MEDICAL ROBOTS

Metabolically efficient walking assistance using optimized timed forces at the waist

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The metabolic rate of walking can be reduced by applying a constant forward force at the center of mass. It has been shown that the metabolically optimal constant force magnitude minimizes propulsion ground reaction force at the expense of increased braking. This led to the hypothesis that selectively assisting propulsion could lead to greater benefits. We used a robotic waist tether to evaluate the effects of forward forces with different timings and magnitudes. Here, we show that it is possible to reduce the metabolic rate of healthy participants by 48% with a greater efficiency ratio of metabolic cost reduction per unit of net aiding work compared with other assistive robots. This result was obtained using a sinusoidal force profile with peak timing during the middle of the double support. The same timing could also reduce the metabolic rate in patients with peripheral artery disease. A model explains that the optimal force profile accelerates the center of mass into the inverted pendulum movement during single support. Contrary to the hypothesis, the optimal force timing did not entirely coincide with propulsion. Within the field of wearable robotics, there is a trend to use devices to mimic biological torque or force profiles. Such bioinspired actuation can have relevant benefits; however, our results demonstrate that this is not necessarily optimal for reducing metabolic rate.

INTRODUCTION

Robots often incorporate anthropomorphic designs (*1*). In the subfield of rehabilitation robotics, different groups develop biologically inspired exoskeletons that assist with moments at the biological joints (*2*). Although exoskeletons have appropriate applications, simple pendulum models suggest that timed linear forces acting through the center of mass (COM) can actuate walking more efficiently than moments (*3*). Gottschall and Kram (*4*) conducted foundational research on the effects of linear forward aiding forces with constant magnitude at the COM and show that the metabolic rate of walking in healthy adults can be reduced by up to 47% with a long elastic tether. They report that optimal aiding forces minimize propulsion at the expense of increased braking ground reaction forces (GRFs) and called for further research on devices that could specifically assist propulsion, perhaps without impeding braking.

There is increasing interest in devices that can apply such nonconstant force profiles during specific phases of the gait cycle (*5*, *6*). Bhat *et al.* (*5*) used stiff tethers to elicit cyclic force profiles from the back-and-forth movements on a treadmill. They found smaller metabolic rate reductions than those for constant forces (*4*, *7*), which suggests that their force profiles a suboptimal. Penke *et al.* (*6*) used a pulley system that connected the COM to one of the ankles to apply cyclic force profiles. This system reduced the metabolic rate of individuals poststroke by 12%, demonstrating potential clinical applicability. In healthy participants, they found relatively smaller reductions than those for constant forces, which suggests that there is room for further improvements.

Certain clinical populations have large increases in metabolic rate during walking [e.g., 200 to 300% in cerebral palsy (*8*)]. Exoskeletons can currently reduce the metabolic rate by up to one-fourth in healthy individuals (*9*, *10*). Even if, potentially, similar reductions in metabolic rate versus unassisted walking could be obtained in clinical populations, this might be insufficient to bring the metabolic cost to normal levels and allow for sustained walking practice in certain patients who have a metabolic cost that is higher compared with healthy individuals. In the current study, we investigate different ways of assisting treadmill walking using timed forward forces at the COM instead of exoskeletons. Simple pendulum models (*3*) and studies with exoskeletons (*9*–*14*) show that the parameters that define the shape of the actuation profile during the walking cycle can influence the metabolic rate. We aimed to investigate the effects of timing and magnitude for nonconstant force profiles at the COM in healthy individuals. This initial work is intended to assess this type of assistive strategy at the COM using a robotic tether system with the goal of reducing the metabolic rate of walking in healthy adults. Depending on the outcome, this could be a preliminary step toward potentially testing such a system in clinical populations. Gottschall and Kram (*4*) reported that the metabolically optimal magnitude for constant forces minimizes propulsion. Therefore, we expected a similar relationship between propulsion reduction and metabolic rate reduction, and we hypothesized that nonconstant force profiles in which the peak magnitude coincides with propulsion would optimally reduce propulsion and metabolic rate.

RESULTS

Robotic waist tether experiments

We conducted experiments with a cable robot that applied forces to a waist belt in 10 healthy participants (Fig. 1A and movie S1) (*15*, *16*). A force control algorithm was used to apply 32 conditions with

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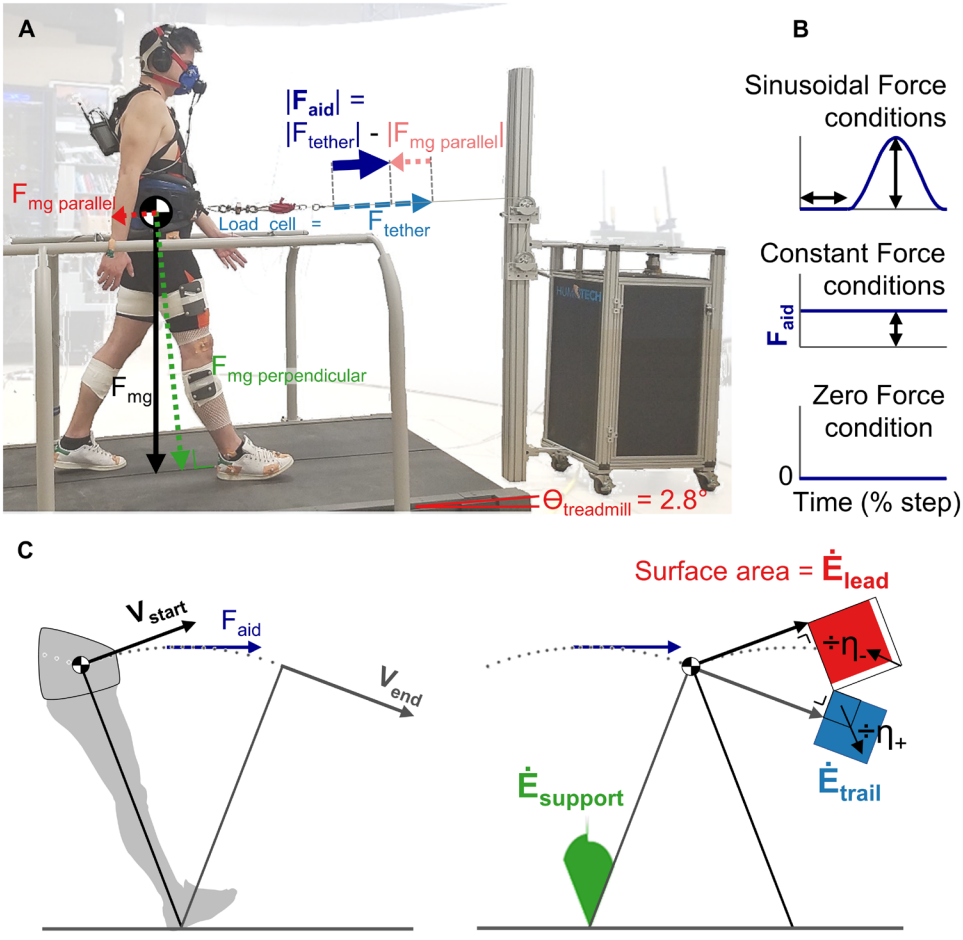

