HUMAN BODY AS A MECHATRONIC SYSTEM
Complex Modelling, Simulation and Control

Dorin Andreescu[1], Hartmut Riehle[2], Florin Ionescu[3,4] and Stefan Arghir[5]
[1]*Württembergischer Leichtathletik-Verband e.V., Stuttgart, Germany*
[2]*University of Konstanz, Konstanz, D-78467, Germany*
[3]*University of Applied Sciences HTWG Konstanz, D-78462, Konstanz, Germany*
[4]*Steinbeis Transfer Institute Dynamic Systems, D-10247, Berlin, Germany*
[5]*University "Politehnica" of Bucharest, RO-060042, Bucharest, Romania*

Keywords: Human body, Multibody mechanics, 3D CAD, 3D CAE, Identification, Modelling, Simulation.

Abstract: The modelling of the human locomotor system and its simulation are subjects of intensive studies, due mostly to the development of the computer processing power and the appropriate software. Most fields of application are located in the reconstruction of human movements: the motor, its transmission and the necessary control systems. The goal to have a general approach fully describing the Human Body as a System, with high accuracy and open set of functions for its entire complexity is still to be reached. Envisioning the body as an open system we refer to: the 3D-geometry of all bones and their 3D-defined positions (six degrees of freedom, the corresponding coordinates, restrictions and anomalies), the joints, ligaments and muscles with their frictions, both viscous and dry, and the contact pressures, the sensorial system with its information conduits and control mechanism and, last but not least, the human brain, as a hard-soft-controller for this most intricate and complex system that is the human body. This paper presents some main ideas for this approach and achieved results concerning steps on the way towards obtaining this goal. The first beneficiaries to welcome these results are, on the one hand, the sportsmen and, on the other, the architects and engineers working on humanoid robots.

1 INTRODUCTION

The goal of this paper is to demonstrate a practical approach towards 3D modelling and simulation of a realistic human body. More specifically, it focuses, as a first step, on how to gain the most valuable information about a real athlete.

Practically, the paper is focusing on the modelling of the body and the locomotor system as an inverse dynamic paradigm. While any human mechanical system can be moved with direct and inverse dynamics, we have selected the second approach, as convenient for research stage (Andreescu et al., 2007). Thus one can consider, that any human body can be described as a specifically adapted abstraction as a generally defined solid multibody system. It follows the CAD-methodology typical for machine or plant design. This approach will be illustrated, step by step, in the following chapters and accompanied by appropriate figures.

The body receives information through various sensors distributed all over the body. This includes: hearing (both frequency and amplitude are qualitatively "understood"), seeing (concerning images as forms, colours, distances, movements) tasting, touching (concerning pressure, temperature and humidity), smell. Information from outside the body is received by the different sensorial organs via different types of energy corresponding to each of the five human senses. Data from the sensors are then directed to the brain directly or indirectly through various relay stations in the form of bio current.

In Figure 1 the sensors are noted with s_k, while e_l denotes, in a simplified manner, some well known hand and foot joints. The brain receives and processes all the signals in order to produce an effect on the environment.

To obtain a Model of the Human Body to be simulated, two paradigms of thinking are used, by adopting the manner of robot modelling (Stefanoiu et al., 2004; Borangiu and Ionescu, 2002):

Andreescu D., Riehle H., Ionescu F. and Arghir S..
HUMAN BODY AS A MECHATRONIC SYSTEM - Complex Modelling, Simulation and Control.
DOI: 10.5220/0003600903390342
In *Proceedings of 1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2011), pages 339-342
ISBN: 978-989-8425-78-2

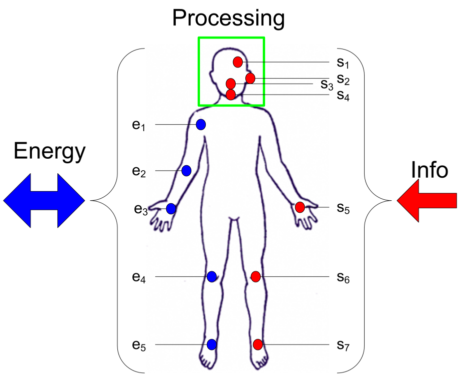

Figure 1: The human body as an open system.

