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VISUALISATION OF BIOMECHANICAL STRESS QUANTITIES WITHIN CAD ENVIRONMENTS

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Abstract

The demographic development in many industrialised societies and markets with a growing power of the customers augments the importance of user-centred design approaches. In this regard it is crucial for design engineers to understand how the use of a product is affecting the prospective user physically and emotionally. In this contribution an attempt is made to quantify physical
effects on the human body during the interaction with technical systems. We present an approach to visualise biomechanical stress quantities obtained from simulations with musculoskeletal human models within CAD engineering environments. The objective is to enable
designers to intuitively estimate how their solutions will influence the physical state of the user. The topic is relevant for the design of technical artefacts that are characterised by a close interaction with people. This comprises ergonomic questions in product design but also the
planning of manufacturing processes as well as the development of medical devices for training and rehabilitation.

Keywords: Computer aided design (CAD), User centred design, Visualisation, Biomechanics, Ergonomics

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1 INTRODUCTION

The industrial designer Henry Dreyfuss is regarded a pioneer in user-centred design. Already in the 1940s 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. His famous statement, *[...] if the point of contact between the product and people becomes a point of friction, then the designer has failed* (Dreyfuss, 2003) is particularly relevant these days. A growing awareness of health in society and the saturation of markets emphasise the importance of systematic approaches to provide an optimal fit between human beings and technical systems. Therefore designers need to analyse and understand the interaction processes between their products and the prospective users. As depicted in Figure 1 these interaction processes can be understood as feedback loops between human behaviour and product behaviour (Seeger, 2006). Because of this mutual interference product and user form a system that should be treated as a whole.

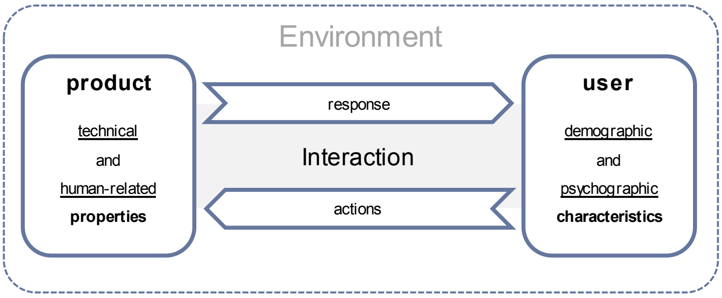

Figure 1. Model of user-product interaction

There are two questions arising that need to be answered already in early stages of the design process. The first is: *"how will the product behave during use?"* The second: *"How does this affect the user?"*
In engineering there is a wide variety of traditional and modern methods that support the designer to find a quantitative answer to the first question. This includes analytical calculations but also numerical simulations to predict the motion of mechanisms, structural properties as well as the behaviour of complex control systems. In contrast, information on how the user behaves and is affected during the phase of use is by far more difficult to acquire. Empirical user-tests can give answers on a person's performance and feelings. However since these tests require prototypes of the products they are usually conducted in later stages of the design process, if at all.
In this contribution an attempt is made to quantify physical effects on the human body during the interaction with technical systems. We present an approach to visualise biomechanical stress quantities obtained from simulations with musculoskeletal human models within CAD environments. The objective is to enable designers to intuitively estimate how their solutions will influence the physical state of the user. The topic is relevant for the design of technical artefacts that are characterised by a close interaction with people. This comprises ergonomic questions in product design but also the planning of manufacturing processes as well as the development of medical devices for training and rehabilitation.

