INTRODUCTION
While the majority of recreational runners strike the ground with their heel first, a greater proportion of elite competitive runners strike the ground with their midfoot first [1]. It is generally unknown why different runners naturally select different foot-strike patterns. However, there is a growing movement in the running community to train natural recreational heel-strike runners to instead strike the ground with their midfoot first (e.g. ChiRunning and the Pose Method).

A primary rational behind these training programs is the suspicion or assumption that midfoot striking is more metabolically efficient than heel striking. Regarding the metabolic cost of running, two potential problems with a converted foot-strike pattern are: (1) there is no strong scientific evidence that heel striking is more energetically costly than other strike patterns, and (2) naturally-selected stride parameters tend to incur lower oxygen costs than prescribed parameters [2]. In addition, running shoe designs generally focus on heel rather than midsole cushioning, suggesting that running with a midfoot strike could incur greater injury risks by not taking advantage of a shoe’s protective features [3].

To evaluate the efficacy of these training programs, it is therefore important to gain a greater understanding of the relationship between metabolic cost and foot-strike pattern selection in runners. Measuring subtle changes in metabolic cost on human subjects can be difficult due to experimental and equipment limitations, and because human runners may optimize their performances on criteria other than metabolic cost. With a computer modeling and simulation approach, researchers can have more precise control over these factors.

METHODS
Forward dynamics simulations of one full step of running were performed using a two-dimensional bipedal computer model (Fig. 1). Each leg was actuated by 12 Hill-based muscle models. Ground contact was modeled by viscoelastic frictional elements on the foot that were parameterized to represent shod human feet [4].

The muscle model included a sub-model of human muscle energy expenditure [5]. The energy rate of a muscle was the sum of the activation, maintenance, and lengthening/shortening heat rates and the mechanical work rate of the contractile component.

To allow the model free selection over the foot-strike pattern, the simulation began at the initiation of the right leg’s swing phase and ended at the initiation of the left leg’s swing phase. The simulation thus had to contain one full stance phase of the left leg, but no constraints were directly imposed on the kinematics of this phase. Initial kinematic conditions were derived from a human subject running at 4.0 m/s. The objective function
of the simulation was to minimize the total muscle energy expended per distance traveled, while closely matching the initial kinematics of the right leg with the final kinematics of the left leg, and vice-versa. The control variables were the muscle model excitation signals and the initial segment angular positions and velocities. The initial kinematics were allowed to vary within the ranges exhibited by the subject when running at this speed with heel, midfoot, and forefoot strike patterns. The optimal control variables were found using a parallel simulated annealing algorithm.

RESULTS AND DISCUSSION

Over the time of the simulated step (363 ms), the model ran at an average speed of 3.95 m s\(^{-1}\), with a stride frequency of 1.38 Hz and a stride length of 2.86 m. The speed and stride parameters were within 5\% of the performance of the subject from whom the simulation’s initial conditions and the model’s parameters were derived.

The simulation spent 15.9 W kg\(^{-1}\) to run at this speed, which is close to the rate of 16.1 W kg\(^{-1}\) predicted from the oxygen cost vs. speed relationship for trained human runners [6]. When running with this energy rate, the simulation exhibited a distinct heel-first foot-strike pattern when initiating ground contact (Fig. 2). A follow-up simulation with kinematic constraints forcing the model to land on its midfoot used an increased energy rate of 16.9 W kg\(^{-1}\) to run at the same speed.

CONCLUSIONS

A variety of other factors not considered here (e.g. running speed, anthropometry, muscle mechanical properties, footwear, three-dimensional motion) could influence the selection of a foot-strike pattern and the metabolic cost of running. However, under these particular simulated conditions, a heel-first strike pattern was selected when the goal was to minimize the metabolic cost of a step of running. Since the simulated running performance was minimally constrained by input experimental data, we conclude that the heel-first strike pattern was less metabolically costly than other strike patterns that could have been chosen instead. If another foot-strike pattern was less costly, it should have been chosen as the optimal solution.

If the simulation is assumed to be a reasonable analog of the mechanical and metabolic aspects of the human subject’s running performance, the results demonstrate an example where converting to an unnatural midfoot strike pattern increased the energetic cost of running at a given speed. Further experimental and simulation-based work is needed to investigate the relationship between foot-strike pattern and the energetics of human running. Training programs that advocate an improvement in metabolic efficiency through the adoption of a midfoot strike pattern may not necessarily confer this improvement to all runners.

REFERENCES

![Figure 2: The posture of the model at the first instance of foot contact (vertical ground reaction force > 0).](image-url)