1. The Direct Dynamics (DD), which corresponds to the previously described mode: starting from the brain a set of commands are provided via nerves to the muscles giving them the order to act; the body is moving according to the set of commands, by consuming energy. During the movement the brain is continuously correcting the command set, in order to attain the desired input variables set;
2. The Inverse Dynamics (ID) implies a different way for the flow of information and it only exists in theory: the realistically achievable movement of different reference points (joints, for example) is given, from what the forces and moments of all joints. Thus, all the human body parts are moved as a result of the energies calculated to be needed to be introduced into the body via the imposed movements.

The ID paradigm was used for the present research. The model to be simulated is a reconstruction/replica of a real skeleton. Having chosen a specific skeleton, a real human being must be found having very close constitutional resemblance. On this real human being it can measured, by using appropriate techniques, the movement of the appropriately selected joints/points. Afterwards, data have to be denoised and organised as ASCII files. Through the ASCII file, these points can be assigned to the corresponding points on the Computer Model.

2 MATHEMATICAL FORMULATION

These interactions can be formulated as differential equations of different types: mechanical, hydraulic, electrochemical, and other. In the general form, such a mechanical equation can be depicted as in 1. With several such equations, a system is formed. Reference for mathematical modelling of the human body can be found in (Hanavan, 1964; Ballreich, 1996)

$$[M]\cdot\{\ddot{q}_i\}+[D]\cdot\{\dot{q}_i\}+[C]\cdot\{q_i\} = [A]\cdot\{\dot{Q}_i\}+[B]\cdot\{Q_i\}+[E]\cdot\{U_i\} \quad (1)$$

with: $i \in [1,\ldots,6n]$, $k \in [6n-5,\ldots,6n]$, $[M]$-inertia matrix {kg or Nms^{-2}}; n - total number of degrees of freedom (DOF), $[D]$- the Damping Matrix {in N/(m/s) or Nm/(rad/s)}; $[C]$ - elasticity matrix {N/m or Nm/rad}, $[A]$ -coefficients' matrix of the first derivative of the perturbation vector $\{Q\}$; $[B]$-coefficients' matrix of the perturbation vector; $[E]$-coefficients' matrix of the input vector $\{U\}$.

3 FROM HUMAN SUBJECT TO MODEL SKELETON

In order to model an simulate the human locomotor system the authors applied a two step approach (Riehle, 1979; Vieten, 2004; Zahran et al., 2002). First the bones need to be mechanically modelled. For this purpose a human skeleton was used. Each bone is modelled independently.

After having the bones as separate static models, they can be combined with joints to form a piecewise modelled skeleton. Nevertheless, this is still a static model. At this point we have obtained just an innert object with no laws to move it or restrictions for the movement.

The animation of the model will be done by mimicking the movements of a real human body. For this purpose, a human test subject is needed. This person must be healthy, at least without any locomotor problems or peculiarities and he or she must have approximately the same dimensions as the skeleton used previously to obtain the static model. More details on the actual modelling are provided in Chapter 5.

4 DIRECT AND INVERSE DYNAMICS

The direct dynamic problem consists of finding a transformation matrix that relates the reference coordinate frame to the reference frame of each segment in a kinematic chain. In other words, the direct dynamic model determines the actual motion of a body when certain forces and or moments of force are applied to certain points. Typically, it uses link-segment models to represent the mechanical behaviour of interconnected segments, such as the limbs of humans, animals or robots. Thus, the movement is completely defined by the aggregated movements of all degrees of freedom. Presuming that each articulation has a maximum of 6 degrees of freedom, then the set of equations described in 2 completely describes the cinematic chain.