2 BIOMECHANICAL STRESS

2.1 Definition

The concept of load and stress is an essential element of the engineering way of thinking. In general, loads are external influences to an object whereas stresses denote their consequences within the object. Engineers associate these terms primarily with the mechanical strength theory which provides the relationship between mechanical loads such as forces and torques and the corresponding stresses and strains within a material. This relationship is the foundation for the structural dimensioning of technical systems. However looking at the interaction between people and products it appears reasonable to extend the principle to the human body. Figure 2 shows a simple interaction between a human being and a technical artefact: a person doing a pull-up on the high bar. On the one hand the person causes the bar to bend whereas the deformation and the bending stresses depend on its geometry and material properties. On the other hand the person's organism is subject to the reaction loads of its own weight inducing biomechanical stress. We understand biomechanical stress as an umbrella term for dynamic effects within the human musculoskeletal system that are caused by gravity, motion or external forces. Analogous to the corresponding notions in engineering mechanics the relationship between loads and biomechanical stress is determined by physiological characteristics of the person.

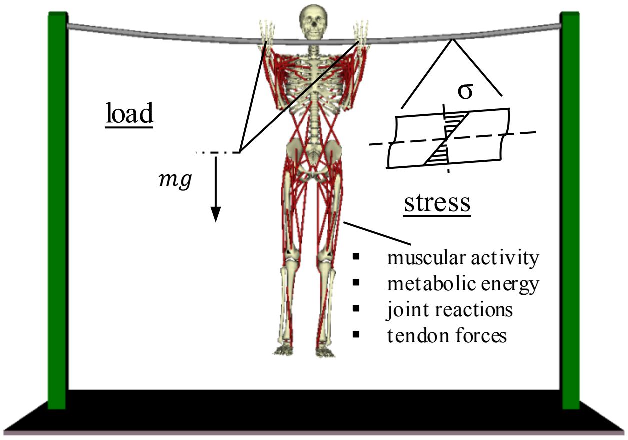

Figure 2. Concept of load and stress in humans and technical systems

The human musculoskeletal system is composed of bones, joints, ligaments and muscles. Bones equip the body with mechanical stability whereas the interconnecting joints and ligaments provide the degrees of freedom necessary for its mobility. The skeleton is actuated by muscles that are responsible for the postural stabilisation and the conduction of voluntary movement. The active force generation of a muscle takes place within contractile *motor units* that are triggered by efferent nervous signals. In addition, muscles also have passive viscoelastic characteristics so that the maximum force a muscle can produce depends on its current length as well as on its contraction velocity. Two important quantities to characterise the stress level of a muscle are *activity* and *metabolic energy rate*. Muscular activity indicates how many of a muscle's motor units are currently excited. Thus it is a relative quantity expressing to what extent a muscle is exhausting the maximum force it could generate at its current length and contraction velocity. It is not only suitable to compare the stress of muscles of different absolute strength but further contains a natural threshold: an activity value of 1.0 means that the muscle is operating at its force limit. However, computational muscle models can deliver activity values greater than 1.0 indicating that the action being analysed (e.g. a work process) is actually infeasible. The muscular metabolic energy rate, in contrast, is an absolute quantity. It captures the amount of energy a muscle is currently consuming. It is therefore a direct indicator for fatigue effects and the overall stress put on the cardiovascular system. An analytic model of muscle metabolism has been published by Umberger et al. (2003). Examples of skeletal stress quantities are *joint reaction forces* and the *tendon forces* (generated by muscles) since they act directly on the bony structures.

2.2 Simulation

Since biomechanical stress is a phenomenon inside the human organism, it is not accessible to direct measurement. In practise, the determination of stress quantities is accomplished using digital musculoskeletal human models. Available simulation codes like *OpenSim* (Delp et al. 2007) or *Anybody* (Damsgaard et al. 2006) describe the human musculoskeletal system 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 path forces and 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 time 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 post processing steps additional stress quantities can be determined.

