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ASSESSMENT OF TASK AND JOINT-BASED EXOSKELETON DESIGNS FOR ELBOW JOINT REHABILITATION

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ABSTRACT

Exoskeletons and robots have been used as a common practice to assist and automate rehabilitation exercises. Exoskeleton fitting and alignments are important factors and challenges that need to be addressed for smooth and safe operations and better outcomes. Such challenges often dictate the exoskeleton design approaches. Some focus on simplifying and mimicking human joints (joint-based) while others have a focus on a specific task (task-based), which does not need to align with the corresponding limb joint/s to generate the desired anatomical motion. In this study, the two design approaches are assessed in an elbow flexion-extension task. The muscle responses have been collected and compared with and without the exoskeletons. Based on 6 with no disability participants, the normalized Electromyography (EMG) RMS values are plotted. The plot profiles and magnitudes are used as a base to assess the exoskeleton alignment. For this specific task, the task-based exoskeleton has shown a profile closer to the one without exoskeleton with a relatively identical support as the joint-based one; the latter is evidenced through most subjects' muscle response magnitudes. This preliminary data has shown a good methodology and insight towards the assessment of exoskeletons, but more human subject data is needed with different task combinations to further strengthen the findings.

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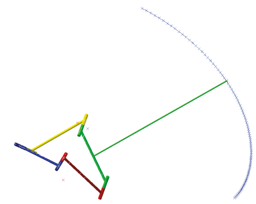
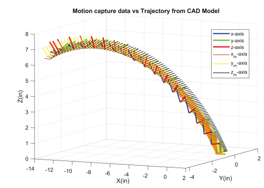
1 INTRODUCTION

The demand for physical therapy has been on the rise due to the increasing amount of strokes in the aging community leading to paralysis and motor disabilities [1]. Automating the therapy process can help ease the pressure in the healthcare system and increase its efficiency and outcome. Exoskeletons and robots have been used as a common practice to assist and automate rehabilitation exercises. Most exoskeletons are joint-based in which they try to align and mimic the corresponding human joints. This assumes that the location of the axis can be accurately known, and that such a fixed axis exists for the range of motion of the joint or set of joints, which is not always the case [2]. Thus, replicating such joints with revolute/hinge joints will lead to misalignment and stress on the user [3, 4]. This misalignment between the exoskeleton and the joint can lead to the creation of unnecessary external forces that could possibly result in premature loosing of the muscles and unusual wear [5]. Task-based exoskeletons are the other design approaches in which the mechanisms are designed to follow a desired task than mimicking the corresponding joints [6]. Task-based exoskeleton has shown a reduced joint alignment [7]. Most task-based exoskeletons are designed based on overconstrained mechanisms; such mechanisms require specific conditions of the linkage structural parameters in order to become mobile; at the same time, this condition could be easily affected by changes in manufacturing tolerances and assembly errors. Thus, beside the inherent design challenges of such mechanisms, finding a proper fit and alignment of the exoskeleton to the user and task are challenging research topics.

In this study, the comparison of task-based and joint-based mechanisms are presented. The two design types are assessed while performing the elbow flexion-extension movement. In our previous study, the kinematic synthesis of the task-based exoskeleton has been presented [8]; the resulted exoskeleton did not need to align with the corresponding elbow joint to generate the desired anatomical elbow flexion-extension motion. Here, the detailed mechanical design and prototype testings are presented, and a comparison analysis is made with the joint-based exoskeleton while doing the same elbow flexion-extension exercise.



(a) CAD Model



(b) Limb Trajectory and Synthesized Trajectory

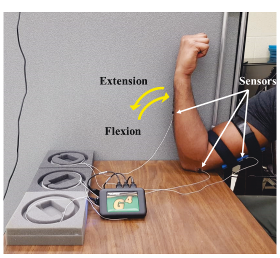
FIGURE 2: CAD MODEL OF THE PROPOSED MECHANISM AND TRAJECTORIES FROM MOTION CAPTURE SYSTEM VS THE GENERATED BY THE CAD MODEL

2 Description of the exoskeletons

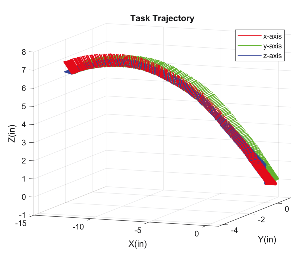
In this study, joint-based and task-based exoskeletons are designed and manufactured to execute the elbow-flexion and extension tasks. The description and analysis of the exoskeletons are also discussed.

2.1 Description of the task-based Exoskeleton

The kinematic synthesis of the mechanism procedure uses motion capture data from the target limb using Polhemus G4 tracking system. The experimental setup (Fig.1a) and the desired limb trajectory (Fig.1b) are used for the mechanism synthesis. As it is shown, the path generated by the elbow flexion-extension motion is not planar and is difficult to be generated by a single hinge joint mechanisms.



