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TWO DEGREE-OF-FREEDOM UPPER LIMB EXOSKELTON TRAINER FOR ELDERLY PEOPLE

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Abstract: *The rehabilitation of people with mobility difficulties is an issue that deserves attention. Conventional methods such as face-to-face physiotherapy offer a solution but demand huge resources in form of man-hours. In addition, face-to-face therapy is time consuming for the patient. An exoskeleton trainer, which can be used from the comfort of the patient's home, might provide safe method for training.*

This paper describes a concept of two degree-of-freedom (DOF) exoskeleton trainer. The 2-DOFs Exoskeleton trainer, described in this paper, is designed for upper-limb rehabilitation purposes for elderly people. The device provides the operator with controlled and safe training of upper limb muscles. The purpose of the trainer device is to create resistive force that acts against the operator's movements.

Key words: muscle rehabilitation, upper-limb exoskeleton, isokinetic velocity, exoskeleton trainer.

1. INTRODUCTION

The population of people aged 60 or above, is predicted to increase by approximately three times of the current population by 2050 [1]. Increase in population requires innovation in the healthcare sector in order to keep up with the problems experienced by the ageing population. The effect of ageing on muscles includes loss of muscle mass, muscle fibres, and decrease in the water content of tendons [2]. These effects result in reduced strength, longer response time, loss of motion and flexibility of joints in elderly people. These effects are further accelerated by a sedentary lifestyle and can be slowed down significantly by regular exercise involving basic movements of different body parts [3,4]. However, certain amount of caution is required in the case of elderly people to ensure that the muscles and joints are not overstressed during exercising.

There is a significant amount of research about exoskeletons [5], but it mainly focuses on military and muscle assistance applications. There is little information about the use of exoskeletons in rehabilitation, or about how these technologies could be applied into rehabilitation. The study referred [6], which focus on exoskeletons that assist muscles had similar overall mechanical design, very similar parts and mechanical concepts as the exoskeleton presented in this paper. The structural implementations from these applications were used as a basis in the designs of the current paper. Only few research papers [6][7] discussed exoskeleton robots for rehabilitation and had similar focus and concept as our project.

This paper describes a two-degree-of-freedom (DOF) upper-limb exoskeleton trainer for elderly people rehabilitation purposes. The device described in this paper was developed for controlled training of the arm and shoulder muscles. The article addresses the mechanical design, electrical design and control design of the 2-DOF exoskeleton trainer.

2. SYSTEM REQUIREMENTS

The requirements for the 2-DOFs exoskeleton trainer are set according to rehabilitation purposes, safety and elderly people's limitations. The requirements of the 2-DOFs exoskeleton trainer are:

i) Safety. The device should be safe to operate and cause no harm to the user in any situation. The range of motion of the device should be limited according to restrictions set by human physiology.
ii) Two degrees of freedom. The device should have rotating joints at the elbow and at the shoulder to enable exercising and rehabilitation for certain upper-limb muscles: deltoid muscle, biceps and triceps.
iii) Ergonomic design. The device should be fast and easy to wear, it should fit on any person and it should be mobile. In addition, the device should be lightweight.
iv) Motion resisting operational principle. The device should exercise upper-limb muscles by resisting the movements and not provide additional force.
v) Position sensing technology.
vi) Load sensing technology.

The exoskeleton trainer described in this paper is designed for rehabilitation of upper limb muscles. The controlled movements implemented for the upper-limb are: lateral raise for deltoid muscle, bicep contraction for arm and triceps extension for arm.

It was decided that the device should enable 2 to 3 exercising movements and that it should be mobile and that the arm would be a good focus point, because the arms are used extensively in everyday life. The concept was further simplified to include only the shoulder and elbow joints. Design work began on building the idea around the two joints, the controller and actuators were chosen and, lastly, also the sensors. The aim was to keep the device compact and simple but also useful, accurate and generally functional.

