that focus on the feedback loop (interface) between user and product. Optimal control algorithms, together with suitable force prediction methods (Krüger and Wartzack, 2017; Fluit *et al.*, 2014) may enable the computation of a dynamic equilibrium between the user's movement behaviour and the product's dynamic behaviour. The development of products with a lower level of interaction but with a broader variety of movement possibilities, in contrast, demand for movement prediction approaches that focus on a movement's manifold. Data driven approaches in combination with musculoskeletal simulation may enable a prediction of movements based on user and product properties (Wolf *et al.*, 2019a).

3.3 Co-simulation/ integration of multibody and finite-element-models

Digital multibody (musculoskeletal human) models enable the assessment of user-product interactions regarding movement dynamics. The applicability of these models, however, is limited to the musculoskeletal locomotion apparatus, wherefore they are not able to address human factors relying on soft tissue behaviour. Opposing, finite element (human) models like CASIMIR (Pankoke and Siefert, 2007), or THUMS (Iwamoto *et al.*, 2002) enable the computation of soft tissue deformation and stress. A co-simulation or integration of both digital human model types would not only be a step towards a more holistic digital human model, but would also enable new possibilities. In order to model sensorimotor behaviour for instance, the finite element model could act as a tactile sensory model that affects the interaction behaviour and therefore the movement (described using a musculoskeletal model) and vice versa.

For the design of products that highly interact with the user, like exoskeletons or implants, a co-simulation of multibody and finite-element-models also exploits new possibilities. Those products represent the highest level of interaction a user can possibly have with a product. Accordingly, the analysis and evaluation of the user-product interaction is crucial for the development of those products (Miehling *et al.*, 2018). To virtually model this interaction, an integration of finite element product

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models into a musculoskeletal human model seems promising. A certain movement leads to a load profile (computable via a musculoskeletal model), acting on the product and causing a products' reaction (computable via finite element model), which in return affects the movement and so on. In order to enable the optimization of products, like exoskeletons or implants, optimization algorithms need to be developed that maintain dynamic equilibrium between the multibody and the finite-element model.

3.4 Affordances

The principle of affordances was originally applied in cognitive psychology (Gibson, 1979). Affordances are interaction possibilities directly linked to geometry, which result from the characteristics of an object and the abilities of the user. As an example, cylindrical objects, such as a lever, offer users the possibility of a palm grip. They literally invite people to do so. On the other hand, compact cylinders (e.g. control knobs) are more likely to be operated with fingertip grips (compare Figure 4).

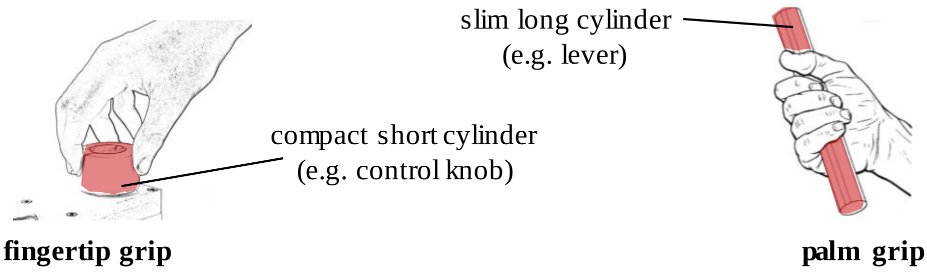

Figure 4. Affordances of cylindrical parts based on (Kapandji and Koebke, 2009)

Norman (2013) transferred this principle to product design. Affordances in this context are possible interactions between user and product that are intended by the designer and result from a product's shape. Therefore, affordances could contribute significantly to the virtual prediction and evaluation of user-product interactions, since they contain information on how a human (model) interacts concretely (mostly with his extremities) with certain product geometries.

