Towards a Testbed for Robotic Neuromuscular Controllers

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I. Introduction

Current control approaches to robotic legged locomotion rely on centralized planning and tracking or pattern matching of predefined joint motions extracted from normal human gait. The first approach is used in humanoids [1], but cannot be applied to robotic assistive devices where the central state of the human user is unknown. The second approach, common to rehabilitation robotics, enforces a limited set of pre-defined motion patterns [2], which severely limits a user's functional dexterity. To improve dexterity, motion libraries have been combined with pattern recognition techniques to control speed and slope adaptation in prosthetics [3]. However, control strategies that generate the stability, maneuverability, and adaptability seen in biological systems have not been identified.

Biological systems realize dexterous segmented leg performance largely via local feedback controls that bypass central processing, and by biomechanical structures that encode functional leg responses [4,5]. Recent neuromuscular models controlled by autonomous local feedbacks without central planning adapt to their environment and show substantial robustness of locomotion [6,7]. Part of this feedback control has been implemented in a powered ankle-foot prosthesis, enabling it to adapt to the environment without requiring explicit terrain sensing [8].

Fig. 1: Robotic testbed development. (L) Major human leg muscles with monoarticular knee extensor and biarticular knee flexor highlighted. (C) Testbed concept. (R) Current robotic implementation of RNL. Thigh coupled to cage for experiments.

Generalizing neuromechanical controllers to powered segmented legs has the potential to greatly improve the functional dexterity of users that rely on robotic rehabilitation devices. We present initial development steps of a robotic gait testbed to implement and test neuromuscular controllers for robotic assistive devices (Fig. 1). The current implementation of the robotic neuromuscular leg (RNL) is a half-human sized, two segmented, antagonistically actuated leg with joint compliance. The electromechanical design of RNL is driven by three themes: dynamic similarity, antagonistic actuation, and leg compliance.

II. Dynamic Similarity

	Human	RNL	Scaling Factor
Leg Length (*m*)	1	0.5	1/2
Thigh Length (*m*)	0.46	0.23	1/2
Shank Length (*m*)	0.54	0.27	1/2
Knee Radius (*m*)	0.06	0.03	1/2
Total Mass (*kg*)	80	20	1/4
Thigh Mass (*kg*)	8	2	1/4
Shank Mass (*kg*)	3.7	0.9	1/4
Foot Mass (*kg*)	1.2	0.3	1/4
Vastus Max Force (*N*)	6000	1500	1/4
Vastus Max Velocity (*m/s*)	0.96	0.68	√2/2
Hamstring Max Force (*N*)	3000	750	1/4
Hamstring Max Velocity (*m/s*)	1.2	0.84	√2/2
Max Joint Torque (*Nm*)	368	45	1/8
Max Joint Velocity (*rpm*)	153	217	√2

Tab. 1: Human & RNL performance limits and scaling factors.

For cost and safety considerations, we target a testbed that is half the size and a quarter of the weight of a human leg. To ensure that the dynamic behavior of RNL matches human legs, we use dynamic scaling and define actuator performance envelopes based on human physiology for major leg muscles. RNL design targets and corresponding human limits are summarized in Table 1.

