Predictive Joint Space Model of Human Energy Expenditure during Gait

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1 Motivation

Energy expenditure is an important comprehensive performance measure of human locomotion. Experimental measurement allows us to create predictive equations for use in exercise science and other fields [1, 2]. Simulation of energy expenditure has various biomechanical and physiological implications as well, and can be used both within and outside the scope of experimentally validated gait measurements [3].

2 State of the Art

Energy expenditure is commonly measured experimentally using indirect calorimetry. However, the predictive capabilities of such experimental results are limited by the scope of the experimental data. Additionally, existing measurement tools rely on steady state activity, and are cumbersome for testing motions other than normal gait. Since the oxygen exchange method takes several seconds to register changes in actual energy expenditure, the measurements using this method are also out of phase with reality.

3 Own Approach

We have derived an expression for the rate of energy expenditure from the laws of thermodynamics based on mapping muscle space observations to generalized coordinates in the joint space. This enables energy expenditure to be predicted from kinematics and kinetics of any gait motions, with coefficients related to heat dissipation that can be tuned to individual subjects:

$$\dot{E}(t) = \sum_{i=1}^{n} \left|\tau_i(t)\dot{q}_i(t)\right| + \sum_{i=1}^{n} h_i^{am} \left|\tau_i(t)\right| + \sum_{i=1}^{n} h_i^{sl} \left|\tau_i(t)\dot{q}_i(t)\right| + \sum_{i=1}^{n} \dot{Q}_i^{cc}(t) + \dot{B}(t)$$

where n is the degrees of freedom, $\tau(t)$ is the actuator torque, $\dot{q}(t)$ is the angular velocity, h_i^{am} is the coefficient of the generalized activation and maintenance heat, h_i^{sl} is the coefficient of the generalized shortening-lengthening heat, $\dot{Q}_i^{cc}(t)$ is the energy expenditure rate due to baseline and excessive cocontraction, and $\dot{B}(t)$ is the basal metabolic rate. Through full body motion capture and metabolic energy expenditure analysis (Fig. 1: Human testing), the heat coefficients are estimated and the resulting model is demonstrated during walking with various gait parameters.

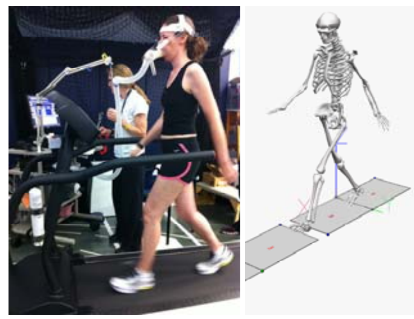

Fig. 1: Human testing and inverse dynamics

4 Current Results

The heat coefficients were initially assumed to be homogenous across the degrees of freedom, and were estimated from experimental gait data.

Table 1: Model Estimation Results

Parameter	*Value*
B (W)	75
E (W)	263
h^{am}	0.1
h^{sl}	0.219

5 Best Possible Outcome

The final outcome of this research is a completely predictive joint-space model for human energy expenditure during locomotion with different gait parameters.

Acknowledgement

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References

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Robotic Energy Expenditure with Implications in Humanoid and Human Gait

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1 Motivation

Modeling energy expenditure in a robotic system enables control through minimizing energy expenditure for a given task [1]. This is particularly important for walking robots and prosthetic joints [2] where extended operating times are desirable but sub-optimal movement patterns can lead to unnecessary energy expenditure. Furthermore, an energy expenditure model as a function of dynamic parameters will provide a reliable method for design and planning of locomotion, and can be used to represent more realistic cost of transport.

2 State of the Art

Electrical energy expenditure for a DC motor actuated system can be experimentally measured from the current and voltage usage during a given task. However, as for dynamic models of energy expenditure, incorporating the effects of negative mechanical work is not consistent in the literature [1, 3]. Negative work is common in manipulator and humanoid gait movements, so modeling energy expenditure correctly in this phase is critical. Similar problems can be found in human gait, in which the metabolic energy expenditure during negative work phase of walking is not well formulated in the literature.

3 Own Approach

The laws of thermodynamics are used to identify the energy expenditure of a robotic system during negative, as well as positive work. While some of the energy expenditure of the system is attributable to mechanical work, the rest is dissipated as heat in various forms (Fig. 1). The mathematical model of the total robotic energy expenditure rate as a function of dynamic variables (joint angles and velocities) and system parameters (inertia properties and motor constants) is established, in which the effects of the negative work is incorporated in a uniform approach. For mobile or humanoid robots, the results can be used to determine realistic cost of transport. Our fundamental model is also applied to human gait, where human-specific system parameters (e.g., metabolic heat coefficients) are included.

4 Current Results

As an illustrative example, a 2-DOF robotic arm during the task of drawing a vertical line while in two separate configurations that required different amounts of negative work is demonstrated both experimentally and computationally (Fig. 1). (The results for human gait are in a separate abstract.)

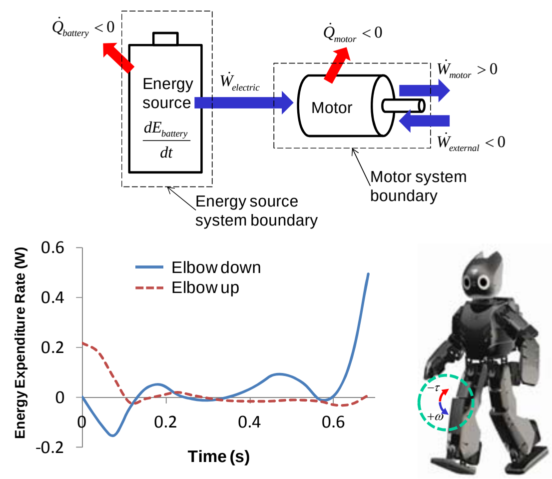

Figure 1: DC motor energetics, 2-DOF robotic arm results, and humanoid gait experiment.

5 Best Possible Outcome

The predictive dynamic model for energy expenditure in DC motor actuated systems is experimentally validated with a walking robot (Fig. 1).

Acknowledgement

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References

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