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SIMULATION-BASED DESIGN OF EXOSKELETONS USING MUSCULOSKELETAL ANALYSIS

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ABSTRACT

Exoskeletons are a new class of articulated mechanical systems whose performance is realized while in intimate contact with the human user. The overall performance depends on many factors including selection of architecture, device, parameters and the nature of the coupling to the human, offering numerous challenges to design-evaluation and refinement. In this paper, we discuss merger of techniques from the musculoskeletal analysis and simulation-based design to study and analyze the performance of such exoskeletons. A representative example of a simplified exoskeleton interacting with and assisting the human arm is used to illustrate principal ideas. Overall, four different case-scenarios are developed and examined with quantitative performance measures to evaluate the effectiveness of the design and allow for design refinement. The results show that augmentation by way of the exoskeleton can lead to a significant reduction in muscle loading.

INTRODUCTION

Exoskeletons and orthoses are defined as mechanical devices that are essentially anthropomorphic in nature, are 'worn' by an operator and fit closely to the body, and work in concert with the operator's movements [1]. While both devices serve to augment the performance of wearer, ‘orthoses’ tend to be used as assistive devices that are used by a person with limb pathology whereas ‘exoskeletons’ are worn by able-bodied users. Performance enhancement studies in the past range from improved environment interaction and/or metabolic economies among others.

There are numerous industrial, military and medical applications of exoskeletal robotic systems. In 1960s and 1970s the main focus was the application of active exoskeletons for industry and medical purposes. In early 1990s, some of them were designed to augment the strength of the humans. Recently, their use in the area of rehabilitation and power assist became significant in the society for the individuals with a physical weakness (due to age, injury and/or handicap). The upper limb exoskeletons are primarily used for teleoperation and power amplification. Finally, due to their ability to apply independent dynamic forces on human limbs, these devices are providing a basis for neuromotor research. Every field of application has its specific requirements in terms of structural design and control algorithms.

Exoskeletons have been used in various operational modes including the assistive mode and the resistive mode. In the assistive mode the exoskeleton provides power to support the movement of the human limb, while in the resistive mode it opposes motion/forces. Though significant literature is available that discusses the design of upper-limb exoskeletons, but there still is a necessity to study the effects of exoskeletons on human musculoskeletal system to improve the design of these robotic devices. However, there are many challenges related to (i) kinematic compatibility, (ii) dynamic matching, (iii) lack of performance evaluation criterion, and (iv) lack of design and analysis tools.

Simulation-based-design, otherwise known as Virtual Prototyping (VP), is a methodology to iteratively refine design of a product using computer-based functional physical simulation(s). Rapid quantitative and computational investigation of numerous “what–if” design scenarios at relatively low cost is what makes VP a successful design refinement technique. This can include studying the effects of variability; determining the “best” geometries for performance; and to examine the linkage between form and function using “virtual experimentation” to name a few [2].

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In this paper, we discuss the use of simulation-based design techniques together with musculoskeletal analysis tools to study and analyze the performance of an upper-limb exoskeleton. Different cases scenarios are considered in order to evaluate the performance of the robotic device in conjunction with the human user. The rest of the paper is organized as follows: we first discuss the relevant background and prior work studying the challenges entailed in attaching and effectively using exoskeletons. The Implementation section deals with a discussion of an illustrative example of an upper-limb exoskeleton. Various case scenarios considered in this paper along with a discussion of the results obtained are then presented. Finally, the final section concludes the paper with a summary of results and direction for future work.

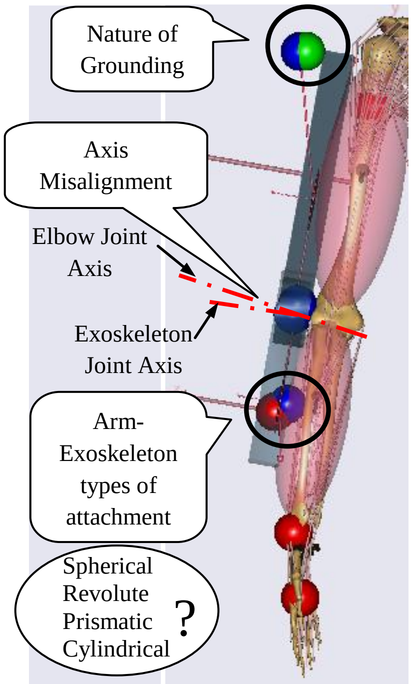


Figure 1. CHALLENGES INVOLVED IN MUSCULOSKELE-TAL ANALYSIS OF EXOSKELETONS.

