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DESIGN PROPOSAL FOR A PORTABLE ELBOW EXOSKELETON

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BACKGROUND

Exoskeleton based rehabilitation for post-stroke recovery is being aggressively pursued due to unavailability of adequate number of caregivers and huge investment for the manual treatment [1]. The structural framework for providing different training exercises is not similar for all exoskeletons and there is no standardized protocol for rehabilitation following stroke [2]. Various approaches have been undertaken to come up with customized exoskeleton design for implementing a specific type of exercise. Though a few exoskeletons have proved to be beneficial in terms of clinical outcomes, there is still a long way to go before a useful rehabilitation device becomes acceptable to the users. After reviewing the 46 exoskeletons (commercial or prototypes) [3], two key requirements can be considered for the design of an exoskeleton; the structural parameter which decides the size, weight and the ease of control and the other is the nature of rehabilitation therapy which defines the type and intensity of the exercises performed during training.

The main objective for rehabilitation is to improve muscle strength and to provide smooth joint controllability of post-stroke patients. Therefore, the rehabilitation training should be adaptive to the patient's requirement. Generally three modes of rehabilitation are incorporated at different stages of rehabilitation after stroke [4]. Fig. 1 shows the type of rehabilitation required in each stage along with the role of exoskeleton in order to enhance the recovery rate. Therefore it is important to integrate the three modes of rehabilitation in a single exoskeleton for delivering maximum benefit to the post-stroke users.

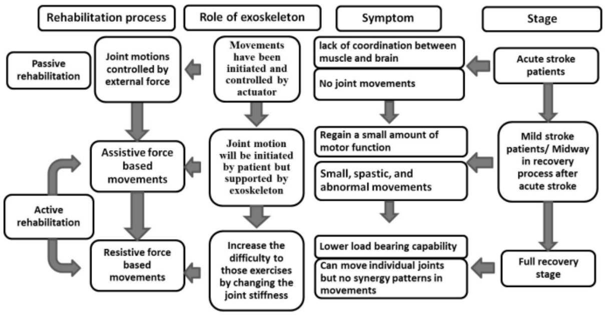

Figure 1. Standardized rehabilitation training strategy

Most of the developed exoskeletons have used electric motor coaxial to the joint for actuation [2] as it offered linear and easy control options. Using different adaptive controls it is now possible to generate a wide range of torques in the motor based on the patient's requirement [5]. Although this mode of actuation is considered to be the simple, it has lots of limitations which make the device structurally inefficient for rehabilitation such as:

1. For generating varying level of motor torque, the control architecture of the exoskeleton requires different biosensors. This creates some limitations in extracting the signal from patients through biosensor [6].
2. The size and weight of the motor is increased to produce more joint torque when directly mounted at the joint. It reduces the portability of the device.
3. The exoskeleton may constantly drain energy because motor is always in the running condition. As a result the size of the energy source is increased to provide uninterrupted energy supply.
4. Adaptive joint control makes the user totally reliant on the exoskeleton by taking full control of the joint motion, therefore reduces the patient's involvement in the movement and so is the recovery rate [7].
5. There are safety issues to restrict the joint movement within the anatomical limits.

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A couple of portable exoskeletons have been developed using the elastic property of different passive elements such as spring and rubber band [8] without any actuators. It was possible to develop energy-less systems using these passive elements; patients can be rehabilitated under assistive force based training. However, as it is shown in Fig. 1 that actuators are required in the acute phase of stroke for controlling the joint motion because patients are unable to move their joint themselves; therefore this is not achievable using this technique. If it is possible to combine the benefits of passive elements with the active actuation in a single device which will produce all different modes of rehabilitation and maintain its portability, it can satisfy the desired properties for a portable device.

METHODS

In an attempt to achieve the above requirements, in this paper an elbow joint exoskeleton has been considered which is one of the simplest human joints yet it is so significant for the upper arm rehabilitation. To overcome the above problems a new hardware design is implemented where electric motor controls the joint movements and spring energy is used in the successive phases of recovery for giving assistive and resistive forces. With this technique the energy source is only used during active actuation to provide power to the motor whereas other two modes can work without any power supply due to the stiffness of the springs. To integrate three modes of rehabilitation in a single structure the whole operating range is divided into three sections where each section can provide a specific mode of rehabilitation (Fig. 2) and the rehabilitation mode can be simply altered by moving into different operating regions. This technique offers the flexibility to the user to select a particular mode of exercise. The exoskeleton uses a couple of springs (compression and extension) for operating into different modes and switching between different rehabilitation regimes. All these features are achieved using a single motor.

