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Computer-Aided Design and Applications

Design an Upper Limb Exoskeleton Robot

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Abstract. Robot applications in the fields of life and production are becoming more and more popular due to the advantages they bring. Rehabilitation robots have also proven their importance in the task of supporting patients and stakeholders during the exercise phase. In this study, an upper limb rehabilitation robot model (UExosVN) consisting of 7 active and 3 passive degrees of freedom was proposed. The study synthesized the main requirements when designing a rehabilitation robot model. It is specifically related to the user-friendly factor in Vietnam and the comfort and safety factors when using it. Next, the study carried out calculations and simulations to select important equipment, especially the counterweight system, to both reduce the actuator's size and ensure the safety of users in the event of a power failure or emergency stop. Finally, the study conducted simulation testing for most of the important details, especially the safety shafts of the joints. Calculations, simulations, and tests have proven that the robot being designed and manufactured meets the set design requirements and ensures safety when working.

Keywords: Upper limb rehabilitation robot, CAD, ADAMS View, Dynamics, Simulation.
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1 INTRODUCTION

Demand for rehabilitation treatment has tended to increase rapidly in the past years. According to annual statistics in the US [1] 795,000 Stroke patients need to participate in rehabilitation training every year. More than 10 million new trauma patients every year [2]. Particularly for developing countries like Vietnam, Malaysia, Thailand, etc., the number of new patients is increasing very fast and tends to be younger. According to statistics, in 2017, for every 100 thousand people, more than 2,500 Vietnamese people died or became disabled due to stroke. [3]. The number of stroke patients under 45 years old is increasing rapidly. Consequences of improper treatment and rehabilitation greatly influence the integration back to life as well as the work of those patients. [4].

The traditional rehabilitation method is a one-to-one approach performed by physical therapists. This method has the disadvantage of requiring hardworking manpower and is time-consuming. As a result, training sessions are often shorter than required. Not only that, because doctors and technicians support patients by hand, this leads to poor repeatability [4]. Studies have shown that the application of rehabilitation robots can overcome these disadvantages above [5]. The application of rehabilitation robots in this process helps to reduce tedious and heavy work for physiotherapists and easily measure parameters to help evaluate the effectiveness of exercises [6]. In addition, the combination of graphic techniques such as games and virtual reality technology has helped these robots increase the level of stimulation for the patients, thereby improving the effectiveness of the training process [7]-[9].

Upper limb rehabilitation robots can be divided into 2 types based on structure: exoskeleton robots and end-point robots. Endpoint robots usually have a simple structure; the user only needs to attach to the end of the arm. This method provides exercises mainly in 2D space. The exoskeleton robot can support exercises in three-dimensional (3D) space. They are complex and practical exercises such as Activities of Daily Living (ADL). In addition to complex exercises, the robot can also provide independent exercises for each joint. At present, the exoskeleton robot design topic is a hot topic in rehabilitation robot research. With different principles and different actuator sources, a number of robotic exoskeleton structures have been developed and are being developed. Some case studies include a dynamic exoskeleton system ADEN-7 robot containing 7 degrees of freedom (DOF) [10], an ARMIN robot with 6 DOFs [11], etc. Another classification is based on the actuator's sources. Some popular power sources are electric motors, pneumatic muscle drives, unpowered, hydraulic driver. [13]-[16].

Regarding the new trends aimed at increasing the effectiveness of patient training and shortening recovery time, research has identified several approaches, such as applying interactive games and using VR technology. [17][19], and combining biological signals such as EMG/EEG signals for control processes, etc. [19].

In this study, first, the necessary requirements to design an exoskeleton robot for upper limb rehabilitation were synthesized. These requirements focus on the Vietnamese user's anthropometric issues as well as the safety issues when using the device. Next, the study proposes a design for a robot model that meets the above requirements. Finally, to ensure the feasibility of the design option, calculation, and simulation by using CAD, CAE software is carried out to select important components as well as test important structures.

Some of the main contributions of this paper are summarized as follows:

- Based on the patient's anthropometric requirements with parameters of segment length, angle range of movements, and requirements for safety issues, an upper limb rehabilitation robot model consisting of 7 active degrees of freedom and 3 passive degrees of freedom has been proposed. The detailed design of each link and joint was described to ensure the operation of the system and the safety of the users. Among the structures, the shoulder joint structure is the most complex, and the research has focused on describing its structure. One of the important structures in the shoulder structure is the deflection and counterweight structures.
- The study presented the process of calculating and selecting important components of the system. In order to select the motor and gearhead parameters as well as to test the system's durability in the next step, the study also synthesized important kinetic parameters. Since then, combined with the detailed system structure above, the dynamic simulation process was deployed to determine the parameters for selecting the appropriate motor and gearhead.
- Durable testing for critical system components. These details include moving parts and transmission parts. In particular, to ensure the safety of the system and the users, the safety shafts are also tested in the most dangerous conditions. From there, the structure and size of the safety shafts were selected appropriately.