BACKGROUND

We discuss the prior background in the context of a few relevant topics. The task of correctly positioning the exoskeleton on the human arm model offers a challenge as alignment of critical axes is important for biomechanically correct operation (Fig. 1). The issue of matching the two axes and its effects on arm movement becomes more significant when axes move in space and time, due to the imperfect nature of the human arm joints. Past work on prosthetic design focuses on using interesting mechanisms such as 6 bars to allow alignment of such axes. The action of the misalignment above a certain degree can give rise to an unnatural restraint and affect limb mobility [3]. Thus, the human-robot physical interaction imposes several constraints and requirements on the design of wearable exoskeletons. The problem may be analyzed in a detailed manner by conducting a parametric study and understanding the effects of the misalignment on human muscle force and activity. Typically such over-constraint is released by addition of mechanical compliance.

There are various possible options for joints in the arm-exoskeleton system as presented in Fig. 1. However, a modeled joint should be representative of the actual condition and should not lead to hyperstaticity. A set of design rules and possible solutions to avoid such hyperstaticity are discussed in [4]. Considering that both the conditions need to be satisfied simultaneously, the issue of choosing appropriate type of joint for the model becomes significant. However, combined performance is not only architecture but also selection of parameters to provide any precise quantification of the performance.

Recently, a few tools such as SIMM (Software for Interactive Musculoskeletal Modeling) [5], OpenSim [6], AnyBody Modeling System [7], SimTK [8], LifeModeler [9], Virtual Interactive Musculoskeletal System (VIMS) [10] in the form of commercial packages have been made available for musculoskeletal analysis. These computational tools perform kinematic and dynamic analyses of vertebrate musculoskeletal systems, building on an articulated multi-body systems (AMBS) framework. Constrained musculoskeletal system-level computational models can be constructed modularly by placing physiologic and behavioral constraints on anatomical components (e.g., bone, muscle, and tendon). Such musculoskeletal analysis tools allow monitoring of internal human variables – a wide variety of biologically relevant data (from lengths, forces, reactions of muscles/tendons/joints, to metabolic power consumption, and mechanical work) can be accessed. Alternatively, other higher level abstracted performance measures may be developed, allowing a designer to flexibly assess the performance of a design.

VP tools in engineering have capitalized on setting up and solving such problems by coupling parametric models with functional simulation tools and optimization methods [11]. Recently, predictive dynamics has emerged as a successful approach for analyzing bio-systems, where the applied force and the response both are unknown [12]. Multi-objective optimization has been used together with such models for enhancing predictions in lifting motion simulations [13]. In particular, the availability of low-cost PC-based parametric simulation and analysis tools, and integrating multiple functionalities into a unified environment, has favored the adoption and rapid proliferation of the "computational/virtual exploration" approach. Nevertheless, there remain significant obstacles to successful implementation of VP as an exoskeleton design tool. On one hand, the effectiveness is limited by the extent of capture of the underlying physics, the modeling and analysis fidelities, and ultimately computational power. On the other hand, effective simulation of interactions between the user, the device, and the environment becomes critical in developing efficient designs [11]. We capitalize on this "insight" into the internal human variables, including muscle and joint motions, and forces, in our work (details are provided in Case Study Modeling). This work provides a means to overcome some of the challenges such as kinematic compatibility and dynamic matching pertaining to analysis and design of exoskeletons.

IMPLEMENTATION

In order to evaluate the performance of the exoskeleton a simplified yet representative case study is carried out which can cater both the applications of the device i.e. Assistive and Rehabilitative (Resistive). The following are the requirements of the case: (1) An Experiment/Activity to be performed, (2) Musculoskeletal Analysis Software, and (3) Exoskeleton Model.

Activity

The human arm is capable of producing various complex motions. In this paper we have selected arm flexion (Fig. 2) as the activity to be performed to evaluate the performance of the exoskeleton. An experiment that can simulate both the applications is biceps arm curl. The parameters related to all cases are: (i) Arm flexion with an angle of 60^o is considered as shown in Fig. 3(a). This large angle is selected in order to understand the behavior of muscles under varying moment loading. (ii) Time in which the arm flexion angle is traversed is considered to be 2 seconds.

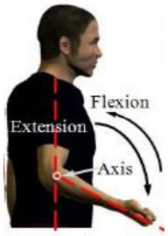


Figure 2. CURL MOTION UPPER-LIMB [14].

Musculoskeletal Analysis Software

In our study, AnyBody Modeling System is employed for the analysis. The AnyBody musculoskeletal model is built up as a constrained articulated multibody system with rigid skeletal bones overlaid with multiple muscles that serve to both constrain and actuate the system. The governing equations can be obtained as the constrained dynamic equations of this articulated multibody system. However, the significant actuation redundancy creates indeterminacy for resolving muscle–actuator forces via inverse dynamic analyses. The indeterminacy in muscle force distribution is resolved using an optimization approach. In AnyBody [15], redundancy resolution takes the form of minimization of the maximal muscle activity subject to equality constraints (multibody dynamic equations) and nonnegative muscle force constraints.

$$\min_{f} G(f_{muscle}) = \max\left(\frac{f_{muscle,i}}{N_i}\right), \quad i = 1, 2, ..., n \ \ muscles \tag{1}$$

