Analysis of movement of an elbow joint with a wearable robotic exoskeleton Using OpenSim software*

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Abstract— **Human body movement occurs as a result of a coordinated effort between the skeleton, muscles, tendons, ligaments, cartilage, and other connective tissue. The study of movement is crucial in the treatment of some neurological and musculoskeletal diseases. The advancement of science and technology has led to the development of musculoskeletal model simulation software such as OpenSim that plays a very significant role in tackling complex bioengineering challenges and assists in our understanding of human movement. Such biomechanical models of musculoskeletal systems may also facilitate medical decision-making. Through fast and accurate calculations, OpenSim modelling enables prediction and visualisation of motion problems. OpenSim has been used in many studies to investigate and assess movements of the upper limb under various scenarios.**

This work investigates elbow movement of a paretic arm wearing a myoelectric robotic exoskeleton. The simulation focuses on the exoskeleton elbow joint with one degree of freedom for individuals that we have developed to support and rehabilitate a weakened/paretic arm due to a spinal cord injury for example. Accordingly, it simulates the kinematic characteristics of the human arm whilst the exoskeleton assists the arm flexion/extension to maximise its range of motion. To obtain the motion data required for this study, a forward dynamics method must be implemented. Firstly, inverse kinematics is applied to the joint angles, and then, the torque and force required for angular motion of the elbow joint are calculated using forward dynamics.

The results show that the muscle forces required to generate an elbow flexion are considerably less when the exoskeleton is worn.

Clinical Relevance— **The exoskeleton assists patients to extend and flex their arm, thus supporting rehabilitation and arm function during activities of daily living. Exoskeleton movement is derived from residual myoelectric signals extracted from the patient's arm muscles. Modelling the dynamics and kinematics of the arm with the exoskeleton can reveal and predict any movement issues that need to be addressed.**

I. INTRODUCTION

Each year, worldwide, between 250 000 and 500 000 people suffer a spinal cord injury and disease (SCI/D) [1]. According to National Spinal Injury Statistical Center (NSCISC) database, in recent years, incomplete tetraplegia has been the most common neurological damage. Complete and incomplete paraplegia are virtually equivalent in frequency. By the time of hospital discharge, only less than one percent of patients had completely recovered their neurological function [2]. Therefore, spinal cord injuries are among the most devastating injuries and can lead to a variety of dysfunctions and disabilities. As a result, in addition to reducing social and economic participation, spinal cord injuries are associated with substantial individual and societal expenses [3].

A spinal cord injury survivor's quality of life immensely depends on the way we harness and unleash the power of technology to dismantle barriers to independence. The use of exoskeletons has the potential to empower people with SCI/D to achieve and maintain the highest level of independence, thus creating a more inclusive world for them.

Exoskeletons are wearable devices attached to the human body for the purpose of power enhancement or motion assistance [4]. The application of exoskeletons can be found in a wide range of fields, such as wearable technology, industry, robotics, rehabilitation, sports, and military [4]-[8].

Rehabilitation of patients with spinal problems often involve intensely repetitive exercises [9]. Robotic exoskeletons may be used to assist patients during these exercises and reduce hands-on assistance provided by therapists, hence freeing up their time to address other aspects of patients' care. Robotic exoskeleton models and simulation software packages are used to provide a digital twin to facilitate motion analysis, motion prediction, forward and inverse dynamics as well as kinematics calculations. The main advantages of motion simulation software are as follows:

1. Simulation software can model the movement of the robotic actuator (for joints) and predict it [10].
2. Simulation software can simulate the movement of joints during different activities such as lifting objects of variable weights [12].
3. Simulator software can potentially reduce research time and costs especially for visualisation and testing the models [13].
4. Some biomechanical parameters are invasive (muscle forces, joint forces) and cannot be measured without computational or simulation software. Therefore, such

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computational tools can calculate variables that are challenging to measure *in vivo* [10].

Taking these advantages into account, modelling software is a complementary method for experimental analysis and testing of human movement when wearing an exoskeleton.

