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Supplementary Materials for

Human-in-the-loop optimization of hip assistance with a soft exosuit during walking

Y. Ding, M. Kim, S. Kuindersma, C. J. Walsh*

*Corresponding author. Email: walsh@seas.harvard.edu

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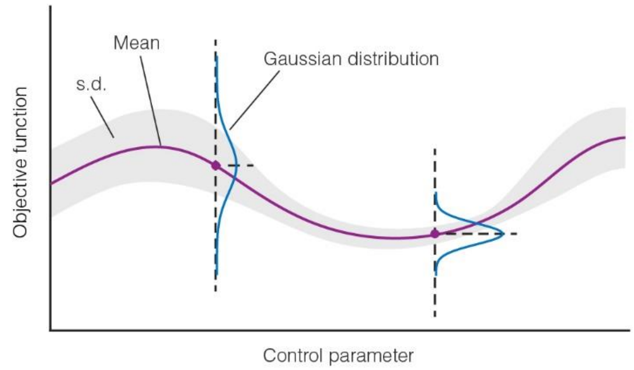

Fig. S1. Illustration of 1-D Gaussian process. *A Gaussian process is a statistical model that generalizes the multivariate Gaussian to continuous domains—conceptually specifying a distribution over functions. Every observed data point is associated with a normally distributed random variable. The purple line represents the mean function of the posterior and the shaded area represents the standard deviation. Two example data points are shown with their corresponding Gaussian distributions.*

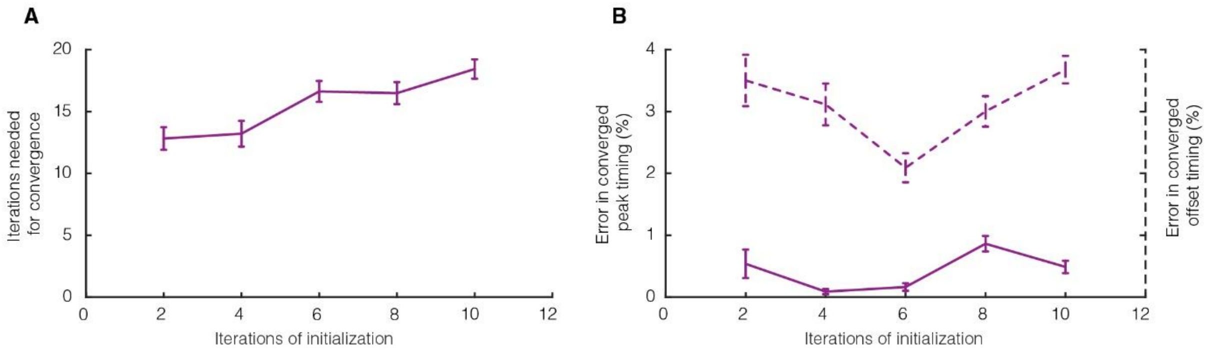

Fig. S2. Simulation results on the number of iterations needed for the optimization. *A simulation using the same generative model and convergence criteria described in the convergence time analysis section was used to evaluate the required iterations for both the initialization phase and the convergence of the Bayesian optimization. This simulation was repeated 100 times and the needed convergence time and error were evaluated when using different iterations for initialization. Lines represent the mean and error bars represent the standard error. (**A**) The needed iterations for convergence with respect to different iterations of initialization. All configurations converged within twenty iterations. (**B**) The error of the converged peak and offset timing. The minimum error was with the configuration of using six iterations for the initialization.*

