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Computational Modelling of Musculoskeleton to Predict Human Response with Upper Arm Exoskeleton

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ABSTRACT

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There are many situations where elderly people find it difficult to do their daily work, stroke affected people face difficulty in doing their daily routines independently, soldiers of the country also face problems in carrying heavy loads in rough terrains for long time. An external wearable outfit which increases the capabilities of a normal human being is called the exoskeleton. To design and manufacture an upper arm exoskeleton for upper extremity of human body, computational studies and analysis is to be made as the working model is a wearable device, it should not harm the user in any condition. To analyze the effect of wearing an upper arm exoskeleton, an inertial measurement unit is placed on a subjects forearm at the center of mass point. The specified arm movement considered in sagittal plane is performed wearing the IMU so that the angular displacement readings are extracted. The extracted data is fed to a human body simulation software lifemod where the human model does the same arm movement as the subject. Kinematic parameters are plotted from the software, to check whether the software's reading is appropriate a mathematical model is developed using lagrangian equation for the same arm movement in sagittal plane and the torque equations obtained are solved using matlab software. Both the plots of kinematic parameters are compared. The plots from both software's match perfectly proving that the simulation software readings are near to reality. Muscle activation plots without exoskeleton condition are plotted for different weights and for different wrist positions. An upper arm exoskeleton is designed in ADAMS software and is imported to the model and analysis is made while lifting different weights and for different wrist positions. Muscle activation plots are obtained for all the cases with exoskeleton condition. Muscle activation values from with and without exoskeleton condition proves the usefulness of using an exoskeleton. The muscle activation is very low in case while using an exoskeleton which shows that with minimal human effort more work can be done.

Keywords : Exoskeleton, Inertial Measurement Unit, Lifemod Software, Mathematical Model, Lagrangian Equation, Muscle Activation

I. INTRODUCTION

On earth, humans stand as the superior, when it comes to intellectual thinking. Nature has been kind to humans and given them the power to think. But humans do not enjoy the same benefits when it comes to physical strength. Many creatures of nature have exhibited strengths that are far more powerful than what humans are capable to do. Humans thrive to better their physical strengths to accomplish many tasks. Humans adopt to the terrestrial environment they grow up in. Sometimes nature also has its darker side on humans by denying them with certain basic physical abilities like walking, grasping etc. which are accomplished by the use of their hands, legs and other parts of the body. We come across many situations like elderly people facing difficulty doing their day to day work, stroke affected people face difficulty in walking by their own and even the brave soldiers of the country find it difficult to carry different things like weapons and other essentials to far places as it weighs too much and their working conditions are adverse. Humans are very keen observers of these issues and aim to tackle such inabilities with his intellectual thinking.

Man's ability to solve problems and the advancement of science and technology has demanded to improve and better the physical abilities of humans. Traditional physical therapy have made a serious impact on improving the muscle strength of humans. This comes with many therapy techniques which concentrate on particular muscle and aim in controlling them. These therapies have their own disadvantages such as, it needs more time and patience by both the trainer and the patient, these exercises sometimes are very inconsistent and there are no accurate measuring method to check the patient's progress. With advancement in science and technology, we humans have always tried to integrate latest technologies like robotics, artificial intelligence, biomechanics and many other wide range of fields to tackle such inabilities of humans. Many attempts to recover the physical disabilities have been developed and have proved to be a better alternative for physical therapy as they are more effective and efficient. Robotic rehabilitation is a research field that tries to understand the rehabilitation process and improve it by applying robotics devices. This rehabilitation process develops therapies using robots as therapy aids devicesone such rehabilitation device which has been a topic of great concern and development is exoskeleton.

The exoskeleton word is derived from Greek language, where "*exo*" = outer, "*skeletos*" = skeleton, is an external structure that supports and protects human body. For decades engineers and scientists have designed and prototyped many models of exoskeleton. With advancement in technology portable ones with actuators that can be embedded in the device and new power sources have been investigated and studied. All these advancements have given the path way in taking exoskeletons to a whole new level and to reach morecloserto real life joints.

