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VIRTUAL ASSESSMENT OF PRODUCT USE BASED ON BIOMECHANICAL HUMAN MODELS

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1. Motivation

For a long time the dominating view on product design was affected basically by functional and economic aspects. Today a growing awareness of health in society is emphasising the importance to put the human into the center of all considerations. In fact the value of many products is determined essentially by how well their properties harmonise with the individual competencies and needs of the people who use them. [Dreyfuss 2003] The objective must be to provide an optimal fit between human beings and technical systems. The idea of an user-centred design is reflected in considerations that focus on aesthetics but most of all on product ergonomics. This however requires detailed information on the prospective use, especially on the direct interaction between users and products to be available already in the early stages of the development process. The use of a product (figure 1) is always associated with a task the user wants to accomplish. Therefore a sequence of actions is chosen that trigger appropriate functions of the product. At the same time the user constantly adjusts his behaviour based on the perception of the products response. It is important to notice that human behaviour (action) and product behaviour (response) are mutually dependent and cannot be analysed separately.

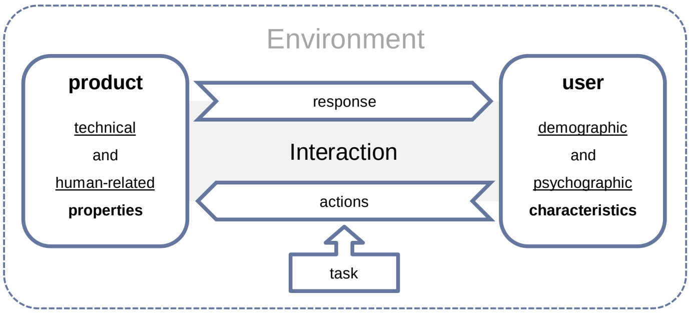

Figure 1. User-product interaction

From an ergonomic perspective the matter of interest is how the organism of the user is affected by the interaction process. Therefore the popular concept of load and stress [Bullinger 1994] is applied to product use. While interacting with a product a person can be subject to external loads such as mechanical forces, vibrations, noise, chemical substances and also cognitive loads (information). These external influences induce an internal stress on the organism. Mechanical loads for example mainly affect the persons musculoskeletal system resulting in biomechanical stresses. The ergonomic load-stress concept is analogous to the corresponding notions in engineering mechanics, which is shown by a simple example in figure 2. A cantilever beam is loaded by a force. The resulting deformation (stress) is a function of the load but also of the physical properties Young´s modulus and moment of resistance. Equally ergonomic stresses not only depend on the loads but also on the biomechanical, physiological and psychological characteristics of the user.

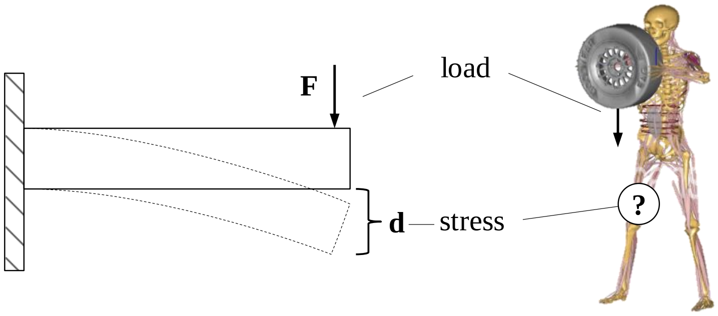

Figure 2. Equivalence of the load - stress concept in engineering mechanics and ergonomics

Biomechanical stresses, e.g. muscular activity or joint reaction forces, can be associated with ergonomic goals like comfort, safety and harmlessness. Hence if designers were able to simulate the relationship between product characteristics and the level of stress prevalent during the phase of use they would gain valuable insights on how to improve the ergonomic quality of products.

In this paper therefore a novel application of biomechanical digital human models is proposed to simulate ergonomic aspects of product use employing virtual product prototypes only. The objective is to provide a framework to analyse interaction processes between users and products within a common computer-aided design (CAD) environment. Further it is shown how user or user-group specific properties can be considered in biomechanical human models. Even though the scope of this paper is on the design of products with close user interaction like vehicle interior, medical devices or sports equipment, many aspects are also relevant for the design of workplaces and the planning of assembly processes.