The rest of this paper is organized as follows. From the perspective of bionics and safety, Section 2 analyzes the requirements for the system. The requirements include anthropometrics, safety, and some other ones. The mechanical design of the robot was presented in Section 3. The result of the design process and durable evaluation are shown in Section 4. Conclusions are drawn in Section 5.

2 DESIGN REQUIREMENT

2.1 Anthropometric Requirement

The human arm is a very complex motor system consisting of many joints. In order to serve the full rehabilitation training of the robot and create comfort for the patient during use, the robotic arm must be able to simulate the operation of the closest human arm movements. The operating range of the joints and the required length of the links of the robot must be within the operating range and the corresponding link length of the human arm to ensure safety during use.

Anthropometric parameters include the links' length and joints' range of motion of the human arm. Dimensions of human arm' links are determined based on the ratio of human height, [21]. The operating range of motion, as well as the average height, are synthesized through a survey, [12]. These anthropometric parameters of Vietnamese people have been compiled and given in the document. [23] and it is shown in Table 1.

Joints	*Movements*	*Range of motion (ROM) (Degree) [12]*
Shoulder (Shld.)	Abduction/Adduction (Abd./Add.)	[175, -50]
	Flexion/Extension (Flx./Ext.)	[165, -50]
	Internal/External rotation (Int./Ext. Rot.)	[70, -45]
Elbow (Elb.)	Flexion/Extension (Flx./Ext.)	[145, 0]
	Pronation/Supination (Pro./Sup.)	[75, -110]
Wrist (Wri.)	Flexion/Extension (Flx./Ext.)	[75, -70]
	Radial/Ulnar deviation (Rad./Uln. Dev.)	[20, -35]

Table 1: RoM of a human arm.

Movements	Range of motion (Degree)
Elevation / Demotion and Abduction/Adduction (q2)	[40, 135]
Change the plane (q2)	[-40, 130]
Upper arm rotation (q3)	[-90, 90]
Elbow flexion/extension (q4)	[0, 120]
Forearm Pronation/Supination (q5)	[-70, 85]

Table 2: RoM of the developing robot's joints.

2.2 Safety Requirements

UExosVN robot is a device used directly on patients, so safety requirements for users are very important. In addition to the requirements for the durability of the structures, the main cause of unsafety for the user is the loss of control over the robot's joints.

The control of robot joints is mainly based on two main factors: operating range and operating speed. If the joint is overactive, the operating angle range as well as the operating speed is too large, both will cause unsafety to people. Therefore, it is necessary to control these two parameters strictly.

Range control is done through limit control (both hardware and software), while speed control is done through actuators' parameters and control software. So, to ensure safety, the robot requires hard safety shafts to limit the travel for the joints, as well as a travel switch to limit the soft stroke for these joints. Choosing motors and transmissions for the robot must also be within the safe operating speed range of the joints.

2.3 Other Requirements for Shoulder

Most joints in the human arm are hinge or ball joints, and rotational movements are performed around the centers of these joints. However, the shoulder joint is a spherical joint with a wide range of action, and combined with the center of this joint, it can change position significantly during operation. Therefore, to ensure the comfort and safety of the user, the robot's shoulder joint is required to simulate closet the operation of the shoulder joint.

3 PROPOSED DESIGN OF THE UEXOSVN

3.1 Proposed Structure of the Upper Limb Exoskeleton

The human shoulder joint performs three main movements: shoulder abduction/adduction, Shoulder flexion/extension, and Shoulder internal/external rotation. In principle, this is a ball joint. However, in practice, manufacturing and operating a ball joint is very difficult, and it is difficult to simplify the replacement of the ball joint with three hinge joints with perpendicular centers.

In addition, the center of the shoulder joint is more flexible than that. In fact, the entire center of the shoulder joint can move up/down and forward/backward. To increase the flexibility of the human shoulder joint (HH: Human humerus), the M2 lifting joint of the Robot has been deflected to an angle as shown in Figure 1. As a result, the center of the human shoulder joint HH will be flexible up and down in a circle with center M2.

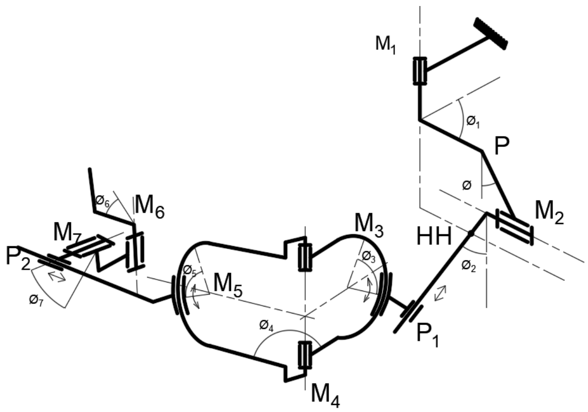


Figure 1: Principal structure for the robot UExosVN.