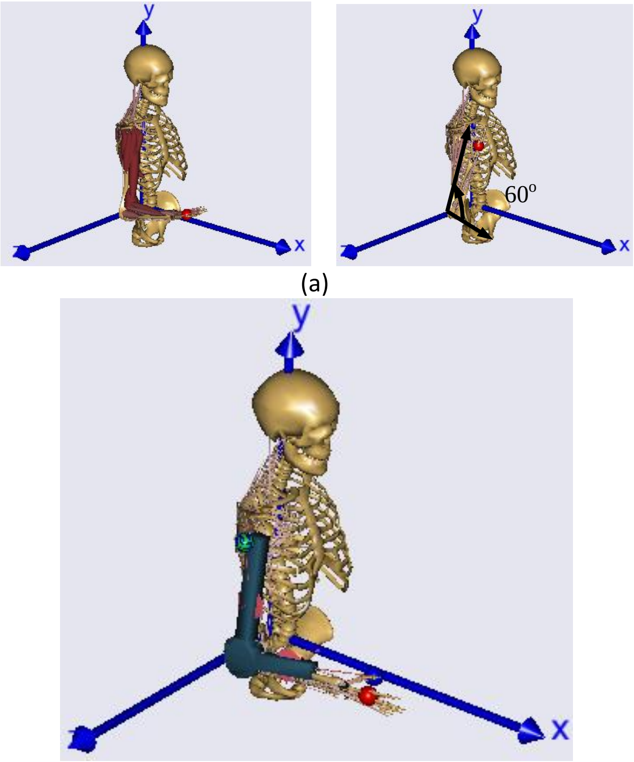
$$\begin{aligned} Subject\ to: \ \ & Cf = r \\ & f_{muscle,i} \geq 0 \end{aligned} \tag{2}$$

where G is the objective function of the recruitment strategy stated in terms of the muscle forces, $f_{\text{muscle,}}$ and minimized with respect to all unknown forces (muscles forces and joint reactions) in the problem. Eqn. (2) acts as constraints for the optimization problem are the dynamics equilibrium equations. C is coefficient-matrix for the unknown forces and d contains all known applied loads and inertia forces. The second constraint in Eqn. (2) is a non-negativity constraint on the muscle forces, signifying that muscles can only pull, not push. Many contemporary studies [16-18] have examined the validation of AnyBody dynamic simulations in various application contexts. The ability to resolve muscle activities/forces (beyond the more traditional joint forces and moments), and relate these directly to electromyography (EMG) data was also extremely attractive [16-17].

A model can be developed in AnyBody using either the bottom-up approach or top-down approach. The bottom-up approach model a musculoskeletal system by assembling smaller sub-systems. However, developing a model by the bottom-up approach from scratch is a very time consuming process. Alternately, one can take advantage of the human model repository [19]. The designer can download the human model at various fidelities and add necessary design components to complete the model. This top-down modeling approach simplifies the overall modeling process tremendously and is the recommended approach [7]. Parametric models of the human exoskeleton are extracted from model libraries. The muscles (145 in number) connected to the human right arm are considered in the analysis with pelvis being fixed and relative movement between thorax and pelvis being constrained. The following are the common parameters taken into consideration while modeling the system in AnyBody: (i) Muscle Strength is considered to be constant strength for all muscles; (ii) Limb mass and length of various bones in the arm is chosen as per the standard models available in AnyBody repository; and (iii) The dumbbell is modeled as a constant force of 60 N acting in the vertically downward direction, roughly equivalent to a 6Kg dumbbell.

Exoskeleton Model

A simplified version of the exoskeleton is considered for the analysis. The exoskeleton has two links connected by a revolute joint. Figures 3(b) depicts the CAD model of the exoskeleton mounted on the human arm. The model of the robotic device is developed using SolidWorks 3D CAD Design software and imported into AnyBody.



(a)

(b)

Figure 3. (a) INITIAL AND FINAL POSITION OF THE HUMAN ARM FOR ARM FLEXION USED IN THE ANALYSIS, and (b) SIMPLIFIED EXOSKELETON MODEL MOUNTED ON THE HUMAN ARM.

In this paper, individual muscle forces and elbow flexion moment serve as our performance measures. Such performance measures allow the designer to directly judge the effectiveness of the exoskeleton design. These measures are considered for analysis because of the following reasons: (i) Individual muscle forces show which muscles play a significant role in performing the given experiment and hence, how can modifications in design relieve them; and (ii) Elbow flexion moment signifies the load carried by the human elbow joint, thus gives an idea of the external load acting on the joint. Thus, the lesser the individual muscle force the better the performance of the exoskeleton. Also, the lesser the elbow flexion moment the better the exoskeleton is performing.

