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Design and Preliminary Testing of a Soft Exosuit for Assisting Elbow Movements and Hand Grasping

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***Abstract*—Most of the currently available exoskeletons for upper limbs are constrained by limited portability, ergonomics, weight and, energy-wise, autonomy. Moreover, their high cost makes them available only for the most affluent users, ruling out the majority of the population in need. By replacing rigid aluminum links and transmissions with fabrics and bowden cables, we can both cut down the cost of the assistive device and design it to be portable, comfortable and lightweight. We present the design and a preliminary testing of a soft exosuit for assisting elbow flexion/extension and hand open/close. Our system comprises two proximally located tendon-driving actuators, and two textile-based frames that route the tendons and transmit forces to the human joints, namely an elbow sleeve and a glove. A preliminary test on a healthy subject is presented with an adaptive controller that achieves good tracking accuracy despite of the system's non-linear and time-varying dynamics.**

I. Introduction

STROKE is among the leading causes of death and impairment worldwide [1]. Most stroke survivors exhibit persistent motor deficits in the upper limbs 6 months after the seizure, which significantly affects their quality of life [2].

Current traditional devices for aiding these people in their daily life are made of load-bearing rigid links that allow them to provide large forces for assistance but obstruct the natural kinematics of human movements. Moreover, their weight, complexity and power requirements make them unsuitable for at-home, unsupervised use on a daily basis.

Recent advances in soft robotics, applied to wearable assistive devices, have shown promising potential. Specifically, cable-driven, wearable soft frames have shown exciting results for both reducing the metabolic expenditure of walking [3] and assisting hand movements [4]. Whilst not being able to provide the degree of assistance of traditional systems this alternative approach is more likely to find successful application because of its lower cost, intrinsic mechanical transparency, low weight and high portability.

We hereby present the design and a preliminary test of a textile-based exosuit for assisting elbow movements and hand grasping. The system comprises a soft glove and an arm sleeve used to route a set of tendons driven by two proximally-located actuators. We then perform a preliminary test on a healthy subject. By adopting a control paradigm that uses data from a flex sensor and a supervised machine learning model, we can compensate for the strongly non-linear dynamics of soft frame.

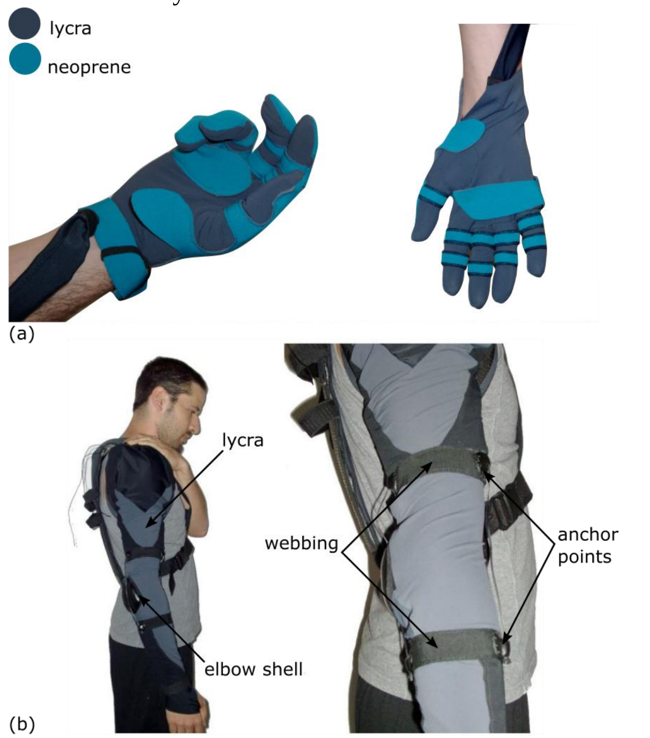

Fig. 1. Lycra and neoprene layers of the first prototype of the glove for hand grasping assistance (a) and prototype of the sleeve for elbow flexion/extension.

II. Exosuit design

The glove and the sleeve forming the exosuit are shown in Fig. 1. Tendons are routed in the suit in an antagonistic fashion, assisting both directions of movement.

To achieve both comfort and functionality, we used a combination of fabrics with different elastic properties. The substrate of the suit, having the function of adhering to the body of the user and keeping it in place, is made of lycra, a synthetic elastic fibre. Inextensible nylon webbing lines the substrate along the direction forces are applied to transmit them efficiently to the body. 3D printed guides sewn on the nylon route the tendons and serve as artificial ligaments anchored to the body. Finally, a layer of neoprene at the interface between the anchor points and the skin avoids peaks of pressure. Both the glove and the elbow sleeve are tighten against the body using buckles and Velcro straps.

