The 6th Joint International Conference on Multibody System Dynamics and
The 10th Asian Conference on Multibody System Dynamics
October 16-20, 2022, New Delhi, India

Multibody Constrained Dynamic Modelling of Human-Exoskeleton: Toward Optimal Design and Control of an Active-passive Wearable Robot

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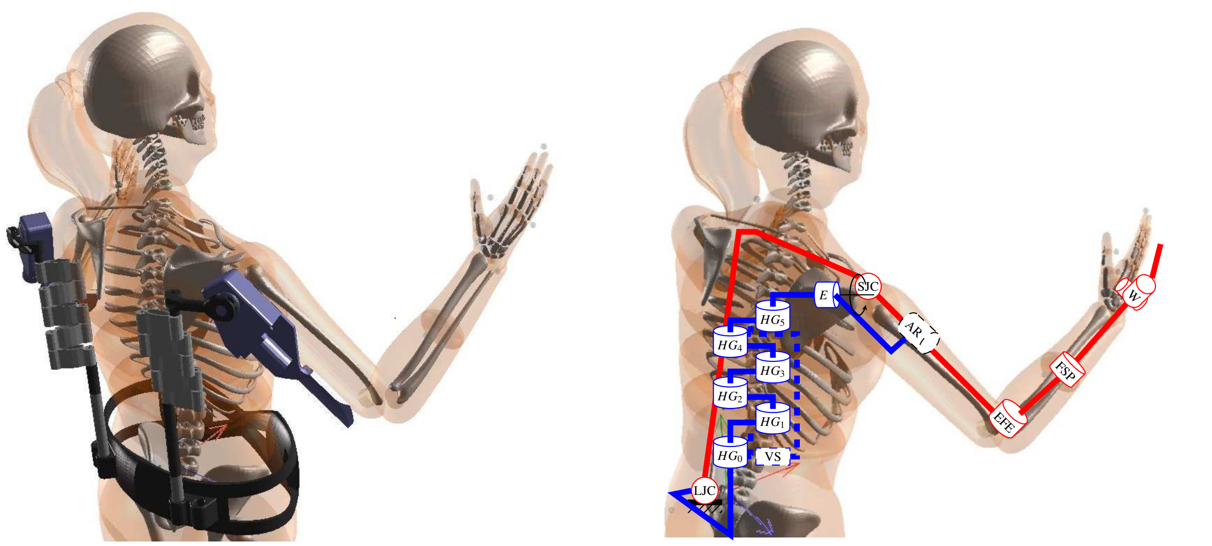
Abstract

Wearable exoskeletons improve human performance by assisting human motions, reducing user effort, fatigue, and the risk of work-related musculoskeletal injuries [2]. Actuator design, performance evaluation, and control of an exoskeleton necessitates a thorough understanding and modeling of 6 sub-models: the human musculoskeletal system, the human coordination by the central nervous system (CNS) [3], the robot dynamics (links, joints, and power transmission), the human-robot contact-and-interaction system [3], and the human-robot closed kinematic chain [2]. This study aims to develop a method for dynamically synthesizing an active-passive exoskeleton.

The human body was modeled using a scalable musculoskeletal (MapleSim) model, which was developed and validated using experimental dynamometer data for dynamic simulations of movement. The upper body model has 20-DoF and is made up of 8 body segments. The MapleSim model consists of skeletal dynamics and a biomechanical joint torque model. Muscle torque generators were used to create a biomechanical joint torque model that includes six functions: passive torque, peak joint strength, active-torque-angle scaling, active-torque-angular-velocity scaling, and activation dynamics. The human body coordination by CNS was mimicked by using nonlinear model predictive control (NMPC) to predict optimal motion and correct prediction errors [3].

We modeled the rigid links, the joint configuration, and the passive torque of the EVO upper limb exoskeleton (Ekso Bionics Holdings Inc, California, USA), and modeled a brushless direct current (BLDC) motor for actuation. The exoskeleton's belt was connected to the lumbar joint center or wrapped around the hip. The exoskeleton's armrest was rigidly connected to the human upper arm through a 1-DoF revolute joint, which may rotate about the upper arm axis. However, it forms a closed kinematic chain and introduces a coupling between the exoskeleton's joints and human joints. As shown in Figure 1, the exoskeleton's armrest transmits the five revolute joint constraint forces and torques to the human upper arm. 30 generalized coordinates and 10 algebraic constraints were used to model the multibody system.

