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Approaching an ergonomic future: An affordance-based interaction concept for digital human models

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Abstract

Digital human models offer great potential for the evaluation of physical human factors throughout all phases of product development. Unfortunately, digital human models lack a generic user-product interaction model to use them as universal and truly predictive CAE tools. In this contribution, we propose a concept for a generic and integrated interaction model based on the concept of affordances, the technology of CAD features and posture- and movement-prediction methods. Furthermore, we propose an affordance taxonomy, which shall enable a universal methodical description of interactions occurring during product use.

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Keywords: user centered design; user product interaction, digital human models, affordances, CAD features, human factors

1. Introduction

After decades of economical selection and engineering research and development work, the majority of modern products have reached a state of satisfactory fulfilment of their functional requirements. Consequently, additional demands such as perceived quality, user experience or ergonomics gain more importance in order to obtain differentiation in a global market of competing products. Classic product development methods, such as the approach according to Pahl/Beitz [1], are closely linked to the concept of function in the sense of a transformation of material, energy or signal. This way of thinking reaches its limits in the formulation of non-functional requirements, which occur particularly when humans are involved as active product users [2, 3] . For example, it is difficult to formulate a functional "ergonomic requirement", because it is not directly associated with any transformation.
For this reason, the classical **function-oriented** development approach of technical systems is increasingly supplemented with **relation-oriented** development approaches, such as user-centered design. User-centered design considers the relation of product, user and environment holistically, throughout the entire product life cycle [4]. In this paper, we want to focus on physical human factors, which are usually connected to requirements regarding ergonomics, comfort/ discomfort and usability.

In the early phases of product development (development of concepts, definition of product characteristics, etc.) user-centered design principles are currently characterized by the application of design guidelines and normative specifications. For example, Schmidtke et al. [5] give recommendations for the geometric characteristics of seats, footrests and worktables, or the DIN EN 894-4 [6] provides specifications for the position and arrangement of displays and actuators on machines. These examples show the restricted applicability of user-centered design when it comes to actual product design. A transfer of the guidelines to other products is problematic, due to the complexity of human factor related contexts. Therefore, empirical analyses and evaluations, by means of user tests and observations, are currently the major application of user-centered design. The prospective use cases are recreated under laboratory conditions using product prototypes or predecessors. The evaluation of a design regarding ergonomics or comfort is commonly derived from observations or user interviews [7].

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The results are therefore subjective and must be understood as an observation of a specific situation. The derived evaluation is solely valid for the considered design and is furthermore not holistically back traceable to product characteristics. Optimizing a design in terms of ergonomics or comfort would mean to pass many iterations of development and testing.

1.1. Virtual evaluation of user-product interactions

As in other areas of product development, there is a trend in user-centered design to replace user tests - at least partially - with computer-aided simulation methods. This corresponds to the idea of virtual product development, which intends to provide information about the effects of decisions on prospective product characteristics as early as possible in the development process [8]. In this context, simulations using digital human models (DHM) are of increasing importance. User tests are replaced by evaluation procedures that abstract an ergonomic problem into a mathematical model [9]. Simply speaking, DHM allow for specific virtual user-tests at all phases of product development. Figure 1 depicts the general relationship between the user, described by demographic and psychographic characteristics and the product with its technical, economical and human-related properties. The interaction is composed of a process of perception and response [10]. The idea is to evaluate the interaction between user and product completely virtually, by using a virtual representation of the product (e.g. computer aided design (CAD) part or assembly) and a virtual representation of the user (e.g. digital human model) [11, 12].

