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DIGITAL HUMAN BODY MODELLING TO SUPPORT DESIGNING PRODUCTS FOR PHYSICAL INTERACTION

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1. Introduction

Within the field of Industrial Design Engineering a Digital Human Model (DHM) can be used to support designing consumer goods such as supports, tools, protective means, but also for the design of working environments. A DHM is especially needed when the design requirements refer to processes that are normally inaccessible for investigation (outside the context of, for instance, a medical examination). As an example we mention the effects of externally applied forces on the blood flow in tissues, which may lead to tissue damage. In such cases a simulation of the human body is a prerequisite for the design and optimisation of any consumer product that have serious physical interactio with the human body. However, using DHM in design processes has a wider scope of interest. When during the product development cycle user trials are needed to obtain ergonomics requirements, a first impression of the interaction and the internal effects can be obtained with a simulation, so that expensive (time, finances) user trials can be reduced or even omitted. Further, if an optimisation of a product is needed, then experiments, that are based on expensive prototypes can sometimes be replaced by doing simulations, which is cheaper and can work faster. Therefore, a DHM should allow (i) acceleration of the design process, (ii) assessing mechanical and physiological loads inside the body and in the contact area between body and an artefact, (iii) application in a process for optimisation of the quality of the product, (iv) avoiding expensive user trials. To avoid confusion we stress that in the end user trials are always needed to (i) test the model and its underlying assumptions, and (ii) to test the final prototype for fulfullment to the requirements.

In the past DHM-s were created for various purposes. *Geometric models*, derived from 3D scanned data sets, served purely geometry oriented applications such as medical imaging and industrial applications (clothing) [Siebert & Marshall 2000] [Simmons 2002]. [Jones & Rioux 1997] gave an overview of the state of the art and an inventory of the possible applications. In design of consumer goods it is used to evaluate available space, reach, visibility, etc, but also for assessing stresses and strains at the surface of the human body as well as inside. In a medical context it is used for examination of tissues (damage, cancer), preparation of surgery (haptic evaluation, visual inspection of internal tissues), and in animation (avataers). Creating *avataers* requires visual realism of the kinematics of the outward shape [Luciano et al. 2001]. [Oliveira et al. 2003] extracted features from high resolution scanned 3D data to generate an assumed skeleton from surface landmarks and the surface itself. In general, it seems that the avataer technology is not yet able to handle human variability with sufficient spatial accuracy.

Using such DHM-s it proves to be very difficult (i) to simultaneously consider the stresses or deformations of tissues, and the physiological effects of such tissue loads, (ii) to apply the model for optimisation of product properties, (iii) to adapt the model to the requirements of varying product types, (iv) to create instances for a particular (sub) user group. We concluded that the main problem is the level of knowledge intensity of the models. Apparently, a DHM, that meets these requirements must be knowledge intensive with respect to (without being exhaustive) human shape variation, included tissues, material properties and human physiology. Therefore we defined the concept of an Advanced Digital Human Model (ADHM). An ADHM is based on algorithms that process and relate the knowledge from several disciplines. Since human properties are uncertain, and their measurements incomplete and biased, the model must be defined in *vague* terms (e.g. fuzzy or statistical). Since the model must allow the representation of different persons or groups of people it must consider variable properties such as the shape of the body and the internal tissues, the material properties of the different tissues and the physiological criteria for tissue functioning. Depending on the application at hand the model must be multi-functional by allowing the inclusion of specific submodels. In other words, the model must be *adaptable* to variability and application.

It is our goal to stepwise develop an ADHM, based on natural data such as shape and material properties, that allows (i) the evaluation of internal stresses and deformations, tissue relocations, muscle activation and the effects on the physiological tissue functioning under external loads, (ii) the application in an optimisation process. The specific knowledge, that is needed for an ADHM, depends on the application at hand. The basic research problem is formulated as follows: *What knowledge is needed to build a quasi-organic model of the human body, that can support designing products for physical interaction, and how must this knowledge be managed and implemented?* This paper presents (i) the knowledge, that is needed to build such model for application in a design process, (ii) the procedures to reduce and synthesise the knowledge, (iii) summary of the first experimental results, (iv) the application in ergonomics design, (v) what has been realised so far, including a design example.

