Predictive Gait Simulations of Human Energy Optimization

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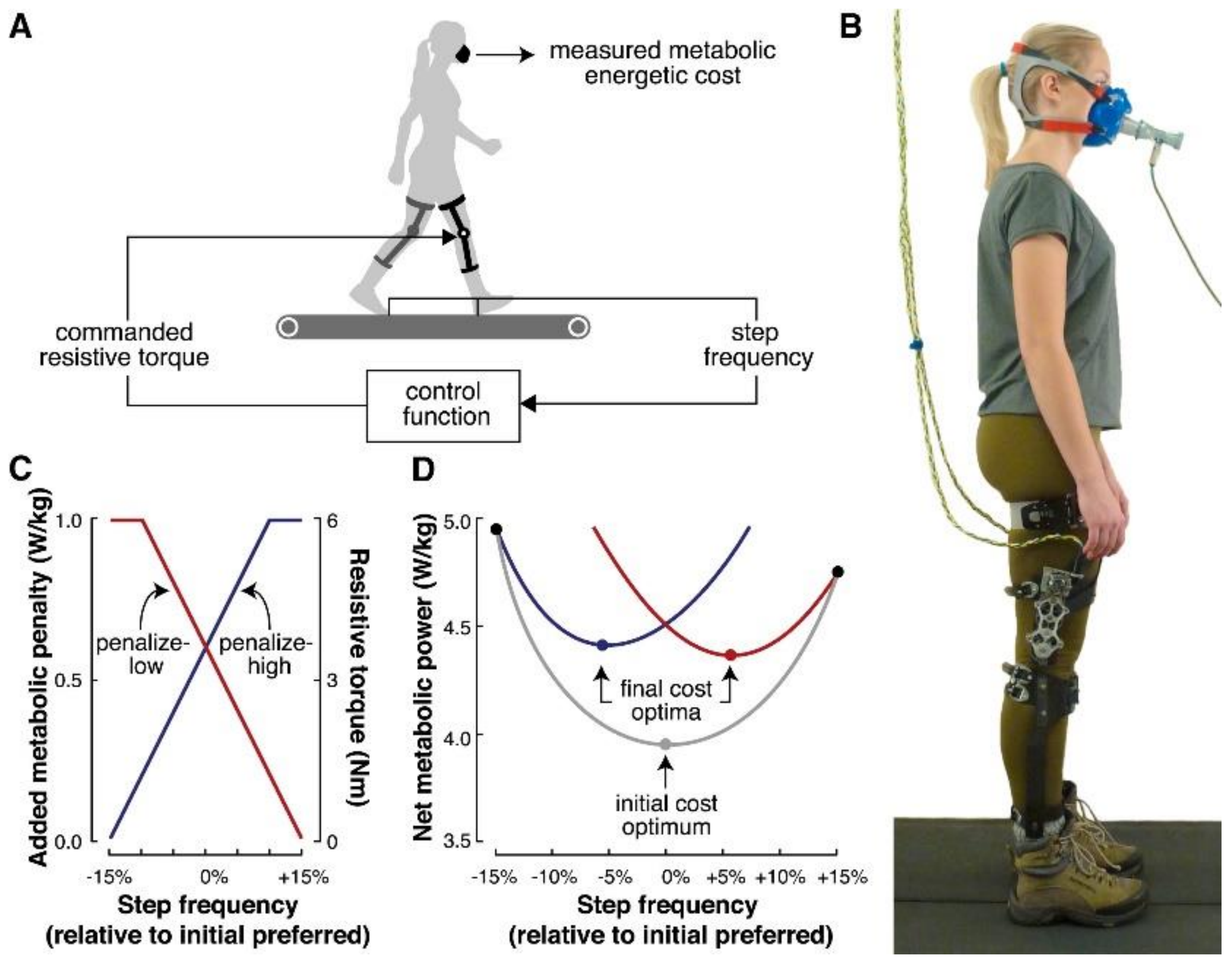
Introduction



