

UNIVERSITY AT BUFFALO

**Modeling, Analysis and Simulation
of
Exoskeleton for a Human Arm**

[Independent Study MAE-501]

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Acknowledgement

We would like to thank Dr. Venkat Krovi for providing us with this opportunity and for his time, patience that he set aside for us. We offer our gratitude to our friends and colleagues Mr. Madhu S Narayanan and Srikanth Kannan for their support during the project. Our sincere thanks and appreciation goes to the AnyBody Technology support team for answering all the queries that we posted during our study.

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1. Introduction

For centuries, man has been building machines to serve his needs. With his ability to imagine and his creativity, he was able to nurture his thoughts and give rise to machines that would work for him incessantly and do his bidding. This enabled Man to exert his superiority over other species that roamed the earth. Over the centuries man's needs have grown increasingly complex and as a consequence so has the level of sophistication of his Machines.

The advanced functional capabilities of the human brain enabled man to mimic the features of the other species. One such adaptation is the Armour, an artificial Exoskeleton that Man has used for protection, especially in combat. An Exoskeleton is an external skeleton that supports and protects an animal's body, for example the Tortoise, in contrast to the internal endoskeleton of, for example, a human. The concept of the Artificial Exoskeleton further evolved through the ages.

Early in 1965, attempts were made to build powered Exoskeletons for practical purposes. General Electric's "Hardiman" was the first practical powered Exoskeleton of its kind. The machine was intended to allow the wearer to lift loads of 1500 pounds with great ease.

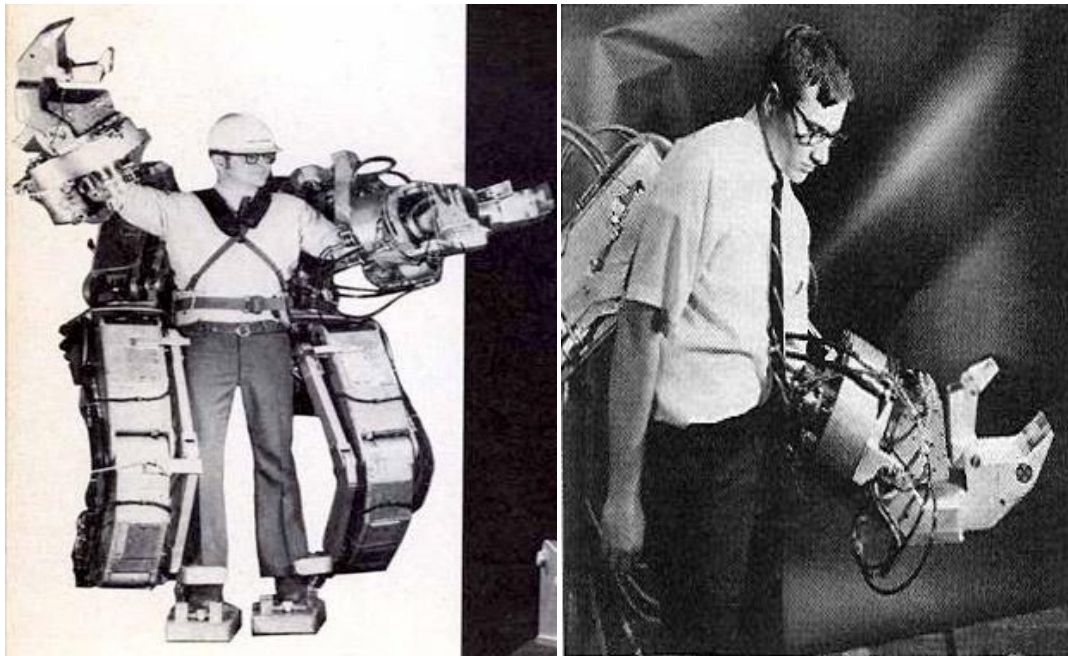


Figure 1: General Electics's "Hardiman", 1965 (DAVIDSZONDY.COM)

The project however was unsuccessful for any attempt to use the whole Exoskeleton resulted in a violent uncontrolled motion. Engineers focused their research on the Exoskeleton arm alone which, although could lift its specified load of 750 pounds, but weighed over twice the lift able load .This limited the uses of the “Hardiman” project.

Even with General Electric’s first attempts in creating the “Hardiman” and attempts by many others after that, powered human Exoskeletons was a topic of science fiction writing for long .However recent technological advancements in the 21st century bring about the prospects of developing Human Exoskeletons as machines designed for everyday use like the Automobile and the Cell Phone.

Lately, powered human Exoskeletons, which was earlier a fancy of Engineers is now a topic of great interest to the researchers in the Medical Community as well. The reason being that the idea of integrating Man and Machine into a single unified system offers remarkable opportunities for creating a new generation of assistive technology for both healthy and disabled people . It is a known fact that humans possess naturally developed algorithms for control of movement, but are limited by their muscle strength. Also muscle weakness is a major cause of disability in people suffering from neuro-muscular diseases and injuries to the central nervous system. On the other hand, robotic manipulators can perform tasks that require enormous forces, but their artificial control algorithms fail to provide the high level of control over movement as seen in humans and as a result are of no match to the humans in terms of flexibility and performance under a wide range of conditions. (ucsc.edu)

It is easily understood that combination of the two subsystems, the Human and the Robot, into a single system under the control of the human would give rise to a system that would be benefitted by the advantages of each subsystem or entity. A poor understanding of this concept seemed to be the cause for the failure of GE’s “Hardiman” project in 1965.

Based on these ideas and concepts, the Exoskeleton is now redefined as an external structural mechanism with joints and links resembling those of the human body. When worn by the human, the Exoskeleton transmits torques from proximally located actuators through rigid exoskeletal links to the human joints.

When Exoskeletons are coupled with different control algorithms, they may be used for a wide range of applications such as:

- 1) Assistive Device: The user wearing an Exoskeleton experiences scaled down loads while interacting with objects and the environment, most of the load being carried by the Exoskeleton. This idea is being extensively researched and developed by the US military with prospects that would eventually lead to the deployment of soldiers wearing Exoskeletons during times of war.



Figure 2: Wearable Robots in Warfare (HOWSTUFFWORKS)

- 2) Physiotherapy : The patient wearing an Exoskeleton perform a task based occupation or physical therapy in an active or passive mode with the Exoskeleton



Figure 3: Wearable Robots in Physiotherapy (ESA)

- 3) Haptic device: The user wearing an Exoskeleton such as the one in the picture can physically interact with virtual reality objects .The forces generated through this interaction are fed back to the user through the Exoskeleton conveying the shape stiffness texture or any other physical characteristics of the virtual objects to the user.



Figure 4: Wearable Robots in Haptics (ESA)

- 4) Master Device – The operator may use the Exoskeleton to control a robotic system in a Tele-operation mode, where the Exoskeleton (master) reflects back to the user the forces generated as the slave robot interacts with the environment.



Figure 5: Wearable Robots in Tele-Operation (ESA)

The integration of the Human and the Robot, with no doubt, brings about the best feature of each entity in the in the super system but also contributes greatly to complexity of the Man-Machine system. Some of the challenges faced by engineers and scientists working on Exoskeletons are:

- Structures: Developing and using Lighter and Stronger material composites for the designing the structure of the Exoskeleton.
- Energy Requirements: Batteries should last for at least for 24 hours and must be portable, light and easily rechargeable
- Controls: Should provide the user with seamless control under any conditions.
- Actuation: The actuators must be designed to operate smoothly, silently and more importantly provide the right amount of actuation force as required by the task being performed by the user.
- Bio Mechanics: One of the major challenges in this field is to establish an effective human-machine interface i.e. between the operator and the wearable robot, such that the robot becomes a natural extension of the human body. The Exoskeletons should be able to sense human motion and react accordingly.

Understanding the mechanics that couples the Human and Robot systems, developing model solutions that illustrate the intrinsic interaction between the Man-Machine systems and to study their combined performance under different operating conditions is the motivation behind this Independent Study.

2. Background

2.1 Virtual Engineering

Virtual engineering , is defined as integrating geometric models and related engineering tools such as analysis, simulation, optimization, and decision making tools within a computer generated environment that facilitates multidisciplinary collaborative product development.

Of late, Virtual Engineering has gained immense popularity and forms a crucial part of most engineering processes today. The reason for popularity is quite evident from what Virtual Engineering has to offer to the engineering community.

Virtual engineering provides a user-centered, first-person perspective environment that enables engineers to interact within a virtual system, using a wide range of tools. It essentially requires a computer model that includes the geometry, physics, and any quantitative or qualitative data from the real world problem. By interacting with this model, within the virtual environment, the user can now observe how the virtual model works and responds to changes in design, operation, or any other engineering modification. Thus with the help of Virtual Engineering, the user is now able to explore and discover critical details about the system's behavior.

Key features of Virtual Engineering include:

- User-centered virtual reality visualization techniques: Virtual engineering helps present complex 3D data in a familiar and natural interface which make analysis and interpretation easy.
- Interactive analysis and engineering : The time required to set up, compute ,understand the result and then repeat the process until an adequate answer is obtained, significantly exceeds the time available. Using techniques such as computational fluid dynamics, finite elements methods, and optimization an engineer can provide limited insight to the problem, to sharpen an answer, or to understand a design failure and further improve it.
- Computer Aided Engineering (CAE): Integration of real processes into the virtual environment. A methodology for storage and rapid access to engineering analyses, geometry, and all other qualitative and quantitative engineering data related to operation still needs to be developed and can be achieved through CAE.
- Engineering decision support tools: Optimization, Cost analysis, Scheduling, and knowledge-based tools that is to be integrated into the engineering processes.

Virtual engineering allows engineers to work with models in a virtual computer environment without having to think about the underlying technical information of the model which simplifies their task. With Virtual Engineering, one can possibly hope to answer questions that may be difficult or even impossible, costly, and/or unethical to answer through human subject testing. Owing to these reasons, many of the methods used in the following study is based on the practices followed in Virtual Engineering.

