THE ANYBODY PROJECT – COMPUTER ANALYSIS OF THE HUMAN BODY

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INTRODUCTION

The AnyBody project is an initiative to enhance our understanding of the mechanics of the human body. This is accomplished by development of a software system for detailed multibody biomechanics modelling, the so-called AnyBody system. The special features of this system enable analysis of body models that are very complex in terms of number of muscles and degrees of freedom. The system handles body models with several hundred muscles, and realistic models of the entire human body are expected within a few years. This paper introduces the basic concepts of the AnyBody system with special focus on the problems of muscle recruitment and shortest-path muscle wrapping.

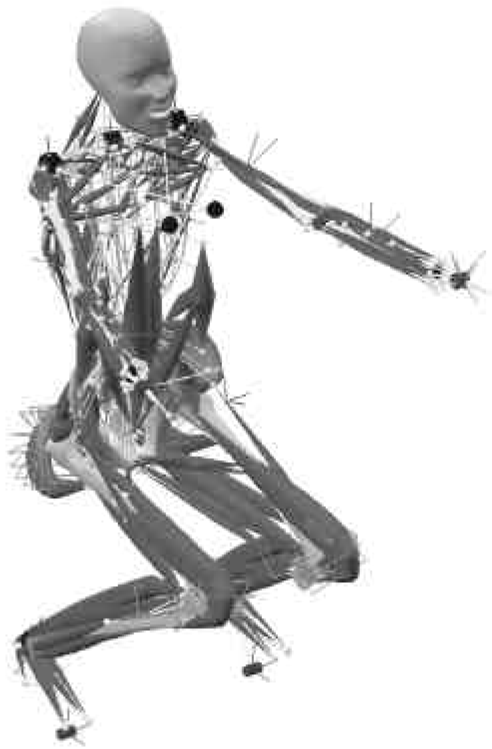

Figure 1: AnyBody model of a full body comprising more than 200 individual muscles.

METHODS

The AnyBody system is based on inverse dynamics, the idea of computing backwards from a specified movement to the interior forces in the body. The realization of such a system requires solution of several problems that lie in the interdisciplinary field between mathematics, mechanics, numerical methods, and physiology. This paper addresses particularly the following two issues:

1. The body is statically indeterminate, i.e., there are more muscles than degrees of freedom, and consequently not enough equations available to solve the equilibrium conditions to find the muscle forces.
2. Muscles do not pass in a straight line from origin to insertion. They wrap over bones and other tissues on their way, and this influences their effective moment arms and contributes to changing their properties as the movement progresses.

It turns out that the solutions to both these problems involve carefully developed optimisation algorithms.

MUSCLE RECRUITMENT

In the AnyBody system, the musculo-skeletal model is a standard rigid-body mechanism equipped with Hill-type muscles (see fig. 1). To carry out the inverse dynamic analysis, the equations of the known motion are set up and solved for the unknown forces. Due to the redundancy of the muscle actuator configuration, this system has more unknowns than equations, corresponding to the fact that there are infinitely many different muscle recruitment patterns that can balance the body at any given time. Technically, the body is statically indeterminate.

The statical indeterminacy is resolved by the central nervous system (CNS). In each position, movement, and external loading condition, the CNS instantly chooses a set of muscle actions that realise the desired motion. We are able to repeat movements with considerable precision, so the control of muscle forces must be based on some rational criterion. Indeed, Prilutsky et al (1997) state on the issue of muscle coordination: “It is not known why in skilled multi-joint tasks such as cycling, the pattern of muscle activity is rather stereotypical at similar cycling conditions, whereas an infinite number of activity patterns can theoretically be used by the CNS to perform the same task -- to produce the same combination of joint moments”. It appears that the muscle recruitment is not a random process, and it consequently seems that if we can guess the right criterion, then we can simulate the body’s muscle recruitment.