Fig. 1. Experimental conditions and simulation model. (**A**) Photograph of the robotic waist-tether setup. A cable robot (HuMoTech, Pittsburgh, PA, USA) applied force profiles to a waist belt. To avoid the tether going slack during portions of the step cycle, a constant backward force was simulated by inclining the treadmill (*17*, *62*) by a 2.8° angle. The reported aiding forces are the forces measured with a load cell minus the parallel component of gravity. (**B**) Schematic of the force profile conditions. We used the cable robot to apply Sinusoidal Force conditions, Constant Force conditions, and a Zero Force condition. (**C**) Simple pendulum model. We modeled an inverted pendulum (*3*, *18*) with the mean mass and leg length of our participants. This model was used to simulate different aiding force timings and magnitudes. For each condition, we identified the initial COM velocity required to match the experimental step time and the velocity at the end of single support. On the basis of COM velocity, we estimated the metabolic rate (visualized as colored surfaces) of the trailing and leading legs during the step-to-step transition and the support leg during single support (*15*). The metabolic rate of the step-to-step transition was estimated by dividing the redirection work rate that the legs have to produce (*3*) by the assumed efficiencies (*19*).

sinusoidal force profiles with desired magnitudes, timings, and durations (Sinusoidal Force conditions; Fig. 1B) (*17*) as well as 4 conditions where the force had a constant magnitude throughout the step cycle (Constant Force conditions). Because the tether acts symmetrically on both legs, we could not differentiate between the effects of assisting during phases associated with one specific leg (e.g., first or second double support phase). However, we could differentiate between effects associated with the activities of both legs (e.g., single or double support); hence, we expressed actuation timings in percent of the step cycle instead of percent of the stride cycle. We calculated the net aiding work rate by multiplying the net aiding force by the COM velocity, and we estimated the metabolic rate using respiratory measurements.

Participants attended a habituation session and a testing session during which they walked under 36 different force profiles that were randomized and grouped into three blocks, each separated by 10 min of rest (fig. S12A). The force conditions were combinations of three desired durations, four desired onset timings, and different desired peak net aiding force magnitudes. The experiment was conducted using our robotic waist tether system (*17*), which was developed based on a commercially available actuation and control platform (HuMoTech, Pittsburgh, PA, USA; Fig. 1A, movie S1, and table S1). We conducted tests with 10 male participants walking on a treadmill at 1.25 m s^{-1}.

Effects of force profiles on metabolic rate

The greatest significant reduction in metabolic rate compared with the condition with a net aiding force of zero (Zero Force condition) was 47.8 ± 4.7% (mean ± SEM, $P < 0.001$, paired t test with Holm-Šidák correction; Fig. 2A). This reduction occurred in the Sinusoidal Force condition with a peak force of 15.0 ± 0.5% body weight (BW), a duration of 64.1 ± 1.6% of the step, and a peak timing during the double support phase at 21.1 ± 0.3% of the step. The smallest reduction in metabolic rate was 9.1 ± 2.0%. This reduction was also significant ($P = 0.006$) and occurred in the condition with a peak force of 4.7 ± 0.1% BW, a duration of 27.0 ± 0.4%, and a peak timing of 50.9 ± 0.4% of the step.

A mixed-effects model analysis of the effects of the different actuation profile parameters showed a significant effect of peak timing on metabolic rate [$P_{Ppeak\cdot sin(tpeak)} < 0.001$] with an optimum at the middle of the double support phase (15.1 ± 0.1% of step time; Fig. 2B). As expected, different conditions reduced metabolic rate by different amounts, but, unexpectedly, there were no conditions that increased the metabolic rate. Humans appear to be less sensitive to the timing of assistance at the COM than that of joint-level assistance, because certain conditions in studies with exoskeletons increase the metabolic rate (*11*, *14*).

We found a significant U-shaped trend in the effect of net aiding work rate ($P_{\dot{W}aid}$ and $P_{\dot{W}aid^2} < 0.001$) with an optimum at 0.958 ± 0.043 W kg^{-1} (Fig. 2C). There was no significant effect of net aiding power duration. The best Sinusoidal Force condition produced a significantly greater reduction in metabolic rate per unit net aiding work rate than the best Constant Force condition (ratios were 2.06 ± 0.21 and 1.54 ± 0.14, respectively, $P = 0.032$), but there was

