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Development of a Soft Actuated Upper Extremity Exoskeleton Employing Series Elastic Actuator for Post Stroke Rehabilitation

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Abstract

The integration of robotic devices and conventional physiotherapy is becoming more and more acceptable worldwide. When an exoskeleton is in the conceptual design phase, the actuator selection is one of the most crucial sections. In this paper a rotary Seies Elastic Actuator(SEA) is introduced, designed and developed for upper limb application used in the rehabilitation exoskeleton. Albeit the SEA had been used in the lower extremity,it is not utilized for the upper limb rehabilitation yet. This paper will design,implement and analyze the advantages of using SEA in the upper limb instead of conventional electric motors and shows the stability of this system when implemented on the proposed exoskeleton. Actually the designed exoskeleton is performing simultaneous tasks of elbow and shoulder flexion/extension by means of just one electric motor and a SEA mounted on the elbow joint.

Keywords: *Cable-driven exoskeleton, Post stroke patients, Series Elastic Actuator, Upper limb rehabilitation*

1. Introduction

Since stroke turns into a serious cause of adult disability worldwide [1], various efforts have been made by researchers from all over the world to find the more systematic treatment procedure for the post-stroke patients. The reason why the new-tech field is investigating in the robot-therapy is attributed to the fact that this method needs much less physiotherapist effort and less human errors occurred. Moreover the effectiveness of robot-therapy is reported by some researchers like Hermano Igo Krebs et al. [2] and Volpe, B. T [3]. It is not supposed to give a literature about the constructed exoskeletons, since it is available in numerous papers. Instead, the actuation type of each exoskeleton is studied as a literature review in this field. The first actuation method is the electric motors,the most commons. Some exoskeletons used this type of actuation are FreFlex that used electric motor in 1998 [4], after that Arm guide in 2000 used electric motors[5]. MULOS in 2001 [6], Gentle with three DOF in 2003 used DC brushed motors too [7], REHAROB in 2005 with dual six DOF [8], MIT-Manus exoskeleton in 2004 with five DOF [9], MGA exoskeleton in 2005 with five DOF [10], L-EXOS with five DOF in 2005 [11] , CADEN-7 in 2006 [12], and Liszka work with five active degrees of freedom(DOF)[13] ARMin used six DC motors in 2007 [14]. On the other hand Pnuematic and Hydraulic actuators are also utilized for exoskeletons. PMA in 1999 used pneumatic actuator [15]. Rupert in 2005 was equiped with four penuematic muscles [16], in the same year PNEU-WREX also used pneumatic actuator[17]. Hydraulic actuators also used in DEX exoskeleton in 1991 [18] and Sarcos in 2005 [19].

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2. Rotary Series Elastic Actuator Design

The idea of designing and mounting the SEA on the elbow joint to regain the motor function of the elbow joint for post stroke patient is novel to somehow. It is worth to mention the use of rotary Bowdn-cable SEA in the LOPEZ project in [20]. SEA is a novel mechanical actuator that could mimic the elbow flexion and extension by transmitting the torque to the joint. The SEA, known as rotating joint actuator, could mimic the natural motion of the elbow by its cables and springs. It has a rotating joint in the middle which has a responsibility of a torque source and torque transmission to the elbow. One groove plays the driven role and the other pulley is the driver that has been attached to the motor shaft. These 2 pulleys must be connected together with a cable. This is done by 3 millimeter Bowden cable.

Electric motors suffer from poor torque density and in order to carry or handle heavy loads and materials, use of gear reduction seems undeniable. However, gear reduction introduces various disabilities and difficulties. It creates noise, backlash, torque ripple and obviously the friction. Moreover, use of $N{:}1$ gear leads to N^2 increase in reflected inertia. This phenomenon is the main cause of higher force on gear teeth [21].

SEAs are able to give back the properties lost when gears are used to the actuator. Another advantage that has been reported in the literature is the effect of low-pass filter shock loads which leads to significantly reduce the peak gear forces [21].
SEAs turn the force control problem into position control problem, improving force accuracy as well. In series elastic actuator, output force is proportional to the position difference multiplied by the spring constant. As a matter of fact, position is much simpler to control than force. Actually springs are used for force measurements in this thesis. A spring could be used as a low-cost force sensor as its length is proportional to force.

