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MODELLING OF PHYSICAL HUMAN-ROBOT INTERACTION FOR EXOSKELETON DESIGNS

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Abstract. *Light-weight exoskeletons can be used for motion assistance for the elderly or the disabled in their daily lives and for training patients under rehabilitation, for which the physical human-robot interaction is a major concern for a safe and comfortable usage. A model that will help better understanding, estimating and analyzing the physical human-robot interaction is desirable for the purpose of design and control. In this paper, a modelling method comprising the biomechanics of human body as well as the robot dynamics of the exoskeleton was proposed for the modelling of physical human-robot interaction. A human-robot model was developed, which integrates the musculoskeletal model of the human body and an exoskeleton arm. The model is able to estimate the muscles activities in cooperative motions and enables the design analysis and optimization of robotic exoskeletons.*

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1 Introduction

An exoskeleton is a wearable robot attached to the human body to influence or assist human motion. Light-weight exoskeletons can be used for motion assistance for the elderly or the disabled in their daily lives and for training patients under rehabilitation [1]. While they have the potential to allow users to regain an independent lifestyle, the safe and comfortable interaction with human limbs remains as a major design challenge. Different engineering approaches have been proposed by introducing new actuators and control methods to improve the physical interaction between human and robot [2], but they have not achieved satisfying results. It appears that the interaction between the two systems depends on the exoskeleton's mechanical properties, its controlled movement, and also the limb's biological features and activity. A comprehensive model which could evaluate the influences of these factors is desired. However, very few models are available for this purpose. The challenge of modelling lies in the complicated interaction in which the robotic motion is coupled with human bodies, for which the estimation of motion and physiological parameters is very difficult. Moreover, the response of the human body to robotic assistance is not well understood yet.

Attempts have been made to understand the biomechanics of the physical human-robot interaction. Biomechanics of human body in selected activities of daily life was reported in [3]. A model of musculoskeletal kinematics, dynamics and actuation of the human body was developed for robotics applications by Khatib et al. [4]. Since previous studies are mainly focused on the human body alone, biomechanics considered in exoskeleton design is limited to an anthropometric (morphological) analogy [5]. A notable research in the the human-robot biomechanical modelling was reported in [6], in which Lee et al. investigated the interaction biomechanics at the musculoskeletal level for rehabilitation devices. The work was conducted with a biomechanical modelling system, namely, the AnyBody Modeling System [7]. The AnyBody modelling system provides the possibility to investigate the interaction biomechanics at the musculoskeletal level.

In this paper, a modelling method by comprising the biomechanics of human body as well as the multibody dynamics of exoskeleton was developed for the modelling of physical human-robot interaction for exoskeleton designs. The model deals with the human body's biomechanics at the musculoskeletal level, considering the influence of robotic assistance, which is able to estimate the muscles activities in cooperated motions. Such a model enables the design analysis of robotic exoskeletons and also for the optimization of a system.

2 Modelling

A robotic exoskeleton is a typical bio-robotic system which consists two essential subsystems, the human body represented by a musculoskeletal model and the exoskeleton modelled as a robotic multi-body system. The two systems are of different properties: the biomechanics of human body studied mainly by means of experiments and simulation, comparing the analytical robot dynamics. In this work, the study of human-body biomechanics and robot dynamics is integrated in the AnyBody modelling system, where the estimation of the biomechanical response of the human body is formulated as an optimization problem.

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2.1 Biomechanics

It is well known that a human body has more muscles than degrees of freedom. A musculoskeletal model describing the biomechanics of muscles and bones is thus statically indeterminate. The muscle recruitment can be formulated as an optimization problem as:

$$
\begin{aligned}
\min \quad & obj(\mathbf{f}^{(M)}) \\
\text{s.t.} \quad & \mathbf{Cf} = \mathbf{d} \\
& \mathbf{f}^{(M)} \geq 0, i \in \{1, \ldots, n\}
\end{aligned} \tag{1}
$$

where $\mathbf{f}$ is composed of a n-dimensional vector of muscle forces, $\mathbf{f}^{(M)}$, and joint reactions $\mathbf{f}^{(R)}$. The coefficient matrix $\mathbf{C}$ is built from the arm anatomy and muscle attachments, while $\mathbf{d}$ is the external force applied on the body. The choice of objective function depends muscle recruitment criterion. The possible criteria include the quadratic, polynomial and min/max muscle recruitment, etc [8]. The polynomial criterion is adopted here

$$obj(\mathbf{f}^{(M)}) = \left(\frac{f_i^{(M)}}{N_i}\right)^p \tag{2}$$

where N_i is the strength of a muscle. The ratio $f_i^{(M)}/N_i$ is referred as the muscle activity. The power p indicates the synergy of muscles. A value of $p = 3$ yields good results for most submaximal muscle efforts.