The AnyBody system employs the so-called min/max criterion (Rasmussen et al, 2001). Its physiological justification is minimization of muscle fatigue and it has the algorithmic advantage that the problem, after a slight reformulation, can be cast into a linear form and thus can be solved very efficiently. Using upper case bold face letters for matrices and lower caser bold face for vectors, we can briefly state the reformulated mathematical form of the inverse dynamics problem:

$$\min_{\mathbf{f},b} \quad b \tag{1}$$

Subject to $\mathbf{Cf} = \mathbf{d}$ (2)

$$\frac{f_i^{(M)}}{N_i} \le b, \; i \in \{1,\ldots,n^{(M)}\} \quad (3)$$

$$f_i^{(M)} \ge 0, \quad i \in \{1,\ldots,n^{(M)}\} \quad (4)$$

where $\mathbf{f}=[\mathbf{f}^{(M)\,T}\;\mathbf{f}^{(R)\,T}]^T$ is the vector of unknowns comprised by the muscle forces, $\mathbf{f}^{(M)}$, and the joint reactions, $\mathbf{f}^{(R)}$. Equations (2) are the dynamic equilibrium equations, which enter into the optimisation 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 constraints (3) ensure that the only way to reduce the objective, b, is to simultaneously reduce all the relative muscle forces. The non-negativity constraints on the muscle forces, (4), states that muscles can only pull, not push. The coefficients N_i express the relative strength of each muscle at any given time. In AnyBody, this strength is computed based on a Hill model taking the muscle contraction and contraction velocity into account.

Problem (1)-(4) states that we are looking for a muscle recruitment that balances the exterior loads, i.e. fulfils (2), and minimizes the largest relative load on any muscle in the system, thereby postponing fatigue of any muscle as far as possible.

While (1)-(4) can be physiologically justified and has the attractive form of a linear programming problem, investigations show that it is not mathematically well defined for complex body models. Damsgaard et al (2001) have described this problem in detail, and its solution in the form of an iterative computation scheme.

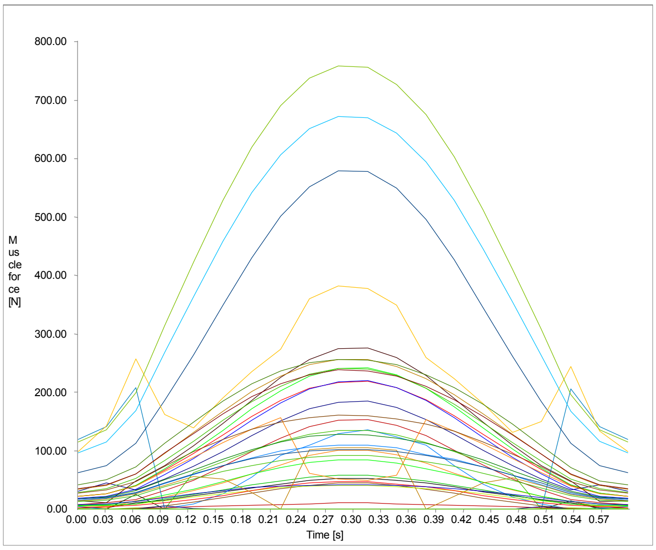

Figure 2: Typical example of muscle force simulation in the shoulder model of Fig. 3 comprising totally 63 muscles.

A realistic full body model will comprise on the order of 1000 muscles. In addition, the problem contains a number of joint reaction forces. This is a medium to large size linear programming problem, and the repeated solutions for the different time steps in the movement, the iterations involved in each solution, and the ambition to simulate the movement in close to real time calls for a careful consideration of the numerical efficiency of the algorithms. Linear programming problems of this size can usually be solved with better efficiency by a so-called interior point method than with the more common simplex methods.

All simplex methods are based on the same idea: The linear constraints form an *n*-dimensional polyhedron, a so-called simplex, in the space of *n* design variables. Due to the linearity of the problem, the optimum will always fall at one of the corners of the simplex. Simplex algorithms consequently step from vertex to vertex while reducing the objective, until the vertex with the minimum objective is found.