2. Knowledge needed for building ADHM

To build an ADHM we need knowledge og the human body, and we have to know how to use that knowledge. Much medical knowledge is available, but not always suited for application in ADHM-ling, especially when it is not quantitative. When quantitative knowledge is available, the mathematical formalisation is not always simple and straightforward. Therefore model simplifications are inevitable. In order that future knowledge can then be included, the model must be *extendable*, which arises additional requirements for the core of the model and representation of the knowledge of the submodels.

In figure 1 we show the basic setup of our ADHM. The central control unit is called the core of the model. To the core several pieces of knowledge can be attached. The core is built on algorithms to (i) process the knowledge that is delivered by the submodels, (ii) communicate between the submodels, and (iii) to take decisions based on the interaction with external conditions such as mechanical load. It does not necessarily contain specific data, that must be delivered by attached submodels.

In an ADHM several types of knowledge, provided by the knowledge-submodels, can be attached, see figure 2 (later on, working-submodels will be introduced, that are developed for improved handling of the operationality of the ADHM). The *anatomical* submodel considers the location of tissues, the internal structure and the contained active and passive elements, and the functional relationships with other tissues. For instance, in order to use a hand tool the biomechanical transmission of forces is directed by the muscle-bone system, where muscles contain active elements. The knowledge on *morphology* considers the shape of the body and the internal tissues, and their connections and contact properties (geometric relationships). *Physiological* knowledge describes the functioning of tissues such as fluids (blood, lymph, interstitial fluid), soft tissues (muscles and adipose tissue), hard tissues (bones), metabolic processes and the nerve system. The mechanical *behaviour* is described by (i) the material properties, which are usually elastic, non-linear and/or viscous, (ii) the activation of muscular structures, (iii) conservative force fields such as gravity. The *posture* submodel describes changes of the positions of the joints. A change of the posture modifies the outward shape of body and the shape of the tissues, it relocates tissues, and it deviates the transmission of forces through the body. It depends on the application at hand what knowledge-submodels are included in the ADHM. For a specific application new submodels can be developed and attached and others removed.

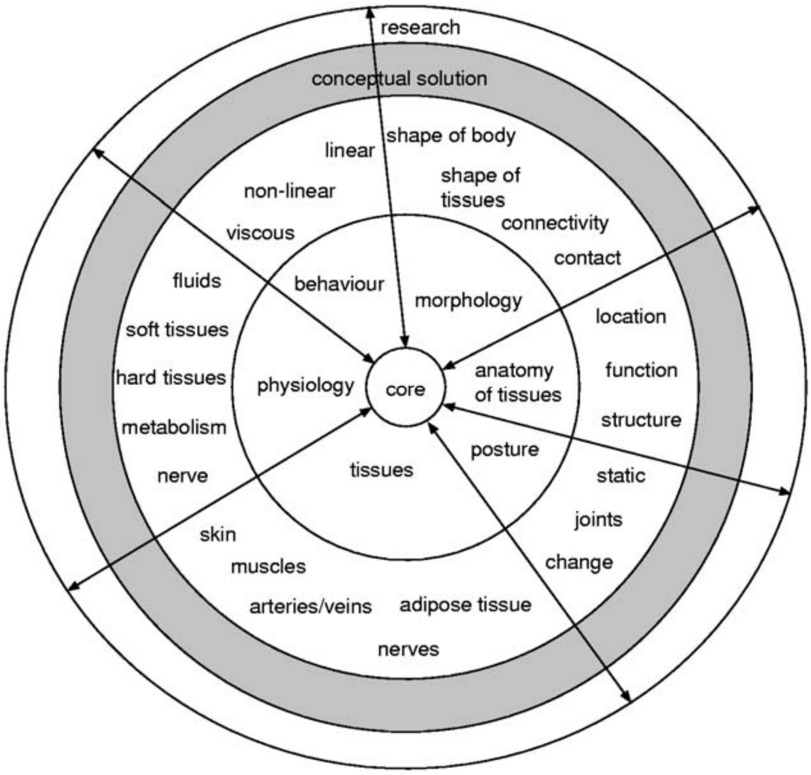

Figure1. The ADHM consists of a core and a number of submodels. This conceptual solution arises fields of research for the submodels and the core system