The stability is another concern in using SEA as an actuator for elbow. G. Pratt and M.Williamson discussed the stability in SEAs. Briefly, the more the series elasticity increases, the more the stability is created for force control. In this case the frequencies of the interface resonances are lowered and the motor's force-feedback loop can perform properly at low frequencies. The stability principle translates to a minimum load inertia simply provided by the mass of the robot. Since natural environments never contain negative masses, therefore the stability is guaranteed under contact with any object from the view of G.Pratt and M.Williamson [21].

One of the basic design factors in SEA is the pulley diameter. The choice of the diameter is somehow a conciliation of the size of the actuator versus the transmission tension amount in the Bowden cables. The rotating joint in this thesis has been designed and modeled as a 2-way pulley with outer diameter of 65mm. For the pulley material it was supposed to use Polytetrafluoroethylene, also known as Teflon. However, it has been rejected due to the corrosion that is inevitable as a result of using Bowden cable in contact with this pulley. Polyamid has been selected as an appropriate alternative. Because it has lots of Teflon properties, but has higher resistance against the corrosion of Bowden cable contacts.

2.1 Spring Design

Another important of great concerns are the spring design, including the stiffness and material, required pre-compressed range and required displacement of one spring in order to move the robot arm. The two pretensioned torsional springs with linear characteristics are selected for this purpose. For torsional spring with length l , wire diameter d, outer diameter D the shear stress formula could be rearranged for designing the minimum diameter for spring wire:

$$d_{min}= \sqrt[3]{\frac{32\, T_{max}}{\pi \sigma_{yield}}} \qquad (1)$$

where T_{max} is the maximum force exerted on the spring (here is the cable force) and σ_{yield} , is the yield stress that is equal to 240 $\frac{N}{mm^2}$ for steel material that used for spring wire.

Moreover, for designing the rod minimum length the equation 2 is used:

$$l_{min} = \frac{\pi\, {d_{min}}^4 G\, \theta_{yield}}{32T_{max}} \tag{2}$$

where θ_{yield} is the angle of twist of the rod .

The stiffness of the spring is obtained from the equation 3.

$$k = \frac{G\, d^4}{8D^3 n_a} \tag{3}$$

where G is shear modulus and n_a is the number of active coils.

The maximum load possible and the maximum shear stress associated with the maximum force and shear modulus of the material are given below:

$$F_{max} = K\,(\,L_{free} - \,L_{Solid}\,) \tag{4}$$

$$\tau_{max} = \frac{8\,W\,D}{\pi\, d^3}\, F_{max} \tag{5}$$

$$G = \frac{E}{2(1+\upsilon)} \tag{6}$$

2.2 Pulley and spring in connection

The basis of SEA actuator is the pulley, cable and spring systems which is shown in the Figure 1 Schematically. This section is calculating the required displacement for the springs (one of them will compress and the other will stretch). It is required to understand that the force applied to the springs is the cable tension and this tension is produced by the rotation of the SEA middle disk and this pulley itself rotates by the rotation of another pulley connects to the motor shaft.

The related dynamics of this system could be simply developed from below equations. Initially the force applied to the cable from the motor shaft should be identified. The pulley attached to the motor shaft has the outer diameter of 6 cm. Therefore:

$$T_{motor} = \; F_{motor} . r_{pulley} \tag{7}$$

By substituting $7.5\; N.m$ for maximum motor torque, the transmitted force to the first set of Bowden cable would be$125\; N$. In this point, simplifying hypothesizes made for neglecting some complex parameters that affect the system to somehow. They are elasticity in the Bowden cable and friction between the cable and the pulleys. Maybe in later investigations, it could be more developed and analyzed for better measurement of system efficiency.

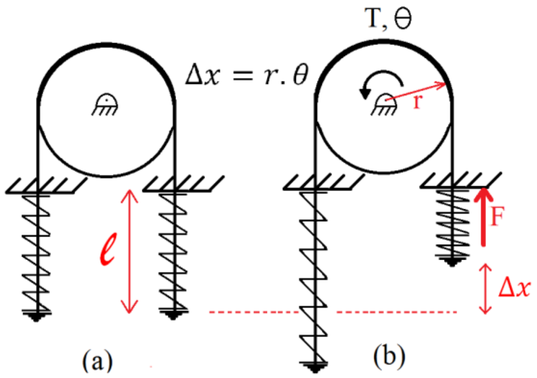

Figure 1 : Two compression springs are connected with an uninterrupted Bowden cable to the actuator disk. By this mechanism the cables are always under tension during the therapy operation. Pulley in this illustration plays a driver role and transmits the force to the springs by cable. (a) Pulley and springs before starting the motor and running the exoskeleton . Springs are in their resting position (b) When the pulley rotates with the Torque of T and angle of θ and causes displacements in the two pre-compressioned springs.

