Proceedings of the 2023 International Conference on Machine Learning and Automation
DOI: 10.54254/2755-2721/31/20230139

Study on the safety of elbow joint with simple upper limb rehabilitation exoskeleton

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Abstract. Due to the great demand for treating physicians for patients with disabilities caused by stroke, in order to reduce the workload of doctors, exoskeleton robots have been effectively applied and promoted in post-illness health care. Because the human rehabilitation movement needs certain accuracy and low error tolerance rate, the rehabilitation exoskeleton robot requires high precision. Since the exoskeleton robot needs to be worn on the human body, there are certain requirements for the size and wearing comfort of the machine, and the functional structure of all aspects of the upper limb exoskeleton rehabilitation robot still needs to be further improved. In the medical rehabilitation exoskeleton, for the elbow exoskeleton of the upper limb, an elbow exoskeleton with binding structure is proposed in this paper. The elastic structure connects the human body with the binding structure, and on this basis, the wearing comfort is improved through the improvement of the structure and the selection of materials. At the same time, the passive joint between the binding structure and the exoskeleton is designed. In case of motion error when the motor is actively driven, the passive joint reduces the harmful force and torque, so as to ensure safety. Finally, the feasibility of this method is demonstrated through simulation and analysis of the movement of exoskeleton machine. It is proved that the design has certain practicability and reference value for practical treatment.

Keywords: upper limb rehabilitation, exoskeleton robot, binding structure, secure.

1. Introduction

For patients with disabilities caused by stroke or other factors, their recovery treatment requires rehabilitation doctors to carry out gradual rehabilitation training. For general rehabilitation training, the core interest is restoring muscle control. Patients move their arms to manipulate objects and can follow a more complex movement plan whose core purpose is to increase the strength, speed, endurance, and accuracy of hand movements and reduce compensatory movements. In order to achieve this, the rehabilitation physician needs to conduct traction training for the patient, and the rehabilitation physician also needs to adjust the training content according to the individual situation to achieve the training goal. In order to reduce the labor cost of rehabilitation physicians and meet the large demand of patients for physicians, exoskeleton robot technology has been applied to the field of rehabilitation medicine [1, 2]. In recent years, with the development of artificial intelligence and robot technology, the application of rehabilitation robots has been widely promoted, and its functions have been further improved. In addition, exoskeletons have also been found to be widely used in daily life and in the military industry

[3]. Existing exoskeleton robots can be roughly divided into whole-body rehabilitation robots, upper limb rehabilitation robots and lower limb rehabilitation robots. Common upper limb rehabilitation robots have several forms of end-execution, scaffolding exoskeleton and wearing exoskeleton [4-7]. Compared with the end-executive robot, the exoskeleton robot avoids as much as possible the problem that the traction force cannot be accurately applied to the joints of the upper limb, thus causing damage to the upper limb [8]. In order to achieve accurate force application, it is often necessary to align the rotation axis of the mechanical structure with the joint axis of the human body. This alignment structure provides precise force while avoiding the generation of singularities and mechanical failures caused by singularities. When the alignment is uneven, the exoskeleton machinery may produce harmful forces and moments, which are applied to the human upper limb that is still in rehabilitation and cannot accurately control itself, which will cause obstacles to recovery and even secondary damage to the upper limb. Due to the differences in body data among human individuals, accurate installation requires adjustment of mechanical structure for different subjects and may have a great impact on wearing comfort [9]. Increasing compliance at the exoskeleton-limb interface, changing the mechanical structure, and allowing for relative displacement between the human upper limb and the exoskeleton machinery under incorrect conditions can reduce harmful forces, and achieving this requires a balance between the functionality and comfort of the exoskeleton.