The principal structure of the shoulder joint includes 3 degrees of freedom: Motor (M1), Motor 2 (M2), and Motor 3 (M3). M1 has the role of changing the plane of action for joint M2 as well as changing the function of this joint. M2 has the function of performing Elevation/Demotion or Abduction/Adduction movements depending on the working plane. M3 has the function of performing arm rotation. The P-joint has a passive degree of freedom to produce circular curvature for HH, depending on the user. The remaining joints have a hinge-like structure and are shown as Figure 1.

In summary, the overall structure of the UExosVN robot includes 7 degrees of freedom to respond to 7 joints on the human arm: M1, M2, M3, M4, M5, M6, M7, and 3 passive joints P, P1, P2 to adjust the arm size to suit many users. The basic dimensions parameters of the robot are shown in Table 3.

3.2 Adaption to the Vietnamese physique

The shoulder joint structure of the UExosVN robot consists of three joints M1, M2, M3 that work together to fully realize the operability of the human shoulder joint with the structure as Figure 2.

The lengths of the arm and forearm segments can be adjusted to fit the individual length of each patient. These adjustable ranges are designed to match the measurements of the Vietnamese population, as shown in Table 3.

Component	Min (mm)	Max (mm)	Mean (mm)
Length of upper arm	245	340	292,5
Length of forearm	190	270	230
Length from wrist to fingertip	140	200	170

Table 3: Dimension parameters of the Robot [22].

The kinematics are determined through statistical measurements and referenced from available robot models. [11] [22] , specifically as Table 4.

Movements	Maximum Speed (Degree/Sec.)	Acceleration (Degree/Sec.^2)
Change the plane	60	129
Elevation and Demotion	71	103
Upper arm rotation	150	245
Elbow flexion/extension	91	116
Forearm Pronation/Supination	60	58
Wrist pronation/ supination and Wrist flexion/extension	60	43

Table 4: Maximum kinematics values for the Robot.

Joint M1 has the function of switching back and forth between the two working planes (frontal plane and Sagittal plane) of joint M2 to change the function of this joint. Therefore, the M1 joint will have a cantilever hinge structure like Figure 2, and this is the first joint of the robot, so the joint will bear the entire weight of the lower arm. The joint also has a safety shaft to protect the user. Joint M2 is used to elevate/lower the arm. It has the hinge and construction described in Figure 3.

In addition, the eccentricity of the M2 joint to create a circular trajectory for the shoulder joint is accomplished through the deflection shaft in conjunction with a worm gear-like, Figure 4. This transmission has the advantage of large transmission coefficient with small size and resistance to back-propagation.

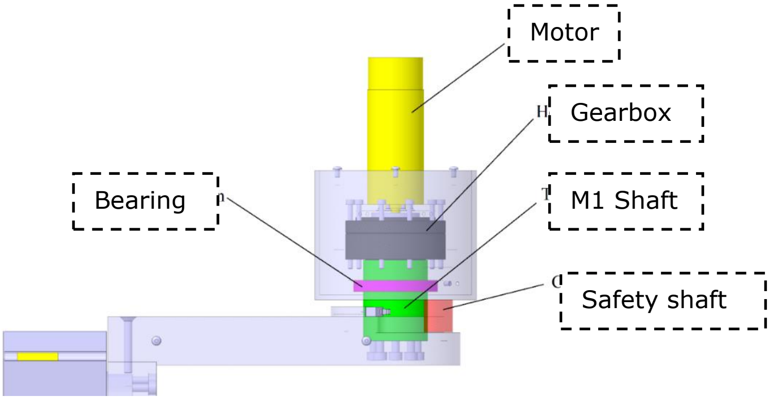


Figure 2: Structure of joint M1.

The shoulder deflection structure described above ensures comfort for the patient during exercise compared to the non-deflection structure in the study. [18]. To implement this deflection principle, the proposed study uses a screw-worm gear mechanism instead of the adjustment and fixation mechanism using screws, as in previous studies. [11]The proposed solution's advantage is its ease of adjustment, which takes advantage of the transmission system's self-locking capability to maintain the position.

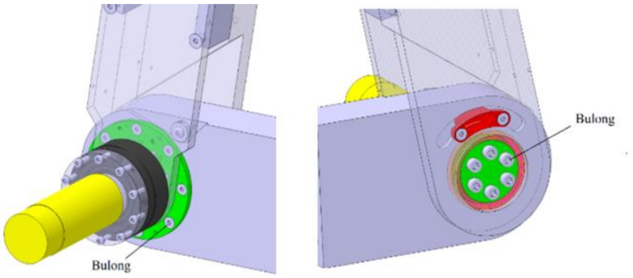


Figure 3: Structure of Joint 2.