Back to the subject, the cable tension is transmitted to SEA middle actuator disk and makes it rotate with the same tension force by means of another set of 3 mm Bowden cable.

$$F_{spring} = K_s . \Delta x \tag{8}$$

Regarding the linear properties of the spring, the maximum spring displacement in presence of $125N$ force, would be7.5 cm. The desired 90 ° rotation of SEA, which is the desired angle for elbow flexion from rest position, the cable should have a displacement of the one-fourth of the pulley circumference which is 5.10 cm. The point is that the 125N force has be ability of moving the spring up to 7.5 cm and all we need for a 90° of rotation is 5.10 cm. This matter could be considered as the validation of motor power to perform the required operation for the exoskeleton. Figure 2 is provided to show the location of the designed SEA on the elbow and demonstrate the mechanism of the proposed exoskeleton named CASSER-Exo (Cable Actuation Soft-orthotic Series Elastic Rehabilitation Exoskeleton).

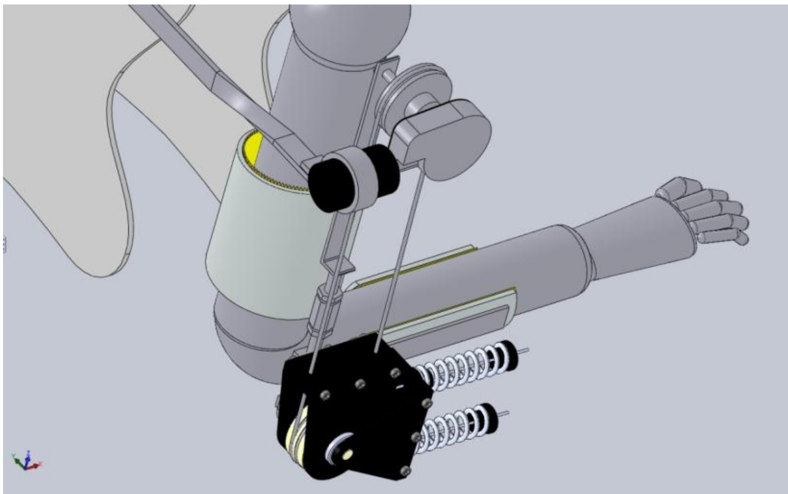

Figure 2 : CAD design of Series Elastic Actuator and the mechanism of actuating the elbow by means of a set of Bowden-cable attached to the motor pulley at the shoulder.

3. Final Bowden-cable rotary series elastic actuator construction

The material for the body of SEA is Acrylic under the trade name of Plexiglass. Plexiglass has various advantages over the steel, aluminum and the same other conventional materials. One of the

main advantages of plexiglass is its light weight property with a density of $1.18\ \frac{gr}{cm^3}$ compared to that of aluminum ($2.7\ \frac{gr}{cm^3}$) or steel ($7.7 - 8\ \frac{gr}{cm^3}$).

The CO_2 Laser-Cut Machine is used to cut the plexyglass plates according to the given drawing sheets to the laser machine computer. The laser cut of plexyglasses has been presented in Figure 3. The thickness of the plates are 5mm and have been attached together first by the chloroform and then by twelve screws. It has the ability of 90° rotation around the $\hat{Z}$ axis and actuates the elbow as well. This rotary actuator then attached to the main robot links and placed concentric with the elbow joint.

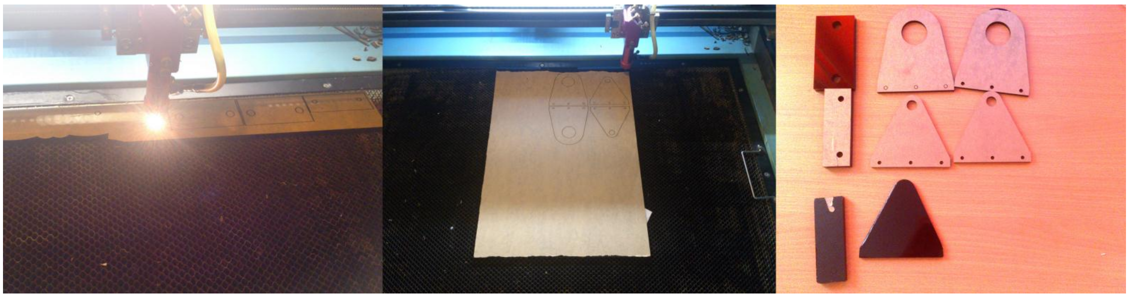

Figure 3: The procedure of the plexiglass laser cutting by the CO_2 Laser-Cut Machine

4. The proposed exoskeleton performance description

The proposed exoskeleton is designed and developed experimentally aimed at post-stroke patients with one active degree of freedom and three passive degrees of freedom, including forearm supination/pronation and shoulder internal/external rotation. The third passive motion is related to the elbow motion with cable actuation system. Since it is actuated by SEA, there is no control on it and it can be noted as passive motion. The whole exoskelton is put on by the author and illustrated in the Figure 4 as below. Moreover the SEA components are numbered and explained.