The efficiency of the simplex methods decreases rapidly with increasing *n*, because the number of vertices in the simplex is combinatorially dependent on *n*. This unpleasant feature has led to development of methods, which do not traverse the feasible domain via the vertices of the *n*-simplex but keep the design point inside the feasible domain, traversing it in large steps independently on the number of vertices. These methods were consequently named interior point methods and they improve the solution efficiency of large-size linear programming problems significantly. The interior point methods seem to be also more resistant to round-off errors than the simplex methods.

The AnyBody system has a so-called primal-dual interior point method implemented. The finer details of this method are described by Wright (1997).

MUSCLE WRAPPING

Development of realistic models of the human body is a complicated undertaking involving literally thousands of components. The manageability of the models therefore becomes an issue to consider in the choice of methods for model development. One of the most complicated mechanical aspects of the human body is the fact that muscles wrap over bones and other tissues on their way from origin to insertion. When doing so, they exert forces to multiple parts of the segment surfaces, and as the model moves, the muscles slide over bones. Existing contact surfaces change or disappear, and new ones may arise.

The correct handling of this behaviour calls for algorithms of contact mechanics. Contact problems are inherently challenging because they are highly nonlinear and lead to nonsmooth contraction velocities of the muscles due to the changing activity of the contact conditions. Furthermore, the bony surfaces over which the muscles wrap are complicated in geometry, and the correct modelling can therefore be a challenging task in itself.

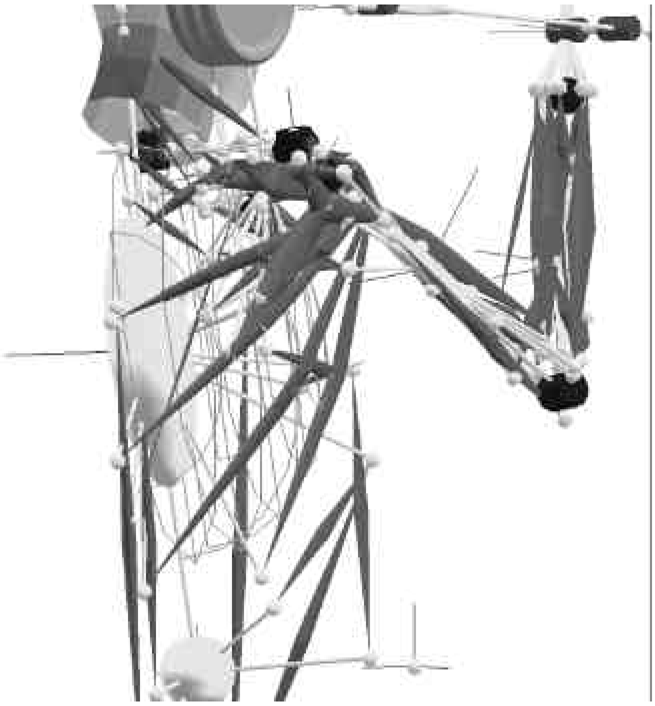

Figure 3: The wire frame approach: Several segments of m. latissimus dorsi wrapping over a rib cage in an AnyBody model of a strength training exercise.

Nussbaum et al. (1995) and Santaguida and McGill (1995) have demonstrated that realistic numerical simulation of the motion of the human body requires muscle models that emulate the behaviour of real muscles and their interaction with the skeleton to a reasonable accuracy. Several studies, for instance Miller and Dennis (1995) and Wickham and Brown (1998), devote a great deal of effort to determine the correct lines-of-action of individual muscles, and some effort (Chen and Zeltzer, 1992, Semwal and Hallauer, 1994) has been devoted to realistic representation of muscle geometries. Delp and Loan (1995) developed a method in which the user can specify a range of joint angles for which a muscle wraps over so-called via points. This method is computationally efficient but requires a-priori prediction of the existence and locations of the via points. Garner and Pandy (2000) developed an automatic method that allows muscles to wrap over a set of geometric primitives such as cylinders and spheres, the advantage being analytically derived solutions to the contact problem, and the drawback being cumbersome or even impossible modelling of complex surfaces.