2. Biomechanical digital human models for ergonomic evaluation

In the early stages of the product development process industry standards like DIN 33401 can provide general guidelines on issues of human-product interaction. However due to the heterogeneity of human characteristics and the huge amount of imaginable products universal rules on ergonomic design are often too generic as being helpful in a specific case. The standard ISO 9241-210 therefore points out the importance of testing. Thereby a fully or partial functional physical mock-up of the product is presented to persons in order to evaluate its ergonomic quality. Even though the informational value of physical experiments is undoubted they are always time consuming and costly. Consequently as in other areas of engineering there is a strong motivation to replace physical testing with computer simulations. This gives rise to digital human modelling. The idea is to have a virtual model of the user interacting with a virtual prototype of the product. This not only leads to a reduction of costs but also gives much more freedom to designers to think through multiple concepts because the results of a virtual experiment are usually available within a short time span. Biomechanical simulation systems like OPENSIM [Delp 2007] or ANYBODY [Damsgaard 2006] were developed to describe structure and motion of the human musculoskeletal system based on multibody dynamics. The skeleton is modelled as a set of rigid or partially compliant bodies that are interconnected by joints. Muscles, tendons and ligaments are represented by special force actuators. Some advanced muscle models even consider effects of fatigue. The primary purpose of these software packages is the analysis of human motion sequences employing inverse dynamic calculations (figure 3). This method requires that the motion of the human model is unambiguously determined by time series of the generalised coordinates and their derivatives $q, \dot{q}, \ddot{q}$ which correspond to the angles of human joints. If further all external forces F acting on the body are known the equations of motion can be solved for the actuating forces T which are identified as the joint torques generated by the muscles. In subsequent postprocessing steps additional indicators of biomechanical stress like the level of muscular activity, metabolism and joint reaction forces can be determined. Even though biomechanical digital human models were developed for applications in motion medicine, they perfectly fit into the ergonomic load-stress concept. Since they reveal the physiological causes for ergonomic issues, the simulation results (e.g. muscular activity) can directly be regarded as ergonomic assessment criteria.

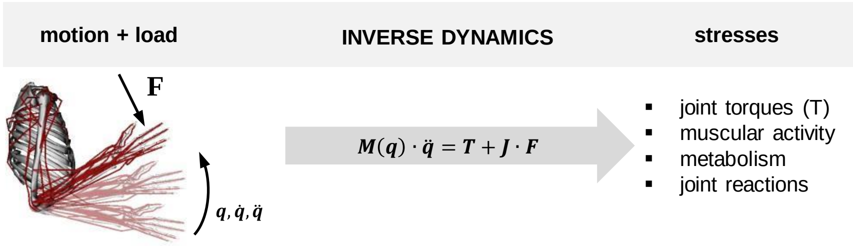

Figure 3. Inverse dynamic analysis of motion

Being among the first to suggest biomechanical human models as design tools [Rasmussen 2003] used the ANYBODY modelling system to optimise the ergonomic properties of a hand saw. Also the US Defense Advanced Research Projects Agency supports an effort to use OPENSIM for design activities within the scope of developing special suits for soldiers that reduce the risk of injuries and fatigue in combat missions [Simtk 2013]. A broader application in design however may be inhibited by the fact that biomechanical simulation systems have not been integrated into the processes of virtual product development. Inverse dynamic simulations determine the biomechanical stresses as a consequence of posture, motion and external forces. The problem is that in case of a truly virtual simulation the information on how a user will move during the interaction with a product is not available. A possible solution is to record the motion of a test person and map the data on the human model [Robert 2013] but this would again mean that a physical experiment had to be conducted and the major benefits of virtual testing would be lost. In this paper therefore a concept for a CAD integrated biomechanics laboratory is presented. The objective is to improve the usability of biomechanical simulations in design. Usability in this context means that the person that uses a simulation program must be able to provide the input data required to setup the computations as well as understand and interpret the results. Design engineers usually know very precisely what functions of the product have to be triggered in order to fulfil the tasks it has been designed for. A formulation of the interaction processes between the user and the product should therefore rely on task descriptions that encode information on how the state of the product or the environment has to be manipulated. Human actions (posture and motion) that achieve these manipulations should not be required as input information but be predicted by the simulation. Since a huge proportion of the synthesis work in design is nowadays done using computer-aided methods it is reasonable to postulate a close **integration of biomechanical simulations with CAD** engineering environments. In this regard user or user group-specific properties are to be taken into consideration in the preceding digital human modelling step, eventually facilitating robust designs concerning ergonomic aspects of the end product.

