Understanding artifacts of discretization. Discretization can lead to the splitting of one actual optimum into many numerical optima; the discretization can make the landscape bumpy. This creation of minima by the solution technique has been observed in classical elastic structures problems as well. When queried, most biomechanics investigators note that in multiple optimizations of the same problem, the best solutions are often not consistent from simulationto simulation. We suspect this could be not just from lack of convergence, but from artificial minima created by discretization. Increasing the number of parameters can, rather than fixing the problem, introduce an ever-growing number of artifactual local minima. We will explore this phenomena and means of avoiding it. The sources of the kinks are from interaction ofgeometric limits with the discretized but still smooth control functions and from discontinuities in the cost functions (or their derivatives, e.g. $|\dot{W}|$). Softening the constraints and smoothing the cost functions eliminates the kinks at the price of high stiffness. One approach we will investigate is a coupled refinement of mesh with stiffening of constraints so that the softest possible system is used for any mesh refinement.

Use of already existing software. While we hope to improve the state-of-the-art in biodynamics optimizations methods, we will compare with already available optimal control software (e.g., DIRCOL) and large-scale numerical optimization software.

Other optimization concepts. There are a variety of ideas we have for improving optimization in biomechanics that we hope explore. One is the use of Principal Component Analysis to tease out the essential control parameters so that the space of candidate solutions is of lower dimension. New numerical techniques, “validated arithmetic” and “interval analysis” might allow some questions can be answered, using numerics, with the confidence of a mathematical theorem. For example the exact number of local minima for an objective function may be determined. Our intuition is that such methods will not bear fruit for complicated problems, but we want to explore this area.

Model applications. Our optimization studies will be tied tightly to our muscle-law studies. We want to learn what aspects of muscle laws influence what aspects of predicted optimizations. And, in turn, which of these best mimics human behavior. Towards this end we plan to study simple model-problems that have stereotypic coordination patterns, namely rowing and swinging. Pedaling is another candidate, but is so-constrained that it may not well-separate candidate muscle laws. These model tasks willbe investigated from model to human subject and back to model refinement. In the end we will be able to describe what model features do and do not well-predict the observed range of coordination patterns

D.4. What this proposal is not about

For clarity, we review here some computational approaches to large-scale body function which are not of central concern in this proposal and we explain why we are not pursuing these.

Induced Acceleration Analysis (IA). The review-panel for this NIH batch of proposals may include discussions of IA and its merits. Here are my 2 cents. I feel that it is not useful to describe the importance of a muscle in terms of its rank in an IA-based sum.

We want to find, interpret and optimize the appropriate solutions of non-linear differential equations that are relevant to biodynamics. The difficulty of such tempts the pursuit of simple accounting schemes like IA which is describedas follows. The standard classical linked-rigid-object (frictionless) equations of motion relate all the contact forces, excitation forces, accelerations and angular accelerations by linear algebraic equations (these equations also include acceleration terms which are linear in the squares of the velocities). The coefficients in these weighted sums depend on the instantaneous configuration. Thus at any instant in time any quantity of interest can be found as a linear combination of other quantities. For example, the forward component of the acceleration of the center of mass can be written as a sum of contributions from the muscle tensions, gravity forces, and v^2 terms as

$$\begin{aligned} m_{tot}a_{cmx} \quad = \quad & c_1T_1 + c_2T_2 + \ldots \\ & +d_1G_1 + d_2G_2 + \ldots \\ & +e_1Q_1 + e_2Q_2 + \ldots \end{aligned} \tag{8}$$

where the T_i are muscle tensions, the G_i are gravity forces on the links, the Q_i are terms quadratic in the velocities, and the coefficients $c_i, d_i,$ ande_i depend linearly on the masses and inertias of the parts and nonlinearly (e.g. products of sines and cosines) on the configuration variables.

By some mixture of measurement and simulation one might imagine knowing all about a person's mechanical state at some time. So one can formally define the fractional contribution of muscle 17 to forward acceleration at one instant in time, the *induced acceleration*, as

$$a_{cmx17} = \frac{c_{17}T_{17}}{m_{tot}}. \tag{9}$$

Further

1. Eqn. 9 gives the fraction by which the forwards acceleration of the center of mass would decrease if the tension in muscle 17 were instantly set to zero and all other muscle tensions were held constant (assuming validity of the frictionlessly-linked rigid-object model). And
2. The term $c_{17}T_{17}/m_{tot}$ is equal to the forwards acceleration of the center of mass if the model person is put at zero velocity in the instantaneous configuration of interest and muscle 17 suddenly has tension T_{17} (with all other muscles and gravity turned off throughout).