(a) Experimental Setup



(b) Limb Trajectory

FIGURE 1: MOTION CAPTURE DATA SETUP AND LIMB TRAJECTORY

An over-constrained RR-RR parallel mechanism was selected to generate the desired elbow flexion and extension tasks [8]. The mechanism was modeled and assessed based on its trajectory as shown in Fig.2a and Fig.2b.

2.1.1 Prototype Development

Once the location of the joints and dimensions of the links are specified thorough the synthesis, a detail design is done considering mechanism rigidity, adaptability, and cost. A stress analysis was performed to verify the structural rigidity while considering an average male weights 73kg and the percentage of weight that the forearm and hand take up is 2.52% resulting in 1.83kg [9]. This is the weight that the mechanism can support in addition to its own weight, it was estimated a total force of 36N and 1.2Nm, with 6.7Nm moments in orthogonal plane to account the attachment length from the coupler link. Using these three loads, the analysis was performed in Solidworks, and it was found the maximum stress is 39 MPa, which is statistically safe given the yield strength of PLA is 60 MPa [10]. Note that the prototype is 3D printed and will handle a lower maximum stress.

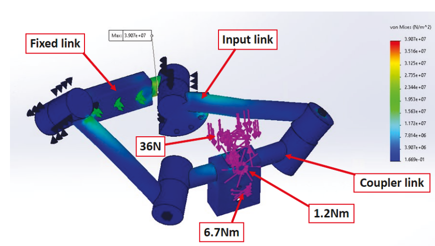
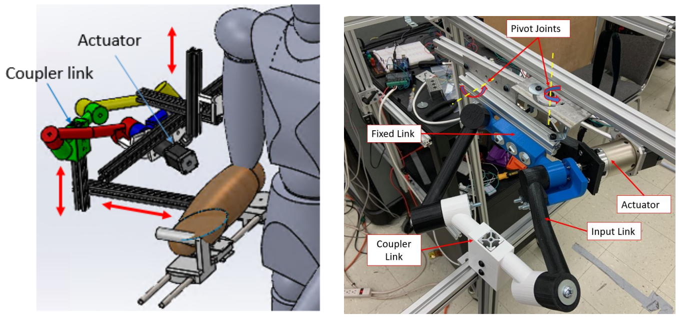


FIGURE 3: STATIC STRESS ANALYSIS OF THE MECHANISM IN SOLIDWORKS

Passive adjustable joints are added (fig. 4a) to accommodate and adapt to different anatomical variations of subjects. 80/20 aluminum extrusion was used to make the manufacturing easier, cheaper, and provide enough rigidity and strength to hold the weight of the subjects forearm. The fixed link is attached to two 180 degree pivot aluminum plates that allow adjustment to properly fit and align subjects as shown in fig. 4b. In fig. 4 shows the degree of adjustability of the exoskeleton setup.



(a) CAD Model (b) Prototype

FIGURE 4: CAD MODEL AND PROTOTYPE OF THE TASK-BASED ELBOW FLEXION-EXTENSION MECHANISM

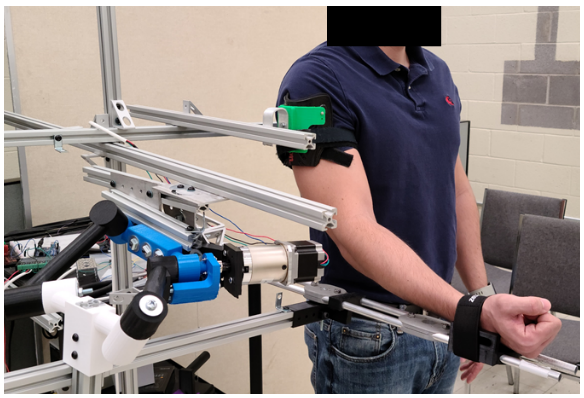


FIGURE 5: SUBJECT WEARING THE TASK-BASED EXOSKELETON

2.2 Joint-based Exoskeleton

The proposed upper limb joint-based exoskeleton for rehabilitation contains five degrees of freedom that allows for a large range of motion and contains five links that allow adjustment to fit 95% of the population; the exoskeleton design is shown in Fig.6. The exoskeleton was designed with light-weight material. Mechanical stoppers were included within the exoskeleton's joints to prevent motions beyond the natural human kinematics. The details of the design are discussed in [11]. The resulting design CAD model and prototype are shown in Fig.6.

