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SIMULATION OF TENDON ENERGY STORAGE IN PEDALING

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Abstract: The role of elastic energy stored in tendons during pedaling is investigated by means of numerical simulation using the AnyBody body modeling system. The loss of metabolic energy due to tendon elasticity is computed and compared to the mechanical work involved in the process. The AnyBody simulation system is based on inverse dynamics, where the redundancy problem is solved by a minimum fatigue criterion guaranteeing maximum inter-muscular collaboration. The tendons are assumed to be linearly elastic. It is concluded that tendon elasticity is responsible for metabolic power loss, and that the movement strategy is influenced by the presence of elasticity.

Introduction

The role of tendon elasticity in locomotion is a much debated issue [1,2], and one of many practically interesting cases is bicycling. It is well known that elasticity in some movements can have a beneficial effect on the efficiency. Could this also be the case in pedaling, and if not, how much energy is lost in the process due to tendon elasticity? If we regard tendon stiffness as a function of muscle strength, how much efficiency could then be gained by increasing the strength of the muscles?

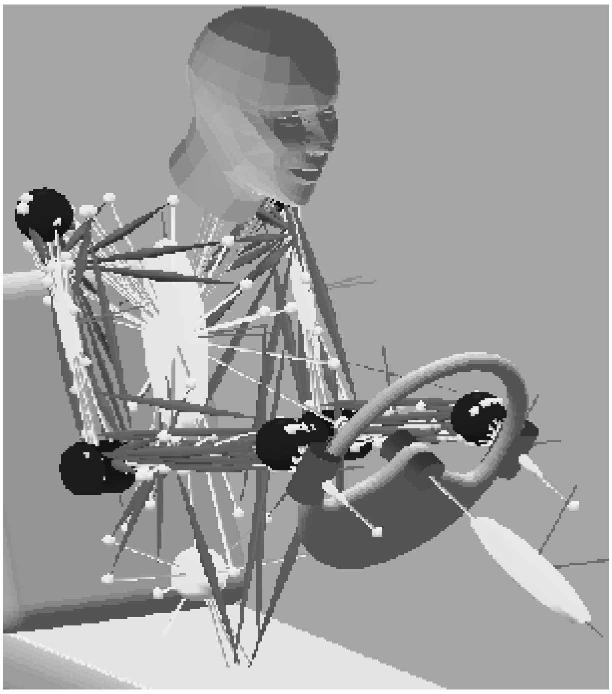

Figure 1. An example of a complex AnyBody model: A seated car driver comprising more than 100 muscles.

Tendon elastic energy is unfortunately very difficult to quantify experimentally. Experimental methods, however sophisticated, fail to directly measure the force and strain of each muscle-tendon unit involved in a typical motion. This means that the effect of tendon elasticity must be quantified by indirect methods, for instance oxygen consumption in concert with measurements of exterior mechanical work, or computation of muscle forces from ground reaction measurements [3].

Mechanical/numerical models of the body, on the other hand, can provide detailed information about the state of every element of the model, and would allow investigation of the role of each elastic element in the system. The body is a very complex mechanical system, and such models have therefore been subject to either significant simplification, or exorbitant modeling and computation costs.

Recently, the authors have developed the body modeling system AnyBody [4]. This system, based on so-called inverse-inverse dynamics and a minimum fatigue criterion for muscle recruitment, simplifies the modeling and simulation of the human body significantly, and this paves the way for a numerical investigation of the role of tendon elasticity in human movement. This paper reports an attempt to use AnyBody to compute the loss of metabolic energy due to tendon elasticity in pedaling.

Methods

AnyBody is a general software system for simulation of human movement. Models are constructed from bones, joints, muscles and tendons, and smaller or larger subsets of the body can be modeled and analyzed. The system is based on inverse dynamics and solves the redundancy problem by means of a minimum fatigue criterion that can be cast into the form of a linear programming problem [5]. This provides the system with a very high numerical efficiency allowing moving models involving hundreds of muscles, as shown in Figure 1, to be analyzed in a few seconds on an ordinary personal computer.