We considered the full assist-as-needed (AAN) approach to provide the required assistance torque. This approach computes the desired actuator torque by boosting the human active torque via the required



(a) EVO with a 20-DoF MapleSim model (b) The human-exoskeleton closed kinematic chain

Figure 1: EVO upper limb exoskeleton with a 20-DoF MapleSim model of a human upper body with closed kinematic chain. There are two 3-DoF spherical joint at the lumbar joint center (LJC) and the shoulder joint center (SJC). There are 1-DoF for the Elbow Flexion/Extension (EFE), 1-DoF for the Forearm Supination/Pronation (FSP), and 2-DoF wrist joint. The exoskeleton has hinge (HG), elevation (E), and virtual spring (VS) joints.

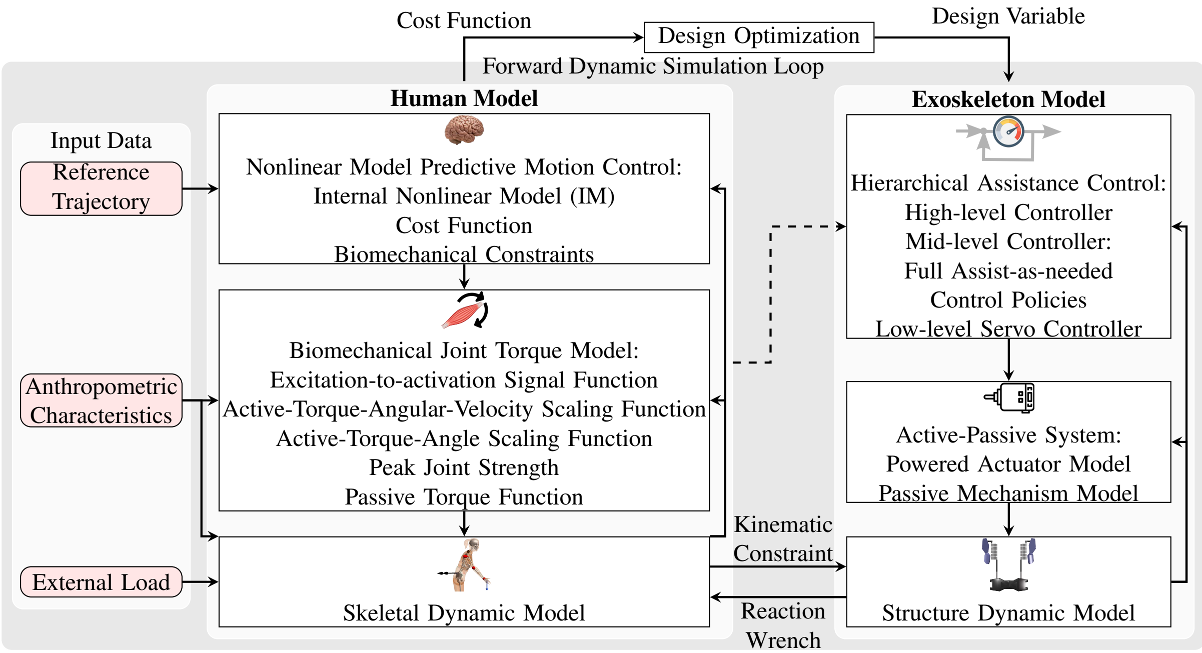


Figure 2: Schematic of simulating, analyzing, and optimizing the human-robot multibody system.

strength variable and merging the robot's powered actuator model [1]. In practice, the elevation torque would be approximated utilizing human data from a high-level controller, such as MuscleNet [1].
A forward dynamic simulation of the human-robot interaction was used to design, synthesize, analyze, and optimize the actuator model (Figure 2). As shown in Figure 2, an optimum controller follows the desired trajectory and commands the human. The actuator command (specified by the assistance model) and human input were both inserted into the multibody system's forward dynamic simulation. The optimization loop calculates the objective function before guessing and choosing the actuator parameter (BLDC motor id, passive assistive strength and profile).
We recorded kinematic data of experimental motion from 6 different occupational tasks with and without a heavy object to determine the reference trajectory. Then, the forward dynamic simulation in Figure 2 was used for different active motors and passive mechanism assistive torque. According to the simulation findings, the active-passive exoskeleton provides more assistance than the fully active, fully passive exoskeleton; meanwhile the exoskeleton's weight does not increase as much as the fully active exoskeleton. In addition, the optimization provides a back-drivable motor with lower inertia, gear ratio, and viscous damping coefficients instead of a powerful motor that is not back-drivable. The active-passive exoskeleton uses less energy than a fully active exoskeleton, allowing for a smaller and more portable exoskeleton. Future wearable exoskeletons are likely to have a component that combines passive and active support technologies.

References

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