3. Consideration of user-specific characteristics in biomechanical digital human models

As biomechanical digital human models, also called musculoskeletal models, comprise just a skeleton as well as muscles, in the first stage we focus on differences in anthropometry as well as motor functions like strength, range of motion and motion speed. [Miehling 2013] proposed a process for the conception of biomechanical digital human models taking the interdependences of the considered domains into account. This procedure is outlined in figure 4. The relevant data to consider the heterogeneous differences over the human life span in the conception stage are taken from literature.

First of all **gender** and **age** of the model to be generated have to be chosen according to the target group of the product to be developed. In the consecutive steps of the adaption process percentile values in conjunction with already existing population data are favourable to specify the model. However, data from manual measurements can be beneficial to model a specific person or user group.

The method of choice for specifying the **body measures** in most cases is to chose a percentile. The height and consequently scaling information 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 in most cases can be presumed to follow a normal distribution. Studies therefore mostly make the body height distribution of a specific age group and sex available as mean value accompanied by the standard deviation or standard error as for example in the National Nutrition Survey II (NVS II) published by the Max Rubner-Institut in 2008. This representative survey among others reports the socio-demographic characteristics as well as anthropometric measures of the german population. In contrast, if the model to be generated should resemble a specific (real) person, manual measurements have to be conducted to get the overall body height as well as values for the dimensions of the individual body segments. Regardless of the data origin, subsequently scaling factors for all body segments are calculated which are eventually used to scale the musculosceletal model.

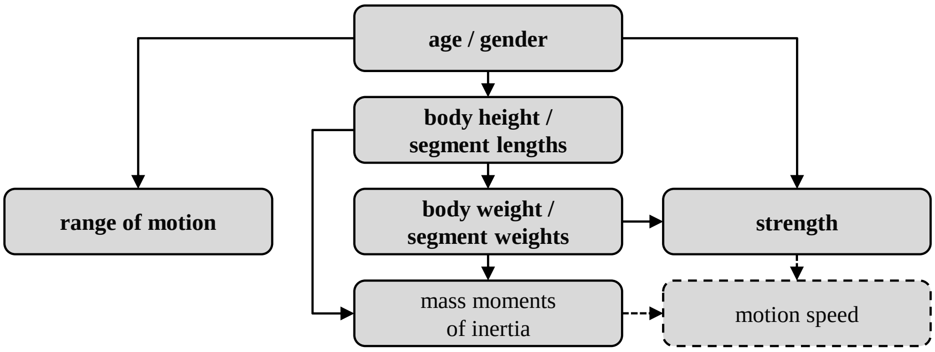

Figure 4. Overview of the conception process [Miehling 2013]

Another sophisticated method is to retrieve the segmental lengths through optical, marker-based or markerless measurement systems usually used for motion capture purposes. [Krüger 2012] for example developed a system for the markerless capture of motions as well as scaling of biomechanical digital human models using the Microsoft Kinect sensor, originally developed as game controller. This system automatically provides the scaling factors for the body parts without need for further computation. Its user interface is depicted in figure 5.