Hence, the affordance approach must be further developed in the context of product development. Affordances may be a key factor towards a useful integration of digital human models into CAD. As proposed in one of our previous contributions (Wolf *et al.*, 2019b), certain geometry elements in a CAD model could for instance be connected to an affordance, using feature technology. The geometry element therefore contains the information on how to interact with it. This interaction behaviour is kinematically describable and can be considered as a constraint in a posture or movement prediction approach for digital human models.

3.5 Derivation of product/user-oriented properties

In order to create a good usability and an even better user experience, it is important to have an optimal fit between the user and the product as well as having an error-free and highly positive interaction. In this context, those properties influencing the user-product interaction need to be considered (Schröppel *et al.*, 2019b). On the one hand, the product's properties affecting the interaction are of interest (e.g. surface, shape of a product). On the other hand, the user's characteristics that are actually important for product usage need to be addressed (e.g. strength, personal attitudes toward a product). The main challenge for product development is to decide which of those are actually important and can thus be used to efficiently improve the user-product interaction.

Hence, the aim of product development should be the development of a computer-aided method to identify relevant product- and/or user-oriented properties. Therein, the user's characteristics, which are significantly important for product use, as well as the important product properties that refer to the user-product interaction have to be considered. Such an approach can help to identify the key parameters to model smooth and pleasurable interactions and thus lead to an improved product design.

3.6 Joint consideration of physiological and psychological aspects

User-centred design generally addresses both physiological and psychological components of the user. So far, they have only been considered separately. In order to create a more holistic understanding of

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the user also the interdependencies of physiological and psychological user demands have to be addressed. To do so, a methodical and well-founded approach for dual user integration is essential (Schröppel *et al.*, 2019a). In this context, such a methodology not only has to focus on the physiological capacity (e.g. motor and sensory abilities) but also on psychological factors (e.g. personal values and attitudes). Hereby vision as the essential sensory system as well as haptic as it strongly influences long-term user satisfaction are of great importance (Fenko *et al.*, 2010). Figure 5 illustrates the general structure of such methodology.

Figure 5. Generic structure of dual user integration

Dual user integration starts with a generic user description. Schröppel and Wartzack (2018) already analysed possible ways to describe a user in both ways. Capturing those characteristics of the user enables the analysis of the correlation between the two perspectives and therefore provide a better understanding of the user's needs. Additional to the user's description, a dual product assessment allows the generation of a mathematical link between product properties/characteristics and the user's physiological capacity and subjective expectation. This is the basis for dual product optimization. Before the method can be used efficiently, especially a valid link between the user's characteristics and product properties has to be modelled. In addition, studies are needed to better understand the relationship between physiological and psychological user needs.
Models like dual user integration are not yet fully integrated into virtual product development. In the long-term, this might change due to a modification of digital human models. Such advanced models may provide physical sensory data that can be used as input variables for dual user integration (e.g. pressure while touching a table). General physiological variables can already be extracted (muscle forces/ activation), but specific (sensory) physiological and psychological components are missing. Considering that the sensory system is the basis for a subjective evaluation of products (Zöller and Wartzack, 2017), such aspects should be primarily focused on. To begin with, sensorimotor components, for instance, would enable a more realistic representation of the interaction between user and product (e.g. taking target movements or reflexes into account).