2.1.1 Virtual Prototyping

There is always great uncertainty when it comes to the performance of new design in real time scenarios. Engineers often used physical prototypes used as part of the product design process. It gave them ability to explore possible design alternatives, test design theories and performance and if possible even refine the design before commencing production of a new product. But it always required engineers, a great deal of skill, understanding and experience use physical prototypes as an effective design verification tool mainly because physical prototypes are very expensive in terms of time and cost.

However advancements in computer simulation and modeling have pushed physical prototypes back in time and have paved way for what is now known as Virtual Prototypes. Virtual Prototyping has rapidly gained popularity and is now an integral part almost any design processes. It has proved to be highly efficient in terms of time and money, to model all aspects of a design as a computer model (Virtual Prototype). For example see images below

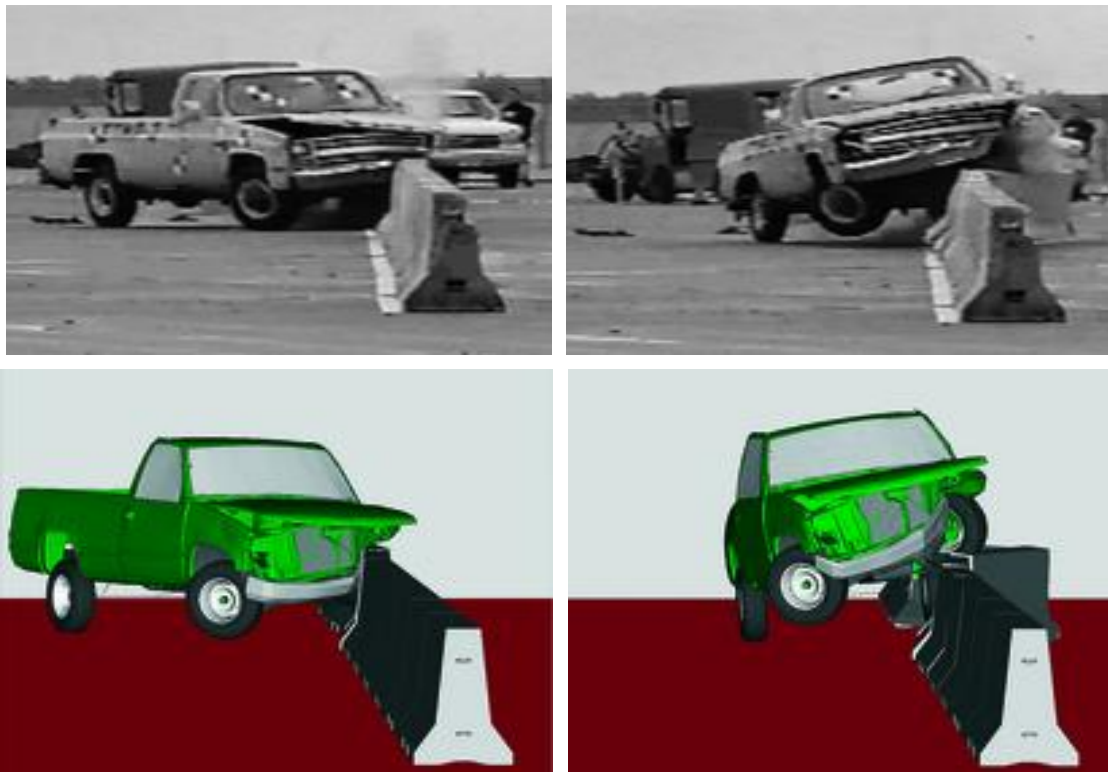


Figure 6: Above: Crash Tests on a Car (NCAC)

Figure 7: Below: Crash Simulation on a virtual prototype (NCAC)

2.1.1.1 Musculoskeletal Modeling

Researchers, clinical professionals and companies are now using virtual prototypes (Musculoskeletal Models) to study the kinematics, dynamics of movement in humans and also to develop related products. Advancements in the field of graphics and simulation have made it possible actually to visualize the responses

of a model in a 3D interactive virtual environment thereby allowing interpreting results and making modifications in a short time frame.

A musculoskeletal model, as the name suggests, is the representation of the skeletal and muscular structure in a system e.g. The Human being or an animal. The model also takes into account the Bio Mechanics that actually governs the movement of the system. Bones, joints, muscles, tendons etc. comprise of the basic elements of a typical musculo-skeletal system.



Figure 8: Musculoskeletal model of a Human holding an object (AnyBody)

An articulated mechanical system can be developed by linking the basic elements together. For instance Bones can be connected together by means of kinematic pairs or in other words “Joints”. By imposing constraints on motion of these joints, the articulated mechanical system can be made to produce any desired motion. The muscles are made span the joints and are used to develop force, thus generating moments about the joints. By calculating the joint moments that are generated by each muscle at anybody position an analysis of a musculoskeletal model can be performed. By manipulating a musculoskeletal model using the graphical interface, one can explore the effects of changing musculoskeletal geometry and other model parameters on the muscle forces and joint moments. These musculoskeletal models are paving the way for ground breaking research activities, products development and effective solutions in fields such as Robotics, Human ergonomics, Defense, Surgery, etc.

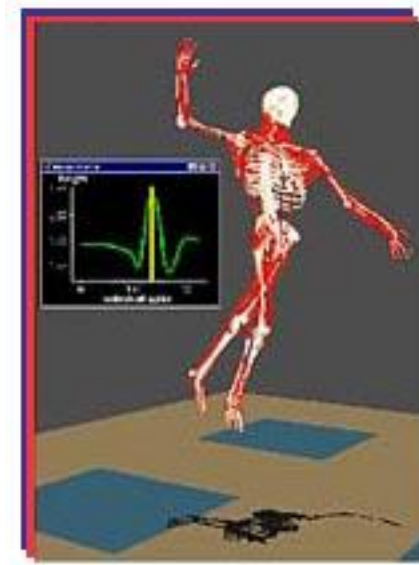


Figure 9: The figure above shows a human musculoskeletal model being used to study the motions involved while playing a game of Volley Ball –
(<http://www.musculographics.com/products/rtmotion.html>)

2.1.2 Bio Mechanics

So far we have seen how the virtual prototypes (Musculoskeletal models) can be created to suit their intended areas of applications. To study the forces, parameters involved in bodily motions, it is essential that the musculoskeletal models perform the desired motion in close resemblance to the actual motion to be studied. In order to achieve these test motions, the musculoskeletal models must be coupled with relevant algorithms that induce and govern movements in every component of the model. These algorithms are based on the concepts of Bio Mechanics, which in simple terms, is defined as the application of principles of mechanics to living organisms.

The Bio Mechanics of the Human body and any other living organism in general, is a result of the dynamics of 3 systems working in accordance with each other, namely:

- A) Musculoskeletal dynamics - The Musculoskeletal dynamics involves mechanical properties of the body and joints and the laws of motion to which they are subjected due to the earth's gravitational field.
- B) Actuator dynamics - For a model including muscles, actuator dynamics refers to the response of the muscle to the neural control signal. Such a model may include the electrochemical delay, force-length and force-velocity properties of muscle, tendon slack lengths, muscle fiber angles, curvilinear muscle wrapping paths, etc. These give rise to differential equations relating muscle activation to the force it

produces. The muscle force accelerates the body segments producing joint rotation and full-body motion

- C) Neural dynamics- Neural dynamics refers to the generation of control signals to selectively activate the appropriate muscles or joint moments at the correct time and with the necessary strength to accurately and efficiently produce the desired smooth, coordinated performance. Neural dynamics is perhaps the most complicated part of the total model.

The algorithms to be coupled with the musculoskeletal model must efficiently implement the dynamics of the 3 systems in order to reproduce the actual motion in the model to a significant level. (M, June 02)

2.1.3 Simulation

Simulation is a method based on the approach where numerous experiments are conducted on a model. Few of the benefits in using simulation as a part of Virtual Engineering is that it allows for control over the features and characteristics of the model, the experimental “test” conditions and can be used to assess the performance of mathematical models with remarkable accuracy. In the field of Bio Mechanics, performing simulated experiments on a virtual (computer) model is one of the most powerful methods to elucidate relationships between physiological structure and biomechanical performance. The simulation framework lends itself to predicting the effect of neural, muscular, or skeletal alterations on performance. It is a powerful tool which helps in the integration of many different kinds of biomechanical information from which meaningful interpretations can be deduced.

The concepts that go into the creation of virtual models are multidisciplinary in nature. Therefore assessing the consistency of models is a major obstacle to obtaining maximum benefit from simulation as a variety of strategies can produce a single movement. The similarity of model performance to reality does not ensure consistency between mathematical and natural control schemes.

Biomechanical simulation is therefore, still a developing field. Much of the effort goes into developing, controlling, and validating models. As the field matures efficient control techniques, accurate subject specific data acquisition methods, and supercomputing are a few areas that can significantly enhance the practical utility of simulation as a tool. (M, June 02)

3 Some Existing Virtual Engineering Software applications in the field of Bio Mechanics

3.1 Musculoskeletal Analysis Tools

With the recent development in computational technology, a number of biomechanical analysis tools have been developed for modeling complex musculoskeletal systems. In this section we will discuss some of the widely used tools and their limitations with respect to our analysis method and available data.

3.1.1 Software for Interactive Musculoskeletal Modeling (SIMM)

The SIMM Biomechanics Software Suite is a powerful and popular tool kit developed by MusculoGraphics, Inc to facilitate the modeling, animation and analysis of 3D musculoskeletal systems. Unlike traditional animation and CAD packages, the SIMM software suite is specifically designed to work with systems that consist of bones, muscles, ligaments and tendons.

Building dynamic models with SIMM requires substantial C programming which limits its use. SIMM also has substantial limitations on its ability to incorporate runtime changes of muscle excitation and external forces, which handicap its use to study control algorithms [16]. Hence, the above limitations on the software restricted its usage for the present analysis.

