

# AnyBody

## - a System for Biomechanical Analysis and Ergonomic Design

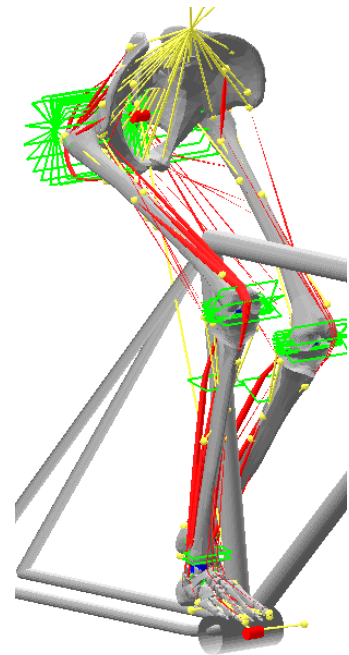
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### 1. Introduction

In recent years, the use of design optimization has propagated from structural problems to other disciplines, such as electro-magnetics, acoustics, mechanisms and fluid dynamics. However, typical for these applications is that they only deal with technical artifacts. The technology has not until now been extended to include the human body as part of a mechanical system, i.e., the cases where the design problem involves a man/machine interface.

This poster deals with such problems, and it shows that in the design of man/machine interfaces, the man as well as the machine must be part of the analysis model. The body and the machine are modeled as one mechanical system using a standard multibody dynamics formulation. The body is, however, a complicated system to model for several reasons:

- The musculo-skeletal system, i.e. the mechanical system, consists of complex and often compliant structures that are difficult to model and to obtain proper parameters for.
- The muscles constitute a complex actuator configuration. They change characteristics with the working conditions and moreover the body is over-actuated, i.e., there are more muscles than needed to drive the body.
- The central nervous system (CNS) is a very sophisticated control system that is not yet well documented. It adapts the body's performance to changes in the working conditions.



In this work, we present a simple model human, which is numerically efficient allowing for subsequent parameter optimization, and yet reasonably detailed to capture essential mechanical functions of the body. The model is basically an inverse dynamics, rigid-body model to which an optimization technique is applied in the process of finding the redundant actuator forces. Following from this type of analysis, all sorts of mechanical and biomechanical properties can be estimated and used for evaluation of the performance of a given design.

The method is implemented into the general body-modeling and optimization software system *AnyBody*. This system we believe to be an efficient tool for design optimization of man/machine interfaces, where the man supplies a significant power or force input. This poster aims at presenting the method and the system in general. Firstly, it presents the basic ideas of the model and the way it is analyzed. Additionally, it presents the state of the ongoing development by examples of experimental validation and applications of optimization in biomechanical analysis and ergonomic design.

### 2. Inverse Dynamics of Musculo-Skeletal Systems

The model of the mechanical system is a standard rigid multibody model. We implement this by a simple method using Cartesian coordinates, i.e., coordinates assigned to each body of the system. Sufficient kinematic constraints are imposed to make the system determinate. These constraints consist of joint constraints and driving constraints that serve to specify the motion.

To carry out the inverse dynamic analysis, the equations of motion are setup and solved for the unknown forces, i.e., reactions and muscle actuator forces. Due to the redundancy of the muscle actuator configuration, we formulate the inverse dynamics problem, *the muscle recruitment problem*, as an optimization problem:

$$\begin{array}{ll} \text{Minimize} & G(\mathbf{f}^{(M)}) \\ & \mathbf{f} \end{array} \quad (1)$$

$$\text{Subject to} \quad \mathbf{C}\mathbf{f} = \mathbf{d} \quad (2)$$

$$f_i^{(M)} \geq 0, \quad i \in \{1, \dots, n^{(M)}\} \quad (3)$$

where  $G$  is the objective function of the recruitment strategy stated in terms of the muscle forces,  $\mathbf{f}^{(M)}$ , and minimized with respect to all unknown forces in the problem,  $\mathbf{f} = [\mathbf{f}^{(M)T} \ \mathbf{f}^{(R)T}]^T$ , i.e., muscle forces,  $\mathbf{f}^{(M)}$ , and joint reactions,  $\mathbf{f}^{(R)}$ . Equation (2) is the dynamic equilibrium equations, which enter into the optimization problem as constraints.  $\mathbf{C}$  is the coefficient-matrix for the unknown forces and the right-hand side,  $\mathbf{d}$ , contains all known applied loads and inertia forces. The non-negativity constraints on the muscle forces, Eq. (3), state that muscles can only pull, not push.