Most of the existing exoskeletons use motors with high reduction ratio gearboxes, their actuator weight is quite large, complex structure makes them occupy a large space, reduce portability while increasing the cost, resulting in a lower degree of application promotion. For the low cost, simple structure of the wearing exoskeleton, its control and mechanical motion field still have a large room for enhancement. The research in this paper will keep the simple structure of the elbow joint and based on the alignment of the exoskeleton motion axis with the human joint axis, the elbow joint will be studied, with the aim of providing a simple and safe exoskeleton robot design scheme. For this reason, a motor connected to a linear SEA, attached to the outer side of the humerus, is presented in this paper to control the motion of the elbow joint and ensure the motion field. At the same time, this study also designed and analysed the lower arm binding structure. By designing the compliance of SEA, an adaptive structure with three passive joints was added to the binding structure to enhance the safety of the exoskeleton robot. In the following content, the details of the elbow joint and the kinematics analysis of the exoskeleton robot are described in detail in chapter 2. The third chapter introduces the simulation experiment. Finally, the thesis is summarized in chapter 4.

2. Methods and materials

2.1. Design requirement

For the design of exoskeleton machinery, it is necessary to make the mechanical motion domain a proper subset of the motion domain of human daily activities. That is, without exceeding the range of human movement, the exoskeleton machine can drive the upper limb of the patient to any point in the movement space, while ensuring the safety of rehabilitation movement [10]. This exoskeleton design is mainly used in post-disease rehabilitation, that is, to assist patients to recover the daily movement ability of the upper limb. According to the anatomical position, the joint movement direction is divided into sagittal plane, coronal plane and axial plane, as shown in the Figure. Figure 1 shows the sagittal plane, coronal plane and axial plane of human movement. Figure 2 shows the flexion of the elbow and the pronation and supination of the forearm.

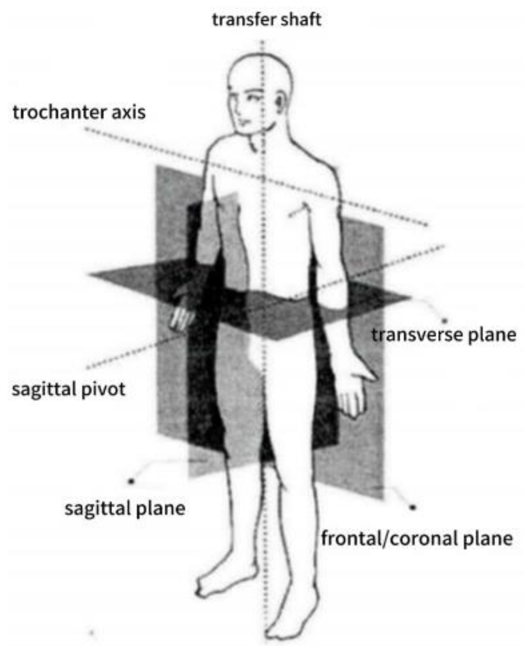

Figure 1. Schematic diagram of the axial plane of the human body [10].

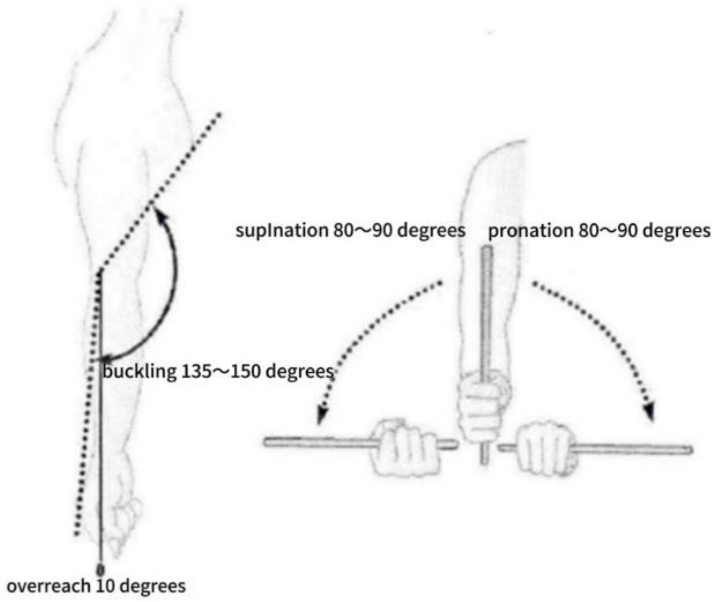

Figure 2. Diagram of elbow joint rotation [10].