The first device that can be considered a precursor of modern exoskeletons is a machine called Hardiman shown in figure 1.1. It was developed by General Electric in 1965 and was intended to allow the user to lift 25 kg, but the user should feel it as just 1 kg. The device has never been used in practice, since any attempt to perform manoeuvres by the user became a violent incontrollable motion, impeding the control of the machine. Many application can be listed where exoskeleton can be used such as military, physically disabled person etc.

Figure 1: Hardiman

In the current investigation an attempt is made to overcome some of the limitation of the existing exoskeleton.

- Experimental failures may lead to serious injuries to the users and patients, sometimes may lead to the user's death.
- Designing an exoskeleton with right adaptation that fits subject's physical parameters is very time consuming and a lengthy process, which involves knowledge and integration of many fields of science and engineering.
- Analyzing and studying the conceptual design before actually prototyping will always yield better solutions and more refined, accurate and efficient models.

This project includes two major study conditions

1. With exoskeleton
2. Without exoskeleton

For both the above mentioned condition the following procedure was followed,

- Simulating the motion of forearm in an analytical software LifeMOD, for both the conditions with and without exoskeleton.
- Analytically deriving equation of motion for upper arm motion with the help of Lagrangian equation.
- Creating and importing an exoskeleton through ADAMS, a plugin to LifeMOD
- Comparing the results of kinematic parameters from mathematical model and from that of the LifeMOD software.
- Studying the level of muscle activation of muscles set for both the conditions 1 and 2.

Our work aims at studying the effect on human body by wearing an exoskeleton and hence we have not designed an actual exoskeleton here in this project, instead we have created an exoskeleton like environment that can be used for analyzing and getting the actual results.

➢ LifeMOD

LifeMOD is a sophisticated 3-D virtual human body modelling computer software. Its advanced capabilities and graphical interface enable to create human models of any required condition and environment. It enables to report actual and real time data and also the software enables rapid and repetitive testing. These points make this software more reliable and time saving for studies on biomechanics. As mentioned above a complete design of an exoskeleton is not employed here in this project, hence to create an exoskeleton like environment dynamic analysis software ADAMS, a plugin for LifeMOD was used. ADAMS is an accurate and extensible software built for standard mechanical simulation. LifeMOD is integrated with the ADAMS so as to incorporate computer added engineering models onto the human body.

LifeMOD is designed to plot results for various mechanical parameters like displacements, velocities, accelerations, torques, forces acting on a particular segment and various other such quantities.

- Mathematical model

A study of this kind always requires exact and précised results. Relaying on the software blindly for the results might not yield exact results, hence results from software needs validation. The results obtained from that of the LifeMOD software is validated with that obtained from that of the equation of motion we derived for our arm movement.

The model we adopted for our project is Lagrangian dynamics given by,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \left(\frac{\partial L}{\partial \theta_i}\right) = T_i$$

Where,

L = Lagrangian Function
L = K – V
K = Total kinetic energy
V = Total Potential energy

Lagrangian equation of motion consists of partial and full derivative terms. The main purpose of adopting lagrangian dynamics is that the right hand side of the equation is time dependent function of a mechanical quantity. We have considered moment or torque on the right hand side of the equation. 'i' in the above equation indicates the variable which defines the segments considered.

'L' is called the lagrangian function which is given by

L = Total kinetic energy – Total potential energy
L = K – V

Inertial Measurement Unit (IMU)

Input is highly necessary for any sort of analysis, both the analytical and computational solving was provided with same experimental input. The required motion was performed by the subject and the angular displacements during this motion was recorded. This was done by using an electronic device, which measured angular rate of the body using combination of accelerometers and gyroscopes called as Inertial Measurement Unit (IMU) shown in Figure 2. To estimate the forearm angles, it is necessary to measure the orientation of the forearm segments and an IMUwas used during the experiment to obtain the real time data. For the study,the IMUwas mounted on the forearm to record the data. The data was recorded at 128 Hz. Later these values were extracted into an excel sheet. This output data from the sensor was the input to both mathematical model and simulation of the motion in LifeMOD software.

