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Balance Stability and Energy Efficiency: Towards the Analogy between Robotic and Human Gait through Unified Models

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1. MOTIVATION AND STATE OF THE ART

Robotic biped locomotion provides advanced mobility, flexibility, and collision-avoidance that can be extended to rough irregular terrains and civil structured environments. Although the performance (functionality, stability, and efficiency) of robotic biped locomotion has been studied using various approaches with remarkable recent achievements [1,2], it is still far away from what is expected for practical applications. Since biped locomotion is a unique capability of humans by origin, benchmarking human gait is a conceivable approach for the design and control of humanoid robots. In this presentation, the stability and efficiency of biped walking, which are associated with the passive dynamic nature of normal human gait [3], are discussed for robots and humans along with their unified models.

2. BALANCE STABILITY AND CRITERIA FOR LEGGED MECHANISMS

The balanced state domain is the domain in phase space of states other than falling or fallen, such that at least one feasible phase trajectory brings any initial state in the domain to a final state of static equilibrium in the domain, while maintaining the zero-moment point within the foot support region under no-slip condition and actuation limits. These explicit forms of necessary and sufficient conditions for balancing are incorporated into a multiple-loop nonlinear constrained optimization problem for a multi-segmental single-support legged mechanism (Fig. 1) to construct the balanced state domain. The numerically constructed balanced state manifold [4,5] along with the gait phase trajectories of a robot

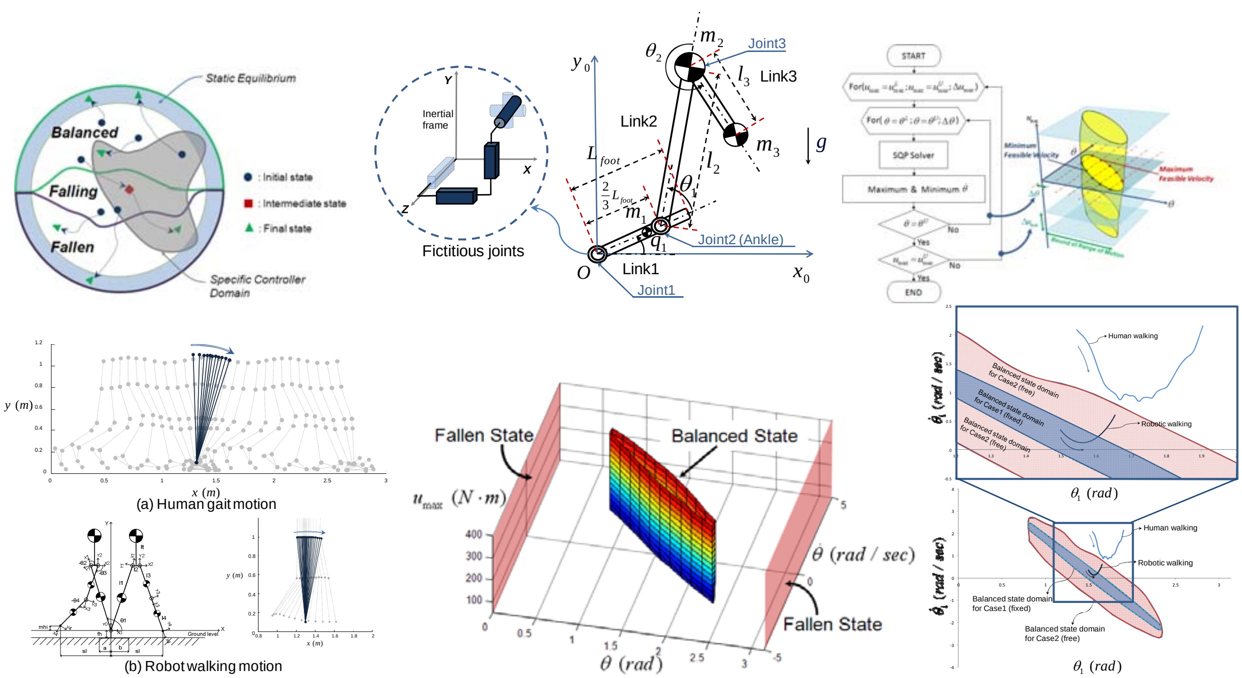

Fig. 1. Balanced, falling, and fallen states (top left); multi-segmental legged mechanism (top center); algorithm flow chart (top right); human gait experiment and robotic gait simulation (bottom left); numerically constructed balanced state manifold (bottom center); and gait phase trajectories on the domains for fixed and free segment (bottom right).