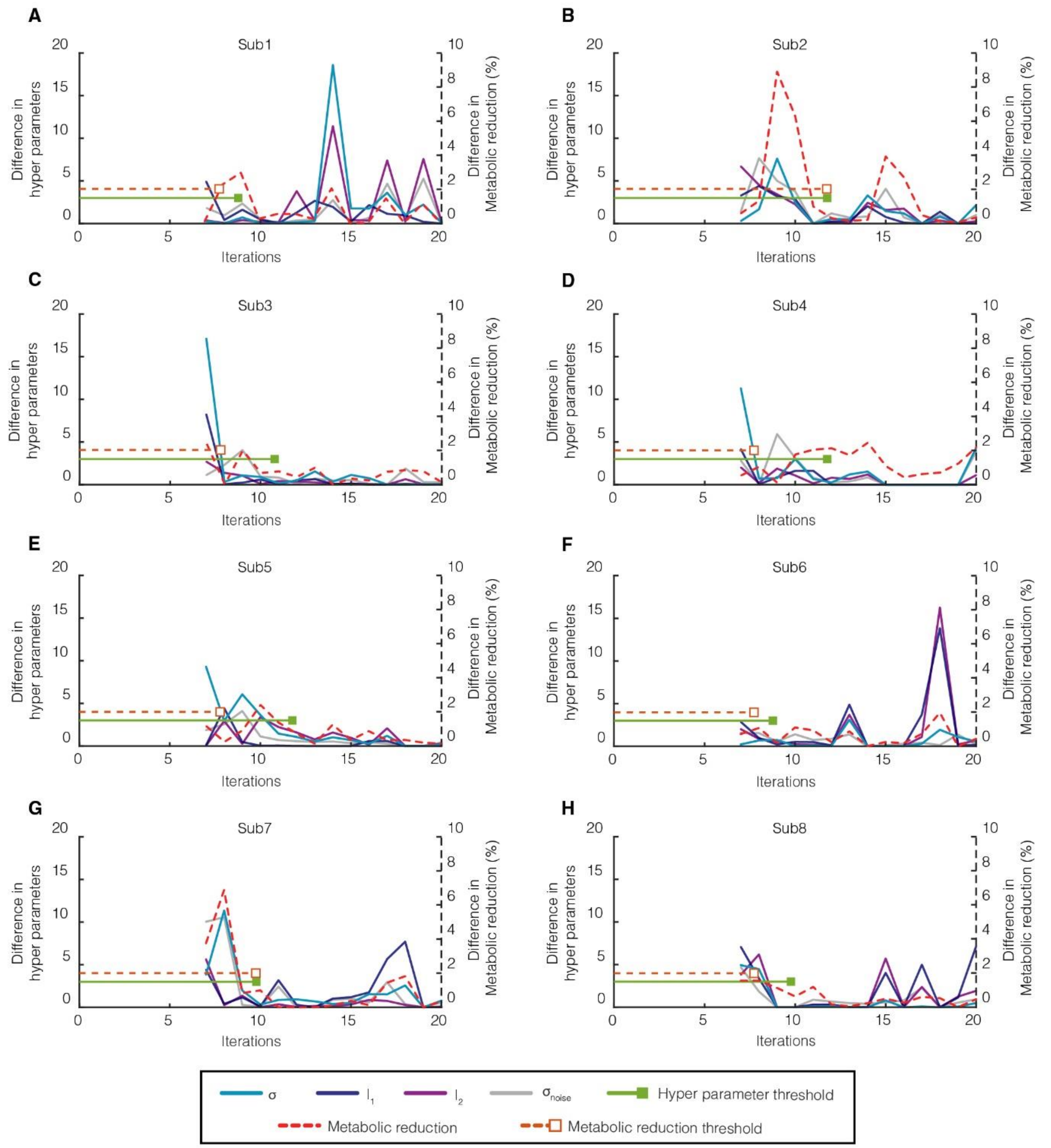

Fig. S3. Convergence analysis. *The solid lines represent the difference in hyper parameters of each iteration and its convergence threshold ($t_h = 3$). The dashed lines represent the difference in maximum metabolic reduction calculated from the metabolic landscape for each iteration and its convergence threshold of ($t_m = 4\%$). The squares indicate the iterations that satisfy the convergence criteria respectively. The convergence time for each subject was determined by the latest time when both conditions were satisfied. Subfigures (**A** to **H**) represent subject 1 to subject 8 respectively.*

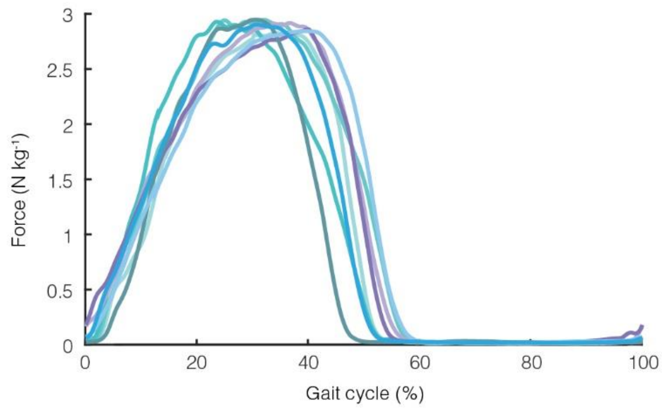

Fig. S4. Optimized hip extension force profiles for all subjects. *Patterns varied widely and spanned a large portion of the allowed search area. Lines are measured force, normalized to body mass and stride time. Each force profile is averaged by ten strides during the last minute of the validation condition.*

