OPTIMALITY CRITERIA FOR HUMAN RUNNING INVESTIGATED BY FORWARD DYNAMICS SIMULATIONS

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There are currently no generally accepted optimality criteria for human running. The purpose of the study was to test a set of potential criteria by generating performance-based forward dynamics simulations. Simulation results were compared to measurements from human runners. Minimizing muscle activation generated the simulation that most accurately matched the experimental kinematic and metabolic data. The results suggest that minimizing activation, which avoids fatiguing any one muscle, is an important control policy for human running.

KEY WORDS: running, optimization, simulation.

INTRODUCTION: Although a variety of biomechanical characteristics subtlety distinguish between runners from various populations, the stereotypical patterns of lower limb kinematics, ground reaction forces (GRF), and muscle electromyograms (EMG) are quite similar between individuals. These stereotypical features suggest there is an underlying optimality criterion that governs the control of human running. However, this criterion is unknown. Knowledge of an optimality criterion for human running would be useful for generating predictive performance-based simulations, which have been fruitful in the study of jumping (e.g. Selbie & Caldwell, 1996) and walking (e.g. Umberger, 2010).

Experiments on human runners have suggested a potential optimality criterion in the cost of transport (CoT; metabolic energy consumed per distance travelled), which is relatively low when humans run at a given speed using the preferred combination of stride length and frequency compared to other combinations (Gutmann et al., 2006). However, it is not clear if the CoT is absolutely minimized under these conditions, or if minimizing the CoT governs all salient biomechanical features of human running. Optimality in human movement is formidable to study experimentally, since it can be difficult to quantify and manipulate the criteria on which humans optimize their movements, particularly for submaximal movements like walking and running. Computer simulations allow researchers to specify an optimality criterion, and can be useful in these cases (e.g. Ackermann & van den Bogert, 2010). Previous performance-based simulations of running have assumed a “minimum CoT” criterion (e.g. Sellers et al., 2010) without testing other potential criteria. It is not clear how the choice of criterion affects the simulation results.

Therefore, the purpose of the study was to evaluate several potential optimality criteria for generating performance-based simulations of human running. We hypothesized that minimizing the cost of transport would generate the most realistic simulation in comparison to data from human runners.

METHODS: Simulations of one stride were generated using a nine-segment 2D forward dynamics model actuated by nine Hill-based muscle models per leg (Fig. 1). The simulation results were compared to the mean experimental data (joint angles, GRF, EMG, and metabolic data) from 12 adult females running at a “normal and comfortable” speed (3.80±0.50 m s^{-1}). A data tracking simulation that minimized the average root mean squared error (RMSE) between the simulated and experimental joint angles and GRF was first performed to establish the model’s ability to replicate the gross biomechanical features of human running. Next, performance-based simulations were generated by optimizing the model’s control variables to minimize the value of an objective function:

$$J = OC + \left(0.01\varepsilon_{\theta} + 0.0001\varepsilon_{\omega} + 0.001\varepsilon_{hex}\right)$$

where OC is the optimality criterion and the bracketed variables are penalty terms. ε_{θ} and ε_{ω} were the sums of the squared differences between the initial and final segment angular

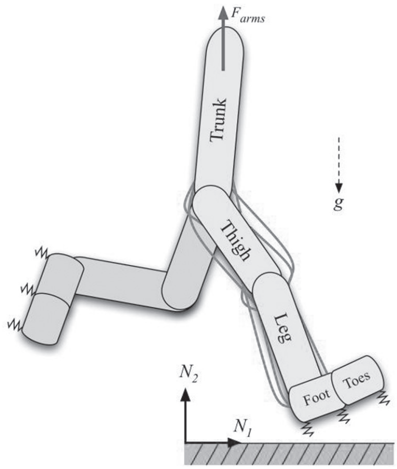

Figure 1: Schematic of the musculoskeletal model with nine segments (trunk and bilateral thigh, shank, foot, and toes) and nine muscle models per leg (iliopsoas, glutei, vasti, biceps femoris, tibialis anterior, soleus, rectus femoris, hamstrings, gastrocnemius). F_{arms} is the arm swing force.

