The Influence of Inter-joint Force-dependent Feedback on Whole Limb Impedance Over a Range of Frequencies

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Introduction
Neural feedback pathways arise from a variety of sensory receptors. Muscle spindles measure changes in length and velocity, while Golgi tendon organs measure contractile force. Understanding the functions of these pathways is important because they become disrupted in stroke and Spinal Cord Injury. While length and velocity-dependent pathways are relatively localized, force-dependent feedback is asymmetric and can be widely distributed within the limb.

Although the muscle-level distributions of force feedback have been measured under different conditions, it is not known how these distributions regulate limb mechanics (stiffness and interjoint coordination). We analysed the frequency dependent impedance properties and interjoint coordination of a cat hindlimb with intrinsic musculoskeletal impedance. Our hypothesis was that force feedback would reduce whole limb impedance and promote proportional coordination between the knee and ankle.

Methods
We developed a three segment model with realistic lengths and masses [1], with muscles represented as rotational springs and dampers, whose values are based on our physiological best guess, as shown below. The rest angles of the springs were chosen as weight acceptance during landing as defined in [2]. Force feedback was implemented as a generalized torque at the joints in addition to the spring and damper torques, and the values of these torques were calculated at each time step using the following equation, where $\tau_{fb,n}$ is the force feedback torque, $[\alpha]$ is a 3x3 matrix of force feedback gains, $[K]$ is the stiffness matrix, and $[B]$ is the damping matrix:

$$\tau_{fb,n} = [\alpha] \ast ([K]\{\Delta\theta_{n-1}\} + [B]\{\dot{\theta}_{n-1}\} + \tau_{fb,n-1})$$

We performed a sinusoidal analysis based on the study in [3] adapted here to the whole limb. We applied an endpoint force whose average value was 60N directed at the hip joint center. Using a technique in [4], we calculated the apparent impedance properties and proportionality cost, defined as the integral of $((\theta_k - \theta_\omega) - (\theta_a - \theta_\omega))^2$ over time for one sinusoidal cycle, over a range of frequencies for the uni-articular musculoskeletal distribution and two experimentally observed force feedback distributions between the ankle and knee [5].

As expected, all of the impedance values were lower for the proximal to distal distribution of force feedback than for the uni-articular musculoskeletal distribution without force feedback. However, contrary to our hypothesis, these impedance values were higher for the distal to proximal force feedback distribution than for the uni-articular musculoskeletal distribution. Examining how force feedback influences the relative contributions of the joint torques to the overall limb force response will elucidate the reason for this outcome. Also contrary to our hypothesis, the proportionality cost was lowest for the uni-articular musculoskeletal distribution without force feedback.

Significance
Patients with stroke and Spinal Cord Injury have impaired knee and ankle coupling compared to able-bodied humans. Therefore, understanding how force feedback influences interjoint coordination, and not only limb impedance, could inform the design of therapeutic and rehabilitation techniques (ex. robotic devices, drug therapies, surgeries).

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References