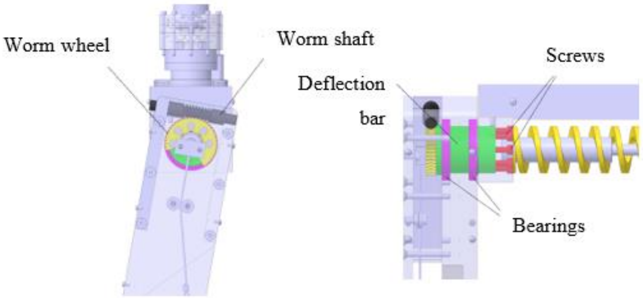


Figure 4: Deflector mechanism for Joint M2.

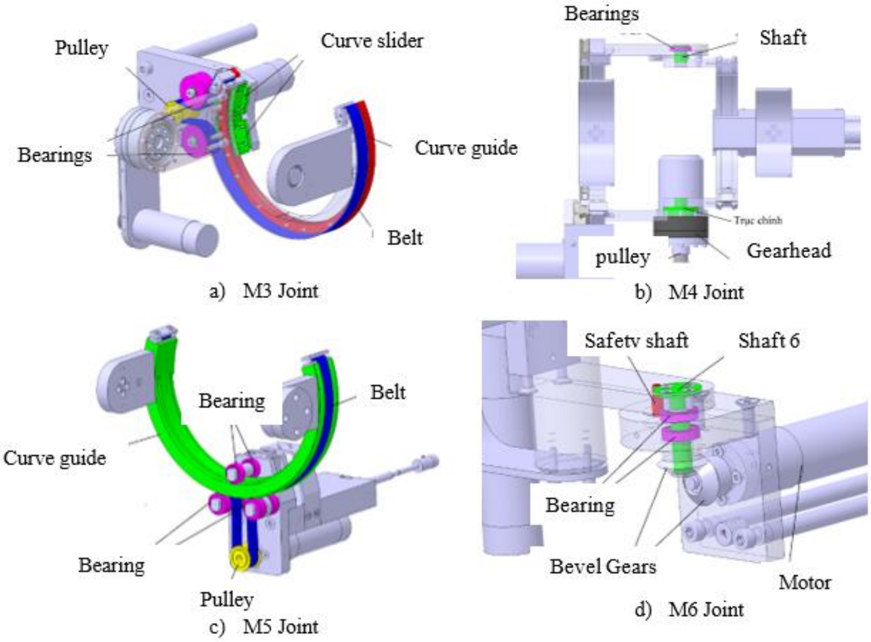


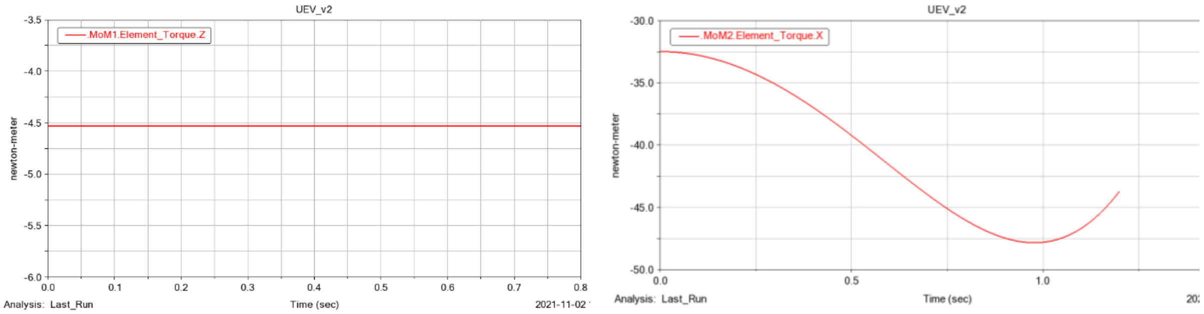
Figure 5: Structure of joints M3-M7.

4 RESULTS

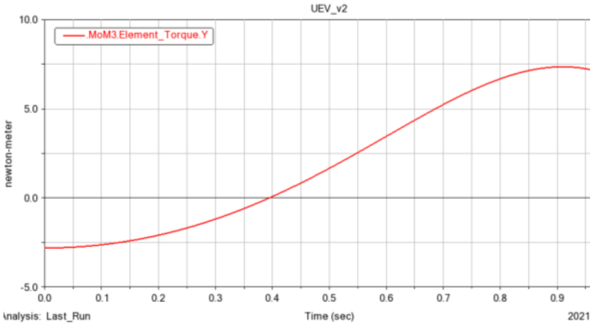
4.1 Selection Of Some Important Components