Based on daily and clinical experience, the activities of the elbow joint are mainly flexion (forearm movement from the front towards the humerus) and extension (movement from flexion back) around the elbow joint. The normal human body buckling value is 0 ~ 145 degrees, and the overextension is 0 ~ 10 degrees. Based on the above, the rotation range of the robot for elbow rehabilitation exoskeleton is 135 degrees, and the parameters of the rod are summarized as follows Table 1:

Table 1. Robot rod parameter determination.

Item	Parameter (mm)
Upper arm length range	240.5-310
Forearm length range	250-370
Large armband size	124
Forearm ring size	102

2.2. Exoskeleton structure design

Based on ergonomic analysis, this paper focuses on the elbow joint of the upper limb and ensures safety and comfort through active and passive combination. In this paper, an elbow joint motion structure with one active degree of freedom and three passive degrees of freedom is proposed, including two binding mechanisms on the upper and lower arms and the elbow joint controlled by linear SEA. Through the design of mechanical structure, rotation can be transformed into linear motion, and the elbow joint can maintain a simple mechanical structure through linear SEA control. It also meets the range of motion required for rehabilitation. Through the structural design of the binding mechanism, the performance of the exoskeleton machinery in assisting rehabilitation is guaranteed, the universality of the exoskeleton rehabilitation mechanism is realized, and the wearing experience is optimized to ensure the safety and health of patients in the process of exoskeleton mechanical rehabilitation. Figures 3 and 4 show the flexion and extension of the upper limb exoskeleton, respectively.

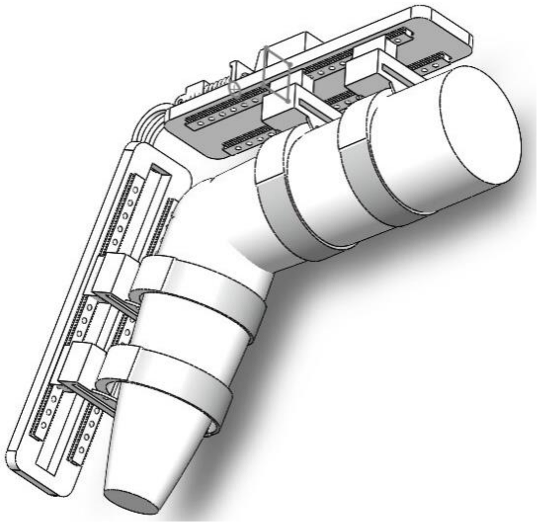

Figure 3. Upper arm bending diagram.

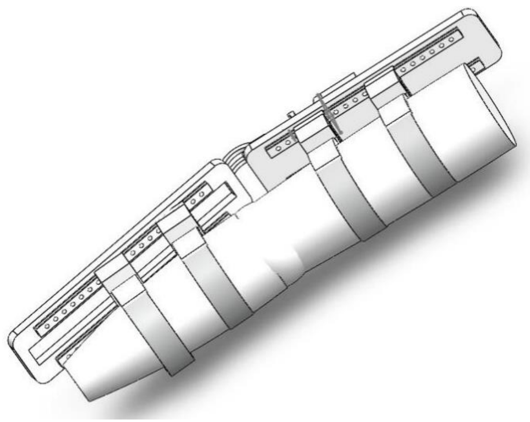

Figure 4. Upper arm extension diagram.

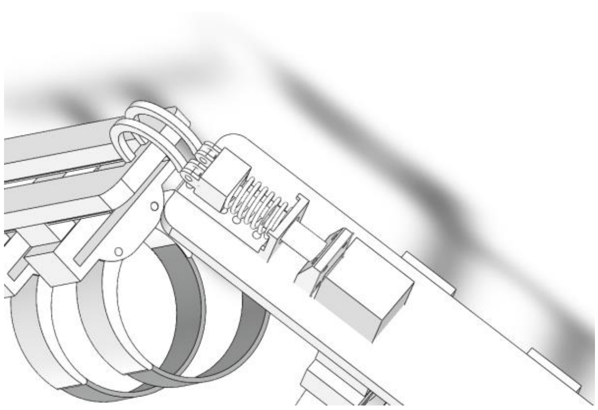

Figure 5. SEA.