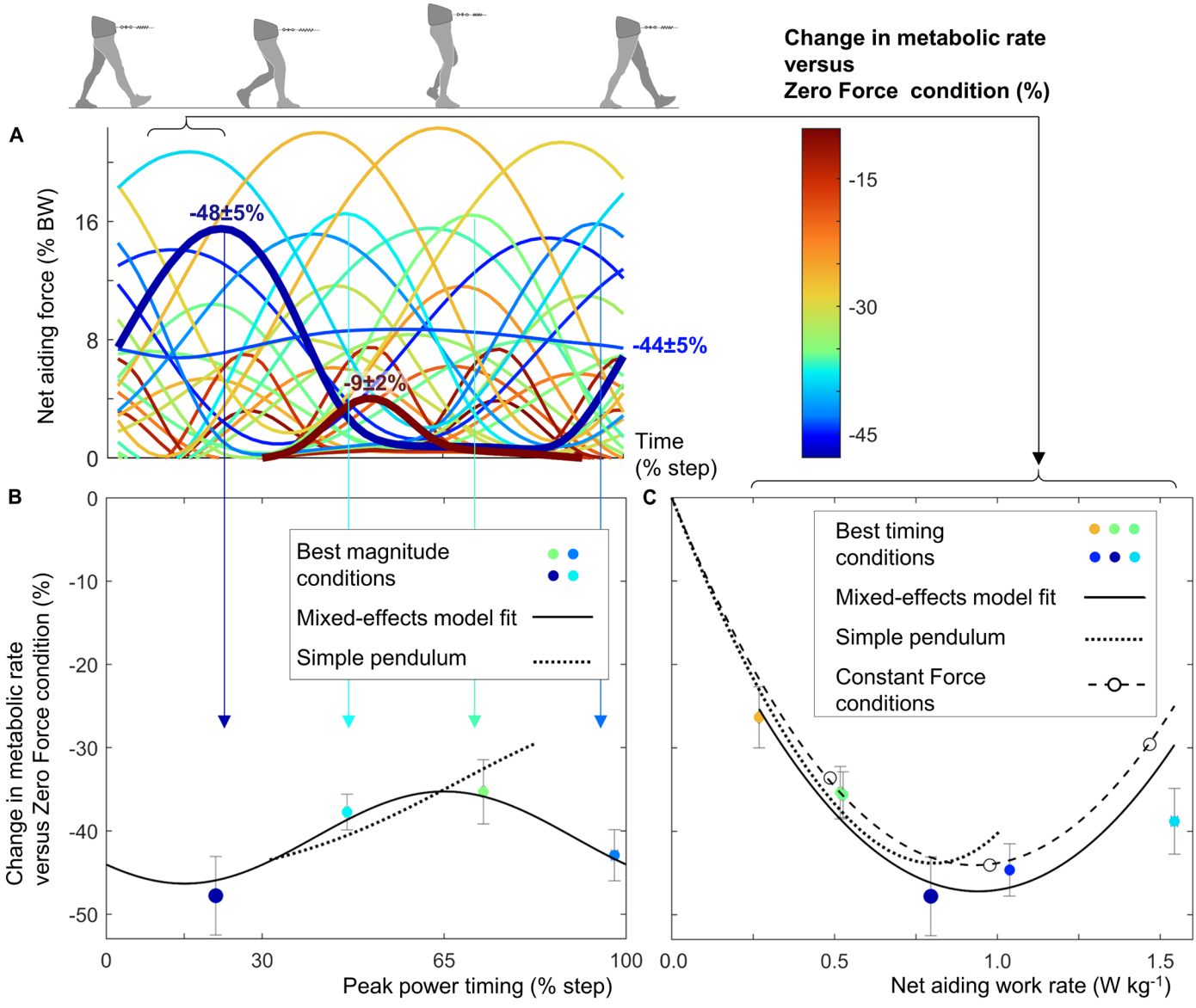

Fig. 2. Effects of force profiles on metabolic rate. (**A**) Net aiding forces and corresponding metabolic rate reductions. Lines represent the means of the participants for the Sinusoidal Force conditions and the best Constant Force condition. The color scale indicates metabolic rate reduction. Thick lines indicate the highest and lowest reductions. We applied the same profile during left and right steps; therefore, we plotted profiles versus step instead of stride time. (**B**) Effect of peak timing on metabolic rate. Dots and error bars represent means and SEMs of participants for conditions with different timings but approximately the same duration and net aiding work rate as the condition with the highest reduction. Solid line represents the mixed-effects model fitted on all Sinusoidal Force conditions evaluated at the mean magnitude of dots. Dotted line represents the estimation from the simple pendulum simulated over the feasible range. (**C**) Effect of net aiding work rate on metabolic rate. Dots and error bars represent means and SEMs for conditions with different net aiding work rates within a timing range of ±6% from the optimum (15.1%). Circles and the dashed line represent Constant Force conditions. Independent variables of (B) and (C) were selected from different candidate metrics (*15*). *P* values of reductions in metabolic rate versus Zero Force condition were smaller than 0.05 for all conditions (paired *t* test with Holm-Šidák correction, $n = 10$).

no significant difference in the metabolic rate. We also used the fits of the mixed-effects model analysis equation to each participant to improve the estimates of the individual optima. This analysis suggests that there was still a small but significant metabolic rate benefit of 3.9 ± 1.5% of the optima of the Sinusoidal Force conditions compared with the optima of the Constant Force conditions ($P = 0.030$). The highest reduction in the metabolic rate of the Constant Force conditions (44.0 ± 4.4%) and the Constant Force level that minimized the metabolic rate (7.9 ± 0.03% BW) were similar to other studies [47% with a net aiding force of 10% BW (*4*), 35% with a net aiding force of 8% BW (*7*), and 34% with a net aiding force of 8.4% BW (*6*)].

Interpretation using inverted pendulum model

To understand the potential underlying mechanisms of the effects seen during experimentation, we conducted an inverted pendulum simulation (*3*, *18*) and analyzed relevant biomechanical measurements. The simple pendulum model (Fig. 1C) reproduced the changes observed in metabolic rates with increasing net aiding work

rate but reached its optimum at a lower work rate (0.796 W kg^{-1}; Fig. 2C). The model also closely reproduced the effect of assistance timing over the feasible simulation range. The model could not simulate timings at the beginning of the step because double support is instantaneous. In addition, the model could not simulate timings at the end of the step. This occurred because the centripetal component from gravity minus the component from the tether force that pulls the COM away from the ground contact point (due to the alignment between the tether and the leg) was not sufficient to sustain the radial acceleration (Fig. 2B). We plotted the results from the model over the time range that corresponds to the single support phase from the human experimental data (immediately after toe-off at 30% of the step cycle until the end of the feasible simulation range). This simple model explained that aiding forces early in the step cycle were optimal because they help accelerate the COM, thereby reducing the positive leg work required to reach the apex of the inverted pendulum movement. Aiding force after midstance was suboptimal because the COM spontaneously accelerates due to gravity.

Effects on GRFs and COM velocity

We found significant effects of net aiding work rate and peak timing on the propulsion part of the bipedal sum of the GRF (all P values < 0.001, mixed-effects model analysis; Fig. 3A and table S4). As expected, the peak timing that resulted in the greatest propulsion

