Integration of Musculoskeletal Analysis with Engineering Design for Virtual Prototyping of Exoskeletons

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INTRODUCTION

Human-worn exoskeletons have the ability to both augment the physical capacity of its wearer and assist in rehabilitation therapy. Design of these devices that physically interact with the human user is challenging because of user safety and comfort requirements in addition to typical robot performance measures (e.g. quick response, back-driveable etc.). Ultimately, models of the musculoskeletal and mechanical systems need to be combined so that the performance of the integrated human-exoskeleton system can be evaluated and optimized using computer simulations. We propose a novel framework for virtual prototyping of exoskeletons by merging musculoskeletal analysis with simulation-based engineering design. The framework provides a platform in which the design and control algorithm of exoskeletons can be iteratively optimized using three distinct types of performance measures—biomechanical, morphological, and controller. We present a case study that develops a virtual prototype of an index finger exoskeleton to illustrate the application of the framework using the OpenSim environment.

METHODS

Virtual Prototyping Framework

The framework provides a synergistic platform for developing and refining the engineering design and control algorithms for exoskeletons. With combined analysis of the musculoskeletal, mechanical and control systems, measures from the musculoskeletal model (e.g. muscle forces etc.) quantify the biomechanical performance, measures characterizing the physical design (e.g. stiffness etc.) of the exoskeleton (e.g. coupled system range of motion etc.) define morphological performance, and measures quantifying the performance of the exoskeleton controller (e.g. steady-state tracking error etc.) define controller performance.

The virtual prototyping framework consists of the following steps (Fig. 1): (1) Virtual Design: develop an initial coupled exoskeleton-limb musculoskeletal model along with a controller. Identify the key biomechanical, morphological, and controller performance measures and a desired motion trajectory for the coupled model. Refine the coupled model using experimental data to improve its fidelity. Iteratively optimize the biomechanical or morphological performance measures or both while reproducing the desired motion trajectory. (2) Virtual Control: iteratively develop and refine control algorithms for the coupled system and optimize the controller performance measures while tracking the desired motion trajectory. (3) Virtual Experimentation: study specific “what-if” scenarios (e.g. specific muscle impairments in a patient) and modify design and control to improve performance. The presented framework can offer significant value not only for traditional hypothesis testing such as functional muscle group studies, but also for effective design, control, experimentation, and performance enhancement of exoskeletons with quantitative performance evaluation leading to shorter development life cycles.

Finger Exoskeleton Prototyping Case Study

We model and analyze an index finger exoskeleton system with the specific goal to identify the role of spring elements in achieving more comfortable interactions with the device and to accommodate
A coupled finger-exoskeleton model was developed in OpenSim using the index-finger model [1] having wrapping surfaces and 4 Hill-type musculotendon actuators to closely resemble the preliminary prototype of the device (Fig. 2). Passive rotational stiffness was added at the three index finger joints to represent the passive torques due to ligaments and other structures. In addition, linear springs (k1-k4) coupling the various exoskeleton links were added to the model. We treated the three actuated tendons on the exoskeleton (exotendons) as the force generating elements and modeled them as musculotendon units. Their optimal fiber length was chosen such that the actuators can generate a wide range of forces over the exotendon excursions corresponding to the range of motion for the finger joints. To improve model fidelity, we also optimized (using an interior-point algorithm) the moment arm of each muscle individually by altering the muscle path based on experimental measurements [2].

Virtual design is carried out using Computed Muscle Control (CMC) analysis of the optimized model with sinusoidally varying finger joint angles as the desired flexion-extension motion trajectory in OpenSim. Also, a constraint was imposed on the maximum excitation of the index finger muscles to simulate a pathological finger. CMC analysis was carried out by changing the exoskeleton spring stiffness (k1-k4) to study its effect on muscle/exotendon forces, joint reaction forces, and joint angle tracking. A “what-if” study was performed to investigate how changing the upper limit on the excitation of the finger muscles (e.g., representing an improvement in a recovering finger) can be simulated to gain insight into the finger-exoskeleton interactions.

RESULTS AND DISCUSSION

Figure 3 presents the required actuator forces obtained using CMC for the tracking task. Finger muscle forces were generated due to their passive stretching. However, the majority of the forces were applied by the exotendons. Furthermore, increasing the stiffness of the exoskeleton resulted in better tracking of the joint angles, but with increased exotendon forces and joint reaction forces.

CONCLUSIONS

We presented a framework for virtual prototyping of exoskeletons using musculoskeletal analysis and simulation-based design. Modeling and simulation of the coupled index finger and exoskeleton system led to the quantification of the exoskeleton performance in ways not possible with isolated mechanical models. The framework is generalizable to a wide range of exoskeleton systems designed for both augmentation and rehabilitation. In future work, we plan to apply this framework to optimize the design and controller of a wrist-hand exoskeleton.

REFERENCES