NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

A simplified approach towards integrating biomechanical simulations into engineering environments

D. Krüger, J. Miehling, S. Wartzack
University of Erlangen-Nuremberg, Chair of Engineering Design
Martensstrasse 9, 91058 Erlangen, GERMANY
kruger@mfk.uni-erlangen.de

Abstract
In human-centered design biomechanical simulations can be used to predict the characteristics of the interaction between the user and the product in order to optimize the design with respect to ergonomics. However since biomechanical modelling has its origin in medical applications the simulation procedure is not familiar to product designers yet. In this paper an approach towards the integration of an arbitrary biomechanical simulation system into the CAD/CAE engineering environment is proposed. The objective is to enable the analysis of user-product interaction in early design phases based on virtual prototypes. A major focus of this work is the fast acquisition of human body measures and motion sequences using an inexpensive depth imaging device originally designed for entertainment applications.

Keywords: biomechanics, simulation, human-centered design, ergonomics

1 Introduction

The field of biomechanics addresses structure and motion of human and animal musculoskeletal systems. This comprises the mechanical behaviour of bones, joints and muscles as well as the complex sensorimotor processes that control the motion of the entire system. Numerical simulation tools like *OpenSim* [1] or *Anybody* [2] have been developed to describe and simulate the behaviour of biomechanical systems based on multibody dynamics. The skeleton is modelled as a set of rigid bodies that are interconnected by joints whereas muscles are represented by special force actuators that take into account the physiological contraction velocity-force relationship.

In design there is a growing field of applications for biomechanical simulations. Biomechanical models have been successfully used to optimize human-machine interaction by means of simulated muscle activity patterns [2]. Further applications exist in the field of medical technology: for the structural design of medical implants such as artificial hips, detailed information on mechanical loads occurring during the patient's daily activity is needed. This data can be provided by means of a biomechanical simulation in terms of muscle and joint reaction forces [3].

However since biomechanical modelling has its origin in medical applications and sports sciences, the simulation procedure is not familiar to product designers yet. A possible reason for this is that the simulation systems available are not well integrated into CAD/CAE engineering environments and lack the capability of interacting with virtual product prototypes (e.g. CAD geometry).

In this paper an approach towards the integration of an arbitrary biomechanical simulation system into the CAD/CAE engineering environment is proposed. The objective is to enable the analysis of user-product interaction in early design phases based on virtual prototypes. The benefit of the suggested methodology is that it has very low computational costs. Since the basis of every biomechanical simulation is anthropometric data, a major focus of this work is the fast acquisition of human body measures and motion sequences using an inexpensive depth imaging device originally designed for entertainment applications.
For illustration purposes the biomechanical model of a car driver depicted in Figure 1 is used as a demonstrator. The intention is to analyse the joint torques that occur while the driver is turning the steering wheel by 45°.

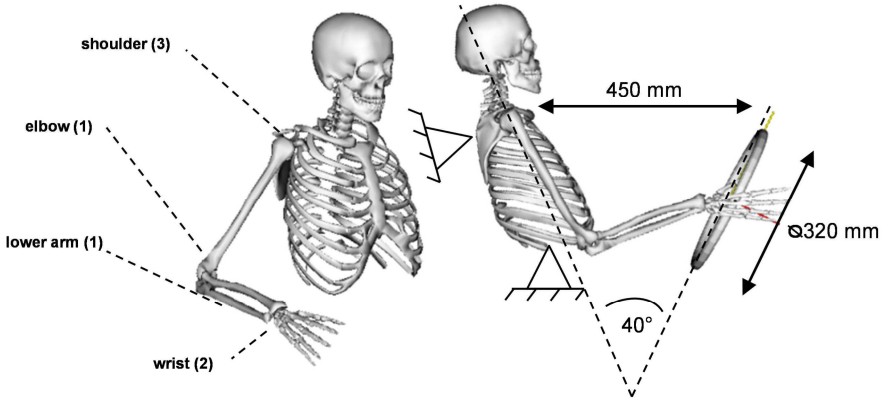

Figure 1 Demonstrator (left: degrees of freedom, right: dimensions)