3.7 Object perception

In terms of increasing the subjective quality of a product, it might not be necessary to revise the whole product but only specific areas. To identify relevant areas visual routines can be used to better understand the assessment process of a user. Hereby, quantitative parameters like the direction or duration of a person's gaze might be useful. A possible way for subjective optimization can then be the transferring of aesthetic principles (e.g. gestalt principles) to the design of the product.
Currently, eye tracking is often used to investigate object perception, as it enables the necessary collection of visual data in an easy and objective way. The main challenge is the proper interpretation and evaluation of the database. Hereby, gaze behaviour is primarily influenced by top-down and bottom-up processes. The bottom-up mechanism is stimulus-induced, whereas top-down processes start with an initial intention that controls gaze and attention (Ansorge and Leder, 2017). Hence, a given task changes the gaze behaviour of a person. For instance, if a participant of a study is asked about particularly beautiful parts of a product, he would look at the object differently as if no specific task is specified. Thus, to find subjectively relevant areas for product development, it is necessary to identify the key factors in terms of technical applications and derive appropriate study designs. Another challenge when analysing gaze data is the holistic view. According to Hammer (1992) there are two strategies for evaluating products. With the focal strategy, individual elements of the product are considered, whereas in the holistic strategy, the whole product is captured via peripheral vision (Kukkonen, 2005). Thus, even if the gaze database indicates specific fixations, it might just be the centre of a holistic process. Despite various studies using okulometry, those processes are not completely understood yet.

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In order to enable a proper identification of subjectively relevant product areas in product development, the main influencing factors need to be identified to develop an adequate study design. To ensure a reliable evaluation and interpretation of the data, holistic and focal gaze behaviour need to be better understood. Would it be possible to force a focal gaze behaviour for instance, subjectively relevant product areas can be directly derived from the visual data. Those areas can then be designed more attractive by using aesthetic principles.

3.8 Psychological assessment methods

In order to subjectively optimise products, the general necessity to do so has to be identified first. This need for action normally results from existing differences between the actual and the required perceived quality of a product. Thus, product development needs a sufficient and quantitative measuring instrument to detect such discrepancies.

Hereby, numerous influencing factors for subjective product evaluation have to be considered. According to Kroeber-Riel *et al.* (2009), the assessment of a product bases on two main aspects. The current information like the price or technical properties and characteristics as well as individual personal experiences and subjective expectations. Among others, those individual aspects can be strongly influenced by the user's personality. Which includes factors like personal attitudes and habits as well as emotional reactions and external influences like culture (McCrae and Costa, 1996). Such psychological aspects strongly affect the general evaluation process. Yet, product development does not consider them sufficiently. Additionally to the mentioned personality factors, the user's acceptance and preferences towards products also need to be addressed. Other disciplines like marketing already deal with those kind of topics. As an example, the additive difference model measures the user's preferences by evaluating two products and successively compare their characteristics and properties (Enders, 2013). Such assessments provide useful insights whether the user likes a product or not.

However, such models are rarely used in technical disciplines. In the future, acceptance and preference models as well as subjective influencing factors are essential for product development. Therefore, relevant aspects in terms of subjective evaluation need to be identified and integrated into the process of product development. An efficient use of such approaches and models enables the enhancement of the quality of subjective product optimization.

4 CONCLUSION

This contribution introduces the **UCD house** as a roadmap to a more holistic consideration of physiological and psychological aspects of the user-product interaction. Thereby, further research in the identified scientific subject areas, on the one hand, supports the efficient use of digital human models in product development (sections 3.1-3.4) and on the other hand provides a better understanding of the importance of subjective factors (sections 3.6-3.8). In addition, key parameters to model smooth and pleasurable interactions in general can be identified (section 3.5). Thus, it is not only possible to ensure the physiological virtual validation of products, but also to focus on long-term user satisfaction and improve user-centred product design. In the end, the interaction of all pillars of the UCD house enables a more holistic representation of user-product interaction. Accordingly, especially those products having a strong user interaction will benefit from such a holistic view including e.g. assistive devices like exoskeletons, applications in orthopaedics, medical technology and rehabilitation, the development of consumer goods or sports equipment, but also applications in the automotive sector or the design of work processes.

REFERENCES

Ackermann, M. and van den Bogert, A.J. (2010), "Optimality principles for model-based prediction of human gait", *Journal of biomechanics*, Vol. 43 No. 6, pp. 1055–1060.

Akao, Y.1990), *Quality function deployment: Integrating customer requirements into product design*, Productivity Press, Cambridge, Mass.