DOI: 10.54254/2755-2721/31/20230139

The mechanical structure proposed in this paper is shown in the Figure3 and 4, in which a series of motor elastic brakes are attached to the upper arm exoskeleton, one of which is responsible for controlling the relative rotation between the upper arm exoskeleton and the joint parts, and the other motor is responsible for controlling the relative rotation between the lower arm exoskeleton and the joint parts. For our mechanical structure, its range of motion can cover most of the elbow activities of the human body in life. Figure 5-7 shows the more detailed structure of the upper limb exoskeleton, Figure 5 shows the motor attachment, Figure 6 shows the slide rail structure, and Figure 7 shows the binding structure.

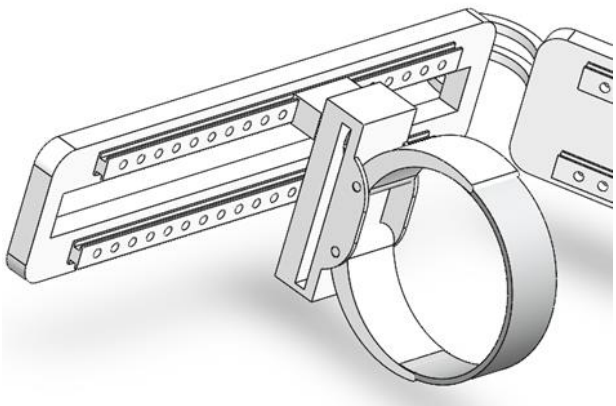

Figure 6. Slide rail connection structure.

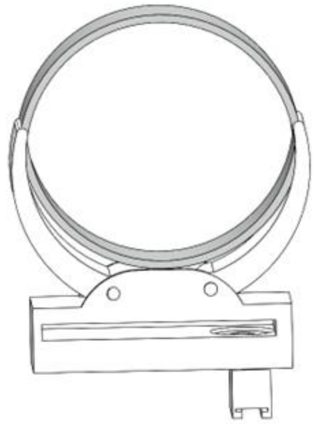

Figure 7. Binding structure.

In order to achieve safe interaction, we use linear series brakes to achieve free movement of the elbow joint. The series of elastic joints can measure joint torque beyond the spring deflection, and for both brakes, an encoder is equipped to measure their range of motion. When assisting rehabilitation in practical applications, the doctor can make the exoskeleton machine reach the corresponding position through active guidance, record the data and send it back to the computer, so as to realize the establishment of the rehabilitation plan. After the establishment of the rehabilitation plan, the exoskeleton machine can conduct rehabilitation training for patients according to the previously recorded data. When the patient's rehabilitation has progressed to a certain extent, the physician can also change the training plan by re-guiding, so that the rehabilitation training is appropriate.

The structural design of the binding mechanism is shown in the figure, which is composed of three parts: human body-mechanical fastening mechanism, binding base and sliding rail mechanism. Among them, for the human-mechanical fastening mechanism, a curved rigid structure and elastic belt are used between the binding mechanism and the human upper limb, and the static friction force is fixed between the human body and the mechanical body. The binding mechanism also includes two passive degrees of freedom, which are the relative rotation between the human-mechanical fastening mechanism and the binding base, and the relative sliding of the fastening base on the circular guide rail. When the exoskeleton is improperly installed or operated, the mechanical axis of the exoskeleton and the joint axis of the human body are not aligned, which will cause harmful forces and moments to the human body. In the case that the harmful force and the harmful moment are not too large, the elastic binding mode and the two passive joints will produce motion, counteracting part of the harmful force and the harmful moment.

2.3. Simulation

After the design is completed, the model is built in SolidWorks, and then imported into ANSYS for simulation. The step is set to 1, takes 3 seconds, and the translation and joint rotation between the binding structure and the slide are carried out simultaneously. The rotation Angle is 50 degrees, and the movement is repeated for 200s to simulate the situation of a large workload. The cumulative shape variables of the calculated model are shown in Figure 8.