Several simulation software packages are currently available for analysis and computation, with OpenSim software among the most effective [11]. Many researchers in the field of biomechanics and orthopaedics as well as people interested in human or animal movement use OpenSim as a standard tool to implement musculoskeletal modelling on the target body part(s).

OpenSim can be used to analyse and evaluate kinematics, dynamics, and biomechanical and kinetic variables. Additionally, this open-source software helps optimise organ movement and estimate activation. C++ programming language is used to develop OpenSim libraries [13].

In the current research, we focus on the analysis of movement of the elbow joint attached to a wearable robotic exoskeleton for the upper limb rehabilitation. The upper limb can be divided into three segments: upper arm, forearm and hand (fingers and palms) [9]. The movements at the elbow joint involve movement of the forearm at the elbow joint with actions like flexion, extension, and forearm supination and pronation. This study will consider the elbow as a hinge joint, so movement is limited only to one plane, i.e. we only investigate flexion and extension movement. This work simulates the movement of the elbow joint with one degree of freedom (1-DOF) (flexion/extension) when a robotic exoskeleton is worn on the human arm. The particular robotic exoskeleton [14] simulated has been developed to facilitate rehabilitation and assistance of a weakened/paretic arm. It uses residual myoelectric signals to control the movement of the arm. The exoskeleton is attached to the arm using adjustable arm bands housing sensors for detecting activity and monitor axes alignment. The robotic elbow joint is actuated using a servomotor.

Kinematics equations are calculated using simulation results and motion equations are calculated using forward dynamics. By performing the Static Optimization simulation, the values of force, as well as the values of muscle activation which are similar to the EMG signals received from the patient's arm. By comparing the elbow movements with and without the exoskeleton, we could estimate the extent of improvement and assistance provided by the exoskeleton to the elbow joint movement of the spinal patient are obtained. Hence, the purpose of this work is to explain, devise and promote the use of the exoskeleton models for estimation and prediction of dynamic joint movements to provide further insight on human movement with an exoskeleton.

II. METHOD

The simulation includes six muscles as shown in Figure 1 left panel: (1) TriLong: Triceps brachii (long head), (2) TriLat: Triceps brachii (lateral head), (3) TriMed: Triceps brachii (medial head), (4) BicLong: Biceps brachii (long head), (5) BciShort: Biceps brachii (short head), (6) Brac: brachialis. Fig 1 right panel illustrates the 6 muscles simulated in OpenSim.

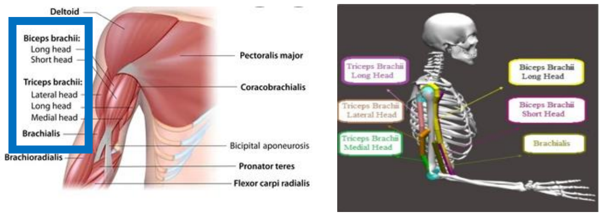

Figure 1 left panel illustrates arm muscles anterior view showing the six muscles (boxed in blue) simulated in our model. Right panel shows the six arm muscles in the simulated model.

The model is built in five steps. In the first step, the structural features for the exoskeleton are sketched in inventor software [16] as shown in Figure 2. Using OpenSim Software, the model is exported to a file in "stl" format. The exoskeleton movement was simulated first. To achieve this, the exoskeletal model was modelled simultaneously with the exoskeleton in OpenSim software in the following step.

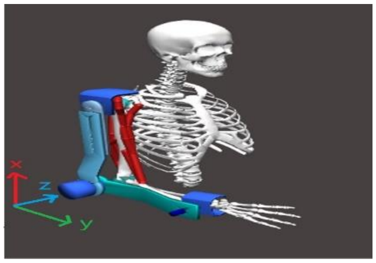

Figure 2 Simulation of the worn robotic exoskeleton for upper limb visualised in OpenSim

The length of the arm was not of major concern as our exoskeleton can be adjusted and customised to suit the arm dimensions of the user, therefore, we used the default model for right arm and its muscles. Each segment of the exoskeleton was designed as a new body (coded in C++).