2 Procedures of biomechanical simulation

In principle there are two possible approaches towards biomechanical simulation: forward and inverse dynamics. As a first step both methodologies require a scaling operation. Biomechanical human models are usually generic, that means they correspond to an average persona (e.g. 50th percentile male) that doesn't necessarily have to exist in reality. In order to consider the physical properties of a specific individual, the generic model has to be scaled. The scaling comprises the lengths of limbs and torso, the mass distribution as well as the strength properties of the muscles.
The inverse dynamics approach is based on a given motion sequence and given external loads. In practice this means that motion sequences of a real test person have to be recorded, e.g. using optical motion capturing systems. Since the kinematics of the motion is unambiguously determined, it is possible to calculate the corresponding dynamic quantities (torques, forces) very efficiently by a direct evaluation of the equations of motion. Although the inverse dynamics approach is the standard procedure for biomechanical analyses in sports science and medicine, an application in product design is not without problems: the interaction between the user and a product is accompanied by a movement of the user that on the one hand is influenced by the user's habits and physical properties. On the other hand, the movement depends significantly on the shape of the product. However it is assumed that the product only exists as a virtual prototype. Therefore it is not available to the test person for direct interaction.
For the analysis of the interaction with virtual prototypes, the forward dynamics approach seems to be more appropriate. The procedure is based on one or more motion objectives which have to be given in advance. Referring to user-product interaction, the motion objective in many cases can be thought of guiding specific points of the limbs on spatial trajectories. The car driver for example keeps his hands on the steering wheel with the consequence that they always move on a circular path defined by the shape and position of the wheel. Hereafter

optimal control strategies [4] are applied to determine dynamic quantities (torques, forces) that drive the biomechanical system so that all motion objectives are fulfilled. Because the human musculoskeletal system is dynamically underdetermined, no unique solution to this problem exists. Instead the solution is always optimal with respect to one or more optimization criteria which have to be defined. Consequently, the style of the synthesized motion highly depends on the selection of those criteria and its naturalism is not assured. In addition the computational costs of the simulation procedure are quite high which is caused by the necessity to iteratively integrate the equations of motion.
In summary both approaches have advantages and disadvantages. The inverse dynamics approach requires only decent computational effort and since it is based on recorded data, it can be assured that a natural motion is analysed. However for the same reason it is difficult to examine the interaction between the user and a virtual prototype of the product. Adopting the forward dynamics approach the interaction with virtual prototypes can be modelled by defining suitable motion objectives. But the drawbacks are the enormous computational costs and the strong dependency of the motion style on assumptions concerning the optimization criteria.

3 Integration of biomechanical models into engineering environments

3.1 Simulation framework

In the following a simplified approach towards biomechanical simulations in product design is introduced that combines advantages of both, inverse dynamics and forward dynamics procedures.
Since industrially manufactured products are rarely tailored for a single person, user-product interactions have to be simulated for multiple sample individuals of the target group in order to obtain statistical results. Additionally there are always iterations in the product development process, so most likely a huge number of simulation runs have to be performed. Consequently the computational costs of a single simulation should be as low as possible. Therefore the inverse dynamics approach is chosen as the core operation principle. The simulation framework of the approach is outlined in Figure 2: the idea is to create a generic interface through which an arbitrary biomechanical simulation system can be supplied with motion data and external loads. Therefore a simplified human model that only represents the kinematical structure of the musculoskeletal system is integrated into the CAD/CAE environment. The interaction between this **kinematical dummy** and the virtual product model is defined by several motion objectives alike those mentioned with regard to forward kinematics. However these motion objectives are purely geometrical and constitute the boundary conditions of an inverse kinematics problem. Inverse kinematics can be solved by numerical optimization methods under realtime conditions. The solution is a motion sequence, which is transferred to the biomechanical model along with external forces. Since the external forces depend on the product's properties, they have to be obtained by additional CAE-simulations. In order to ensure a sufficient degree of realism the inverse kinematics solver should take into account motion sequences recorded from a real person. These sequences as well as scaling information for the kinematical dummy are provided by a user database.
In the following two aspects of the approach are discussed in detail. At first a software tool for the fast acquisition of user data is presented. The tool utilizes an inexpensive depth imaging device to capture body measures and motion sequences of test persons. Afterwards a short explanation on a possible inverse kinematics solver is given.