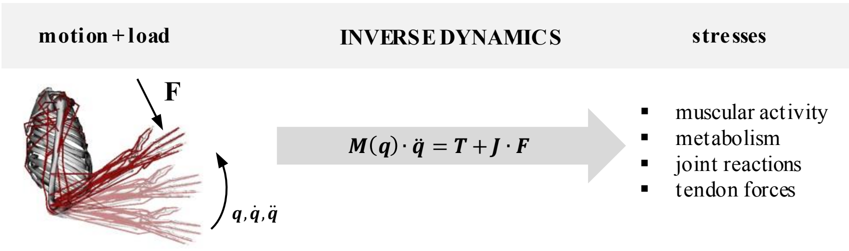

Figure 3. Inverse dynamic analysis of motion

2.3 Implication on design

In human-centred design applications biomechanical stresses could be what engineering stresses are in structural dimensioning problems. This is of particular relevance if there is a close physical interaction between the user and the technical system which applies, among others, to the following problem areas.

Ergonomic assessment: The field of ergonomics and human factors is aimed at the understanding of interactions between humans and technical systems with the objective to improve human wellbeing and the total performance of the human-machine system. Scientific findings result in design guidelines like ISO 6385:2004 (ISO, 2008), data and assessment methods that can be applied to the design of consumer product and workplaces. From a design perspective, it is common to cast ergonomic aspects in appropriate requirements like safety, harmlessness, comfort of use, efficiency and usability. Some of these requirements are related to mechanical influences so that it seems natural to consider using biomechanical stresses as criteria for the coverage assessment. Even though comfort is regarded a subjective feeling, Fritzsche (2009) proved that there is a correlation with postural parameters (joint angles) and muscle forces. A similar relationship was used by Rasmussen (2005) to assess the comfort of a car ingress motion. Harmlessness is a requirement that is very important in the design of workplaces and -processes. A human-machine system is considered harmless if it does not have negative effects on the health of the operator. According to an annual report of the German federal institute for occupational safety and medicine (BAuA, 2012), the costs for the loss of production caused by musculoskeletal disorders and the related inability to work were €12bn in 2012. Major risk factors for work related musculoskeletal disorders are heavy physical work, awkward posture and frequent repetitive tasks (Da Costa and Vieira 2009). This shows the importance to consider biomechanical stress when *designing* human work.

Another area of application is the development of *devices for training and rehabilitation*. These products have in common that they are designed to stimulate a very specific group of muscles within the user's body. Kim and Lee (2012) published a work on the design optimisation of a smith machine, a training device used to strengthen the lower body. Based on experimentally acquired electromyograms (record of the electrical activity produced by skeletal muscles) from subjects doing workouts with free weights, modifications to the kinematics of the smith machine were derived that led to a more intense stimulation of the lower musculature.

3 CAD-INTEGRATED STRESS VISUALISATION

3.1 Computational framework

In order to provide information on biomechanical stresses within a CAD environment, it is necessary to integrate a biomechanical simulation system into the CAD software. Our research is based on *OpenSim* (Delp et al. 2007), a software platform for the creation and analysis of musculoskeletal dynamic simulation models. An open-source licensing model and its expandability predestine *OpenSim* for scientific applications. Moreover, there is a worldwide community of researchers who are sharing their expertise by contributing simulation models to the community. In order to access this source of interdisciplinary knowledge from an engineering perspective, we developed a connexion between the *OpenSim* platform and the widely used CAD system *PTC Creo*

Parametric as previously published in (Krüger and Wartzack 2014). Our software integrates into *Creo's* user interface whenever the designer is working in assembly mode. The workflow (Figure 4) is inspired by what can be found in FE analysis tools. In a first step, the user chooses a musculoskeletal model from the *OpenSim* repository that, in general, has been created by a biomechanics specialist. Note that *OpenSim* provides tools to scale the anthropometric parameters of a model so that it represents the actual group of people the designer might be interested in. As soon as the model has been loaded into memory, its geometric and kinematic structure is translated into a CAD model which is added to the current product model as a sub-component.