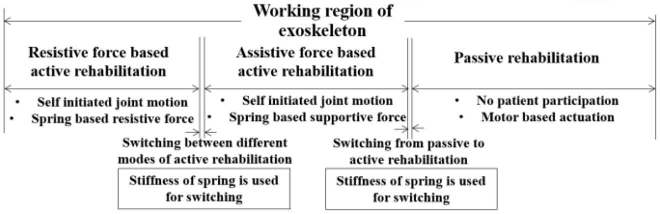

Figure 2. Working modes of the proposed exoskeleton

Design of the mechanism

Reducing the weight of the actuator is one of the key factors for designing a portable system. With an innovative joint mechanism it was possible to reduce the required joint torque compared to the existing models. A small motor is capable of providing higher torque with less amount of energy used. To achieve this goal the elbow exoskeleton uses leadscrew based transmission in combination with a slider crank mechanism. The schematic diagram and the 3D model of the elbow exoskeleton are shown in Fig. 3 and Fig. 4 respectively.

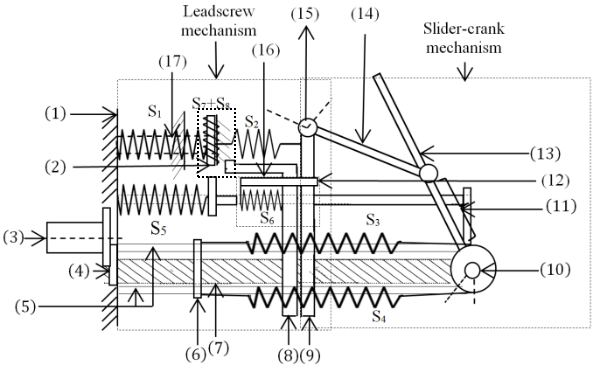

Figure 3. Schematic diagram of the exoskeleton

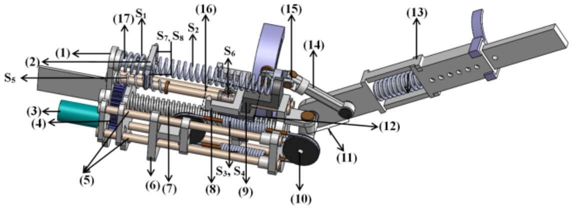

Figure 4. 3D model of the exoskeleton

(1) Baseplate
(2) Rectangular slider
(3) Motor
(4) Gear
(5) Solid rod
(6) Slider for variable stiffness
(7) Leadscrew
(8) Nut slider
(9) Concentric slider
(10) Elbow joint
(11) Crank
(12) Claw type jaws
(13) Forearm support
(14) Connecting rod
(15) Universal joint
(16) Self-actuating lock
(17) Small cylindrical rod

In this design, a region based rehabilitation strategy is implemented and the mode of the rehabilitation is decided by the position of the nut slider on the leadscrew. A small electric motor is connected at the end of the leadscrew near the baseplate. A fixed number of rotations restricts the mode of rehabilitation to a specific region in the whole working regime. Therefore it is possible to switch between the modes of rehabilitation by simply changing the number of rotations made by the motor.

Mode of rehabilitation=Passive rehabilitation $0 \le x \le x_1$
= Assistive force based active rehabilitation $x_1 < x \le x_2$
= Resistive force based active rehabilitation $x_2 < x \le x_3$
(x_1, x_2 and x_3 are the switching position of the nut slider.)

Two types of sliders are used in this design; nut slider guided on the path of the screw-thread and a concentric slider

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which does not move with the leadscrew, here the inner diameter is equal to the outer diameter of the leadscrew. In the first phase, (when the position of the nut slider is between 0 and x_1) both nut slider and concentric slider are attached by a self-actuating lock pressed by S_6 (Fig. 5), thus creates a formation where crank rotation can be controlled by the motor rotation. A closer view of the locking system shows that two claw type jaws are connected to the nut slider in a form of four-bar mechanism. In the normal condition the compressive force generated by S_6 latches both sliders (concentric and nut slider) by keeping the two jaws parallel. The torque requirement of the motor is considerably reduced in this mode; the range of motion provided in the elbow joint is 0-135°.