3.1.2 SIM Mechanics

SIM Mechanics is a tool with which mechanical systems can be analyzed and simulated in a virtual environment. A tool such as SIMM Mechanics eliminates the mathematical formulation usually performed by the user. Some of the key features of the software are:

- Modeling of three dimensional rigid body mechanical systems with block diagrams in Simulink
- Performing kinematic, forward, and inverse dynamic analysis of the systems.
- Enabling the implementation of high-fidelity, nonlinear plant models in Simulink to support the development and testing of control systems.
- Providing visualization tools for animating the models

In case of musculoskeletal models we need to define the mathematical models of muscles (obtained from physical experiments). Though many people tried to develop mathematical muscle models they could only capture part of the muscle properties. These difficulties have restricted us from using SIM Mechanics. (SIMM), (KONAKANCHI, MUSCULOSKELETAL MODELING OF SMILODON FATALIS FOR VIRTUAL FUNCTIONAL PERFORMANCE TESTING, 2005)

3.1.3 AnyBody

AnyBody musculoskeletal modeling software was developed as a part of the 'The AnyBody Project'. Its key features are (i) Incorporating real bone geometries to the models, (ii) calculating muscle forces by performing IDA, (iii) addresses issues such as redundancy, multiple muscle recruitment pattern etc.

Anybody and its features provide us with an ideal environment to explore our research goals and therefore the AnyBody software was made use of extensively in this independent study. (AnyBody) ,(KONAKANCHI, MUSCULOSKELETAL MODELING OF SMILODON FATALIS FOR VIRTUAL FUNCTIONAL PERFORMANCE TESTING, 2005)

4 Applications

A musculoskeletal model can be used for a number of applications. To name a few:

- Ergonomics
- Physiotherapy
- Studying the extinct creatures by reconstructing their musculoskeletal models,etc.

5 Project Goals

For our study, we focus on the use of musculoskeletal analysis and in particular the use of AnyBody software tool so as to provide a quantitative frame work to systematically study the performance characteristics. A study of the upper arm system performing the elbow flexion-extension under different loading conditions and assistive methods was done.

Our main aim is to create an Exoskeleton model for a human arm which can be used as a loading device or an assistive device.

6 Implementation

6.1 Creation of Arm Model

A musculoskeletal model is a combination of bones, muscles, tendons, joints, etc. The software is developed in such a way that all these elements are built in a systematic manner to perform kinematic and dynamic analysis. In this section, we describe the overall procedure of building the Arm Model in Anybody, as shown in below.

- 1) Define Global Fixed frame and corresponding Fixed points
- 2) Define Segments or rigid elements (like bones etc.)
- 3) Define various Joints (Joint Constraints)
- 4) Define Drivers to move the Joints
- 5) Define Muscles and run the Analysis

The resulting Arm curl model is shown in the figure below which is obtained the Anybody model repository.

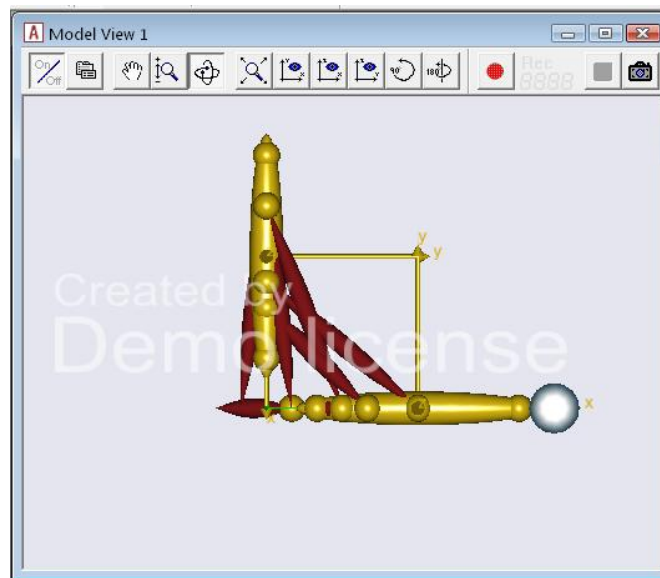


Figure 10: Arm Curl Model in Anybody

We can have a more complicated model of an arm with complex muscles, but for our study we conduct the various analyses using this simple model.

The different muscles in the above model are:

- 1) Brachialis
- 2) DeltodeusA
- 3) DeltodeusB
- 4) Brachioradialis
- 5) Biceps Short
- 6) Triceps Short
- 7) Biceps Long
- 8) Triceps Long

6.2 Exoskeleton Model Creation

To create an Exoskeleton we need to have two more segments connected to the Arm Model appropriately. The main challenge here is to make a kinematically determinant model, where the number of degrees of freedom of the system should be equal to the number of constraints. We accomplished this in two different ways and created two Exoskeleton models and compared the performance of them.

6.2.1 Exoskeleton Model 1

To create the Exoskeleton model, the Arm Model above is taken as a starting point. Then two segments named UpperExo and LowerExo are added to the Arm Model and connected by giving appropriate joints and drivers.

Two extra nodes are added to the Upper and Fore Arm segments to provide attachment points to the Exoskeleton segments.

Two segments identical to Upper and Fore Arm segments are added to the Arm Model and displaced by a distance of 0.03m from the corresponding segments.

The Exoskeleton segments are connected to the appropriate Arm Segments at the appropriate nodes.

- a) An exo-elbow joint is created between the two Exoskeleton segments
- b) The elbow joint in the actual model is removed to resolve the redundancy in the system.
- c) The UpperArm and UpperExo are connected by a revolute joint.
- d) The UpperExo and LowerExo are connected by a revolute joint
- e) The ForeArm and LowerExo are connected by a prismatic joint
- f) The exo-elbow joint is now driven by a AnySimpleDriver
- g) The segments are drawn in an easy to see way using the AnyDrawSTL command in Anybody to replace the segments. The STL (Stereo Lithography) files themselves are made using Pro-E software.
- h) The application of the force at the palmnode is now decided.

The resulting model is as shown in the figure below:

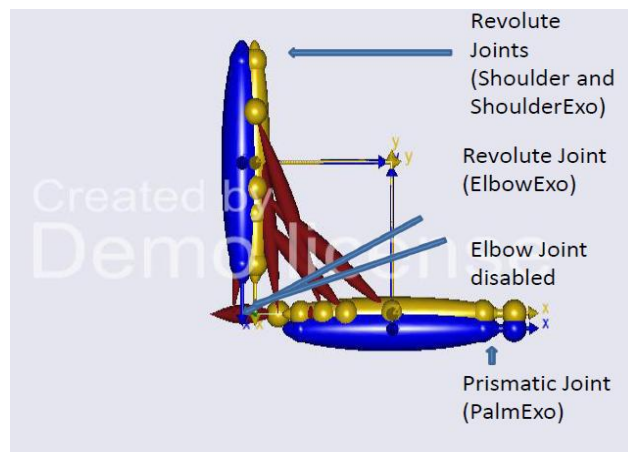


Figure 11: Exoskeleton (Model1)

6.2.2 Exoskeleton Model 2

To create the Exoskeleton model, the Arm Model above is taken as a starting point. Then two segments named UpperExo and LowerExo are added to the Arm Model and connected by giving appropriate joints and drivers.

Two segments identical to Upper and Fore Arm segments are added to the Arm Model and displaced by a distance of 0.03m from the corresponding segments.

- a) An exo-elbow joint is created between the two Exoskeleton segments
- b) The UpperArm and LowerArm are connected by a revolute joint
- c) The UpperArm and the UpperExo are connected by a spherical joint.
- d) The UpperExo and the LowerExo are connected by a revolute joint.
- e) The ForeArm and the LowerExo are connected by a cylindrical joint.
- f) The Elbow joint is now driven by a AnySimpleDriver.
- g) The force is applied at the PalmNode.

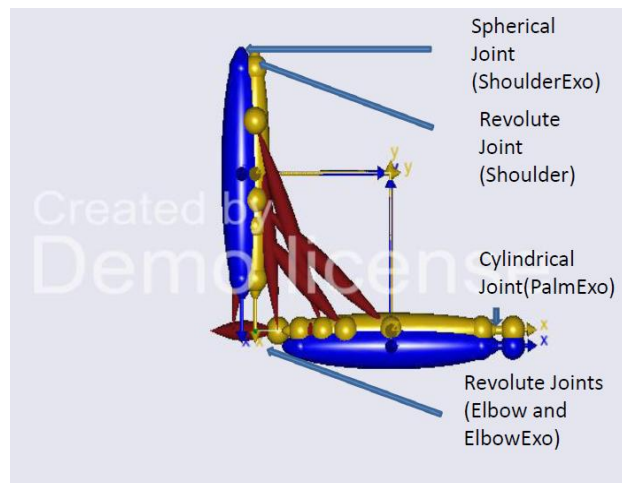


Figure 12: Exoskeleton (Model2)

6.3 Analysis

Once the model is built, the software has the capability to perform a number of studies that will help in the analysis of the results. There are mainly 4 different modes in the Anybody study. They are:

- Setting Initial conditions
- Kinematic Analysis

- Inverse Dynamic Analysis
- Muscle Calibration Analysis

6.3.1 Setting Initial Conditions:

Helps in tuning the parameters that define the initial configuration of the model, i.e. the starting position of the simulation. In order to perform any type of analysis, the model needs to be kinematically determinate right from the initial stage.

6.3.2 Kinematic Analysis:

In kinematic analysis, the main emphasis is on the system motion without taking into consideration of the forces or reactions that are acting on/by the system. However, the system has to be kinematically determinate, where the number of equations to solve the system is equal to the number of unknowns. If there are 'n' segments in the system the model will have a total of $6n$ degrees of freedom, unless they are constrained. In order to solve these $6n$ unknowns, we need $6n$ equations. The main purpose of this kinematic analysis is to solve for these $6n$ unknowns, i.e. the position and orientation of all the segments at all times throughout the simulation process. From the kinematic analysis we can obtain the position, velocity and acceleration information for each and every point of interest.