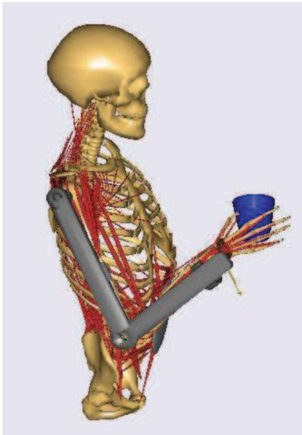

Figure 1: A human-exoskeleton model

2.2 Robot Dynamics

The equation of motion of a n-dof open-chain manipulators can be expressed as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{e}(\mathbf{q}) = \boldsymbol{\tau} \tag{3}$$

where $\mathbf{q}, \dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are n-dimensional vectors of generalized joint positions, velocities, and accelerations of the exoskeleton, respectively. $\mathbf{M}$ is the $n \times n$ general inertial matrix, $\mathbf{c}(\mathbf{q}, \dot{\mathbf{q}})$ is a n-dimensional vector representing the Coriolis and centrifugal forces. and $\mathbf{e}(\mathbf{q})$ is a n-dimensional vectors accounting for the force due to gravity. In the equation, $\boldsymbol{\tau}$ is the vector of general external forces applied at joints.

When there are forces applied to the end-effector, the EOM becomes

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{e}(\mathbf{q}) = \boldsymbol{\tau} + \mathbf{J}^T\mathbf{F} \tag{4}$$

where $\mathbf{J}$ is the Jacobian of the exoskeleton arm. For the human-robot system, Eq. (4) is added to eq . (1) as an additional constraint.

2.3 A Human-Robot Model

A human-robot model was developed with an exoskeleton and a musculoskeletal model, as shown in Fig. 1. The exoskeleton arm has two rotational degree-of-freedoms (dof), one at the shoulder and one at the elbow. The shaft of the shoulder joint is grounded, which in practice

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Table 1: Mass properties of the exoskeleton

	mass	Moment of Inertia $[I_{xx}, I_{yy}, I_{zz}]$
The forearm	$1.5kg$	$[0.01, 0.01.0.15]kg \cdot m^2$
The upper arm	$2.5kg$	$[0.02, 0.02.0.2]kg \cdot m^2$

means that it is fixed to, for instance, a wheel chair. The musculoskeletal model is sized as a 50th percentile European male. Only the upper trunk and the right arm are included in this model.

The model was developed with the AnyBody modelling system [7], by taking advantage of a repository of musculoskeletal models for implementation. The musculoskeletal model is comprised of 39 joints and 134 muscles. Hill-type muscle models are used, which consist of three elements, namely, the contractile element (CE) that generates force and represents the muscle fibers, the passive element (PE) in parallel with CE, and a serial elastic element (T) connected in series with the CE and PE.

The exoskeleton was first built in SolidWorks and then was exported to AnyBody. All joints are needed to be redefined in the AnyBody. The attachment of the exoskeleton to the human wrist is modelled as a spherical joint.

3 Results and Discussion

A simulation of the physical human-robot interaction was conducted for a cooperative motion of the exoskeleton and a human-arm in lifting a payload of $F = 50N$. In the simulated motion, the shoulder and the elbow joints rotate at angular velocities of $15°/s$ and $5°/s$. The maximum input torques applied to the shoulder and elbow joints, namely, M_s and M_e, were defined, varying in the range of $[5, 30]N.m$, which implies a variable assistive input power to the human body. The maximum input torques were increased without overloading the muscles.

