

Optimization of Human Motion: To Invert Inverse Dynamics

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Introduction

Simulation of human movement by inverse dynamics requires all details of the movement and the external forces to be known, before the internal muscle and joint forces can be computed. One could say that inverse dynamics only analyzes movements that are already known. This paper presents a new inverse dynamics simulation method that can be used for realistic and very efficient simulation of partially unknown human motions. The technology is implemented into software in the form of the body modeling system, AnyBody, currently under development at Aalborg University in Denmark. AnyBody is a general body modeling system capable of analysis and optimization of very complicated 3-dimensional body models as the one shown in Figure 1.

A simpler, yet typical, example is pedaling. Figure 2 shows a kinematical model of a leg driving a pedal. (The mechanical model comprises two legs with each nine muscles: soleus, tibialis anterior, gastrocnemius, biceps femoris (short head), hamstrings, vasti, rectus femoris, gluteus maximus, and ilio-psoas.) The position of the hip, \mathbf{H} , is assumed fixed, and we furthermore specify that the crankshaft is moving at a constant angular velocity, so that the position, \mathbf{P} , of the pedal at any instant can be computed. This, however, does not define the pedaling

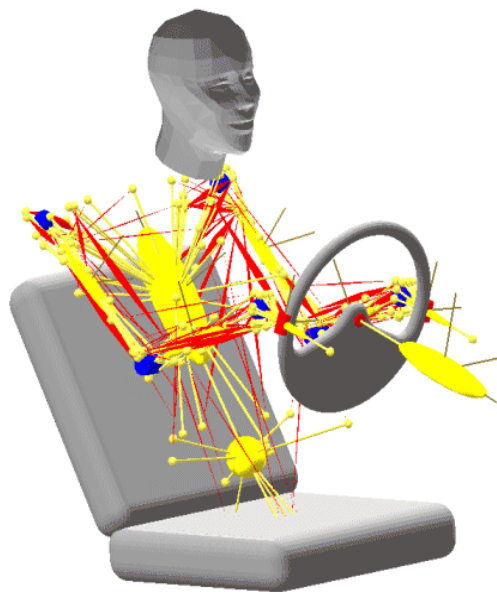


Figure 1: AnyBody model of a seated car driver comprising more than 100 muscles.

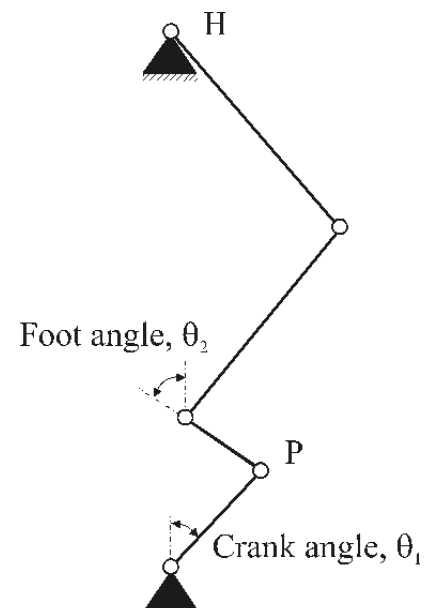


Figure 2: Kinematical model of a leg driving a bicycle pedal.

motion uniquely. For given positions \mathbf{H} and \mathbf{P} , the leg still has one degree of freedom, for instance the foot angle, θ_2 . We could conduct an experiment to measure the variation of the foot angle for a particular individual and use the result as input to an inverse dynamics analysis, but this would not solve the problem of analyzing other pedaling situations. It is unlikely that the foot angle variation would remain the same if, say, the position of \mathbf{H} were changed. Each new position would require a new experiment.

On the other hand, inverse dynamics has several advantages over the recently popular forward dynamics methods (see, e.g., Pandy et. al., 1992). One of them is a much superior numerical efficiency. In this paper, we propose to make use of this superior efficiency to create an optimization loop that modifies the positions of the indeterminate degrees of freedom and iteratively feeds them back to a new analysis, thereby gradually identifying the correct motion pattern for the situation at hand.

In addition to identification of unknown motions, the method can also be used for optimization of the environment that determines the motion, i.e., ergonomic optimization. In the pedaling example above, the set position, crank length, and other bicycle design parameters could be variable in the optimization problem, and an ergonomic optimization of the bicycle frame layout would be the result.