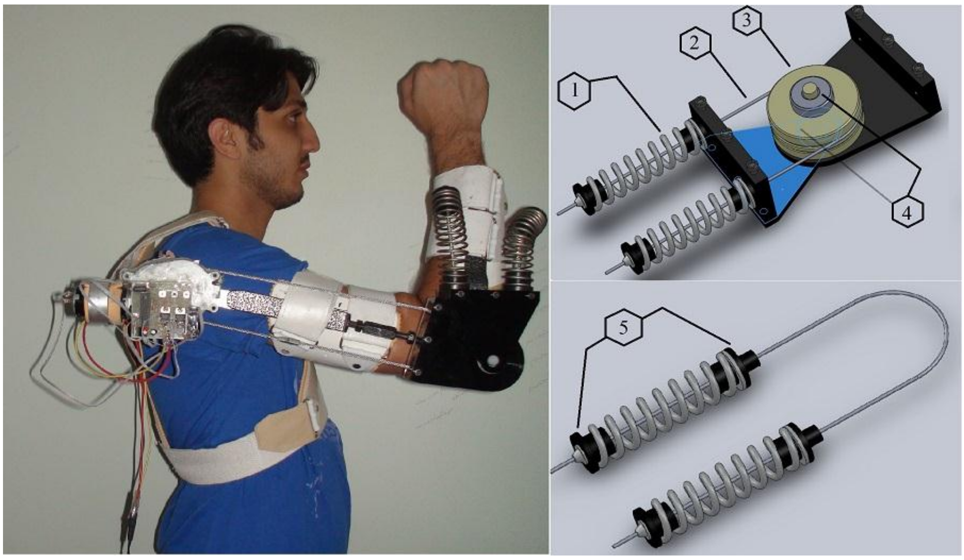

Figure 4: Illustration of Bowden-cable series elastic actuator and the developed rehabilitation exoskeleton used SEA. Moreover the constructed exoskeleton is shown in this figure. The actuation disk is dynamic and plays both the driver and driven role. Numbered parts: 1. It is the series elastic element of the elbow actuator. Set of two pretensioned compression springs. They can rotate the elbow around the joint axis and make a flexion/extension motion, 2. Set of one pair of uninterrupted Bowden cable transferring torque from the pulley to the springs via friction, 3. Actuator disk of SEA. This is a 2-way pulley which rotates independently of both sets of cables. It is driven from another pulley connected to the motor shaft and on the other hand plays a driver role in transmission the force to the springs, 4. Two sets of single row deep groove ball bearings of SKF Company. These ball bearings have been applied in order to make the rotation for triangle-shape part of SEA around the center, 5. Spring holders; these components hold the spring and resist against unwanted bending and twisting of the springs during operation.

The main task is performing the shoulder and the elbow physiotherapy training at home. The shoulder is equipped with an electric motor and the elbow is actuated simultaneously by a Bowden-cable Series Elastic Actuator which is connected to the motor by a pulley mounted on the motor shaft. Elbow flexion strats when the elbow is in the rest position(when the forearm is in the coronal plane and is parallel with the thorax) and goes up to 90° in the sagittal plane. For elbow extension the whole forearm returns to the non-angle position or the rest position. This actuation is done with the torque transmitted by the DC brush motor with a worm gear mounted on the patient's shoulder and is aimed at shoulder flexion and extension in the sagittal plane. Therefore, when the motor is turned on the shoulder flexion is started simultaneously with the elbow flexion until they reached to the desired point (90°). It is noted that two infrared sensors are designed and mounted on the motor house in order to control the position of the shoulder. Sensors and other components are programmed by Bascom-AVR software and the whole system is controlled by AVR micro-controller. By using a novel joint the carry angle problem is covered and solved easily and every person could put on and off this exoskeleton by any carry angle and any shoulder dimension including the muscle volume and the length since the anthropological data is considered and it is designed according to the 5^{th} and 95^{th} percentile of individuals. Moreover an AVR Micro-controller is designed and installed so that the shoulder will not extend beyond the defined angle. In this project defined angle is 90° and could be varied by changing the first link input data in the micro-controller. The velocity and the applied torque are completely controlled by controlling the input voltage and current using micro-controller. Position is also controlled by the mounted IR-sensors as it is discussed above.