positions and velocities, respectively, and encouraged periodic kinematic states. ε_{hex} was the sum of the integrals of the squared passive joint moments, and discouraged joint hyperextension. The control variables were: the muscle excitation signals (parameterized by 21 nodal values per muscle), the seven initial angular velocities, the stride duration, the angular stiffness of the toe joint, and the amplitude and phase shift of a force representing the kinetics of arm swing. The three candidate optimality criteria were: 1) MinCoT: the square of the cost of transport; 2) MinAct: the sum of the squared muscle activation integrals; and 3) MinStress: the sum of the squared muscle stress integrals. MinCoT minimizes the amount of metabolic energy consumed at the whole-body level predicted by metabolic cost algorithms within the muscle models (Umberger, 2010). MinAct minimizes the chance of exhausting any one single muscle, regardless of its size or strength. MinStress also avoids fatigue in individual muscles, but is based on a mechanical variable (muscle stress) rather than a biochemical one (activation, which relates to the proportion of bound calcium ions).
Optimizations were performed using a parallel simulated annealing algorithm (Higginson et al., 2005) on a cluster of eight CPUs. Three days of CPU time were needed to determine solutions that were invariant to the random nature of the algorithm. The initial posture of the model was defined as the mean values from the experimental data at heel-strike. To reduce computation time, one stride was reconstructed from simulations of one step by assuming bilateral symmetry. Simulations were compared to the experimental mean data (speed, stride length and frequency, CoT, joint angles, GRF), with the smallest deviations designating the most accurate simulation and most likely optimality criterion.

RESULTS: The tracking simulation matched the mean experimental joint angles and GRF to within 1.1 standard deviations (SD) in average RMSE, indicating that the model is capable replicating the general features of human running. The speed, stride parameters, and metabolic cost of transport for the four simulations are compared to the experimental data in Fig. 2. The tracking simulation's speed (3.76 m s^{-1}), stride length (2.59 m), and stride frequency (1.45 Hz) were within 2% of the experimental means, but it expended energy at a very high rate. Its cost of transport (9.8 J m^{-1} kg^{-1}) was over twice the mean of the human subjects (4.2$\pm$0.9 J m^{-1} kg^{-1}). The high metabolic cost was due to high levels of antagonistic muscle co-activation, which gave the model finer control over the shapes of the joint torque profiles used to track the experimental data.

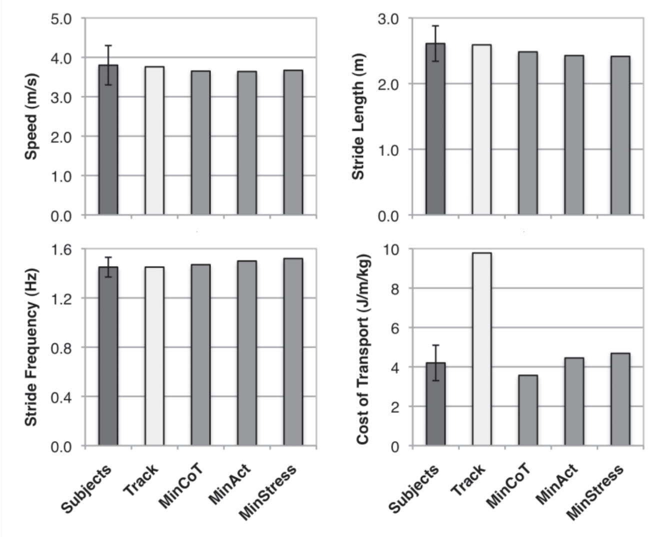

Figure 2: Speed, stride length, stride frequency, and metabolic cost of transport for the human subjects (mean in blue, SD error bar), the tracking simulation (yellow), and the three performance-based simulations (red).

The three performance-based simulations were slightly slower (average 3.65 m s^{-1}) than the tracking simulation, with shorter stride lengths (2.44 m) and higher stride frequencies (1.50 Hz), but were all within one SD of the experimental means. The cost of transport was also within one SD of the mean for all three simulations, but was more sensitive to the chosen optimality criterion than the speed and stride parameters. The MinAct simulation had the most accurate cost (4.4 J m^{-1} kg^{-1}, +6% above the mean), followed by the MinStress (4.7 J m^{-1} kg^{-1}, +12%) and MinCoT (3.6 J m^{-1} kg^{-1}, -15%) simulations.
The simulated joint angles and GRF are compared to the experimental means in Fig. 3. RMSEs for the three performance-based simulations were 1.9 SD for the MinAct simulation, 2.1 SD for the MinCoT simulation, and 2.2 SD for the MinStress simulation. All were larger than the tracking simulation (1.1 SD). Most of the differences between the performance-based simulations were seen in the middle of the swing phase. The peak hip angle in the MinStress simulation was 14° less flexed than the MinAct and MinCoT simulations. In the MinCoT simulation, the peak knee angle was 16° less flexed and the peak ankle angle was 10° more plantarflexed than the MinAct and MinStress simulations.