This much is not in question. But does the relative rank of a muscle, as scored by Eqn. 9, have clinical significance for the importance of that muscle for the task at hand? I think generally not.

Here are some of the issues about the applicability of IA analysis.

- Finding the IA-based contribution of a muscle to a person's forward acceleration assumes that more forward acceleration is good. But walking, say, depends *exactly* as much on backwards acceleration. Using the contribution to quantities that are not actual goals, like transient forwards acceleration, as a figure of merit is questionable.
- The IA-based contribution assumes all muscles are force actuators. But over any extended time they are not. Any actual strength or muscle deficit will be compensated-for or reacted-against by the passive and neurally controlled responses of other muscles in a manner that will swamp any IA based transient.
- In a task where there are agreed-upon figures of merit, say, the work needed to walk up hill or pedal a bicycle, the big IA contributors are poorly correlated with the big work performers.
- The result of an IA calculation can be highly sensitive to details to which the real system is not sensitive.

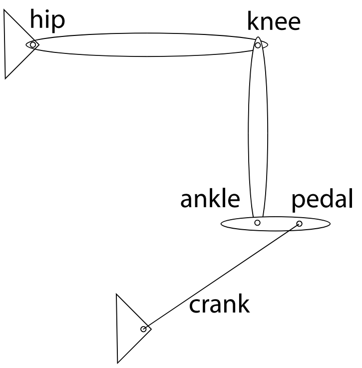

Figure 12: **A simple model of pedaling.** Assume only single-joint muscles for simplicity of discussion. Although the hip dominates the work, IA says the ankle makes the dominant contribution to the pedal force. Whether this is a positive or negative contribution depends on whether the ankle is a shade to the left or a shade to the right of the center of percussion of the foot relative to the pedal.

Certainly a biodynamics evaluation scheme has to demonstrate sense in simple non-pathological situations before its utility to more complex situations can be assumed. I use a pedaling example [65] which is a special case of the model discussed at length in the generally excellent review [87]. The problems the example highlights persist for less-simple geometries and less-simple mechanisms ([21]) although these arguments have not yet been accepted by IA proponents [88].

Assume a leg with only single joint muscles, and that the hip and knee muscles do most of the work over a cycle, that the masses and sizes are similar to those of a typical person, and that the instantaneous configuration of interest is that shown in Fig. 12. Assume the bicycle is in high gear so that the acceleration of the pedal is fixed. Assume that all the center's of mass lie on the joint-to-joint lines. The IA analysis can be done by inspection.

1. By IA the contribution of the work-dominating hip muscle to the downwards component of the pedal force is close to zero, and could be positive or negative depending on whether the ankle is to the right or left of the center of percussion of the foot with respect to the pedal. This is an extreme model sensitivity.
2. By IA the contribution of the ankle muscle dominates the contributions to the pedal force.
3. If the ankle angle was held constant and thus the ankle muscles did no work, IA analysis still says that the ankle muscles make the dominant contribution to the pedal force
4. If the ankle muscles were replaced by ligaments, called muscles because of the presence of a stray muscle fibe, the ankle muscle would be determined by IA to dominate the downwards pedal force.
5. If the person had a fused ankle that was accidentally called a muscle, that locked joint would be determined by IA to dominate the downwards pedal force.

This much is almost directly stated in [87]. These are features of IA accounting. But rather than taking these features as downgrading the relevance of IA, [87] uses these counter-intuitive features as an explanation of the poorness of our previous understanding.

In fact, the clinically relevant, dominant balance for light body parts is a static balance of rate-dependent active and passive muscle forces. This can be demonstrated by the following thought or simulation experiment: imagine a person is altered only by halving or doubling her foot mass. This would have little consequence on her coordination patterns, muscle tensions, measured forces or accelerations or the predicted optimal coordination patterns from a large-scale forward-dynamics model. Yet, in this hypothetical analysis, the IA equations would give results for the contributions of many body parts that would scale with the foot mass. The IA arithmetic and ranking is mediated by inertial terms even if those terms are almost irrelevant.