CASE STUDY MODELING

Figure 4 represents the complexity involved in successful simulation of a musculoskeletal model coupled with an exoskeleton. The different problems are represented as different axes with a graduation for respective degree of complexity involved. We focus on a set of case scenarios in order to assess the efficacy of exoskeleton robot design by quantifying its effect on human muscle performance parameters. The rationale behind selecting these cases is three-fold: (i) to study the performance of exoskeleton in assistive mode; (ii) to study the effects of hyperstaticity; and (iii) suitable selection of exoskeleton design parameters to realize “best” performance. The following four case scenarios are simulated: (i) Arm curl with dumbbell case forms the baseline for all studies thus providing information on how muscles perform during arm curl without any external aid; (ii) Arm curl with dumbbell and constant assistive moment (Idealized Constant Moment Assistive Mode) case is an idealized version of exoskeleton working in assistive moment mode but providing a constant moment; (iii) Arm curl with dumbbell and variable assistive moment (Idealized Variable Moment Assistive Mode) case is an idealized version of exoskeleton working in assistive moment mode with the moment requirement being exactly met; (iv) Arm curl with dumbbell and exoskeleton assistive moment (Assistive Mode) case determines the performance of the considered exoskeleton model in assistive mode.

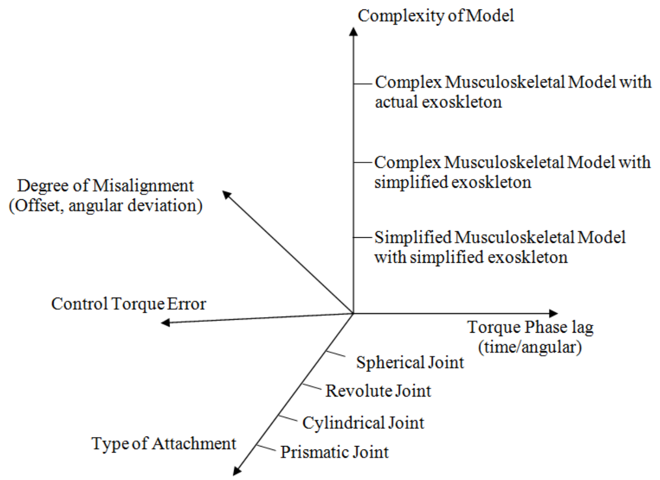


Figure 4. MULTI-DIMENSIONAL VIEW OF THE PROBLEM WITH DIFFERENT LEVELS OF COMPLEXITY.

Case A: Arm Curl with Dumbbell

The rationale behind this experiment is to develop a basic understanding of how the muscles in the arm are loaded when a force acts on the palm in the vertically downward direction. This also provides a basis for comparing the muscle forces with other cases such as the one with exoskeleton working in assistive mode. The model involves an application of load on the palm against which the arm is to perform flexion as shown in Fig. 5. The curve shown in Fig. 6(a) depicts that the muscle forces decrease with time as the simulation proceeds. Considering the fact that the moment arm of the load acting on the palm will continuously reduce, the moment required to balance the load will also reduce with time. The elbow flexion moment profile shown in Fig. 6(b) also shows a gradual reduction with time. The simulation of this arm curl case study is shown in Fig. 7.

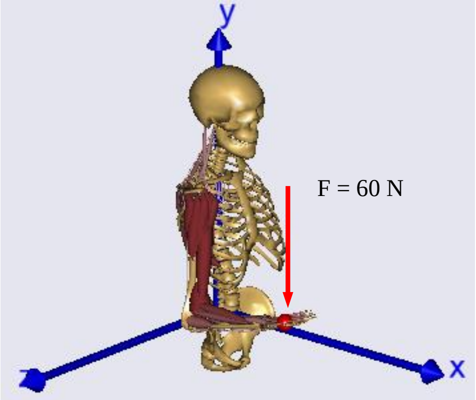
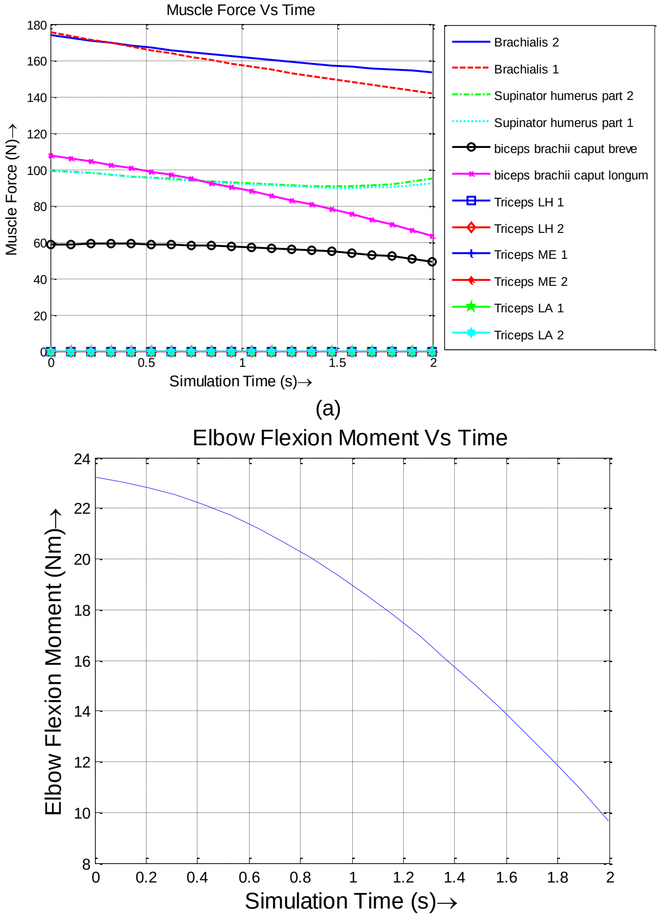