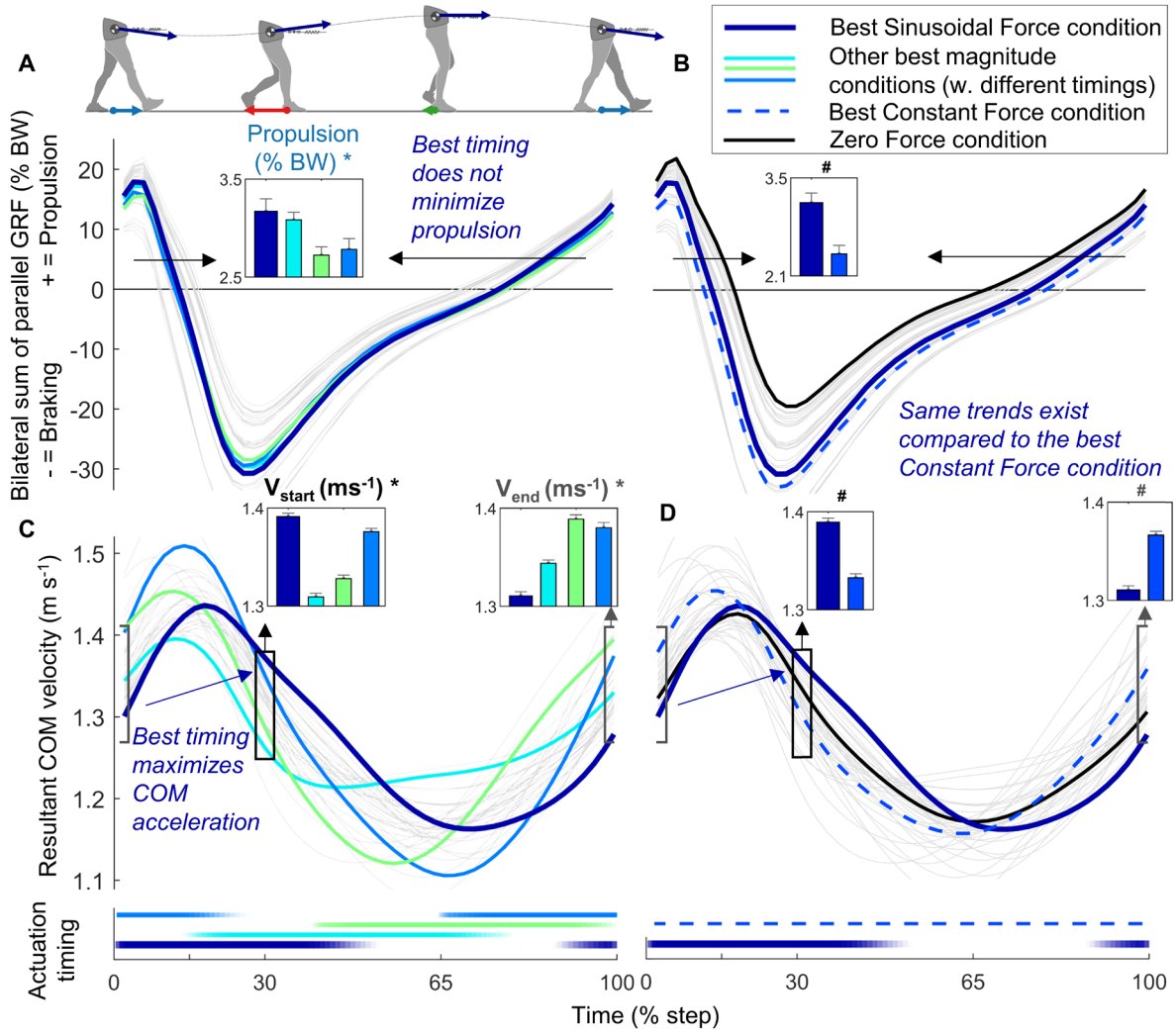

Fig. 3. Effects of timing on GRF and COM velocity. (**A**) Effect of timing on bilateral parallel GRF. The tether does not act unilaterally on one leg; therefore, we chose to analyze the bilateral GRF instead of the unilateral GRF. Colored lines represent the means of participants from conditions with similar actuation magnitudes and approximately the same net aiding work rate as the best condition from Fig. 2B but with different timings. The GRFs of the colored conditions appear offset because of the net aiding force that is not shown here. Gray lines represent all other conditions. Bar plots represent the average propulsion GRF averaged over the entire step duration. The thick line marks the condition that showed the highest metabolic rate reduction. (**B**) Comparison of bilateral parallel GRF between the condition with the highest reduction in metabolic rate (thick blue line), best Constant Force condition (dashed blue line), and Zero Force condition (black line). (**C**) Effect of timing on the resultant COM velocity. Bar plots represent the magnitude of the COM velocity vector at the beginning and end of single support. Horizontal lines represent the actuation periods. The condition with the highest reduction in metabolic rate (dark blue bar) has the lowest COM velocity at the end of single support, the highest COM velocity at the beginning of single support, and thus the highest acceleration during double support. (**D**) Comparison of COM velocity between the condition with the highest reduction in metabolic rate (thick blue line), best Constant Force condition (dashed blue line), and Zero Force condition (black line). * means P value of effect of peak timing < 0.05. # means P value of paired t test versus Best Constant Force condition < 0.05 (n = 10).

reduction fell inside the propulsion phase (mean ± SEM of the peak timing that minimized propulsion was 74.7 ± 0.2% of step, mixed-effects model analysis). However, the influence of timing on propulsion GRF was small (range between minimum and maximum propulsion GRFs of conditions with the same magnitude in Fig. 3A is 0.6 ± 0.1% BW). Even force profiles that fell entirely during the braking phase also significantly reduced propulsion by up to 36.5 ± 1.6% at the expense of a significant increase in braking GRF and significantly reduced the metabolic rate by up to 37.7 ± 2.1% compared with the Zero Force condition ($P < 0.001$, paired t tests with Holm-Šidák correction). Contrary to our hypothesis, the peak timing that minimized metabolic rate based on the mixed-effects model analysis (15.1% of step time) aligned with the transition from propulsion to braking (the first zero crossing occurred at 15.4 ± 0.6% of step time, mean ± SEM from all conditions; Fig. 3A) instead of aligning with the middle of the propulsion phase. The simple pendulum model proved to better explain our results than the GRF hypothesis. We found large significant effects of peak timing on the resultant COM velocity at the beginning and end of single support ($P < 0.001$; Fig. 3B and table S4). The metabolically optimal timing was close to the timing that maximized the COM velocity at the beginning of single support (the peak timing that maximized initial COM velocity was 10.0 ± 0.6% of step time, mixed-effects model analysis). The peak timings that minimized leading leg negative work and trailing leg positive work all occurred in the first half of single support, as predicted by the model. The peak actuation timings that minimized collision and push-off were 32.6 ± 1.3 and 54.0 ± 0.5% of step, respectively, and the middle of single support was at 65% (all P values for timing < 0.001; table S4). These results confirmed the model prediction that assisting COM acceleration at the beginning of the step reduces the required leg work (Fig. 4). The Sinusoidal Force condition that minimized the metabolic rate significantly increased not only the required propulsion by 15.1 ± 0.6% compared with the best Constant Force condition ($P < 0.001$; Fig. 3B) but also the COM acceleration compared with the best Constant Force condition. Specifically, the Sinusoidal Force condition had 4.6 ± 0.2% greater COM velocity at the beginning of the single support and 6.1 ± 0.2% smaller COM velocity at the end of the single support compared with the best Constant Force condition (all P values < 0.001; Fig. 3C). This shows that the Sinusoidal Force