Ansorge, U. and Leder, H. (2017), *Wahrnehmung und Aufmerksamkeit*, Springer, Wiesbaden.

Bichler, R.J. (2015), *Biomechanik und Fahrzeugentwicklung: Erstellung und Anwendung eines Modells zur virtuellen Beurteilung des Ein- und Ausstiegs*, Zugl.: München, Techn. Univ., Diss., 2015, *Reihe Sportwissenschaften*, Vol. 16, 1. Aufl., Sierke, Göttingen.

Bubb, H. (2015), *Automobilergonomie, ATZ / MTZ-Fachbuch*, Springer Vieweg, Wiesbaden.

https://doi.org/10.1017/dsi.2019.406 Published online by Cambridge University Press

Damsgaard, M., Rasmussen, J., Christensen, S.T., Surma, E. and Zee, M.d. (2006), “Analysis of musculoskeletal systems in the AnyBody Modeling System”, *Simulation Modelling Practice and Theory*, Vol. 14 No. 8, pp. 1100–1111.

Enders, A. (2013), *Informationsintegration bei der Produktbeurteilung: Eine empirische Studie unter besonderer Berücksichtigung der Produktvertrautheit und des Produktinvolvements*, Springer, Heidelberg.

Farahani, S.D., Andersen, M.S., de Zee, M. and Rasmussen, J. (2016), “Optimization-based dynamic prediction of kinematic and kinetic patterns for a human vertical jump from a squatting position”, *Multibody System Dynamics*, Vol. 36 No. 1, pp. 37–65.

Fenko, A., Schifferstein, H.N.J. and Hekkert, P. (2010), “Shifts in sensory dominance between various stages of user-product interactions”, *Applied Ergonomics*, Vol. 41 No. 1, pp. 34–40.

Fluit, R., Andersen, M.S., Kolk, S., Verdonschot, N. and Koopman, H.F.J.M. (2014), “Prediction of ground reaction forces and moments during various activities of daily living”, *Journal of biomechanics*, Vol. 47 No. 10, pp. 2321–2329.

Freudenthal, A. (1999), *The design of home appliances for young and old consumers, Series ageing and ergonomics*, Vol. 2, Delft University of Technology, Delft.

Gibson, J.J. (1979), *The Ecological Approach to Visual Perception: Classic Edition, Psychology Press & Routledge Classic Editions*, Taylor and Francis, Hoboken.

Glende, S. (2010), Entwicklung eines Konzepts zur nutzergerechten Produktentwicklung mit Fokus auf die “Generation Plus”, *Dissertation*, Fakultät für Verkehrs- und Maschinenwesen, Technische Universität Berlin, Berlin.

Gößling, R., Eicker, H., Bartz, M. and Bender, B. (2014), “Biomechanische Betrachtungen der Berechnung von Kräften mit Menschmodellen”, *Beiträge zum 25. Symposium Design for X*, TuTech, Hamburg, pp. 110–120.

Gould, J.D. and Lewis, C. (1985), “Designing for usability. Key principles and what designers think”, *Communications of the ACM*, Vol. 28 No. 3, pp. 300–311.

Hammer, N. (1992), *Möglichkeiten und Grenzen der Überprüfung von Designprodukten durch Okulometrie*, Die Blaue Eule, Essen.

Hassenzahl, M., Burmester, M. and Koller, F. (2003), “AttrakDiff. Ein Fragebogen zur Messung wahrgenommener hedonischer und pragmatischer Qualität”, In: G. Szwillus and J. Ziegler, 57, *Mensch & Computer 2003: Interaktion in Bewegung*, Teubner, Stuttgart, pp. 187–196.

Holden, D., Saito, J. and Komura, T. (2016), “A deep learning framework for character motion synthesis and editing”, *ACM Transactions on Graphics*, Vol. 35 No. 4, pp. 1–11.

Iwamoto, M., Kisanuki, Y., Watanabe, I., Furusu, K. and Miki, K. (2002), “Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction”, *International Research Council on Biomechanics of Injury*.