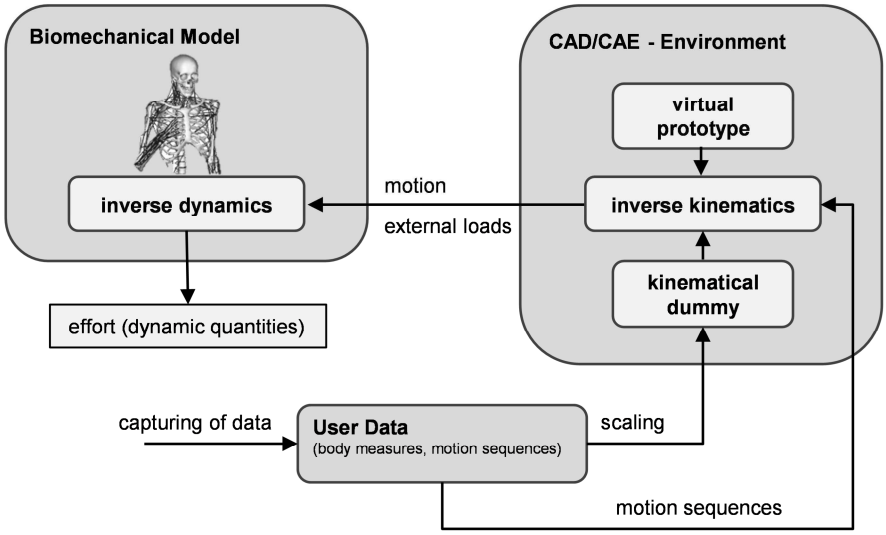

Figure 2 Simulation framework

3.2 A tool for the fast acquisition of user data

3.2.1 The KINECT-sensor

Marker-based systems consisting of multiple cameras constitute the state of the art in capturing body measures and movement of a test person. This especially applies to applications in medicine and sports science where the accuracy of the recorded data plays a major role. Even though the performance of marker-based motion capturing cannot be questioned, they require substantial effort for preparation: the camera system has to be calibrated and a huge amount of markers must be placed precisely on the test person.

In 2010 *Microsoft* introduced an inexpensive depth-imaging device into the market, which was originally designed to control video games. The **KINECT-sensor** [5] uses structured infrared light to generate a depth map of the scene in front of the camera. A depth map is a rastered image with distance information stored in each pixel. In combination with **NITE,** an image processing library published by *PrimeSense* [6], it is possible to detect outlines of human bodies in image data and extract position and spatial orientation of the limbs.

Based on this technology a software tool has been developed which is capable of capturing body measures and motion sequences. In spite of some drawbacks concerning accuracy and time resulution, the benefit over marker-based systems is, that there is almost no expense for preparation. In the following the functionality of the tool is described in detail.

3.2.2 Retrieving scaling information

The determination of body measures based on image data can be realised easily using the NITE image processing library. As soon as a person is recognized by the system, the joint positions are estimated based on the body outline and subsequently written to a suitable data structure (vector skeleton). The segment length of a limb is determined by computing the vector difference of the adjacent joint positions (Figure 3).

At present, the software tool is capable of determining the lengths of the upper and lower legs, torso, head as well as upper and lower arms. Each data set created that way is added to a user database. It is used to scale both, the biomechanical simulation model and the kinematical dummy.