3. Formal theories and procedures

If the needed medical, ergonomics, etc. knowledge is available, it must first pass a number of conversion steps so that it can be used for building an ADHM. Figure 2 shows our basic procedural model of knowledge management. It consists of the reduction, formalisation and utilisation of available knowledge, and a pilot implementation. An action that converts knowledge into a higher level of abstraction, is called a Knowledge Engineering Action (KEA). The diagram consists of four groups of KEA-s. The first is the development of the conceptual solution. It converts the aggregated knowledge into a mathematical formalisation, that in principle solves the problem of building an ADHM. The second group is the conversion of the mathematical solution into a set of algorithms and procedures. The third group of KEA-s implements the algorithms using suitable software. The last group synthesises the knowledge for a particular implementation and does the testing of the ADHM. Now the question arises about the actual contents of the KEA-s. We will describe them briefly in the next subsections.

3.1 KEA 1: Reduction and structuring of the knowledge

Aggregated knowledge e.g., raw measurement data, are usually not very efficient to understand and describe the underlying phenomena. They have to be converted to a higher level of abstraction using for instance statistical techniques, so that they can be used to to express the underlying phenomenon using a reasonable number of parameters, and to find formal theories and suitable procedures for the solution. For example, shape data consist usually of a high amount of numbers, obtained from laser scanning or other devices. These numbers represent the carthesian coordinates of the measured points of the surface of a body. However, for the actual description of a phenomenon, for instance the anthropometric spatial domain of the shape of the skin of a group of people, the data must be presented at a more abstract level using techniques like vague discrete interval modelling (VDIM) [Rusak 2003], which enables describing shape in terms of the location of a set of spatial surface points as a function of, for instance, body characteristics [Moes 2004].

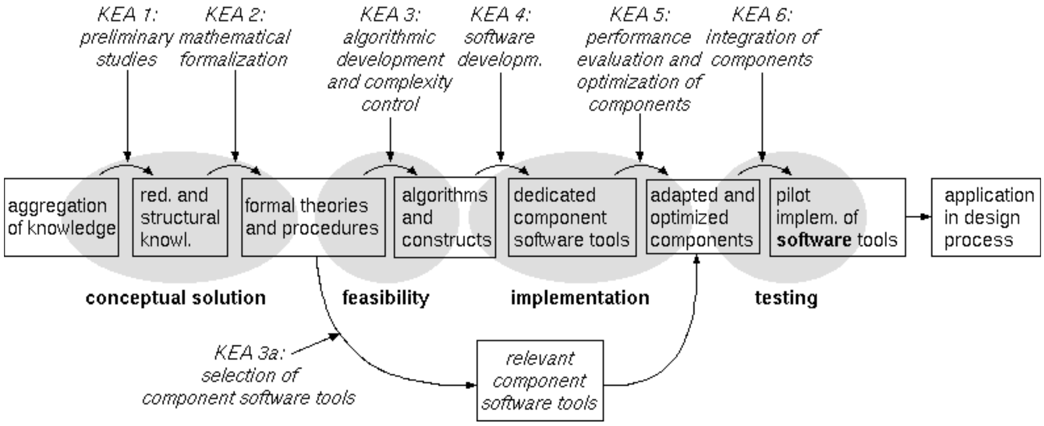

Figure 2. The procedural model for the conceptual solution, tool development and implementation. The level of abstraction increases from left to right

In order to manage the complexity, the total model can be divided in a set of *working*-submodels, which are able to handle coherent parts of the total knowledge of figure 1. For our ADHM this has been realised using a morphological model, a behavioural model and a product shape model, see figure 3. The morphological model describes shape of and connectivity between the tissues, and the contact conditions. The behavioural model describes the effects of external stimuli on the body. If the model is used in a product design environment, the artefact in question must be modelled in conjunction with the ADHM. The product shape model is used to derive the shape of the contact area and the mechanical properties of the product surface from the loaded ADHM. This requires the optimisation of internal quantitieas using the interaction between the ADHM and an accordingly modelled product.