$$\begin{aligned}\{\ddot{q}_k\} = -[D]\cdot[M]^{-1}\cdot\{\dot{q}_i\} - [C]\cdot[M]^{-1}\cdot\{q_i\}+\\ +[A]\cdot[M]^{-1}\cdot\{\ddot{Q}_i\}+[B]\cdot[M]^{-1}\cdot\{Q_i\}+\\ +[E]\cdot[M]^{-1}\cdot\{U_i\}\end{aligned} \quad (2)$$

Inverse rigid-body dynamics is a method for computing forces and/or moments of force (torques) based on the kinematics of a body and its inertial properties (mass and moment of inertia). Opposite to the direct dynamics, given the kinematics of the various parts, the inverse dynamics derives the minimum forces and moments responsible for the individual movements. In practice, inverse dynamics computes these internal moments and forces from measurements of the motion of limbs and external forces such as ground reaction forces, under a special set of assumptions.

A general procedure is given in Figure 2.

The first step was to identify a suitable structure.

All bones of the human locomotor system were identified. Each bone was described in terms of weight, density and dimensions. All bones are considered to be perfectly rigid.

All joints were determined. The normal orientation for the coordinate frame was established for each joint. The second step was to identify measurement points on the skeleton model as shown symbolically in Figure 3a

5 MODELLING

The modelling and simulation environment of choice was Solid Dynamics SDS (SolidDynamics, 2005). This software can only "animate" solid bodies by applying predefined forces/torques. Paradigmatically, this corresponds to the direct dynamics mode. As a result, our case is basically an inverse dynamics problem: from the recorded movement of a real person, the necessary forces are to be determined in order to move each joint. This is shown in Figure 3b.

After selecting the segments of interest, several markers were placed on the on the body of the athlete.

Recording point movement was accomplished using procedure described in Figure 3b.

Modelling was done using mirrors in order to gain more visibility on the markers. In case that during a movement a certain marker gets hidden from a certain camera, then maybe that marker can be viewed indirectly in one of the mirrors, thus insuring constant marker tracking. Afterwards, during image processing, virtual images in the mirror must be transformed relative to the basis coordinate frame.

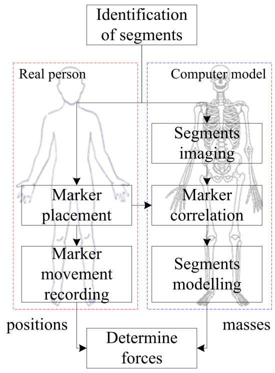

Figure 2: Solving the inverse dynamic problem.

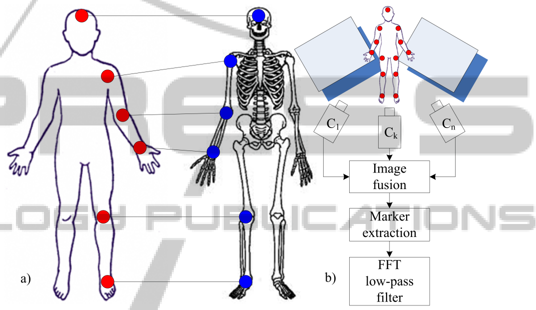

Figure 3: a) Identifying markers between real body and model; b) Solving the inverse dynamic problem.

On the ASCI file, a FFT low pass filter was applied in order to remove all the noise from the data. From this processing, the path of each marker relative to time is determined.

At this point, in order to calculate the forces driving the bodyes, all relevant masses are needed. To this end, and considering a mean bone density, only the volume of the bones must be determined. The volume for each bone can be easily extracted from its 3D shape.

A 3D model of the bones is obtained by following the procedure described in Figure 4.

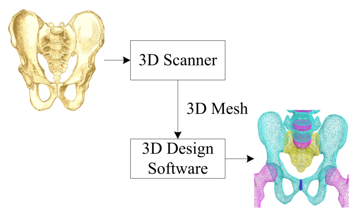

Figure 4: Obtaining a 3D model of a bone.