III. Antagonistic Actuation

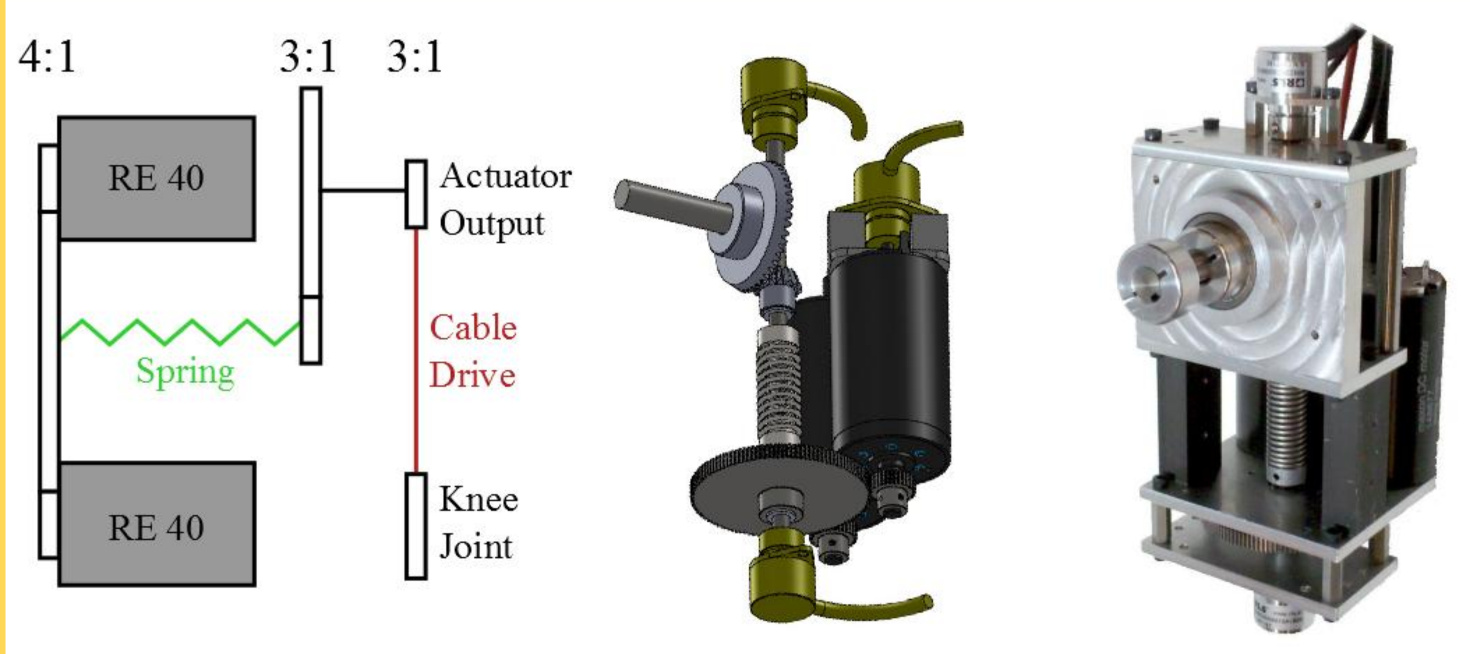

Fig. 2: RNL SEAs. (L) Drivetrain schematic. (C) Drivetrain assembly. (R) Prototype.

RNL incorporates antagonistic actuation using cable driven SEAs, which simultaneously enable passive dynamics by providing the ability to actively command zero joint torque, satisfy human mass distribution, and allow actuation across compliant joints. RNL's SEA configuration was optimized to meet dynamically scaled human muscle performance envelopes (Tab. 1). The actuators utilize parallel actuation and are designed to provide a maximum joint torque of 45*Nm* and enable robot joint velocities up to 217*rpm*.

IV. Leg Compliance

Fig. 3: Floating compliant joint. (L) Concept. (C) Prototype. (R) Implementation.

Humans are not rigidly coupled kinematic chains, possessing interjoint cartilage and soft tissue around bones. To capture this aspect in RNL, we incorporate a floating compliant joint design into the robot (Fig. 3). Structural compliance provides increased shock tolerance to unexpected disturbances, further decouples motor and load inertia during impacts, and enables us to incorporate force sensing to provide local feedback for neuromuscular controllers.