2.3 Experiment Setup

The experiment is designed to study the effect of the different exoskeleton designs on the muscle responses while automating the same rehabilitation task, elbow flexion-extension. The EMG data from the Bicep muscle was collected and analysed when subjects execute the elbow flexion-extension motion. This task has been compared with and without wearing the exoskeletons. The Polhemus G4 tracking system is also used to validate

(a) CAD Model (b) Mechanism Prototype

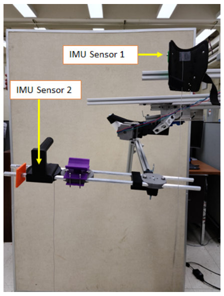
FIGURE 6: JOINT-BASED EXOSKELETON

the range of motion of both exoskeleton during the experiment (The validation is presented in Fig.7). The Delsys Trigno EMG data collection system is used to collect the muscle activity from the subjects, and two type of exoskeletons presented in the previous sections, the task-based and joint-based are utilized in the study. During the testing, only one joint was actively driven in both exoskeletons.

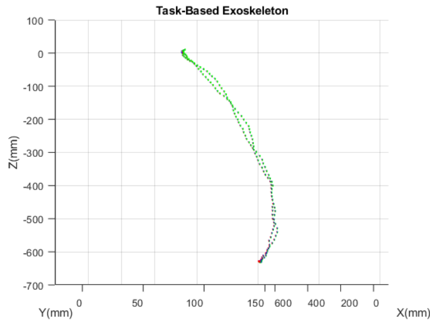
In the fist step, the maximum voluntary contraction (MVC) of the bicep is collected in order to normalize the muscle activity of each subject, then a 3 minutes rest is given to re-stabilize the muscle. Second, each subject is asked to wear each one of the exoskeletons, making sure that both devices are adjusted to each individual anthropometric measures. Each trial is consisted of flexing and extending the elbow joint from extended (0°) to 110° and done twice for 35 seconds while wearing the exoskeletons, then, a third trial is performed without wearing the exoskeleton. During the trials the bicep muscle engagement is being recorded at a sample frequency of 1926Hz. Lastly, root-mean-square (RMS) values of the EMGs verses time were plotted for a time window of 2 seconds to identify any signal pattern variations among them. Hypothetically, if there is no misalignment and fitting problems, each exoskeleton are expected to generate a similar signal profile on the targeted muscles. As an ideal exoskeleton should adapt and generate natural motions of the limb without causing stress due to extra load or misalignment.

3 RESULTS AND DISCUSSIONS

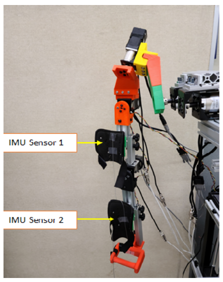
Six participants with no disability with an age range from 20 to 30 years volunteered for this study. The collected date of each subjects is shown in Fig.8, where the red curve represents the RMS values of the task without wearing the exoskeletons, the blue curve represents the data when the subject was wearing