6.3.3 Inverse Dynamic Analysis:

Inverse dynamics analysis (IDA) can be thought as the main process that lead to the success of AnyBody modeling system. Muscle and reaction forces are calculated by setting up the equations of motion. Problems pertaining to static indeterminacy, limitations on the maximum muscle forces need to be resolved before the analysis. Redundancy posed by the system indicates that there is no unique solution to the inverse dynamics problem. While performing a body motion the muscles collaborate according to some rational criteria. These criteria when combined with the fact that muscles can only pull and not push results in a unique recruitments pattern. This suggested that the central nervous system applies some sort of optimality criteria to determine the muscle activation order. If such optimal criteria are combined with the equilibrium equations, we can have unique solution for the problem. The basic optimality assumption is that "the body attempts to use its muscles in such a way that fatigue is postponed as far as possible".

6.3.4 Muscle Calibration Analysis:

A muscle tendon unit is generally attached to two segments i.e. one at the origin and the other at the insertion. These muscles wrap around the joints and bones. During the range of motion it is assumed that the muscle-tendon unit has its optimal length at some particular position of the joint span. The muscle calibration analysis adjusts the length of the tendons such that the optimal length is obtained in the middle of the

simulation. If we run the IDA after the calibration analysis, the simulation makes use of these calibrated tendon lengths for the calculating the muscle forces.

Anybody has three types of muscle models. The simple muscle model is not affected by the calibration analysis while the other two that have force-length relationships (Hill Model) do have an effect.

6.4 Optimization

The purpose of creating an Exoskeleton is to provide assistance to human arm for lifting of heavy weights (like dumb-bells). Here is where optimization comes into picture. The Exoskeleton has to provide assistance such that the muscle forces in the arm are minimized to the maximum possible extent. The main problem here is to know what are the optimum(in our case minimum) muscle forces, and determine the torque that is required to be applied at the Exoskeleton joint to achieve this desired optimum muscle forces, depending on the weight that the arm is supposed to lift.

- a) The AnyBody modeling system has a nice mechanism that allows to perform optimization. The AnyOptStudy is one such functionality. It's a systematic way to vary a number of model parameters and have the system automatically run one or several analyses for each combination of parameters.
- b) Using the above functionality that AnyBody modeling system provides our objective of minimizing the muscle forces can be set up as an optimization problem. The objective here is to minimize the muscle forces i.e to reduce the energy consumed by the muscles while doing the exercise. And minimizing the energy consumption of the muscles during the exercise directly minimizes the muscle forces produced while doing the exercise. Therefore, we choose the objective function as Metabolic energy consumption. And the design variable here is the 'Moment' that we are going to give at the Exoskeleton joint. Thus in the study it becomes the parameter. And we vary this parameter over a range of values and run the inverse dynamic analysis for each value and compute the corresponding muscle forces. And the moment at which we obtain minimum muscle forces is our required optimum. However, we have to choose the range of values over which the moment has to be varied. Setting up this Optimization problem forms an important part of our study. Therefore, we would like to look into the code that does this which is provided in the appendix section of the report.
Objective Function: Minimize Metabolic Energy Consumption
Subject to: Moment
Where in: $Moment_{Min} < Moment < Moment_{Max}$

6.5 GUI Implementation in MATLAB

In our Study Matlab is used for the following purposes:

- To create a GUI which can take system parameters like Force lifted, body weight, simulation time etc from the user.
- Update the AnyBody model files with the new parameters.
- Run the AnyBody analysis using 'AnyBodyCon' executable.
- Read the results from the AnyBody output files and display them in GUI.

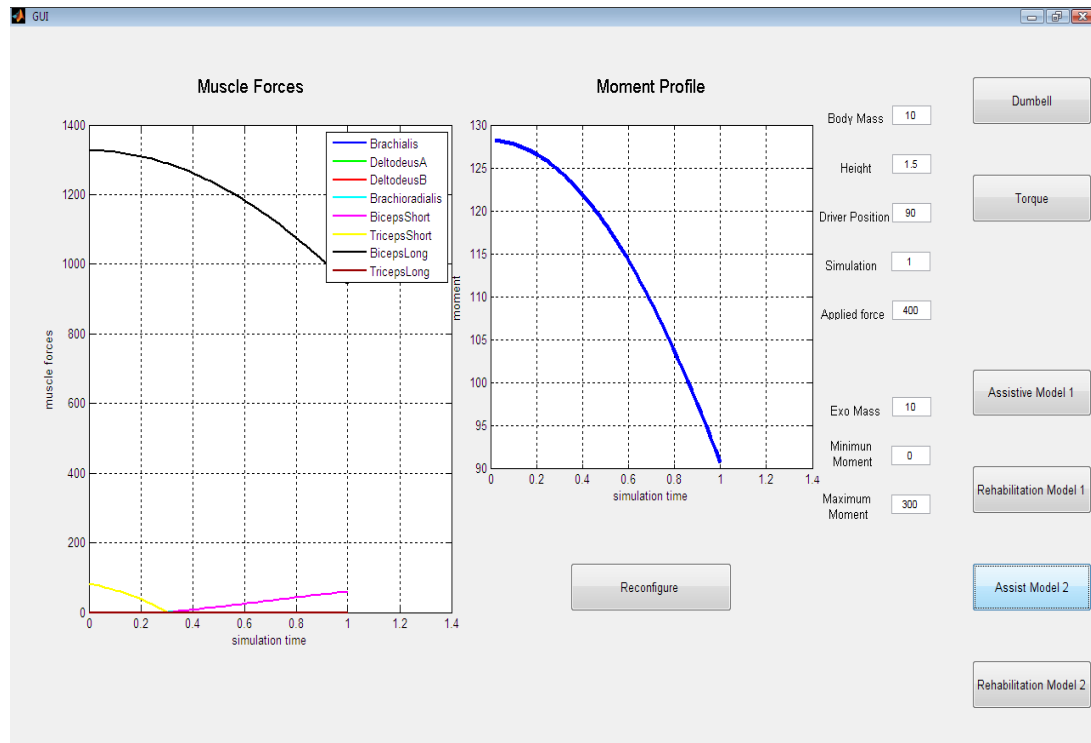


Figure 13: Graphical User Interface

The input parameters are:

- Force: The force expressed in terms of mass, in kg, that has to be lifted.
- Simulation Time: The total time of the movement in seconds.
- Body-Mass: The mass of the arm segments and Exoskeleton segments is directly proportional to this parameter.
- Height: The length of the arm segments and Exoskeleton segments is directly proportional to this parameter.
- Driver Position: The angle, in degrees, at which the exercise should start
- Driver Velocity: The angular rate, in degrees/sec, at which the exercise should be done
- Moment Min: The minimum torque applied by the motor of the Exoskeleton
- Moment Max: The maximum torque applied by the motor of the Exoskeleton

The various entities used in the GUI are:

- a) Axes: Used to plot graphs
- b) Push Button: To select between different modes of operation.

There are two plots in the GUI:

- a) Muscle Forces: It plots the muscle forces in different modes
- b) Torque Graph: It plots the torque profile required at the Exoskeleton joint to produce the required effect

7 Results

In the inverse dynamic analysis the arm is allowed to do the arm curl motion against the resistance (dumb-bell/Torque). The muscle forces for the six different cases of study are obtained. The results below are plotted for the given values of the model parameters:

Body Mass: 60 Kg

ExoMass: 10 Kg

Height: 1.5 m

Simulation Time: 1 sec

Driver Position: 90 deg

Driver Velocity: 45 deg/sec

Applied Force/Torque: 400 N (Nm)

MomentMin: 0

MomentMax: 300

Case1: Dumb-bell

In this case the arm model is used to lift a dumb-bell of given mass (AppliedForce) from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec.