AnyBody is fully three-dimensional. However, pedaling is usually assumed to be modeled reliably in two dimensions only, and this is the approach we shall take here. The model comprises two legs, pedals, and the crank shaft as shown in Figure 2.

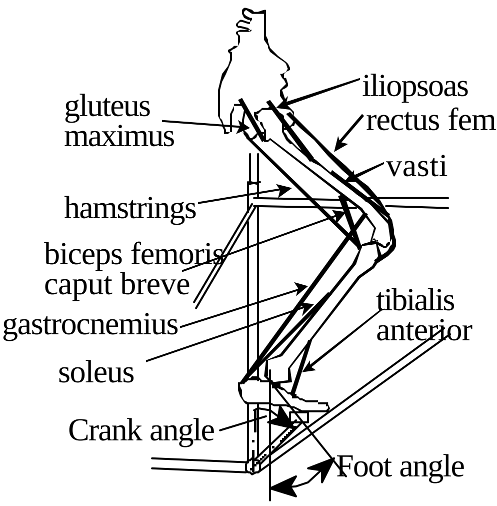

Figure 2. Model of pedaling (only one of two legs shown). Each leg has nine muscles. The system has three degrees of freedom and 18 muscles. Notice the definition of the foot as a line from the ankle joint to the pedal axle.

Each leg has nine muscles: gluteus maximus, ilio-psoas, rectus femoris, hamstrings, vasti, biceps femoris (short head), gastrocnemius, soleus, and tibialis anterior. A muscle-tendon unit spans the path from its anatomical origin to insertion. It comprises a muscle segment and a tendon segment. The computational length of the muscle segment is the current fiber length, and the remaining part of the origin-insertion length is assumed to be tendon. Muscle data are compiled from [6]. The stiffness of each tendon is scaled to the strength of the muscle, such that the tendon has a strain of 6% when the muscle exerts is maximum force. The muscles are Hill type with force/length and force/velocity dependency according to an adaptation of Zajac [7].

Determination of muscle forces in inverse dynamics is complicated by the fact that there are more muscles than degrees of freedom. This means that the muscle forces cannot be determined from equilibrium alone. The usual solution is to assume that the body recruits muscles optimally according to some criterion, and prediction of muscle forces hence involves the solution of an optimization problem. It is generally accepted that a linear criterion, i.e., a weighted sum of muscle forces, does not produce physiologically realistic results, because it fails to make muscles collaborate. Nonlinear criteria can and have been applied, but they require iterative solution methods with the associated computational performance cost.

For the AnyBody system the authors have developed a minimum muscle fatigue criterion that can be cast into the form of a linear programming problem, thus providing very high numerical efficiency. It minimizes the maximum load on any muscle relative to its momentary strength. This means that the muscles collaborate as much as possible to balance the exterior load. The algorithm reproduces many physiological qualities of muscle systems, for instance the presence of antagonistic muscle forces [8].

All elements in the body except the tendons are assumed to be rigid. The tendons are modeled as linearly elastic springs. Real tendons have nonlinear elasticity, but we accept the approximation because tendons in bicycling are stretched only in the lower part of their total elastic range.

The motion of this system is given by a constant rotation of the crank shaft combined with the two foot angles (see Figure 2). The muscles are working against a sinusoidal crank torque producing a net mechanical power of 200 W. The analysis proceeds in 100 time steps covering a full round of the crank shaft. In each time step, the system computes the position, velocity and acceleration of each bone, the length, length rate and strength of each muscle, all muscle and joint forces, the mechanical muscle power of each muscle, elastic tendon energy, the metabolic energy consumption of each muscle, and several other properties. Following the analysis steps, data for the entire system and the total cycle can be found by summation over all elements and time steps. The metabolic energy consumption of each muscle is computed by assuming an efficiency of 25% for concentric muscle work and -120% for eccentric work. This reflects the thermodynamic fact that muscle work is irreversible, and that even negative muscle work requires positive combustion.