DISCUSSION: The purpose of the study was to evaluate several optimality criteria for generating performance-based simulations of human running. It has been suggested that humans run in a way that minimizes the metabolic cost of transport. This theory is based primarily on measurements of metabolic energy rates when humans run at various combinations of speed, stride length, and stride frequency (e.g. Gutmann et al., 2006).
The present result suggest that, at least in simulated running, a variety of variables can be minimized to generate reasonably realistic running motions that incur physiologically plausible costs of transport. The capability of the model was established in a data-tracking simulation, which tracked the mean experimental joint angles and GRF to an average error well within the same statistical distribution (1.1 SD) as the human subjects, but had an unrealistically large cost of transport. The hypothesis that the MinCoT simulation would be the most realistic one was not supported. Among the performance-based simulations, which tracked no data explicitly, the MinAct simulation had the smallest RMSE (1.9 SD, compared to 2.1 and 2.2 SD for the other two simulations) and the most realistic cost of transport (6% error, compared to 12 and 15%). These results suggest that minimizing muscle activation, which avoids maximally activating any one single muscle regardless of its size or strength, is

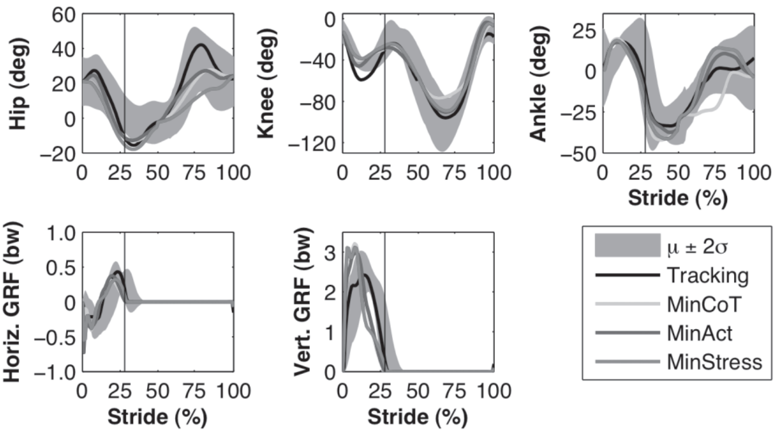

Figure 3: Joint angles and GRF components vs. the stride cycle for the tracking (black), MinCoT (green), MinAct (blue), and MinStress (red) simulations. Shaded area is +/- two standard deviations around the mean experimental data. Vertical lines indicate toe-off.

an important optimality criterion for human running, perhaps more so than minimizing the cost of transport or the amount of mechanical stress experienced by the muscles. Ackermann and van den Bogert (2010) recently reached a similar conclusion regarding human walking.

The least accurate variable in the performance-based simulations was the vertical GRF (Fig. 3), which deviated from the experimental mean by 4.7 SD on average. The net vertical impulses were more accurate (under 1.0 SD on average), suggesting that most of the error was due to the stance duration, which was shorter in the performance-based simulations (30% of the stride on average) than in the humans (38±5%). The short stance time was endemic to all performance-based simulations, suggesting it was not a function of the optimality criterion. The short stance duration in the tracking simulation (33%) suggests that this deviation is a limitation of the model, perhaps due to the simple design of the foot.

CONCLUSION: Sagittal plane simulations of human running were sensitive to the form of the optimality criterion defined as a task objective. Stance phase motions were similar regardless of the optimality criterion, but minimizing muscle activations generated the most realistic swing phase motions and incurred the most realistic cost of transport. These results suggest that minimizing fatigue at the individual muscle level by avoiding high activations is an important priority of the neuromuscular system during running, perhaps more so than the absolute metabolic cost of the movement.

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