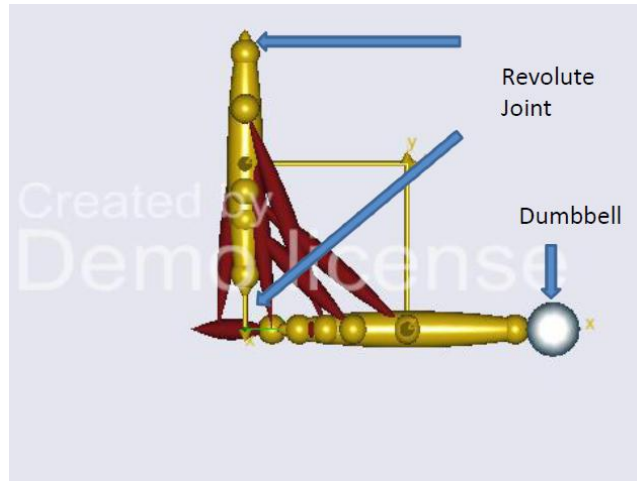


Figure 14: Lifting a dumbbell

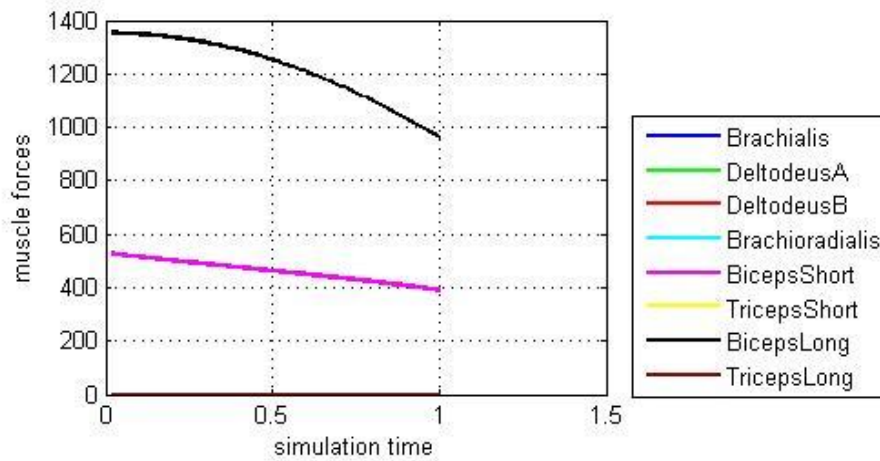


Figure 15: Muscle Forces

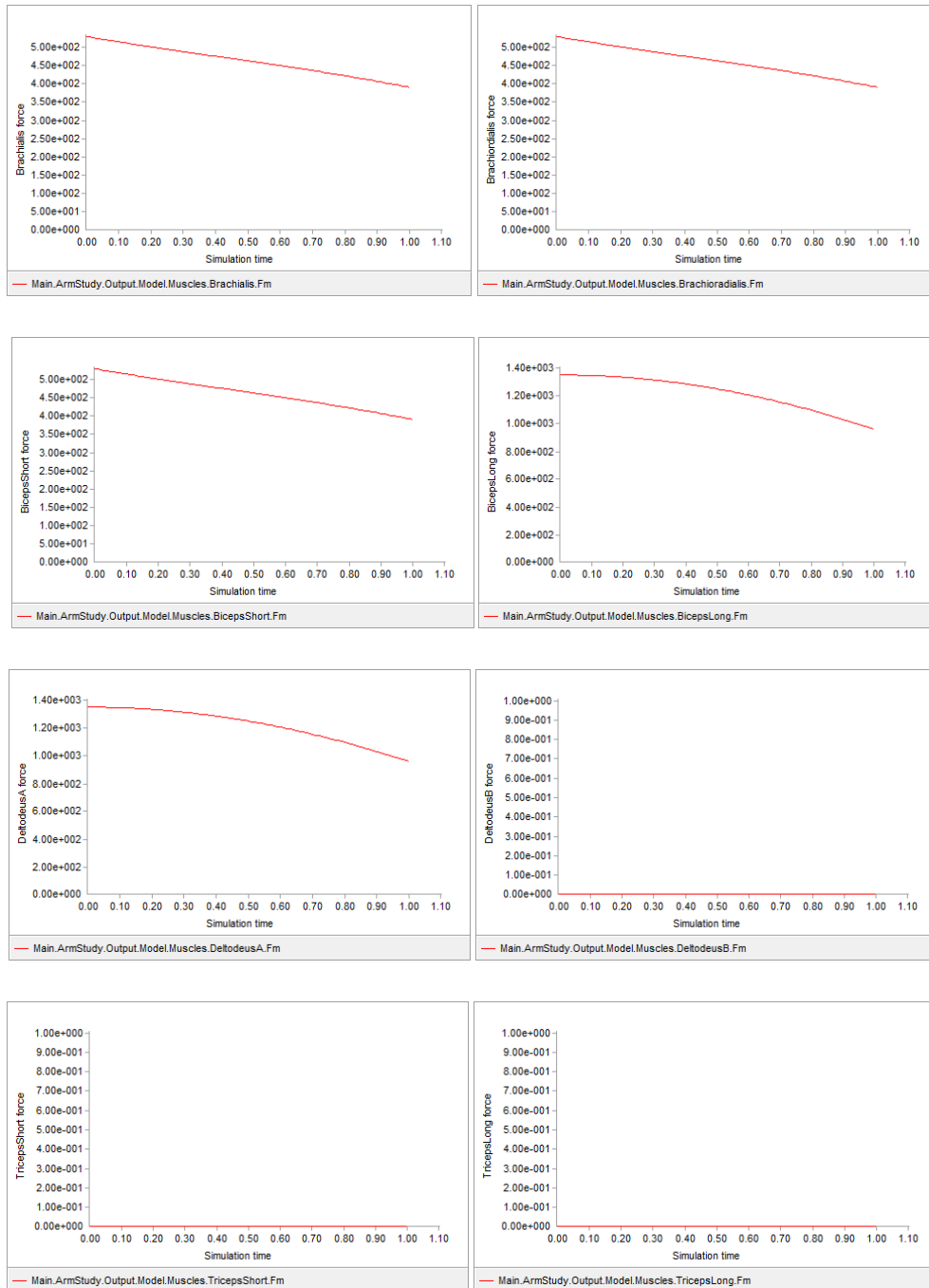


Figure 16: Individual Muscle Forces

Case2: Torque

In this case the arm model is used to do an arm-curl against a torque of 400 Nm applied at the elbow joint from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec.

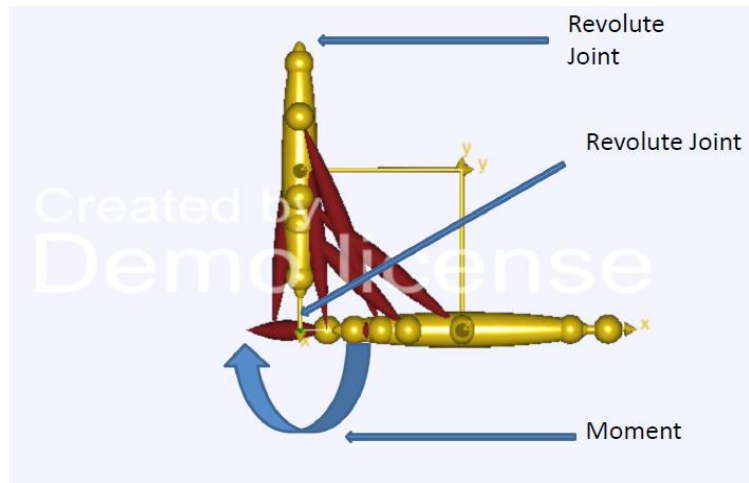


Figure 17: Lifting against a moment at elbow joint

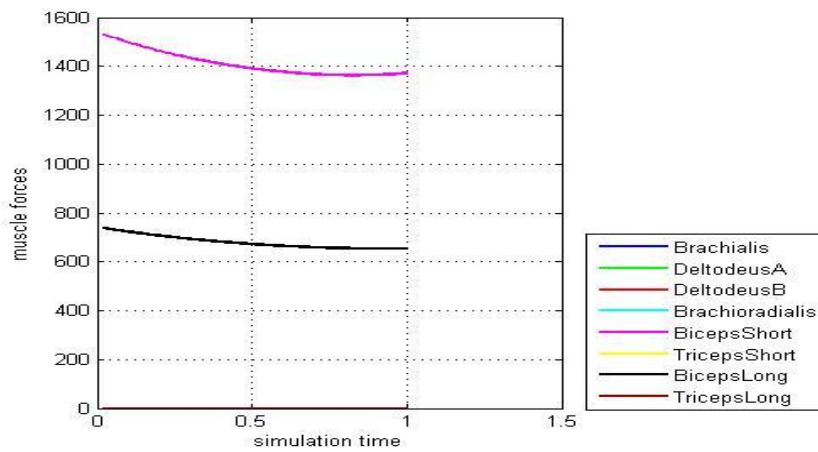


Figure 18: Muscle Forces

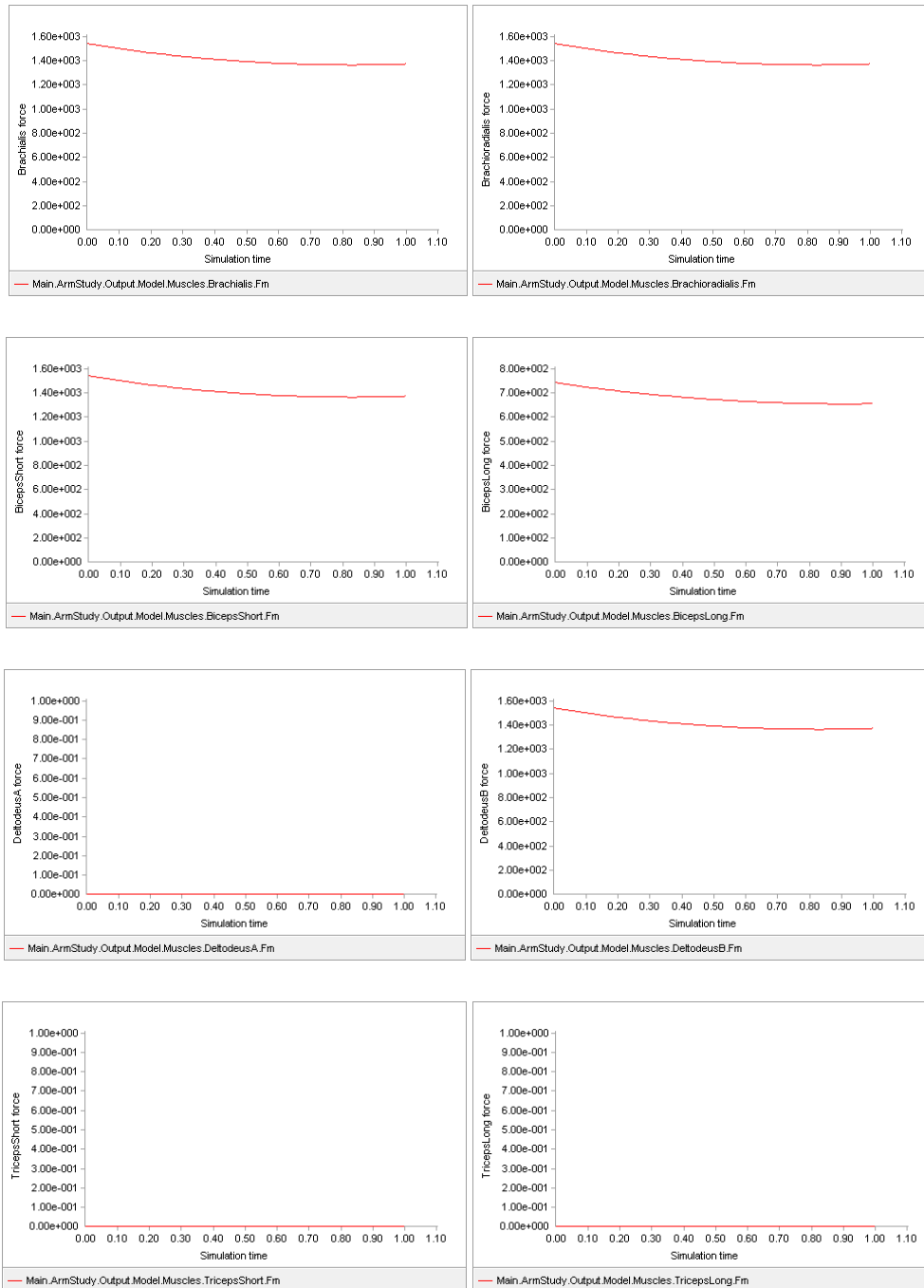


Figure 19: Individual Muscle Forces

Case3: Exoskeleton for Assistance (Model 1)

In this case the arm-curl model is equipped with an Exoskeleton model 1 and it is used to lift a dumbbell of given mass (AppliedForce) from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec. Here the moment applied at the Exoskeleton joint is varied until we obtain the minimum possible forces in the muscles.

