# ERGONOMIC OPTIMIZATION OF A BICYCLE CRANK BASED ON MUSCULOSKELETAL MODELING

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## INTRODUCTION

AnyBody is the name of a research project as well as a software tool for musculoskeletal simulation. AnyBody is not much different from other musculoskeletal software systems in its description of the mechanical system in terms of rigid segments, perfect joints, and Hill-type muscles. However, AnyBody distinguishes itself in relying on inverse dynamics as its basic analysis method. It is not very widely known that inverse dynamics is no obstacle to performing outer-loop optimization of movements and boundary conditions. In fact, the numerical efficiency of inverse dynamics makes the outer loop optimization tractable on inexpensive PC hardware. The objective of this paper is to demonstrate this methodology by means of a bicycle optimization example.

It is difficult for the human body to produce much crank torque near the top and bottom dead centers of the pedal cycle because the tangential pedal force direction is perpendicular to the preferred force direction of the legs. Much effort has been invested into mechanisms that reduce or eliminate these dead centers. One of the best known initiatives is the Biopace oval chain wheel marketed by Shimano. Rasmussen et al. (2004) demonstrated an intricate mechanism for paraplegics' bicycles that helps overcoming the dead center by making sure that it does not occur simultaneously for the two legs.


Figure 1. Two springs suspended between the frame and the crank mechanism. The two green "cylinders" indicate the position of two similar springs.

Another possible solution would be to allow the mechanism to store energy when the leg has maximum leverage and subsequently release the energy when the dead center is approached. A spring arrangement as depicted on **Error! Reference source not found.** may serve this purpose. The two springs are stretched and compressed as the crank revolves, and careful positioning may allow the legs to store elastic energy that can subsequently help overcome the dead centers of the pedal cycle. On the other hand, it is almost universally accepted that storage of elastic energy due to flexibility of the bicycle frame is a disadvantage in pedaling. Furthermore, the symmetrical arrangement of the two springs may lead to the suspicion that they will cancel out whatever beneficial effect they may have individually. A musculoskeletal model can clarify the situation considerably.

## METHODS

*Inverse dynamics*

Inverse dynamics is often misinterpreted as being limited to identification of quasi-static joint moments in open-loop mechanisms where the reaction forces from the environment are known from experiments. In the following we shall briefly sketch how the AnyBody Modeling System manages to perform general analysis of realistic dynamic musculoskeletal models.

Inverse dynamics is haunted by the problem of statical indeterminacy: not enough equilibrium equations are available to determine all the muscle forces. A possible solution is to determine the muscle forces by an optimality criterion. This technique is sometimes erroneously referred to a static optimization, but there is no mathematical or mechanical reason for not taking the dynamic forces into account in the computations according to the principle of d'Alambert. In the bicycle model of Figure 1, muscles are recruited according to a min/max criterion:

Minimize
$$G(\mathbf{f}^{(M)}) = \max\left(\frac{f_i^{(M)}}{N_i}\right) \tag{1}$$

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

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

where $\mathbf{f}$ is the vector of $n^{(M)}$ unknown muscle forces, $\mathbf{f}^{(M)}$, and joint reactions, $\mathbf{f}^{(R)}$. $\mathbf{C}$ is the coefficient matrix, $\mathbf{d}$ is the right hand side comprising external forces, inertia forces, and passive elasticity in the tissues of the body, and $N_i$ is the momentary strength of muscle $i$. For further details about the solution of the problem, please refer to Damsgaard et al (2001).

*Kinematics*

The kinematical analysis is carried out in a full Cartesian Newton-Euler formulation, i.e., we assemble the coordinate vectors for all $n$ segments of the system, including both human segments and machine parts. Each segment has seven degrees of freedom because the formulation is in terms of three spatial coordinates and four Euler parameters, so this provides $7n$ independent non-linear equations:

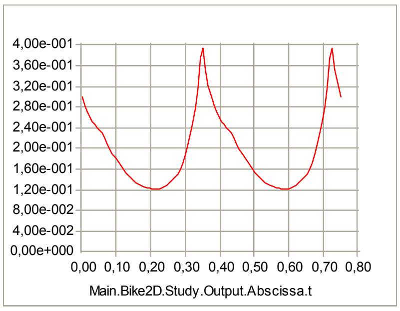


Figure 2. Maximum muscle activity over a pedal cycle at 80 rpm and constant crank moment of 30 Nm.