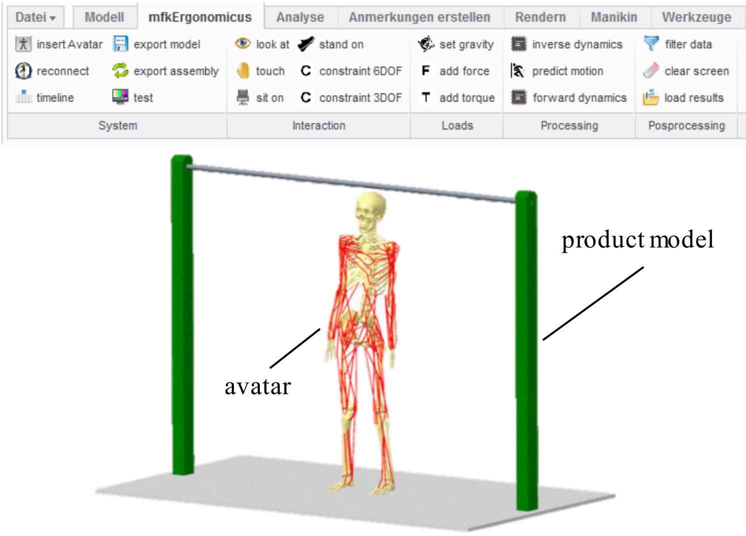

Figure 4. Connexion between OpenSim and PTC Creo (mfkErgonomicus)

This *avatar* acts as an interface to share geometric information between the CAD environment and *OpenSim*. In the subsequent preprocessing steps the user is asked to define the interaction between the human model and the product model. This is accomplished by creating geometric constraints between human end-effectors (e.g. hand, feet) and the product geometry. Moreover, it is possible to define external forces and torques that act on the human body. Based on this information, the system can predict a posture of the skeleton that a human would most likely adopt in the given situation. The solution of this inverse kinematical problem is obtained by numerical minimisation of the joint torques required to maintain the posture. The processing step is initialised by sending the input deck (posture, loads and constraints) to *OpenSim* where the corresponding biomechanical stresses are calculated by inverse dynamic or controlled forward dynamic simulation. Depending on the complexity of the model the processing times can range between a few milliseconds (single frame) and a several hours (motion sequences). Within the postprocessing stage the results have to be presented to the designer in a way that allows an intuitive interpretation even for persons lacking anatomical knowledge. Therefore, biomechanical stress quantities should be visualised on the human model at the locations where they actually occur. A complete stress dataset can easily contain hundreds of objects, which makes it hard to explore. Thus, there is a need for problem specific filters that draw the designer’s attention to the most relevant data points. In ergonomic applications, for example, it is usually more important to recognise the overrun of given thresholds than to keep track of the exact stress magnitude. *OpenSim* itself has only basic visualisation capabilities. There is a plot window where the numerical values of one quantity can be displayed with respect to another. In addition, it is possible to identify the level of muscular activity for each muscle by the colour in which it is rendered within the 3D graphics window. Pronost et al. (2011) published a visualisation library for biomechanical data that features rendering programs for kinematic data (motion paths of points), muscular activity (colour encoded) and forces drawn as arrows. However, to our knowledge no approach to visualise biomechanical data directly within a CAD system has been published yet. In the following, visualisation techniques for muscular activity, metabolic energy rate and joint reaction forces are introduced and further illustrated within a case study in section 4.

3.2 Muscle related stresses

For the visualisation of the muscle related quantities activity and metabolic energy rate we propose two different methodologies: *lines of action* and *bone aggregation*.

The first method visualises the stresses directly at their location of occurrence. Therefore, the lines of action of all the muscles in the biomechanical model are rendered on top of the CAD avatar whereas colour and thickness of the lines encode the magnitude of the associated stress quantity. In Figure 5 this is shown for muscular activity by the example of a simplified arm model that is balancing a weight against gravity. Despite of the lack of a monotonic perceptual ordering, we decided to use a rainbow colour map since it is a de facto standard in CAE applications. Depending on the numerical range of the stress value the designer can specify a lower (lb) and an upper (ub) visualisation bound. These bounds essentially determine how the data values are related to visual cues. For muscular activity a reasonable choice is lb= 0.0 and ub=1.0 as an upper bound. The colour of a muscle line is determined by interpolating linearly between blue (~lb) and red (~ub) on the rainbow colour map. In addition to colour, the thickness of each muscle line varies linearly between 1mm (~lb) and 10mm (~ub). In the example the muscle *biceps longum* is activated to 0.71 of its maximum force potential followed by the two *triceps* bundles with an activation level of 0.55.