Figure 2: Inertial measurement unit

Experimental Protocol

The experiment was conducted in a safe environment in the lab of IISc with all safety measures considered. A 22 year old healthy male subject of 186cm height and weighing 65kg was considered for conducting the experimental trials. The subject's right arm was considered for the experiment. The centre of mass of the fore arm was marked with a marker on which the inertial measurement unit was placed. The IMU sensor of 128Hz sampling frequency was selected for the experiment i.e the sensor records 128 readings in 1sec of run time. 128Hz sampling frequency was selected as to increase the accuracy of the analysis.

The inertial measurement unit was tested before the commencement of the experiment. Inertial measurement unit was calibrated and was checked for the accuracy by connecting it to a computer. After calibrating and checking the inertial measurement unit it was then attached on the centre of mass of the right fore arm of the subject using a Velcro. The subject was able to move the arm freely after attaching the IMU. The subject was instructed to move the arm in the sagittal plane very slowly as the angular displacements would be recorded by the IMU. The IMU was placed correctly at the centre of mass point and it was held very stable in that position. The subject was made to stand straight with the IMU mounted on the right hand. The wrist of the subject was closed and was facing the front side (-90 degree wrist position).

The experimental trial was instructed to the subject to stay in the initial position for first 20 seconds and then move the fore arm slowly upwards to a position where the fore arm and the upper arm were perpendicular to each other and stay in that position for another 20 seconds and then move the fore arm slowly downwards and reach the initial position where the upper arm and fore arm were 180 degrees apart and made to stand in the initial position for another 20 seconds.

First trial of the experiment was started when the subject was in the initial position where the upper arm and fore arm were 180 degrees apart with the subject standing straight and the folded wrist facing front. On a count of three the stop clock and the IMU on the subject was started simultaneously and till the completion of first 20 seconds the subject remained in the initial position and then the subject started to lift the fore arm slowly in upward direction keeping the scalper joint fixed and reaching the final position where the upper arm and fore arm were perpendicular to each other and was made to stay in that position for another 20 seconds after reaching that point, as shown in Figure 3, then the subject moved the fore arm slowly in downward direction to reach the initial position and made to stay in that position for another 20 seconds and then the stop clock and the IMU was stopped simultaneously and the total elapsed time for the first trial was noted which was around 106 seconds.

The whole experiment was also captured in a camera to record the proceedings of experiment. The IMU was removed carefully from the subjects arm and it was connected to the computer to extract all the recorded angular displacements. The extracted data was then copied to the excel sheet and then it was ready to be used for further analysis with the software. The experiment was repeated for two more trials and the best possible output data from the IMU was considered for the analysis.

Figure 3: Conduction of experiment

Mathematical model for the specific arm motion is developed and solved using lagrangian equation of motion by considering three segments namely upper arm, fore arm and wrist segments connected through 3 joints as shown in Figure 5. The shoulder joint is fixed and l_1 is the length of upper arm from the fixed point. l_2 is the length of fore arm and l_3 is the length of wrist segments.θ_1 is the angle of inclination of upper arm with respect to horizontal,θ_2 is the angle of inclination of fore arm with respect to horizontal and θ_3 is the angle of inclination of wrist with respect tohorizontal.m_1 is the center of mass point of the upper arm segment which is at a distance of l_{c1} from the fixed point. m_2 is the center of mass point of the fore arm segment which is at a distance of l_{c2} from the end of upper arm joint and m_3 is the center of mass point of the wrist segment and is at a distance of l_{c3} from the fore arm joint. By naming the segment joints as 1,3 and 5 we can name the center of mass points as 2,4 and 6 respectively. M_1 is the moment of inertia acting on the joint 1(shoulder joint). M_2 is the moment of inertia acting on the fore arm joint and M_3 is the moment of inertia acting on the wrist joint.