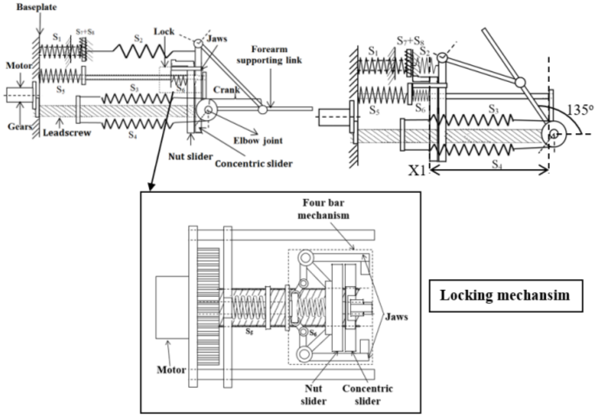

Figure 5. Exoskeleton operation during passive rehabilitation

If the position of the nut slider crosses the region of passive rehabilitation ($x>x_1$) due to further rotation of the motor, the locking system encounters another compression spring S_5. The locking condition will remain the same till S_5 and S_6 clash with each other. After this, S_6 is compressed because the stiffness of S_5 is higher than S_6. Due to this, the lock opens the two jaws and sets the concentric slider free from the attachment as shown in Fig. 6.

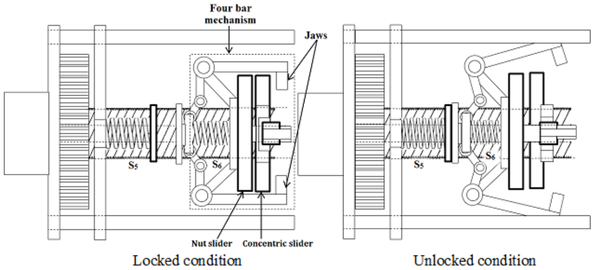

Figure 6. Switching from passive to active rehabilitation

If the user covers the whole region of passive rehabilitation, the elbow joint will rotate to the full range of motion. Position of the nut slider beyond the passive rehabilitation region will automatically open up the lock and release the joint control from the motor. In the unlocked condition, users are free to move their elbow joint using their own effort and the movement is supported by the assistive force provided by S_2. The spring based supportive mechanism can generate a higher range of assistive force to support a wide range of users. The range of assistive force can be changed by expanding the span of displacement of S_2. The structure will restore to its original position at the end of the rehabilitation regime. The arrangement includes two torsional springs (S_7 and S_8), one compression spring (S_1), one small cylindrical rod, one rectangular slider and two connected plates (Fig. 7). These two plates are connected to the rectangular slider using S_7 and S_8 on both sides in such a way that those plates can rotate about the axis of these springs. To increase the spring force, the front-end of S_2 (which is connected to the rectangular slider) is shifted in the backward direction near the baseplate using the backward movement of the nut slider. Because of having high stiffness of S_7 and S_8, the whole arrangement connected to the rectangular slider will slide on a small cylindrical rod in the backward direction along with the nut slider. These two mechanical restrictions on the cylindrical rod restrict the movement of the rectangular slider in a specific region as shown in Fig. 7. Further, the backward movement of the nut slider will put pressure on both torsional springs (S_7 and S_8) beyond their end limit and both plates move to come out from the range of the nut slider. At this point S_1 brings the whole arrangement to its initial position.

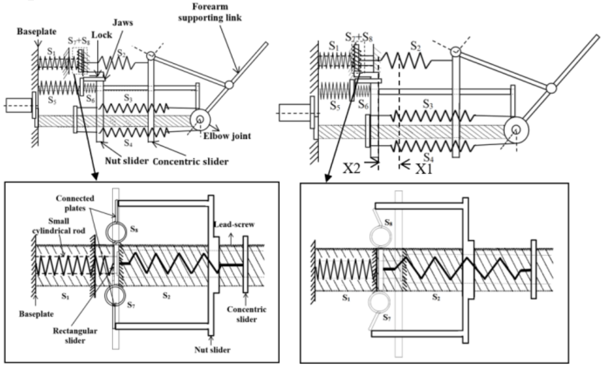

Figure 7. Assistive force based active rehabilitation regime

In the resistive force based active rehabilitation the resistive force can be increased by changing the contact force around the elbow joint. Further backward movement of the nut slider beyond this region ($x>x_2$) will push the slider connected to an extension spring assembly of S_3 and S_4. This action will stretch both S_3 and S_4 resulting in higher contact force at the elbow joint, as a result the joint stiffness of the elbow will be increased (Fig. 8). Therefore, user needs to put more effort to overcome this torque. In this mechanism two solid rods are used as a guide to the slider at the time of stretching the parallel springs (S_3 and S_4).