Incidently, the scanning process provides noisy outputs. Nevertheless, after some final manual modifications, each bone from the locomotor system has a 3D model.

By having a 3D model of all the objects, based on their dimensions and an average bone density, a mass can be attributed to each one.

As a result, the force applied to each marker can be easily determined from the formula $F(t) = m \cdot a(t)$.

6 SIMULATION

By applying this method, various techniques from different sports and other physical activities have been modelled. Two examples are shown in Figures 5 and 6.

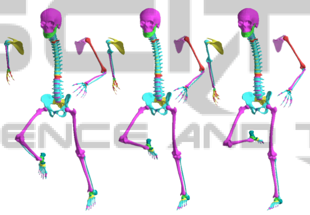

Figure 5: Athlete sprinting. 3 consecutive frames.

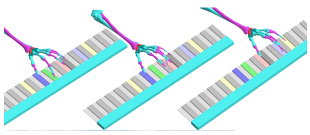

Figure 6: Piano playing. 3 consecutive frames.

7 CONCLUSIONS

The aim of the work was to illustrate a methodology of representing the human body as a mechatronic system. The modelling was performed in the multibody technology and the preferred tool was the SolidDynamics Modelling and Simulation program.

Obtaining the models and animating them exceeds the normal frame offered by SDS and its environment. Thus, other means had to be employed.

An own technology was developed and presented for obtaining models of the human body via scanning of bones and their translation into generalised meshes to be afterwards endowed with structural and dynamical properties.

Different layers of pre processing software were developed and are briefly presented in the paper. The paper demonstrates that the implementation of modern technologies allows the modelling and simulation of the human body as a most complex bio mechanical system. New approaches and new generations of computers will facilitate more and more complex approaches, as already mentioned, as well as shorter computing times, (quasi) real time simulations, the gradual implementation of FEM components and a bio control strategies for both direct and inverse dynamics.

Possible applications include medical care, post traumatic or post accidental recovering, rehabilitation of handicapped persons. In conjunction with the CAE of medical and fitness machines as well as for sport articles as shoes,and others, important information can be obtained for an optimised design of these products through simulation. The achieved results and the auxiliary methods used are quite promising. This opens new prospects for further developments in various industrial applications.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the support to the University of Konstanz/Institute of Sport Sciences, Deutsche Forschung Gemeinschaft (DFG), Steinbeis Transfer Institute Dynamic Systems of the Steinbeis University Berlin, and HTWG Konstanz Germany.

REFERENCES

Andreescu, D., Ionescu, F., and Riehle, H. (2007). Modelling and simulation of human body by considering of skeletons bones. In *Proceedings of IASTED International Conference on Bio Mechanics*, pages 153–159, Hawaii, USA. ACTA Press.

Ballreich, R. (1996). Grundlagen der modellmethode. In *Grundlagen der Biomechanik des Sports: Probleme Methoden, Modelle*, pages 118–159. Ferdinand Enke Verlag Stuttgart, Stuttgart.

Borangiu, T. and Ionescu, F. (2002). *Robot Modelling and Simulation*. Academic Edition, Bucharest, Romania.

Hanavan, E. P. (1964). A mathematical model of the human body. In *AMRL TR*, pages 64–102, Ohio, USA.

Riehle, H. (1979). Die biomechanik der wirbelsäule beim trampolinturnen. In *Schriften der Deutschen Sporthochschule Köln*, volume 2. Richard Verlag.

SolidDynamics (2005). *User Manual*. Annecy, France.

Stefanoiu, D., Borangiu, T., and Ionescu, F. (2004). *Robot Modelling and Simulation-Problems and Solutions*. Academic Edition, Bucharest, Romania.

Vieten, M. (2004). *Virtual Biomechanics and its Physics*. PhD thesis, Universität Konstanz. Habilitation Thesis.

Zahran, K., Vieten, M., and Riehle, H. (2002). Quantification of technical skills in weightlifting. In Gianikellis, editor, *XXth International. Symposium on Biomechanics in Sport*, page 478.