# TOWARDS CAD INTEGRATED SIMULATION OF USE UNDER ERGONOMIC ASPECTS

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1. Motivation

For a long time the dominating view on product design was affected basically by functional and economic aspects. In the 1940s the American industrial designer Henry Dreyfuss was among the first to explicitly incorporate the user into design theory: *it must be borne in mind that the object being worked on is going to be ridden in, sat upon, looked at, talked into, activated, operated, or in some way used by people [...] If the point of contact between the product and people becomes a point of friction, then the designer has failed* [Dreyfuss 2003]. He realised that 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. Today a growing awareness of health in society and the saturation of markets emphasise the importance of scientific approaches to provide an optimal fit between human beings and technical systems. The idea of 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 of the product to be available already in the early stages of the development process. In this paper therefore a novel application of biomechanical digital human models is proposed to simulate ergonomic aspects of product use employing virtual prototypes only. The objective is to provide a framework to analyse interaction processes between users and products (see Figure 1) within a common CAD environment. The use of a product is always associated with tasks 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.
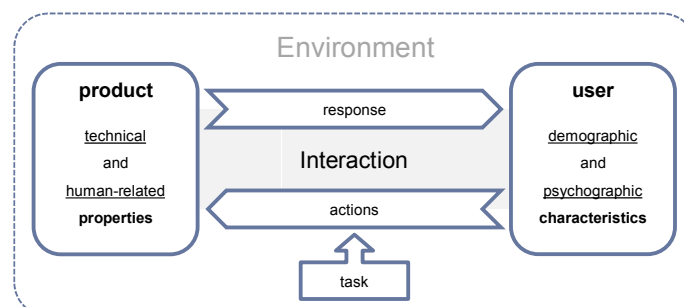
Figure 1. User-product interaction

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 and Ilg 1994] is ap-

plied 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 like muscular fatigue. 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.
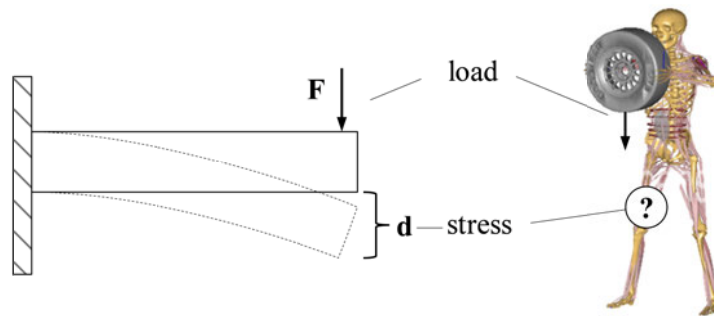
Figure 2. Equivalence of the load - stress concept in engineering mechanics and ergonomics

Biomechanical stresses like muscular activity, joint reaction forces or metabolism 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.

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. Guidelines and testing methods to support ergonomic design

Industry standards like DIN 33411 provide general information about 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 design case. The standard ISO 9241-210 therefore points out the importance of testing and evaluation. Thereby a fully or partial functional physical mock-up of the product is presented to test persons that represent the target user group. 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 hybrid mock-ups and digital human modelling. Hybrid mock-ups employ virtual reality (e.g. CAVE projections) in combination with real time simulations and haptic interfaces to enable test persons to interact with virtual prototypes [Krueger 2011]. Compared to physical mock-ups this approach is more flexible but still quite elaborate. Finally the idea of digital human modelling 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. Anthropometric human models for ergonomic assessment are included in major CAD systems. Based on a relatively simple representation of the human skeleton they feature analysis methods for several ergonomic goals mainly related to vehicle interior design. Examples are the analysis of reachability, field of vision and the assessment of comfort. Comfort is assessed by the evaluation of static postures regarding their joint angle constellations based on empirical data. A prediction of posture is achieved by inverse kinematic computations which means that the designer only needs to specify the position of human end-effectors e.g. the hands and a reasonable constellation of joint angles is chosen automatically. Popular repre-

sentatives of CAD integrated anthropometric human models are JACK (Siemens PLM), HUMAN BUILDER (Dassault Systèmes) and RAMSIS (Human Solutions). [Duffy 2009], [Bubb 2002] Examples of standalone software systems for ergonomic assessment were further published by Medland and Gooch [2010] and Hareesh et al. [2010].