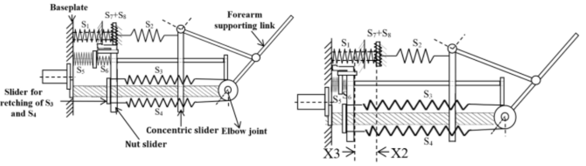

Figure 8. Resistive force based active rehabilitation

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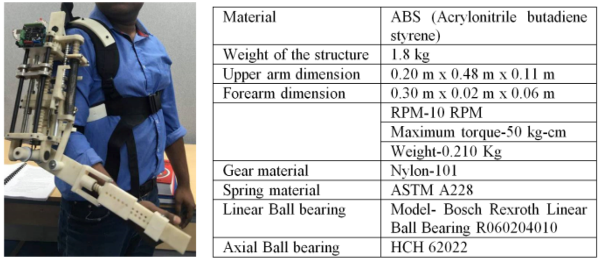
The exoskeleton uses a universal joint to replace the normal revolute joint used for elbow rotation (Fig. 3 and 4). If the arm segment is connected rigidly to the exoskeleton, it can cause discomfort to user skin and its articulation. Therefore, the universal joint allows a slight movement (±5 deg.) laterally during elbow joint rotation. Out of the two degrees of freedom possessed by the universal joint, the active one is responsible for flexion-extension of the elbow whereas the passive joint supports the flexibility in the lateral plane during joint movement. The types of different springs used in exoskeleton are shown in Table. 1.

Table 1. Type of springs used in exoskeleton

Springs	Type	Activity
S_1	Compression	Restoration of the rectangular slider assembly after active rehabilitation (assistive force)
S_2	Extension	Generation of the assistive force during active rehabilitation (assistive force)
S_3 and S_4	Extension	Variation of the joint stiffness
S_5	Compression	Generation of the opposite force to open the lock
S_6	Compression	Generation of the force to maintain the unlocked condition
S_7 and S_8	Torsional	Switching between assistive force based active rehabilitation to resistive one

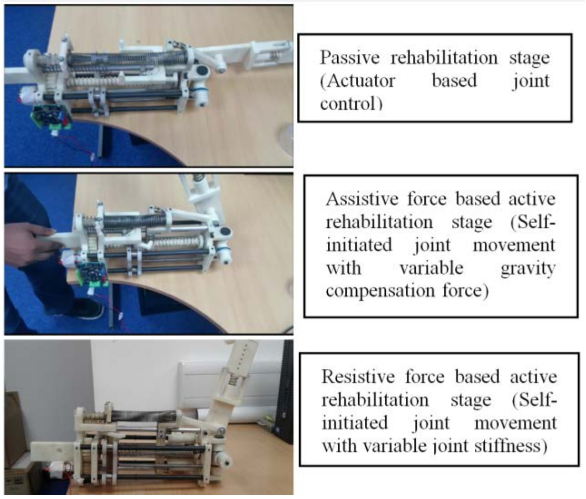
Prototype of the exoskeleton

Fig. 9 shows the developed prototype of the proposed elbow exoskeleton with its specifications. The 3D model has been designed in Solidworks^{TM} and all customized mechanical components have been manufactured using a 3D printer. The three states of the exoskeleton are shown in the rehabilitation stages in Fig. 10. All the rotational and sliding contacts have been developed with a bearing to reduce the frictional loss during motion including the leadscrew motions. Dimension and stiffness of the springs are selected based on static force analysis.