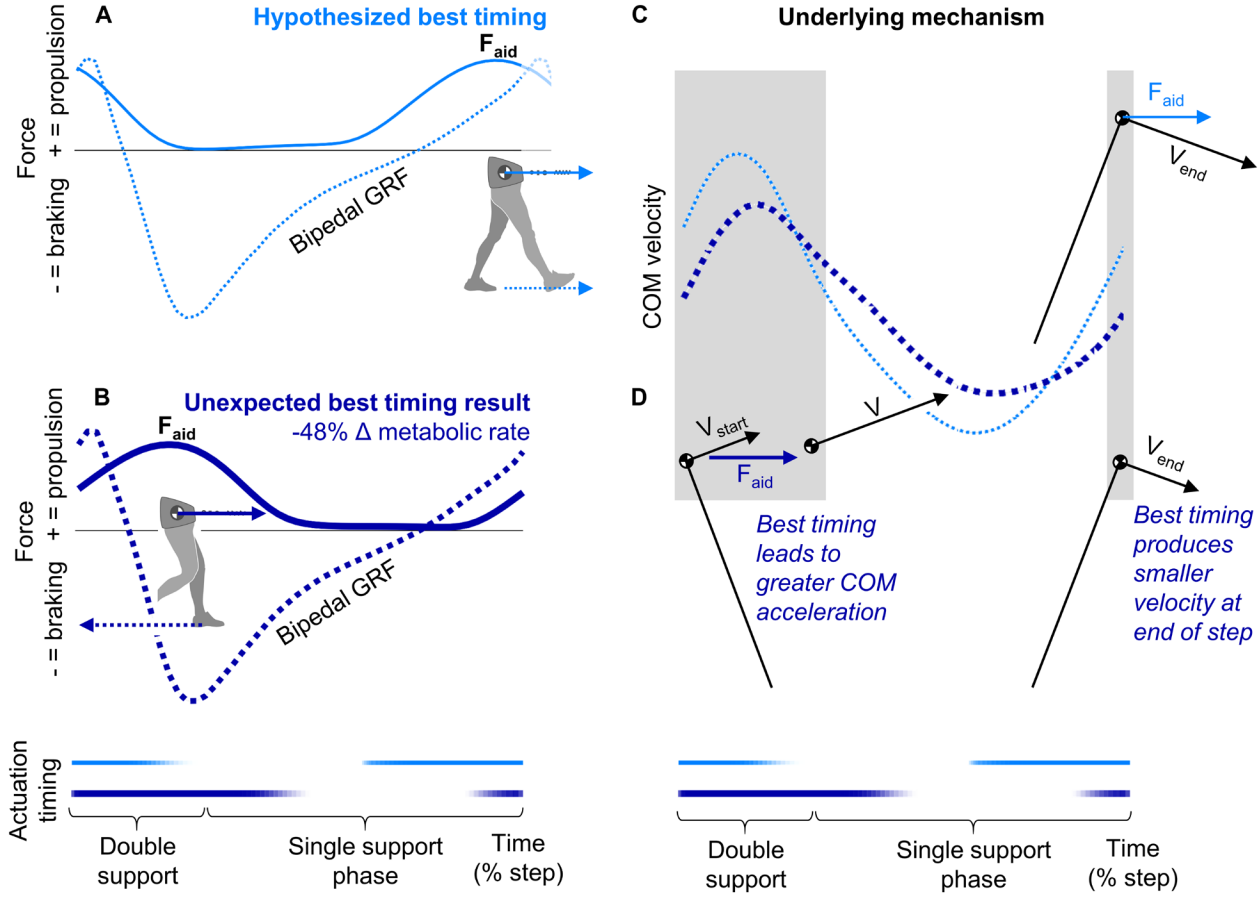

Fig. 4. Hypothesis and underlying mechanism. (**A**) Hypothesized best timing of a Sinusoidal Force condition. The plot shows the mean net aiding force (solid line) and the bipedal sum of the parallel GRF (dashed line) from the participants in the Sinusoidal Force condition where the net aiding force matches closest to the bipedal propulsion timing, plotted versus step time. (**B**) Best timing result. Condition with the highest reduction in metabolic rate. (**C**) Explanation based on COM velocity effect. Plot showing the mean COM velocity of all participants of the conditions with the hypothesized best timing and the highest metabolic rate reduction. (**D**) Simple pendulum model. Stick figures show the higher COM acceleration at the beginning of the step and lower COM velocity at the end of the step in the condition with early peak timing compared with the condition with late peak timing. The pendulum model predicts that the higher initial acceleration and lower final velocity will result in lower positive and negative leg work rates required to redirect the COM ($n = 10$).

conditions reduce the metabolic rate in a different way than the Constant Force condition, not primarily by reducing propulsion GRF.

Proof-of-concept studies in impaired gait and patients

As an initial evaluation of the applicability of the waist tether in impaired gait, we conducted an experiment in a healthy participant in which we induced a nonconstant COM velocity by unilaterally restricting plantarflexion. The results of this single-participant experiment suggest that it is possible to change the metabolic rate from +2 to −42% compared with the Zero Force condition or +7 to −35% compared with a No Tether condition using different Sinusoidal Force profiles after one habituation session. We also conducted an experiment to evaluate the feasibility of using the waist tether system as a method of exercise therapy in patients with limited mobility due to a prevalent disease. Two patients with symptomatic peripheral artery disease (PAD) walked with the waist tether during two sessions, referred to as habituation and testing sessions. During the testing session, we performed repeated comparisons between a Sinusoidal Force condition with low peak force and peak timing during double support and a No Tether condition, and we found reductions in metabolic rate of 12.0 and 9.7% in one patient and 23.1 and 20.1% in the second patient (*15*).

Comparison with literature on linear and angular assistance devices

Plotting reductions in metabolic rate versus net aiding work rate allows for comparing results with devices that provide angular assistance, such as exoskeletons (Fig. 5). This analysis confirmed that applying constant aiding forces with tethers (*4*, *7*) has similar effects as downhill walking (*19*, *20*). Nonconstant force profiles obtained with passive tether systems that were tested in healthy adults have peak timings around 85% of the step time (*5*, *6*), and this was close to the least optimal timing according to our data (65.1%). This result could explain their smaller observed reductions in healthy participants. Reductions in metabolic rate in W kg^{-1} from the Sinusoidal Force conditions with the best timing were greater than the best-in-class results for a wide range of devices, including exoskeletons and prostheses (all P values ≤ 0.036, t tests) (*4*–*7*, *9*–*14*, *16*, *21*, *22*), except for one condition in a study (*6*) that uses constant aiding force in healthy participants (P = 0.691, one-sample t test).

DISCUSSION

The field of wearable robotics has evolved from sophisticated full-body exoskeletons (*2*) toward simpler single-joint exoskeletons that first achieved metabolic rate reduction (*9*, *21*, *22*). Our study suggests that a simpler strategy of accelerating the COM with linear forces can provide further gains in stationary applications such as treadmill exercise therapy. Although robotic tethers cannot assist with overground mobility similar to exoskeletons, the greater reductions could enable treadmill exercise therapy applications.

Clinical practice guidelines recommend that combining robotic assistance with higher intensity stepping is an area that remains to be investigated (*23*). The large effects of robotic waist tether assistance could allow for higher intensity stepping training. However, it remains to be seen whether the effects observed in healthy participants transfer to patients. Although the effect of timing on the horizontal GRF was small, we found large effects on the COM velocity. Using their pulley mechanism that allowed for applying nonconstant force profiles, Penke *et al.* (*6*) found a 12% reduction