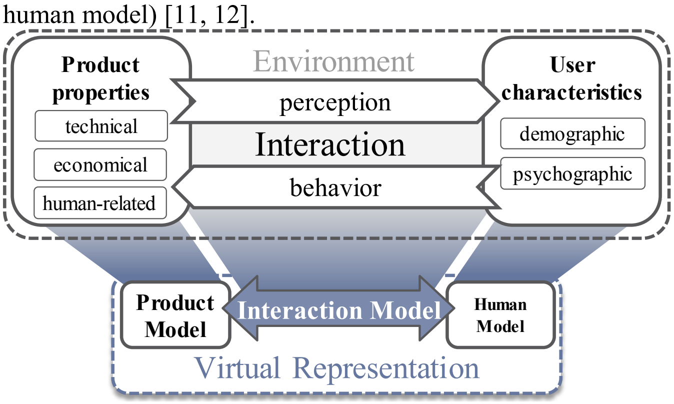

Fig. 1. User-product relationship based on [10], with virtual representations

Depending on the purpose, the digital representatives have to model/ contain the necessary properties and characteristics of their "real live equivalents". Accordingly, different DHM are applied for different evaluations.

1.2. Digital human models: potentials and drawbacks

Digital anthropometric human models are widespread and are usually integrated into CAD systems as additional modules. The main objective of these models is the realistic representation of the human body dimensions within a CAD assembly. The human models, which are mostly implemented as CAD geometry themselves, are scalable on the basis of anthropometric data collections. Thus, for the anthropometric extreme percentiles of a population (see Figure 2), corresponding representatives can be generated and integrated into a product model. Examples of industrially used anthropometric human models are Human Builder (Dassault Systémes), Jack (Siemens PLM) and RAMSIS (Human Solutions) [9]. Their major application are space requirement analyses, reach analyses or visual analyses. In order to evaluate certain usage scenarios, the human model needs to be manually positioned in a CAD assembly.

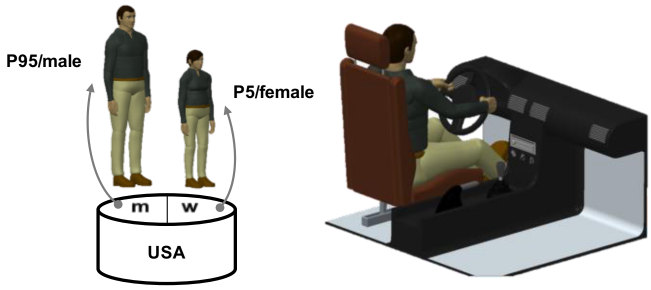

Fig. 2. Scaling of anthropometric human models (left); Anthropometric human model positioned in a car interior (right)

Additionally ergonomic evaluations are executable using assessment tools like NIOSH [13], RULA [14] or EAWS [15]. These methods refer to the assumption that ergonomic aspects are derivable from body postures.

Digital musculoskeletal human models allow a far more differentiated and direct evaluation of ergonomic aspects, as they enable dynamic analyses (i.e. for movements) regarding the stress of the human locomotor apparatus (in form of muscle- and joint-reaction forces). The human musculoskeletal system is modeled as a dynamic multi-body model, which is usually simulated inverse dynamically due to the high number of degrees of freedom and individual muscle actuators. This means, that the posture (or the movement) of the human body as well as all external forces acting on the body must be known a priori (Figure 3) [16].

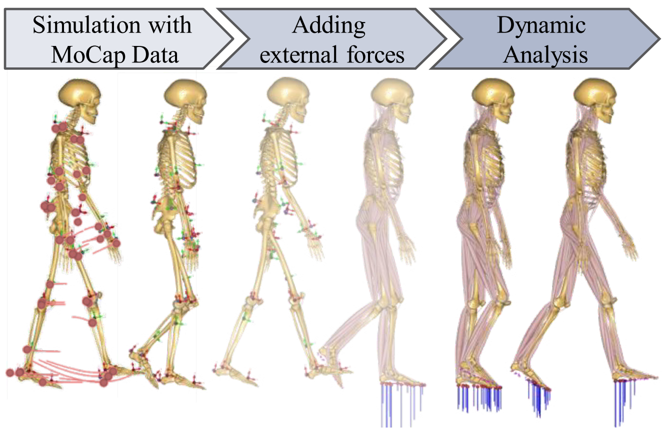

Fig. 3. Conventional approach to musculoskeletal simulation using the inverse dynamic approach at the example of a biomechanical gait analysis

In practice, this typically requires both the human movement and the external forces to be measured in a motion capture laboratory in order to simulate the interaction and calculate the inner body stress. Examples of scientifically and industrially prevalent musculoskeletal simulation frameworks are OpenSim [16] and the AnyBody Modeling System [17].