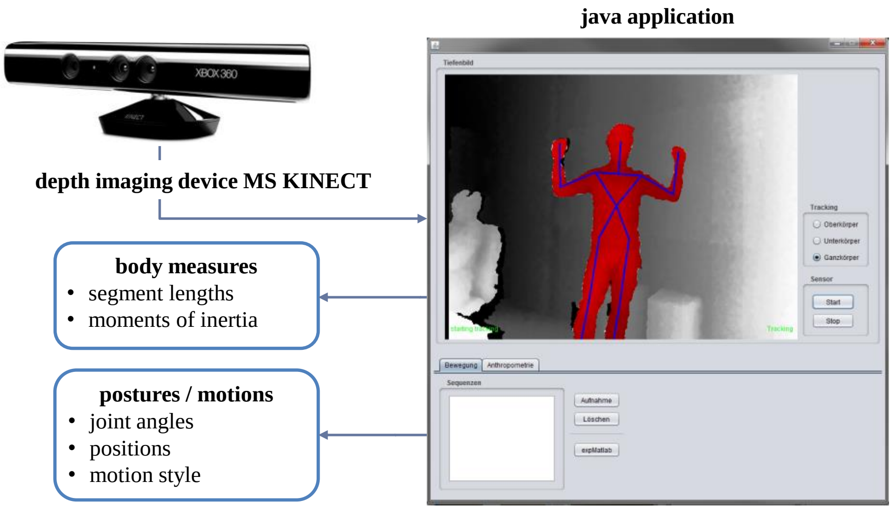

Figure 5. Low-cost motion capture system based on Microsoft Kinect

After collecting the data for the segmental lengths, the **body weight** of the model to be generated has to be specified. Even though body weight is usually not normally distributed, the majority of surveys report the weight in the same way as the body height and therefore neglect valuable information about the underlying sample. Moreover, body weight tends to increase with body size. This correlation hampers the computation of the body weight using the body weight distribution of the population. In the present approach body weight can therefore either be chosen directly or by the body mass index (BMI). [Keys 1972] advised the BMI (body weight [kg] / (body height)² [m²]) as a measure for the physical constitution of populations. It removes the dependency between weight and height and is a good predictor for body fat percentage. [Hemmelmann 2010] calculated the BMI distribution for both genders and every single year of age using the LMS method based on the raw data of the NVS II. After chosing a percentile of the BMI distribution, the BMI can be computed. Hereafter, the body weight can be calculated taking into account the body height of the preceding step. The entire body's mass distribution, respectively individual body segment weights, are then computed considering the scaling factors for the body part dimensions. If the human model's dimensions are scaled just considering the overall change in body height, the mass distribution stays unaffected. The **mass moments of inertia** of the individual body segments are especially important in dynamic simulations. If the changes in the segments' mass and dimensions are known, the inertia tensors can be calculated. The **maximum isometric forces** generated by skeletal muscles are highly dependent on age, weight and size. 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 on, the maximum muscle forces decrease steadily. Women are generally less strong than their male counterparts. [Stoll 2002] measured and percentiliced the maximum isometric voluntary joint torques for a healthy population in a given joint angle constellation. This data is used to scale the maximum isometric force of every muscle of our biomechanical digital human model. Unlike with body measures, weight and strength, there seems to be no clear correlation between the range of motion 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 2008]. The maximum **motion speed** does not directly depend on body weight and size. The execution of movements decelerates just a small proportion 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. Taking the age distribution of the targeted culture into account, representative user groups can be generated for the following virtual assessment of product use.

4. A CAD integrated biomechanics laboratory

4.1 Concept and related work

In section 2 a **task oriented** formulation of user-product interactions and a seamless **integration with CAD environments** have been identified as the most important requirements on an application of biomechanical simulations in product design. Existing approaches to connecting biomechanical models and CAD systems are mainly addressing the problem of data exchange. The ANYBODY modelling system e.g. provides an import filter for product geometry created in SOLIDWORKS. A closer integration can be achieved by coupling a complex biomechanical model to the kinematics of a CAD integrated anthropometric model as published by [Jung 2013] and previously by [Krüger 2012].

Our concept (figure 6) uses a similar idea: an anthropometric human model (*skin model*) inside a common CAD environment serves as a front-end the design engineer uses for preprocessing. Preprocessing mainly comprises the definition of geometric relationships between the user and the product that are needed to setup the actual simulation performed on the *musculoskeletal model*.