In this pedaling example we know before hand that the hip and knee muscles dominate the net contribution to pedal work and IA results are interpreted in that light. But if we did not already have understanding of the task, mightn't we deduce from IA that the ankle muscle was the most important for pedaling? Even though, say, fusing the ankle has only small effect on any aspect of pedaling whereas fusing the "less important" muscles ruins performance. Would we make analogous errors by using IA for more complex tasks like walking where we don't have such clear intuitions to protect ourselves? I think so.

Also, attempts to overcome the instantaneous nature of the IA method by linearizing the equations of motion with respect to imagined perturbations in one muscle force (e.g. [6]) are similarly doomed. Over time muscles are not force actuators and the real transients after perturbations will depend on rate-dependent muscle properties and on compensations that the patient makes.

Other non-IA mechanical observations from measurements or simulations offer simpler and more useful information. Noticing that a muscle is in substantial tension shows that the muscle is important for a task. Showing that the actual muscle-work is a substantial fraction the total work of the task is also important, as for the hip muscle in pedaling. IA ranking of the muscle adds little, if anything, to those observations. Using the language of IA to express simulation results, as in the pedaling discussion in [87], more obscures than helps useful interpretations. Imagine that pedaling was more than a useful model task, but was also clinically important. Which of these two statements would be more informative to a clinician or to a biomedical researcher?

1. "Despite what you may think, actually it is the ankle extenders that are the main contributors to the

crank torque." or

2. "A person with severed ankle extending tendons corrected by an externally locked ankle is predicted to use 3% more fuel for a given amount of work than an unimpaired person. This can be reduced to a net 2% *decrease* in fuel use by means of an appropriate energetically passive external orthotic device." (this quote is an imagined statement of the type the research I propose should enable to be made with reasonable confidence)

The first statement is straight IA, the second statement is informative (that is, I for one would like to know if it, or something like it, is true or not).

Note, the linearity of the instantaneous-mechanics equations *is* useful for some purposes, including the approximate solution of the distribution problem [8], the design of elastic-compensation devices, and the development of intuition for how mechanisms work (this was D'Alembert's great and useful insight, that dynamics could be reduced to statics).

These words from [87] seem applicable: "*The concept of [some non-IA accounting scheme] seems to have developed because mathematical relevance was mistaken for physical relevance. It is important to recognize that one type of relevance does not necessarily imply the other.*" The IA bandwagon seems also to be following the attractive scent of formalization. Perhaps the one small contribution I can make to the proponents of IA techniques is to aid the redirection of their efforts. All of the IA proponents have done excellent biodynamics simulation work which points in useful directions and which should continue.

Detailed kinematics and geometry calculations. Computers, in conjunction with well measured human bone, ligament, and tendon geometry, might be used to predict range of motion of various body parts. We do not plan to pursue such an approach because of our lack of expertise in the needed anatomy and lack of experience with the needed geometry calculations.

Large scale anatomically accurate simulations. Large-scale anatomically accurate simulations of the general class developed by Anderson and Pandy [64, 7] are a necessary part of the overall research of which this proposal is another part. Again, we do not want to pursue those ourselves because of our lack of expertise in the needed anatomy and because we feel we are more usefully used developing tools for others who do these simulations.

Near-photo-realistic computer animations. For communicating with medical practitioners realistic animations will surely be useful. But development of the final animation and rendering tools is not work at which we have any special talent or experience.

D.5. Final comments

Although I take full responsibility for the final content, the present proposal was put together with the help of my planned collaborator John Bertram at FSU and students Manoj Srinivasan and Sam Walcott doing their PhD research on the initial stages of this project, PhD students Dave Cabrera and Mario Gomes who have done work that motivates this proposal, and Steve Collins who is working on the new efficient powered robot.

New PhD student Anne Gutmann has NSF funding of her own to use simulations to address comparative anatomy models of running. Her planned research is complementary to that proposed here and will use results of this proposed research as they become available.

The previous-work section of this proposal overlaps with that of a proposal now in review at the National Science Foundation, to build an anthropomorphic bipedal robot. Also, in the fall of 2003 we may submit to the NSF a proposal overlapping this one in content. We will withdraw that NSF proposal if this more-comprehensive and more-applied NIH research is funded.