Methods

Determination of individual muscle forces in inverse dynamics is complicated by the fact that there are more muscles than degrees of freedom; the problem is statically indeterminate. This means that the interior forces cannot be determined from equilibrium alone. The usual solution is to recruit muscles to minimize some criterion. We employ a minimum fatigue criterion (Rasmussen et. al., 2001), leading to a numerically efficient algorithm for calculation of the internal forces in the body. One time step is analyzed as illustrated in Figure 3.

We now parameterize the motion of the model by functions depending on a simple set of input parameters. In the case of cyclic motions, it is obvious to choose trigonometric functions. We consequently specify that the foot angle can be described as $\mathbf{q}_2(t) = B_A + A_A \sin(\mathbf{w}t + \mathbf{j}_A)$, where the circular frequency, \mathbf{w} , is considered constant and equal to the angular velocity of the crankshaft. The offset, B_A , the amplitude, A_A , and the phase shift, \mathbf{j}_A , are variable and will be decided by the optimization procedure.

In voluntary motions like pedaling where the objective is to produce an overall result such as a certain work against the environment, the body is often at liberty to accomplish this result by different force application patterns. In cycling, for instance, the force at any time can be distributed between the two feet, and each foot has the opportunity to perform its work by a combination of vertical and horizontal forces. Furthermore, the force can vary freely over time as long as it produces the average power necessary to drive the bicycle at the desired speed. This means that it is also necessary to parameterize the force application pattern with a function similar to that of the pedal angle. We choose to parameterize the crank torque by the function $M(t) = B_M + A_M \sin(2\mathbf{w}t + \mathbf{j}_M)$, thus adding B_M , A_M and \mathbf{j}_M as optimization parameters to the problem. Notice that the frequency of the torque function is twice as high as the pedal angle variation because of the two legs involved in the process. The realization of this moment by application of pedal forces is left to the minimum fatigue criterion in the sense that the pedal forces are functions of the muscle forces. This means that the inverse dynamics algorithm will choose the pedal forces that minimize the fatigue of the muscles of the system. Pedal forces identified this way are very close to experimental data.

Analysis of a total cycle is accomplished as illustrated in Figure 4. Based on the current set of parameters, B_A , A_A , \mathbf{j}_A , B_M , A_M , and \mathbf{j}_M , a function computes the pedal positions, foot angles, and crank torques for a series of time steps, say 100, spanning a total pedaling cycle. These time steps are analyzed one by one by

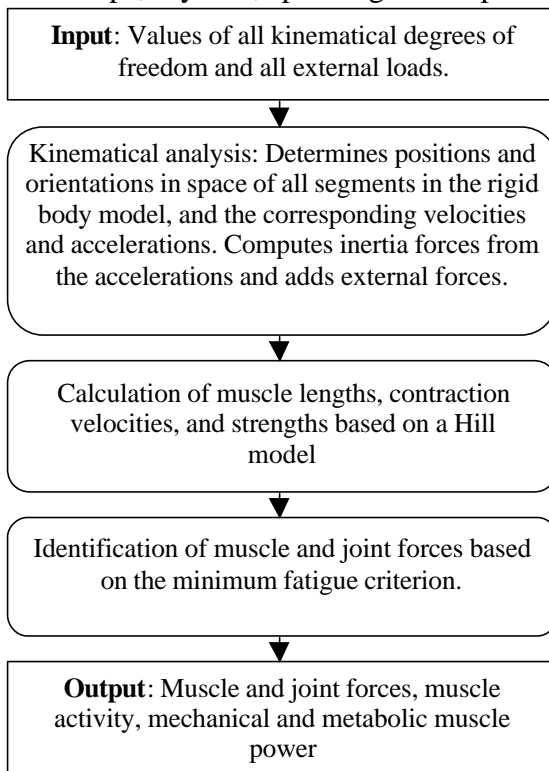


Figure 3: Inverse dynamics analysis of one time step.