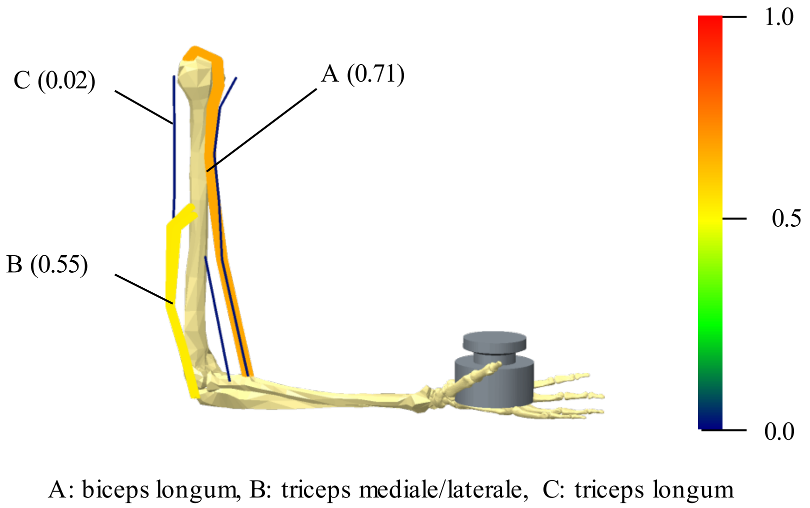

Figure 5. Muscular activity visualised on the muscle lines of action

The visualisation of metabolic energy rate is done in the same way. However, it is necessary to choose different visualisation bounds since the numerical values for the muscular energy rate of a single muscle lay between 0.0 J/s and ~ 100 J/s.

The second visualisation method, *bone aggregation*, provides a coarser view on the stress distribution within the body. The idea is to aggregate the stress value of a muscle to the bones it spans. The aggregated values are then visualised by colouring the bones using a rainbow map.

The aggregation is computed as follows: in *OpenSim* the geometric path (line of action) of a muscle is modelled by a series of via points that contain a reference to the bones they are attached to. In Figure 6 this is shown by the example of two arm muscles. Under the assumption that the number of via points a muscle shares with a bone is a measure for spatial proximity, it is possible to distribute the stress value of a specific muscle to the adjacent bones by the proportion of via points. In the example the muscle bundle *biceps breve* is defined by in total six points. One point is attached to the *scapula* bone, four to *humerus* and one to the *ulna/radius* group. Hence, the stress contributions of *biceps breve* to the bones would be 1/6 to *scapula*, 4/6 to *humerus* and 1/6 to *ulna/radius*.

