Mechanical Arm for Soft Exoskeleton Testing

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Abstract. Soft robotic exoskeletons offer multiple advantages in the field of motor rehabilitation and assistance with activities of daily living This paper reports the design process of a mechanical arm for upper-limb soft exoskeleton testing. The main requirement of the test bench was to simulate five degrees of freedom (DOF) of the human arm, and in particular i) shoulder flexion/extension, ii) shoulder adduction/abduction, iii) shoulder medial rotation/lateral rotation, iv) elbow flexion/extension and v) forearm supination/pronation. An additional requirement included the possibility to alternatively lock each DOF. The final concept was designed using Autodesk Inventor and it is composed of 32 parts, 18 of which were particularly designed for this application. Topological optimisation and Finite Element Method (FEM) analysis were performed to some custom components to obtain the final design. The final concept was manufactured by means of additive manufacturing of PLA (polylactic acid) and laser cutting of PMMA (poly methyl methacrylate) sheets. After testing and validation, the prototype was able to meet the desired requirements and it can be used for soft-exoskeleton testing.

Keywords: Motor rehabilitation · Exoskeleton · Industrial sector · Upper limb · User feedback

1 Introduction

Robotic exoskeletons have been increasingly studied in the field of biomedical engineering [1]. These devices can be used for the rehabilitation and assistance of people affected by motor impairment as a consequence of neurological or neuro muscular disorders. Soft exoskeletons, also referred to as exosuits, offer the possibility to assist the user when performing physical tasks and simultaneously guarantee enough flexibility and comfort by adjusting to the wearer's body, making them good candidates to assist the wearer with daily activities [2].

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Fig. 1. Example of upper-limb assistance exoskeleton. [4]

Among the possible types of actuators that can be used with exosuits, electric motors which employ cable driven transmission seem to be the most promising in terms of ease of control. An example of a cable-driven exosuit for upper-limb assistance was developed by [3,4] and is shown in Fig. 1.

Although exosuits are a promising technology in the field of assistive devices, they are still in a preliminary development phase and few degrees of freedom (DOFs) are actuated simultaneously, mainly to preserve portability, which is a key feature. We believe that more effort should be put in optimizing the cable routing and understanding the effect of the actuation on non-targeted joints.

Indeed, the development of these assisting devices requires a deep understanding of bio-mechanics and anatomy. To create a high-performance exoskeleton, an extensive design process must be carefully followed. It is important to consider factors such as safety, comfort and most importantly optimization of the forces, which should accurately adjust to the biological moments created at the arm joints level. The testing procedure is an essential part of the design process and thus requires high-quality testing components that can replicate the final operation of the device. The aim of this project is to design a test-bench for the testing of a upper limb assistive soft exoskeleton.

The mechanism initially used for testing is shown in Fig. 2-a. and lacks features which are essential to perform accurate measurements and to test the device for different arm configurations. The test-bench is composed of a two degree-of-freedom metallic arm with a couple of anchor points to which a string is attached, as shown in Fig. 2-b. The string is connected to a motor which drives one of the two DOFs, e.g. shoulder flexion or elbow flexion.

Project Proposal and Requirements. The proposal for the improved test-bench was based on multiple requirements and criteria. The foremost criterion was the resemblance from a kinematic point of view of the mechanism to that of an actual human arm, in terms of both degrees of freedom and dimensional parameters. The dimension of the final device was based on the statistical data published by [5] on the human upper extremity dimensions. Considering the

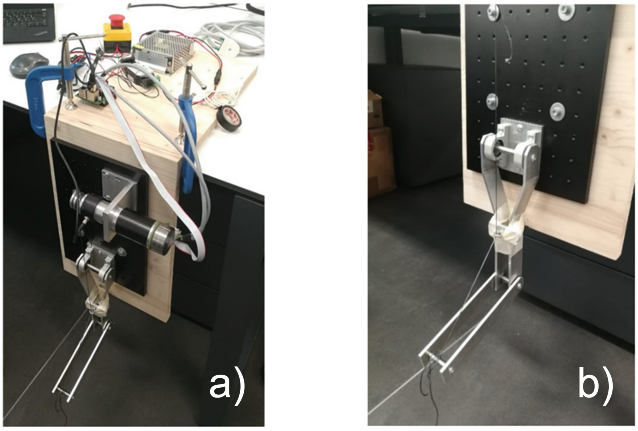


Fig. 2. First prototype of the mechanical arm.