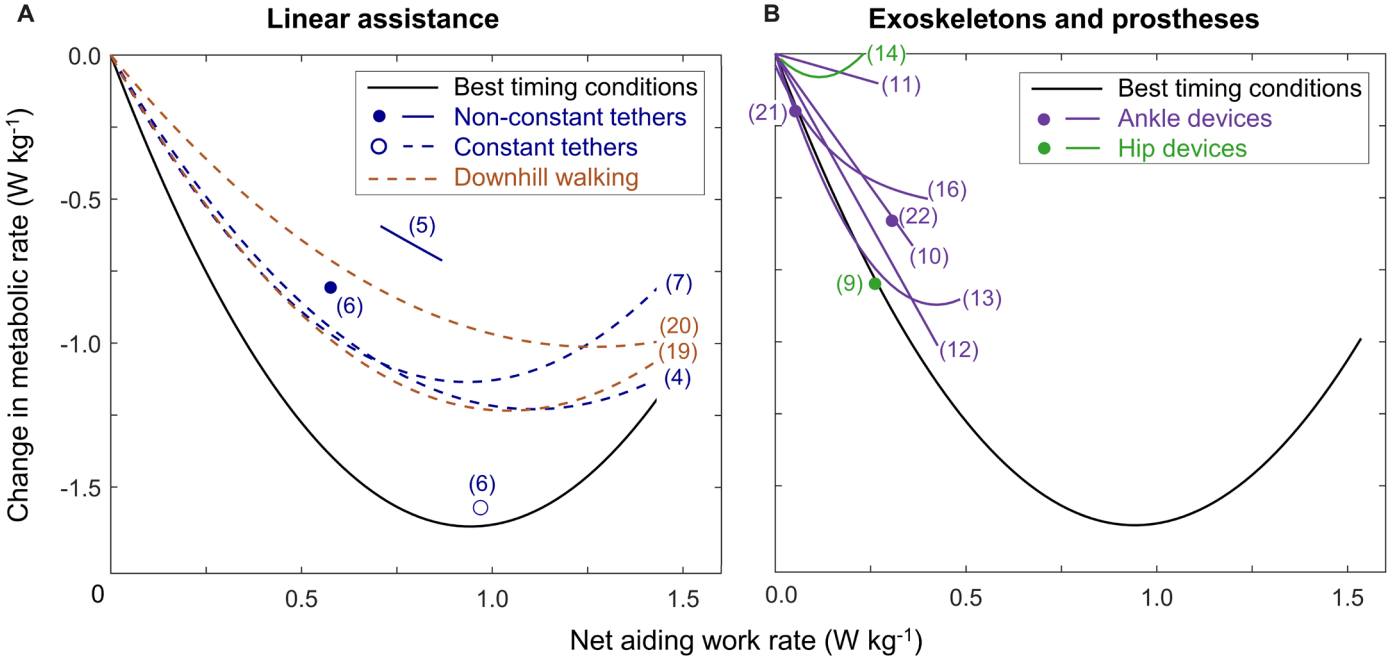

Fig. 5. Literature comparison within the field of wearable robotics. (**A**) Studies with linear assistance strategies (constant and nonconstant tethers and downhill walking) compared with the mean trend of 10 participants from our study. (**B**) Studies with exoskeletons and prostheses compared with our study. Reductions in metabolic rate compared with a Zero Force or no assistance condition versus net aiding work rate. The black line represents the effect of magnitude of conditions from the present study within 6% of the optimum peak timing (Fig. 2C). Colored lines represent trends from actuation magnitude parameter sweeps (*4*, *5*, *7*, *10*–*14*, *16*). Circles represent results from studies that do not use actuation magnitude sweep protocols (*6*, *9*, *15*, *21*, *22*).

in metabolic cost in individuals poststroke but no reduction using constant forces. Thus, timing could potentially have a greater influence in populations with nonconstant walking velocity, such as individuals poststroke, but this remains to be tested. Evaluating the effect of timed assistance at the COM in clinical populations requires an investigation of the targeted clinical population because there are different instances where the effects of assistive devices in healthy participants did not translate to patients (*24*–*27*). In clinical populations or older adults, it is possible that the effects of nonconstant forces on maintaining balance eliminate any metabolic cost reduction benefit. We evaluated the applicability of sinusoidal waist tether assistance in impaired gait in a healthy participant and two older adults with PAD and found that it could reduce the metabolic rate of walking. However, it is not yet possible to draw general conclusions from these small sample size experiments. Further experiments are needed to evaluate whether these results are reproducible in larger samples of patients.

Our work shows that it is possible to reduce the metabolic rate of walking by half by accelerating the COM. Although the results from our main study in healthy participants show benefits of optimally timed forces, the effects of timing were relatively small compared with the effect of aiding work rate. This could be considered as a limitation given the fact that applying different timings is more challenging than applying different constant magnitudes, which can be done with a passive tether system. Another limitation is that we only tested sinusoidal force profiles and did not evaluate whether other force profiles could provide greater assistance.

The observation that all force profiles with suboptimal timing still reduced the metabolic rate suggests that further reductions can be obtained with profiles that do not stay at a force level of 0% BW during a part of the step cycle. Using a simple pendulum model, we predict that one could approach an 80% reduction in metabolic rate by accelerating the COM during the first half of single support, followed by decelerating the COM during the second half (with a backward force) (fig. S10) (*15*). Such strategies could be implemented in cable robots for treadmill exercise therapy (*28*) or mobile devices that assist via the trunk, such as motorized rollators (*29*).

A number of wearable robots for clinical populations are designed to assist specifically during propulsion (*30*) or mimic biological kinematics or kinetics (*31*). We found that assisting during propulsion can reduce the metabolic rate but does not optimally reduce the metabolic rate, and even net aiding force profiles that occur entirely during braking reduce the metabolic rate. This finding indicates that bioinspired controls that mimic biological kinetics are not necessarily optimal for reducing the metabolic rate.

MATERIALS AND METHODS

Participants

Ten healthy male participants (age: 28.0 ± 4.7 years, body mass: 83.2 ± 12.2 kg, height: 1.80 ± 0.05 m, leg length: 0.993 ± 0.036 m; mean ± SD; table S5) took part in the main study. Participants were recruited using a convenience sampling strategy. We only included participants without a previous history of musculoskeletal or neurological disorders. The sample size was selected to match the largest sample size from studies that report effects of waist tethers on metabolic rate [$n = 6$ (*5*), $n = 7$ (*6*), $n = 10$ (*4*, *7*)] and studies with wearable robots on the effects of actuation timing and magnitude on metabolic rate [$n = 7$ (*12*, *32*), $n = 8$ (*11*), $n = 9$ (*21*), $n = 10$ (*13*, *16*, *33*, *34*)]. The researchers were not blinded to the data. The participants could not be blinded to the conditions in which they were tested, but they were not informed about any hypothesis regarding which conditions were optimal. All participants provided written informed consent. The Institutional Review Board of the University of Nebraska Medical Center approved the study.

Protocol

The study consisted of a habituation session and a testing session 1 week later. Each session contained 1.8 hours of walking. The habituation session duration exceeded reported durations to maximize benefits from different wearable robots [40 min for a hip exosuit (*35*) and 105 min for an ankle exoskeleton (*36*)]. The testing session started with a 5-min standing trial to measure resting metabolic rate (K5, Cosmed, Rome, Italy). To ensure accurate measurement of the resting metabolic rate, we had the participant rest for at least 15 min while we prepared the experiment, and we asked the participants to have fasted for at least 5 hours, abstain from caffeine and alcohol overnight, and abstain from vigorous physical activity for 14 hours before the data collection (*37*). Both sessions had a 10-min warm-up, during which we cycled through all conditions and tuned the robotic tether gains. The desired treadmill speed was set to 1.25 m s^{-1} (Bertec). Near the end of the warm-up, we determined each participant's preferred step frequency under the Zero Force condition. This step frequency was used to pace the participant via a metronome to avoid walking pace changes that would affect the metabolic rate (*38*). Participants were able to keep their mean step time within 0.011 ± 0.008 s (mean ± interparticipant SD from all conditions) of their instructed step time (0.562 ± 0.021 s).