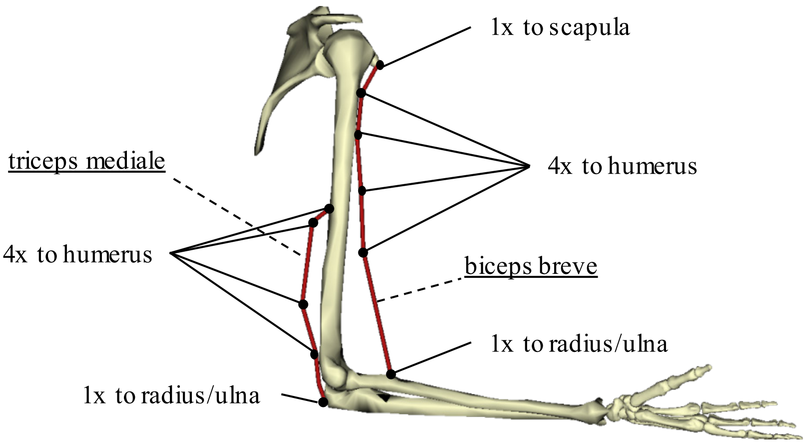

Figure 6. Spatial proximity of muscles and bones

Since bones are always spanned by multiple muscles each bone is assigned a vector containing the stress contributions of the adjacent muscles. In the example the stress vector for *humerus* would contain the two contributions of *biceps breve* and *triceps mediale*. For the visualisation these vectors have to be further aggregated to a scalar value that can be mapped to a colour value. For muscular activity we tested the *maximum* and *arithmetic mean* value of the vector elements. In contrast, for the metabolic energy rate the *total sum* of all elements is reasonable since the energy consumption is an absolute quantity with additive character. In Figure 7 the two methods to visualise muscle related stresses are compared by the example of metabolic energy rate.

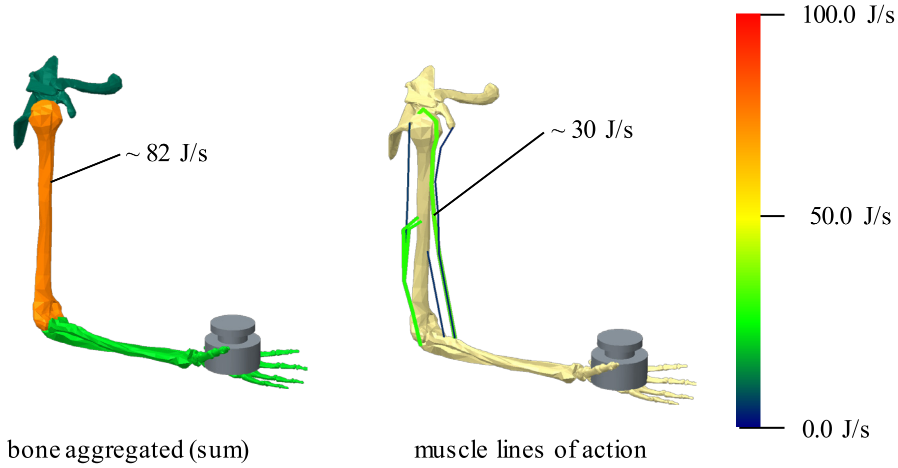

Figure 7. Metabolic energy rate: bone aggregated and visualised on muscle lines of action

3.3 Joint reaction forces

For the visualisation of joint reaction forces we propose a methodology that uses size and colour of spheres that are rendered on top of the CAD avatar at joint positions as indicators for magnitude. Their diameter grows linearly with the force magnitude between 10mm and 100mm. The expressiveness is further augmented by colouring the spheres according to the rainbow map. As in case of muscle related stresses, the user can specify visualisation bounds to adjust the mapping between force magnitude and size/colour to the numerical range of the data. Since not only the magnitude but also the line of action may be a matter of interest, the directions of the force vectors can be symbolised by arrows. In Figure 8 the joint reaction forces are shown for the simple arm model. At a first glance, a value of 1200N for the reaction force within the elbow joint may appear unexpected high but note that the reaction loads are caused for the most part by the muscle tension forces that can amount to more than thousand Newton in that region of the body.

