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Direct Drive Elbow Orthosis

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Abstract-The present work examines improvements to the mechanics and control system of an active elbow orthosis. The weight is reduced, a direct drive actuator with a greater torque is used. The other improvements consist in greater positioning accuracy and the ability to achieve higher flexion/extension speeds.

Keywords—active elbow orthosis, actuator, controller

I. INTRODUCTION

The elbow joint is critical in human daily activities, making it possible to reach an object in space, hold tools, and achieve precision in both closed and open force circuits. In the case of a damaged elbow joint, a stable and comfortable orthosis with sufficient strength and range of motion is needed to support the movements of the arm for the correct function of the elbow. Stroke or injuries to the elbow are the most common cause of stiffness, resulting in loss of functional range of motion. Prolonged immobilization of the elbow joint, following stroke or elbow injuries, leads to stiffness and can cause significant impairment of upper limb function. Problems arise after hospitalization for stroke or elbow injuries that require a minimum protective period in which the joint must be immobilized in a cast [1]. It is then critical to continue with rehabilitation of the joint to avoid the development of stiffness in the elbow. Because it takes a long time - 6 to 12 months - to improve, the patient should continue with exercises after discharge from the hospital, and follow a rehabilitation program during the recovery at home. The development of a smart elbow orthosis as a home elbow training aid for patients with elbow stiffness would improve their recovery.

II. EXISTING PROTOTYPE

The mechanics of the existing elbow orthosis prototype [2,3] consists of two arms connected at the elbow joint by a hinge with one rotational degree of freedom providing flexion and extension. The motor is attached to the upper arm of the orthosis. To increase the total torque, a belt drive is added, lowering the engine speed. The size of the desired angles of movement and safety during operation are ensured by mechanical stops. The CAD model of the elbow orthosis is presented in Fig. 1. The upper arm of the device is also used as a housing for electronic modules [3]. In Fig. 2. a photo of the orthosis prototype with the actuator and reduction gear installed is shown.

An electrical actuator Dynamixel XH430-W350-T [4] was chosen to drive the orthosis as optimal for the requirements of the system. Its main technical characteristics are:

- Supply voltage [V] - 10.0–14.8;
- Maximum torque [N•m] - 3.40 (12V);
- Maximum current [A] – 1.36;
- Position sensor - non-contact, absolute (12 [bit], 360 [°]);
- Dimensions (WxHxD) [mm] - 28.5 x 46.5 x 34.0 ;
- Weight [g] - 82.00.

The actuator is controlled via a serial channel by an OpenCM9.04 controller [5].

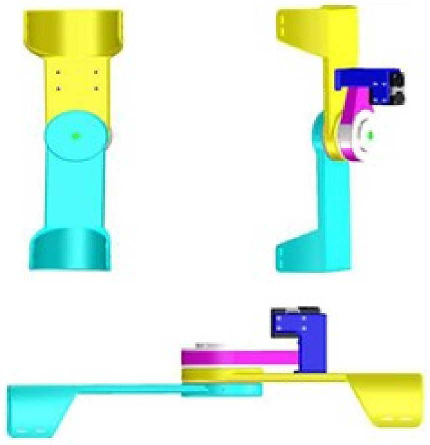

Fig. 1 CAD model of an active elbow orthosis with a gear-belt reduction gear

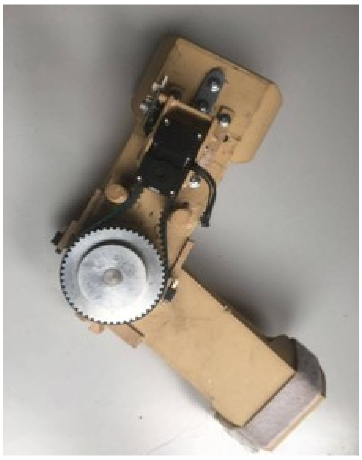

Fig. 2. Prototype of the orthosis with actuator and a reduction gear

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III. IMPROVEMENTS TO THE EXISTING PROTOTYPE

After experiments with volunteers and evaluation of the work of the above-described prototype, it was decided to be improved it in the following directions:

- To reduce the total weight of the orthosis;
- To avoid belt transmission;
- To increase the speed of movement of the orthosis;
- To reduce the inaccuracy of positioning due to looseness in the structure.

The main activities were carried out in two directions - mechanical design and actuator/control.

The existing prototype was manufactured, assembled and tested in real conditions, and in conclusion it can be considered that it is proposed as a relatively simple and reliable mechanical design of a future orthosis, which provides one degree of mobility in the sagittal plane for the elbow joint. On its basis, after tests, an optimization of the mechanical design was carried out, with the aim of further lightening the units and additional considerations regarding the size (length of the units) and safety during use. The orthosis created in this way is suitable for serial production and use in the field of rehabilitation.

