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Multibody System Dynamics: A Fundamental Tool for Biomechatronic System Design

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EXTENDED ABSTRACT

1 Introduction

Humans are unique in our ability to create and use advanced tools. Today's mechatronic tools are more complex than ever, involving advanced computer control of systems of interconnected components from mechanical, electrical, and other physical domains. Human dynamics and motor control are even more complex; understanding the dynamic interactions between humans and their machines is critical to designing biomechatronic systems, which include rehabilitation robots, automotive systems, assistive devices, sports equipment, and exoskeletons. The U.S. Food and Drug Administration has recently endorsed the use of computer models to design new medical devices, in order to reduce the expensive and time-consuming design iterations of physical prototyping and testing [1]. Multibody system dynamics is an ideal tool to support the growing demand, partly driven by aging demographics world-wide, for a new generation of biomechatronic systems. Here, we discuss the application and research challenges of using multibody system dynamics to design, model, and control human-machine systems.

2 Multibody dynamic modelling and simulation of biomechatronic systems

Given that the goal is to design and control a human-machine system, it is desirable to have a single unified system model. Unfortunately, many multibody dynamic programs are targeted either for humans without closed kinematic chains (e.g. AnyBody or OpenSim) or for machines (e.g. MSC.Adams or MapleSim). In our experience, it is easier to add a library of musculoskeletal components to the latter, which are already capable of solving the differential-algebraic equations (DAEs) of motion, than to incorporate machines and kinematic constraint equations into the former. Shown in Figure 1 are examples of unified multibody dynamic system models, created using the MapleSim software, that were subsequently used to optimize the design of a stroke rehabilitation robot [2], a lower-limb exoskeleton [3], and the bicycle and pedaling strategy used by an Olympic cyclist [4].

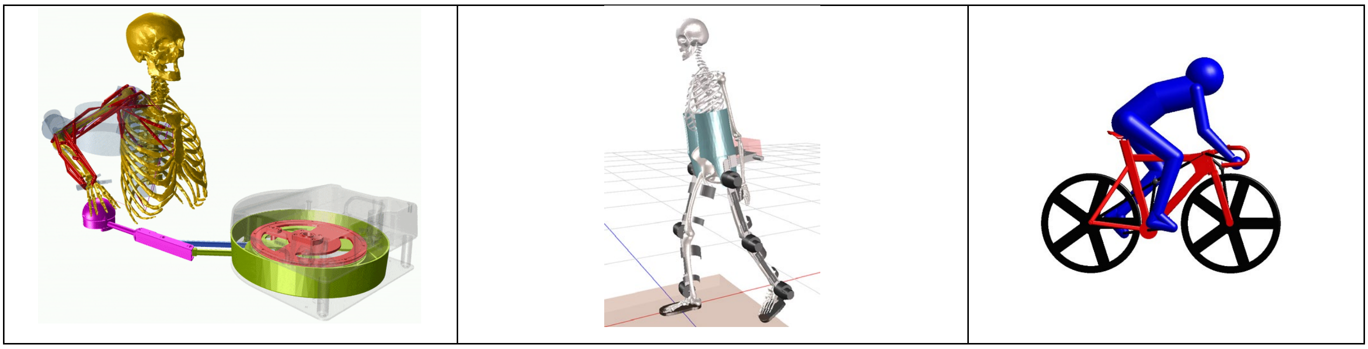

Figure 1: Multibody dynamic models of human-machine systems: rehabilitation robot [2], exoskeleton [3], Olympic cyclist [4]

Once a system model has been created, predictive dynamic simulations can be used to explore different "what-if" scenarios in order to optimize the machine design or controller. Optimal control theory is well-suited to the solution of this problem, but one must know what is the underlying cost function being optimized [5]. This is usually easy to determine for athletes, where the cost function is often "faster, higher, stronger" (the Olympic motto), but much more difficult to determine for activities of daily living such as walking, reaching, or standing up from a chair. In the next section, we present a case study in which multibody system dynamics and predictive simulations were used to optimize the design and control of a biomechatronic device.