Participants walked under 36 different force profiles that were randomized and grouped into three blocks, each separated by 10 min of rest (fig. S12A). Thirty-two Sinusoidal Force conditions were combinations of three desired durations (33, 66, and 99% of step time), four desired onset timings (0, 25, 50, and 75%), and different desired peak net aiding force magnitudes (ranging from 4 to 24% of BW; all force levels are reported as net aiding forces, and the tether forces were 5% higher to offset the parallel gravity component from the treadmill inclination). As with other devices (*39*, *40*), our system had a specific bandwidth limit [3 dB bandwidth = 10 Hz (*17*)]. This required us to use lower peak force ranges at shorter durations (fig. S12B). We tested three conditions where the desired net aiding force remained at a constant level (4, 8, and 12% BW) throughout the step cycle (Constant Force conditions). The second-highest constant force level was chosen on the basis of the mean of the optima of earlier studies [7% (*7*) and 9% (*4*)]. We compared the effects of all the Sinusoidal and Constant Force conditions with a baseline condition where the desired net aiding force was set to 0% BW (Zero Force condition). Because of potential metabolic drift (*41*–*43*), we repeated the Zero Force condition, similar to other studies (*12*, *22*). We also repeated one Sinusoidal Force condition that was randomly selected for each participant in each block, resulting in a total of 40 conditions. The first and last conditions of each block lasted 5 min to ensure that the metabolic rate could reach steady state. We switched between the other conditions every 2 min, and we used estimation methods from the literature (*10*, *44*) to calculate the steady-state metabolic rate.

Measurements and data processing

Metabolic rate

Oxygen consumption and carbon dioxide production were measured using indirect calorimetry (K5, Cosmed, Rome, Italy) during the

entire protocol. We calibrated the indirect calorimetry system before every session using a gas container with a known oxygen and carbon dioxide concentration and a 3-liter fixed-volume calibration syringe that delivers simulated breath volume. The experiments occurred in a large and well-ventilated room. Breath-by-breath measurements were converted to W kg^{-1} using the Brockway equation (*45*). The respiratory exchange ratios were significantly lower than 1 (0.768 ± 0.053, mean ± interparticipant SD of all conditions, $P < 0.001$, one-sample *t* tests), which confirmed that the intensity level was within the aerobic range where it is appropriate to use the Brockway equation (*46*). We estimated the steady-state metabolic rate of the resting trial and the conditions at the beginning of each block by averaging the breath-by-breath data in the final 2 min. For all other conditions, the steady-state metabolic rates were estimated by fitting the breath-by-breath data from immediately after the transition to each new condition until right before the change to the next condition with an exponential function and estimating the asymptote (fig. S13A) (*10*, *44*).

For each participant, we identified the time constant that minimized the squared error of the exponential fits versus the breath-by-breath metabolic rate measurements following guidelines from Selinger and Donelan (*44*). On the basis of the properties of our data (breath frequency of 19.8 ± 2.04 breaths min^{-1}, inter-breath SD of 0.656 ± 0.189 W kg^{-1}, average change between conditions of 0.664 ± 0.193 W kg^{-1}), the recommended minimum number of conditions to approximate time constants with a confidence interval of 95% is 49. Data from both sessions (80 conditions) were used to meet this recommendation for time constant identification, and the resulting time constants of our participants (46.1 ± 15.7 s, mean ± interparticipant SD) were close to the time constants reported by Selinger and Donelan (*44*) (41.8 ± 12.1 s). To evaluate the metabolic rate estimation accuracy, we compared estimations based on 2 min of data with estimations that used 5 min from the final conditions of each block. The mean absolute error was 4.24 ± 2.60% of the Zero Force condition, and this result is on the lower end of a range of errors in similar methods [from 4.3% (*10*) up to 12.4% (*47*)].

We calculated the net metabolic rate by subtracting the resting metabolic rate. To evaluate metabolic drift due to the long protocol, we fit a linear trend through the net metabolic rate of the Zero Force conditions over time (fig. S13, B and C). We chose a linear fit because, according to the literature, the metabolic drift trends look predominantly linear (*42*, *43*). The average slope of this trend during the testing session was significantly higher than zero ($P = 0.0256$, one-sample *t* test). Studies show that prolonged downhill running can evoke a linear drift in oxygen consumption (*42*, *43*). Thus, the fact that walking with net aiding forces is mechanically similar to downhill locomotion might explain why a drift occurred in our experiment. To correct for the metabolic drift, we calculated all W kg^{-1} reductions in metabolic rate from the testing session versus the linear drift trend. To avoid the metabolic drift affecting normalization of the percentage reduction in metabolic rate, we divided the drift-adjusted reductions by the intercept value of the linear fit, which represented the Zero Force metabolic rate before fatigue. Analysis of the repeated Sinusoidal Force conditions showed that the drift correction improved the intraclass correlation of the repeated conditions from 0.629 to 0.766. This is considered good to excellent for intraclass correlation and is of a similar order of magnitude as reported intraclass correlations for within-session repeatability of $\dot{V}O_2$ measurements [0.87 (*48*)].

GRFs and COM mechanics

We measured the GRF and load cell data during the last minute of each condition. Crossover steps between belts were removed, and ~50 steps per condition per participant were used. The force treadmill (Bertec) was calibrated using an instrumented pole (C-motion, Germantown, MD) (*49*) with an accuracy threshold of ±5 mm for the center of pressure. We minimized signal drift by zeroing between walking blocks and subtracting the median of the swing phases. The GRF and load cell (Futek) signals were smoothed with a 10-Hz low-pass filter. We chose the cutoff based on the typical frequency content of walking [6 Hz (*50*)] and the robotic tether bandwidth [10 Hz (*17*)]. We calculated the parallel and perpendicular GRFs by performing a coordinate transformation over the treadmill inclination. This inclination was verified using a bubble level and a motion capture system (VICON Vero), which was calibrated to an accuracy of 0.6 mm. There was a strong linear relationship between the mean parallel GRF and net aiding force with a slope coefficient of −1.004 ± 0.005 (mean ± interparticipant SD), which confirmed that the calibration of both devices was consistent. To further minimize errors due to the load cell offset, we subtracted the mean sum of the parallel components of the GRF, gravity, and the load cell force based on the fact that the sum of all forces must be in equilibrium, on average.