On the basis of the above-described construction, a new concept was applied: instead of the conventionally used gears, a "Direct drive" drive was used. This ensures a smooth transmission of the rotational movements from the engine in the appropriately developed rotational joint within the safety stops laid down in the structure, and also frees the shoulder joint from unnecessary details. The links were lightened based on force analysis using the finite element method A better attachment of the belts to the orthosis was provided. A new CAD model was created, which was detailed and fabricated in its main part on a 3D printer.

The mechanical module (Fig. 3.) consists of a motor fixed on the stationary body by means of a suitably made holder. A shaft driving the orthosis is attached to the motor shaft, on which a bearing unit is built by means of stabilizing bushings, part of which are fixed to the fixed arm. Part of the shaft is made as a threaded part, on which a nut with a counter element is inserted. By means of this nut, it is possible to remove the clearance of the bearings in the bearing assembly, as the main part, which would create clearances in the movement of the arms of the orthosis. The bearing assembly is fixed to the movable arm by means of a splined joint supported by suitably made retainers. On the movable and immovable arm are built-in fixed and movable retainers, determining the angle of rotation of the movable arm of the orthosis, in order to protect the arm from trauma. In Fig. 4. asconometric projections of the newly created orthosis are presented.

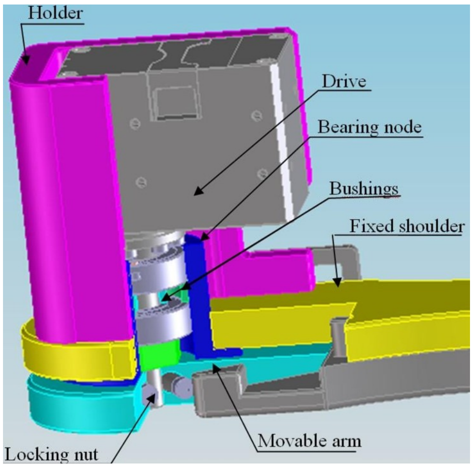

Fig. 3. Partial section of the drive part

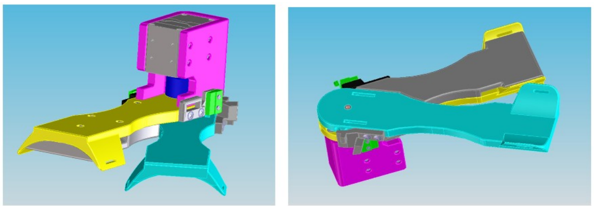

Fig. 4. Asconometric view of the newly created orthosis

As in the existing version, as in the new prototype, an actuator from the company Dynamixel, in this case XM540-W270-T, was chosen to drive the orthosis [6]. Its main technical characteristics are:

- Supply voltage [V] – 10.0–14.8;
- Maximum torque [N•m] – 10.6 (12V);
- Maximum current [A] – 4.4;
- Position sensor - non-contact, absolute (12 [bit], 360 [°]);
- Dimensions (WxHxD) [mm] - 27 x 58.5 x 51.9 ;
- Weight [g] – 165;
- Feedback – Position, Velocity, Current, Real-time tick, Trajectory, Temperature, Voltage, etc.
- It has to be mentioned that for additional patient safety the torque (current) could be software limited.

In Fig. 5. the relationship between torque, RPM and efficiency of the XM540-W270-T is graphically presented.

The orthosis is controlled by a hierarchical three-level control system with a possibility of an EMG feedback. The main requirements to such a system are:

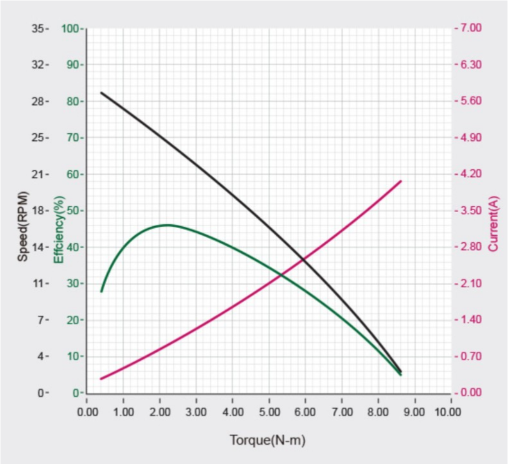

Fig. 5. Dependence between the main parameters of the XM540-W270-T actuator

- Safe-for-health voltages and currents;
- Additional safety of mechanics;
- Sufficient torque;
- Suitable dimensions and weight;
- Real time motion PID control;
- Easy access to orthosis position, speed, current, and other system parameters;
- A wide set of drive and operating modes;
- Precise control possibility in different modes.