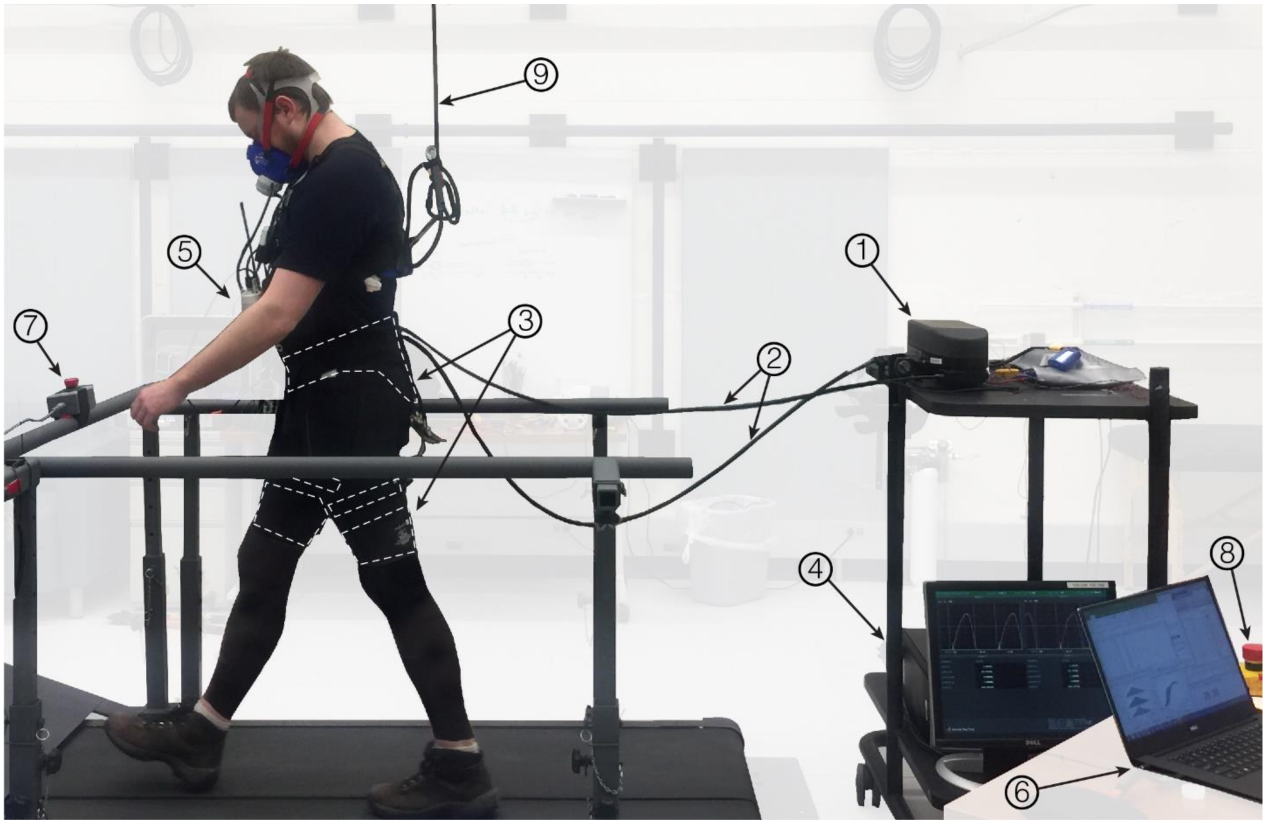

***Fig. S5. Experimental setup. 1**, Tethered actuation system including two Bowden actuators; **2**, Braided cable sleeves compromising Bowden cables for transmitting assistive force from actuators to soft exosuit and sensor wires for transmitting IMU and load cell signals to the real-time target computer for control tasks; **3**, Soft exosuit (Fig. 2A); **4**, Real-time target computer that collects the measured sensor information and tracks the configured assistive profiles; **5**, Wireless respiratory device that includes a mask and a transmitter; **6**, Optimization computer that iteratively updates the optimal control parameters and communicates with the real-time target computer; **7**, Safety switch for the treadmill; **8**, Safety switch for the tethered actuation system; **9**, Safety harness to prevent falls.*