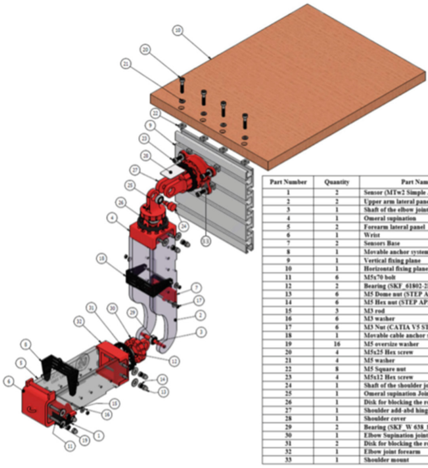
male mean values of the lengths of the arm and the forearm, an approximated ratio of 1.25:1 was estimated between these two parts of the arm. Therefore, the final design dimensions were set to stay close to this ratio.

The human arm is composed of 7 DOFs nonetheless two of them are for positioning of the hand (i.e., end-effector) - wrist flexion/extension and the wrist abduction/adduction - which are out of scope when designing a device to assist upper limb movements. Therefore for this project, we have considered as requirement the 5 DOFs associated to the development of the upper-limb exoskeletons.

Therefore, the degrees of freedom required for this application are:

- Shoulder flexion/extension
- Shoulder adduction/abduction
- Shoulder medial rotation/lateral rotation
- Elbow flexion/extension
- Forearm supination/pronation

An additional requirement was the possibility for the user to lock certain degrees of freedom at a certain angle, to test the device at different configurations. This requirement applied only to the shoulder adduction/abduction, the shoulder medial rotation/lateral rotation and the forearm supination/pronation. With the aim of allowing the user to perform analyses for different cable-routing designs, the user should be able to move the anchor points to different locations of the arm. Being the string tension controlled by the DC motor, the different locations of the anchor point permit the study of the forces needed to move certain degrees of freedom when the string is attached to different parts of the arm. Therefore, this requirement was of utmost importance for the purpose of this research. The initial model has the DC motor and the mechanical arm placed on the same plane which is perpendicular to the working table. The requirement was to move the location of the motor to the upper part of the base, on the plane



Part Number	Quantity	Part Name	Designed
1	2	Sensor (MTw2 Simple Assembly)	No
2	2	Upper arm lateral panel	-
3	1	Shaft of the elbow joint	-
4	1	Omeral supination	-
5	2	Forearm lateral panel	-
6	1	Wrist	-
7	2	Sensors Base	-
8	1	Movable anchor system	-
9	1	Vertical fixing plane	-
10	1	Horizontal fixing plane	-
11	6	M5x70 bolt	No
12	2	Bearing (SKF_61802-2RS1)	No
13	6	M5 Dome nut (STEP AP203)	No
14	6	M5 Hex nut (STEP AP203)	No
15	3	M3 rod	No
16	6	M3 washer	No
17	6	M3 Nut (CATIA V5 STEP Exchange)	No
18	1	Movable cable anchor system	-
19	16	M5 oversize washer	No
20	4	M5x25 Hex screw	No
21	4	M5 washer	No
22	8	M5 Square nut	No
23	4	M5x12 Hex screw	No
24	1	Shaft of the shoulder joint	-
25	1	Omeral supination Joint	-
26	1	Disk for blocking the rotation	
27	1	Shoulder add-abd hinge	-
28	1	Shoulder cover	-
29	2	Bearing (SKF_W 638_8-2Z)	No
30	1	Elbow Supination joint	-
31	2	Disk for blocking the rotation	-
32	1	Elbow joint forearm	-
33	1	Shoulder mount	-

Fig. 3. Assembly and Bill of Materials

parallel to the working table. This was required as to resemble more accurately the final application of the soft exoskeleton which would have the motor placed distally with respect to the arm of the user (e.g., on the back). In this way is possible to correctly study what the behaviour of the string would be in the real application. Moreover, the attachment of the motor to the base should allow to change the position of the motor if required by the researcher.