Both human models have their legitimacy for their specific applications. What DHM have in common, however, is that they are marginally applied in product development, as they are insufficiently integrated in the computer-aided design process [9]. This does not relate to the exchange of geometric data with CAD systems, but rather to the cumbersome modeling of the interaction between the user (human model) and the product (CAD model). Usually the postures expected in a certain usage scenario are specified manually. This is not just time-consuming and unhandy, but also requires expertise when it comes to the modeling of realistic and physiological postures. Modeling physiological movements manually, is far more challenging and circumstantial. Therefore, motion capturing methods are the gold standard, when it comes to simulations of DHM. Performing motion capturing however, again corresponds to an evaluation via classical user tests in an empirical way. In conclusion, digital human models lack a generic interaction model - embedded consistently in the computer-aided design process - to make them a universal and truly predictive computer aided engineering (CAE) tool [4, 11].

In this contribution, we propose a concept for such a generic and integrated interaction model based on the concept of affordances, the technology of CAD features and posture and movement prediction methods. Furthermore we propose an affordance taxonomy, which shall enable a methodical description of interactions occurring during product use.

2. Methods

2.1. Affordances

Originally, the term affordances (= to afford something) was introduced in cognitive psychology by Gibson [18]. Affordances are possibilities of interaction directly linked to physical objects, which result from the abilities of the actor (human or animal) and the characteristics of the object. Daily experience indicates that slim, cylindrical objects (e.g. a broom handle) offer us humans the possibility of a palm grip. They practically invite us to do so. On the other hand, compact cylinders (e.g. knobs) are more likely to be contacted by a fingertip grip (Figure 4).

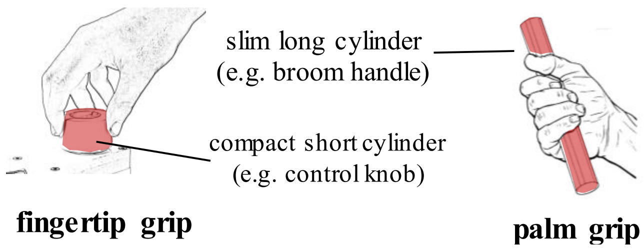

Fig. 4. Affordances of cylindrical objects according to [19]

The corresponding affordances (e.g. "can be grasped") are attributed to the objects based on the anatomy of the human hand and the associated abilities. For physically disabled people, these affordances may not exist. According to Gibson, it does not matter whether the actor recognizes the affordances associated with objects, or not. The term describes a basic possibility of interaction.

Norman [20] later transferred the concept of affordances to product design. According to his understanding, affordances are possible interactions between user and product, which are intended by the designer and result from the structure and form of the product. Norman defines affordances as a relationship not a property, since the existence of an affordance depends upon the properties of both the product and the user. Furthermore, Norman contradicts Gibson by postulating that affordances depend on the perception of the actor.

Galvao and Sato [21] propose developers to consider affordances at three instances (1) the affordances embedded in a product, (2) the perceptual attributes of these affordances in users' mental models and (3) the instantiation of affordances when users perform their actions. For example, a chair has the embedded affordances "climb-ability" and "lift-ability". These are perceivable by human users as affordances in the form of "can be sat on" and "can be lifted". Consequently, the act of sitting instantiates the affordances and closes the interaction cycle.

2.2. Feature technology

With the goal of shortening development times, former sequentially executed activities are increasingly parallelized in the product development process. This procedure, known as simultaneous engineering, requires the availability of product information throughout all life phases and domains. Based on this motivation, feature technology was established in product data modeling. The aim of this technology is the simplification of information exchange throughout the entire product life cycle. In particular the support of data exchange between different CAD/ CAE tools a is major advantage [8].