In Fig. 2, activities of three selected muscles of the upper limb are displayed. These three muscles include the biceps, brachialis and br. radialis, which are considered as the major extensor/flexors of arm motion. Note that each of these muscles is composed of two to six muscles, which are modelled separately in the AnyBody. We evaluate the muscle activities by taking the mean activity of muscles in each group. It is seen that these muscles exert different strengths in the four cases of simulation with the payload of $F = 50N$. The variations of the maximum activities of all muscles in the upper limb are displayed in Fig. 3a, showing together with the interfacing forces in Fig. 3b. The influence of the assistive torques on the muscle activities is significant, comparing the muscle activities in carrying the same payload without assistance as shown in Fig. 4.

In another simulation, the physical human-robot interaction with a payload of $F = 20N$ applied at the hand was conducted. This is a light-duty manipulation like a daily activity. The upper bounds of the input torques were defined in the range of $[3, 10]N.m$. The maximum muscle activities for all muscles and the interfacing forces are shown in Fig. 6, while the muscle activities of individual muscles are not included.

The effect of the input power level on the muscle activities for both simulations are shown in Fig. 5, where the input power index is defined as

$$P_I = \sqrt{P_1^2 + P_2^2}/F$$

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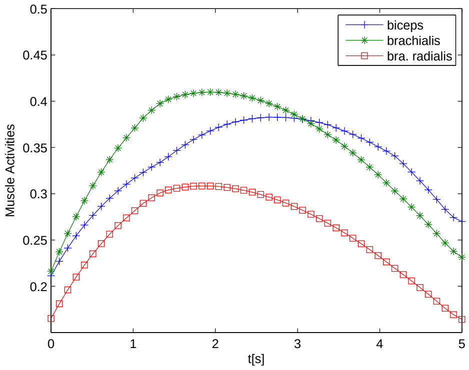
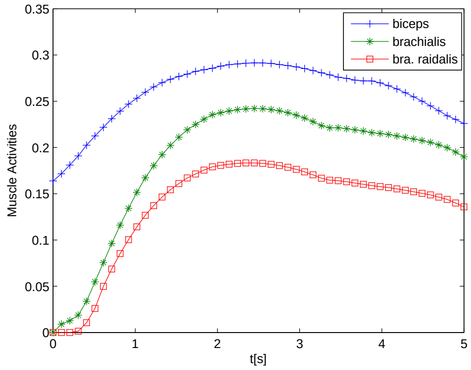
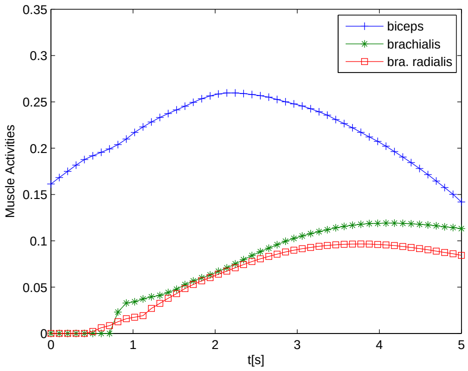


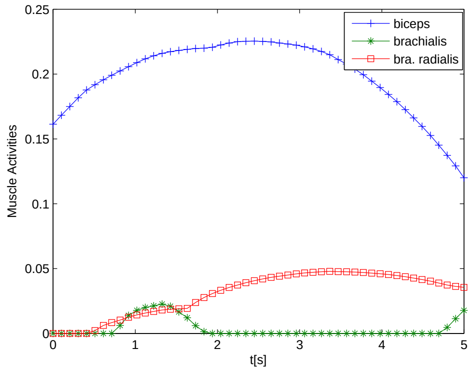
(1) $M_s = 5, M_e = 5$[N.m]



(2) $M_s = 10, M_e = 10$[N.m]

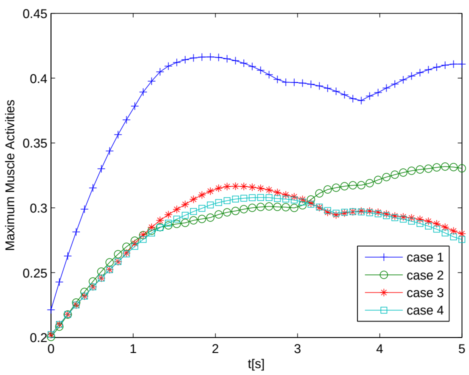


(3) $M_s = 20, M_e = 20$[N.m]

