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OPTIMIZING AN EXOTENDON AT AN INCREASED RUNNING SPEED

Jon P. Stingel[1], Nicholas Bianco[1], Carmichael F. Ong[2], Jennifer L. Hicks[2], Scott L. Delp[1,2]

[1]Department of Mechanical Engineering, Stanford University, USA
[2]Department of Bioengineering, Stanford University, USA
Email: stingjp@stanford.edu, Web: https://nmbl.stanford.edu/people/jon-stingel/

ABSTRACT

The exotendon is a passive device that reduces the energetic cost of running at 2.7 m/s, but its potential benefits at higher speeds remain unclear. Experimental testing is limited by the need for participants to stay below their aerobic threshold. Here, we use muscle-driven simulations to overcome these constraints and inform exotendon design. We validated a framework that estimates changes in energy expenditure, kinematics, and muscle activations with and without the device. Simulations at 4 m/s predicted a 10% reduction in energy cost with the exotendon compared to natural running. Testing 25 designs, we found that a longer, stiffer exotendon yielded the greatest savings (12%).

INTRODUCTION

Assistive devices are increasingly used to enhance human motion, but complex human-device interactions make assessing the benefits of each device and its various parameters difficult [1–3]. Additionally, tuning even a few parameters may require an impractical number of physically demanding experimental tests [4]. Previously, an exotendon, a passive assistive spring connecting a user's shoes, has been shown to reduce energy expenditure during slower recreational running (2.7 m/s) [5, 6]. It is unclear if benefits extend to higher speeds, and extensive experimental testing at these speeds is impractical due to physical demands. Musculoskeletal simulation enables evaluating device parameters without physical testing. In this study, we used musculoskeletal simulations to assess the energetic impact of the exotendon at a faster speed (4 m/s) for a range of exotendon stiffness and lengths. We hypothesized that the exotendon would provide energetic benefits at 4 m/s and that increasing its stiffness and slack length would further reduce energy expenditure compared to the device used at a slower speed.

METHODS

We developed a planar, 20-degree-of-freedom musculoskeletal model with 18 musculotendon units spanning the lower limbs, four contact spheres per foot, and a spring-damper at the metatarsophalangeal joint [7–11]. To ensure sufficient moment generation capacity for faster running with a reduced muscle set, we doubled the default maximum isometric force values of the Hill-type muscles in the model [11]. We simulated exotendon-assisted running by adding a linear spring between the model's feet, parameterized by stiffness and slack length. To assess whether optimizing these parameters could improve energetic efficiency at 4 m/s, we tested five stiffness and lengths and evaluated energy expenditure across 25 exotendon parameter combinations.

We generated simulations of natural and exotendon-assisted running at 4 m/s using direct collocation in OpenSim Moco [12]. OpenSim generated muscle-driven kinematic- and kinetic-tracking simulations, with light tracking of joint coordinate trajectories and ground reaction forces while constraining the solution to the target running speed and stride duration. The simulation cost function was formulated as:

$$J = w_1 * \int_0^{t_f} \sum (q_i - q_i') + w_2 * \int_0^{t_f} \sum (f_j - f_j') + w_3 * \int_0^{t_f} \sum (a_m^2) + w_4 * \int_0^{t_f} \dot{E}$$

The first term computes kinematic tracking as the difference between the joint coordinate values and speeds for the reference (q) and simulated (q') data, summed across all joints, and integrated over the full simulated step duration. The second term computes ground contact tracking similarly between the reference (f) and simulated (f') ground contact forces. We minimized the sum of activations squared of all muscles (a_m) in the model, integrated over the duration of the step as a third term, as well as the integral of the rate of metabolic energy expenditure $(\dot{E})$ as the fourth term [13]. Each term in the cost function also has an individual weight (w).

As reference data, we used kinematics and kinetics from a published dataset of natural running at 4.0 m/s [14]. We simulated stride

Table 1. Percent changes in average energy expenditure for each exotendon parameter combination at 4.0 m/s compared to natural running. Increases (+) are highlighted in pink, decreases (-) in green. Stiffness values (k, rows) range from 25-200% of the original 120 N/m, and lengths (l, columns) from 25-200% of the original 0.29 m. The original parameters (l = 0.29 m, k = 120 N/m) are outlined in black.

% change in energy expenditure Natural to Exotendon 4.0 m/s		Exotendon length (m)				
		l=0.07	l=0.14	l=0.29	l=0.43	l=0.57
Exotendon stiffness (N/m)	k= 30	-3.9	-3.2	-2.4	-0.7	-0.1
	k= 60	-9.9	-9.1	-6.2	-3.9	-1.9
	k= 120	-11.4	-11.7	-10.0	-9.6	-5.4
	k= 180	-9.0	-10.8	-12.1	-11.7	-8.8
	k= 240	1.3	-4.8	-11.7	-12.2	-11.1

durations of 88, 94, 100, and 106% of the duration in the reference data, since the exotendon previously led to changes in stride duration [5]. Results are evaluated at the stride duration with the minimum energetic rate, indicating the model's optimal performance for that set of device parameters.

RESULTS AND DISCUSSION

The simulation predicted that the exotendon that was effective at lower speed (2.7m/s) would benefit runners at 4 m/s. We found a 10% (0.73 J; 1.13 W/kg) reduction in rate of energy expenditure compared to natural running (Table 1), a larger change than the 6.4% savings reported at 2.7 m/s experimentally [5]. The savings primarily occurred during stance, with the quadriceps muscles having the largest savings during stance (0.36 J; 1.53 W/kg). Simulations showed that a number of the exotendon parameter combinations would be beneficial for runners at 4 m/s (Table 1). We saw that exotendons that had a high stiffness and short slack length increased the energetic burden, while long exotendons with low stiffness had little effect. The exotendon combination with the largest savings was one with a slack length of 0.4305 cm and a stiffness of 240 N/m. The exotendons with the five largest reductions in energy expenditure had an average peak tension of 102±17 N, though a majority of the exotendon parameter combinations were beneficial compared to natural running (Fig. 1). These results suggest that there is some flexibility in the amount of force that a runner can benefit from when using the exotendon, but that there may be a more optimal range of force input from the greatest energetic savings.

CONCLUSIONS

Our musculoskeletal simulations suggest that an exotendon can reduce energetic burden at 4 m/s, extending its benefits to faster running speeds. The results identified several effective exotendon parameters at this speed. This simulation framework enables efficient testing and optimization of device parameters, which can guide future experimental studies and reduce physical burden. We plan to test the exotendon in a prospective experiment at 4 m/s to evaluate its efficacy and our model predictions.

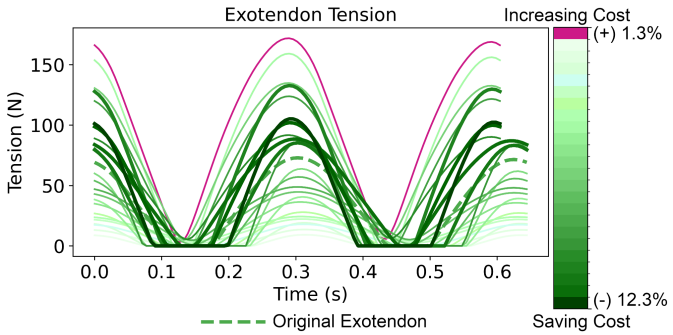

Fig 1: Exotendon tension force over a stride time is shown, with color indicating energetic impact: darker green for savings, darker pink for increased expenditure, and lighter colors for minimal change. The original exotendon is marked with a dashed line.

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