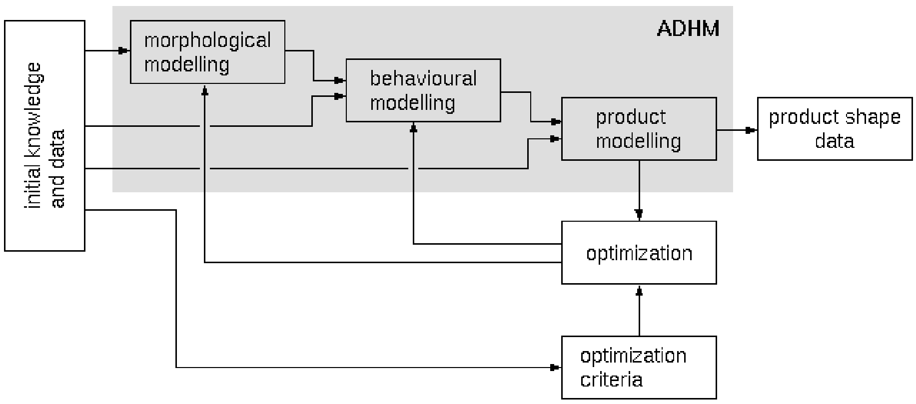

Figure 3. The general process diagram of generating and optimising the product shape

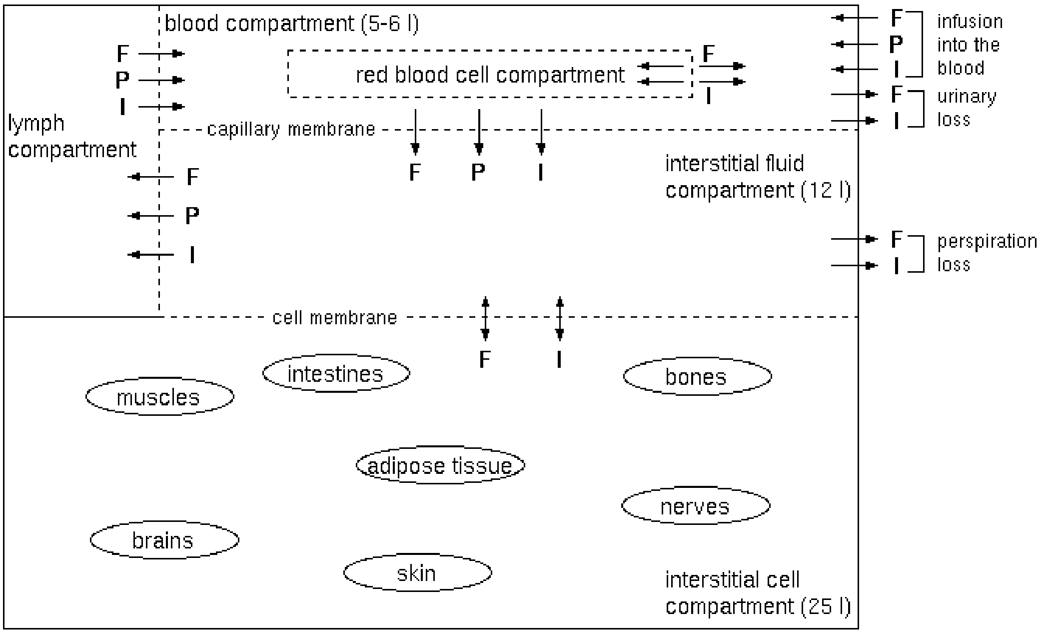

Figure 4. Scheme of the transport of fluid, proteins and ions related to the five compartment model. The semi-permeable membrane functions are shown by dashed lines. The bold capitals represent the transfer of fluid, proteins and ions

3.2 KEA 2: Formal representation of the knowledge

The basic ideas of a conceptual solution are usually not very difficult to understand. We know intuitively reasonably well what data should be collected, how they should be related, etc. However, the actual implementation needs mathematical expressions that describe the concrete processing of the knowledge: every detail of the processes inside an ADHM must be expressed in mathematical terms. It requires a profound knowledge of the human anatomy, physiology, biomechanics, etc. An example may clarify this.

Essentially, the interstitial fluid transports fluid, ions and proteins from the blood capillaries to the interstitial cells (for instance muscle cells), and to the lymph system, which transfers it back to the blood system. Based on the findings of [Gyenge et al. 1999], figure 4 shows these transfers for the five compartments of blood, red blood cells, interstitial fluid, interstitial cells and lymph.