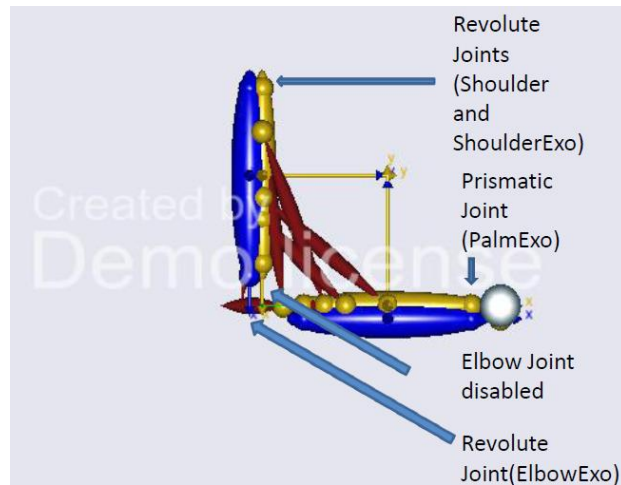


Figure 20: Lifting a dumbbell with the aid of an Exoskeleton (Model 1)

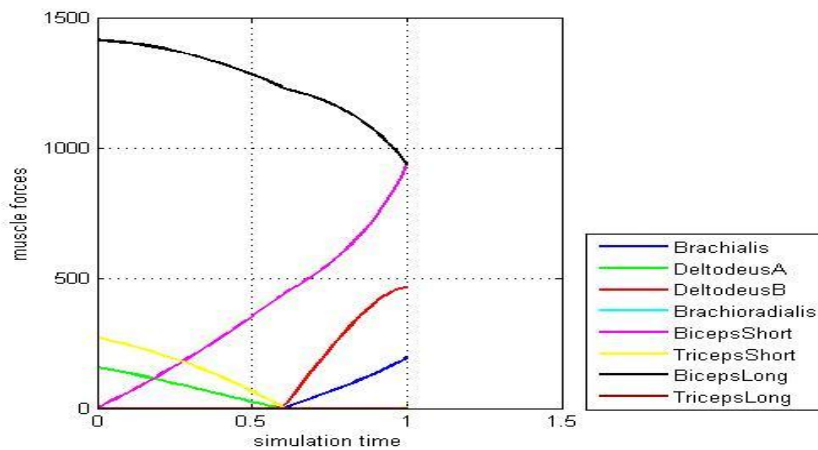


Figure 21: Muscle Forces



Figure 22: Individual Muscle Forces

Case4: Exoskeleton for Rehabilitation (Model 1)

In this case the arm-curl model is equipped with an Exoskeleton model 1. A torque of 400 Nm is applied at the elbow of the Exoskeleton joint and the arm-curl motion is performed from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec.

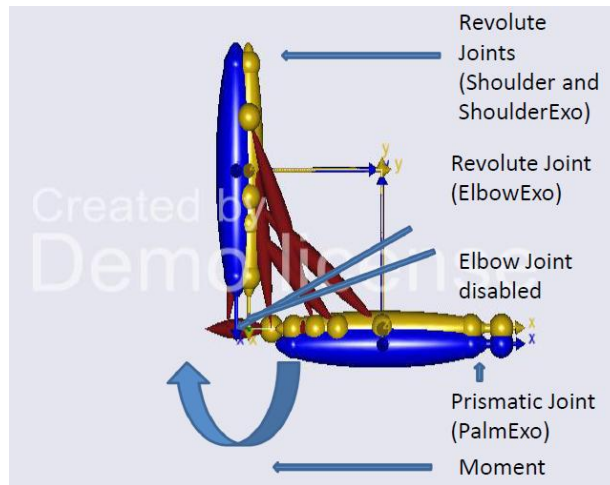


Figure 23: Performing arm-curl against a moment applied by the Exoskeleton (Model 1)

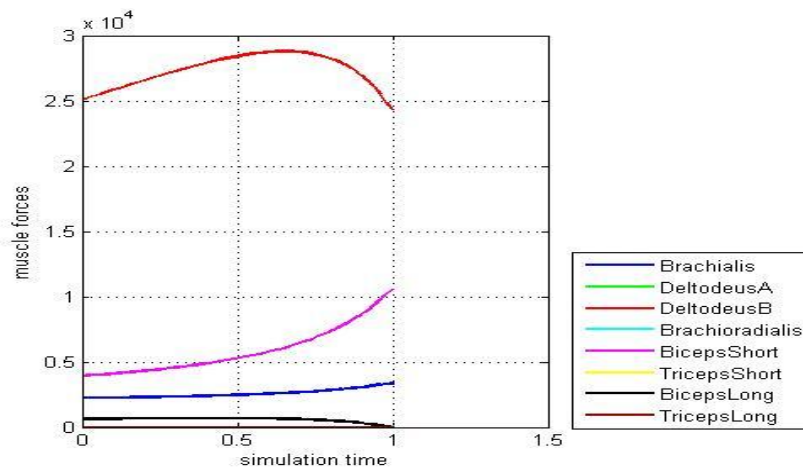


Figure 24: Muscle Forces

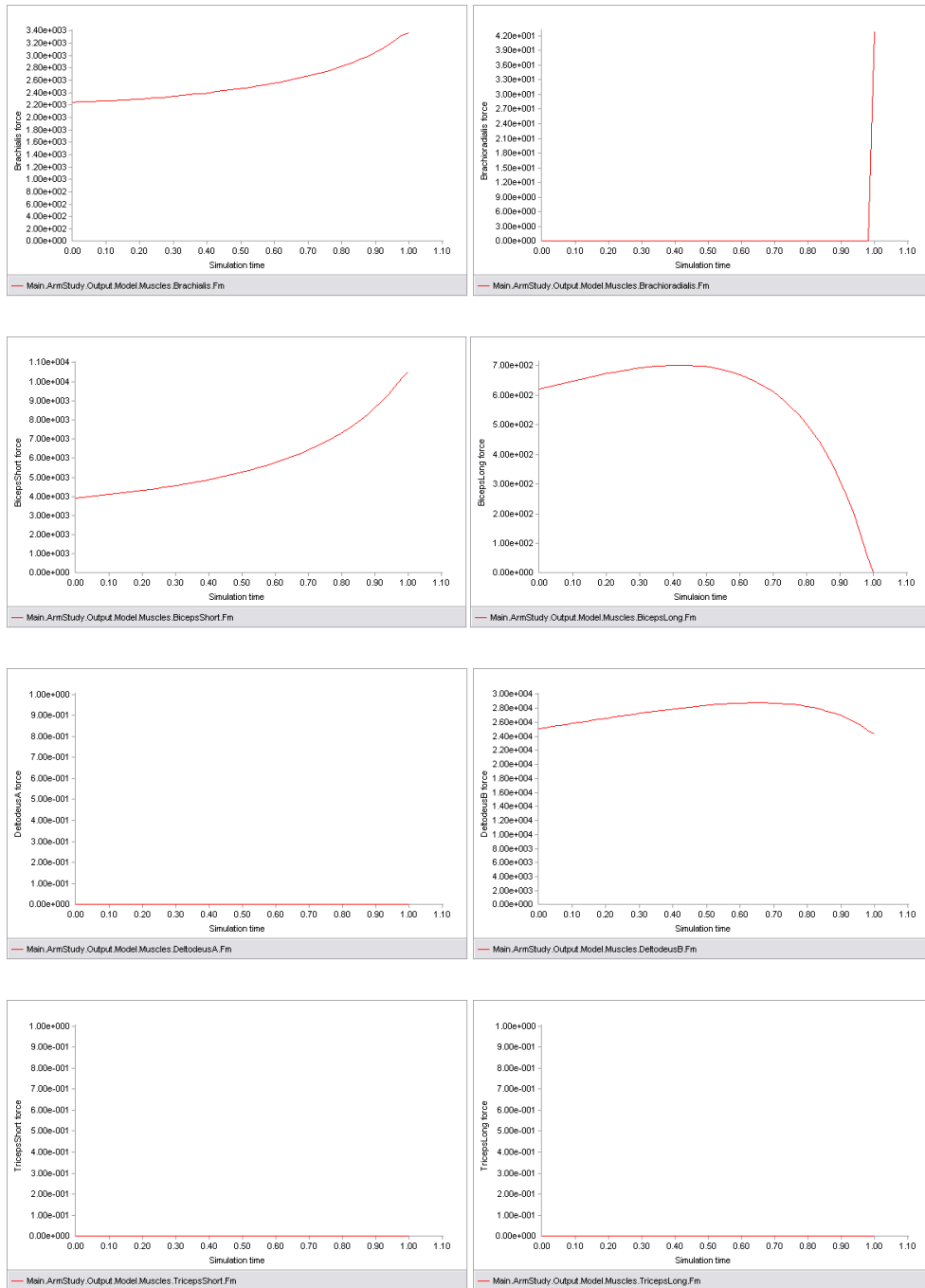


Figure 25: Individual Muscle Forces

Case5: Exoskeleton for Assistance (Model 2)

In this case the arm-curl model is equipped with an Exoskeleton model 2 and it is used to lift a dumbbell of given mass (AppliedForce) from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec. Here the moment applied at the Exoskeleton joint is varied until we obtain the minimum possible forces in the muscles.

