MUSCULOSKELETAL MODELING
AS AN ERGONOMIC DESIGN METHOD

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This paper describes how computer modeling of the musculoskeletal system can be used for ergonomic design of products and workplaces. The AnyBody Modeling System is introduced, and its underlying methods are explained. Two examples, the analysis of forces in a model of a seated human, and the design of the handle of a hand saw, demonstrate the methodology. It is concluded that musculoskeletal modeling has the potential to revolutionize the field of ergonomic design.

INTRODUCTION

Influences between different branches of science have been known to cause sudden changes in scientific paradigms because new opportunities for progress suddenly appear when different technologies are combined. The remarkable progress in computer technology has certainly influenced just about any field of science. This paper argues a similar potential in the unification of the fields of computational mechanics, biomechanics, and ergonomics.

Convergence of scientific fields is sometimes difficult because of diverging paradigms. The bulks of work in the sciences of ergonomics and medicine are based upon an empirical tradition, where mechanics is firmly rooted in analytical approaches, a distinction tracing back to the philosophical differences of Plato and Aristotle in ancient Greece. The potential outlined in this paper pertains to progress in biomechanics that allows for creation of detailed computer models of the musculoskeletal system. We expect these models to complement the role of subjective studies in many ergonomic design tasks.

MUSCULOSKELETAL SIMULATION

A brief review of the attempts to simulate the human body as a mechanical system is best initiated with the observation that the methods traditionally fall into one of two categories, inverse dynamics and forward dynamics, which, as the names indicate, are opposite approaches.

In inverse dynamics, the motion and the external loads on the body are assumed known, and the purpose of the computation is to determine the internal forces. When the "internal forces" are mere joint moments and joint reaction forces, inverse dynamics is in most cases a straightforward procedure involving the solution of a system of linear equilibrium equations. However, for the purpose of computing individual muscle forces, inverse dynamics is haunted by the so-called redundancy problem: not enough equilibrium equations are available to determine all the muscle forces. Infinitely many different sets of muscle forces, of which the central nervous system (CNS) instantly chooses one, can therefore produce the identified joint moments. This is due to the fact that we have more muscles than strictly necessary to drive most motions. Constructing an algorithm to determine the activation of each muscle therefore entails guessing the motives behind the CNS's function. We are able to repeat movements with considerable precision so many researchers believe that the control of muscle forces must be based on some rational criterion.

Assuming that muscles are recruited according to an optimality criterion, we are faced with the task of selecting the right one. Let us briefly state the mathematical form of the inverse dynamics problem:

$$\underset{\mathbf{f}}{\text{Minimize}} \quad G(\mathbf{f}^{(\mathrm{M})}) \tag{1}$$

$$\text{Subject to} \quad \mathbf{Cf} = \mathbf{d} \tag{2}$$

$$f_i^{(\mathrm{M})} \geq 0, \quad i \in \left\{1,\ldots,n^{(\mathrm{M})}\right\} \tag{3}$$

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

Surveys of suggestions for the objective function G can be found in the literature (van Bolhuis and Gielen, 1999). Most of the reasonable criteria are functions of the normalized muscle forces, $f^{(M)}_i/N_i$, where N_i is some measure of the muscle strength at each muscle's current working conditions. Rasmussen et al (2001) demonstrated that many of the criteria are asymptotically equivalent to a minimum fatigue criterion that can even be formulated as a linear problem, thus leading to a very high numerical efficiency. Care must be taken, though, to avoid indeterminacy of sub-maximally activated muscles (Damsgaard et al. 2001).

Figure 1. A model of the human body comprising more than 300 muscles developed in the AnyBody Body Modeling System.

The principal advantage of inverse dynamics for ergonomic investigations is that its computational efficiency allows for realistic models of the human body comprising hundreds of muscles as shown in Figure 1. The main disadvantage is that activation dynamics is not taken into account, and the method inherently assumes that the CNS is able to activate the muscles optimally. This means that inverse dynamics as it was outlined above is only suitable for static postures or relatively slow and skilled movements. Most cases of occupational ergonomics and design of products with ergonomic properties, however, do meet these requirements.

EXAMPLES

The AnyBody Modeling System (www.anybodytech.com) is a software tool for modeling and analysis of the musculo-skeletal system based on the methods outlined in the preceding section. It presumes the musculoskeletal system to be a mechanism of rigid segments connected by joints and actuated by Hill-type muscles. The examples of this section have been prepared with the AnyBody Modeling System.

