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Supplementary Materials for

Improving the energy economy of human running with powered and unpowered ankle exoskeleton assistance

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The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

(available at robotics.sciencemag.org/cgi/content/full/5/40/eaay9108/DC1)

Movie S1 (.mp4 format). Video showing a participant running with exoskeletons in Optimized powered, Optimized spring-like, and zero-torque modes and with running shoes.

SUPPLEMENTARY MATERIALS

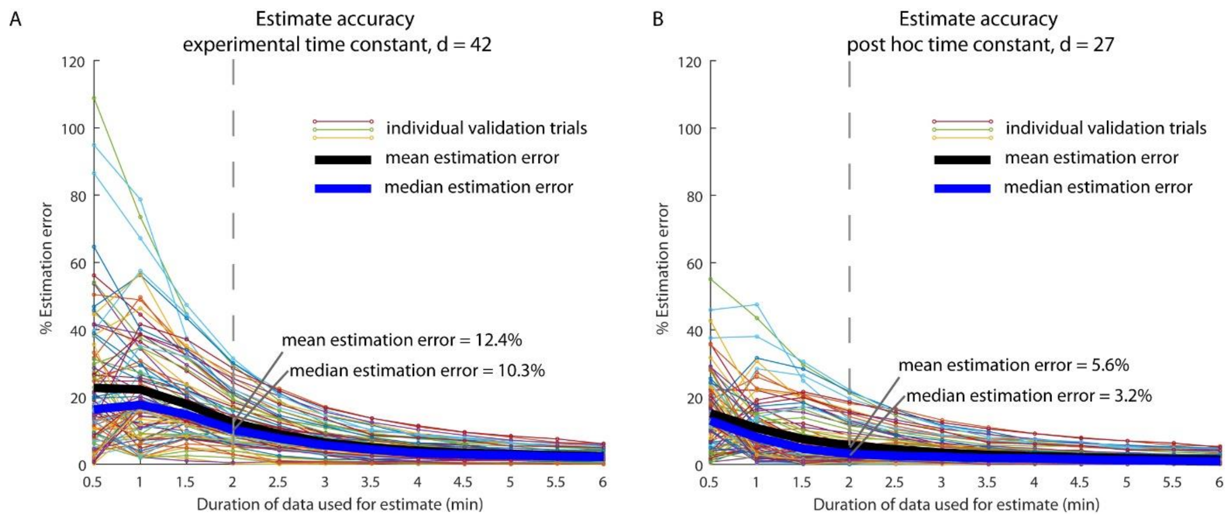

Fig. S1. Accuracy of steady-state metabolic rate estimates during optimization. We assessed the accuracy of the estimate of steady state metabolic rate used during two-minute optimization trials based on a retrospective analysis of data from the six-minute validation trials (n = 88). Estimates were obtained by fitting a first-order dynamical model (*58*) to breath-by-breath metabolic rate data. (**A**) In our experiment, we used a time constant of 42 s and a trial duration of two minutes because these values resulted in low error during pilot testing, consistent with prior work (*34*, *62*). The retrospective analysis shows that error was higher than expected, with a mean of approximately 12%. The model fit typically overestimated metabolic rate. Because the optimization method we employed (CMA-ES) is based on ranking of conditions, rather than absolute values, this consistent estimation error does not seem to have disrupted the optimization process. (**B**) We then tested a wide range of model time constants and found that, for these data, a time constant of 27 s would have resulted in lower estimation error. The faster time constant would have resulted in a mean error of approximately 6%. Although CMA-ES is robust to measurement error, improved accuracy could have sped convergence of the optimizer, which could have resulted in larger improvements in metabolic rate with Optimized assistance. This faster time constant provides a better initial guess for future experiments performing optimization of exoskeleton assistance during moderate-speed running.

Table S1. Values of Optimized parameters for each participant.

Participant	Spring-like Parameters: Torque at Max Dorsiflexion (Nm/kg)	Engagement Angle (% range)	Shape Constant (% torque Range)	Powered Parameters: Peak Torque (Nm/kg)	Onset Time (%stance)	Peak Time (%stance)	Off Time (%stance)
1	17.05	91.50	59.24	28.32	29.69	72.64	98.00
2	6.77	73.73	44.55	25.20	22.85	79.52	97.78
3	30.96	90.17	61.94	13.18	40.46	70.85	96.38
4	48.96	86.21	38.60	24.65	17.06	79.52	95.51
5	16.43	52.15	28.84	25.20	13.61	76.28	98.00
6	29.76	87.81	50.37	24.81	14.88	79.52	95.54
7	29.86	73.11	76.72	23.80	30.89	72.78	97.51
8	35.31	73.00	59.86	22.75	13.74	64.53	93.89
9	5.76	64.07	31.21	24.91	15.91	79.52	95.84
10	14.02	64.73	55.87	23.40	25.85	78.13	97.49
11	0.71	38.65	86.65	24.12	27.12	79.52	95.12
Average	**21.42**	**72.28**	**53.99**	**23.67**	**22.91**	**75.71**	**96.46**

Table S2. Values of metabolic rate (watts per kilogram) for each participant under each condition.

Participant	Rest	Control Shoe	Zero-Torque	Spring-like	Powered
1	1.41	11.06	12.75	12.58	9.75
2	1.67	12.37	14.36	13.80	10.35
3	2.09	12.34	13.51	13.32	10.01
4	1.76	12.64	13.97	13.60	12.28
5	1.38	10.58	11.74	11.83	8.95
6	1.85	12.70	14.12	13.60	11.11
7	1.73	13.98	15.89	15.36	11.92
8	1.89	13.55	15.15	14.34	10.76
9	1.69	12.87	14.22	14.20	11.19
10	1.66	12.22	12.96	13.14	10.54
11	1.30	12.63	14.31	14.20	12.84

Movie S1. Video showing a participant running with exoskeletons in Optimized powered, Optimized spring-like, and zero-torque modes and with running shoes.