We calculated the COM acceleration from the GRF, tether force, and gravity using Newton's second law (*51*). The total mass was measured by the force treadmill (Bertec), and we verified that this value corresponded to the body mass plus the added mass (~4.9 kg for the waist belt, calorimetry unit, shoes, and other small equipment). We calculated the velocity and position of the COM by integrating the COM acceleration (*52*). To obtain the COM velocity relative to a coordinate system that moves with the treadmill belt, we added the treadmill velocity. The actual treadmill velocity (1.26 m s^{-1}) was obtained by recording motion capture markers attached to the treadmill belt (*53*). To calculate the net aiding power, we multiplied the net aiding force by the COM velocity in the direction of the force and relative to the treadmill belt coordinate system. We calculated individual leg COM power by taking the dot product of the COM velocity and the individual (right) GRF (*54*). GRF recordings in 3 of the 400 trials from the testing session failed due to equipment malfunctions. For these trials, we calculated the net aiding power by assuming that the parallel COM velocity was equal to the treadmill velocity. The GRF variables of these trials were treated as missing values.

Data organization

We segmented each time series into steps and strides based on heel strike detection using the vertical GRF. For each participant and condition, we calculated the median of the strides (data S3). For the Repeated Sinusoidal Force conditions and the Zero Force condition, we averaged three repetitions of these conditions. The metabolic rate and kinetic time series were normalized relative to body mass. The peak values, step averages, and averages of positive and negative portions of tether and GRF variables were calculated from the time-normalized data (table S6). We also calculated the net aiding force duration and net aiding power duration by evaluating the length of the net aiding force and net aiding power profile that was higher than 1% BW or 0.15 W kg^{-1}. When calculating the peak force timing and peak power timing, we avoided creating artifacts in interparticipant variability from step segmentation by converting peak timings that were close to 0 or 100% to a percentage below 0% or above 100% in cases where most of the peak timings in the same

condition occurred at the opposite end of the step. For example, if the peak timing of a certain condition was 99% of the step in one participant and 1% in all the other participants, then the peak timing of 99% was converted to a value of −1%, which has the same meaning as a peak timing of 99%.

Statistical analyses

To determine the effects of the actuation profile shape parameters on the dependent parameters, we used mixed-effects model analyses with participants as random factors (*21*, *55*, *56*). To avoid overfitting, terms that did not significantly contribute were removed using a stepwise elimination procedure whereby the least significant terms were removed until only significant terms remained (*57*–*59*). Because earlier research shows that the metabolic rate follows a U-shaped trend versus aiding force magnitude (*4*, *7*), we included first- and second-order terms for the actuation magnitude parameter. There are no prior data on the effect of actuation duration, and in light of this, we began using both first- and second-order terms for this parameter. Because the timing was varied over the entire step, we expected a continuous trend between the end of the step cycle and the beginning of the step cycle. In other words, even if the step cycle were defined differently (e.g., from toe-off to toe-off instead of from heel strike to heel strike), we would expect to see a similar (but shifted) continuous trend. Therefore, a periodic term was included for timing. We identified the mean phase shift that minimized the sum of squared errors between the model and the measurements for each participant. There cannot be an effect of duration or timing when the peak magnitude is zero, so the duration and timing terms were multiplied by the peak magnitude (*13*, *58*). Because the actuation magnitude and reduction in metabolic rate were zero in the Zero Force condition, we did not include an intercept. Last, because we aimed to compare our results with those of devices that provide joint work and because mechanical work is a component of muscle energetic cost (*60*), we initially chose to express all parameters based on work rate and power instead of the average force and peak force, resulting in the following initial statistical model:

$$c_1 \cdot \dot{W}_{aid} + c_2 \cdot \dot{W}_{aid}{}^2 + c_3 \cdot P_{peak} \cdot \Delta t_P + c_4 \cdot P_{peak} \cdot \Delta t_P{}^2 + c_5 \cdot P_{peak} \cdot \sin\left(\frac{t_{P_{peak}} + c_6}{100} \cdot 2\pi\right) \quad (1)$$

where $\dot{W}_{aid}$ is the net aiding work rate obtained by averaging the net aiding power over the step duration, P_{peak} is the peak net aiding power, Δt_P is the duration of the power burst, and $t_{P_{peak}}$ is the timing of the peak power. The metabolic rate, $\dot{W}_{aid}$, and P_{peak} are in W kg^{-1}. Δt_P and $t_{P_{peak}}$ are expressed in % of step time.

To evaluate these choices, we compared the estimated and actual condition averages for several alternative models (*15*). Because we eliminated nonsignificant terms, all terms in the final equations were significant ($P < 0.05$). We used the adjusted R^2 values to assess the added value of different numbers of predictors. The final equation after the selection of the predictors and the backward elimination of nonsignificant terms was

$$-3.13 \cdot \dot{W}_{aid} + 1.67 \cdot \dot{W}_{aid}{}^2 + 0.09 \cdot P_{peak} \cdot \sin\left(\frac{t_{P_{peak}} + 60.16}{100} \cdot 2\pi\right) \quad \text{Adjusted } R^2\text{:95.3\%}$$

To analyze the Constant Force conditions, we used a model that included only the net aiding work rate terms:

$$c_1 \cdot \dot{W}_{aid} + c_2 \cdot \dot{W}_{aid}{}^2 \quad (2)$$

The final equation was

$$-3.25 \cdot \dot{W}_{aid} + 1.76 \cdot \dot{W}_{aid}{}^2 \qquad \text{Adjusted } R^2\text{: 99.8\%}$$

The controller did not keep the aiding work rate constant between conditions with different timings because this would have required real-time COM velocity measurement. However, the used statistical method of linear mixed-effects model analysis does not require varying the different independent parameters in isolation [e.g., unlike approaches such as repeated-measures analysis of variance (ANOVA)]. To determine the effects of timing isolated from work, we evaluated the mixed-effects model analysis equation over the range of timings while keeping the magnitude parameters ($\dot{W}_{aid}$ and P_{peak}) constant. To determine the effects of the net aiding work rate, we evaluated the equation while keeping the timing term that contains $t_{P_{peak}}$ constant. All statistical analyses were performed in MATLAB (MathWorks, Natick, MA, USA) using a significance threshold of 0.05. To analyze the interparticipant variability, we fit the significant terms of the equation to each participant's data using the fminsearch function in MATLAB, and we determined the metabolic rate, peak timing, and net aiding work rate at the optimum of each participant. This interpolated optimum was defined as the Optimum timing and magnitude, and the condition with the best mean reduction in metabolic rate was defined as the Best timing and magnitude. To evaluate differences in the metabolic rate, propulsion GRF, COM velocity, and COM power between conditions, paired *t* tests with Holm-Šidák correction were used for multiple comparisons (*61*). For statistical tests that relied on the normality assumption, we verified that the data followed a normal distribution using the Jarque-Bera test (table S6).

SUPPLEMENTARY MATERIALS

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Supplementary Materials and Methods
Supplementary Discussion
Figs. S1 to S13
Tables S1 to S6
Movie S1
Data S1 to S3
References (*63*–*131*)

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