Several suggestions for the objective function can be found in the literature, see for instance [1]-[4] containing surveys of the more popular ones. Most of the reasonable criteria are functions of the normalized muscle forces,  $f_i^{(M)}/N_i$ , where  $N_i$  is some measure of the muscle strength. The ratio  $f_i^{(M)}/N_i$  is also called the muscle activity. Muscles are complicated actuators the strengths of which depend on their working conditions. Furthermore, muscles normally do not follow straight lines between their attachment points on the body but wrap over bones and other tissues, effectively forming problems with contact constraints. The *AnyBody* system takes all these properties into consideration by use of a Hill-type muscle model, see [5], in combination with the wrapping over wire frame structures as shown in the figure above.

We choose the so-called min/max criterion, i.e., a minimization of the maximal muscle activity. Via the bound formulation, this can be expressed as:

$$\begin{array}{ll} \text{Minimize} & G = \beta \\ & \mathbf{f}, \beta \end{array} \quad (4)$$

$$\text{Subject to} \quad \text{Eqs. (2) and (3)}$$

$$\frac{f_i^{(M)}}{N_i} \leq \beta, \quad i \in \{1, \dots, n^{(M)}\} \quad (5)$$

We choose this formulation for two reasons. Firstly, it is physiologically reasonable as it corresponds to a minimum fatigue criterion. Secondly, it is a linear problem, which can be solved very efficiently. We notice that reaction forces can be eliminated from the problem enhancing both efficiency and numerical stability of the process.

The min/max criterion does however have some deficiencies. Firstly, the fact that solutions are found in corners of the feasible simplex leads to jumps in the time variation of muscle activity. This is, however, regarded as a minor problem. More problematic is the fact that there typically are multiple solutions to the problem. It arises from the inherent property of the min/max formulation that it only cares about the maximal activity of the muscles. This leaves some indeterminacy because only a subset of the muscles are actually represented in the objective, whereas subsets of sub-maximally activated muscles are not determined uniquely. As solution to this, we apply an iterative scheme of solution. In other words, we apply the min/max criterion not only to the full system, but also to sub-systems of sub-maximally activated muscles. For more details please refer to [4].

Output from the analysis is all sorts of mechanical properties such positions, velocities, acceleration, forces, energy and power, etc. Additionally, much information can be estimated from muscle activities/forces, for instance metabolic power consumption and potential energy in the tendons. All this output is available for evaluation of the performance of a given design.

### 3. Experimental Validation

Experimental validation of the model is important but also a very complex and difficult task. Currently, experiments have been and are being conducted with bicycling, which is a nice setup due to the relative simplicity of the motion and the external loads. We compare both detailed and more general information from experiments and model.

Detailed information is for instance the activation patterns of the muscles. Experimentally, these can be estimated by measurement of the electric stimulation (electro-myography or EMG) of the muscles. This can be compared to the mathematical muscle activity in the model. An agreement between these quantities is, however, only expected to be of a qualitative nature, because EMG measurements are very inaccurate and an indication of activity rather than a direct measure of the magnitude of the muscle force.

Therefore, more investigation of general information is important too. In bicycling, we investigate the mechanical output, for instance the tangential and radial pedal forces, which are available in the model and can be measured. This is not detailed information related to a single muscle, but a measure of their combined effort in driving the motion.

Another form of general information is qualitative studies of each parameter's influence and significance. Experiments are currently targeting this by investigating a rider's performance and other output in different riding postures. In the particular study the saddle positions are varied.

#### **4. Design optimization**

The *AnyBody* system is developed with an object-oriented data structure, where almost everything is derived from the same basic data classes. Included in these basic structures is the design parameter, which implies that everything in the model can take part in the optimization. In other words, not only the design of the mechanical components of the machine can be optimized but also the parameters of the human body and the prescribed motion of the system can be variable. This allows for more than typical machine design tasks to be handled, and the poster demonstrates that this is indeed an important feature.

Currently, the system is only equipped with one optimization algorithm for design optimization. This is a feasible-directions search method supplied with numerically computed design sensitivities. This choice of this algorithm is based on the idea that, when derivatives are only available through overall finite difference computations, and the criterion functions tend to have some degree of non-smoothness, the dependency on gradient information should be limited as much as possible. This is accomplished by using a robust algorithm with zero'th order line search.