3 Real-time model-based control and design optimization: a case study

Multibody system dynamics was used to create a single unified model, shown in Figure 2(a) of a human and upper-limb exoskeleton. To the authors' knowledge, this is the first upper-limb exo that combines passive and active sources of assistance to the user [6]. An exo with passive assistance (e.g. a spring) is only effective for certain postures; a purely-active exo can be quite heavy due to the weight of motors and batteries. Our goal was to provide an optimal combination of passive and active assistance to the user. This was achieved by: (1) adding appropriately-sized motors to an existing passive exo from Ekso Bionics, (2) determining the torque provided by the user using electromyography (EMG) sensors and machine learning, and (3) augmenting the user torque as appropriate with a real-time control system. Multibody system dynamic simulations were used to optimize the exoskeleton design and controller before testing on humans. The results are shown in Figures 2(b-d), which show the reduction in fatigue for the active-passive exo, compared to an inactive exo providing no assistance, a fully passive exo, and a fully-active exo that required heavier motors and batteries (which was more fatiguing) than the active-passive solution.

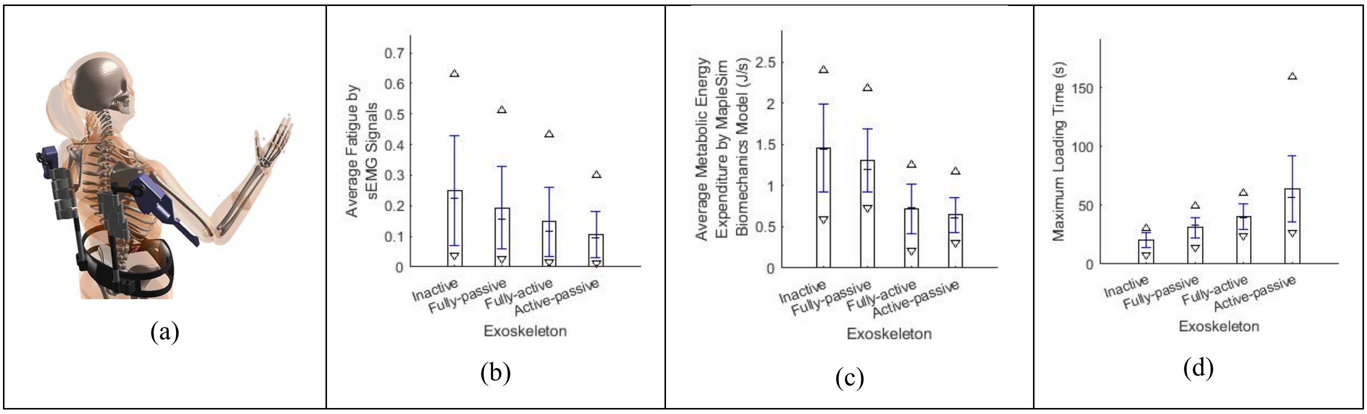

Figure 2: Multibody dynamic model of passive-active upper-limb exoskeleton (a), and reduction in user fatigue evaluated using EMG signals (b), computed metabolic energy (c), and time that user can hold up a weight (d)

4 Research Challenges

Multibody system dynamics is well-suited to the modelling, design, and optimization of human-machine systems, but there are many research challenges facing the model-based creation of new biomechatronic devices, including:

- User-friendly multibody dynamics software that can create unified models of human-machine systems, including components from neuromusculoskeletal, mechanical, and electrical domains, should be developed.
- New models of the contact dynamics between semi-rigid machines and soft human tissue are needed.
- Current exoskeletons often assume that mechanical joints are aligned with human joint axes. Multibody dynamics could be used to develop new kinematic designs for wearable robots that accommodate the complexity of human joints, e.g. an exoskeleton that facilitates the shift in the knee joint center during flexion/extension.
- To facilitate the real-time control of human-machine systems, fast solutions to the DAEs of motion are required.
- Models of the human motor control system are needed to guide predictive dynamic simulations (e.g. by identifying an underlying cost function) and to model how a human adapts to a mechatronic device over time.
- Engagement with health care professionals to create and evaluate patient-centered solutions may be biggest challenge.

Acknowledgments

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