3. Biomechanical human models

The field of biomechanics addresses structure and motion of human and animal musculoskeletal systems. This comprises the mechanical behaviour of bones, joints and muscles. Biomechanical simulation software packages like OPENSIM [Delp et al. 2007] or ANYBODY [Damsgaard et al. 2006] describe biomechanical systems based on multibody dynamics. The skeleton is 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 musculoskeletal stress like the level of muscular activity, metabolism and joint reaction forces can be determined.
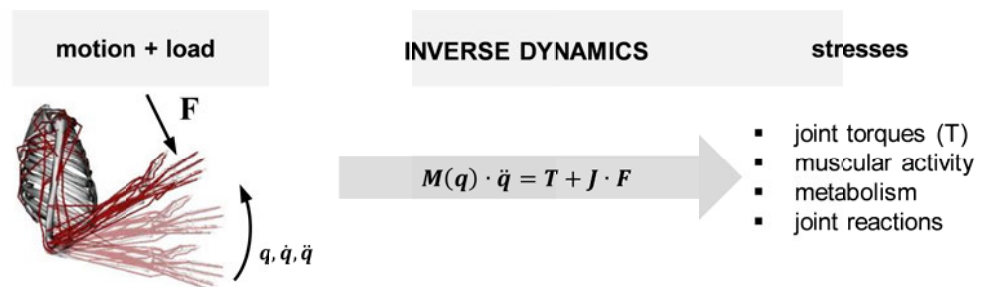

motion + load   **INVERSE DYNAMICS**   **stresses**

F

$$M(q) \cdot \ddot{q} = T + J \cdot F$$

$q, \dot{q}, \ddot{q}$

- joint torques (T)
- muscular activity
- metabolism
- joint reactions

Figure 3. Inverse dynamic analysis of motion

Even though biomechanical human models were developed for the purpose of analysis in motion medicine, they perfectly fit into the ergonomic load-stress concept. In contrary to anthropometric models information on the physiological causes for ergonomic issues are revealed. Indicators of musculoskeletal stress e.g. the level of muscular activity can therefore directly be regarded as ergonomic assessment criteria.

Being among the first to suggest biomechanical human models as design tools [Rasmussen et al. 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 et al. 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.

4. A CAD integrated biomechanics laboratory

4.1 Concept and related work

In the previous section a **task oriented** formulation of user-product interactions and a seamless **integration with CAD environments** have been identified as the most important requirements on a virtual biomechanics laboratory. 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 et al. 2013] and previously by [Krüger et al. 2012].

Our concept (Figure 4) 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*.
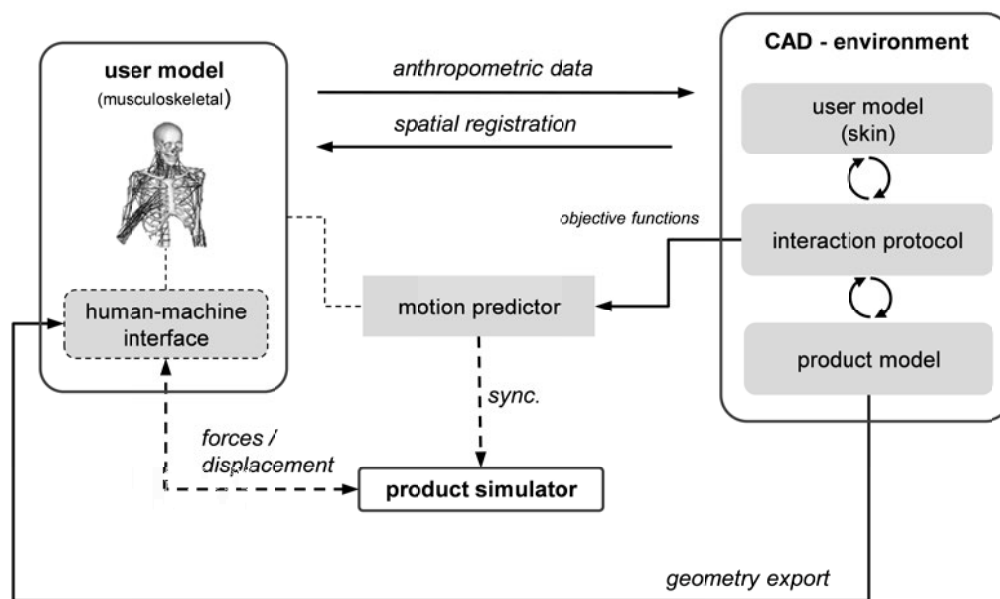
**Figure 4. Concept of a CAD integrated biomechanics laboratory**

