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Design of a Series Elastic Transmission for hand exoskeletons☆

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ABSTRACT

Recently, the wearable robotic field has become extremely prolific in terms of active devices for human body assistance. Nevertheless, unfortunately, owing to strictly motor and sensor requirements in terms of mechanism, weight, size and dexterous manipulation capabilities, portable hand exoskeletons for rehabilitation and assistance have not been developed as much as the exoskeletons for lower and upper limbs; in fact, only a few of them present an outcome of their use in the clinical practice as positive as expected.

This research work aims at designing an aid for the hand function based on exoskeleton technologies for patients who have lost or injured their hand skills.

In particular, this paper presents a novel Series Elastic Transmission (SET) used as power transmission on a Hand Exoskeleton System (HES) based on a Series Elastic Actuator (SEA). The elastic element of the transmission has been designed through the innovative topology optimization approach which has led to manufacture a component whose mechanical features strictly replicate the desired ones. The authors have validated the proposed approach by testing a real elastic component. Suitable mechanical tests, whose results are reported in the paper, were executed in order to evaluate the goodness of the design procedure.

1. Introduction

The demand for rehabilitation therapy has been increasing rapidly in the last years. Two aspects are contributing significantly to this situation. The former is that aging is a global problem, so the number of elderly people, who need resources for rehabilitative therapy, is going to raise unceasingly. The latter is that, not only as a consequence of aging, more people are suffering from neurological and musculoskeletal diseases such as stroke [1], Parkinson's Disease [2] and degenerative arthritis [3].

From the rehabilitation viewpoint, successful sessions require to perform intense and continuous therapeutic tasks. In this field, robotic systems allow to provide prolonged and high-intensity rehabilitation treatments, involving a reduction of costs and burden for the therapists. Wearable robotic devices are indeed strongly addressed by rehabilitation researches [4], because they can control and manage independently the user's single body segments and anatomical motions or joints.

Unfortunately, up to 66% of post-stroke patients cannot regain the dexterity of the damaged arm after 6 months from the stroke [5,6]. In some cases, hand functions may not be totally reacquired even after an intense rehabilitation process. Thus, the hand exoskeletons may serve as an aid to assist the user in the Activities of Daily Living (ADLs) amplifying the hand gripping force or automating the motion.

Even if robotic technologies are more and more pervasive and deployed in clinical environments, reliability and cost-effectiveness are still mandatory aspects for their acceptance and use during the ADLs. These tools need to have flexibility to meet various sets of requirements and also societal expectations. Novel methods and tools need also to be adaptable, to be used by different patients and with different kinds of settings. New solutions should be easy to use and they should be accepted by end-users: elderly/patients, medics, care service providers but also insurance companies and such.

For all these reasons, the adaptability of a robotic device fulfills a key role in the development of human-interactive machines [7,8]. In this regard, rising research activities on rehabilitation and assistive robotics are focusing on these technological advancements [9]. In particular, many researches struggle with reaching the conflictive requirements imposed by such devices: both high precision of motion and of exchanged interaction forces, and inherent safety and adaptability [10] are requested.

Soft systems have been widely investigated in this scenario and both

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pneumatic [11,12] and tendon-driven [13–15] gloves represent nowadays valid solutions in the wearable robotics field.

Many strategies have been studied and also adopted to achieve a suitable compliance even in rigid active robots: inherent compliance obtained through compliant actuators [16], deformable structures [17], smart materials [18,19] or emulated compliance obtained through impedance or admittance controller [20]. However, even if they represent a very promising solution, when highly dependable and robust systems are needed, classic actuation technologies (electrical motors or hydraulic pistons) are preferred, because of easy control and high reliability yielded by their wide use in different applications. In these cases, compliance can be embedded within the transmission.

According to this, several scientific and technologies solutions are reported in literature [21,22]. Among them, one of the most promising is the well-known Series-Elastic Actuators (SEAs, [23]) technology. Such design provides a pre-defined mechanical stiffness, properly combined with suitable sensors, interposed in the mechanical power flux pathway. This solution allows to measure the forces exchanged between the mechatronic system and the external environment, storing an energy load during the interaction, and also providing the safety of not fasten the person to a rigid robot [21].

SEA architectures are currently adopted in wearable robotics by many devices, e.g. exoskeletons [24–27]; most of them usually proposes specific and properly designed custom springs or elastic mechanical assemblies to realize revolute actuated joints, coupled with the hip, knee, shoulder or elbow joints of the wearer.

As reported above, the SEA approach lowers the rigidity of the robotic structure but its use has a negative effect on the performance of the actuated joint, limiting the bandwidth to its natural frequency and the maximum output force to a trade-off with the maximum strain of the compliant element. Thus, the design of a SEA faces the hurdle in matching the maximum bearable deformation and the specific stiffness, according to the desired performances, into the small given required space. Up to now, results from the state of the art are still under investigation to be easily implemented in real applications, especially concerning the exoskeletons field.

