# WHY IS THE METABOLIC COST OF LOCOMOTION HIGHER ON SAND?

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## Introduction

Locomotion on sand elicits a higher metabolic cost than on hard ground. Previous work attributes this to two main factors: sinkage into the sand itself, and the structural properties of the human leg. Losses due to sinkage into the sand are conventionally estimated as a function of kinematic properties such as depth, contact area, intrusion force, and ground material properties such as density or grain size. However, at the human muscle level, increased metabolic cost exceeds the expected penalty based on efficiency of positive mechanical work of 0.25. (i.e., more than a x4 penalty). Our previous work *in-silico* suggests that this discrepancy is due to increased MTU length changes and higher CE shortening velocities during locomotion over dissipative substrates, thereby requiring higher muscle activation to meet the force demands of the task. Here, we seek to test these predictions *in-vivo*. We hypothesize the added metabolic cost of hopping on sand is due to unfavourable muscle length and velocity operating points. This study presents the first muscle-level analysis of human locomotion on dissipative terrain and sets the stage for a new paradigm of terrain-capable wearable device design.

## Methods

One participant (height = 1.82m, mass = 80kg) performed a 5-minute resting metabolic trial, followed by 3 maximum voluntary contraction trials of the soleus, tibialis anterior, and gastrocnemius, and then a first full mechanical baseline trial at 2.5Hz on hard ground to a set height and then finally 5 5-minute hopping trials to their preferred height on hard ground at 2.2, 2.5, 2.8, and 3.2 Hz and their preferred frequency in random order. After this, the participant performed 6 5-minute hopping trials to their preferred height on sand at 2.2, 2.5, 2.8 and 3.2 Hz in random order, and then matched the height and frequency of the hard ground mechanical baseline. Metabolic rates were monitored during trials to ensure that participant maintained sub-maximal aerobic effort for each condition, indicated by an RER<1.0. Indirect calorimetry, motion capture, ground reaction forces, surface EMG, and soleus cine B-mode ultrasound were collected. Biofeedback was provided to allow the participant to maintain a specified hop height for the necessary trials. Sand hopping was performed over a custom-built sand pit that uses dry, loose packed poppy seeds as simulated sand, and allowed for self-leveling through a combination of pivot enabled shaker panels and airflow to maintain a constant sand depth. We quantified muscular demand using surface EMG, as well as fascicle velocity and length change profiles using B-mode ultrasound.

## Results and Discussion

Consistent with literature [1,3] and previous modelling and simulation work [2], we found a ~35% increase in metabolic cost at the mechanically matched condition (6.5cm, 2.5Hz) (fig. 1a). Similarly, consistent with previous work, we found a local frequency minimum for the self-selected height trials in sand (2.8Hz) and a trend that mimics that on hard ground, with a constant metabolic offset of ~39%. Increased cost was explained by shorter soleus fascicles (fig. 1c, e) and faster soleus shortening velocities (fig. 1d, f) that were reflected in increases soleus muscle activation (fig. 1b).

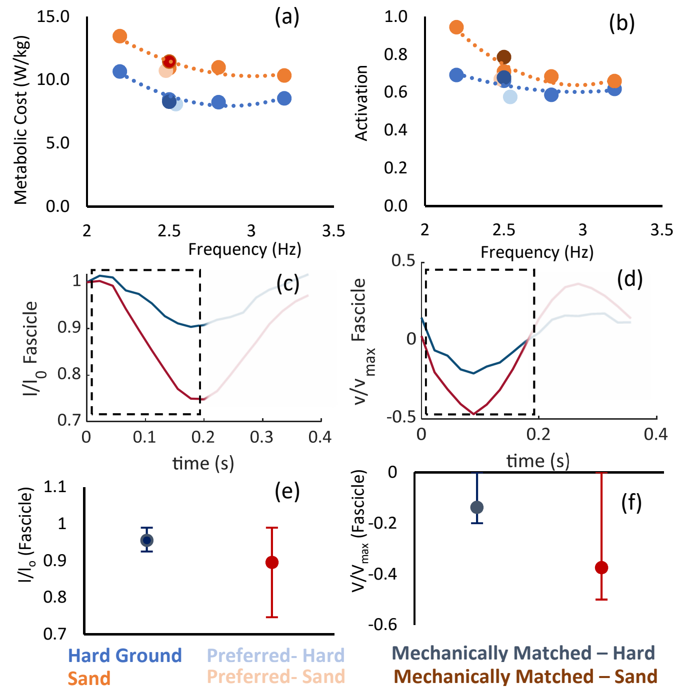


**Figure** 1. Initial data for metabolic cost and soleus (a) activation (b,d) length (length over cycle, max, min average) and (c,e) shortening velocity (velocities over cycle, max, min, average) (d,f). The mechanically matched conditions are used to make controlled comparisons in muscle dynamics on hard ground vs. in sand.

## Significance

Human locomotion on deformable media has been studied for decades, but little has been done at the neuromuscular level to understand why it is more metabolically expensive, particularly when compared to the increased mechanical work required for locomotion in dissipative environments [1]. On the other hand, there have been many studies linking metabolic cost and center of mass, limb-joint and muscle-level neuromechanics on hard ground. Our study begins to bridge this gap, using a customized in-lab apparatus to perform the first comprehensive analysis of the human neuromuscular response to the complex non-linear behavior of propulsion on sand. Additionally, our results provide further evidence that neuromuscular effects that increase active muscle volume (higher fascicle velocities and shorter fascicle lengths) increase net metabolic power [4]. These results will help inform design of wearable devices that can mitigate energetic penalties associated with 'real-world' locomotion over dissipative terrain.

## References

[1] T. M. Lejeune et al, *JEB,* 1998.
[2] J. R. Gosyne, et al in *ASB, 2020*
[3] A. E. Minetti et al, *JTB,* 1997
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