4.1.1 Experiment setup to select actuator and counterweight.

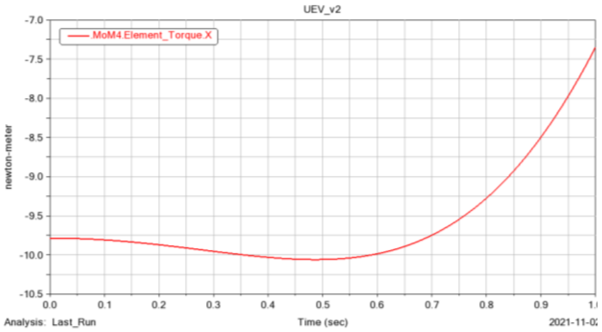
In order to select the right motors for the robot, it is necessary to determine some important kinematics and dynamics parameters for these joints. These values include maximum velocity, maximum acceleration, and torque. The kinematics parameters were determined in 3.1. Meanwhile, the torque values are determined by calculation from the robot model. To reduce the calculation time and to improve the accuracy, the study used a simulation method using the Multidynamics simulation software of ADAMS view. After setting up the model and the input kinematics parameters, as in the Table 4, the values of the dynamic were generated and shown in Figure 6.



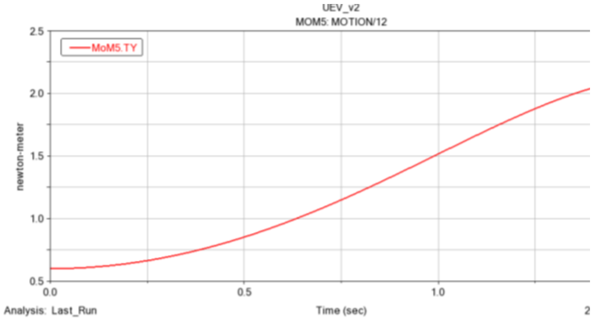
a) M1 Joint b) M2 Joint



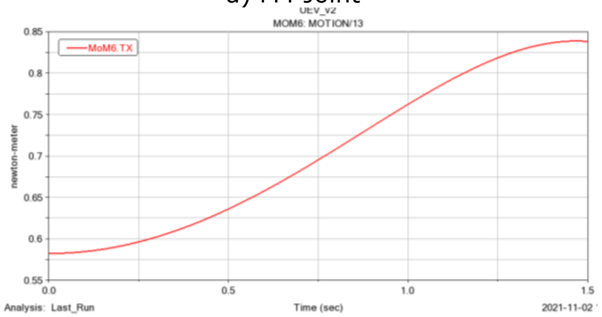
c) M3 Joint



d) M4 Joint



e) M5 Joint



f) M6 Joint

Figure 6: Simulation of the Dynamic values of the UExosVN robot's Joints.

4.1.2 Counterweight selection result

Based on the aforementioned simulation results, the torque acting on the M2 joints is very high. This is because it is used to lift the whole upper arm and forearm of the robot model. With the high torque requirement, the power motor and motor size will be very large. To overcome the problem, the study used a spring-type counterweight. The system in Figure 7 consists of a compression spring and a cable system used to change the direction of the force.

The counterweight selection is changed to choose the suitable spring stiffness. From the torque graph required on joint M2 as Figure 6b. a suitable counterweight should generate the linear torque. If the counterweight can satisfy this, it helps the system simply because the spring force itself is a linear force. Then, in order to generate the linear torque, the lever arm should be constant. This is done by using the cable system, as in Figure 7. Based on the structure, the system used the value r=40 (mm) as Figure 7.b. Using the trial and error method combined with data from the manufacturer, the research decided to use a compression spring SWF40-175 with a stiffness of 14300 N/m, an outer diameter of 40 mm, and a length of 175 mm. The spring calculation is depicted in Figure 7.

M2 is the required torque on joint 2; Mc is the counterweight torque, and M2a is the actual torque required on joint 2 after having a counterweight. It can be seen that, after having the counterweight the maximum required torque on M2 reduced from around 48 Nm to 26 Nm. Using the spring counterweight also has another important function of safety. It prevents the robot arm from dropping freely due to sudden power-off.

Joint	Maximum speed (^{0}/s)	Maximum acceletion (^{0}/s^2)	Maximum Torque (Nm)

Joints	Actuator	Gearbox	Additional Transmission
M1	Maxon RE 35, 90W	Harmonic Drive CSD17-100-2UH	

M1	60	129	4,5
M2	71	103	26
M3	150	245	7,4
M4	91	116	7,4
M5	60	58	2,1

Table 5: Kinematics and Dynamics summary for the UExosVN.

M2	Maxon RE 35, 90W	Harmonic Drive CSD17-100-2UH	
M3	Maxon RE 35, 90W	Harmonic Drive GP32 16659	Belt (
M4	Maxon RE 35, 90W	Harmonic Drive CSD17-100-2UH	
M5	Maxon RE 25, 20W	Maxon GPX 26	Belt (
M6	Maxon RE 25, 20W	Maxon GPX 26	
M7	Maxon RE 25, 20W	Maxon GPX 26	

Table 6: Motors and gearheads selection results for the UExosVN robot.