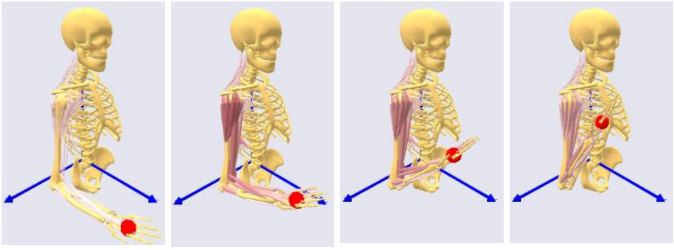
Figure 5. ANYBODY MODEL FOR ARM CURL WITH DUMBBELL (CASE A).



(a)

(b)

Figure 6. VARIATION OF MUSCLE PERFORMANCE PARAMETERS WITH TIME FOR CASE A: ARM CURL IN DUMBBELL MODEL. (a) MUSCLE FORCE, and (b) ELBOW FLEXION MOMENT.



$t = 0\text{sec}$ $t = 0.7\text{sec}$ $t = 1.4\text{sec}$ $t = 2\text{sec}$

Figure 7. SIMULATION OF CASE A: ARM CURL WITH DUMBBELL FOR 2 SECONDS.

Case B: Arm Curl with Dumbbell and Constant Assistive Moment

Traditionally, misalignment of critical axes in the arm-exoskeleton system is considered as a cause of the poor performance of the robotic device. Hence, in this case, we perform the arm curl experiment by assuming that assistive moment is applied directly at the elbow joint as shown in Fig. 8. Note this may not be possible in real life – however, this idealized case allows to create a benchmark without effects of misalignment. In this first of two benchmark cases we apply a constant assistive moment. Applying a constant moment is simple and requires no exoskeleton model. The value of the moment is decided from the mean requirement obtained in the case A. A constant assistive moment of 16 Nm is provided at the elbow joint during arm flexion.

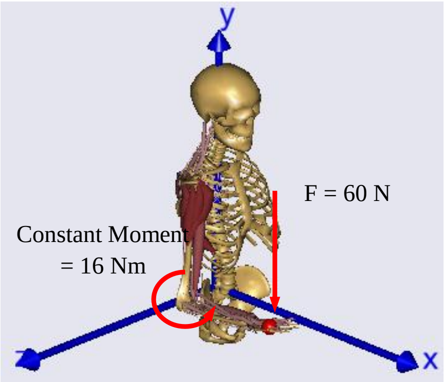
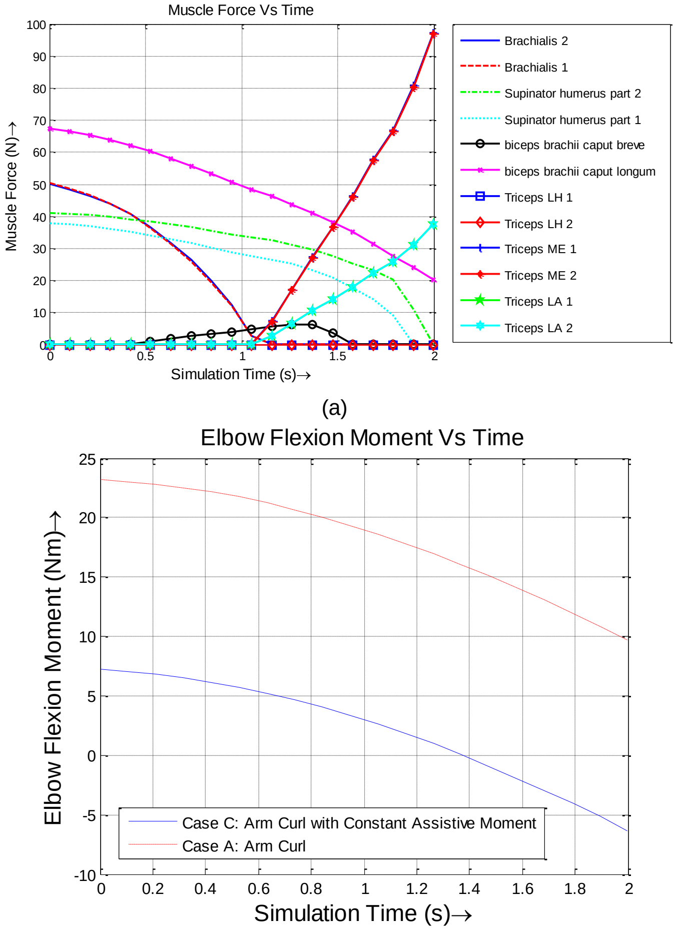


Figure 8. ANYBODY MODEL FOR CASE B: ARM CURL WITH DUMBBELL AND CONSTANT ASSISTIVE MOMENT.