After creating the exoskeleton, the links' interdependence and the joints' positions were defined and modelled.

Joints are divided into pin (*PinJoint*) and welded (*Weljoint*) joints according to their degree of freedom with regards to exoskeleton movement. *PinJoint* are joints that have one degree of freedom centred around the z-axis.

Weljoint are joints that have no degrees of freedom and do not move relative to each other.

After defining the body parts and joints, the actuator force values are applied in OpenSim ForceSet parameter. In the fourth step, after completing the modelling of the exoskeleton in OpenSim, motion data is estimated using forward dynamics.

In the fifth and last step, the mentioned simulated exoskeleton is used to perform an elbow flexion and extension which will enable us to generate simulated muscle activity data when the exoskeleton is worn that can be then compared to benchmark EMG datasets.

Forces and moments are estimated using forward dynamics in the simulation using the equation (1) representing multibody dynamics.

$$\ddot{q} = [M(q)]^{-1}\{\tau + C(q,\dot{q}) + G(q) + F\} \tag{1}$$

Where

$\ddot{q}$: the coordinate accelerations,
τ : joint torques,
$C(q,\dot{q})$: Coriolis and centrifugal forces,
q : function of coordinates,
$\dot{q}$: the velocities,
$G(q)$: gravity,
F : other forces applied to the model,
$[M(q)]^{-1}$ is the inverse of the mass matrix.

And therefore, we can calculate the moments due to muscle forces, muscle contraction and activation dynamics as follows:

Moments due to muscle forces $\tau_m[R(q)]f(a,l,\dot{l})$
Muscle contraction dynamics $\dot{l} = \Lambda(a,l,q,\dot{q})$
Muscle activation dynamics $\dot{a} = A(a,x)$

Where

τ_m : The net muscle moments,
$R(q)$: the result of the moment arms,
f : multiplied by muscle forces,
a : function of muscle activations,
l : muscle fibre lengths,
$\dot{l}$: velocity,
Λ : Muscle fibre velocity are governed by muscle contraction dynamics,
A : Activation dynamics,
$\dot{a}$: the activation rates,
x : differential equations modelling the musculo-skeletal dynamics.

III. RESULTS

Figure 3 illustrates the muscles recruited during flexion and extension, red denotes agonist, i.e. muscle contracting and blue denotes antagonist, i.e. muscles relaxing/lengthening.

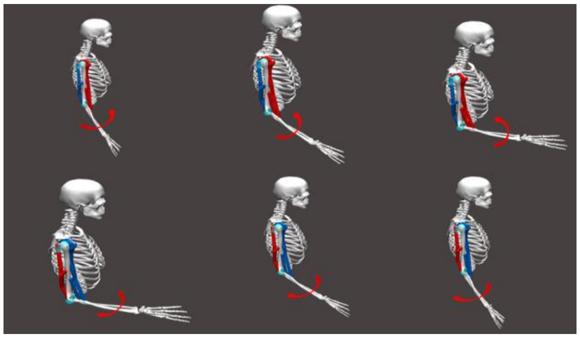

Figure 3 Muscle recruitment during elbow flexion (top panels) and extension (bottom panels) Red denotes agonist and blue denotes antagonist.

Figure 4 illustrates elbow joint extension/flexion in degrees versus time in seconds starting at 90 degrees, where 0 degrees corresponds to full elbow extension when the exoskeleton is worn. Some artifacts are noticed at the transition between extension and flexion due to the movement of the exoskeleton's actuator at the elbow joint.

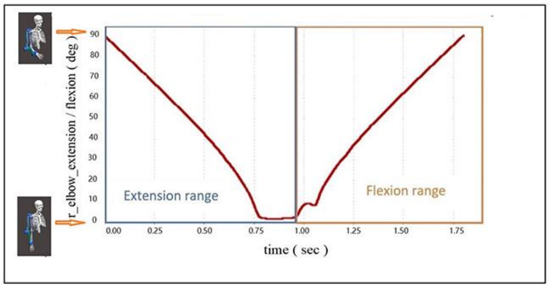

Figure 3. Elbow flexion/extension joint angle with the exoskeleton.