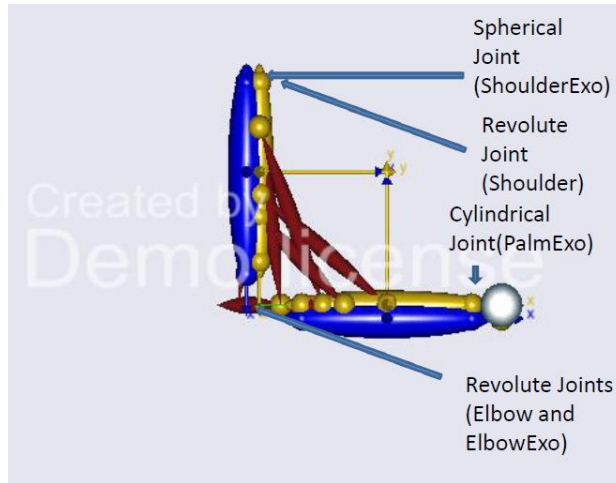


Figure 26: Lifting a dumbbell with the aid of an Exoskeleton (Model 2)

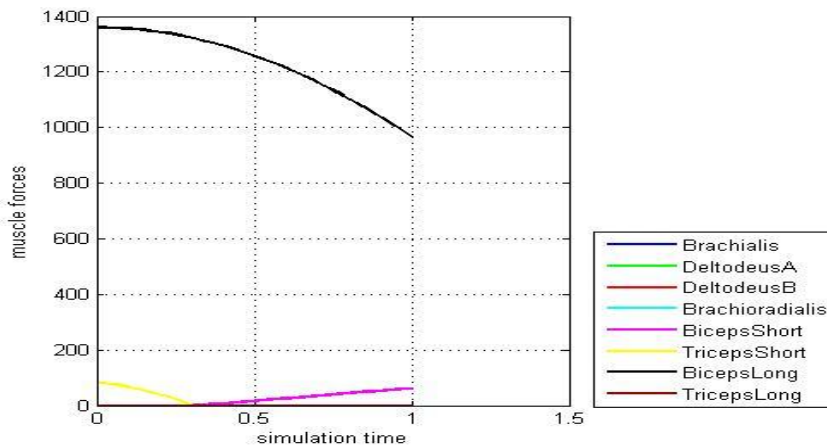


Figure 27: Muscle Forces

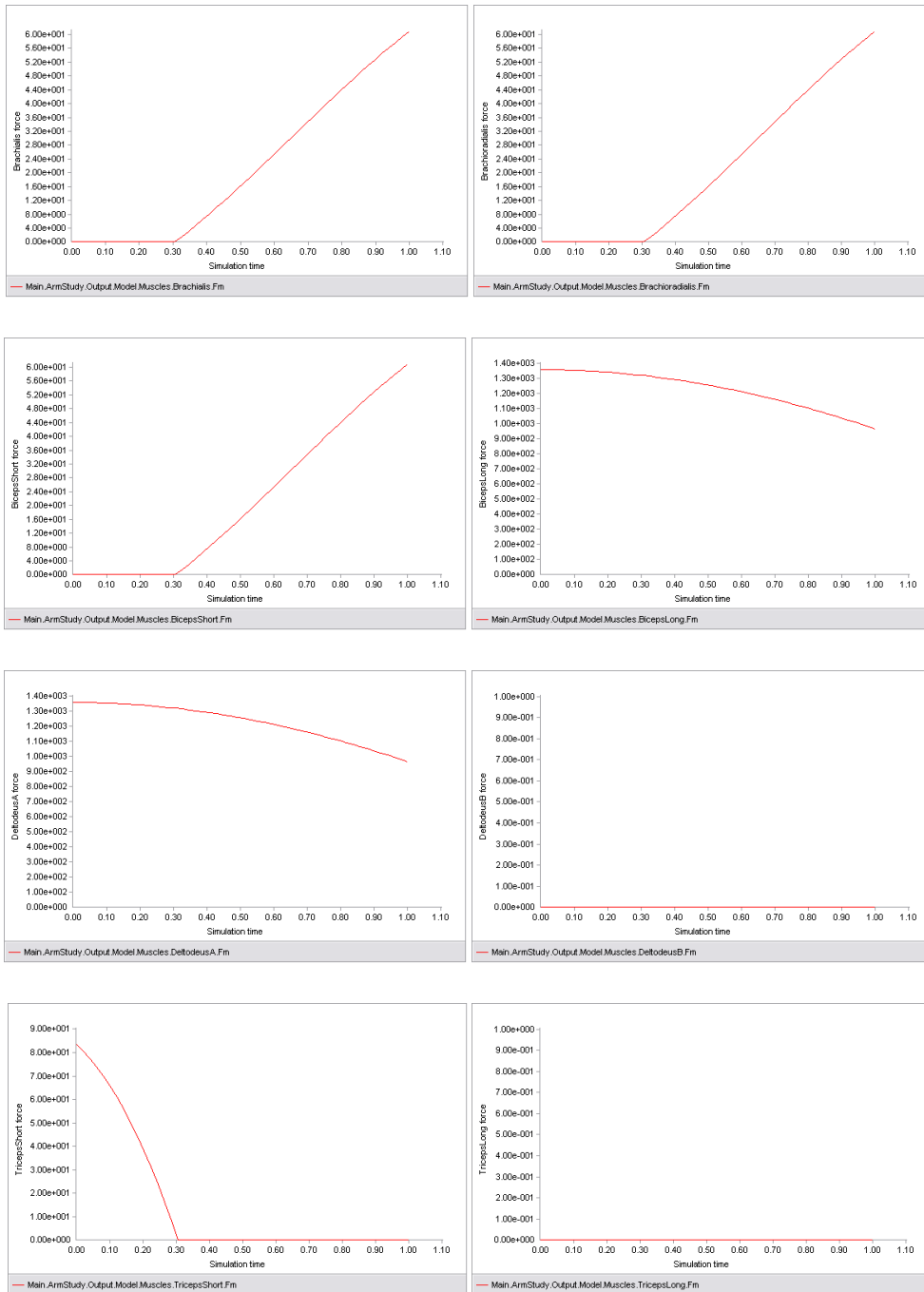


Figure 28: Individual Muscle Forces

Case6: Exoskeleton for Rehabilitation (Model 2)

In this case the arm-curl model is equipped with an Exoskeleton model 2. A torque of 400 Nm is applied at the elbow of the Exoskeleton joint and the arm-curl motion is performed from a start angle of 90 deg at a velocity of 45 deg/sec for 1 sec.

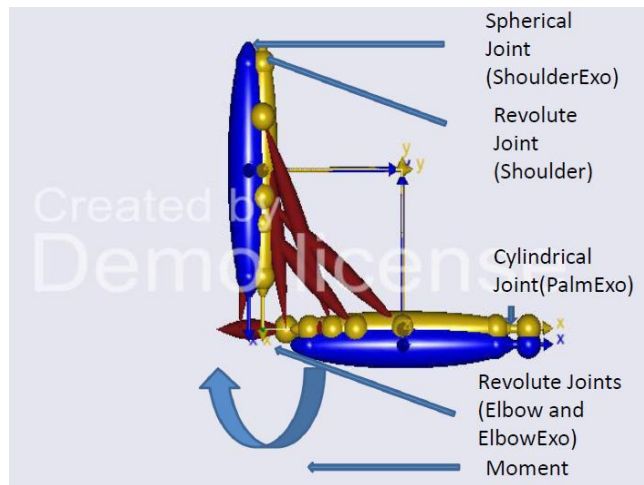


Figure 29: Performing arm-curl against a moment applied by the Exoskeleton (Model 2)