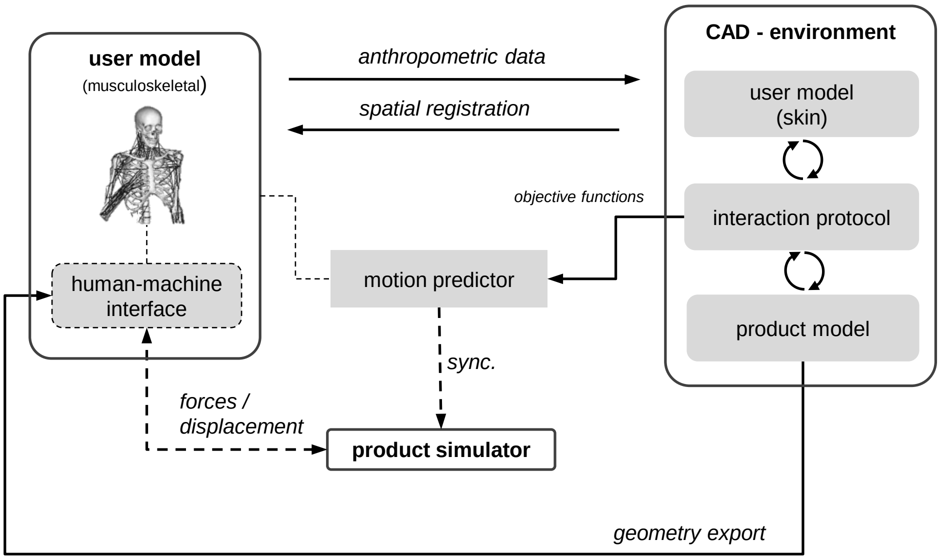

Figure 6. Concept of a CAD integrated biomechanics laboratory

The concept is built on four important pillars: the transfer of anthropometric data and posture (spatial registration) between the skin model and the musculoskeletal model, a task oriented protocol to formulate user-product interactions, a methodology to predict human motion and the simulation of product behaviour. In the following sections these topics are illustrated by means of a simple case study. The interaction process to be analysed is the situation of a person driving a passenger car as depicted in figure 7. Even though in reality the driver is interacting also with the gear lever and the pedal, the only task considered in this example is to turn the steering wheel slightly to the right. The question to be answered by this analysis is which region of the body shows the highest muscular activity.

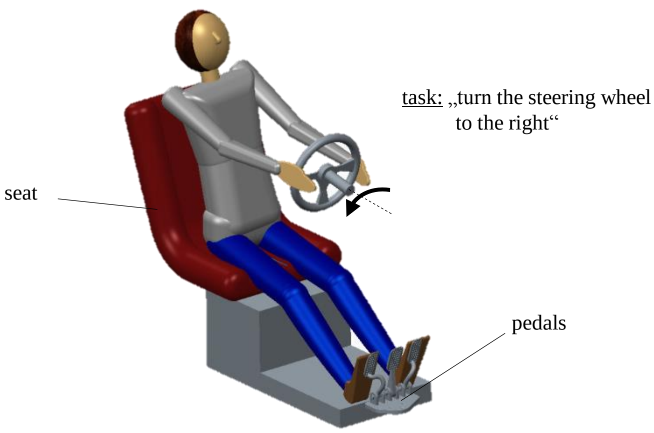

Figure 7. Case study: steering a passenger car

4.2 Transfer of anthropometric data and posture

In the beginning of a virtual experiment all relevant characteristics of the user like body measures or strengths must be choosen according to the procedure described in section 3. The output of this process is a musculoskeletal model for the OPENSIM platform. For the case study the musculoskeletal model has been choosen to resemble the anthropometric properties of an average European male. From within the CAD environment this musculoskeletal model is loaded and connected to the skin model. The connection consists of a scaling operation and a subsequent spatial registration of the two models. In the scaling operation the limb lengths of the musculoskeletal model are determined by calculating the distances of marker points located in the centres of the joints. These values are assigned to corresponding CAD parameters of the skin model. Since the skin model is used as a front-end of the actual simulation model it has to be assured that both models coincide geometrically. This means that for example the location of a point defined on the skin model must be unambiguously found also on the musculoskeletal model. This is achieved by a point by point registration (see figure 8): a set of datum points distributed over the limbs of the musculoskeletal model is fitted to a corresponding set located on the skin model by numerical inverse kinematics. As a result the musculoskeletal model follows the posture specified by the skin model.