##### **4.1. Determination of Unknown Motion**

Inverse dynamics requires the motion to be specified. However, if a proper criterion can be devised, optimization can be used to find the motion. One may say that we invert inverse dynamics by optimization. The reason is that we expect the body to attempt optimizing its performance. If we are able to guess the criterion the body uses, we can let *AnyBody* do the same mathematically.

This type of optimization can be a valuable tool for fundamental biomechanical analysis, because it allows analysis of motion that has not been determined through experimental motion analysis. One thereby skips one step in the process, enhancing the efficiency of the analysis, which may allow more detailed analysis such as large systematic parameter studies.

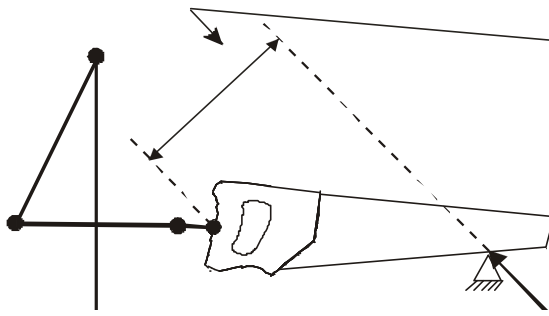
We have demonstrated this type of optimization for finding optimal motion in two cases, bicycling and the so-called squat jump. Bicycling leaves three degrees of freedom to be prescribed, for instance given by the angular motion of the crank and the feet. The crank is typically assumed to rotate with constant angular velocity, leaving only the angular motion of each foot undetermined. Using the objective to maximize the metabolic efficiency and a parameterization of the angle by Fourier series, we can actually produce realistic motion of the feet. Similarly, the squat jump motion has been generated successfully by parameterization of the joint angles of foot, ankle, knee, and hip and optimization for maximum jumping height.

##### **4.2. Ergonomic Design**

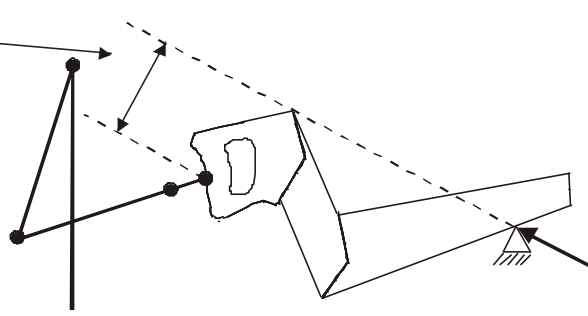
Design of a machine with respect to ergonomic criteria can be setup as the optimizations described above, however, now including design variables of the machine to be optimized. It is important to notice that this type of optimization typically will include variables for the motion, the so-called voluntary motion, and applied loads. The reason for this is to allow the human to adapt to the changes of the design. In other words, the optimum design is the design that performs optimally when operated optimally.

### Initial Design

Moment arm for hand-saw joint



### Optimal Design



The poster shows examples of such applications. Here we shall show a small demonstrative example of optimization of a hand saw. The example is described thoroughly in [6]. The design of the saw is optimized with respect to metabolic efficiency and the result is shown in the figure above. It appears that the optimization decreases the loads on the muscles as indicated by the smaller moment arms of the resulting force from the workpiece with respect to the joints. It should be noticed that constraints on the mechanism's dimensions were active in the optimal design. Furthermore, it is an ideal planar model that does not include out-of-plane stability issues, which probably are important in the optimal design.

## 5. Concluding Remarks

The *AnyBody* system is operational but still under development. The muscle recruitment is numerically very efficient, which is the central point in the system's capabilities, making it possible to analyze systems with hundreds of muscles. Development of body models and validation are also ongoing activities and better models must be created before practically relevant design optimization can be carried out.

The future activities of the *AnyBody* project comprise an extended collaboration with a number of research and development groups, among others "Analysis of driving comfort" with Ford Research Center, Aachen, Germany, "Optimal pedaling mechanisms" with the Technical University of Vienna, "Bicycle riding posture analysis" with Team Fakta and Principia, and "Investigation of over-head work situations" with M.D. Susanne Wulff Svendsen of Aarhus Municipal Hospital.

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