The seated human

The seated human is a research project initiated by the AnyBody Research Group together with three furniture manufacturers. Its purpose is to use musculoskeletal modeling to provide a rational basis for ergonomic design of chairs.

While humans in modern societies spend a significant fraction of their time in chairs of various sorts, remarkably little has been achieved in terms of providing rational and quantitative knowledge of how the shape and support forces of the chair influence the comfort and discomfort of the occupant.

The field of seating ergonomics is dominated by subjective investigations (Mandal, 1981) or investigations based on questionnaire surveys (Zhang et al, 1996). In recent years, computer based models have also been presented, such as finite element models (Moes and Horváth, 2002) and rigid body mechanical models (Lengsfeld et al., 2000)). So far, however, it has not been possible to create a model that can calculate how muscular activity is affected by changes in sitting conditions

By means of musculoskeletal modeling it is now possible to create a detailed human body calculation model including all important components of the musculoskeletal system. With this model it will be possible to examine different postures and support forces in order to minimize discomfort.

The seated human project is recently launched, but a simple demonstration model can be presented here. This model comprises 84 muscles, 16 segments, and 9 joints, (figure 2) and is more detailed than most rigid body models presented in the literature. The spine part (de Zee et al., 2003) is simplified to a pelvic segment, two lumbar segments, and a rigid thoracic segment. It should be emphasized that this example is a work in progress, and the results have not in any way been validated. The presentation here merely serves the purpose of demonstrating the idea.

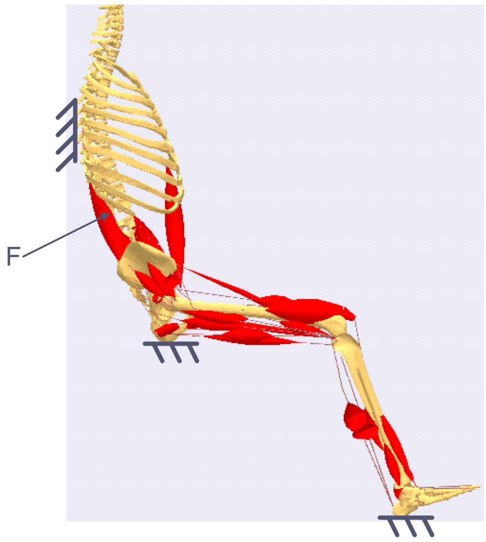

Figure 2. Musculoskeletal model of a seated human in the AnyBody system. The variable force F represents the lumbar support.

We shall consider the optimization of lumbar support for different backrest inclinations. The lumbar support is represented in the model by a variable force perpendicular to a lumbar segment. By using the AnyBody Modeling System for calculating the corresponding muscular activity for different magnitudes, we can identify the magnitude of the lumbar support force that enables the minimum activity of all muscles. We can also extend the investigation by allowing variation of the seat-to-backrest angle. Plotting the maximum muscular activities of the muscles in the upper body against the lumbar support force and the seat-to-backrest angle, we obtain the surface shown in figure 3.

We find that the optimum combination of lumbar support and seat-to-backrest angle is a force of 222N and an angle of 95° (90° represents an upright position). This gives a maximum muscular activity in the trunk of 0.39. Figure 3 indicates as expected that the need for lumbar support increases with the backrest inclination.

Obtaining minimum muscle activity with a nearly upright backrest seemingly contradicts the notion that inclined postures are more comfortable, but it is explained by the fact that the spine in the model is only supported at three discrete points with free spans in between, and the self weight of these spans requires more muscle force when the backrest angle is approaching horizontal.

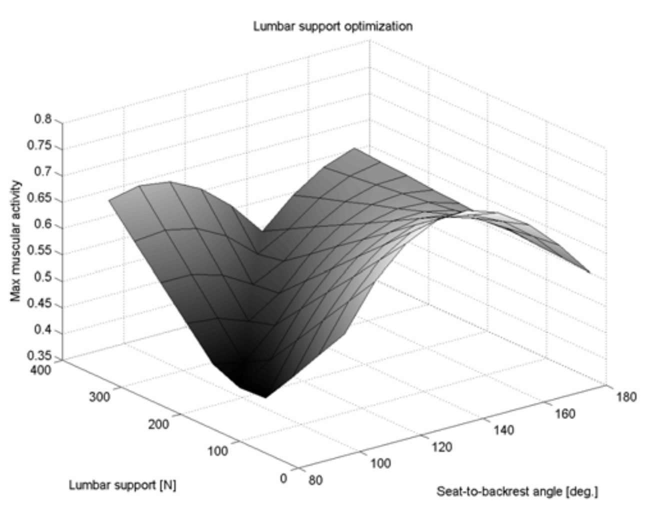

Figure 3. Maximum muscle activity in the upper body as a function of backrest inclination and lumbar support force.