Exoskeletons for the human hand and their actuation technologies represent a very prolific topic [28] and many devices have been presented in literature [29–31]. Nevertheless, the state of the art shows that it is very hard to achieve a SEA architecture in this case, because of lack of physical room and compatibility with the hand morphology. Nonetheless, the interest in force-controllable hand exoskeletons is high, not only for rehabilitation treatment, but also for haptics or teleoperation [32].

The aim of the presented work is the design of a novel Series Elastic Transmission (SET) developed to be exploited on hand exoskeletons.

In this study, particularly, the proposed SET has been designed to be integrated in the Hand Exoskeleton System (HES) developed by the Department of Industrial Engineering of the University of Florence [33]. The fully portable exoskeleton presented in [33] (Fig. 1), making use of a specific single-phalanx kinematic chain based on a rigid 1 degree of freedom (DOF) mechanism, represents a good trade-off between accuracy and functionality. The high portability of this device demanded for a transmission as compact as possible and the SET positioning (directly on the hand back) required extremely low weight. All these features guarantee the portability of the HES both in rehabilitative and assistive context.

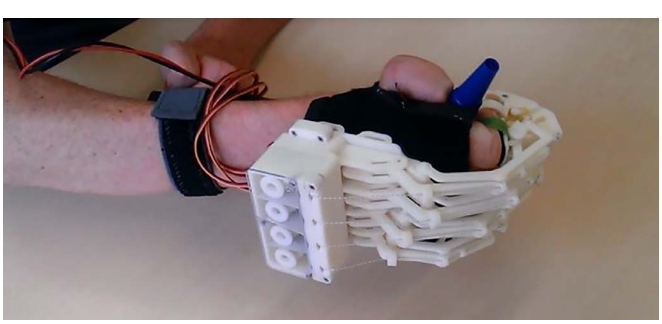

Fig. 1. The first hand exoskeleton prototype, developed by the University of Florence, worn by a patient during the testing phase.

The design of a novel SET has then required the redesign of the whole HES: the ABS-made exoskeleton structure has hence been redesigned for manufacturing in titanium alloy.

In addition, the proposed SET (with its new design method) could be also applied to other mechanisms for different human joints with limited accessibility.

The employment of a SET within the HES leads to important advantages. Indeed, the developed Series Elastic element allows to accurately measure the force exerted on the hand using only angular sensors. Then, an Elastic Transmission implies a compliance, embedded within the system, which softens the device. This is mandatory for a safe exoskeleton, e.g in case of spasms.

Starting from the kineto-static analysis of the finger mechanism, the obtained results have been used to define the quantitative features of the SET. The described in-depth kineto-static analysis has, then, allowed to design the elastic element of the SEA, exploiting innovative topology optimization techniques [34] that were not extensively investigated before in this kind of application.

The experimental validation showed that, thanks to the optimization based design approach, the SET elastic component followed the required features.

The paper is organized as follows. First of all, in Section 2, an overview of the exoskeleton design is reported. The mechanical architecture of the whole system is explained in order to define the application which the SET has been designed to. This particular context has been then taken into consideration throughout the design of the SET. In Section 3, an in-depth analysis of the 1-DOF finger mechanism is presented. The kinematics and the kineto-statics of the mechanism have been studied to define the working conditions for the SET. In particular, the torque required at the actuated joint to achieve the desired movement has been characterized. Section 4 deals with the actuation system. Two strategies exploited to reduce the torque required to actuate the device are reported and explained. In this section, the novel design of the Series Elastic Transmission is illustrated. Finally, in Section 5, the Series Elastic Actuator architecture is given. Focusing on the optimization-based design, a novel elastic element has been characterized and tested.

2. Exoskeleton overview

The HES prototype (shown in Fig. 2a) consists of two main parts: the actuation system and the mechanism of the exoskeleton (Fig. 2b reports an exploded view). As regards the actuation system, two electric servomotors are used to directly actuate joint A in both flexion and extension movements. The use of only two motors is justified by the fact that the index is actuated separately with respect to the other three long fingers (middle, ring, little fingers) which are actuated together. This choice allows to greatly improve the portability of the HES without worsening the performance of the device. In fact, while the isolation of the index is strongly important for the precision grip and for the management of the force expressed by the hand, other types of grasp are guaranteed (in terms of functionality) even without a dedicated actuation for each single finger [35,36]. Mechanically, to make possible this solution, the axes of joints A of medium, ring and middle fingers are aligned to link them together through a single shaft, with the same actuation system.

The parts of the mechanism are designed, starting from the geometry imposed by the kinetic study, which is reported in Section 3, in order to be built in Ti6Al4V using the Electron Beam Melting (EBM) technology.