Development of a human-robot dynamic model to support model-based control design of an upper limb rehabilitation robot

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Abstract

There are a large number of people with movement disorders who have difficulties doing their daily tasks independently. Much research has been devoted to the therapy of these people, and rehabilitation robots have been developed to assist with therapy. In robotic rehabilitation, since the human body is interacting with a mechanical device, safety issues in the design of appropriate control strategies are very important. Thus, rehabilitation robots usually use control approaches that consider the human body interacting with robot as a mechanical impedance [1]. Characteristics of this mechanical impedance may vary depending on different musculoskeletal factors such as posture and muscle contraction dynamics [2], and multiple experiments are required to evaluate them. However, in the current state of the art, rehabilitation robot controllers conservatively assume the robot interacting with some general static impedance models. In other words, there is a lack of research that considers realistic human body interactions with the rehabilitation robot. Since this interaction affects therapy procedures, the objective of the current study is to develop an integrated human-robot dynamic model with real-time simulation capability to support model-based robot controller design. Upper limb motor defects are common among stroke patients, so this study is focused on an upper extremity rehabilitation system.

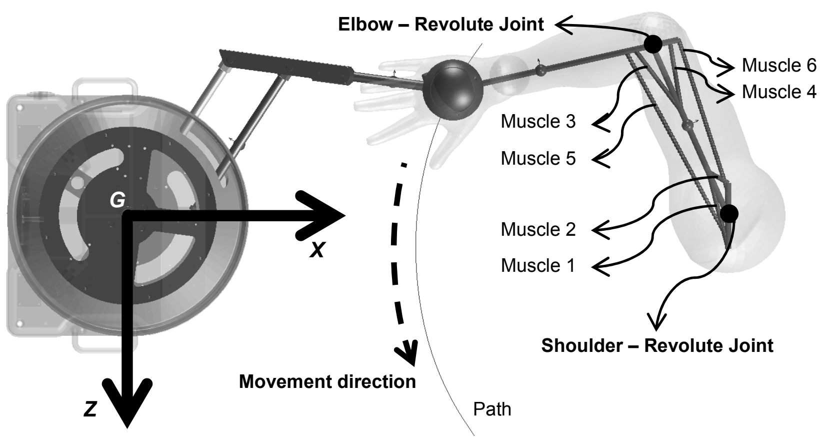
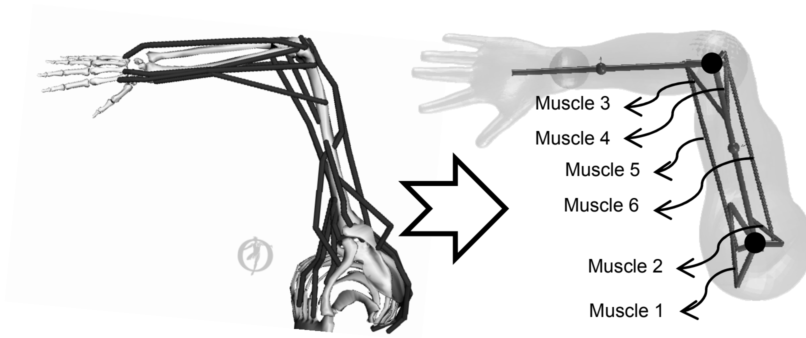


Figure 1: The upper limb rehabilitation robot interacting with the 2D musculoskeletal arm model in MapleSim modeling environment.

In this research, an upper-extremity musculoskeletal model of a human arm is developed to simulate the patient's arm movements. This model interacts with an upper limb rehabilitation robot, which was developed by Huq et. al [3]. Because of its multi-domain capabilities, symbolic processing, and optimized code generation, the MapleSim software is utilized to simulate the human-robot system in this study. This robot is a planar parallelogram arm with 2 degrees of freedom (DOF); to achieve simplicity and low computational cost, a 2-dimensional (2D) musculoskeletal arm model is used to interact with the robot [4] (see Figure 1). This 2D arm model, which is common for studying reaching movements in the horizontal plane, has two hinged links with 6 lumped muscles including shoulder and elbow mono- and bi-articular muscles. For muscle mechanics, it is assumed that only the contractile element (CE) of the Hill-type muscle is generating muscle force. The muscle force sharing problem is solved by the forward static optimization approach [5]. For comparison to and validation of the 2D model, a 3D musculoskeletal arm model based on [6] with 4 DOF (3 DOF at shoulder and 1 DOF at elbow) is developed (Figure 2a) in MapleSim. This model considers 22 muscles (12 muscle groups) of the shoulder, elbow and forearm with the same muscle mechanics as the 2D model.



(a) (b)

Figure 2: (a) The 3D musculoskeletal arm model (adapted from the OpenSim software upper extremity model). (b) The modified 2D musculoskeletal arm model.

In our simulations of reaching movements, the manipulation trajectory is approximated by a smooth circular path with a large radius of curvature (Figure 1). A cubic spline interpolation approach is used to generate this path with a bell-shaped tangential speed profile with continuous jerk. Simulation results for an unactuated robot and healthy hand interactions showed that the 3D model muscle activations are different from the 2D model. Therefore, we modified the 2D model using a weighted average approach to lump the 22 muscles of the 3D model into 6 effective muscles in the 2D model (see Figure 2). After rerunning the simulations, the activations of the modified 2D model were well-matched to the 3D model.

In summary, we show that it is possible to use a 2D musculoskeletal arm model for evaluation of a planar rehabilitation robot. Although development of this 2D musculoskeletal arm model requires a 3D model with muscle wrapping geometries, the lower-fidelity 2D model—in contrast to the higher-fidelity 3D model—can be used in real-time simulations and model-based controllers.

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