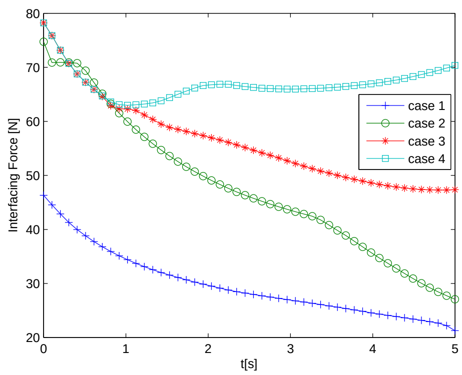


(4) $M_s = 30, M_e = 30$[N.m]

Figure 2: Comparisons of muscle activities with different level of assistive torques. The muscle activity is expressed in percentage of maximum voluntary contraction



(a)



(b)

Figure 3: Variations of (a) maximum muscle activities and (b) interfacing forces for the four cases of Fig. 2

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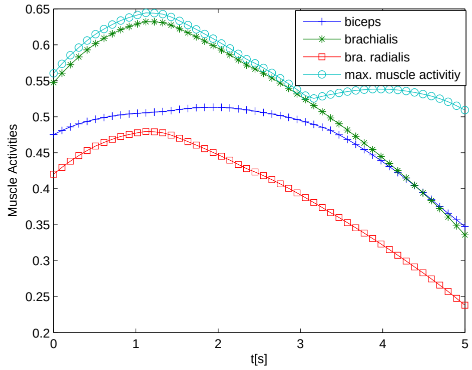

Figure 4: Muscle activity with carrying a payload of $50N$ without assistance

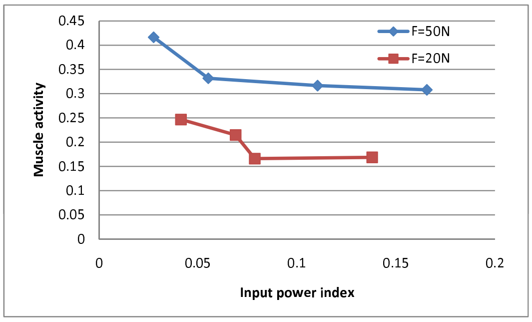

Figure 5: Influences of input power level on the muscle activities

with P_1, P_2 are the input powers at the shoulder and elbow joints, which are obtained from the products of the input torque and the joint angular velocity. It is observed that the maximum activities decrease with an increased input-power level in the two cases of simulation.

The results of the above simulation provide useful information for the motor sizing of assistive robot designs. In a lightweight robot, the weight of motors and transmissions accounts for about half of the total weight. By reducing the size of the motors, the robot weight can be effectively reduced. The developed model can be used to evaluate the muscle activities for motors of given size. By combining with some available robot design optimization method [9], the new model can lead to biomechanically optimized robot design, which will be safe and comfortable to use. In addition, the model can be considered for the simulation of rehabilitation training with varying input powers.

While the simulations can estimate the changes of maximum muscle activities for a given level of input power, the results show that the changes do not follow exactly the same pattern, as can be observed in Fig. 5. This indicates the complexity of the body's response to the robotic assistance. More simulation and analysis, preferably with experimental validation, are desired.

4 Conclusions

A preliminary model was developed with a 2-dof exoskeleton and a musculoskeletal human model. The simulation results show that the model is able to estimate the muscle the activities and reactions forces at interface. The simulation results reveal a different response of body to varied input powers and payloads. Further investigations are required to identify the body's response to the robotic assistance for a better understanding of the physical interaction and for

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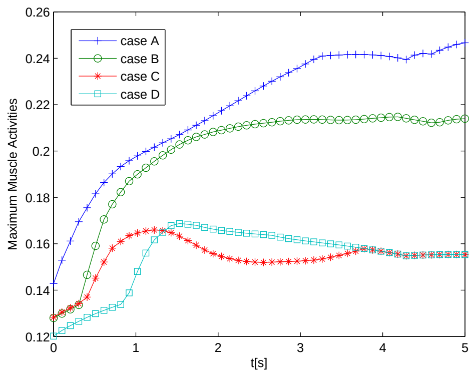

Figure 6: Simulation with a payload of $20N$ for the maximum muscle activities. The input torque limits (unit: N.m) for four simulated cases are: (A) $M_s = 3, M_e = 3$, (B) $M_s = 5, M_e = 5$,(C) $M_s = 10, M_e = 5$, and (D) $M_s = 10, M_e = 10$

the design optimization.

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