We assume that the rider produces 200W net mechanical power at a cadence of 60 rpm, and we set out to investigate the difference in metabolism with and without tendon elasticity present in the model. The tendon elasticity appears as a serial elastic element in the muscle model, and its effect is that the muscle must stretch the tendon before force can be applied to the bones. This requires muscle work and increases the metabolism unless the motion and exterior load allow the elastic energy to be used positively when the muscle is relaxed. The model takes inertia forces of the segments into account, but the muscle-tendon unit is assumed massless in the sense that vibrations, visco-elasticity and the like are not included in the model.

With given net mechanical power and cadence, the bicyclist still has freedom to choose the riding style as defined by the movement of the ankle joint over the pedal cycle, and the variation of the crank torque. We must assume that the skilled rider will optimize his or her style to the given conditions. A study like this would therefore not be possible by the traditional use of inverse dynamics. This method would require knowledge of the ankle motion and the crank torque. They could be recorded for the case of human bicyclists but not for an imaginary rider having perfectly rigid tendons. Instead, AnyBody determines these parameters by optimization. For each case it identifies the ankle motion pattern and crank torque variation that minimize the metabolism necessary to produce the required mechanical output. Sine functions are used to describe the torque and foot angles, and variables in the optimization are amplitudes, offsets and phase shifts. We shall then investigate the difference between the resulting motions with and without tendon elasticity.

Results

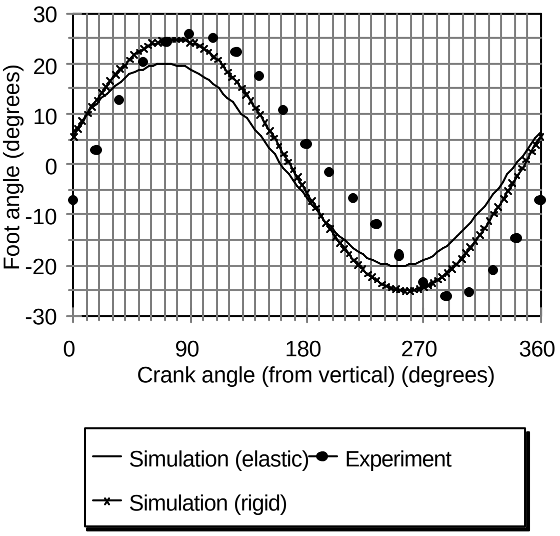

Figure 3. Optimized and measured [9] foot angle variations from mean values.

The optimization of foot angle and crank torque is initiated with the unrealistic case of a constant horizontal foot angle. The initial crank torque is sinusoidal with minima at the pedals' extreme top and bottom positions which, due to the length of the foot and the hip position over the crank, does not exactly correspond to the top and bottom dead centers of the movement. This allows for an indirect validation of the model, because the optimized riding style can be compared with typical styles of skilled bicyclists. Figure 3 shows the optimized foot angle variation with and without tendon elasticity present, and the corresponding measurements digitized from [9], representing an average over seven elite pursuit cyclists. The AnyBody data have approximately 10 degrees less amplitude than the measured angle variation, i.e., the numerical model chooses to rock the foot less than the average of the measurements. There is also a phase shift between the curves, some of which is due to non-symmetry in the measured data. The vertical offset between the curves is due to different definitions of angle origin. Considering that no effort has been made to make the dimensions of the AnyBody model correspond to the test subjects, and considering the variations of natural riding patterns between bicyclists of different dimensions, the agreement is satisfactory and indicates that the numerical model captures the main properties of the human physiology for pedaling.

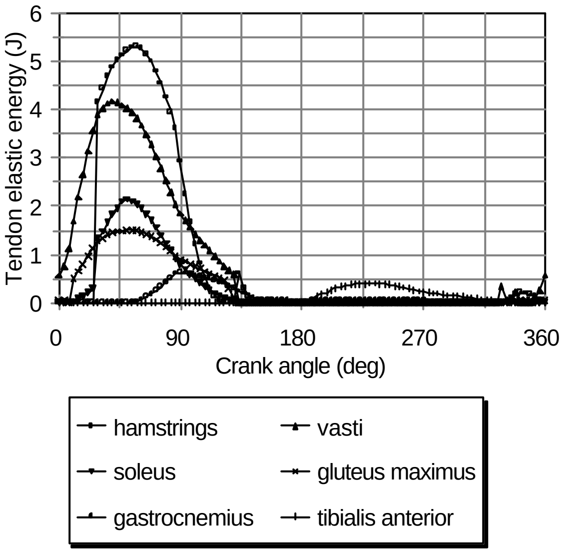

Figure 4. Variation of tendon energies in six muscles (one leg only). The energies in the remaining muscles are insignificant

Table **2**. Summary of results.