Kano, N. (1984), “Attractive Quality and Must-Be Quality”, *J. Jpn. Soc. Quality Control*, Vol. 14, pp. 39–48.

Kapandji, A.I. and Koebke, J. (2009), *Funktionelle Anatomie der Gelenke: Schematisierte und kommentierte Zeichnungen zur menschlichen Biomechanik ; [einbändige Ausgabe: obere Extremität, untere Extremität, Rumpf und Wirbelsäule], 5.*, [unveränd.] Aufl., Thieme, Stuttgart.

Kroeber-Riel, W., Weinberg, P. and Gröppel-Klein, A. (2009), *Konsumentenverhalten*, 9th ed., Vahlen, München.

Krüger, D. and Wartzack, S. (2014), ““Towards CAD integrated Simulation of Use under Ergonomic Aspects”, *Proceedings of the International Design Conference - DESIGN 2014*, pp. 2095–2104.

Krüger, D. and Wartzack, S. (2017), “A contact model to simulate human-artifact interaction based on force optimization. Implementation and application to the analysis of a training machine”, *Computer methods in biomechanics and biomedical engineering*, Vol. 20 No. 15, pp. 1–10.

Kukkonen, S. (2005), *Exploring Eye-Tracking in Design Evaluation*, 25.-28.11.2005.

McCrae, R.R. and Costa, P.T.J. (1996), “Toward a new generation of personality theories: Theoretical contexts for the five-factor model”, In: J.S. Wiggins, (Ed.), *The five-factor model of personality: Theoretical perspectives*, Guilford Press, New York, pp. 51–87.

Miehling, J. (2018), *Berücksichtigung biomechanischer Zusammenhänge in der nutzergruppenspezifischen virtuellen Produktentwicklung, Fortschritt-Berichte VDI. Reihe 1, Konstruktionstechnik/ Maschinenelemente*, Nr. 445, VDI Verlag, Düsseldorf.

Miehling, J., Geißler, B. and Wartzack, S. (2013), “Towards Biomechanical Digital Human Modeling of Elderly People for Simulations in Virtual Product Development”, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 57 No. 1, pp. 813–817.

Miehling, J., Schuhhardt, J., Paulus-Rohmer, F. and Wartzack, S. (2015), “Computer Aided Ergonomics Through Parametric Biomechanical Simulation”, *Volume 1B: 35th Computers and Information in Engineering Conference*, Boston, Massachusetts, USA, Sunday 2 August 2015, ASME. V01BT02A016.

Miehling, J. and Wartzack, S., “Strength Mapping Algorithm (SMA) for Biomechanical Human Modelling using Empirical Population Data”, *Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. 10: Design Information and Knowledge Management*, pp. 115–124.

Miehling, J., Wolf, A. and Wartzack, S. (2018), “Musculoskeletal Simulation and Evaluation of Support System Designs”, In: A. Karafillidis and R. Weidner, (Ed.), *Developing Support Technologies: Integrating*