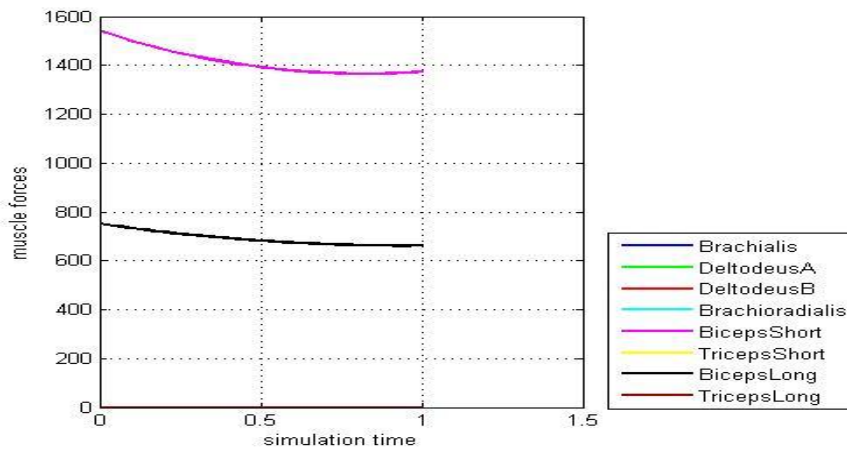


Figure 30: Muscle Forces

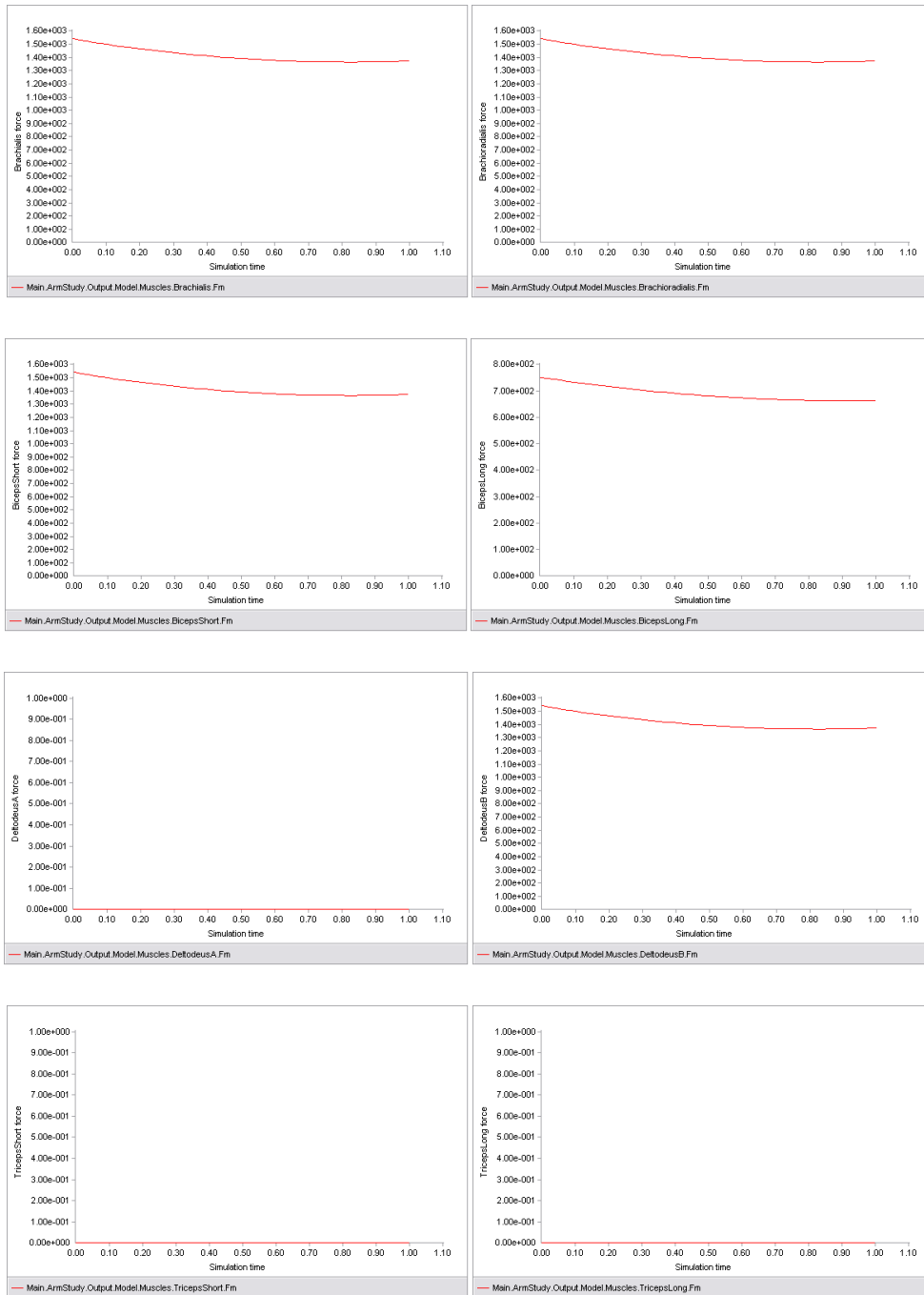


Figure 31: Individual Muscle Forces

8 Discussion

GE's attempt in creating the "Hardiman" in 1965 opened up new regions in the field of engineering that required exploration. It was one of the first attempts in drawing "Exoskeletons" into real world. With inadequate knowledge and relatively primitive technology the "Hardiman" project proved to be a failure but nevertheless, a stepping stone into the future.

The prime focus of our study was the working mechanism, performance of the Human arm and the Human arm – Exoskeleton integrated system. During the course of our study we were able to explore the modeling, analysis, optimization and the GUI features of the AnyBody and Matlab software packages. We developed our model based on certain assumptions in an attempt to avoid the brunt of the complexity that our study posed. We then tested our model for consistency. Once our model of the Human arm was established we further modified it to accommodate the Exoskeleton and subjected the integrated system to tests for consistency and performance. Comparison of the test results of the integrated system with those of the arm model showed that the integrated system performed better than the arm model.

While performing this study, we had the opportunity to understand and apply the concepts of biomechanics and musculoskeletal modeling to figure out the performance characteristics of our virtual models. Apart from our intended goals and objectives, we were able to identify possible venues for application and future scope of our study.

8.1 Why the above six cases?

The main objective of our study is to create an Exoskeleton model for a human arm which can be used as a loading device or an assistive device. To accomplish this we first had to choose the elbow flexion exercise for which the Exoskeleton model is developed. Then we had to look into the muscle forces developed when the arm performs the lifting exercise (case 1). And finally we develop an Exoskeleton which minimizes the muscle forces when the same lifting is performed (case 3).

To develop an Exoskeleton model which can be used as a loading device we first had to look into the muscle forces developed when the same exercise is performed when a certain torque is applied at the elbow joint (case 2). Now we repeat the same exercise by applying the same loading moment at the exo-elbow joint (case 4).

Based on the performance of the Exoskeleton model 1, we developed a second Exoskeleton model by changing the connection points, joints and drivers which showed improvement in the overall performance. This is demonstrated in case 5 and case 6.

8.2 Comparison of results

Muscles	Dumbbell	Assistive Model 1	Assistive Model 2	% reduction in muscle forces (Model 1)	% reduction n muscle forces (Model 2)
Brachialis	515.30	190.42	59.43	63.04	88.46
DeltodeusA	1319.34	152.13	1326.02	88.46	-.50
DeltodeusB	0	465.75	0	0	0
Brachioradialis	515.30	1.81	59.43	99.64	88.46
BicepsShort	515.30	917.2	59.43	-77.99	88.46
TricepsShort	0	262.79	81.49	0	0
BicepsLong	1319.34	1377.72	1326.02	-4.42	-.5
TricepsLong	0	0	0	0	0

Table 1: Comparison of peak muscle forces in assistive mode

Muscles	Dumbbell	Assistive Model 1	Assistive Model 2	% reduction in muscle forces (Model 1)	% reduction n muscle forces (Model 2)
Brachialis	1530.04	2225.42	1531.96	45.44	.12
DeltodeusA	0	0	0	0	0
DeltodeusB	1530.04	28494.68	1531.96	1762.34	0.12
Brachioradialis	1530.04	54.04	1531.96	-96.46	0.12
BicepsShort	1530.04	10412.16	1531.96	580.51	0.12
TricepsShort	0	0	0	0	0
BicepsLong	688.65	683.43	699.14	-.75	1.52
TricepsLong	0	0	0	0	0

Table 2: Comparison of peak muscle forces in rehabilitative mode

From the results we could clearly see that the muscle forces are minimized by the Exoskeleton. However, the Exoskeleton model 1 has clearly two problems:

- a) When used as an assistive device at high moments the muscle recruitment analysis failed when one of the muscle forces goes to zero
- b) When used for loading it gave rise to huge muscle forces.

The performance of the second model was much better both as an assistive and loading device.

8.3 Future Scope

- Develop a more complex model of the human arm that takes into consideration more muscles and actual bone geometry of the human arm.
- Test the performance of the Exoskeleton system on a musculoskeletal model of the whole human body.
- Develop a lower Exoskeleton model for the human body and to test the combined performance of the upper and lower Exoskeleton systems while working in unison.
- To fabricate an actual prototype.

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Annexure

1) Code

The Optimization problem described in section 6.2 of the report is set up as follows:

```
AnyOptStudy OptStudy =  
{  
    Analysis = {  
        AnyOperation &Operation = ..Study.InverseDynamicAnalysis;  
    };  
    AnyDesVar Moment = {  
        Val = Main.ArmModel.Moment;  
        Min = Val + Main.ArmModel.MomentMin;  
        Max = Val + Main.ArmModel.MomentMax;  
    };  
    AnyDesMeasure Metab = {  
        Val = Secint(..Study.Metabolism()...Study.tArray);  
        Type = ObjectiveFun;  
    };  
};
```

In the above code:

Analysis provides the specification of operation(s) to perform to provide the data we are studying in the parameter study which in our case is Inverse Dynamic Analysis.

AnyDesVar is the parameter that is varied in the study for which the model is analyzed.

AnyDesMeasure specifies a property that is a result of the analysis and which must be collected for further inspection as the study proceeds.

The properties we wish to study i.e design measures of the model are defined in the AnyBodyStudy as follows:

```
AnyBodyStudy ArmStudy = {  
    AnyFolder &Model = .ArmModel;  
    RecruitmentSolver = MinMax00SolSimplex;  
    Gravity = {0.0,-9.81,0.0};  
    tEnd = Main.ArmModel.SimulationTime;  
    nStep = 50;  
    AnyVar Pmet = Main.ArmModel.Muscles.Brachialis.Pmet+ Main.ArmModel.Muscles.DeltodeusA.Pmet  
    + Main.ArmModel.Muscles.DeltodeusB.Pmet+ Main.ArmModel.Muscles.Brachioradialis.Pmet+
```



```
Main.ArmModel.Muscles.BicepsShort.Pmet+ Main.ArmModel.Muscles.TricepsShort.Pmet+  
Main.ArmModel.Muscles.BicepsLong.Pmet+ Main.ArmModel.Muscles.TricepsLong.Pmet;  
AnyOutputFun Metabolism = {  
    Val = .Pmet;  
};
```

So we use the metabolism of the muscles calculated in the AnyBodyStudy in the Optimization routine to find the optimum moment that gives rise to minimum metabolic energy consumption.