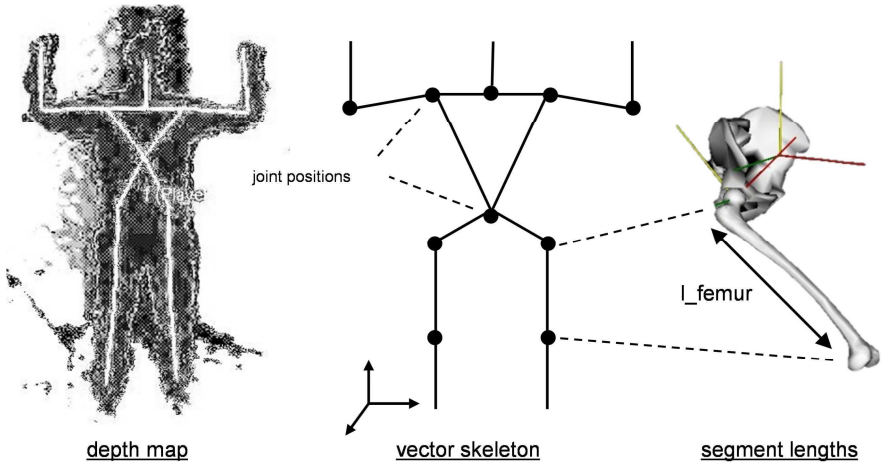

Figure 3 Retrieving scaling information based on depth images

3.2.3 Capturing of human movements

The acquisition of motion sequences is based on the ability of the NITE library to estimate the spatial orientation of detected human limbs and provide these in terms of rotation matrices. However movements in multibody simulations are usually expressed by generalized coordinates (joint angles) as functions of time. To ensure the portability of the gathered data to a biomechanical digital human model, the orientations of the limbs have to be converted into equivalent angles of the adjacent joints. In Figure 4 this is explained for the upper arm: the orientation of the arm relative to the torso is defined by the shoulder joint. As a first approximation the shoulder can be assumed to be a ball joint. A ball joint has three degrees of freedom, which can be described by three successive Euler rotations about mutually perpendicular axes. In the presented case the first rotation is about the y-axis, then about the x-axis, and finally again about the now newly oriented y-axis. These individual rotations are assigned the Euler angles α, β, and γ. The rotation sequence can be described as the product of three rotations, whereas each rotation matrix depends on one of the three Euler angles. The Euler angles and hence the generalized coordinates of the joint are computed by comparing the resultant matrix with the orientation matrix determined by the image processing library.

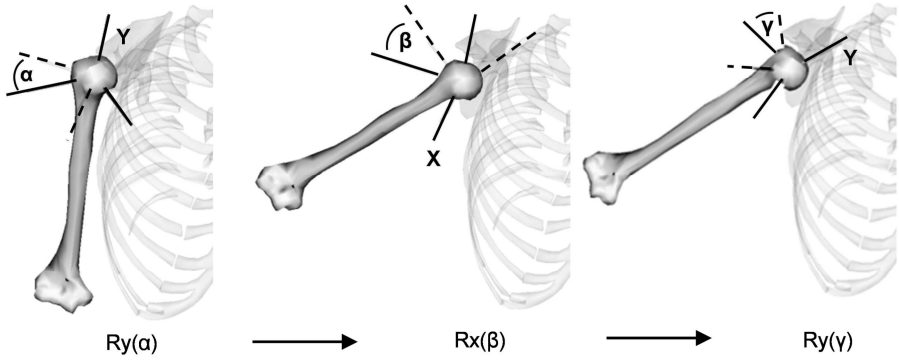

Figure 4 Conversion between limb orientations and joint angles

At present, the software tool is capable of capturing the motion of the elbow, shoulder, hip and knee joints at a maximum frame rate of 30Hz.

3.3 Synthesizing motion through inverse kinematics

The interaction of the kinematical dummy and the virtual prototype is defined by motion objectives. In case of the demonstrator the motion objective is guiding the middle hand on a circular trajectory defined by the steering wheel while the torso is fixed to the seat. For

simplification the system is reduced to a model of the right arm which is depicted in Figure 5. Between the shoulder and the middle hand the arm forms a kinematical chain composed of three segments (upper arm, lower arm, hand) that are linked by joints with seven generalized coordinates or joint angles in total.