The relationships between (i) the hydraulic pressures, (ii) the oncotic pressures, (iii) the concentrations of proteins and ions, (iv) the reflection coefficients and (v) the transfer of fluid (**F**), ions (**I**) and proteins (P), were mathematically modelled by a set of differential equations, that enables the dynamic simulation of, among other things, (i) the transfers through the capillary membrane, (ii) changes of osmolarity, (iii) distribution and transport of substances for each of the compartments, (iv) the trans-cellular potential, (v) changes of volume of the compartments, and (vi) the infusion influx and the out-flux via the perspiration system and the urinary system [Gyenge et al. 1999]. The overall compartment model is based on 20 ordinary differential equations, that describe the balance of fluid volumes, ions and proteins, two implicit non-linear algebraic equations, that describe the cellular trans-membrane potential, and two explicit algebraic equations, that describe the changes in cellular volume, several auxiliary algebraic equations for the compliance relationships, the osmotic pressures.

The incorporation of these factors in an ADHM enables the evaluation of the physiological effects, that result from externally applied loads, and from internal pulsations. These factors, together with the blood volume flow, are essential for tissue viability [Kosiak 1961]. Since the negative pressure values are so important, they should be the main criteria for a shape optimisation of the contact area between skin and product.¸

Select `elements-soft-material' and/or `elements-skin-material'
Assume gener. Mooney-Rivlin strain energy model
  apply James-Green-Simpson coefficients c10,c01,c11,c20,c30
  discard c20 and c30
  optimise coefficients using experimental press. distr. data
    using neo-Hookean approach (c10)
      apply stepwise reduction of c10
      if agreement, then stop optimisation
    using Mooney approach (c10, c01)
      apply stepwise reduction of c10 and c01
      if agreement, then stop optimisation
    using the JGS three parameter approach (c10,c01,c11)
      apply stepwise reduction of c10, c01 and c11
      if agreement, then stop
      if no agreement, repeat algorithm using other const. models

Figure 5. Example of the algorithmic representation of an mathematical formalisation: implementation of constitutive modelling

3.3 KEA 3: Algorithmic representation

The formalised knowledge can be operationalised by the conversion of the mathematical expressions of the modelled processes into practical algorithms. Consider for example the algorithmic representation of the mentioned submodels of the ADHM. The morphological model is based on measured shape data [Moes et al. 2001]. The point clouds of the individual subjects must be aligned according to a set of measured bony landmarks by rotation and translation of the point clouds, which can be computed using matrix operations. Then the resulting total point cloud is analysed for inner and outer hulls, and converted to a shape model of distribution trajectories and statistically defined location indices [Moes 2004]. The resulting model can be used to (i) describe the shape of the body of a (group) of subjects, and (ii) to generate new shapes. In order to support the computation the mathematical expressions are converted to algorithms, and suitable software is used for the actual implementation. In figure 5 an example is given for the implementation of the constitutive equation for the elements of soft tissue.

3.4 KEA 4 & 5: Software

Commercially available software must often be adapted and optimised for the application at hand. In our application commercial Finite Elements Modelling (FEM) software [Marc 2001] and statistical software were used, but the software for the geometric alignment [Moes 2004] and the VDIM [Rusak 2003] were developed at location.

3.5 KEA 6: Pilot implementation

A pilot implementation is needed to test the model for for finding uncertainties, errors, erroneous assumptions, etc. For instance, the constitutive models for the mechanical behaviour of human tissues are quite complex. In the past they have been developed for different applications (for instance prostheses), obtained under varying measurement setup, for different subjects, and for specific interpretation of the measured stress-strain relationships. Therefore we tested many constitutive equations for our FEM [Moes 2004].

4. Application of ADHM in ergonomics design

When an ADHM is applied for ergonomics optimal product design, it must allow the optimisation of product properties for ergonomics criteria. This requires the definition of an ergonomics optimisation criterion, or Objective Optimisation Functional (OOF). This functional, that was earlier called the

Ergonomics Goodness Index (EGI) [Moes 2002], contains the relevant quantities that contribute to the ergonomics quality of a product, for instance the maximum internal stresses or tissue deformation.