The maximum torque values for the shoulder joint and elbow joints are approximately 75 Nm and 65 Nm respectively in healthy individuals aged between 40 to 50 years. However these maximum values are not being targeted since they would be rarely required for muscle training. Such high powered actuators would also increase the overall complexity significantly in terms of design and power requirements which are unnecessary for this prototype. The goal is to only demonstrate basic muscle training operation.

3. SYSTEM DESIGN

3.1 Mechanical design

The mechanical structure of the 2-DOF exoskeleton trainer (Figure 1) consists of:

i) Aluminium frame with PTFE slide bearings
ii) 2 geared DC motors with optical encoders
iii) Microcontroller
iv) Wearable vest.

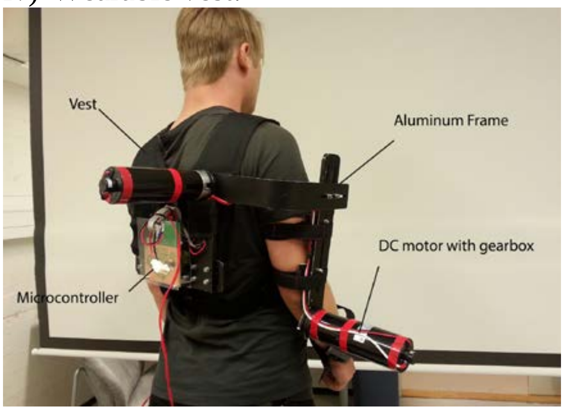

Fig. 1. The exoskeleton trainer.

The shoulder axis of the device for the lateral raise movement is located behind the operator. The elbow axis is located on the side of the operator. The geared DC-motors are attached into the joints. The joints of the exoskeleton are designed to align with the human's shoulder and elbow joint's turning axes (Figure 2). Therefore, lengths of the lever arms do not alter during the operation of the device. However, alignment of the axes of human and exoskeleton set some requirements. The misalignment of the axes in exoskeleton can result into uncontrolled forces and cause extra strain on the muscles. [5] For ensuring the alignment of the axes of the operator and exoskeleton, the described exoskeleton has adjustability in horizontal position of shoulder and elbow axis. In addition, the length of the upper-arm lever arm is adjustable according to user's dimensions.

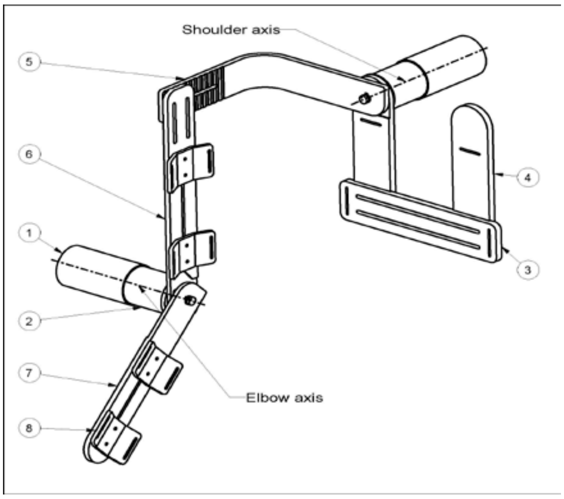

Fig. 2. Exoskeleton trainer components and rotational axes.

ITEM NO	COMPONENT
1	DC motor
2	Gearbox
3	Back plate
4	Support plate
5	Shoulder frame
6	Upper arm frame
7	Lower arm frame
8	Arm attachment pad

Table 1. The main components of exoskeleton trainer.

3.2 Control system design

The system was developed with minimal components and as simple as possible in order to test the proof of concept since this is the first prototype. Electric motors were chosen to be used as the actuators for generating resistance required for muscular exercise. Based on a study conducted by Thomas Harbo et. al. [9], the electric motors with a max torque rating of 8 Nm and stall torque of 54 Nm selected.

The motors were controlled using a microcontroller with a compatible motor driver. The microcontroller was programmed to drive the motors to generate torque in the direction opposite to the motion while maintaining the speed constant, thus obtaining isokinetic movement.