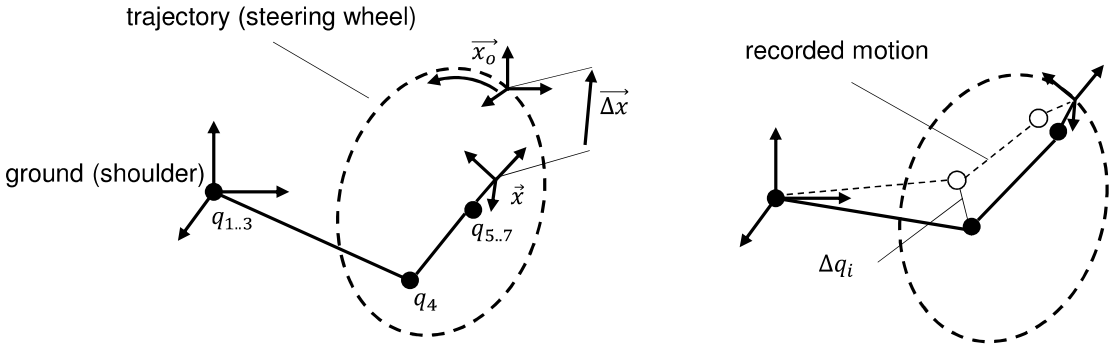

Figure 5 Kinematical dummy of the demonstrator

Assuming that the motion of the steering wheel is given, the motion of the arm is obtained in the following way: for every point on the trajectory a combination of joint angles has to be determined that leads to the desired attitude (position and orientation) of the hand with respect to the trajectory. The attitude of the hand depends on the way the user grasps the steering wheel. However since the system is kinematically underdetermined there is no unique solution. Underdetermined inverse kinematic problems like the present one can be treated with nonlinear optimization [7]. The idea is to select a single solution out of the infinite solution set which is optimal with respect to suitable criteria: every set of joint angles q leads to a uniquely defined attitude $\vec{x}$ of the hand. The distance between the desired attitude $\overrightarrow{x_0}$ and the actual attitude is regarded as a quantity $\overrightarrow{\Delta x}$ to be minimized. Therefore the vectorial quantity has to be expressed as a real-valued objective function depending on the joint angles. The optimization problem has to be solved under the side condition that all joint angles lay within their physiological limits. In order to gain more control over the solution, the objective function is composed of three weighted summands:

$$F = \omega_p \cdot F_p + \omega_o \cdot F_o + \omega_j \cdot F_j$$

The first two summands F_p and F_o (position and orientation) control the attitude of the hand with respect to the trajectory. It is important to notice that position and orientation can be treated independently by choosing appropriate weights. The additional tracking objective F_j is introduced to increase the naturalism of the generated motion. It evaluates the deviation of selected joint positions towards corresponding joint positions of a similar motion sequence recorded from a real person.

A prototype of the inverse kinematics solver has been implemented in MATLAB for the right arm as a kinematical dummy. The optimization problem is solved using a gradient based quasi-Newton method.

4 Results for the demonstrator

The simulation model of the demonstrator has been created using the free simulation environment *OpenSim* [1]. The model is based on an upper extremity model [8] published in the *OpenSim*-community. Figure 6 shows selected snapshots of the synthesized motion sequence. It is important to note that the steering wheel is actually not part of the biomechanical model. It has been added for visualisation purposes only.

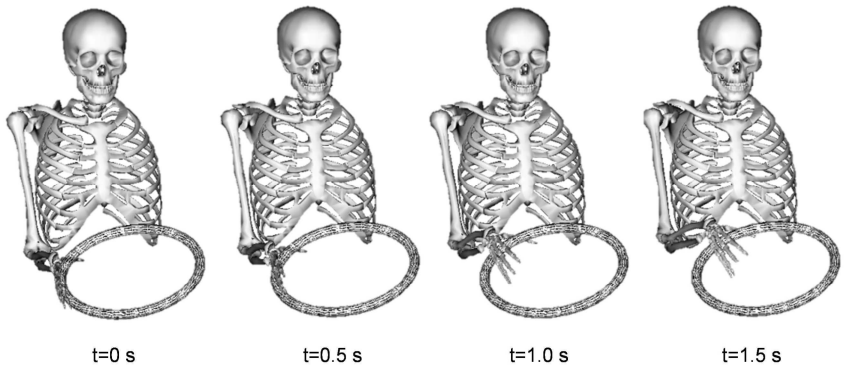

Figure 6 Synthesized motion sequence (steering motion)

The joint torques that drive the motion of the arm were determined using inverse dynamics. Since external loads were not considered yet, the time series depicted in Figure 7 only expresses the effort which is necessary to accelerate and decelerate the right arm.