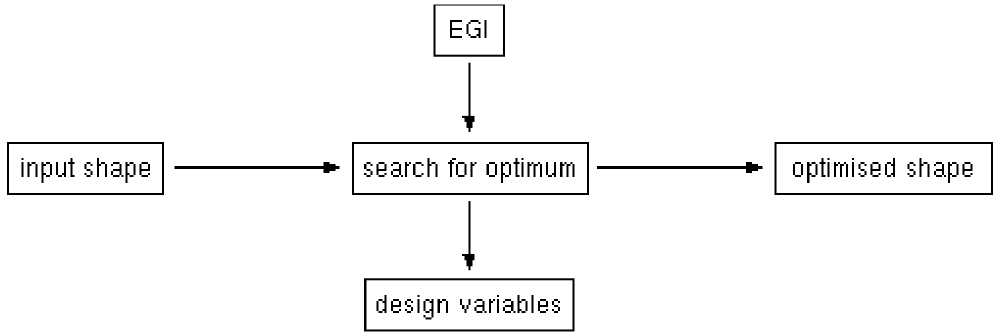

Figure 6. Basic scheme for the ergonomics optimisation of a product shape

By changing product properties (design variables) an optimised EGI can be computed for a specific user product interaction. For instance, the shape of a seat can be modified so that mechanical stresses inside a body will reduce the risk of collapsing blood vessels and the arising of decubitus. An actual implementation for ergonomics optimisation of for instance the shape of a seat requires, see figure 6, (i) an input shape, for instance a flat shape, (ii) an adequate definition of the EGI, for instance based on external pressure distribution data, or on internal stress distribution, and compared with physiological criteria, (iii) the possibility to modify product properties, for instance a parameterised description of the shape of the seat, and iv) an efficient search algorithm, such as gradient search of a random Monte Carlo search.

5. What has been realised so far?

We have developed a first ADHM for the upper leg and buttock regions of the human body. VDIM was used to create a generic[1] shape model (morphological model), based on scanned shape data of the skin of living subjects [Moes et al. 2001] and on scanned data of bones using the images of the Visible Human Project [VHP 1997]. In figure 7 (left) the measurement of the shape of the skin, using the MicroScribe robot arm device, is shown.

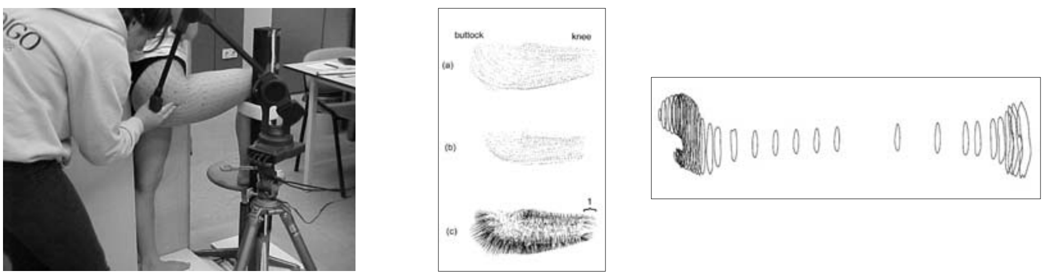

Figure 7. Left: measurement of the shape. Middle: vague shape model. Right: Scanned contour lines of the femur

Theses shape data were collected for a number of subjects. In this way for weach subject a point cloud of the shape was generated. The assembly of the shape data of all subjects was used to create a domain model of the shape. The middle figure shows the outer (a) and the inner (b) hull of the domain model, as well as the set of vectors that connect the inner and the outer hull (c). The shape of the bones was

1 Generic means that shape instances can be computed for specific body characteristics [Moes 2004].

obtained by scanning the contour lines of the VHP images. The right figure 7 gives an example of the femur (thigh bone).
The vague shape domain model, that was developed accordingly, allows the prediction of the shape of the surface of the skin in terms of distributed spatial points, which was supported by applying multiple regression technique using simple body characteristics such as stature, somatotype and gender [Moes 2004]. The adaptability of the bone model was based on fitting specific bony landmarks to the corresponding landmarks, that were measured at the skin surface of the subjects during the shape measurements (ischial tuberosity, greater trochanter, epicondyles of the knee, SIAS). A generated virtual shape was used as the geometric input model for creating a solid FEM. Only part of the model was used for the computations for reasons of computer memory and cpu time. Figure 8-top shows this FEM of the body. It represents the lower aspect of the buttock, including the ischial tuberosity, which region is most vulnerable for the effects of severe tissue loads (e.g., pressure ulcers). Below this FEM four shapes of the seat are shown that were used to load the model in order to compute the internal streses, strains and tissue relocations during loading (sitting). These shapes differ only with respect to the shape, where the lowest shape is a flat surface; the shapes were defined as rigid bodies.