A PID control algorithm was used for controlling the motors. The input given to the control system is motor speed determined using rotary optical encoder with a resolution of 300 pulses per second. The output is varying torque at constant speed. The activation of motors was based on a threshold velocity set and thus the motors stop as soon as the user stops the movement. This ensures safety to a certain extent.

Finally motor current is measured and logged during the exercise and can be used to determine torque throughout the range of motion. This can be used to evaluate muscle performance and improvement over time. Motor current characteristics as given in the data sheet are 0.4 A at no load to 2.2 A at rated speed of 2500 rpm. This information can be used to calculate torque using rated torque value of 8Nm since the current increases linearly with torque. The control system flow chart is shown in Fig. 3

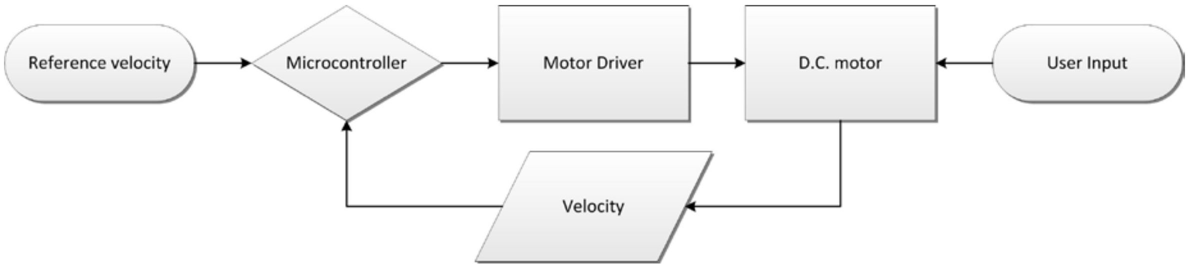

Fig. 3. Control system

The device assists the operator in exercising three different muscles: lateral deltoid, bicep and triceps. The device is programmed to produce isokinetic contraction, so that tension in the muscle remains constant as the muscle's length changes, i.e. the velocity remains constant throughout the entire range of motion. The device assists elderly people to rehabilitate their muscles routinely. The shoulder movements are shoulder abduction and adduction and elbow movements are elbow flexion and extension.

4. RESULTS

The initial plan was to tune to PID parameter by testing of the device but in practice, this proved to be too time consuming. The parameters were tuned as much as possible in the available time but the control system is remained oscillatory in nature. However, it responds to the change in muscle power applied by varying torque. The final output demonstrated the proof of concept of a wearable muscle training exoskeleton.

The mechanical design of the exoskeleton trainer proved the concept working. For the future research, improvements in the areas of user-friendliness, adjustability and overall weight are needed. The greatest challenge in the final prototype was aligning the motion axes of the device and the operator. The device had capability for adjustments in the length of upper-arm part, horizontal position of shoulder joint and horizontal position of upper-arm frame i.e. in elbow joint position. The described adjustability capacity proved to be insufficient. Lack of adjustability resulted in limited range of motion of joints during operation. The overall weight of the device was rather high considering elderly people as the target user group. However, the main source for increased mass of the device was the geared DC-motors, which were over dimensioned. In addition, the integration of the device and the vest requires more attention. Attachments of the device caused flexibilities in the system, which led to misalignment of the motion axes and uncomfortableness in user experience.

Aluminium was the material chosen for the exoskeleton frame. The advantages of aluminium as construction material for described device were lightness, easy manufacturability, relatively low costs compared to more advanced metals and composite materials and satisfactory mechanical properties. The disadvantages of material selection were softness of aluminium and constructions stiffness. Softness of the aluminium resulted in abrasion in parts subjected to forces. Abrasion was significant especially in joints, which implemented keyway design. Abrasion in shoulder part and upper arm part generated gaps between key and keyway. Furthermore, position errors due to increased gaps impeded control design.