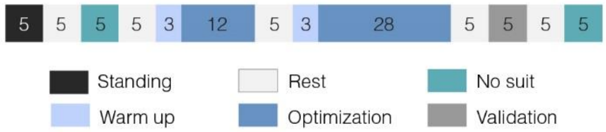

Fig. S6. Experimental protocol. *The blocks from left to right represent the tested conditions in time sequence with numbers showing the length, in minutes, of each condition.*

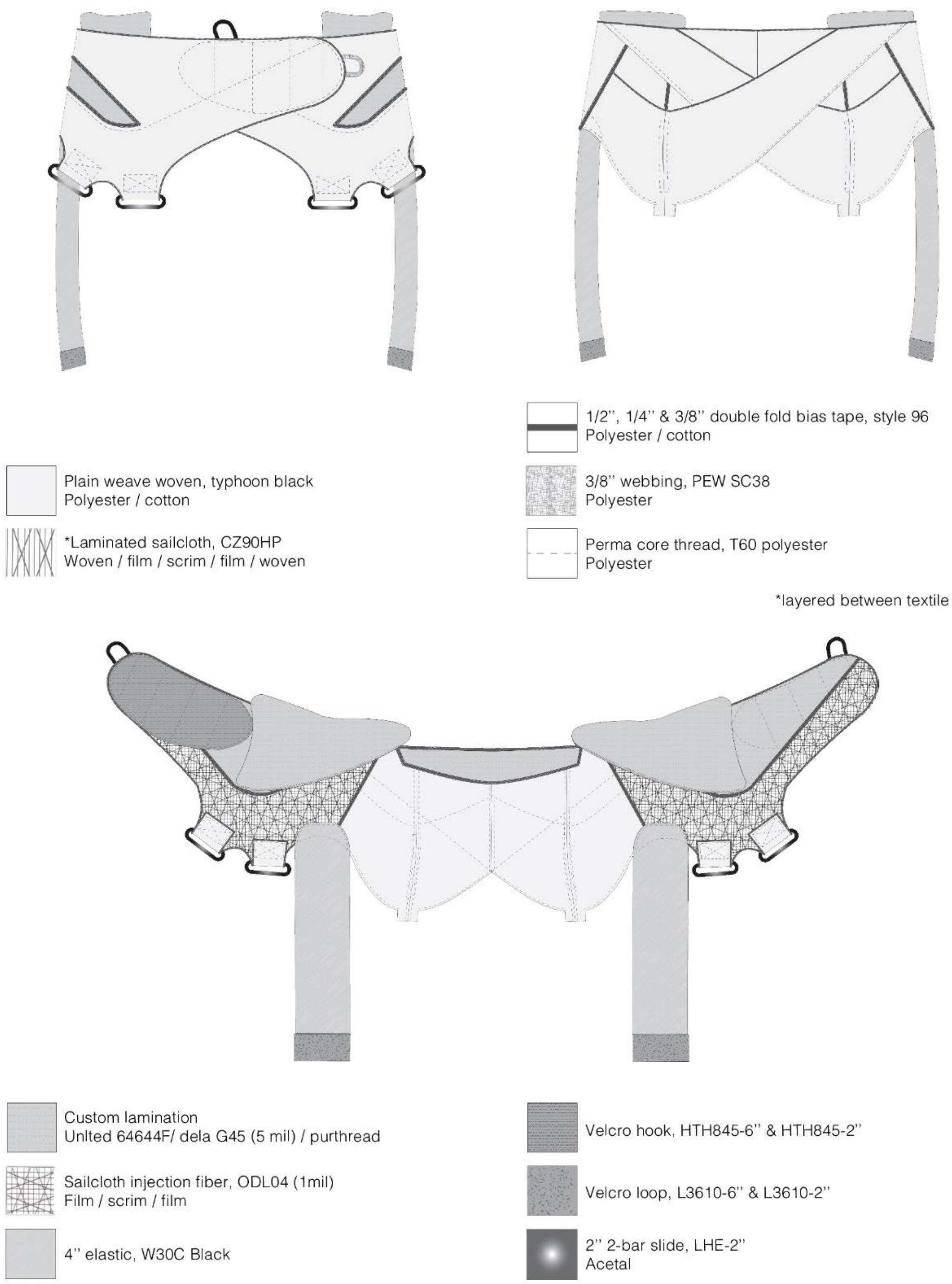

Fig. S7. Structure of the waist belt component. *The waist belt is mainly a plain-woven typhoon sourced to minimize strain and two types of sailcloth injection fiber were used for reinforcement. Velcro hook and loop were used for the front closure. A custom laminated padding was used to line the inside of the belt near the iliac crests and a small window in the woven material allows for a more conformal fit and reduced pressure concentration on the anterior superior iliac spine. Two reinforced load paths were sewn to mainly distribute the hip extension assistance. The 4'' elastic strips coming down off the belt are designed to attach to a thigh brace used when assisting hip extension.*