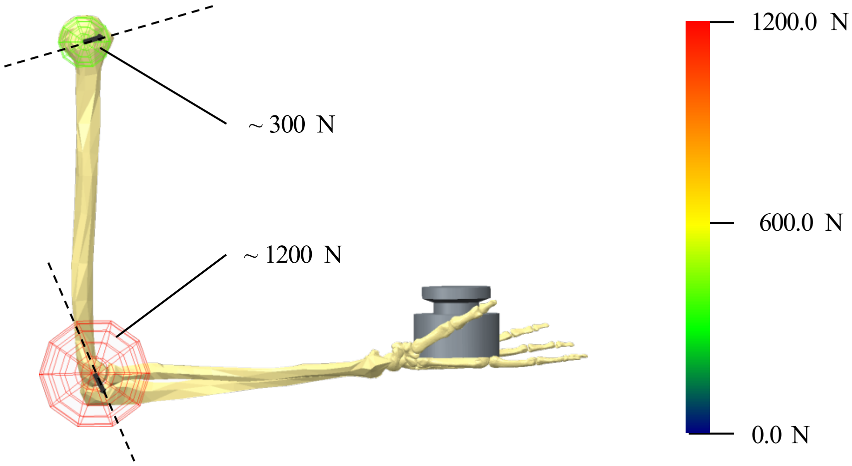

Figure 8. Magnitude and lines of action of joint reaction forces

4 CASE STUDY: PULL-UP ON THE HIGH BAR

In the following, the visualisation methods for biomechanical stresses presented in this contribution shall be applied to a more complex musculoskeletal model. Matter of interest is a person doing pull-ups on the high bar. Even though this example is not related to product design, it has been chosen since it is intuitively accessible. The musculoskeletal human model is grounded on the work of Delp et al. (1990) and Holzbaur et al. (2005). It represents a male subject with a body mass of 74Kg and a body height of 1.76m. For this experiment it has been imported into the CAD system *PTC Creo Parametric* that was also used to model the geometry of the high bar. The interaction between the human model and the high bar is essentially described by two geometric constraints that attach the hands to the bar. The motion was predicted using an inverse kinematic approach that adjusts the posture of the body while minimising the joint torques necessary to drive the motion. This motion sequence was further analysed by a controlled forward dynamic simulation to compute the biomechanical stress quantities muscular activity, joint reaction forces and metabolic energy rate.

The exploration of the result data set started with a coarse screening of the motion sequence using a bone aggregated representation of the maximum muscular activity. The objective was to identify critical time frames of the motion sequence. In the first third of the sequence a very high activity of the upper arm muscles was observed, which is shown in Figure 9.

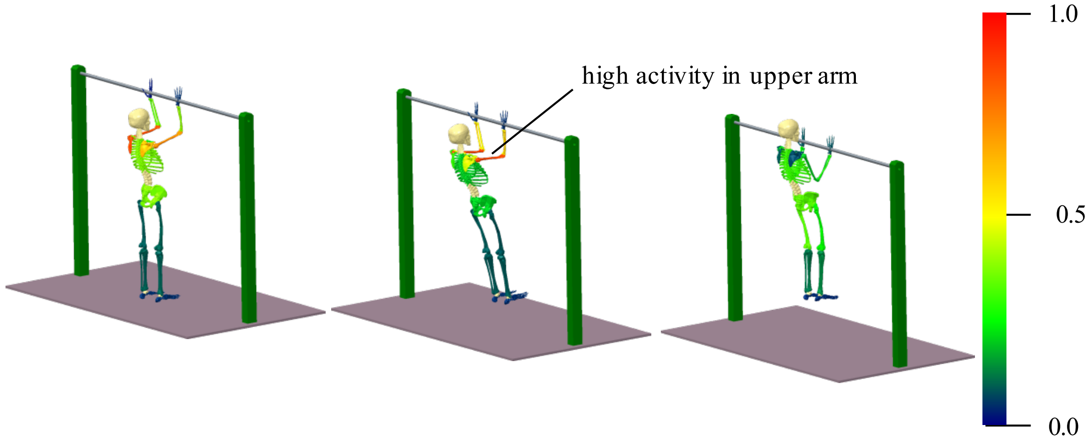

Figure 9. Identification of the critical frame in terms of muscular activity

The critical frame has been analysed more in detail considering the activity of individual muscles as well as the joint reaction forces. According to Figure 10, the muscle *biceps brachii longum* is working very close to its physiological force limit (activity = 1.0). This means that in reality, the person represented by the model could encounter problems doing the pull-up. Figure 11 shows the reaction forces within the joints of the upper body. The highest magnitude can be observed in the elbow joints.