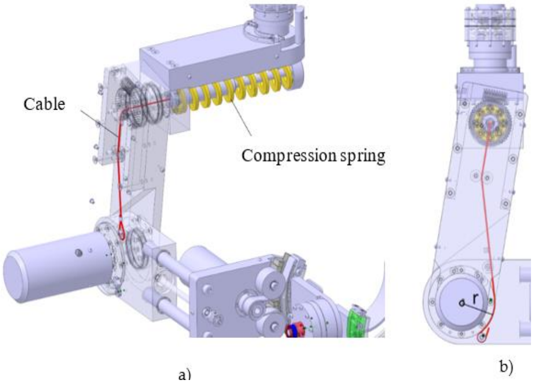


Figure 7: Spring-type counterweight system.

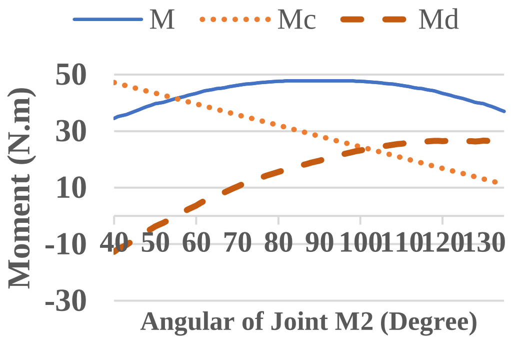


Figure 8: Required torque at M2 joint after having a counterweight.

4.1.3 Result of motors and gearheads selection

From all simulations and calculations above, the required kinematics and dynamics parameters for the 5 important joints of the UExosVN robot are presented in the Table 5. The values were used to select the suitable motors and transmissions, as in Table 6. It is noted that the study chose two types of motor for 7 different joints. This helps to reduce the number of motor types and, as a result, decreases the complexity of manufacturing and maintenance.

4.2 Durable Test Simulation

4.2.1 Experiment setup

For complex systems such as the UExosVN robotic system, the simulation of endurance testing in ADAMS View software is the most suitable. ADAMS View is a specialized software in the analysis of multibody dynamical systems, so it is suitable for both static and dynamic tests. Material setup: almost all components of the UExosVN robot were made from Aluminum to reduce weight. Besides, some important parts that work in high-load conditions were made of steel. Summary of the material setup for some important parts is shown in Table 7. Kinematics and dynamics setup: Motion is applied to the main drive joints established above, with the equation of motion being rotation versus time. The equation is set to 0 in the case of the static strength testing and equal to the maximum joint acceleration in the case of the dynamic solution.

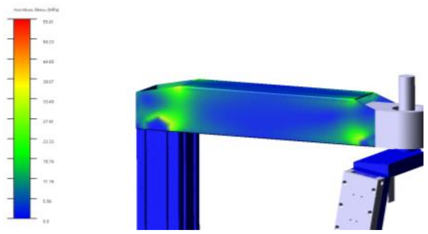
For the test simulation of safety pins in the event of a collision, the input parameter will be the maximum speed of the joints. However, the velocity variable will change when the collision occurs; the velocity after the collision will be the result of the simulation process, so the input variable should be the applied force. This force value will not change during the collision in both direction and value, and the gravitational acceleration is set to coincide with the joint axis so as not to affect the collision process. This velocity is taken in accordance with Table 7.

Joint	Maximum Speed (Degree/s)	Force (N)	Lever arm (mm)
M1	60	20,5	165,5
M2	71	25	165
M3	150		
M4	91	5	109
M5	60	1	109
M6, M7	60	0,5	75

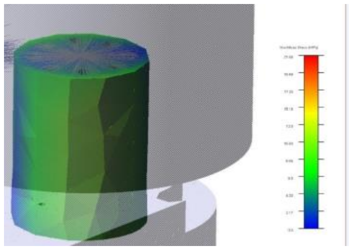
Table 7: Kinematics and dynamics setup for collision simulation.

4.2.2 Simulation results

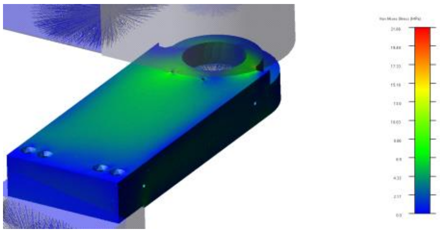
After setting up the kinematics parameters for the model, the study conducted simulations to test for some important parts. The results of the testing process are shown in Figure 9. The maximum stress value results are summarized in Table 8. Through the summary table, it is easy to see that all the important components have maximum stress values less than the allowable stress. This proves that these important parts ensure enough durability when working.