5. State-space control design for the proposed exoskeleton

The advantage of using state-space equations emerges in the point that the state variables need not essentially be physically measured. Some variables than are neither measurable nor observable could be chosen as state variables and this freedom in choosing state variables is a remarkable benefit of the state-space method. The Block diagram of the full-state feedback controller is drawn in the Figure 5 and the response curves to the step input in the Figure 6 proves the stability of the first link (shoulder) and since the second link (elbow) is actuated just like the first link it also shows stable behavior. The output variables are the shoulder joint position and velocity. The linearized state-space equation and output equation are as follows. Linearization process is done by Jacobean command in Matlab.

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (9)$$
$$y(t) = Cx(t) + Du(t) \quad (10)$$

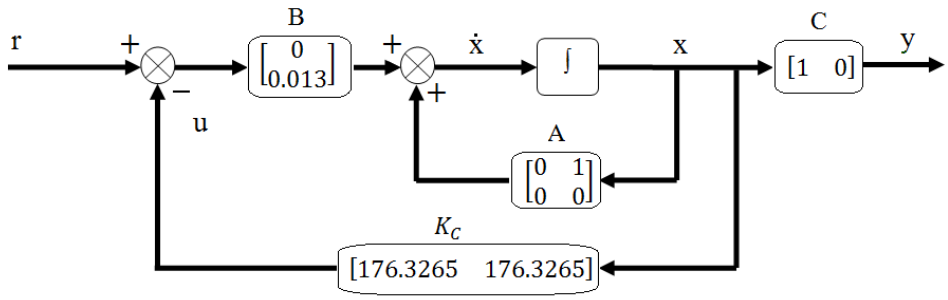

Figure 5: Diagram of full-state feedback controller in state-space. Kc is the state feedback gain matrix

6. Results and discussion

After having designed the full-state feedback controller in the state-space form, it is possible to plot the robot response to the step input in order to observe that whether it is stable or not. By a proper state feedback gain matrix it could be seen that the system shows the stability regarding the two state variables, angular velocity and position of the shoulder. Figure 6 shows that after about

three seconds, the robot link will gain the stability and therefore the second link, which is connected to the first link, would be stable too and the SEA, as we expected, shows the stable behavior.

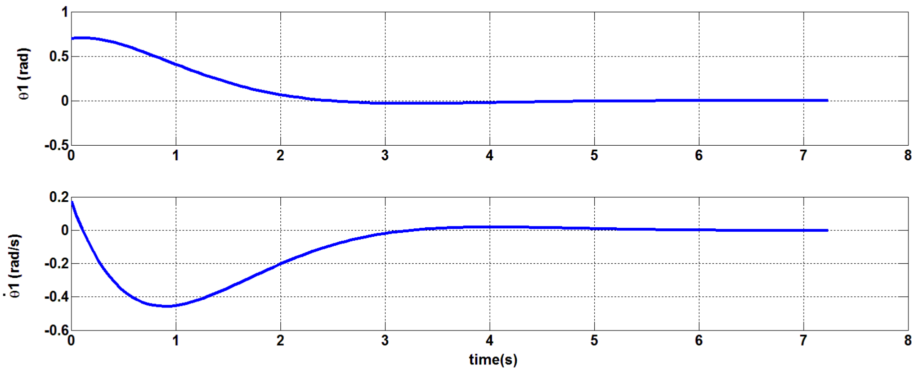

Figure 6: The step response curves for the two state variables. Angle and angular velocity of the first link relate to the shoulder

Conclusion

The first prototype of the upper limb exoskeleton with cable-driven actuation with the aim of rehabilitation has been presented in this paper. Design and experimental investigation of the rotary Bowden-cable series elastic actuator has been performed for the elbow. These simultaneous tasks are accomplished successfully and the whole robotic arm showed stable behavior to the input step. The novelty of this design relates to the use of the Bowden-cable SEA for the simultaneous motions of the upper extremities (minimum number of actuator) and developing a low-cost wearable soft-orthotic exoskeleton system for home robot-therapy for post stroke patients. It is the first prototype and undoubtedly it could be more effective in the future work.

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