Figure 5 compares the elbow flexion trajectory of motion in degrees with (dashed line) and without (solid line) in the simulation.

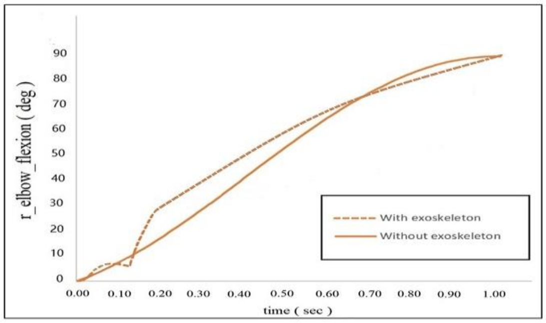

Figure 4. Comparison of elbow flexion with (dashed line) versus without (solid line) exoskeleton from full extension to 90 degrees flexion.

Figure 6 top panel illustrates a comparison between the forces exerted in Newtons by each of the six considered muscles with (dashed line curves) and without (solid line curves) the exoskeleton for elbow flexion estimated in degrees. Figure 6 bottom panel shows the momentum profile of the right elbow with and without the exoskeleton with respect to joint angle.

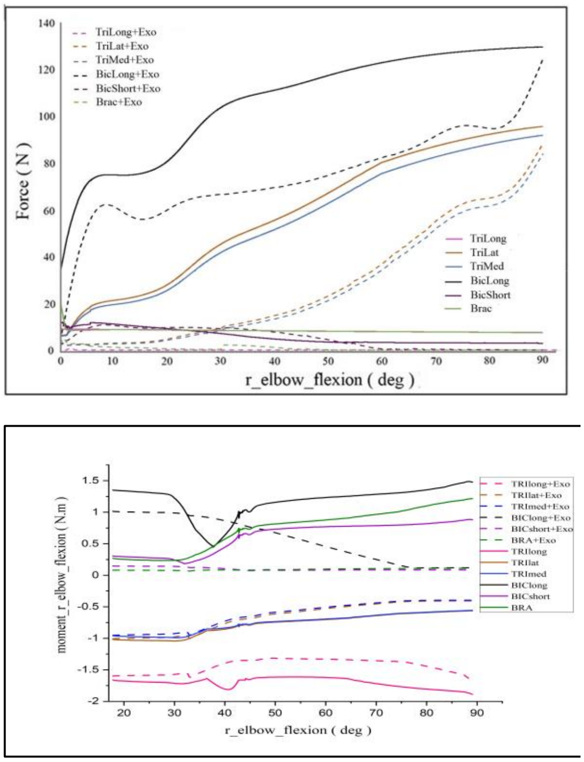

Figure 5. Top panel illustrates the force in (N) produced in elbow during flexion with (dashed line) and without (solid line) the exoskeleton for all six simulated muscles: The bottom panel shows the estimated moments estimated in the right elbow for all six simulated muscles.

It is clear that, muscles require to exert much less force when the exoskeleton is worn.

IV. DISCUSSION AND CONCLUSION

In this study, we have simulated an exoskeleton developed for elbow rehabilitation with a 1-degree of freedom. All design and calculation steps are custom built and integrated with the OpenSim software. This simulation represents a first step towards developing a digital twin for the constructed prototype. The model could further be used to simulate a weakened arm using measured muscle activity datasets. This modelling helps provide further insight and understanding of the performance of the elbow flexion/extension when an exoskeleton is worn and we can then estimate the amount of assistance the exoskeleton can provide to that user. We have used a reference data set to validate the simulated model and compare our results. Our results show that using an exoskeleton to assist elbow flexion reduced the force and moments exerted by the upper arm muscles which is an expected positive outcome.

ACKNOWLEDGEMENT

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