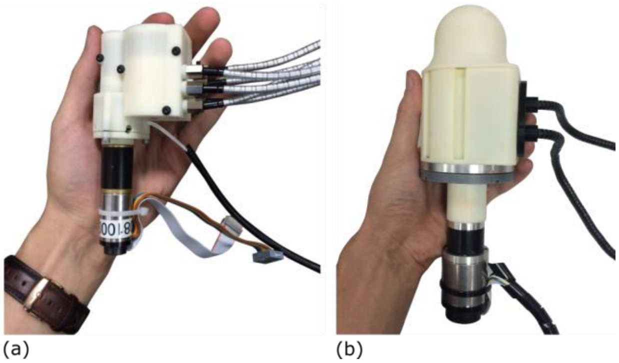

Fig. 2. Tendon-driving units of the glove (a) and of the elbow sleeve (b), both enclosed in a 3D printed case of ABS plastic.

III. TENDON-DRIVING UNITS

The glove and elbow sleeve shown in Fig. 1 are each actuated by the tendon-driving units shown, respectively, in Fig. 2a and Fig. 2b. Using bowden cables to route the tendons allows to locate these actuators proximally, i.e. in belt around the waist (hand unit) or in a backpack (elbow unit).

Both units have the same working principle: each pair of tendons is wrapped around a spool in opposite directions, so that retraction of the agonist tendon causes release of its antagonist. The spool is powered by a DC motor. A feeder mechanism, thoroughly described and tested in [5], keeps the tendons tight around the spool.

A key feature of our design is the possibility of coupling the spool to the frame, thus unloading the motor, by engaging an electromagnetic clutch. This allows to keep the wearer's joints in a static posture with minimal power consumption (5W). Table 1 summarizes the characteristics of both units (1.2-1.6Hz is the average bandwidth required for ADLs).

TABLE I
SYSTEM SPECIFICATIONS

Characteristic	Elbow	Hand
Bandwidth [Hz]	6	8
Max Rated Torque [Nm]	2.6	2
Exosuit weight [Kg]	0.197	0.205
Actuator weight [Kg]	0.880	0.420
Cost [$]	≈ 465	≈ 470

IV. CONTROL IMPLEMENTATION AND TESTING

The use of soft materials poses considerable control challenges: the presence of non-linear phenomena makes a simple feedback controller insufficient for achieving a reasonable accuracy and deriving an accurate model of the system's dynamics is extremely challenging.

We used a supervised machine learning regression that approximates, and continuously updates during operation, the mapping from the joint trajectory to the required motor torque. This allows us to combine a feedback and a feedforward term in the control law, which ultimately becomes: $u = u_{fb} + u_{ff}$, where u_{fb} is the output of a simple PD control and u_{ff} the system's inverse dynamics as predicted by the regression.

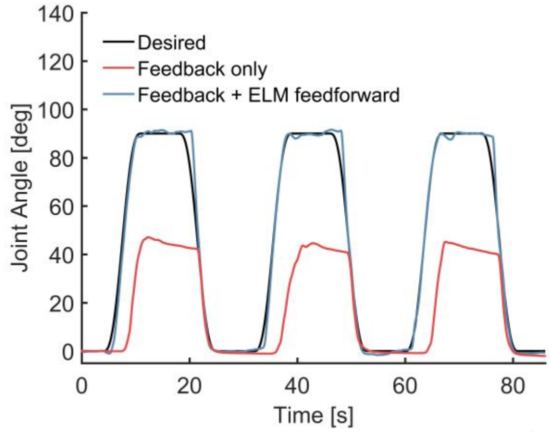

Fig. 3. Elbow trajectory-tracking task with and without the feedforward term estimated by the ELM algorithm.

We tested this control paradigm on a healthy subject wearing the elbow sleeve. Fig. 3 shows a comparison between a simple feedback control and our approach.

The joint angle was monitored using a flex-sensor (SpectraSymbol) sewn on the elbow sleeve. The subject was asked to be relaxed during the trial. Our regressor, based on Extreme Learning Machines (ELM) [6], takes the elbow joint trajectory as an input and the motor current as a target and fits, in the least square sense, the function between the two. New values of the joint trajectories are then used to infer online the feedforward control term.

V. CONCLUSION

We presented the design and preliminary testing of a lightweight, low-profile and low-power consuming exosuit for assisting hand grasping and elbow flexion/extension. A control algorithm that derives the system's dynamics from sensory data was also tested to control the elbow trajectory of a healthy subject. Whilst not being able to provide the same levels of forces of traditional exoskeleton, soft exosuits have the potential of being a more practical solution for at-home, unsupervised assistance. Future works will go towards an evaluation of the interaction forces between the suit and its wearer during motion.

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