Design optimization of a hand saw

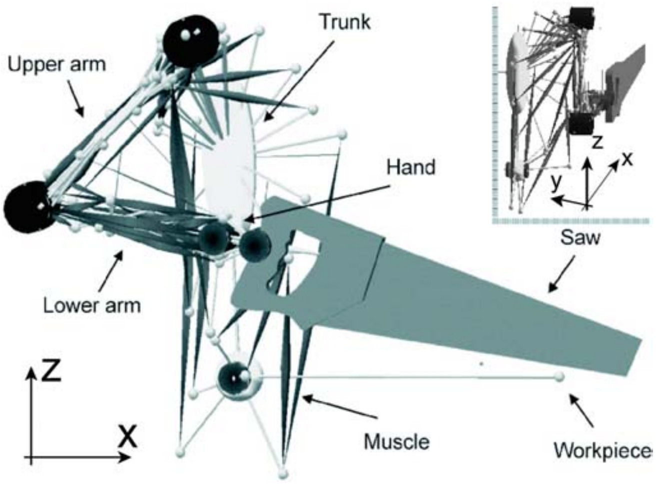

Figure 4. Mechanical model of a subset of the human body operating a saw. The model comprises five segments: trunk, upper arm, lower arm, hand, and saw. The model has a total of 52 muscles as line segments connecting the origin and insertion points of the muscles.

The availability of an analysis method that computes the state of the body as a function of its working conditions opens the possibility of performing ergonomic optimization by simply coupling the analysis with a numerical optimization algorithm. This example demonstrates the optimization of a hand saw with respect to metabolism. Each muscle’s metabolism is computed as its mechanical power divided by an efficiency of 25% for concentric work and −120% for eccentric work.

A model of the upper body operating the saw is developed. The model comprises 52 muscles, 5 segments, and 6 joints, see figure 4.

We seek to optimize the position and angle of the handle w.r.t. the saw blade. The objective is to minimize the metabolism as described above; how do we design a saw that cuts with minimum effort? The following assumptions were made:

The trunk is considered rigid in the model, so the relative motion between the arm and the trunk is only gleno-humeral, whereas the possible motion of the shoulder complex, the scapular-thoracic motion, is disregarded.

The progression of the saw through the workpiece is proportional to the energy dissipated in friction between the saw blade and the workpiece.

We require the saw to cut through the work piece in a given amount of time. This is equivalent to a constraint on average mechanical power.

The friction force is proportional to the normal force between the saw blade and the workpiece, i.e., Coulomb friction is assumed.

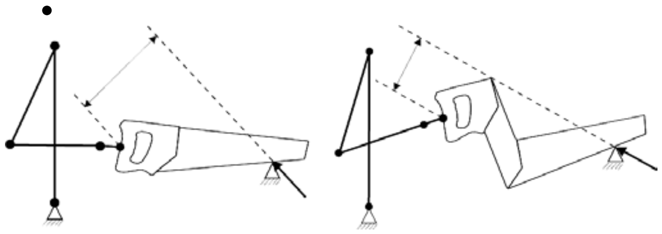

Figure 5. Initial and optimized saw handle positions with an illustration of the moment arm of the cutting force about the wrist joint.

The optimization moves the handle of the saw upwards. The design may look awkward, but a simple investigation of cutting force moment arms confirms that it helps the user reduce the muscle load required to drive the saw. This is valid for the wrist joint moment (figure 5) as well as the elbow and shoulder joint moment. The metabolic efficiency (ratio between mechanical work and metabolic energy consumption is increased from 10 to 24 percent. For further information, please refer to Rasmussen et al (2002).

CONCLUSIONS

The insight into the working conditions of the human body provided by musculoskeletal modeling has the potential to revolutionize ergonomic design because its analytical approach is complementary to empirical investigations. The construction of reliable and scaleable body models is a major but manageable challenge.

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