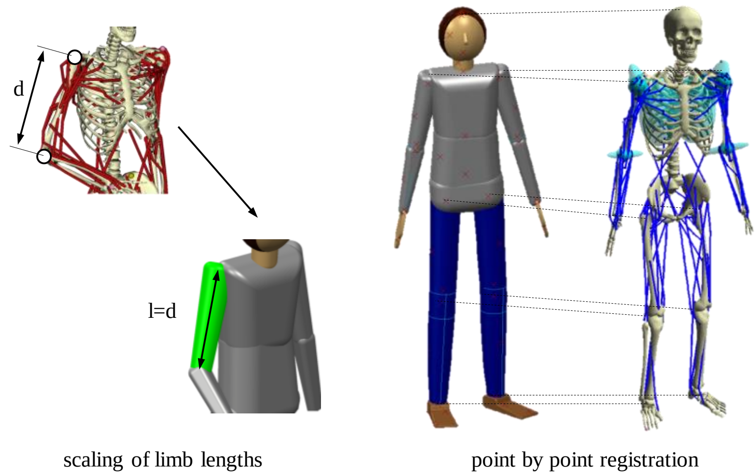

Figure 8. Transfer of information between skin model and musculoskeletal model

4.3 Task oriented interaction protocol

Once the human model is set up the next step is the formulation of the task to be analysed. As postulated in section 2 this formulation should not rely on descriptions of human behaviour (e.g. "move the right arm") but on required manipulations of the product. Therefore a formal interaction protocol has to be elaborated that could rely on a structured model of user-product interaction as published by [Mieczakowski 2010]. The current prototype of the protocol contains action goals and boundary conditions. To define an action goal the designer identifies parts of the product model as human-machine interfaces and describes how these parts have to be manipulated in order to trigger the desired function of the product. A boundary condition is a geometric relationship between the user model and the product model or the environment. In case of the steering example (figure 9) the claims that the buttocks of the user remain on the seat while both hands remain on the whee are typical boundary conditions whereas the required rotation of the wheel link is an action goal.

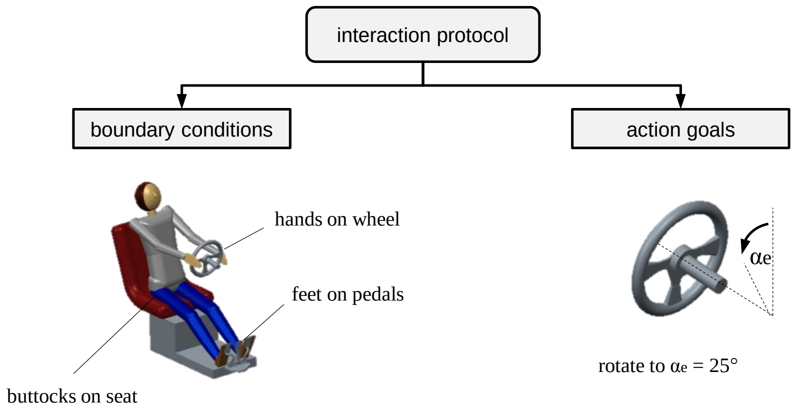

Figure 9. Interaction protocol: boundary conditions and action goals

The boundary conditions and action goals are the input parameters for an algorithm (*motion predictor*) that predicts the motion the user will most likely choose to fulfil the task. This algorithm is described in the next section.

4.4 Prediction of human motion based on the optimality principle

Optimality as the property of a system to maximise or minimise some function under given constraints is often found in nature. Examples are the minimisation of potential energy as a driving force for chemical and physical processes or the assumption of natural selection according to which form and behaviour of creatures are developing towards optima. Many of the characteristics of human motor behaviour can be explained by the optimality principle. It seems natural that humans perform movements in a way that minimum mechanical effort is necessary. But also the elimination of kinematic and dynamic redundancy can be achieved if those joint constellations and patterns of muscular excitation are preferred that entail less effort compared to alternative solutions. Computer simulations based on the optimisation of mathematical functions are therefore very promising approaches to predict posture and motion of biomechanical human models.
The dynamics of the human musculoskeletal system can be described by equation (1).

$$\dot{\vec{y}}(t) = f(u(t), y(t), t) \qquad (1)$$

Here $\vec{y}$(t) is the skeletons physical state vector consisting of the joint angles, the corresponding generalised speeds as well as additional states of the muscles like tendon length, contraction velocity and level of activation. The time derivative of the state $\dot{\vec{y}}(t)$ depends on the current state and the current control vector $\vec{u}(t)$. Controls are time dependent neural signals that activate the muscles and lead to torque generation in the joints. Under a simplified point of view without considering muscles one can also directly apply torques to the joints and regard these as controls. The evolvement of the state (= motion) is simulated by integrating equation (1) over time. Hence predicting human motion means to determine a set of control signals $\vec{u}$ that lead to the achievement of a task defined by the interaction protocol described in section 3. Due to the kinematic and dynamic redundancies of the human musculoskeletal system there is usually no unique solution to this problem. Instead one has to settle for finding a best solution $\vec{u}_{opt}(t)$ that minimises an objective function J given in (2).

$$J(\vec{u}(t), \vec{y}(t), t) = \int_0^T l(\vec{u}(t), \vec{y}(t), t)dt \;\; \text{with } \dot{\vec{y}} = f(u, y, t) \qquad (2)$$