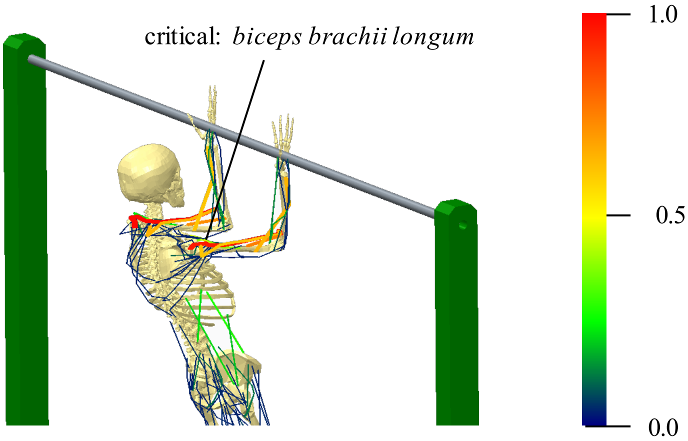

Figure 10. Critical muscular activity during pull-up

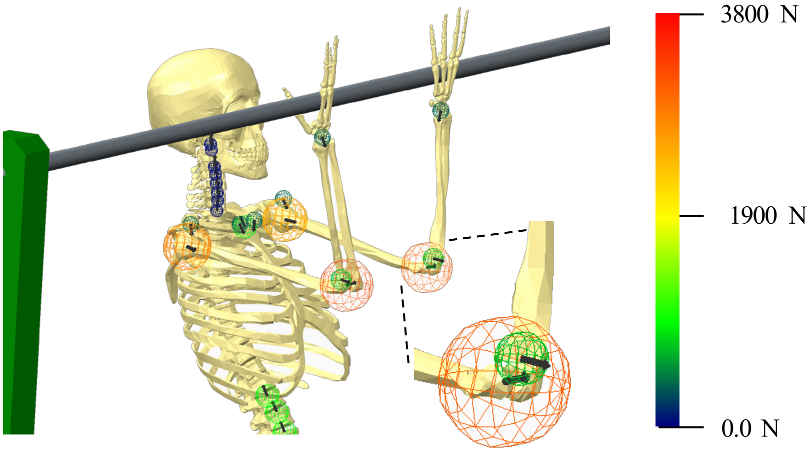

Figure 11. Major joint loads during pull-up

5 SUMMARY AND OUTLOOK

For a long time the dominating view on product design was affected basically by functional and economic aspects. At least the history of Computer Aided Engineering (CAE) has been dedicated primarily to the predictive coverage of product behaviour and the rationalisation of engineering processes. However, the demographic development in many industrialised societies and markets with a growing power of the customers will augment the importance of user-centred design approaches. Designers therefore need the support of methods and tools to understand how the use of a product is affecting the user - physically and emotionally.
In this contribution we used the analogy between stresses within the human musculoskeletal system and engineering stresses to show that classic engineering principles can be applied to human-centred problem areas. We believe that the CAD-integrated analysis of user-product interaction based on musculoskeletal human models could be the foundation of a new universal approach to ergonomics. The presented visualisation methods enable the designer to intuitively browse through big sets of biomechanical data in the immediate context of the product model with the objective to identify relations between design parameters and the physical effects within the user. However there are still some factors that may inhibit a wider application of our approach and therefore should be addressed by further research. Regarding the simulation with biomechanical human models one challenge is the realistic synthesis of human behaviour in especially human motion. Optimisation based approaches are promising but still require the designer to make many assumptions with respect to the proper choice of boundary conditions and optimisation goals. In addition the dynamic simulation of complex musculoskeletal systems entails quite long computation times comparable to FEA problems of

medium size. Coming back to the analogy with mechanical strength theory there is a need for reasonable thresholds of musculoskeletal stress quantities when applied to ergonomic problems.

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