Our aim is to allow muscle wrapping over surfaces of any shape, while maintaining a high numerical efficiency as required for interactive computer simulation. Recently, Feng et al (2002) developed a method based on wrapping over surfaces modeled as wire frames as shown in Fig. 3. It is possible to idealize most surfaces reasonably into a wire frame representation, but the process does require manual intervention, and the result is somewhat dependent on the choice of wire direction.

Here, we shall choose another approach. To enable the direct import of surfaces from CAD systems into body models, we have developed a method that enables muscle wrapping over triangulated surfaces described as STL files. An STL file is merely a collection of triangles, and almost any CAD system is capable of saving a surface representation on STL format. Thus, the CAD surfaces can be imported directly into the body model.

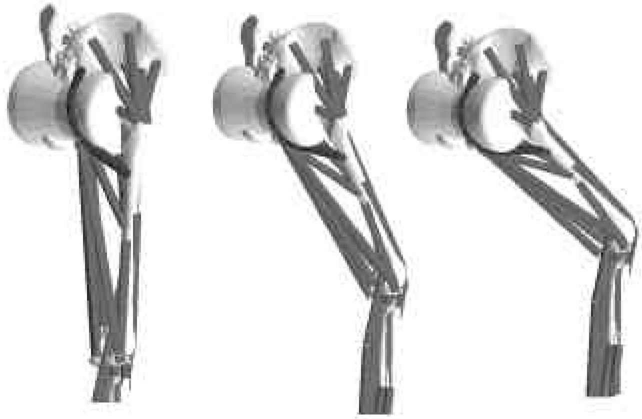

Figure 4. Gluteus maximus wrapping over an artificial STL surface added to the pelvis.

If the contact between the muscle and the bone is considered frictionless, then the identification of the muscle's path over the bone essentially corresponds to an optimization problem: Minimization of the distance between origin and insertion with the bone surface as a territorial constraint on the path.

We model this problem as a 3-D contact problem of an elastic string and a rigid obstacle representing the bone surface as shown in Fig. 4. The goal of this problem is to minimize the potential energy of the string. This way we obtain the shortest path of the string around the obstacle. The most important part in the formulation of this problem is to find correct conditions for non-penetration of the surface. We have chosen linearized contact conditions prescribing non-penetration of the surface by a point on the string in the direction of the outer normal vector to the surface. This model fits very well with triangulated surfaces as described in the STL format as well as with a string discretized by the finite element method. In the discrete case the method of prescribing the contact conditions of non-penetration is based on searching for contact pairs: point of string – closest triangle of surface in normal direction - and collecting these conditions for all points of string discretization. Then the problem could be mathematically written into the form

$$\min \tfrac{1}{2}\mathbf{u}^T\mathbf{K}\mathbf{u} - \mathbf{u}^T\mathbf{f} \quad (5)$$

Subject to $\mathbf{Nu} \le \mathbf{d}$ (6)

where $\mathbf{u}$ is vector of string point positions, $\mathbf{K}$ is stiffness matrix of the string and the $\mathbf{f}$ vector contains external loads and bounding point positions. The inequality constraints $\mathbf{Nu} \le \mathbf{d}$ represent contact conditions of non-penetration, where $\mathbf{N}$ is a matrix collecting normal vectors to the triangles in eventual contact and $\mathbf{d}$ is vector of feasible normal displacements of paired points from the string. This formulation is very suitable for efficient solving in its dual form by fast algorithms as described in more detail by Dostal et al (2001).

CONCLUSIONS

The development of realistic computer models of the musculo-skeletal system is a very challenging task. We have shown here two new ideas that represent important steps on the way to this goal: an interior point method for efficient solution of the muscle recruitment problem, and a contact mechanics algorithm that enables muscles to wrap over realistic bony surfaces in the model and provides a manageable interface between CAD models of bones and the multibody representation of the musculo-skeletal system.

It is characteristic for the development of these methods that they have been conceived in a tight interdisciplinary cooperation between mechanical engineers, mathematicians, and physiologists. It is the experience of the authors that much synergy is generated when the different fields of expertise are brought together to work on a common problem.

In the time to come, models of increasing complexity will be developed using these techniques and eventually form a realistic full-body model of the human.

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