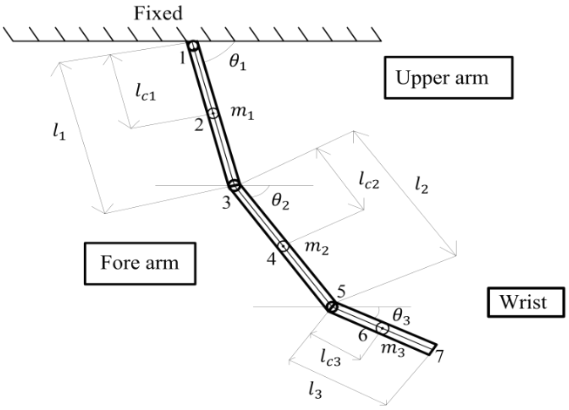


Figure 5: Mathematical model

Lagrangian equation of motion:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \left(\frac{\partial L}{\partial \theta_i}\right) = T_i \quad \ldots\ldots (1)$$

Lagrangian equationof motion is an equation consisting of partial and full derivative terms (1). The main aim of using lagrangian equation is that on the right hand side of the equation it has a function of torque. The aim of deriving the mathematical model is to find the equations of torque for each of the segments. Using above torque equation for forearm, upper arm & wrist were developed.

L is called the lagrangian function which is given by
Total kinetic energy – Total potential energy
L = K – V
L = Lagrangian Function
K = Total kinetic energy
V = Total Potential energy
By substituting the above parameters to the lagrangian equation we get,

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{\theta}_i}\right) - \frac{d}{dt}\left(\frac{\partial V}{\partial \dot{\theta}_i}\right) - \frac{\partial K}{\partial \theta_i} + \frac{\partial V}{\partial \theta_i} = T_i$$

For mechanical system, Potential energy with respect to time and velocity is zero.
Therefore,

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial V}{\partial \dot{\theta}_i}\right) = 0$$

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial K}{\partial \dot{\theta}_i}\right) - \frac{\partial K}{\partial \theta_i} + \frac{\partial V}{\partial \theta_i} = T_i$$

- Method followed in LifeMOD

LifeMOD consists of 19 segments which are connected by 18 joints on modelling skeleton. Muscles are modelled by spring-damper complexes. LifeMOD contains a database for the spring stiffness and damping coefficient based on input parameters (height, weight, etc.). For this study only the spinal and right arm portion of upper torso of a human body was considered, i.e eight joints as shown in the figure. Muscular system of only these segments considered were taken into account.

A human model for above mentioned anthropometric conditions like height, weight etc.was designed in LifeMOD Three wrist angles were considered individually, a separate analysis was done for wrist angle 90, wrist angle 0 and wrist angle -90, with shoulder joint fixed for all the cases. From the ADAMS plugin dumbbell was imported to which material type was specified. Three different dumbbell weights 3kg, 5kg and 7kg were considered. A grip force was added to hand in order to hold the dumbbell. The procedure till here is same for both with and without exoskeleton conditions. Method of simulating the model without exoskeleton is explained below.

The motion was applied only to elbow joint or fore arm, hence the angular displacement data obtained from the IMU sensor were used to give motion to fore arm. In LifeMOD motion for a segment can be given by motion agents, which can be applied to any location on a segment of a human body. Here in this study, motion agent was given in the same place on forearm where the IMU sensor was mounted. Once the motion agent was applied to the model, the motion was simulated. Once the model was simulated, the animation obtained in the software and that of the actual experiment was compared, which matched. Now the muscles were trained for the given motion by removing the motion agent, by doing so the muscle performed the required task of lifting the dumbbell on its own.

The results of kinematic parameters such as output angular displacements, angular velocity of forearm, angular acceleration of forearm and torque output of elbow joint, thus obtained were considered for all the three wrist angles and three different dumbbell weights. These results of all the above mentioned parameters were compared with those obtained from mathematical model. The results was found to be matching, hence validation of software results was successful, i.eit was concluded that the results obtained from the software was valid and correct, hence study of interaction of the body with exoskeleton was initiated.