In CAD technology, the term "feature" strongly relates to geometries. In most cases, they refer to a combination of basic geometric operations to form an application-related geometry (e.g. commands for modeling chamfers, ribs and draft angles). However, features are not limited to geometric information. A concept developed by the FEMEX working group [22] underlines the role of features as integration objects that can link information from different product property classes (geometry, mechanics, manufacturing etc.) and life phases (e.g. design, product use, recycling). Since the property class "geometry" is of outstanding importance for products with a physical shape, features are commonly defined as an aggregation of **geometry elements** and/or **semantics** [22, 23]. Semantics refers to the meaning assigned to a product section/ geometry by the feature in relation to a specific phase of the product life cycle. The theoretical application range of feature technology results from the possible property classes [24] of a technical system and the individual phases of the product life cycle. A hole, for example, may be considered as a negative cylinder in geometric modeling, whilst for manufacturing it may be tagged as threaded hole. Hence, the machine tool "knows" what drill/ thread tap to use. The prospective function in design however, could be the possibility of fixing a screw.

2.3. Posture and movement prediction

Inverse kinematic methods are widespread for positioning digital human models. Those methods are applied to compute joint coordinates ($\boldsymbol{q}$) of a kinematic chain (Fig. 5), which fulfil certain geometric conditions (constraints).

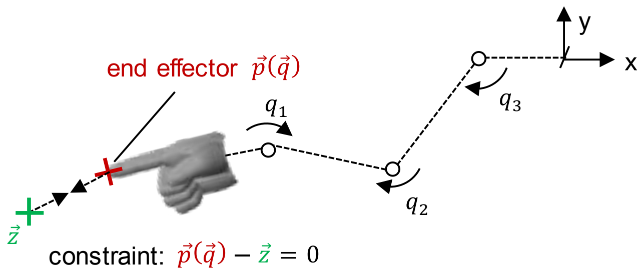

Fig. 5. Inverse kinematic problem

The constraints are usually formulated as spatial relationships between so-called end effectors and the environment. The term "end effector" originates from robotics and refers to a geometric reference (point, vector, etc.) in a kinematic chain, which is of interest for the respective application. Exemplary end effectors of the human body are the fingertips, palms of the hand, but also the sight axis of the eyes for visual interaction. In Figure 5, the constraint equation requires that a point $\boldsymbol{p}$ on the fingertip (end effector) matches a pre-defined position in space $\boldsymbol{z}$. Due to the high number of degrees of freedom (DoF) of the human locomotor apparatus, inverse kinematic problems are generally under determinate, i.e. the joint coordinates $\boldsymbol{q}$ (posture) cannot be directly resolved from the constraint equations (more DoF than constraint equations). Consequently, there may be an infinite number of solutions/ postures.

In order to resolve this kinematic redundancy, especially optimization based approaches [25–27] have been established in addition to heuristic [28] and data driven [29] methods. Within the set of all possible postures is one posture, which fulfils a predefined evaluation criterion (e.g. minimum fatigue) in the best possible way. In order to find this particular posture, nonlinear optimization algorithms are applied. Those search for the extreme value (also called optimum) of an objective function $F(\boldsymbol{q})$, under the condition that the solution fulfils the geometric constraint equations.

3. Interaction model concept

We propose a user-product interaction model based on the methodical concept of affordances. In the following, the term affordances refers to what Galvao and Sato [21] introduced as **operational affordances** regarding to structural attributes: User-product relationships, directly linked to and offered by structural attributes of a product. The research work of Götz [30] and Murakami et al. [31] indicates that the whole spectrum of affordances is based on few geometrical attributes. Considering that, we hypothesize that many interaction concepts occurring in technology can be reduced to a relatively small set of elementary affordances. The idea is to implement this set of elementary affordances as CAD features. These "affordance features" enable the product designer to assign information about the prospective interaction possibilities to the corresponding parts of virtual product models (CAD parts/ assemblies). In other words: The product model contains the information how it would like to be used. This is of outstanding importance for the useful integration of DHM in the computer-aided design process, since it allows simple modeling of interactions between DHM and virtual product models (CAD parts/ assemblies). The interaction information (e.g. can be grasped with a palm grip) can be formalized mathematically and can thus be considered as a constraint (which describes the correct position of the end effectors to an interaction element) in a posture or movement prediction formulation. Figure 6 provides an overview of the interaction model, explained with an exemplary use case, which is briefly described in the following chapter.