Property	**Rigid tendons**	**Elastic tendons**
Initial mechanical power (W)	201.10	201.1
Initial metabolic power (W)	922.3	1012
Initial efficiency (%)	21.80	19.86
Final mechanical power (W)	200.9	200.3
Final metabolic power (W)	820.7	835.3
Final efficiency (%)	24.47	23.98

Table **2** summarizes the results of the minimization of metabolic power consumption with and without tendon elasticity present in the body. The computed efficiencies are as expected. Measurements of the delta efficiency of bicycling [10] reveal best values around 23.5%. The numerical model, however, does not take friction, viscous effects and the like into account and hence arrives at a slightly higher efficiency. Please notice that the maximum attainable efficiency is limited by the assumed efficiency of concentric muscle work of 25%.

Comparison of the foot motion pattern for the two simulated cases in Figure 3 shows that pedaling is indeed influenced by the elasticity, both in terms of amplitude and phase shift.

Figure 4 shows the elastic energies of the six muscles with the larger variations: hamstrings, vasti, soleus, gluteus maximus, gastrocnemius, and tibialis anterior. Only the muscles of the right leg (at top dead center for crank angle 0) are shown. Due to symmetry, the results of the left leg are similar, only shifted 180 degrees. The energies are functions of the muscle force, so they closely follow the muscle force development, and we notice that the pattern is as expected for pedaling with leg extensors dominating as the foot moves down, and tibialis anterior active in the upstroke.

Discussion

The computations suggest that the tendon elasticity is associated with an additional metabolic cost of 15W, which, using the assumption of 25% efficiency for concentric muscle work, could have been converted to maximally 3.75W additional mechanical power. We can conclude that tendon elasticity does not have a beneficial effect on the efficiency of pedaling. Other compliances such as the flexibility of the frame are likely to have the same effect. Bicycle designers have known this fact for decades and consequently strive to make bicycle frames as rigid as possible within the given weight. The computations also show that the tendon elasticity does influence the movement strategy if minimization of metabolism is the goal.

We notice from Figure 4 that the main contributors to elastic energy storage are the hamstrings. These carry less loads than, for instance, vasti and soleus, but the tendon length of the hamstrings is set to be 0.46m compared to 0.29m of vasti, and this gives them more capacity for storing elastic energy at a given muscle force.

The computation of loss of metabolic power depends on the assumptions of the model: the assumed tendon stiffness, the use of linear elasticity, the min/max muscle recruitment criterion, the foot movement, and so on. On the other hand, these data are hardly more inaccurate than typical individual variations between test subjects, and the uncertainties are limited by the fact that the model in each point in time does fulfil equilibrium, produces the required mechanical power, and assures collaboration between muscles.

The qualitative conclusions - that elasticity is associated with loss of energy in pedaling and that the movement strategy is influenced by elasticity - are not likely to change due to different model parameters. It has been verified that imposing the motion pattern of rigid tendons on the elastic case and vice versa reduces the efficiency in both cases.

Conclusions

Detailed numerical modeling of the body allows for investigations that cannot be performed by experimental methods. The modeling is connected with some degree of approximation, but it is possible to obtain qualitative information from these investigations that has a high degree of certainty. The credibility of quantitative results will improve with the development of more detailed and validated models.

The model can also be used to study how much the efficiency can be increased if tendon rigidity is improved by muscular exercise. It is not sufficient to assume unchanged working conditions and compute the change in compliance of the tendon in question. Changes of tendon elasticity will change the load distribution between the muscles and is moreover likely to lead to different movement patterns. Forthcoming investigations will deal with this subject

Acknowledgments

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