V. Velocity-Based SEA Control

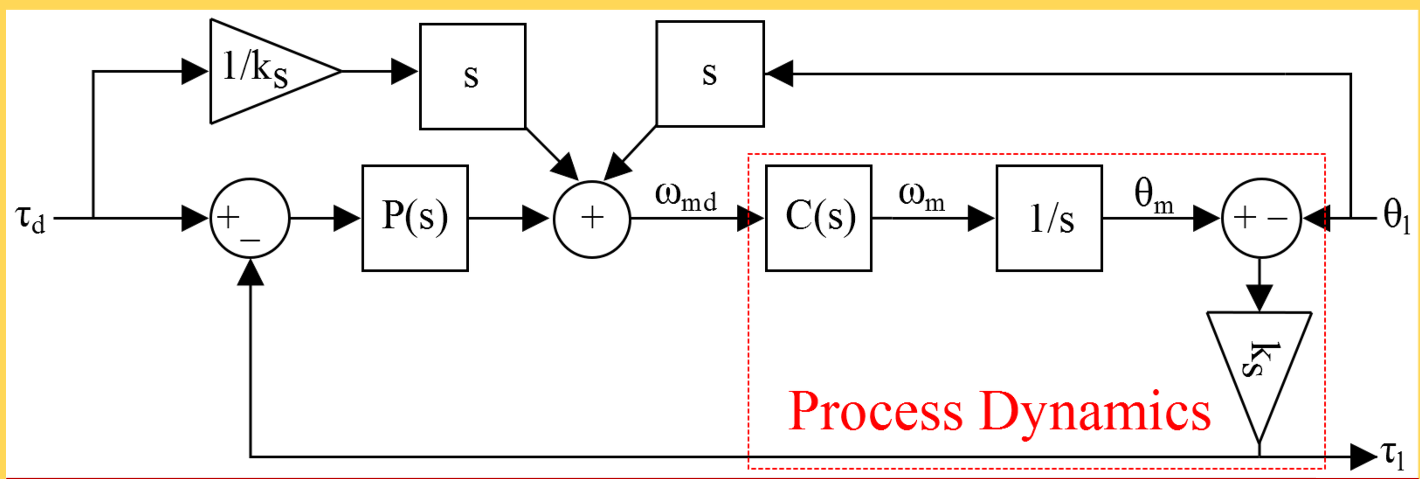

Fig. 4: Velocity-based SEA control system model.

RNL's SEAs generate joint torques using a velocity-based SEA control scheme. Velocity-based torque control automatically compensates for frictional losses in the drivetrain. Additionally the controller's inverse dynamics terms only require the first derivative of motor position, leading to increased system bandwidth. Unlike current velocity-based SEA control implementations [9], our formulation (Fig. 4) does not require load inertia to be known or fixed. This is advantageous because load dynamics for legged systems are not known, but are constantly changing due to joint position and gait phase.