(simulations) and a human (experiments) demonstrate the dynamic nature of normal human walking with self-selected speed and step length and mainly statically-stable robotic gait. Also, the positions and ranges of the phase trajectories indicate that the human body is tilted more in anterior direction during single support phase of normal human walking, which results in falling-like attributes and larger gait velocity at the cost of stability, and demonstrates passive dynamic walking [3,6].

3. ENERGY CONSUMPTION MODELS FOR COST OF TRANSPORT

The energy consumption of a general multibody dynamic system is formulated in terms of dynamic parameters and variables using the laws of thermodynamics and generalized coordinates. The system-specific characteristics of actuators for robot and human energetics are incorporated into the general model. The model parameters are estimated from experiments (Fig. 2) and the resulting energy consumption models are validated. For robot, the mappings of torques and velocities from the generalized coordinates to DC motor actuator space are implemented into the energy consumption rate $\dot{E}(t)$ for each actuator [7]:

$$\dot{E}(t) = \tau(t)\dot{q}(t) + \frac{R}{k_M^2}\tau^2(t) + \frac{L}{k_M^2}\tau(t)\dot{\tau}(t)$$

where $\tau(t)$ is the torque, $q(t)$ and $\dot{q}(t)$ are the angular position and velocity of the motor shaft, respectively, R is the electrical resistance, L is the motor winding inductance, and k_M is the motor constant. For human, the energetic characteristics of musculotendon system and the activation dynamics [8] are mapped to the joint space, and the resulting metabolic energy consumption for each joint is:

$$\dot{E}(t) = \tau(t)\dot{q}(t) + \frac{h^{am}(q,\dot{q})}{\tau^{max}}\left|\tau(t)\right| + \frac{h^{sl}(q,\dot{q})}{\tau^{max}}\left|\tau(t)\dot{q}(t)\right| + \dot{Q}^{cc}(t)$$

where τ^{max} is the maximum joint torque, h^{am} and h^{sl} are the generalized coefficient functions for activation-maintenance heat and shortening-lengthening heat, respectively, and $\dot{Q}^{cc}(t)$ is the generalized excessive cocontraction heat rate. The costs of transport for robotic and human gait derived using these models are the functions of kinematic and kinetic variables, which allows the assessment of the gait efficiency performance before (through simulations) and after (using only kinematic and kinetic experimental data without direct measurement of electric power or oxygen uptake) experiments using robotic prototypes or human subjects.

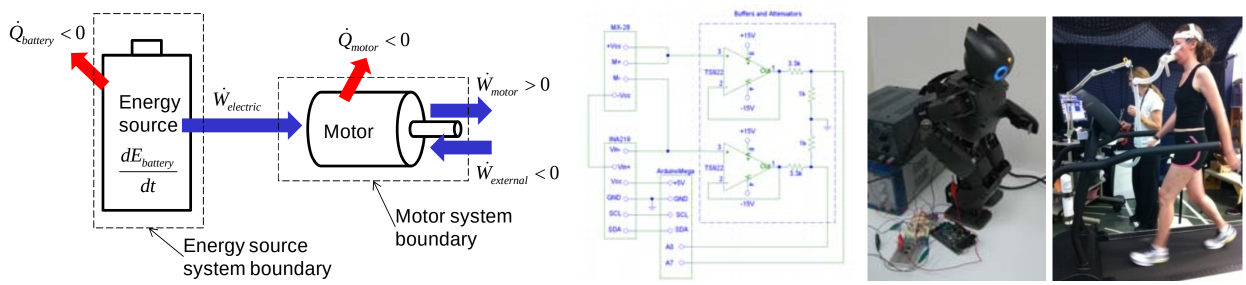

Fig. 2. Actuator energetics (left); experimental power measurement of robotic (electric) and human (oxygen) gait.

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