Figure 9(a) shows the variation of muscle force with time for arm curl with dumbbell under constant assistive moment. Though there is a reduction in the peak muscle forces, a significant rise in muscle forces is observed during the later stages. This increase in muscle forces is attributed to the fact that a constant assistive moment is provided irrespective of the requirement due to which the muscles are loaded to counterbalance this excess moment. This shows that torque synchronization is very important for improved performance of exoskeleton. The elbow flexion moment plotted in Fig. 9(b) also shows similar trend as that obtained in case A with the entire curve being shifted by 16 Nm downward. The moment in this case becomes negative somewhere midway in the simulation as the assistive moment continuously acts irrespective of the requirement.



(a)

(b)

Figure 9. VARIATION OF MUSCLE PERFORMANCE PARAMETERS WITH TIME FOR ARM CURL IN DUMBBELL AND CONSTANT ASSISTIVE MOMENT MODEL (CASE B). (a) MUSCLE FORCE, AND (b) ELBOW FLEXION MOMENT.

Case C: Arm Curl with Dumbbell and Variable Assistive Moment

Now considering the fact that torque synchronization is crucial for improved performance of the device a variable assistive moment is provided at the human elbow joint with no exoskeleton during arm flexion as shown in Fig. 10. The flexion moment obtained in case A is used to drive the model in this case. The muscle forces obtained in this case show a further reduction as shown in Fig. 11 (a). The reason that significant reduction in muscle forces is not achieved even in this case is because the glenohumeral joint and wrist joint are not provided any external moment due to which a large number of muscles are still loaded. This shows that it is not possible to significantly lower the human effort by providing support in the form of external moment to just one of the joints. Since, the human limb joints are loaded serially it becomes mandatory that the designed exoskeleton takes care of the loading at all the human joints. Elbow flexion moment as presented in Fig. 11 (b) is very near to zero as the required moment is provided at the elbow joint.

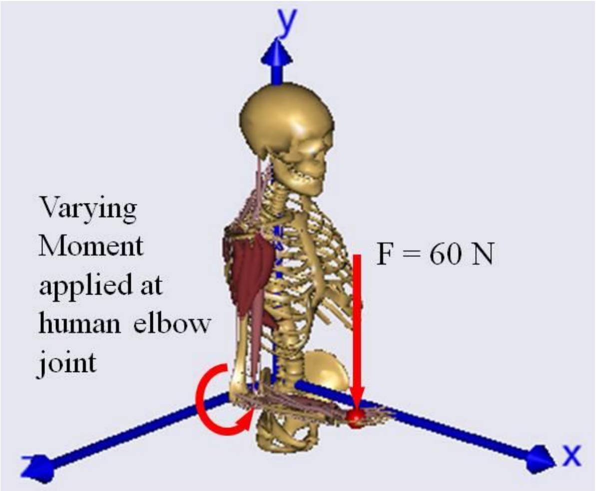
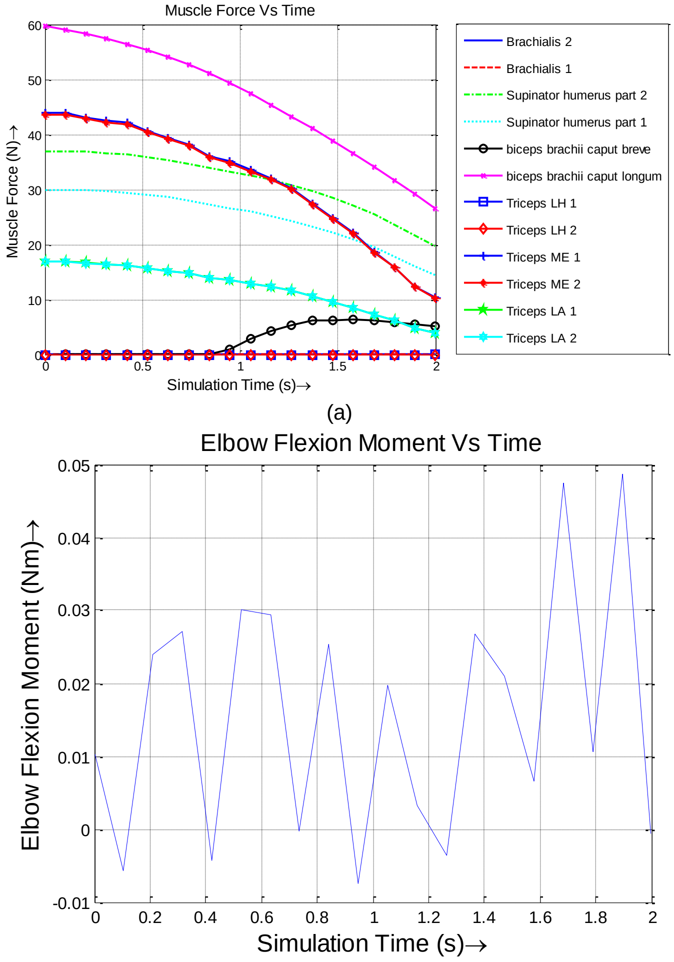