The lower level of the control system is the above mentioned electrical integrated actuator Dynamixel XM540-W270-T, named below "servo" The purpose of the servo is to drive the mechanics of the orthosis in accordance with the motion law chosen.

The middle level of the control system is an OpenCM 9.04 microcontroller [6]. The purpose of this level is: a) to communicate with the upper level for programming and data transfer, and b) to control the servo. It is available with Arduino IDE offered with API functions, sufficient for lower level control. Its main characteristics are:

- CPU – STM32F103CB (ARM Cortex-M3);
- Operating voltage – 5V ~ 16V;
- I/O GPIO – 26;
- Analog inputs – 10 (12bit);
- Flash – 128Kb;
- SRAM – 20Kb;
- Clock – 72Mhz;
- USB – 1 Micro Type;
- USART – 3;
- DYNAMIXEL TTL BUS – 4 (Max 1Mbps) ;
- Dimensions – 27mm x 66.5mm.

As in the existing prototype, the OpenCM9.04B controller (Fig. 6.) is used again. The system software remains the same with some slight differences in the parameterization of the actuator.

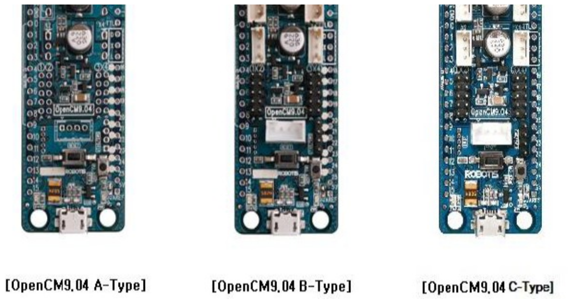
[OpenCM9.04 A-Type] [OpenCM9.04 B-Type] [OpenCM9.04 C-Type]

Fig. 6. OpenCM9.04 Controller

The upper level is a personal computer (laptop) with installed Arduino IDE [web6] with appropriate libraries. It serves for OpenCM 9.04 programming and user interface (UI). UI may be also realized by any Windows/Linux/Android, etc., terminal application or by stand alone human-machine interface.

IV. DISCUSSIONS AND CONCLUSION

The presented prototype of the orthosis with its hierarchical three-level control system has been tested on real patients. Tests were conducted in no-feedback (hard control) mode. The tests have shown sufficient functionality and convenience of the use of the orthosis. The main parameters achieved with the current mechanics and control system are: a) torque 10.6 [N.m], b) speed – 30 [rpm]; c) accuracy < 2 [deg]. The weight of the orthosis is 670g – near twice less than the previous version. In Fig. 7. the new version of the orthosis attached to a volunteer's arm is shown.

The new prototype active elbow brace described above has better characteristics than the existing one. A comparison of their main indicators is shown in Table 1

The future work on the control system of the orthosis is mainly pointed in four directions:

- EMG feedback on–off control;
- Development of a graphic interface for a parameterization of the rehabilitation procedures by

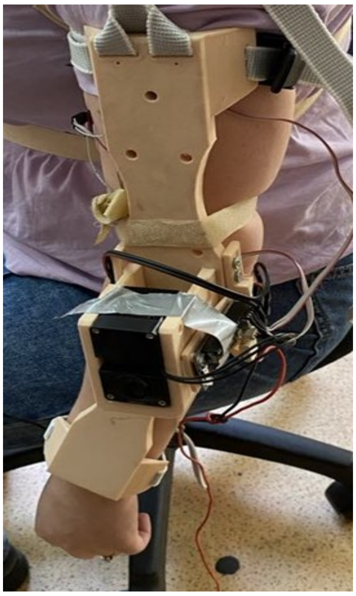

Fig. 7. Photo of the orthosis attached to the shoulder griddle

TABLE I. COMPARISON TABLE

Parameters	**Prototypes**	
	Existing	***New***
Weight [g]	1250	670
Torque [N.m]	7.5 (w. reductor)	10.6
Speed [rpm]	13	30
Accuracy [°]	<2	<0.1

a.

the physiotherapist and its autonomous use of the patient at home;

- Using of wireless communication (bluetooth i.e.) between the high control level and the local orthosis controller;
- Instead of the above mentioned middle control level, a microcontroller with a digital keyboard and display mechanically and electrically integrated in the orthosis to be used. It will give more options and will make the use of the orthosis easier for the patient. This microcontroller will eliminate the need of a visualizing upper level when the patient is working with the orthosis at home.

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