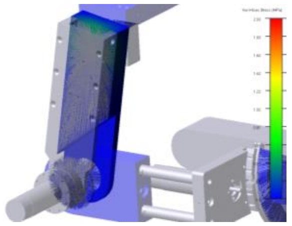
a) Results of horizontal bar
➔ Maximum stress: 55,81 Mpa



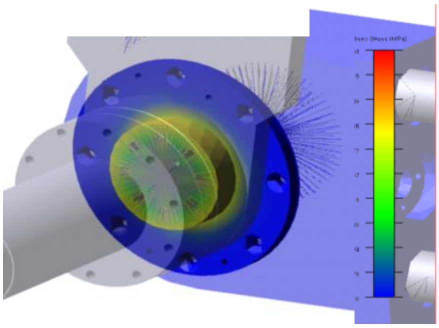
b) Results of Plane inversion shaft
➔ Maximum stress: 21,66 MPa



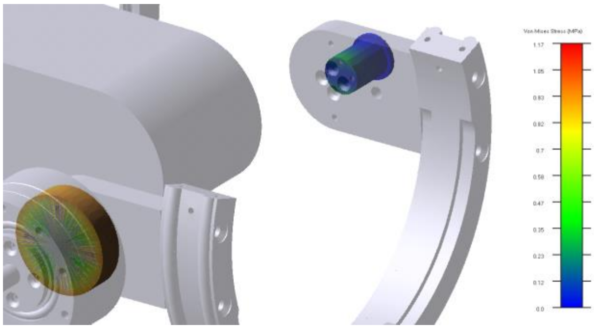
c) Result of Plane inversion bar
➔ Maximum stress: 21,66 Mpa



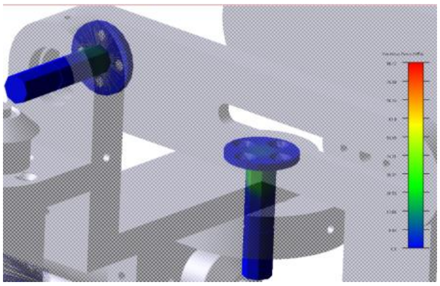
d) Results of Deflector bar
➔ Maximum stress: 2,03 Mpa



e) Result of shoulder shaft
➔ Maximum stress: 7,94 Mpa



f) Result of elbow shaft
➔ Maximum stress: 1,17 Mpa

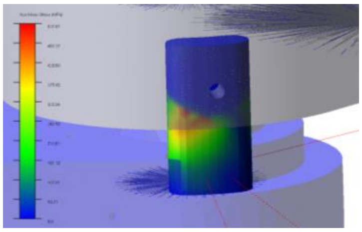


g) Result of wrist shaft
➔ Maximum stress: 88,42 Mpa

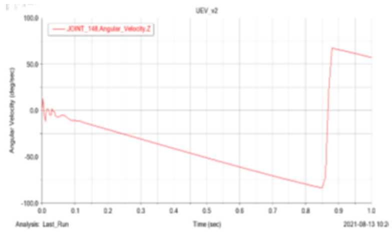
Figure 9: Simulation results for some important parts of the UExosVN Robot.

Part	Maximum stress (Mpa)	Allowance stress (Mpa)	
		A6061 [260]	C45 [570]
Horizontal bar	55,81		<
Plane inversion shaft	11,66		<
Plane inversion bar	21,66	<	
Deflector bar	2,03	<	
Shoulder shaft	7,94		<
Elbow shaft	1,17		<

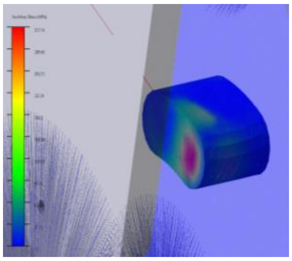
Table 8: Summary simulation results for some important parts of the UExosVN robot.



a) Results of safety shaft 1
➔ Maximum stress: 537 Mpa

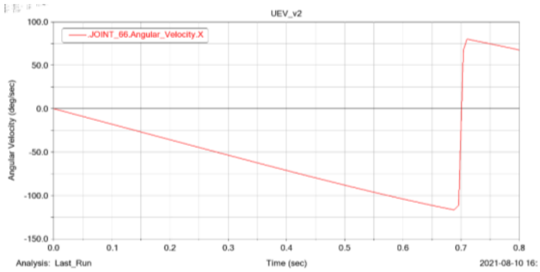


b) Simulation of velocity for shaft 1 when collision
➔ Maximum speed when collision: ~ 80°/s