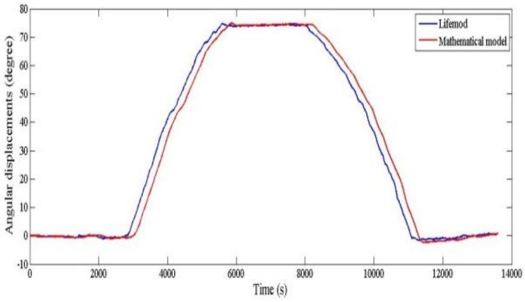
As mentioned earlier, we arecreating a dynamic model of an exoskeleton using ADAMS plugin. Once the upper torso segments of human body and dumbbell was imported. Similarly, an exoskeletonwas imported into the model by creating two links, one for upper arm and other for the lower arm. These two links were joined by a rotational joint, which is parallel to elbow joint. This two links were connected to the human arm by applying bushing joints in upper arm and lower arm. The bushing joints have same stiffness and damping as that of muscles. Hence the exoskeleton modelled here has exact features as that of an actual exoskeleton, with mass, material, mechanical properties same as that of an actual one and thus helps in our study.

Motion to this model was not provided through motion agents, instead torque was directly applied to the rotational joint between the links. The torque obtained from the analysis of model without exoskeleton was taken as input to toque values for the rotational joint. After analyzing this, the output angular displacement was compared with that obtained in earlier without exoskeleton analysis and these two results matched, hence the method of incorporating the exoskeleton into our simulation was proved to be correct and interaction between the human model and exoskeleton device was successful. Here again the muscles are trained in order to carry out the required motion on its own.

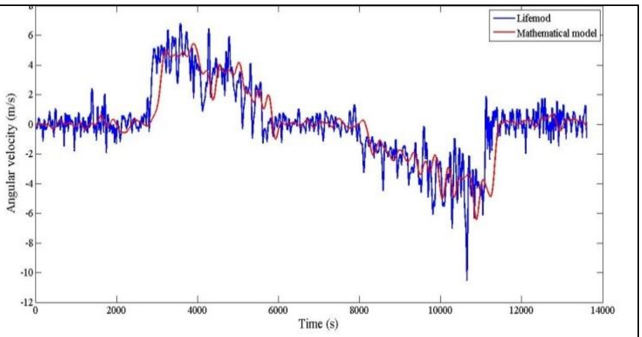
Ultimately, we are studying the activation level of three muscle sets as mentioned earlier in the report. Hence, muscle activation of all the three muscles for all the wrist positions, three different weights and for both with and without exoskeleton were observed and recorded. Obtained results are discussed in results and discussion section.

II. RESULTS AND DISCUSSION

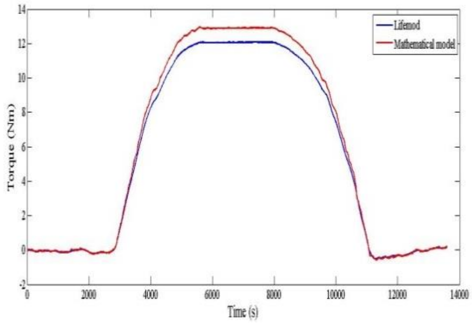
This section mainly deals with angular displacement, angular velocity, muscle activation and torque of the system without and with exoskeleton and for various angular position and the results were depicted. The following were the graphical results noted for system without exoskeleton.



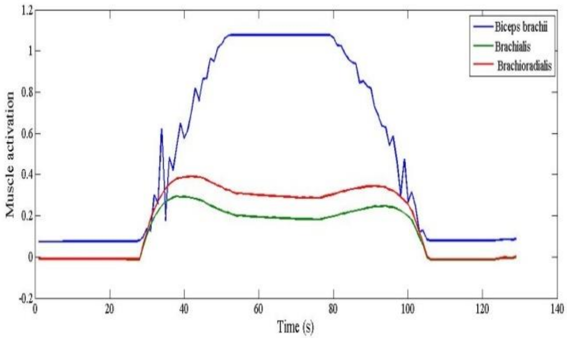
-90 degree wrist position 3kg weight : Angular displacement



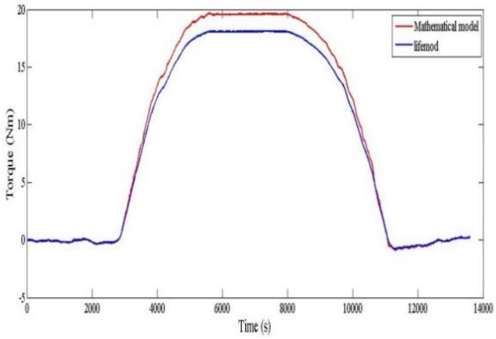
-90 degree wrist position 3kg weight : Angular velocity