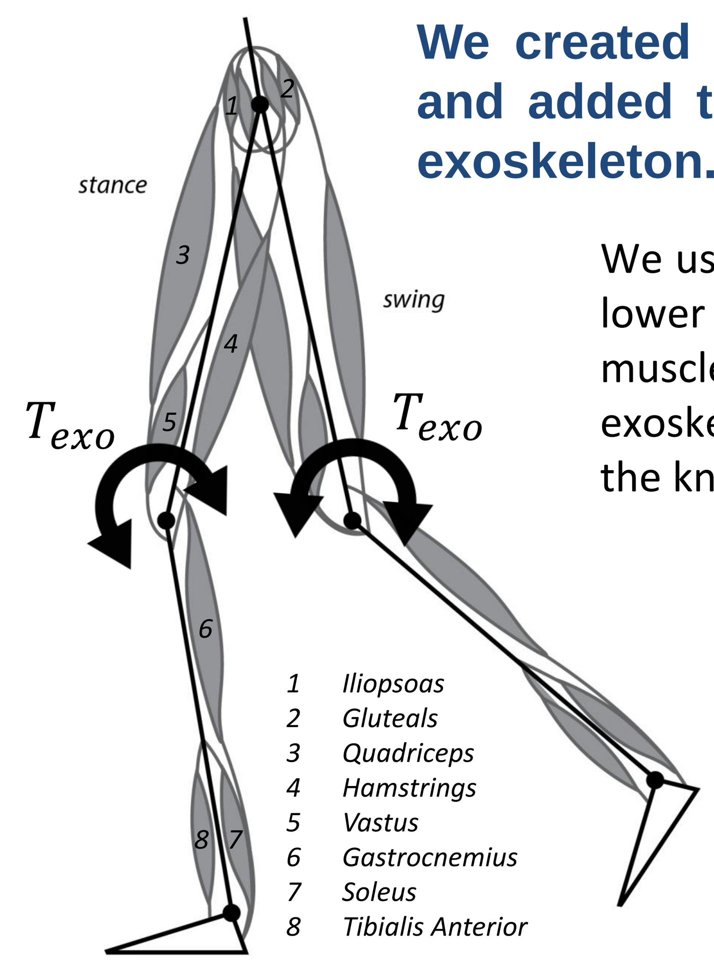
We aim to recreate an experimental energy optimization paradigm using predictive gait simulations.

Humans can adapt their gait to continuously optimize energetic cost in real-time. We have previously demonstrated this using robotic exoskeletons [1]. Subjects adapted their step frequency to converge on the new energetic optima within minutes and in response to relatively small savings in cost.

We aim to create a simulation model of the testbed. This simulated testbed will allow us to probe mechanisms underlying the energy optimization of gait—generating predictions of human behaviour and insight into aspects of optimization that are inherently difficult to investigate experimentally.

Figure reproduced from [1]

Methods: Modeling



We created a lower-limb musculoskeletal model and added torques at the knees to simulate the exoskeleton.

We use a sagittal plane musculoskeletal model of the lower limbs, with nine degrees of freedom and eight muscles in each leg. We added an ideal, massless, exoskeleton to our simulations by applying torques at the knees that resist flexion and extension.

$$T_{exo} = \pm s\, \dot{q}_{knee}\, c_T \leq 12 \text{ Nm}$$

$\pm s$: step frequency
$\dot{q}_{knee}$: knee angular velocity
c_T: constant

Methods: Trajectory Optimization Problems

We simulated a range of gaits, and solved for energy-optimal gaits under the penalize -high and -low exoskeleton controllers.

The following objective was used:

$$J = \frac{1}{T}\int_{t=0}^{T} u^3 + \frac{1}{1000}\left(\sum\left(q_i(t) - q_{i,des}(t)\right)^2 + \left(\sum F_i(t) - F_{i,des}(t)\right)^2\right) dt$$

u: neural stimulation
q: joint angles
F: horizontal and vertical ground reaction force
des: desired joint angles and ground reaction force from [2]

Optimization details [3]:

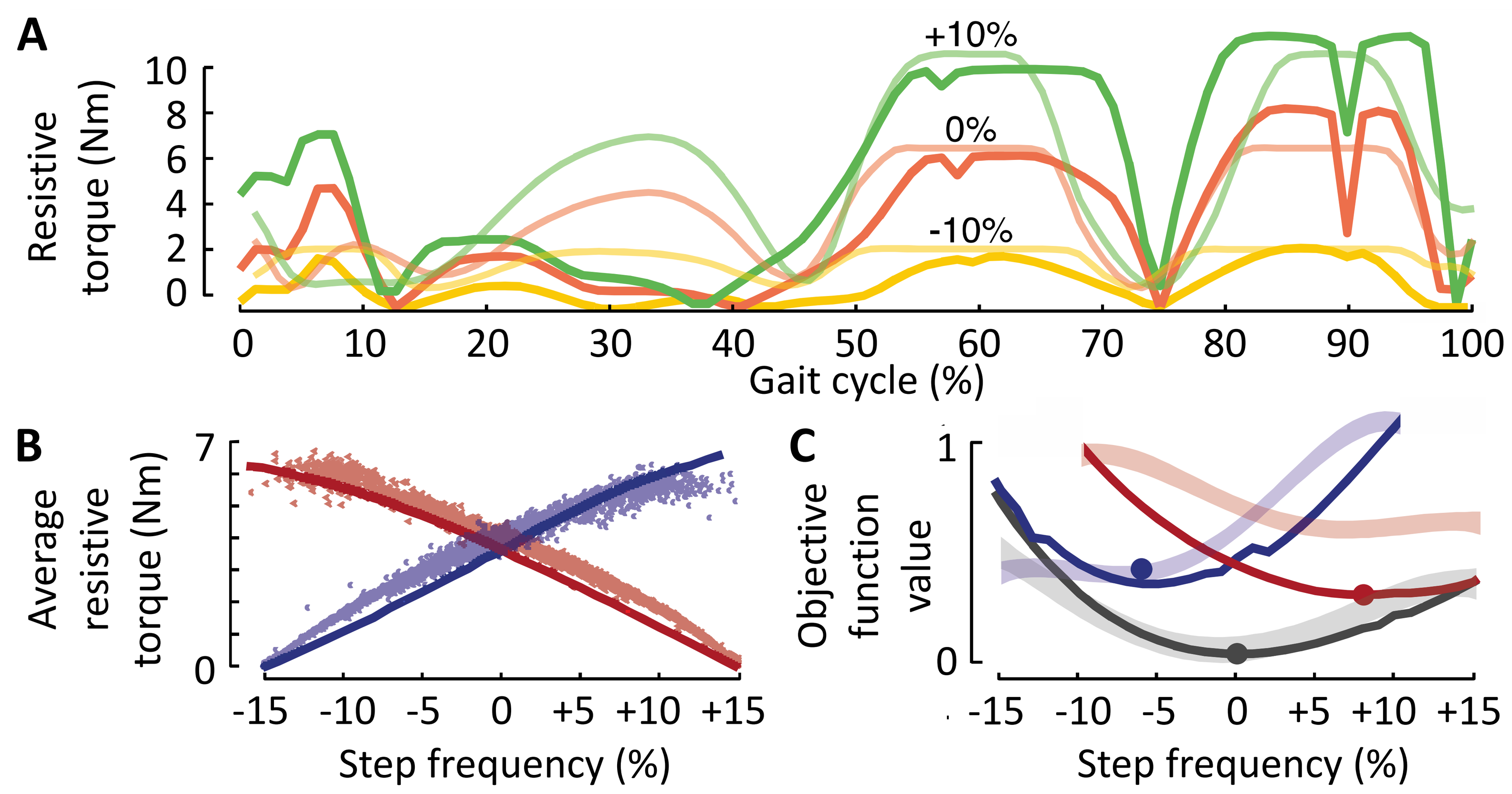
- Left-right symmetry constraint
- Direct collocation, 40 nodes per half-gait cycle
- Implicit dynamics formulation

Simulations created:

- Natural, penalize-low and -high
- Free, optimized step frequency
- Fixed step frequencies: -20% to 20% of natural preferred, 1% increments

Results: Resistive Torque Effects

Comparison of experimental and simulated resistive torque effects from the exoskeleton.