For the purpose of measuring the orientation, acceleration and angular velocity of the arm, an inertial measurement unit (IMU) must be mounted on both the arm and the forearm.

The sensors to be used are the MTw series manufactured by Xsens Technologies B.V. which offer a wireless configuration. The locations of the sensors were specified by the user later in the design process, based on the digital model created. Lastly, to simulate the effect of the weight when a person grabs certain objects, the arm should allow the attachment of weights no heavier than 3 kg at the end of the forearm, where the wrist is located.

Digital Mock Up. The starting point of the project was focused on designing the mechanical arm using Autodesk Inventor software, which has high flexibility in terms of simulating the required degrees of freedom and FEM analysis, including static and dynamic behaviour of the model under certain conditions. As shown below, the final model of the mechanical arm is composed of 33 different parts highlighted by the balloons and named in the Fig. 3. The total mass of the physical model of the mechanical arm was 0.82 kg excluding the horizontal and vertical fixing plane.

There are 14 components which are excluded from design part as they were available in the Inventor library. However, the remaining 19 parts were designed to meet project requirements introduced in the previous section of this paper.

2 Topological Optimization

The digital model of the mechanical arm underwent various physical modifications throughout the design process. Most of these modifications had as objective the reduction of weight and consequently the optimization of material and production time (since components have been realized through additive manufacturing). The optimization process was performed in Autodesk Inventor by using the Shape Generator command. The topological optimization, summarized in Fig. 4, relies on the inputs given to the software related to boundary conditions, applied forces and pressures, areas to be preserved, symmetry planes and volume percentage reduction desired. After correctly setting the inputs, the software generated a model with recommended modifications to achieve the reduction in volume.

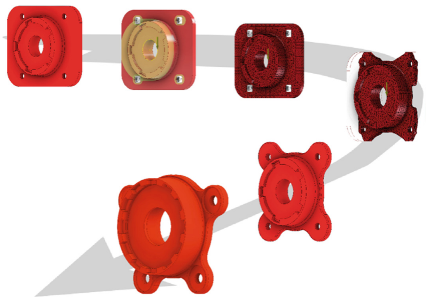


Fig. 4. Topological optimization

From the first draft until the final concept, some components particularly related to the joints had their shapes and thus weight reduced by a significant percent. In contrast, other components such as the lateral panels did not undergo a significant topological optimization as to maintain the structural stability and weight distributed along the structure. In addition, as the production will be done by additive manufacturing, the components will have a rectilinear infill pattern of 20%, already reducing the weight by a significant amount. The removal of material was done mainly in areas where the stresses were significantly low, and the accumulation of material was unnecessary. The failure condition was set to yield strength of the material. The material used for the creation of the parts was polylactic acid (PLA), however, as Autodesk Inventor does not contain this material in its default libraries, acrylonitrile butadiene styrene (ABS) was used for the simulations. Both materials have similar mechanical and physical properties, which is why it was considered as the most suitable solution.

3 Numerical Model Validation

Given the list of requirements, the mechanical arm should withstand a maximum load of approximately 3 kg, corresponding for example, to double the weight of a water bottle held by a human arm. Therefore, it was essential to perform a structural analysis to study the response of the mechanical arm when an external force is applied. Static stress analysis is a type of structural analysis that can be effectively carried out by means of a finite element model. This analysis is a common procedure in mechanical design to investigate stress, strain, and ensure that failure is avoided during the operation. Inventor software provides a practical tool for such analysis, which was used to conduct some stress inspection. In order to have more accurate results and reduce the computational time, only the components which were considered to be critically loaded were analysed. These components were the wrist and the elbows shaft shown in Fig. 5-a.

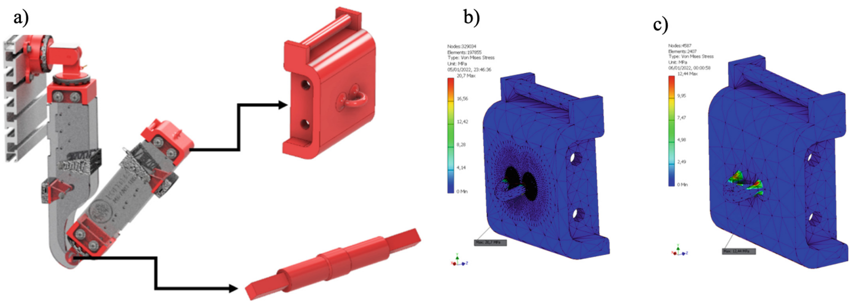


Fig. 5. FEM analysis.