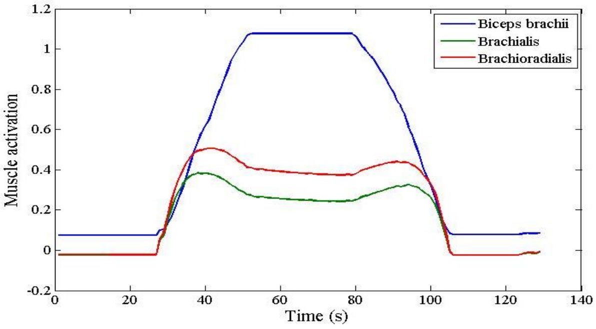
-90 degree wrist position 3kg weight: Torque



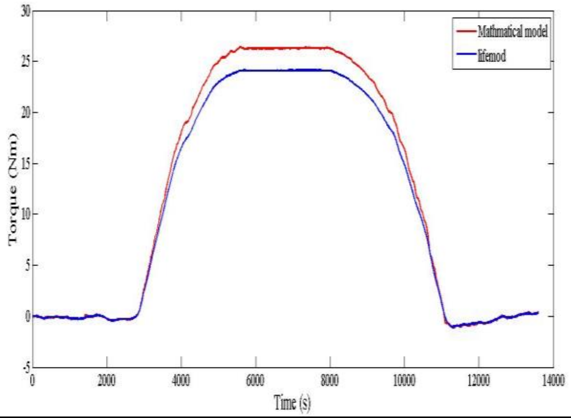
-90 degree wrist position 3kg weight: Muscle activation



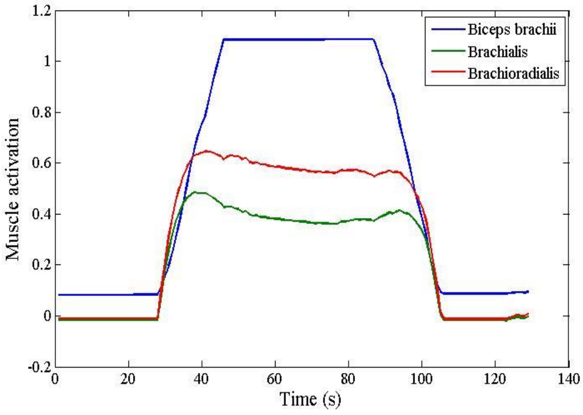
Torque output (for 5Kg, w-90)



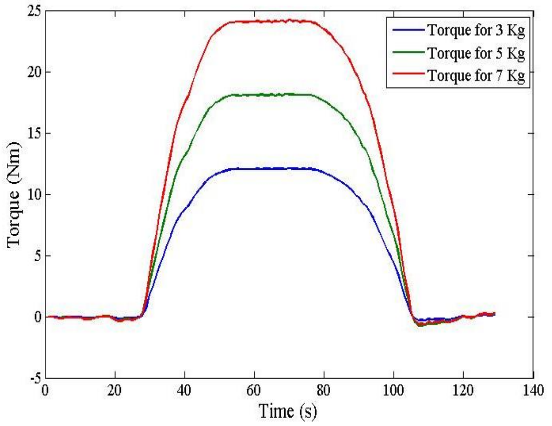
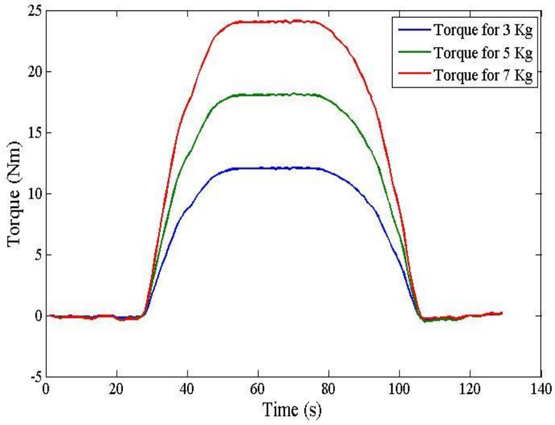
activation of three muscles (for 5Kg, w-90)