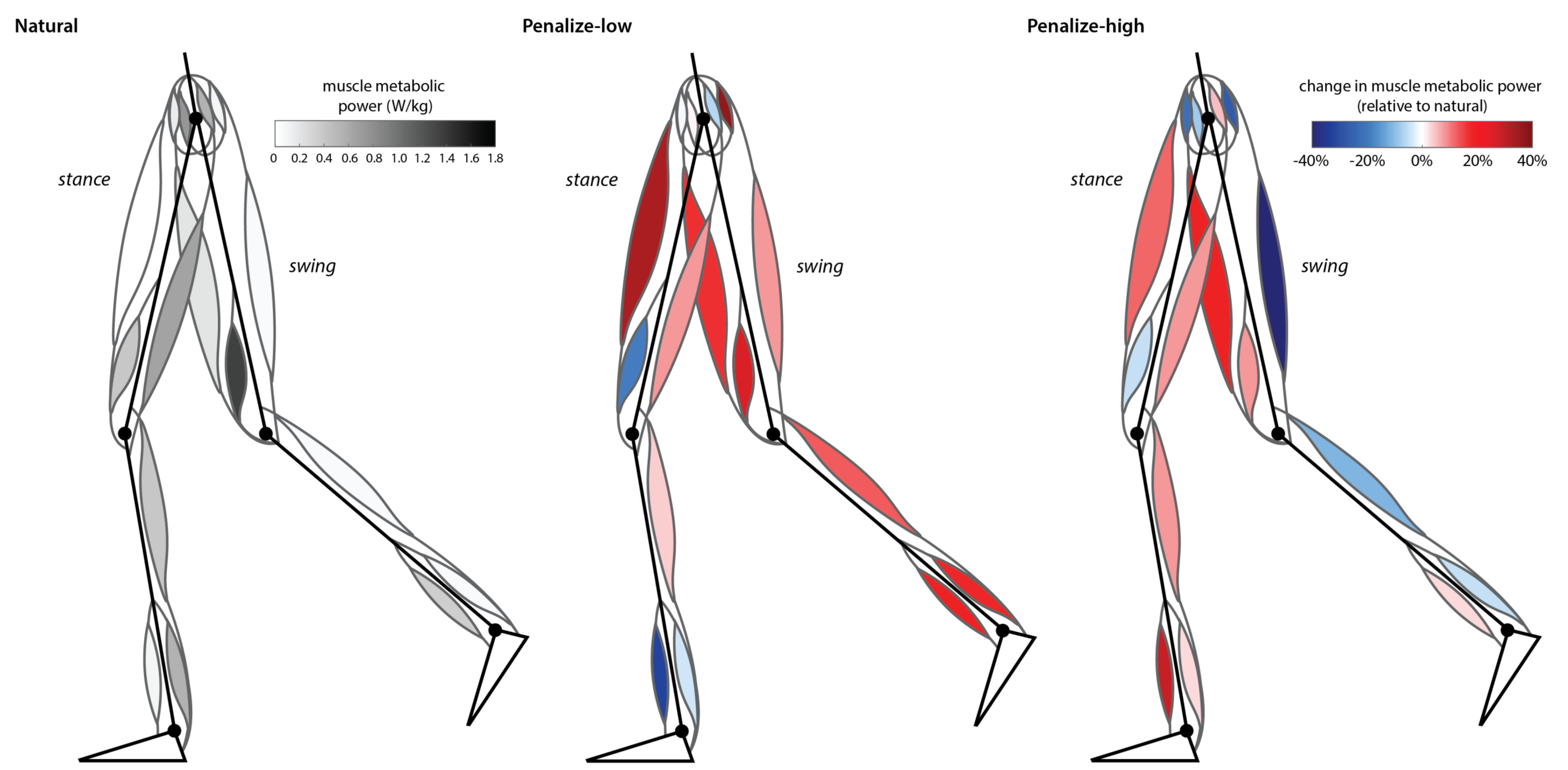


Our simulated exoskeleton torques resembled those from human experiments (AB). These torques changed simulated effort, in a way consistent with our experimental energy landscapes (C).

The optimal step frequency shifted to lower and higher frequencies for the penalize-high and penalize-low conditions, respectively (C).

Results: Muscle Metabolic Work Rate

Absolute muscle metabolic rate for the natural walking condition and the relative changes in muscle metabolic rate for the penalize-low and penalize-high conditions.



The metabolic rate in the vastus and quadriceps, and in stance the hamstrings and gastrocnemius changes similarly in the penalize-high and penalize-low conditions. The metabolic rate in the tibialis anterior, hamstrings in swing and hip muscles change differently.

The metabolic rate is highest in the hamstrings, gluteals and ankle dorsiflexors during stance and in the iliopsoas and vastus during swing

Discussion

We re-created our experimental paradigm where exoskeletons are used to alter preferred and energy optimal gaits using predictive simulations. We were able to replicate the exoskeleton torque applied at the knee joint during gait in simulation, produce effort landscapes with optima at high and low step frequencies, and solve for optimal gaits through adaptations in step frequency.

Using this modelling testbed, we can now explore what particular kinematics of gait or muscles are driving whole body changes in energy expenditure, offering insight into strategies for improved exoskeleton control.

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References

[1] Selinger et al. *Current Biology* (2015).
[2] Winter, *Biomechanics and Motor Control of Human Movement* (2005).
[3] Koelewijn & Van den Bogert. *Gait & Posture* (2016).