Can mechanical work performed on the body center of mass explain the metabolic cost of walking with a carried load?

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It seems costly to walk while carrying an additional load. A load of 50% body weight results in approximately a 100% increase in metabolic cost [1]. The increase in metabolic cost could potentially be explained by the positive mechanical work efficiency of muscle [2]. But unexplained is how mechanical work increases with load and why. Here we studied how load carriage affects mechanical work and metabolic cost during walking, and experimental results with a dynamic walking model with an elastically suspended load. Elastic suspension can have great effect on how much work is needed to carry a load. Our goal was to use model and experiment to determine whether elastic suspension is a plausible model for a carried load.

Metabolic cost appears to be the result of many factors such as mechanical work and production of isometric muscle force. Previous studies show that mechanical work is roughly proportional to metabolic cost with a positive work efficiency of about 20% [2]. T. Griffin et al [3] showed that net metabolic rate increased about 60 W while carrying 30% body weight as an additional load, comparing to unloaded walking (at 1.0 m/s), yet the rate of mechanical work increased by only 15 W, yielding a delta efficiency of about 25%. They also showed the net locomotor efficiency (external mechanical power/ net metabolic rate) did not change with weight of load. This is not explained by a dynamic walking model with rigid legs, for which mechanical work increases in direct proportion to total mass of body and load. It is not understood why mechanical work increases more slowly with load than the walking models.

Here we measured metabolic cost and mechanical work for healthy people walking with additional loads, and proposed a walking model with suspended load that might explain why mechanical work increases slowly with load. Eight (N = 8) healthy adult subjects were recruited to walk with constant speed, while wearing a backpack loaded with a range of extra weights up to about 45% body mass. Metabolic cost, ground reaction forces and marker-based motion capture data were collected. We calculated Center of mass (COM) work defined as the mechanical work done on the COM by the ground reaction force. The rate of mechanical work was defined as the COM work for each step, multiplied by step frequency.

The elasticity of soft tissues may be one of the reasons why the rate of mechanical work increases slower with load in experiments than with a rigid-legged walking model. We therefore developed the elastic suspended load model to examine the mechanical work of walking with carried load. This model was modified from the arc feet walking model [4] with the addition of a torso supported by an axial spring, held vertical. The model has point masses at the end of the torso, pelvis and center of each leg. Instantaneous push-off impulse is applied right before heel-strike to power the model. A hip spring is used to modulate walking speed and step length, both kept fixed at a nominal value.

We found rate of mechanical work performed on the center of mass was roughly proportional to net metabolic rate with slope 0.20 (figure c), which roughly agree with the efficiency of muscle. The net metabolic rate increased with carried load with slope 0.21 (net metabolic rate/gross mass, figure a). The rate of mechanical work also increased with carried load with slope 0.04 (rate of mechanical work/gross mass, figure b), consistent with previous results in the literature [3]. Examining the walking model, its rate of mechanical work increases much slower than for a model with rigid legs. As the stiffness of the spring supporting the load decreases, the rate of mechanical work increases much slower with load (figure d). This could explain why humans can carry loads while not performing much more additional work.

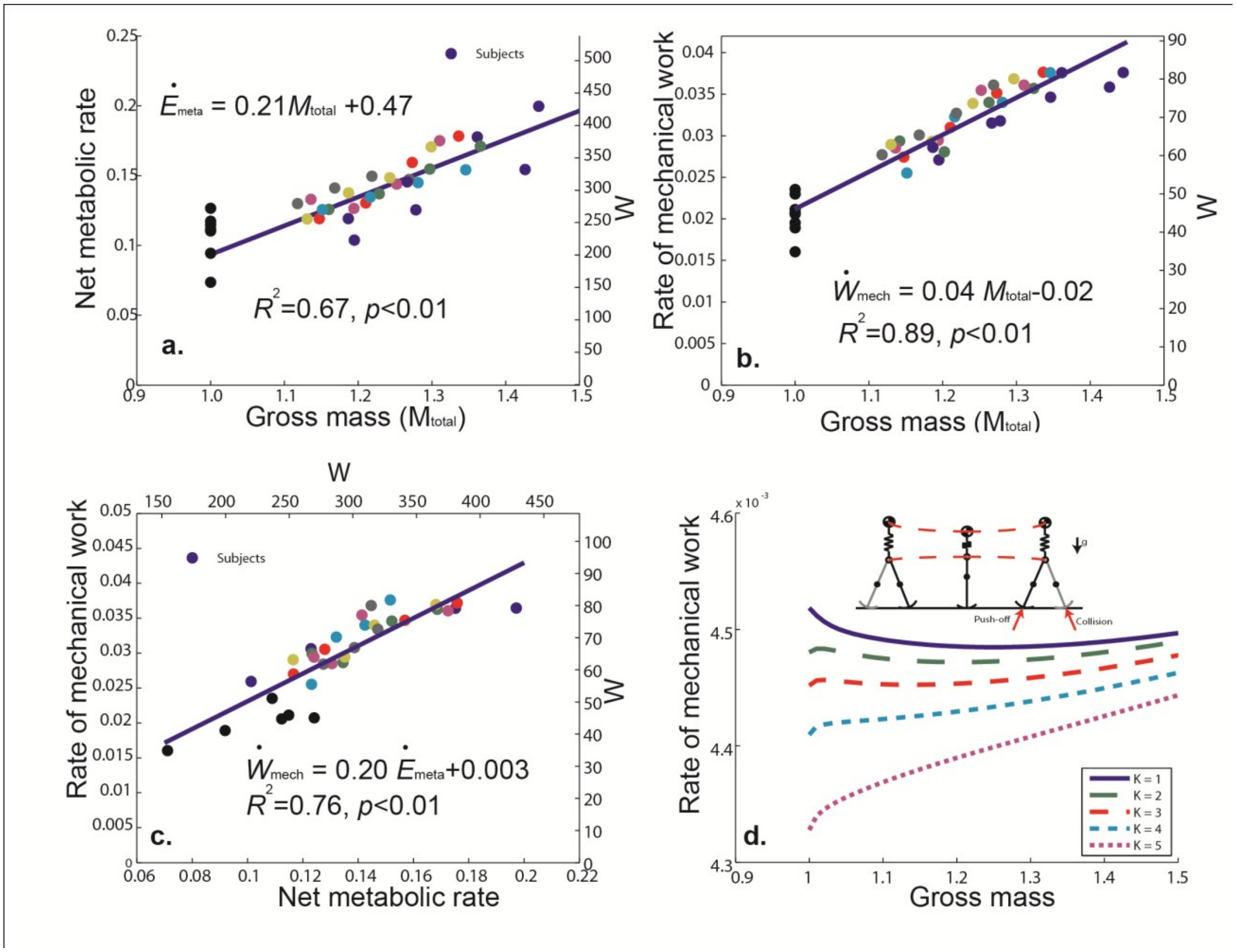

Figure: (a) Net metabolic rate and (b) rate of mechanical work vs gross mass (body mass + load, normalized by body weight). (c) Rate of mechanical work vs net metabolic rate. Least squares linear regression of these data showed linearity. (d) Rate of mechanical work of elastic suspended walking model.

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Reference

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