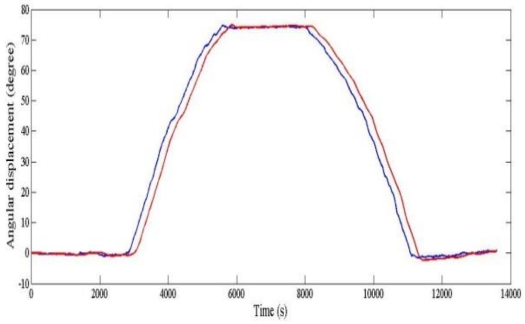
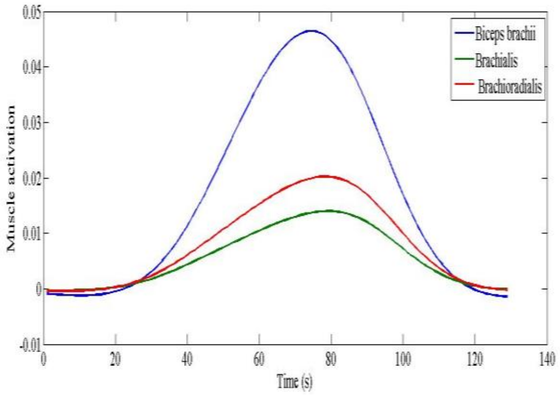
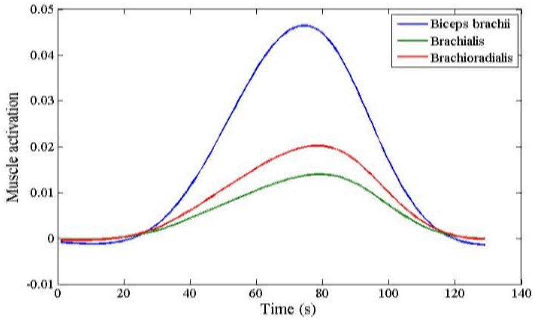
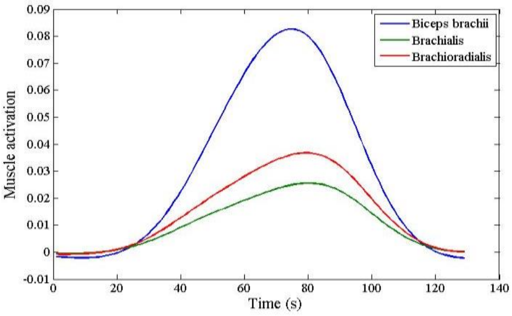
Torque output (for 7Kg, w-90)



Muscle activation (for 7Kg, w-90)

	
Torque output from lifemod for +90 degree wrist position	Torque output from lifemodfor 0 degree wrist position

Graphical results with exoskeleton were presented below.

	
-90 degree wrist position 3kg weight : Angular displacement	-90 degree wrist position 3kg weight: Muscle activation
	
Muscle activation of three muscles (for 5Kg, w-90)	Muscle activation of three muscles (for 7Kg, w-90)

III.CONCLUSION

- This project solely focuses on the biomechanical aspect of human lower arm movement, with and without Exoskeleton
- The human arm movement in sagittal plane was analyzed using analytical and computational methods to obtain better results.
- The torques and other kinematic parameters computed from the mathematical model (Lagrangian Dynamics) and the software were validated.
- Muscle activation for all the wrist positions carrying different weights were plotted to study the amount of activation of three major muscles of the arm without exoskeleton.
- Mathematical model was changed to include the exoskeleton condition. The torque and other kinematic parameters were plotted to analyze the results with the simulating software.
- The muscle activation during arm motion with exoskeleton was found to be less when compared to normal human arm movement, it can be concluded that the expenditure of human energy is minimal while doing work with exoskeleton.

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