This objective function assesses the motion (state and control) of the human model by means of arbitrary optimality criteria encoded by the cost value l that is associated with each time step. Possible optimality criteria are discussed further below. The optimal control signals $\vec{u}_{opt}(t)$ are consequently the solutions of the following dynamic optimisation problem.

$$\vec{u}_{opt}(\mathrm{t}) = argmin \;\; J(\vec{u}(t), \vec{y}(t), t) \qquad (3)$$

Optimal control problems of this type can be solved by several numerical methods [Todorov 2006]. A limiting factor for the application on complex dynamic systems like the human body however is that most of the algorithms are computationally extreme costly.
An exception to this is the *iterative linear quadratic regulator* (iLQR) method that was originally published by [Todorov 2005]. It would go beyond the scope of this contribution to cover all the mathematical details. Instead only the coarse working principle of iLQR and how it is employed to predict human motion within virtual testing of use is explained. The algorithm takes advantage of the fact that for linear system dynamics and objective functions quadratic in $\vec{u}$ the solution to the optimal control problem is relatively straightforward. Unfortunately musculoskeletal dynamics are highly non-linear. The idea of iLQR is to iteratively use linear approximations of the system dynamics function (1) and quadratic approximations of the objective function (2) to construct a sequence of solutions that finally converges to the exact solution. The methodology actually yields an optimal feedback controller which

means that not only the controls $\vec{u}$ are determined but also feedback gains that could be used to correct the motion from external disturbances. An iLQR controller was implemented on top of the biomechanical simulator OPENSIM and applied to the case study introduced in section 4.1. The task (turning the steering wheel) has been formulated using the interaction protocol described in the previous section. The boundary conditions (buttocks on seat, both hands on the wheel, feet on the pedals) are implemented by inserting five kinematic constraints into the musculoskeletal model. The action goal (rotate the wheel to $\alpha_e = 10°$) is used to derive the optimality criteria for the iLQR controller. The resulting objective function is given in equation (4).

$$J = |\alpha(\mathrm{T}) - \alpha_e| + |\dot{\alpha}(T)| + \int_0^{T-1} \vec{u}(t) \cdot \vec{u}(t)\ dt \tag{4}$$

The term in front of the integral only depends on the final time step T and penalises the deviation of the gear levers actual position from the required position. In addition since the motion should stop at the required position the velocity of the lever is required to be zero. The integral term is called the running cost function since it assesses the way towards the target position penalising the control effort for the muscles.

4.5 Simulation of the product behaviour

User-product interaction processes as depicted in figure 1 are actually feedback loops. The behaviour of the product is affected by the behaviour of the user and vice versa. A simulation for virtual testing of use must consequently also contain a behavioural model of the product. Our concept permits a computational separation of the musculoskeletal *user model* and the *product model*. Hence user behaviour and product behaviour can be processed in separate simulation programs that however need to be synchronised to exchange data. The advantage of this co-simulation approach over monolithic solutions [Damsgaard 2006] that handle the product as a part of the multibody system employed to describe the user is that the behaviour of the product is not limited to what can be described by multibody dynamics. In fact the *product simulator* can be any kind of algorithm capable of emulating mechanical responses. A problem of co-simulations is to define the system boundary of each simulation model. In case of user-product interaction it is reasonable to define this boundary along the human-machine interfaces of the product. In the case study the steering wheel can be identified as a part of the human-machine interface. The product behaviour however is mainly determined by the internal design of the steering system. This behaviour is sensed in terms of a reaction force on the wheel. Hence the system boundary is the interface between the wheel and the steering gear. In other words the wheel is treated as a component of the biomechanical multibody tree while the reaction force generated by the steering system could be emulated by an external product simulator. In this case the communication between the simulators would be an exchange of wheel rotation and reaction torque. This approach entails the necessity to export parts of the product model (the human machine interfaces) from the CAD environment into the biomechanical simulation system. A prototypical interface between OPENSIM and the CAD system CREO/PARAMETRIC (PTC) has been developed that allows exporting arbitrary parts or sub-assemblies of the product model into the multibody simulator. Therefore the mass properties of the parts and the kinematic constraints to the surrounding assembly are analysed automatically.