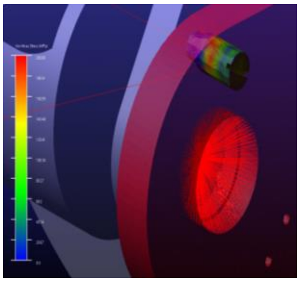
c) Results of safety shaft 2

➔ Maximum stress: 317 Mpa



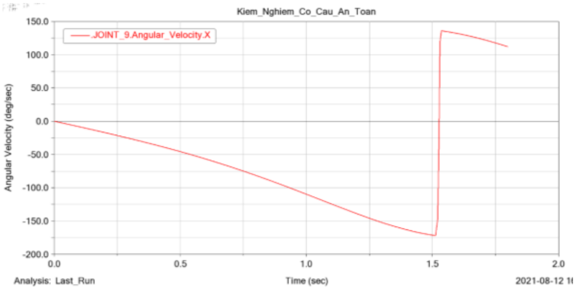
d) Simulattion of velocity for shaft 2 when collision

➔ Maximum speed when collision: ~ 135°/s



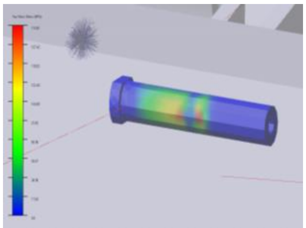
e) Result of safety shaft 2

➔ Maximum stress: 200,68 Mpa



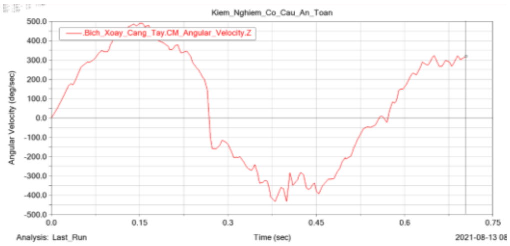
f) Simulattion of velocity for shaft 4 when collision

➔ Maximum speed when collision: ~ 175°/s



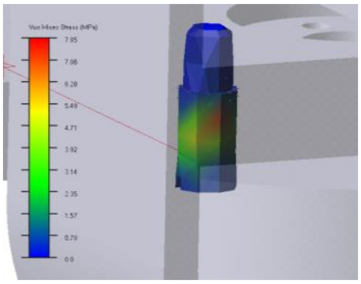
g) Result of safety shaft 5

➔ Maximum stress: 174,43 Mpa



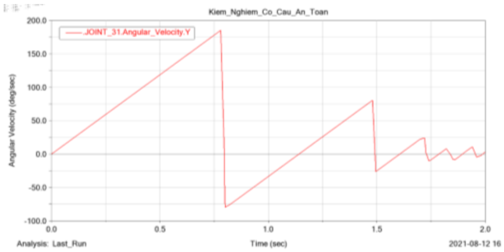
h) Simulattion of velocity for shaft 5 when collision

➔ Maximum speed when collision: ~ 150°/s



i) Result of safety shaft 6,7

➔ Maximum stress: 7,85 Mpa



j) Simulation of velocity for shaft 6,7 when collision

➔ Maximum speed when collision: ~175°/s

Figure 10: Simulation results for safety shafts of the UExosVN robot.

Safety shaft	Maximum speed as (^{0}/s)	Maximum simulated Speed (^{0}/s)	Simulated maximum of stress (Mpa)	Allowance Stress [570 MPa]
M1	60	80	537	<
M2	71	135	317	<
M3	150			
M4	91	175	200,68	<
M5	60	150	174,43	<
M6, M7	60	175	7,85	<

Table 9: Summary simulation results for safety shafts of the UExosVN robot.

As analyzed above, when setting up the collision simulation case, the research has installed the force acting on the links to ensure that the collision velocity must be greater than the maximum speed when working. After setting, the simulation results received include the speed when the collision occurs as well as the maximum stress at these safety shafts. These results were shown in Figure 10 and summarized in Table 9. It can be seen that all velocities of the safety shafts at the time of impact are larger than the maximum speed of the joints during actual working. However, the maximum stress on these shafts at impact is still less than the allowable stress. This proves that the structure and size of these shafts are safe. Another point of note is that the shape of the two safety shafts, M1 and M2, is curved, not cylindrical like the other. The reason is space limitations to increase the size of the shaft. In addition, the force acting on the collision has a coaxial direction of rotation with the center of rotation M1 and M2. That leads to a reasonable increase in the arc size, as suggested.

5 CONCLUSIONS

The study proposed to design a robot model for upper limb rehabilitation consisting of 7 degrees of freedom UExosVN, after proposing the structure based on the input criteria. The research has carried out calculations and simulations to complete the design. The study contributed some results as follows. Firstly, the research has established, calculated, and selected a reasonable compression spring counterweight system to reduce motor size and ensure safety for users when using the device. From there, the research also selects other important components, such as motors and reducers. Secondly, the research was conducted to test the durability of important structures, especially safety shafts. The setting of conditions when simulating is based on the most dangerous working conditions of the equipment. All test simulations proved that the mechanical structure of UExosVN robot is safe. This is even more assured in practice because the speed of exercises is often much lower than these test values. In the upcoming study, the research team will set up a control system to test the accuracy and responsiveness of the system.

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