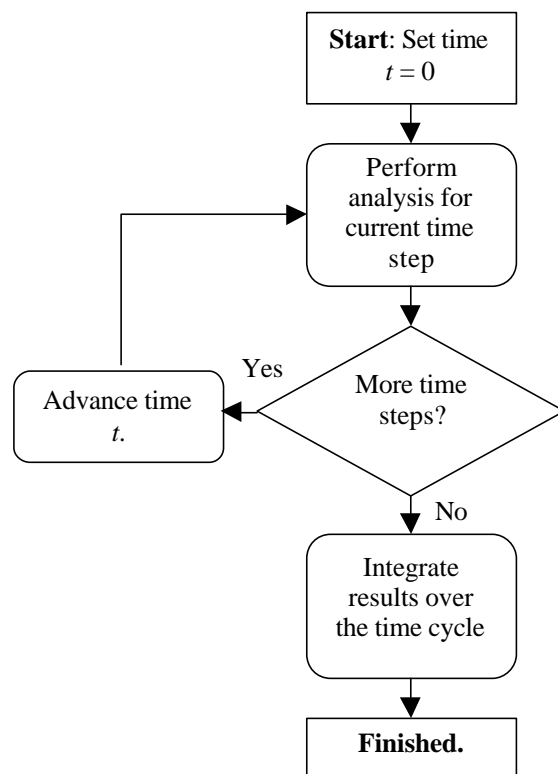


Figure 4: Analysis of a time cycle.

the inverse dynamics algorithm, and the results are accumulated. Finally, overall information about the process, such as total work, average power, metabolism, etc., is evaluated. The metabolism is computed by numerical integration over all muscles and time steps, where it is assumed that the net metabolic efficiency for a muscle is 25% for concentric work and -120% for eccentric work. Please notice that negative muscle work, i.e. antagonistic muscles, is predicted by the minimum fatigue criterion.

The optimization problem can now be described as finding the input parameters B_A , A_A , \mathbf{j}_A , B_M , A_M , and \mathbf{j}_M that will produce the desired average power while minimizing some performance criterion. It is not known what, if any, optimization criterion applies for identification of human motion. However, biological systems tend to economize with their resources as a consequence of genetic evolution, so minimum metabolic energy consumption would be a fair initial criterion choice. We require an average mechanical output of 200 W and set the cadence to 60 rpm. To challenge the algorithm, we shall start the pedaling process from the physiologically unrealistic case of a constant foot angle. The parameters of the crank torques are initially set to $B_M = 32$ Nm, $A_M = -32$ Nm, and $\mathbf{j}_M = 0$. This produces an output power of 201 W with zero crank torques when the pedal arms are in vertical positions. Please notice that this does not exactly correspond to the top and bottom dead centers in a usual bicycle layout.

Results

The optimization proceeds to modify the values of the input parameters while reducing the metabolic power consumption from 913W to 806W corresponding to an improvement of efficiency from 21.9% to 24.8%. The initial and optimized crank torque and foot angle variations are shown in Figure 5. The identified foot motion pattern is very similar to realistic pedaling, see, e.g., Bolourchi and Hull (1985).

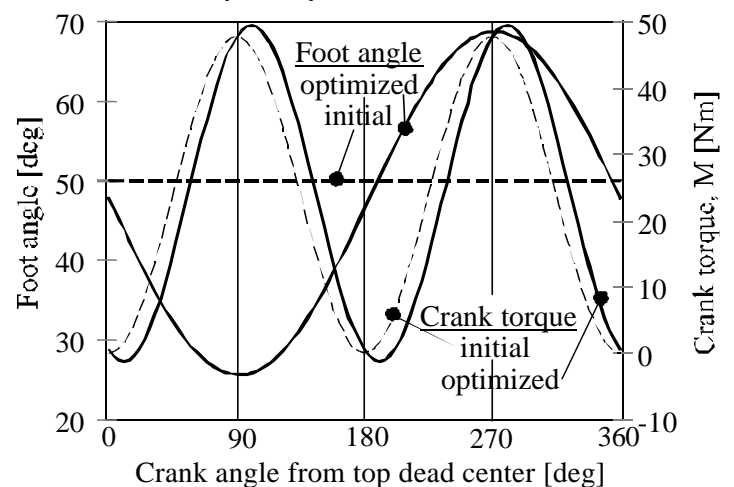


Figure 5. Initial and optimized crank torque and foot angle variations.

Discussion

The inversion of the inverse dynamics methodology by means of an optimizer extends the applicability of inverse dynamics into a new field of undetermined motions. It remains to be investigated how complex the motions can be, before the optimization procedure is unable to perform the identification. It appears that the numerical efficiency will not be the limiting factor. Analysis of the model of Figure 1 comprising more than 100 muscles in 100 time steps takes less than 4 seconds on a personal computer (1.3 GHz Pentium 4 processor), and optimization of the foot motion and crank torque patterns described above is accomplished in less than a minute.

The method is well suited for motions that are not so dynamic that wobbly masses play a significant role. In addition to pedaling, this includes most repetitive work processes, gait, hopping, manual tool operation, car driving, etc. The method is not suitable for very fast motions, such as a football kick, or to involuntary movements, such as the whiplash motion of the head and cervical spine often seen in car crashes.

References

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