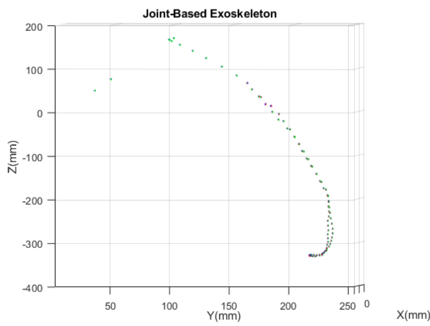
(a) Task-based Mechanism



(b) Task-based Mechanism Trajectory

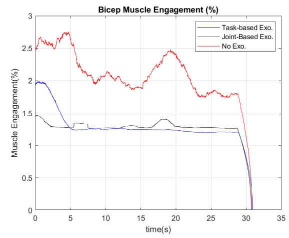


(c) Joint-based Mechanism

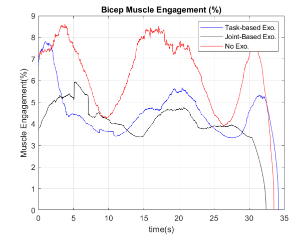


(d) Joint-Based Mechanism Trajectory

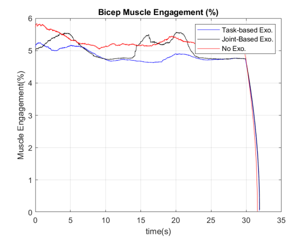
FIGURE 7: MECHANISM TRAJECTORIES



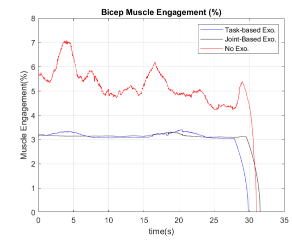
(a) Subject 1



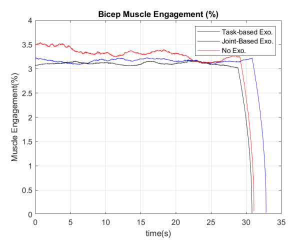
(b) Subject 2



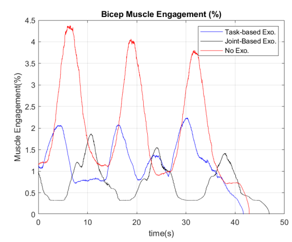
(c) Subject 3



(d) Subject 4



(e) Subject 5



(f) Subject 6

FIGURE 8: EXPERIMENTAL EMG DATA RESULTS

the task-based exoskeleton, and the black one represents the data coming from the subject when the joint-based exoskeleton was being used. The y-axis represents the normalized EMG RMS value with respect to the MVC in percentage, and the x-axis represents time in seconds.

Based on the results, the pattern of the curves representing the normalized RMS values of subjects 2, 3, 5, and 6 are similar to the one showed by the subjects when no exoskeleton being worn but with a lesser amplitude. This was expected, since the exoskeleton was carrying all the weight of each subject's arm during the motion. On the other hand, the pattern of the joint-based exoskeleton signals changed. However, nothing can be clearly inferred from subjects 1 and 4 due to the minimum, almost negligible, muscle engagement presented when both exoskeletons were being worn. Likewise, the RMS values of each subject during this experiment is plotted in Fig.8. Furthermore, the RMS values across participants, in Fig.10, showed a reduction of muscle activity when the subjects were using the task-based and joint-based exoskeletons by 19% and 25%, respectively. This meant that they supported the subjects while performing the elbow flexion-extension task.

4 CONCLUSIONS

The prototyping and real implementation of a spatial parallel mechanism to assist on elbow flexion-extension task was implemented. A comparison between the task-based exoskeleton and a joint-based exoskeleton was presented, where preliminary results showed that in 4 out of the 6 subjects the natural pattern of the bicep muscle engagement during the elbow flexion-extension activity was replicated with the former, but an alteration in the pattern was identified. Amplitude-wise, both exoskeleton reduced the amount of effort required by participants when wearing them, with a reduction about 19% and 25% for the task-based and joint-based exoskeletons, respectively. Based on the results, further testing with a larger and diverse sample size is suggested.

ACKNOWLEDGMENT

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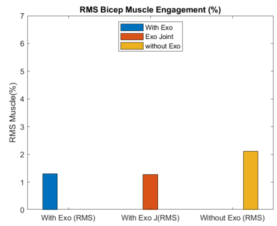
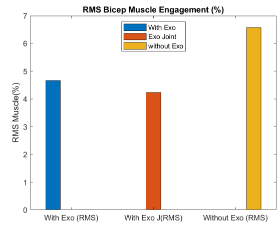
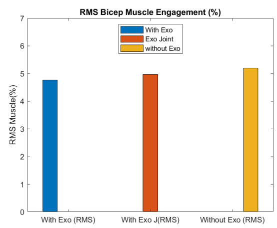


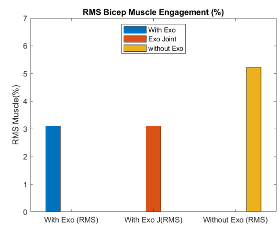
(a) Subject 1



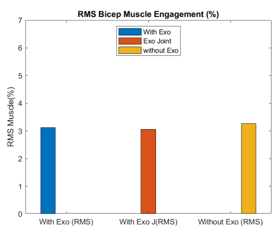
(b) Subject 2



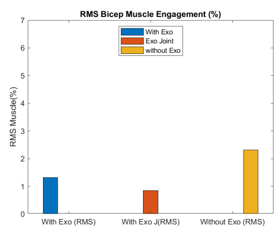
(c) Subject 3



(d) Subject 4



(e) Subject 5



(f) Subject 6

FIGURE 9: EXPERIMENTAL RMS EMG DATA RESULTS

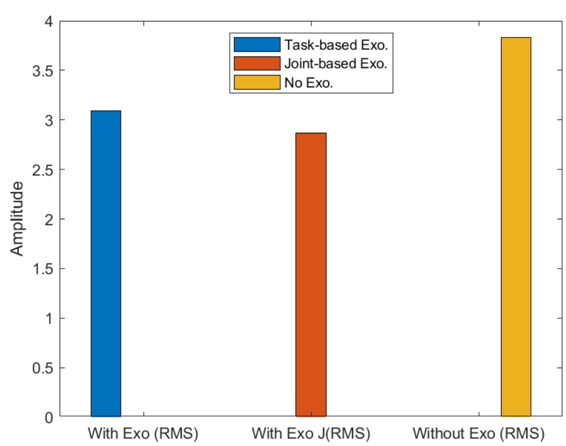


FIGURE 10: RMS VALUE ACROSS SUBJECTS

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