The cumulative deformation of the exoskeleton machine is small, indicating that the unreasonable force and torque with the outside world are small, and it will basically run in accordance with the established trajectory in actual operation, and the damage to the human body is small.

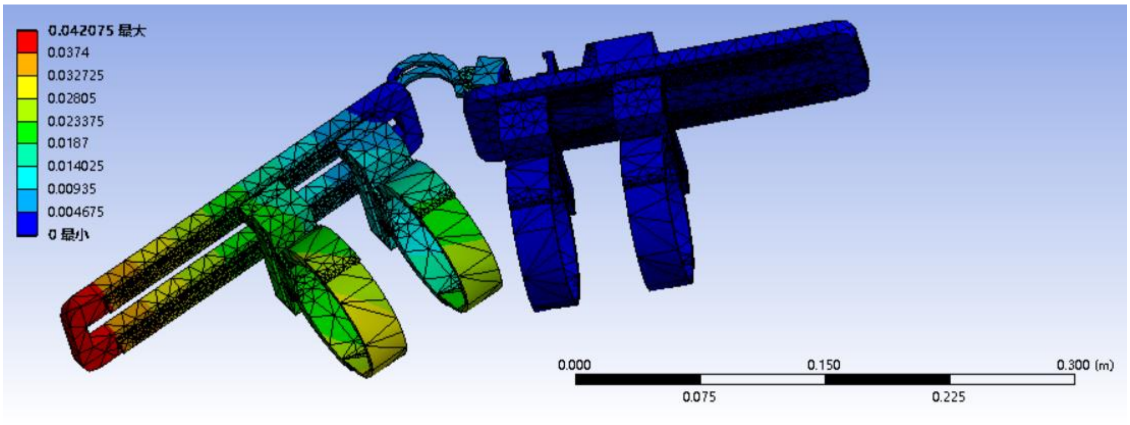

Figure 8. Mechanical simulation of exoskeleton cumulative deformation map.

At the same time, we also obtained the maximum residual force image in the instantaneous state, as shown in Figure 9. The overall residual energy in the machine in the image is less, indicating that the machine is used to resist unreasonable external forces to make less strain. The overall operation of the machine is more reasonable, and it is in a safe and reliable state. It should be noted that there is an extremely large stress at the beginning of the operation, which may be a rigid shock to the structure, which needs to be improved in further refined design. Or require human adjustment at the start of the operation.