Material	ABS (Acrylonitrile butadiene styrene)
Weight of the structure	1.8 kg
Upper arm dimension	0.20 m x 0.48 m x 0.11 m
Forearm dimension	0.30 m x 0.02 m x 0.06 m
	RPM-10 RPM Maximum torque-50 kg-cm Weight-0.210 Kg
Gear material	Nylon-101
Spring material	ASTM A228
Linear Ball bearing	Model- Bosch Rexroth Linear Ball Bearing R060204010
Axial Ball bearing	HCH 62022

Figure 9. specifications of the proposed exoskeleton



Passive rehabilitation stage (Actuator based joint control)

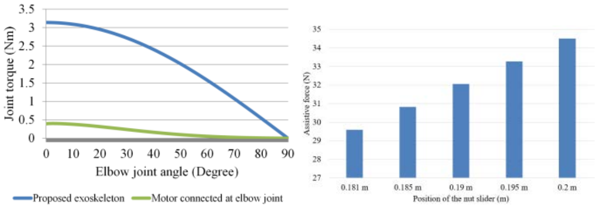
Assistive force based active rehabilitation stage (Self-initiated joint movement with variable gravity compensation force)

Resistive force based active rehabilitation stage (Self-initiated joint movement with variable joint stiffness)

Figure 10. Three states of the exoskeleton configuration

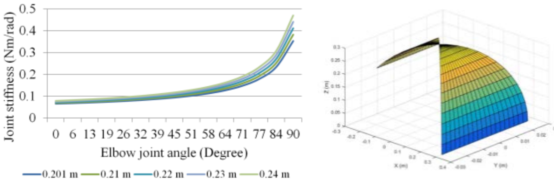
RESULTS

Simulation study of the working model shows that the required motor torque for the developed exoskeleton is eight times lower than the joint actuated mechanism. If the motor is placed at elbow joint directly, it would need a joint torque of 3.2 Nm whereas the motor in the proposed exoskeleton requires only 0.4 Nm to actuate the forearm of 1 kg (Fig. 11a). Also due to the movement of nut slider in active rehabilitation region, S_2 gets an extra span of displacement which provides a higher range of assistive force (Fig. 11b). The study also shows that the variation of elbow joint stiffness depends on the position of the nut slider and elbow joint angle during the resistive force based active rehabilitation (Fig. 11c). The universal joint enhances the flexibility of elbow joint by allowing a slight movement in the transverse plane as shown in Fig. 11d. The structural parameters for the simulation have been taken from (Table 1).



a. Reduction of motor torque

b. Increment of the assistive force



a. Change of joint stiffness

d. Flexibility of the elbow joint

Figure 11. Simulation results under different conditions

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INTERPRETATION

Form the implementation point of view it is clear that all three types of rehabilitation can be incorporated using the developed exoskeleton. All features have been achieved using a single motor and switching between different rehabilitation modes can be accomplished using the stiffness property of the springs and change in motor rotation. Simulation results of the proposed design show that the exoskeleton can attain all the desired properties for a portable rehabilitation aid.

REFERENCES

[1] Lo, H. S., and Xie, S. Q., 2012, "Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects," Medical Engineering & Physics, 34(3), pp. 261-268.

[2] Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy A., and Leonhardt, S., 2014, "A survey on robotic devices for upper limb rehabilitation", Journal of NeuroEngineering and Rehabilitation, 11(3), p. 3.

[3] Manna S. K., and Dubey, V. N., 2017, "Upper Arm Exoskeletons-What specifications will meet users' acceptability?", Robotics: New Research. D. G. Fisher, eds., Nova Science Publisher, pp. 123-169, ISBN: 978-1-63485-986-8.

[4] Takeuchi, N., and Izumi, S., 2013, "Rehabilitation with Poststroke Motor Recovery: A Review with a Focus on Neural Plasticity", Stroke Research and Treatment, vol. 2013, pp. 1-13.

[5] Crespo, L. M., and Reinkensmeyer, D. J., 2009, "Review of control strategies for robotic movement training after neurologic injury", Journal of Neuroengineering and Rehabilitation, 6(1), p.20.

[6] Nazmi, N., Rahman, M.A.A., Yamamoto, S.I., Ahmad, S.A., Zamzuri, H., and Mazlan, S.A., 2016, "A review of classification techniques of EMG signals during isotonic and isometric contractions", Sensors, 16(8), p.1304.

[7] Wolbrecht, E. T. , Chan, V. , Le, V., Cramer, S. C., Reinkensmeyer, D. J., Bobrow, J. E. , 2007, "Real-time computer modeling of weakness following stroke optimizes robotic assistance for movement therapy", 3rd International IEEE/EMBS Conference on Neural Engineering, HI, USA, May 2-5, 2007, pp. 152-158.

[8] Housman S., and Le, V., 2017, "Arm-training with T-WREX after chronic stroke: preliminary results of a randomized controlled trial", IEEE 10th International Conference on Rehabilitation Robotics, Noordwijk, Netherlands, June 12-15, 2017, pp. 562-568.

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