Figure 10. ANYBODY MODEL FOR CASE C: ARM CURL WITH DUMBBELL AND VARIABLE ASSISTIVE MOMENT.



(a)

(b)

Figure 11. VARIATION OF MUSCLE PERFORMANCE PARAMETERS WITH TIME FOR ARM CURL IN DUMBBELL AND VARIABLE ASSISTIVE MOMENT MODEL (CASE C). (a) MUSCLE FORCE, AND (b) ELBOW FLEXION MOMENT.

Case D: Arm Curl with Dumbbell and Exoskeleton Variable Assistive Moment

In this final case, we now consider the actual case of an exoskeleton coupled with the human arm for analysis. The AnyBody model for arm curl with dumbbell and exoskeleton working in assistive mode providing variable assistive moment is shown in Fig. 12. The exoskeleton has upper link fixed to the ground using a revolute joint. The two links of the exoskeleton are also connected using a revolute joint.

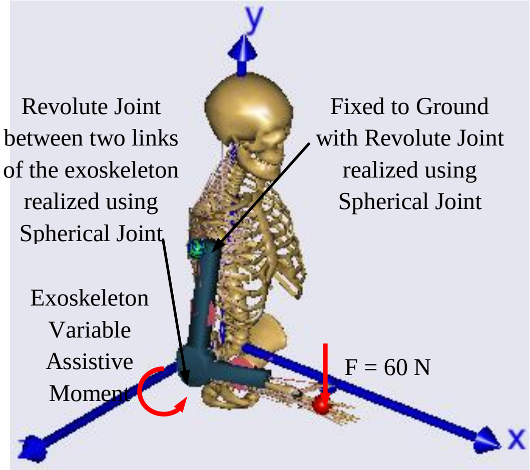


Figure 12. ANYBODY MODEL FOR ARM CURL WITH DUMBBELL AND EXOSKELETON ASSISTIVE MOMENT (CASE D).

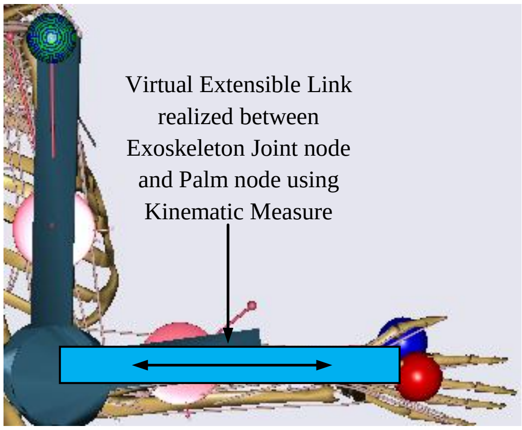


Figure 13. ANYBODY MODELING DETAILS FOR ARM CURL WITH DUMBBELL AND EXOSKELETON ASSISTIVE MOMENT (CASE D).

However, human joint kinematics is so complex that in practice, the kinematics of artificial exoskeletons with conventional joints fails to reproduce it exactly. The kinematic incompatibility occurs when the lower link is attached to the lower arm by a standard joint. Such kinematic incompatibility results in hyperstaticity due to which uncontrolled interaction forces appear [4]. In order to evaluate the nature and scope of the ensuing kinematic incompatibility we examine the use of a “kinematic measure”. A kinematic measure is an equation based representation of kinematical constraints [7]. For example, maintaining distance between two points is an example of kinematic constraint that can either be measured or alternatively driven. So, a virtual link is realized between the exoskeleton joint and the palm node on the arm using a kinematic measure. The model is first run for the forward kinematics with both the exoskeleton and the elbow drivers active, and the linear variation between the two nodes is recorded with respect to time using the kinematic measure. The elbow flexion and pronation drivers are then deactivated and the kinematic measure is driven. The importance of realizing the virtual link with the palm node is that it helps by preventing building up of muscle forces which would otherwise be required to keep the hand collinear with the forearm (i.e. to keep wrist joint at its original position) (Fig. 13).