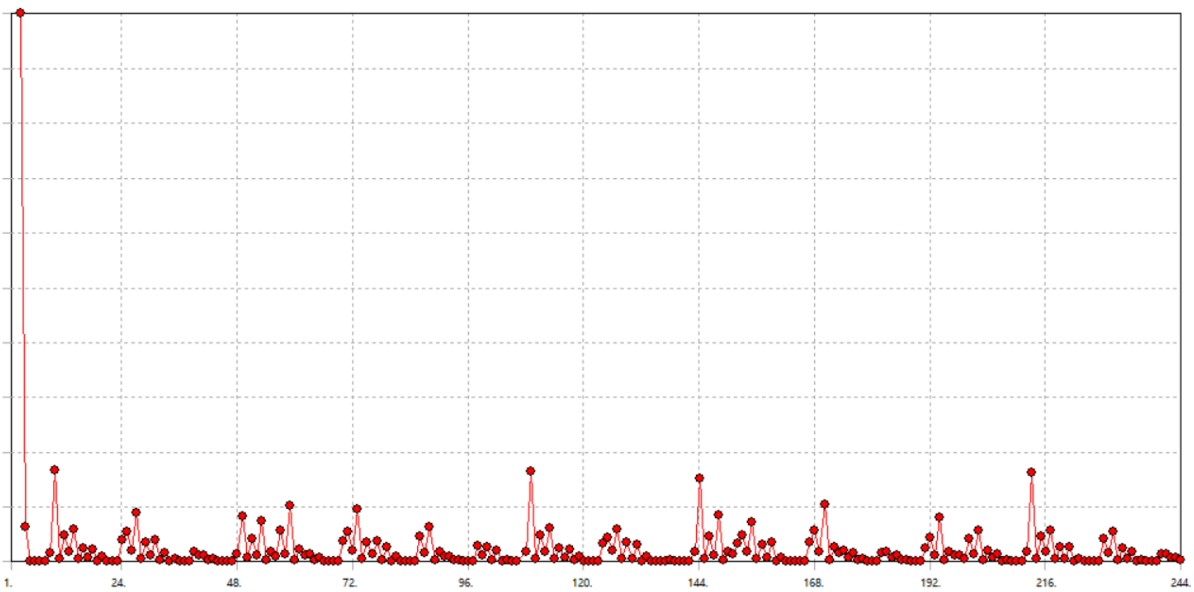

Figure 9. Maximum residual map.

3. Discussion

The study on the safety of the elbow joint with a simple upper limb rehabilitation exoskeleton has provided valuable insights into the potential benefits and safety considerations associated with this technology.

One of the primary findings of this study was the significant improvement in the safety and flexibility of the elbow joint during rehabilitation exercises. The exoskeleton design effectively supported and assisted in the recovery of elbow joint mobility. This finding aligns with previous research highlighting the positive impact of exoskeletons on motor function and rehabilitation outcomes in various limb joints.

The safety analysis conducted in this study demonstrated that the exoskeleton design effectively minimized the risk of injuries to the elbow joint. The rehabilitation program is designed to be adjustable, and the design of the passive joint allows for real-time adjustment, ensuring that the exoskeleton responded appropriately to user movements. By providing adequate support and protection, the exoskeleton reduced the chances of excessive strain or unnatural forces being applied to the joint.

Despite the promising findings, it is important to acknowledge the limitations of this study. Firstly, the sample size was relatively small, which may limit the generalizability of the results. A larger and more diverse population would provide a more comprehensive understanding of the safety considerations associated with the exoskeleton. Additionally, the study duration was relatively short, and a longer-term evaluation would be valuable to assess the sustained effectiveness and safety of the exoskeleton over time.

The implications of this study are substantial for both researchers and clinicians involved in upper limb rehabilitation. The findings highlight the potential of simple upper limb rehabilitation exoskeletons in improving elbow joint mobility and safety during rehabilitation exercises. Further advancements in exoskeleton technology and research are warranted to optimize the design, functionality, and safety features of these devices.

This paper study on the safety of the elbow joint with a simple upper limb rehabilitation exoskeleton has provided some insights into the potential benefits and safety considerations associated with this technology. The findings support the use of exoskeletons as a valuable tool in enhancing elbow joint rehabilitation outcomes. However, further research with larger sample sizes and longer-term evaluations is needed to validate and generalize these findings. With continued advancements, exoskeleton technology may draw on available technologies in computer science, biological science and other fields. Exoskeleton technology has the potential to revolutionize upper limb rehabilitation, improving the quality of life for individuals with elbow joint impairments.

4. Conclusion

An elbow exoskeleton with binding structure is designed and studied in this paper. The rotation of the elbow joint is transformed into a linear motion using the structure and connected to the linear motor by an elastic brake. The bottom end of the binding structure and the guide rod of the exoskeleton are connected by a plane guide rod mechanism through a sliding rail. When necessary, the binding structure can be tightly connected with the guide rod by bolts to avoid relative sliding. For the binding structure, there are two relatively rotating passive joints. When the motor drives the elbow joint of the exoskeleton to rotate, the passive joint will rotate, and the binding structure will slide through the guide rail to offset the harmful force and torque of the exoskeleton on the human upper limb and ensure the safety of the rehabilitation process. The findings of this study indicate that the implementation of a simple upper limb rehabilitation exoskeleton for the elbow joint can enhance the safety and effectiveness of rehabilitation exercises. The exoskeleton demonstrates the potential to facilitate the recovery process by providing appropriate support, protection, and real-time feedback. Further advancements and research in this field hold promise for improving rehabilitation outcomes and enhancing the quality of life for individuals with elbow joint impairments.

DOI: 10.54254/2755-2721/31/20230139

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