5. Results of the case study

The CAD integrated biomechanics laboratory has been used to create a dynamic simulation model for the car driving example introduced in section 4.1. The resulting motion sequence is illustrated in figure 10. Moreover the total sum over the control signals of the muscles that are actuating the right shoulder joint is shown. This muscle group has been identified to contribute the largest part of the actuation effort in the upper extremities of the body. Since control signals are direct proportional to the level of muscular activitiy, they are ideal criteria to assess the risk of muscular fatigue, which is one aspect of discomfort, during the user-product interaction process. In the present case adjustments of the product design that lead to a lower control values can therefore be regarded to improve the ergonomic quality of the vehicle cockpit. However since the complete dynamic state trajectory is known, additional stress indicators (e.g. joint loads) can be extracted in subsequent computations.

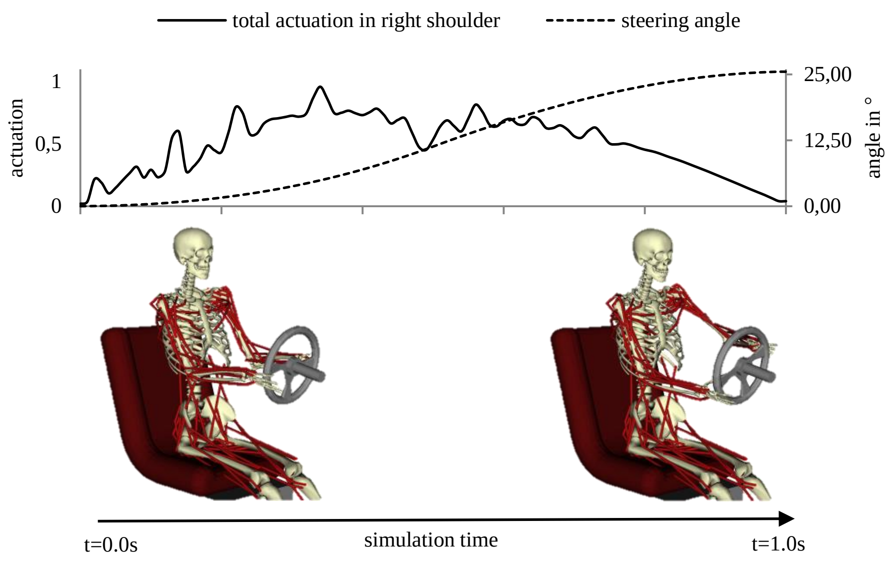

Figure 10. Case study: motion sequence and major actuation

6. Summary and outlook

A growing awareness of health in society emphasises the importance of a user-centred design process. More than in former times design engineers will have to focus on product ergonomics. Since ergonomic product properties are related to the interaction processes with the user, the importance of testing for use is also growing. However traditional testing concepts are time consuming and costly because they usually require the manufacturing of physical mock-ups and the conduction of experiments involving multiple test persons to cover the characteristics of the target user group. In this paper therefore biomechanical human models were proposed as a possibility to simulate ergonomic aspects of user-product interaction already in the early stages of the development process.

Hereby designers are enabled to predict and quantify the relationship between design parameters and the level of biomechanical stress effects prevalent during product use within the users organism. To improve the ergonomic quality of products the design is adjusted so that stress indicators like muscular activity are kept at a moderate level. However the application of biomechanical simulations in design is currently not very widespread. The dependence on experimental data for the specification of human behaviour and the unsatisfying integration with existing methods and tools of virtual product development were identified as the main hurdles. The benefit of the concept for a virtual biomechanics laboratory presented in this paper is the seamless integration into an existing CAD/CAE environment. Designers are not confronted with experimental data and anatomical details on biomechanical modelling. Due to the computational separation of product model and user model it is possible to take advantage of a huge number of sophisticated CAE algorithms to resemble the behaviour of the product. This is especially important since many products today are mechatronic systems that can't be analysed using solely multibody dynamics. The most crucial but also the most challenging aspect of virtual simulation of use is however the prediction of human behaviour. Based on a task oriented formulation of user-product interaction an optimal control algorithm is employed to synthesise the motion of the user. Even though this is regarded a promising approach its validity has not been verified yet. Future research will therefore have to address the experimental validation of motion prediction methods. Equally the implementation of the concept presented is still incomplete. In particular the task oriented interaction protocol and the computational interfaces to perform a co-simulation of user model and product model require additional effort to become usable in industrial applications.

Another important question is how designers have to interpret the results of a biomechanical analysis. Biomechanical stress indicators at first glance tell little about what design changes could improve the ergonomic properties of the product. The simulation system therefore should provide the designer with guidance to design improvements by mapping the results back into the space of design parameters.

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