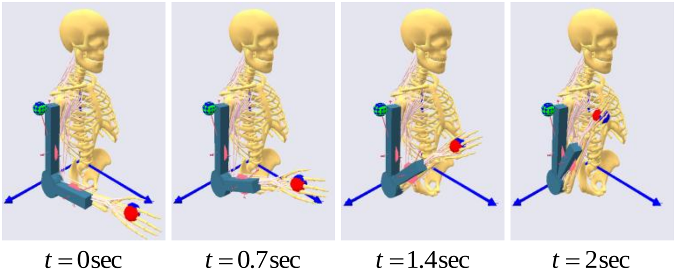
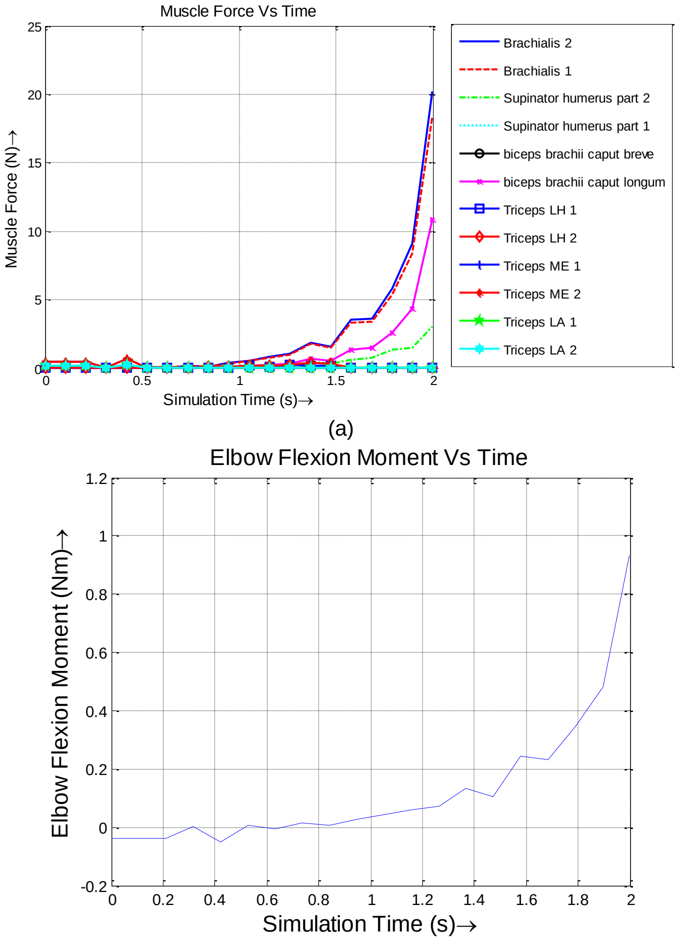

$t = 0\text{sec}$ $t = 0.7\text{sec}$ $t = 1.4\text{sec}$ $t = 2\text{sec}$

Figure 14. SIMULATION OF CASE D: ARM CURL WITH DUMBBELL AND EXOSKELETON FOR 2 SECONDS.



(a)

(b)

Figure 15. VARIATION OF MUSCLE PERFORMANCE PARAMETERS WITH TIME FOR ARM CURL IN DUMBBELL AND EXOSKELETON ASSISTIVE MOMENT MODEL (CASE D), (a) MUSCLE FORCE, AND (b) ELBOW FLEXION MOMENT.

Simulation of case study D is shown in Fig. 14. The muscle forces with respect to time shown in Fig. 15(a) show a drastic reduction with the use of exoskeleton. Such a reduction is expected as now the moment required to overcome the palm load will be provided by the exoskeleton due to which muscles will be very lightly loaded. Also, since the exoskeleton is grounded at one end the moment that would otherwise be developed on the glenohumeral joint is avoided. The elbow flexion moment value obtained is also very low (Fig. 15(b)) which shows that the exoskeleton is carrying significant load.

SUMMARY

In this paper, we presented the use of musculoskeletal analysis for designing an upper-limb exoskeleton. Four different case studies are performed to study the effect of using a simplified exoskeleton on the muscle loading for arm curl with dumbbell. The simulation results showed that with the use of exoskeleton significant reductions in both, individual muscle forces and elbow flexion moment are achievable. The results also showed that the exoskeleton applied-torque synchronization with the required torque is important for the performance of the device. Prior approaches to exoskeleton designs used a more qualitative designer assessment to describe performance and/or fit. This engenders the usual limitations inherent to any semi-quantitative/qualitative design methodology including lack of invariances etc. In contrast, musculoskeletal analysis provide rational basis for biomechanically quantifying the performance of a candidate exoskeleton design and thus in turn provides a means for quantitatively comparing alternate designs. Nevertheless, the resulting copious amounts of raw quantitative data need to be further processed to extract useful metrics. Careful assessment of the quality, sensitivity and most importantly usability, of both the raw information and extracted metrics, is the focus of our current research.

The case with exoskeleton working in resistive mode is also being studied but is not complete at this time. In addition, much work needs to be done in carefully modeling a detailed model of the exoskeleton and analyzing its performance. Parametric studies also need to be conducted in order to select the best possible values for design variables to optimize the performance of the exoskeleton.

ACKNOWLEDGMENT

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