The concept is built on four important pillars: the transfer of anthropometric data and spatial registration, 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 demonstrator. The interaction process to be analysed is the operation of a manual gearbox in a passenger car. In order to insert a gear the driver of the car needs to move the gear lever to the front until it reaches the end stop (Figure 5). Even though the driver is interacting also with other interfaces of the car (clutch lever, steering wheel) the product in this example is reduced to the gear lever, the seat and the gearbox.
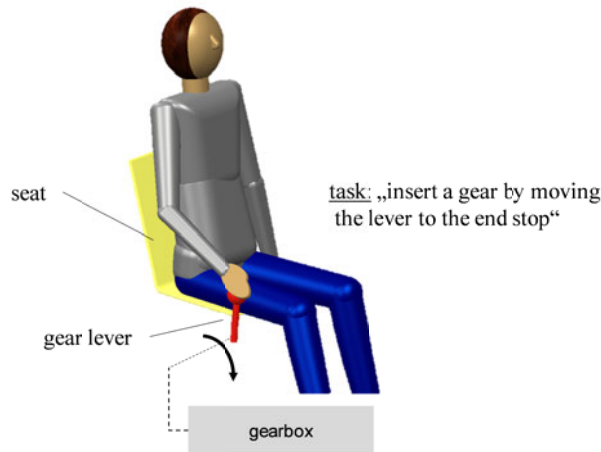
Figure 5. Demonstrator task: inserting a gear

4.2 Transfer of anthropometric data and spatial registration

In the beginning of a virtual experiment all relevant characteristics of the user like body measures or strengths must be defined. For this purpose a scaling process published by [Miehling et al. 2013] is employed. The design engineer selects a percentile value for body size and strength as well as the age group of the prospective user. In future, to augment the informational value of the models, it is planned to include also performance restrictions arising from natural ageing, chronic diseases or disabilities since those users have special demands on the ergonomic properties of a product. The output of this process is a musculoskeletal model for the OPENSIM platform. 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 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 6): 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.
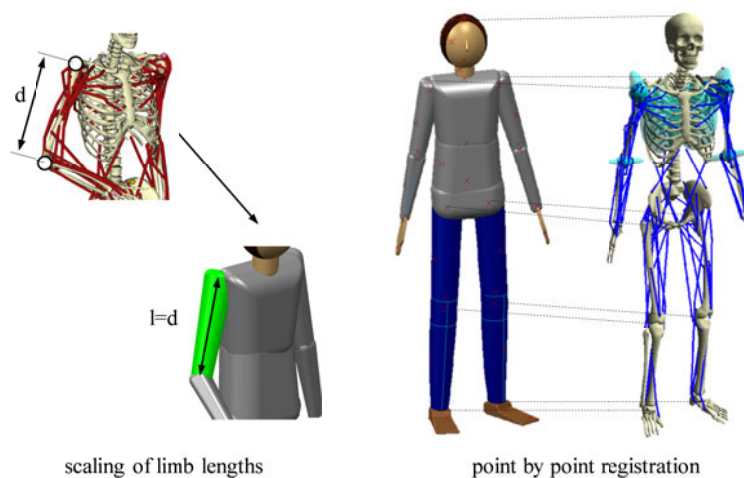

Figure 6. Transfer of data between skin model and musculoskeletal model

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 3 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 et al. 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 gearshift example (Figure 7) the claims that the buttocks of the user remain on the seat while the right hand remains on the gear lever are typical boundary conditions whereas the required rotation of the lever link is an action goal.
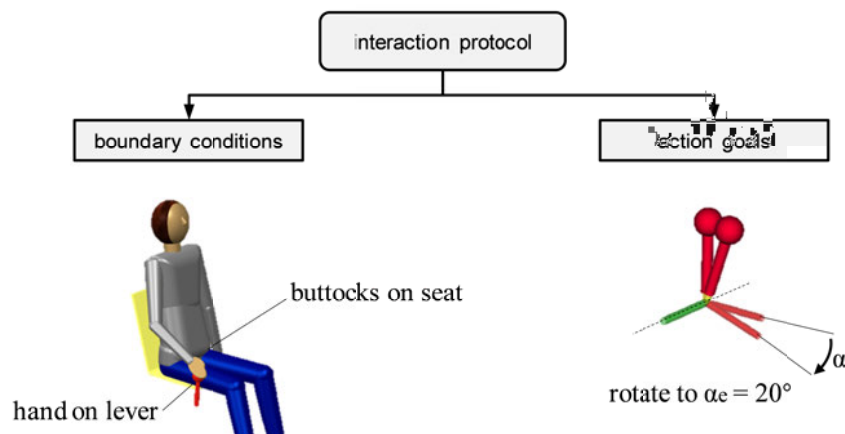
Figure 7. Interaction protocol: boundary conditions and action goals