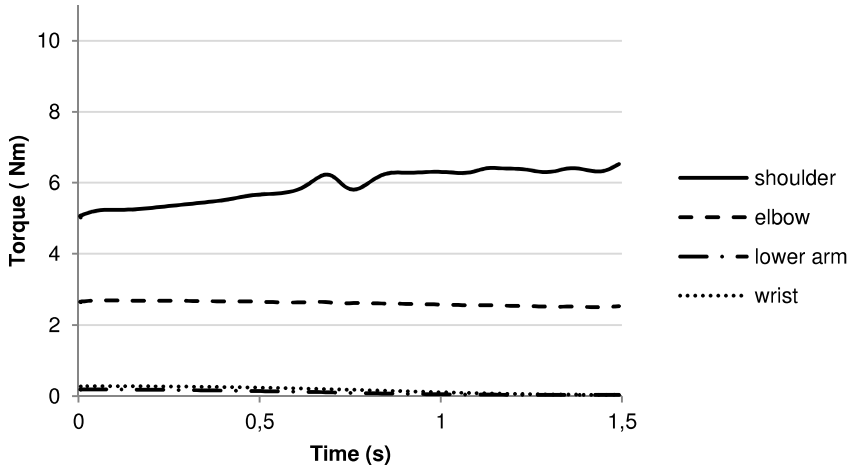

Figure 7 Joint torques (determined using inverse dynamics)

5 Summary and outlook

In times of a worldwide increasing competitive pressure human-centered aspects will get more and more important in product design. Biomechanical simulations are valuable tools for the evaluation and optimization of user-product interactions in early design phases using virtual prototypes. However to increase the acceptance by designers it is crucial to achieve a tighter integration with the commonly used CAD/CAE engineering environments and provide simple methodologies to capture user related data.

In this paper an approach based on inverse dynamics has been proposed that couples an arbitrary biomechanical simulation system with the engineering environment. Further a software tool has been presented that allows the acquisition of crucial user data based on inexpensive hardware. The suggested approach is simplified with respect to several aspects: it has been assumed that the motion objectives used to describe the user-product interaction are

always known in advance. Moreover neither feedback effects between the user and the product nor external loads were taken into account yet. Therefore the significance of the simulation is still quite low. Future research will have to focus on the consideration of neglected influences without losing the main benefits of the approach: its simplicity regarding application and its computational decency.

References

[1] Delp, S. et al., "OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement", *IEEE Transactions on Biomedical Engineering*, Vol. 54, pp 1940–1950, 2007

[2] Rassmussen, J. et al., "Musculoskeletal modelling as an ergonomic design method", In: *International Ergonomics Association XVth Triennial Conference*, Seoul, 2003

[3] Grujicic, M. et al., "Design-optimization and material selection for a femoral-fracture fixation-plate implant", *Materials and Design*, Vol. 31, pp 3463-3473, 2010

[4] Maas, R. & Leyendecker, S. 2010, "Structure preserving optimal control simulation of index finger dynamics", In:*The First Joint International Conference on Multibody System Dynamics IMSD*, Lappeenranta, Finland, 2010

[5] Dal Mutto, C., Zanuttight, P. & Cortelazzo, G., *"Time-of-Flight Cameras and Microsoft Kinect",* Springer, 2012

[6] PrimeSense Natural Interaction, "Prime Sensor NITE 1.3 Controls Programmer's Guide", www.primesense.com, 2010

[7] Krzysztof, Z., "Solving IK problems for open chains using optimization methods". In: *International Multiconference on Computer Science and Information Technology*, Wisla, Poland, 2008

[8] Holzbaur, K. et al., "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control", *Annals of Biomedical Engineering*, Vol. 33, pp 829–840, 2005