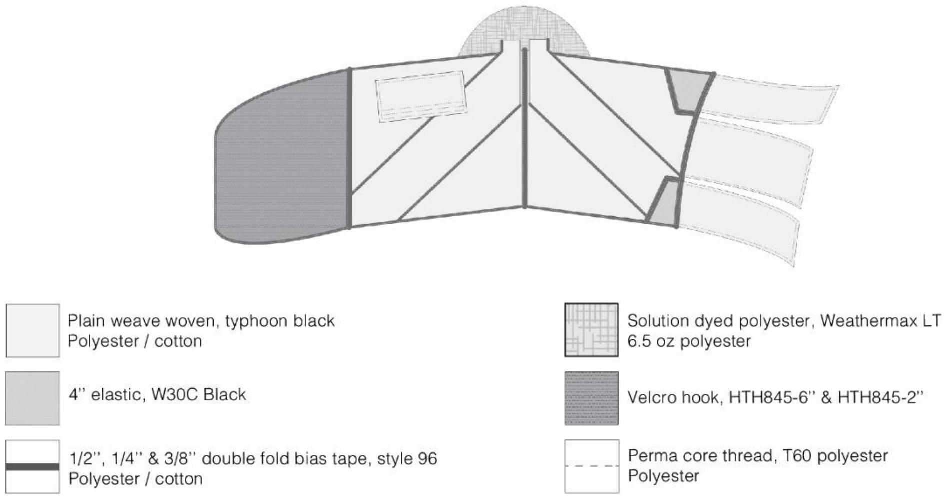

Fig. S8. Structure of the thigh brace. *The thigh brace is mainly composed of a plain-woven typhoon sourced to minimize strain. Velcro loop and hook were used for the thigh brace closure. Two angled woven pieces were sewn on top of the main woven piece to reinforce the load path of the thigh brace. A polyester padding at the top was added as the cushion of the cable attachment point. A small Velcro pocket on the top left was designed to attach the elastic strips of the waist belt to keep the thigh braces from slipping down.*

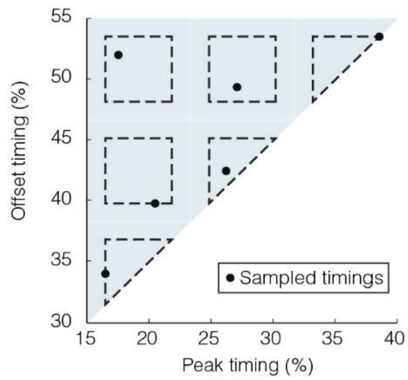

Fig. S9. Pseudo-randomly sampled timings for the initialization of Bayesian optimization. *The whole timing search area is shown as the shaded triangle. Six pairs of pre-fixed peak and offset timing are pseudo-randomly selected from evenly spaced areas shown by dashed squares and triangles. The space left open among squares and triangles is designed to ensure a minimum timing difference of 3%. One sample set of selected timings is shown as the black dots.*