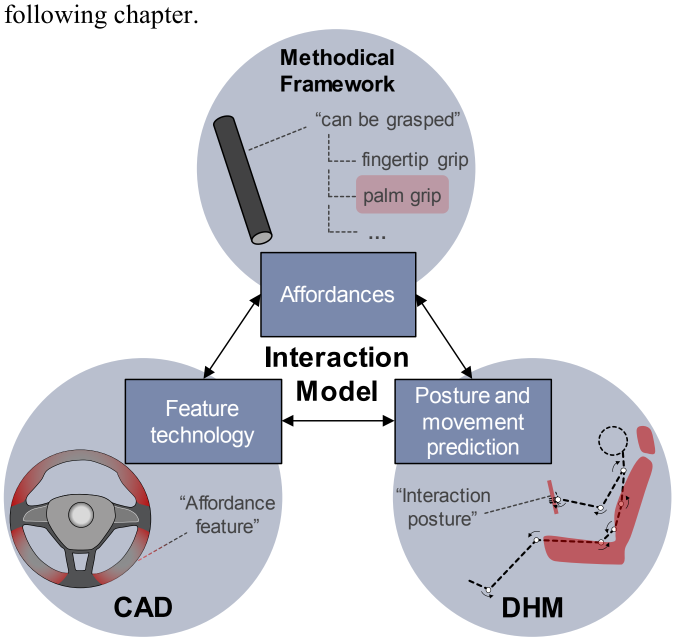

Fig. 6. Interaction model concept

3.1. Exemplary use case of the prospective application

While designing a steering wheel for an automobile via CAD, the product designer assigns an affordance feature to the torus-like geometry (marked red in Figure 6). This geometry (which could be interpreted as the rudimental geometry "slim long cylinder") affords different interactions, such as "can be grasped" or "can be looked at". In our example we assume the designer wants to choose "can be grasped". The geometry of the torus indicates a grasp via a palm grip.

Later in the design process the designer may want to evaluate the automobiles' interior virtually regarding human factors. Thanks to the affordance features the designer is able to model the interaction scenario in a simple way, using a DHM and an assembly of the CAD interior parts. After assigning where the steering wheel shall be grasped, the hands of the human model are automatically positioned correctly on the steering wheel, using inverse kinematic algorithms [25]. Likewise, the buttock and the back can be positioned on the seat, given that the seat-part was previously assigned with the affordance features "can be sat on" (on the seating surface) and "can be leant against" (on the backrest). A posture prediction algorithm computes a physiological posture, taking the given constraints into account. Once the interaction scenario is defined, the interior design (arrangement of the control elements, or the control elements' geometry itself) can be arbitrarily adjusted and virtually optimized regarding ergonomics, comfort/ discomfort or usability.

3.2. Methodical affordance framework (taxonomy)

Affordances are complex and entangled. A push-button affords "can be pressed". The pressing can be done with the fingers (thumb, index, etc.), the palm, the fist and so on. An accelerator pedal would also afford "can be pressed", but is usually operated with the foot. Moreover, both control elements show a different "actuation behavior" (regarding translational way and actuation force), which additionally depends on the interindividual capabilities of the users [32].