Multiple Perspectives to Create Assistance that People Really Want, *Biosystems & Biorobotics*, Springer International Publishing, Cham, pp. 219–227.
Nagamachi, M. and Lokman, A.M. (2011), *Innovations of Kansei engineering*, CRC Taylor & Francis, Boca Raton.
Norman, D.A. (2013), *The design of everyday things*, Revised and expanded edition, Basic Books, New York, NY.
Pankoke, S. and Siefert, A. (2007), "Virtual Simulation of Static and Dynamic Seating Comfort in the Development Process of Automobiles and Automotive Seats. Application of Finite-Element-Occupant-Model CASIMIR", *JUN. 12, 2007*, SAE International400 Commonwealth Drive, Warrendale, PA, United States.
Peng, X.B., Abbeel, P., Levine, S. and van de Panne, M. (2018), "DeepMimic. Example-Guided Deep Reinforcement Learning of Physics-Based Character Skills", *ACM Transactions on Graphics*, Vol. 37 No. 4, pp. 1–14.
Rasmussen, J. (2005), "Musculoskeletal Simulation – (Dis)comfort Evaluation", *S&V OBSERVER*, pp. 8–9.
Schröppel, T., Miehling, J. and Wartzack, S. (2019a), *Roadmap für die Entwicklung einer Methodik zur dualen Nutzerintegration*, Stuttgarter Symposium für Produktentwicklung, 16.05.2019, Stuttgart. accepted Paper.
Schröppel, T., Miehling, J. and Wartzack, S. (2019b), *Konzept zur Identifikation relevanter Produkteigenschaften zur Unterstützung einer positiven User Experience*, Entwerfen Entwickeln Erleben, 27.-28.06.2019, Dresden. accepted Paper.
Schröppel, T. and Wartzack, S. (2018), "Making a difference: Integrating physiological and psychological needs in user description", In: P. Ekströmer, Simon Schütte and Johan Ölvander, (Ed.), *Proceedings of NordDesign 2018, Linköping, Sweden, 14th - 17th August 2018*, LiU Tryck, Linköping, pp. 1–10.
Seeger, H. (2005), *Design technischer Produkte, Produktprogramme und -systeme*, Springer, Berlin.
Seth, A., Hicks, J.L., Uchida, T.K., Habib, A., Dembia, C.L., Dunne, J.J., Ong, C.F., DeMers, M.S., Rajagopal, A., Millard, M., Hamner, S.R., Arnold, E.M., Yong, J.R., Lakshmikanth, S.K., Sherman, M.A., Ku, J.P. and Delp, S.L. (2018), "OpenSim. Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement", *PLoS computational biology*, Vol. 14 No. 7, pp. e1006223.
Thomke, S. (2000), "The effect of "front-loading" problem-solving on product development performance", *Journal of Product Innovation Management*, Vol. 17 No. 2, pp. 128–142.
Vajna, S. (2014), *Integrated Design Engineering: Ein interdisziplinäres Modell für die ganzheitliche Produktentwicklung*, Springer, Berlin Heidelberg.
Wartzack, S. (2001), *Predictive Engineering - Assistenzsystem zur multikriteriellen Analyse alternativer Produktkonzepte*, Zugl.: Erlangen-Nürnberg, Univ., Diss., 2000, *Dissertat*ion. *Fortschritt-Berichte VDI Reihe 1 Nr. 336*, VDI-Verlag, Düsseldorf.
Wolf, A., Binder, N., Miehling, J. and Wartzack, S. (2019a), "Towards virtual assessment of human factors: A concept for data driven prediction and analysis of physical user-product interactions", *22nd International Conference on Engineering Design*, Delft, 05.-08.08.2019, accepted Paper.
Wolf, A., Krüger, D., Miehling, J. and Wartzack, S. (2019b), "Approaching an ergonomic future: An affordance-based interaction concept for digital human models", *29th CIRP Design Conference*, Póvoa de Varzim, 08.-10.05.2019, accepted Paper.
Wolf, A. and Wartzack, S. (2018), "Parametric movement synthesis. Towards virtual design optimistaion of man-machine interaction in engineering design", In: D. Marjanović, M. Štorga, S. Škec, N. Bojčetić and N. Pavković, (Ed.), *Design 2018: Proceedings of the 15th International Design Conference, May 2018, Dubrovnik, Croatia, May, 21-24, 2018*, Fac. of Mechanical Engineering and Naval Architecture Univ, Zagreb, pp. 941–952.
Zöller, S.G. and Wartzack, S. (2017), "Considering Users' Emotions in Product Development Processes and the Need to Design for Attitudes", in Fukuda, S. (Ed.), Emotional Engineering, 5th ed., Springer International Publishing, Cham, pp. 69–97.

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