The joints of the exoskeleton trainer utilized cotter joint design with PTFE-plastic slide bearings. The principle of applying slide bearings proofed to be simple, cost-effective and functional. The coefficient of friction between PTFE and aluminium parts was low enough for enabling proper functionality of the device. Challenges occurred in connections between steel key and key grooves of aluminium parts, which resulted in abrasion.

The presented device also met the set safety requirements. The device had mechanical limitations for the range of motions, which prevented overextensions of operator's joints. The control system was designed to act as resistance, which intrinsically included the safety aspect i.e. the control system did not allow the device to produce torque, which would harm the operator. In addition, a manual kill switch was included into the device, which would switch off the power from the device in case of malfunction.

5. CONCLUSION AND DISCUSSION

This paper described the concept of a 2-DOF exoskeleton trainer for rehabilitation purposes for elderly people. Actuator selection, mechanical design and control design of the device were described. Mechanical design of the device proved the concept functional with certain limitations. Further research is needed for improving user-friendliness and ergonomics and decreasing overall weight. Especially material selection, adjustability and integration of the device to the user's body requires more research. For the commercial products the overall design has to be optimized for comfortable and fast dressing-up. The challenges are the weight and different body sizes, which require attention for aligning motion axes. For the future, more merged design is needed to address these challenges.

6. REFERENCES

1. World Population Ageing 1950-2050. United Nations New York, 2001. http://www.un.org/esa/population/publications/worldageing19502050/pdf/80chapterii.pdf. 10.2.2015.
2. Dorrens, J. M. J. R., and M. J. Rennie. "Effects of ageing and human whole body and muscle protein turnover." *Scandinavian journal of medicine & science in sports* 13.1 (2003): 26-33.
3. Marks, Ray. "The effect of ageing and strength training on skeletal muscle." *Australian Journal of Physiotherapy* 38.1 (1992): 9-19.
4. Goodpaster, Bret H., et al. "The loss of skeletal muscle strength, mass, and quality in older adults: the health, aging and body composition study." *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 61.10 (2006): 1059 1064.
5. Yan, Tingfang, et al. "Review of assistive strategies in powered lower-limb orthoses and exoskeletons." *Robotics and Autonomous Systems* 64 (2015): 120-136.
6. Chong, Yu Zheng, Kwok Hong Chay, and Yee Hern Lim. "Design and development of wearable upper extremities powered exoskeleton-A cost-effective rehabilitation system." *Biomedical Engineering and Sciences (IECBES), 2014 IEEE Conference on*. IEEE, 2014.
7. Rahman, M. H., et al. "Development and control of a wearable robot for rehabilitation of elbow and shoulder joint movements." *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*. IEEE, 2010.
8. Effects of Aging. American Academy of Orthopaedic Surgeons. http://orthoinfo.aaos.org/topic.cfm?topic=A0019. 10.2.2015.
9. Harbo, Thomas, John Brincks, and Henning Andersen. "Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects." European journal of applied physiology 112.1 (2012): 267-275.
10. Andersen, Henning. "Motor dysfunction in diabetes." Diabetes/metabolism research and reviews 28.S1 (2012): 89-92. 10.2.2015.

11. Gopura, R. A. R. C., Kiguchi, K., & Bandara, D. S. V. (2011, August). A brief review on upper extremity robotic exoskeleton systems. In Industrial and Information Systems (ICIIS), 2011 6th IEEE International Conference on (pp. 346-351). IEEE.
12. Stienen, A. H., Hekman, E. E., Van der Helm, F. C., Prange, G. B., Jannink, M. J., Aalsma, A. M., & Van der Kooij, H. (2007, June). Dampace: dynamic force-coordination trainer for the upper extremities. In Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on (pp. 820-826). IEEE.
13. Macaluso, Andrea, and Giuseppe De Vito. "Muscle strength, power and adaptations to resistance training in older people." *European journal of applied physiology* 91.4 (2004): 450-472.

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