To enable a universal description of interactions occurring in product development by means of affordances, we suggest setting up a taxonomy that contains all elementary affordances and classifies them reasonably. An advantage of such a taxonomy is that it provides a standardized methodical framework for the description of interactions. Additionally, such a classification system is systematically convertible into the desired features. As classification criteria for affordances we propose shape, reference, kinematics and dynamics:

- **Shape**: What are the basic geometric features that communicate an affordance? Can these be approximated by geometrical primitives such as points, surfaces, pairs of surfaces, cylinders, etc.?
- **Reference**: Which human end effectors (hands, feet, etc.) can be involved in the interaction? Are several alternatives conceivable? What are the human's/ user's capabilities?
- **Kinematics**: Is the interaction associated with a kinematic change of state of the control element? If so, which degrees of freedom (translational, rotational) are available?
- **Dynamics**: Are forces transmitted between user and control element during the interaction? If so, which components are relevant?

For complex interactions, Gaver [33] introduced the idea of sequential affordances. Sequential affordances refer to interactions, in which acting on an affordance leads to information indicating a new affordance. For example a valve wheel sequentially affords "can be grabbed" and "can be turned". Consequently the affordance "can be turned" might be classified with another affordance "can be grabbed". To describe this entanglement within a taxonomy we suggest to use the terms **intentional affordances** and **intuitional affordances**. The intentional affordance is the primarily interaction ("can be turned) the user intentionally wants to perform, when using a control element. The intuitional affordances are the secondary affordances ("can be grabbed") the user intuitionally performs in order to achieve the goal of the primarily interaction/ intentional affordance. Figure 7 illustrates one possibility of a user-product-interaction description via a taxonomy of elementary affordances.

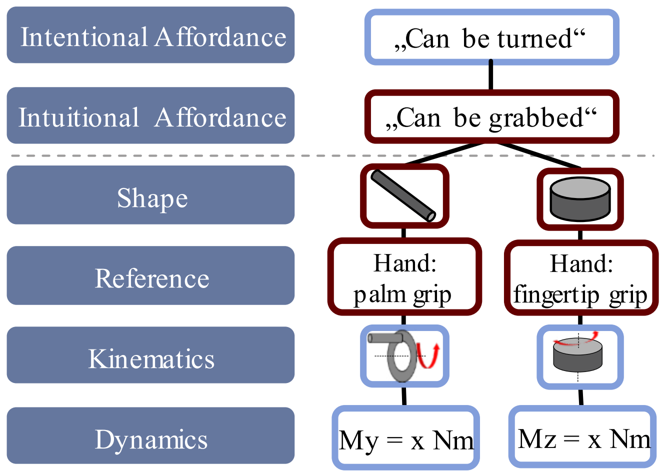

Fig. 7. Description of an interaction with a "valve wheel with handle" and a "potentiometer", via the taxonomy of elementary affordances. The intentional affordance "can be turned" (blue) is hereby classified with the intuitional affordance "can be grabbed" (red)

4. Conclusion & Discussion

The proposed classification criteria of the taxonomy were chosen based on first considerations and the results of published studies [30, 31, 34] and methods/ classifications described in literature [2, 20, 21, 33]. In order to verify and optimize this taxonomy, technical systems (machine tools, construction machines, vehicles, consumer products etc.) should be analyzed, regarding all occurring user-product interactions. Subsequently, it must be examined whether the affordances, underlying the collected interactions, can be described by the proposed classification criterions/ taxonomy.

The proposed interaction concept in combination with the proposed taxonomy provides orientation on how user-product interactions can be methodically described and consistently embedded in the computer-aided design process. Through the implementation of these concepts and with accompanying studies, the concept presented in this paper can be verified and, if necessary, further optimized.

5. Outlook

Although first steps have been made, a lot of research work has to be done, until the vision of virtual user-tests becomes widely implemented. First of all, the proposed taxonomy needs to be verified using the suggested approach (chapter 4). After that, the taxonomy of elementary affordances needs to be converted into CAD features. Another challenge will be the integration of (anthropometric and musculoskeletal) DHM into the interaction model and the virtual CAD environment. Hereby, the selection and implementation of suitable posture- and movement-prediction approaches will be a major challenge. Once all this is achieved, the reward will be a new CAE tool, which will enable the consideration of physical human factors throughout all phases of product development.

Acknowledgements

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