Polylactide (PLA) was used as material for 3D printing the component mentioned for the stress analysis. For the stress analysis it was required by Inventor software to choose the material properties, including the mechanical thermal and strength of the PLA. However, this material was not defined in the inventor library. Therefore, a new material was created and added to the library of Inventor, considering [6] as reference the material properties are shown in Fig. 5-b and 5-c.

4 Results and Validation

The validation of the mechanical arm was based the following steps:

1. Testing of the required DOFs on the physical model, as well as evaluating the correct operation of the locking system. The system showed a correct operation, thus this point was confirmed.
2. Applying a static load on the wrist corresponding to 3 kg of mass in order to check if the FEM static analysis performed in Inventor was valid.

The first condition was studied by fixing the test bench on a table and connecting the wrist to the anchor bases at the forearm and the upper arm by means of the string. By pulling the string, it was possible to analyse the motion of the arm. The second condition was validated by attaching a load equivalent to 3 kg and observing the deflection behaviour of the most critical components. The physical model was able to withstand the load applied considering the initial boundary conditions.

5 Conclusions and Future Work

The 5 °C of freedom required for the test bench to represent the behavior of the real arm were implemented successfully. The implemented setup gives the possibility to lock each DOF at any position. Although, the locking system could be slightly improved by updating the interference between the locking disk and the Omeral Supination which guarantee that the locking disk will not have any displacement while the arm is moving. The FEM analysis demonstrates that the mechanical arm will not fail under static load considering with a load applied of 30N with having the possibility to increase the load but should consider that the safety factor is 3.38 when 3 kg load is added. However, further analysis could be implemented, such as dynamic analysis. A further improvement can be applied by studying a different coupling in the joints for Omeral and Forearm Supination: by changing the design of the joints it is possible to increase the resistance under static load. Right now the joints are kept together through shrink fit of its elements; exploiting the employment of Seiger disks (as happened in the Arm Adduction/Abduction joint) we can increase the maximum axial load that can be bothered by the joint, increasing the safety coefficient. 3D printing technology using PLA material demonstrated to be promising technology for additive manufacturing, in this project it exhibited a high precision and high strength to weight ratio. Therefore, it can be used in many fields. However, the employment of different additive manufacturing techniques (like selective laser sintering) can help in obtaining a denser material and a higher dimensional precision, providing great improvements both in the mechanical resistance and in the working principle (in particular for the locking system).

References

1. Gassert, R., Dietz, V.: Rehabilitation robots for the treatment of sensorimotor deficits: a neu-rophysiological perspective. Neuroeng. Rehabil **15**(1), 1–15 (2018). https://doi.org/10.1186/s12984-018-0383-x
2. Thalman, C., Artemiadis, P.: A review of soft wearable robots that provide active assistance: trends, common actuation methods, fabrication, and applications. Wearab. Technol. **1**, e3 (2020). https://doi.org/10.1017/wtc.2020.4
3. Wang, Z., Cai, Z., Cui, L., Pang, C.: Structure design and analysis of kinematics of an upper-limbed rehabilitation robot. MATEC Web Conf. **232**, 02033 (2018). https://doi.org/10.1051/matecconf/201823202033

4. Xiloyannis, M., Chiaradia, D., Frisoli, A., Masia, L.: Physiological and kinematic effects of a soft exosuit on arm movements. J.NeuroEng. Rehabilit. **16** (2019). https://doi.org/10.1186/s12984-019-0495-y
5. ñzaslan, A., Koß, S., ñzaslan, Tufücu, H.: Estimation of stature from upper extremity. Military Med. **171**(4), 288–291 (2006). https://doi.org/10.7205/MILMED.171.4.288
6. Farah, S., Anderson, D.G., Langer, R.: Physical and mechanical properties of pla, and their functions in widespread applications-a comprehensive review. Adv. Drug Deliv. Rev. **107**, 367–392 (2016)