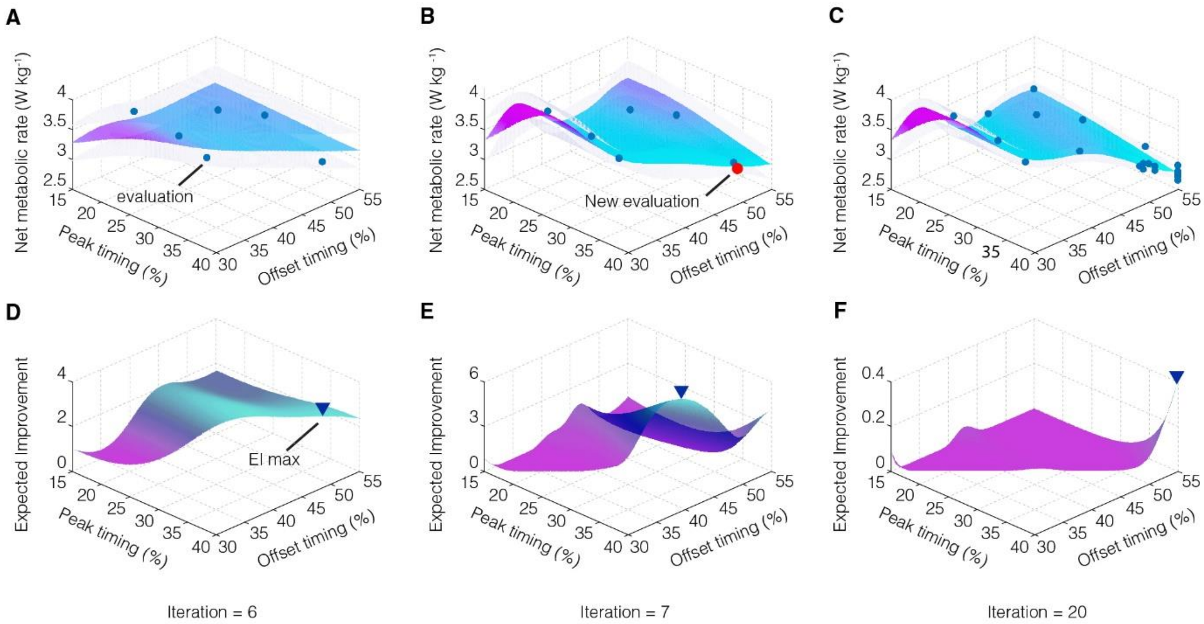

Fig. S10. Optimization process. *An example of Bayesian optimization process with hypothetical data points. The top subfigures (**A** to **C**) show two-dimensional posterior distributions (metabolic landscape with standard deviation) generated by the Gaussian process on iteration six, seven and twenty. The bottom subfigures (**D** to **F**) show the expected improvement landscapes. (**A**) Initialization, evaluation of six pseudo-randomly selected timings. (**D**) The next sampling point was chosen from the timings that resulted in the maximum value of expected improvement. (**B**, **E**) Updated metabolic landscape (posterior) and corresponding expected improvement landscape. (**C**, **F**) The metabolic landscape and the expected improvement landscape for the last iteration.*

Optimization parameters	***Signal-to-noise ratio***	***Variations of Metabolic cost***	***Number of subjects***
Onset & peak timing	*1.1*	*5.0*	*2*
Onset & offset timing	*1.5*	*7.0*	*1*
Peak & offset timing	*8.8*	*18.3*	*3*

Table S1. Signal-to-noise ratio and variations of metabolic cost of the pilot tests*. Different combinations of timings were evaluated as control parameters in our pilot tests. The table summarizes the average of signal-to-noise ratio (SNR), variations of metabolic cost and number of subjects for each combination. SNR is defined as the ratio of the power of a signal and the power of back ground noise. In this study, it was defined as* $SNR = \sigma/\sigma_{noise}$*, which was the ratio of the two hyper parameters in the Gaussian process. Variation of metabolic cost is defined as the differences between the maximum and minimum values of the final metabolic landscape for each subject.*

Participant	*Onset Timing (%)*
Subject 1	*85.6*
Subject 2	*86.4*
Subject 3	*87.0*
Subject 4	*85.9*
Subject 5	*87.4*
Subject 6	*83.8*
Subject 7	*87.6*
Subject 8	*86.2*
mean	*86.2*
s.e.m.	*0.4*

Table S2. Onset timing. *Average onset timing was calculated by using the detection of heel strike from the force plate across ten strides during the last minute of the validation condition.*

Participant	***Age (yrs)***	***Body mass (kg)***	***Height (m)***
Subject 1	*25*	*64*	*1.74*
Subject 2	*26*	*75*	*1.78*
Subject 3	*31*	*77*	*1.80*
Subject 4	*25*	*90*	*1.77*
Subject 5	*29*	*79*	*1.83*
Subject 6	*30*	*80*	*1.75*
Subject 7	*47*	*83*	*1.80*
Subject 8	*29*	*64*	*1.65*
mean	*30.3*	*76.5*	*1.77*
s.d.	*7.1*	*8.9*	*0.05*

Table S3. Participant characteristics. *Relevant characteristics of all study participants.*