V. Experimental Results

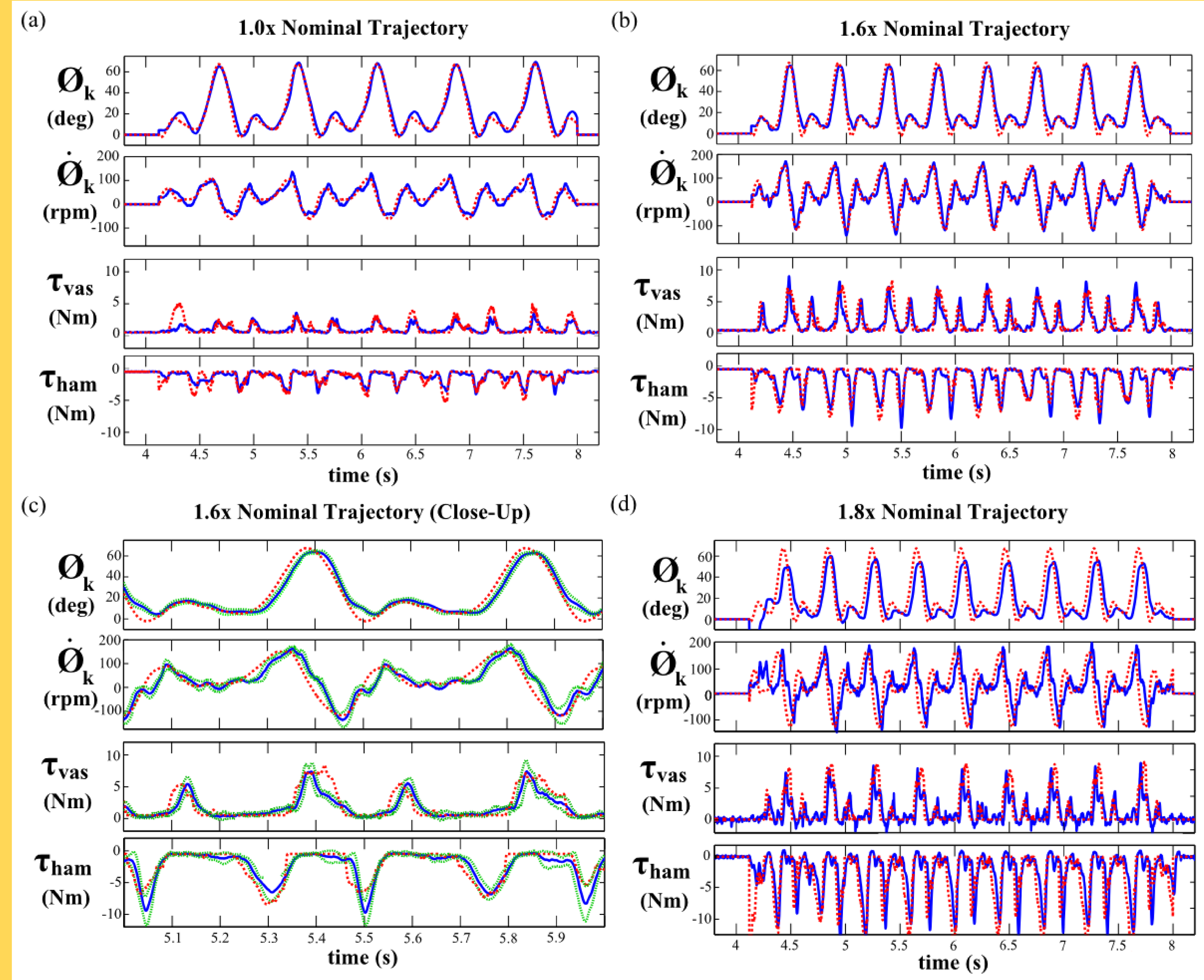

Fig. 5: RNL leg motion trajectory tracking results for 1.0-1.8x nominal walking speed.

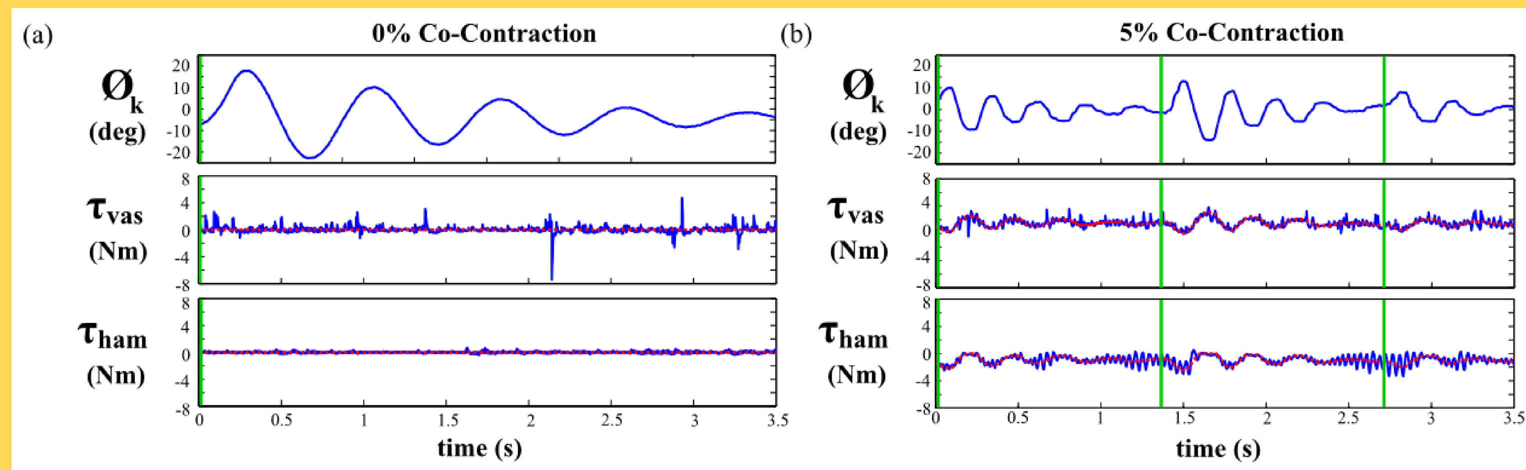

Fig. 6: RNL leg motion during 0% and 5% maximum actuator torque co-contraction.

To verify if RNL's design and control implementation achieves human-like performance, we devised two experiments. In the first experiment, we used biomechanical data of human walking to generate RNL knee joint trajectories that correspond to speeds between normal human walking speed (1.0x) and the theoretical maximum knee joint velocity (2.0x). We observed that RNL tracks joint positions with high fidelity up to 1.6x, and joint velocity with high fidelity up to 1.8x (Fig. 5). In the second experiment, we tested antagonistic co-contraction. We calculated actuator pre-load torques and knee rotational stiffnesses corresponding to vastus co-contraction at human muscle activation levels between 0-15% and compared RNL's behavior to that of an equivalent driven physical pendulum. RNL tracks zero torque (0% co-contraction) within the resolution limits of the SEAs (Fig. 6). Higher levels of co-contraction were possible, but produced oscillations in SEA torque patterns due to low shank mass.

VI. Future Work

Our goal is to expand RNL into a robotic gait testbed to implement and test neuromuscular controllers for robotic assistive devices. As a next step, we hope to expand the current RNL implementation to incorporate three actuated joints, one each for the hip, knee, and ankle. We are currently pursuing nonlinear spring designs for the custom SEAs to improve torque resolution at low commanded torques while maintaining high bandwidth at large torques.

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