$$\Phi(\mathbf{q}, t) = \mathbf{0} \quad (4)$$

The position analysis is carried out by solving the equations by Newton-Raphson iteration using the constraint Jacobian, $\Phi_{\mathbf{q}}$. Velocity and acceleration analysis is subsequently done by solving the linear equations arising from time-derivation of Eq. (4), and knowing the motion completely we can generate the input to the muscle recruitment problem, Eqs. (1)–(3), and solve to find the muscle and joint forces of the system. The methodology is efficient enough to allow for solution of full body systems with hundreds of muscles on an ordinary personal computer.

*Implementation*

The methodology has been implemented into a software package called the AnyBody Modeling System. The software allows for modeling of the musculoskeletal system as well as the environment in which it functions. Moreover, the system works in batch mode as well as interactively, and this makes it possible to hook it up with an exterior loop optimizer that automatically adjusts the parameters of the springs, i.e. attachment points on the crank, the attachment point on the bike frame, spring stiffness, and slack length. When symmetry is taken into account, this amounts to 5 independent parameters.

The musculoskeletal model is essentially two-dimensional with the muscles and movement in the para-saggital plane. Each leg is equipped with nine muscles: tibialis anterior, soleus, gastrocnemius, biceps femoris short head, hamstrings, vasti, rectus femoris, gluteus maximus, and ilio-psoas. The muscle model is the simplest possible with each muscle characterized only by its maximum voluntary contraction force.

To focus the attention on the springs' effect on the prevalence of dead centers, the two legs are artificially required to produce a constant crank torque of 30 Nm at a cadence of 80 rpm corresponding to a power output of 251 W. This is a fairly high power output, and in a real situation it would be produced by an almost sinusoidally varying crank torque causing some amount of speed variation over the cycle. For slow speeds as when riding up hill, the variation may be significant, and cycling coaches recommend riders to make their tread as even as possible.

In the practical implementation, the optimization is controlled by a Matlab function, which uses golden section search to minimize the maximum muscle activity for a variation of each design parameter in turn while keeping the other parameters constant. This, rather primitive, optimization strategy has the advantage of not requiring any sensitivity analysis. Convergence for the optimization problem is obtained after looping the golden section optimization over the variables for less than five minutes on a 1.3 GHz PC computer.

## RESULTS AND DISCUSSION

Disregarding the springs and requiring the model to produce a completely even crank torque produces the variation of maximum muscle activation over the cycle shown in Figure 2. The dead centers are clearly visible as points in the cycle where the muscles are required to work relatively much to produce the required crank torque. The difference in muscle activity over the cycle is more than three times, signifying that torque generation at the dead centers is much more difficult than at the points of maximum leverage.

When springs are added to the model and the optimization of the attachment points and spring parameters is performed, we obtain the design depicted in Figure 1 with the springs visualized as cylinders. They each have a slack length of 240 mm and a spring stiffness of 16.7 N/mm. Figure 2**Error! Reference source not found.** shows the variation of maximum muscle activity over the cycle under these circumstances. The springs make the effort over the cycle almost uniform, allowing the rider to produce an even crank torque. Furthermore, the maximum muscle activity is less than half of the case with no springs mounted.

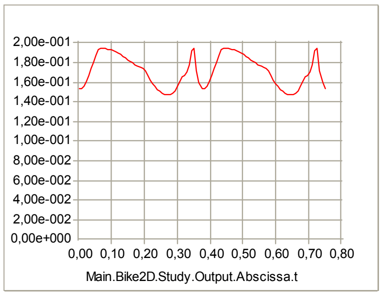


Figure 3. Maximum muscle activity over a cycle with springs added to help overcome the dead centers.

One additional parameter that has not yet been investigated is nonlinearity of the springs. It is possible that this can further improve the crank torque profile. It is important to notice that this spring configuration is optimized for a given cadence and power output. Investigations of the system's adjustability for other riding parameters will have to be made. Experimental investigation of the mechanism is currently in progress.

## REFERENCES

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