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

Within the last century neuroscience greatly augmented the knowledge about the characteristics of human motion behaviour as well as the structure of human control systems. The human body is a highly redundant mechanical system with respect to both kinematics and dynamics. Its kinematic chains usually feature more degrees of freedom than necessary for task execution. Even a simple task like reaching for an object can be achieved with an infinite number of possible joint constellations. The same redundancy is found on the dynamic level since a single joint is always actuated by multiple muscles. This redundancy leads to a huge variability in motor behaviour, even in case of tasks repetitively performed by the same person. Despite humans are able to conduct very accurate and smooth movements, correct external perturbations and adapt to new situations like e.g. motion in the state of zero gravity. Moreover biological movements are performed in a remarkable energy efficient way [Scott 2004]. All modern theories agree that human motor control is implemented in the central nervous system as a distributed hierarchical control system. Further there is evidence that feedback control mechanisms play an important role in particular for slow and accurate motions [Polit 1979].

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 excita-

tion 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).

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

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).

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

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.

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

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 and Weiwei [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 nonlinear. 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 demonstrator introduced in section 4.1. The task (inserting a gear by moving a lever) has been formulated using the interaction protocol described in the previous section. This information now is used to set-up the musculoskeletal simulation. The boundary conditions (buttocks on seat, right hand on lever) are implemented by inserting two kinematic constraints into the musculoskeletal model (Figure 8). The action goal (rotate the lever to $\alpha_e = 20°$) is used to derive the optimality criteria for the iLQR controller. The resulting objective function is given in equation (4).

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

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 torque actuators located in the arm. Since the iLQR algorithm converges only locally it requires an initial guess for the solution. In the example convergence was achieved within 8 iterations (see Figure 8 on the left side) even though the controls were initialised to the trivial value zero.
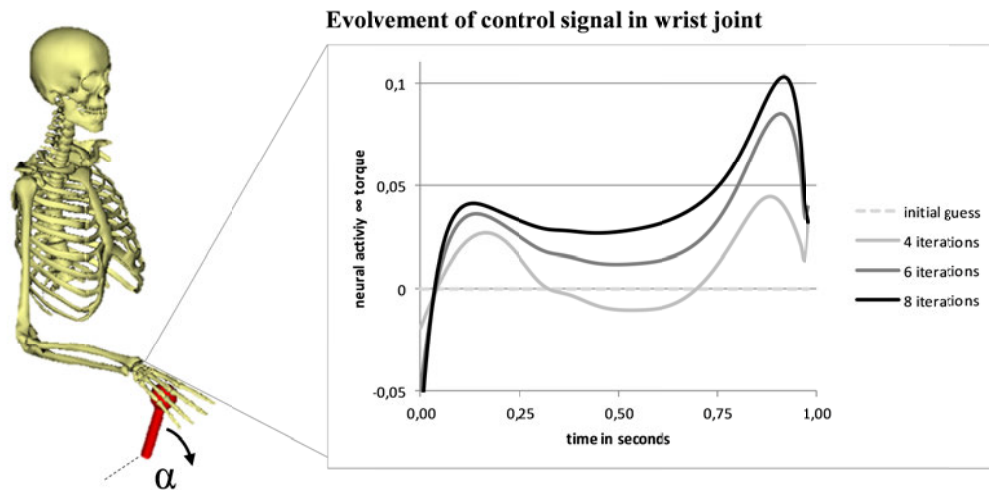
Figure 8. Predicting an arm motion using optimal feedback control

In our concept of a CAD integrated biomechanics laboratory the iLQR algorithm is used to transform the information delivered by the task oriented interaction protocol into a motion of the musculoskeletal user model. Since the control signals are related to the effort of the muscles they can be used directly as a criterion for ergonomic assessment. Adjustments of the product design that lead to lower control values are therefore regarded to improve the ergonomic quality of the product. However since the complete dynamic state trajectory is known, additional stress indicators (e.g. joint loads) can be extracted in subsequent computations.

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 et al. 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 case of the demonstrator example the gear lever can be identified as a part of the human-machine interface. The product behaviour however is mainly determined by the internal design of the gearbox. This behaviour is sensed in terms of a reaction force on the lever. The system boundary is the interface between the lever and the gearbox. In other words the lever is treated as a component of the biomechanical multibody tree while the reaction force generated by the gearbox could be emulated by an external product simulator. In this case the communication between the simulators would be an exchange of lever 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. 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. Despite 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. 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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