Participant	*Metabolic rate (W kg^{-1})*					*Optimal timing (%)*		*Convergence time (min)*
	Standing	*1st No-suit*	*Optimal*	*Validation*	*2nd No-suit*	*Peak*	*Offset*	
Subject 1	*1.17*	*4.21*	*3.83*	*3.87*	*4.45*	*35.5*	*50.5*	*18.0*
Subject 2	*1.43*	*4.01*	*3.46*	*3.43*	*3.90*	*33.0*	*55.0*	*24.0*
Subject 3	*1.37*	*3.69*	*3.27*	*3.33*	*3.47*	*26.5*	*52.5*	*22.0*
Subject 4	*1.40*	*4.38*	*4.26*	*4.24*	*4.65*	*40.0*	*55.0*	*24.0*
Subject 5	*1.70*	*4.42*	*3.89*	*3.86*	*4.17*	*40.0*	*55.0*	*24.0*
Subject 6	*1.23*	*4.03*	*3.57*	*3.93*	*4.57*	*29.0*	*44.0*	*18.0*
Subject 7	*1.07*	*3.30*	*2.91*	*2.63*	*3.43*	*40.0*	*55.0*	*20.0*
****Subject 8***	*1.06*	*4.32*	*4.46*	*5.30*	*5.38*	*30.5*	*45.5*	*20.0*
Mean	*1.34*	*4.01*	*3.60*	*3.61*	*4.09*	*34.9*	*52.4*	*21.4*
s.e.m.	*0.08*	*0.15*	*0.17*	*0.20*	*0.19*	*2.1*	*1.6*	*1.0*

Table S4. Metabolic rates, optimal timing and convergence timing for each subject. *A paired-t test was also performed on the two no-suit conditions. No statistical significance was found (P = 0.466). The subject marked with asterisk (subject 8) was found fatigued in the experiment and the corresponding data was not included in the data analysis. The mean and s.e.m. were also calculated without subject 8.*

Participant	*Quadratic approximation*	R^2	*Model Optima*		*Error (% of range)*	
			Peak timing	*Offset timing*	*Peak timing*	*Offset timing*
Subject 1	$-0.0008258x_p^2 + 0.03694x_p + 0.001433x_o^2 - 0.01178x_o + 4.7$	*0.23*	*40*	*41*	*18*	*38*
Subject 2	$0.0004821x_p^2 - 0.02837x_p - 0.002476x_o^2 + 0.1936x_o - 0.6097$	*0.74*	*29.5*	*55*	*14*	*0*
Subject 3	$0.004319x_p^2 - 0.2314x_p + 0.0005821x_o^2 - 0.09063x_o + 8.134$	*0.90*	*27*	*55*	*2*	*10*
Subject 4	$0.000429x_p^2 - 0.02379x_p + 0.002012x_o^2 - 0.2017x_o + 8.25$	*0.86*	*27.5*	*50*	*50*	*20*
Subject 5	$-0.003231x_p^2 + 0.1246x_p + 0.0009302x_o^2 - 0.06285x_o + 2.983$	*0.88*	*40*	*34*	*16*	*68*
Subject 6	$0.002463x_p^2 - 0.1406x_p - 0.00013x_o^2 + 0.008555x_o + 4.283$	*0.61*	*28.5*	*55*	*2*	*44*
Subject 7	$-0.001124x_p^2 + 0.0476x_p + 0.00263x_o^2 - 0.2418x_o + 7.102$	*0.96*	*40*	*46*	*0*	*36*

Table S5. Quadratic approximation of metabolic landscape. *For each participant except the fatigued subject, we used metabolic rate from the first ten iterations of the optimization process to conduct a model-based quadratic fitting to estimate the optimal peak and offset timing. We assumed a two-variable quadratic function without interactions.* $\dot{E} = c_1x_p^2 + c_2x_p + c_3x_o^2 + c_4x_o + c_5$, *where* x_p *and* x_o*indicated peak and offset timing, and solved for the coefficients,* $[c_1,\ c_2,\ c_3,\ c_4,\ c_5]$ *that resulted in least square error. Then, we identify the optimal peak and offset timing resulted the minimum metabolic rate within the constrained search range. We then calculated the percent error of the estimated optimal values, defined as the difference between the quadratic model-based estimate of the optimal parameters and the experimentally optimized parameter values, divided by the allowable search range. Average errors were [14.6%, 30.9%].*