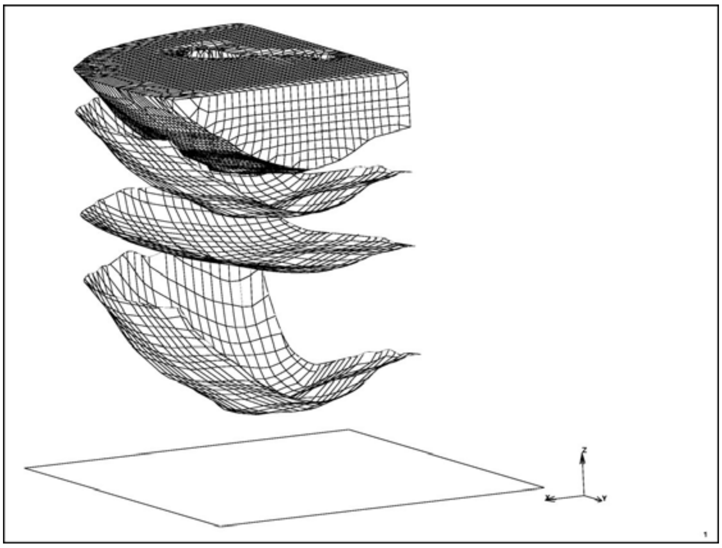

Figure 8. The finite elements models of the lowest buttock region (top) and the four seats that were used to load the model

After having defined the geometry of the model and the solid elements, the material properties of the elements are described by constitutive equations. Simple linear behaviour equations could not be applied because the tissue deformation is extremely large below the ischial tuberosities. We applied the Mooney soft rubber constitutive equations. The validation of the constitutive equations was carried out by a comparison of empirical pressure distribution data [Moes 1998] of sitting subjects with the data that were computed with this model [Moes & Horváth 2002].
Since the pressure distribution between a person and a seat depends strongly on the position of the pelvis, a method [Moes 1998] was developed to measure the pelvis rotation using a very simple device (the antenna method). This method assumes a relationship between the rotation of the sacrum and the rotation of the surface of the skin that covers the sacrum. A strong correlation was proved indeed. Figure 9 shows the antenna and how it is mounted on the skin.
The validity of the constitutive model was tested by comparison of the computed distribution of the internal loads with practical medical knowledge, which has been explained in detail in [Moes 2004]. Good agreement was especially found for the areas where medical phenomena like decubitus usually arise.

Figure 9. The antenna mounted on the skin that covers the sacrum

The relationships between the shape of a seat, and the stresses and strains inside the body were investigated. The resulting shapes of the seat were transferred to a virtual chair [Moes 2004]. In figure 10 three shapes of a seat are shown, each of them causing a specific internal load distribution inside the body. Figure 11 shows these shapes after they were transferred to a real seat.

6. Conclusions

Although a theoretical and experimental study have proven that the proposed approach for an ADHM is feasible, we are far from a final realisation. Much knowledge is still missing, additional mathematics and algorithms have to be developed and elaborated, and only limited software is available. Nevertheless, significant results have been obtained for a specific application (seat). Further research is needed to (i) elaborate the core model, (ii) improve the existing submodels and develop further submodels, (iii) testing and optimisation of the model, and (iv) application of the model in design practice.

In the far future the physically based models can possible be combined by attaching models that operationalise mental models of cognition, motivation, etc.

Figure 10. Three shapes of a seat

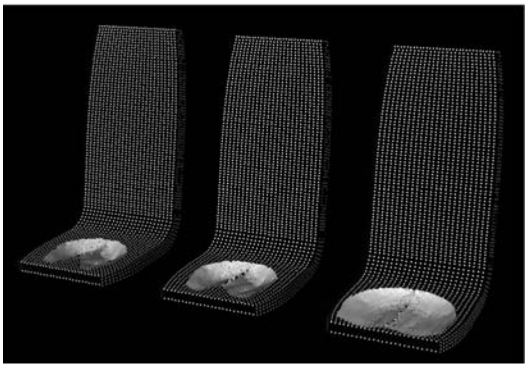

Figure 11. The point clouds of the chairs with the customised seats

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