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Design of a Modular Add-on Compliant Actuator to Convert an Orthosis into an Assistive Exoskeleton

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Abstract— **In an ageing population many people with muscle weakness may benefit from an assisting exoskeleton to improve their mobility. Recent developments in research labs around the world are often complex, not modular and expensive. This paper introduces a novel modular compliant actuator for use in assistive lower limb exoskeletons. It is a low-cost, light-weight, compliant actuator unit that can be easily mounted on commercially available orthoses. It has the versatility to assist hip-, knee- and ankle flexion/extension individually and/or in sit-to-stance or walking activities. An adjustable passive compliance is achieved by a design based on the MACCEPA (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) principle. The assisting output torque and the rendered range of compliance are simulated and experimentally demonstrated.**

I. INTRODUCTION

Lower limb exoskeletons get more and more attention in the last couple of years. This increase of interest originates from their diverse abilities and wide application areas [1]. Exoskeletons can be deployed with a power enhancing purpose. This type carries the major part of the load, while the human operator guides the exoskeleton. An example is the BLEEX exoskeleton [2]. A second exoskeleton application is the deployment in gait trainers for rehabilitation purposes.

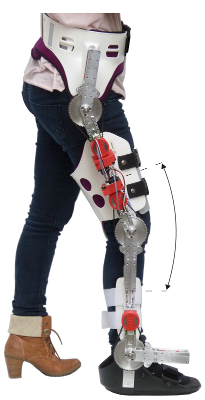

Fig. 1. A two-leg exoskeleton has been developed using the presented actuator (indicated) that assists hip-, knee-, and ankle flexion/extesion. Six identical actuator modules are merged with commercial leg orthoses and ankle-foot orthoses. The photograph shows only half the exoskeleton.

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Examples are the gait trainers Lokomat [3], the Lopes [4] and the knee exoskeleton KNEXO [5]. Next, exoskeletons are deployed in aiding paraplegic patients in walking, replacing a wheelchair [6]. Farris et. al. have developed a powered lower-limb orthosis that provides gait assistance to spinal cord injured individuals. This has been commercialized as the product Indego. They actuate the hip and knee by a geared brushless DC motor [7]. A similar exoskeleton for paraplegics is the Ekso [8] (formerly known as eLegs). A last category of exoskeletons is that of devices which provide assistance as needed [9]. These mainly aim to help people with muscle weakness or an abnormal gait. The goal of those exoskeletons is to assist in for example specific parts of the gait and with the intensity that the wearer needs to complete his actions [10]. Lagoda et. al [11] developed a series elastic actuator to assist stroke patients with an assistance-as-needed strategy.

The various goals of exoskeletons demand for different control strategies [12]. In the mechanical designs, however, many design requirements are in common. The exoskeleton should be comfortable to wear, be safe, have a low weight and compact dimensions. One of the most important aspects in the exoskeleton design is the design of the actuator system.

The lower limb exoskeletons and other orthoses have to exhibit a certain compliant behaviour since they directly interact with the human. To hinder the movements of the human as little as possible the mechanical output impedance must be low. The actuators of the exoskeleton also need to produce high forces/torques to assist the human. A first possibility to incorporate compliance is through control [13]. The stiffness of the system is then regulated by impedance or admittance controllers [12], [14]. To incorporate compliance in the mechanical structure is another valuable (and complementary) method. Passive compliant elements are brought into the mechanical structure of exoskeletons [13] such as steel, rubber or composite springs at the end of the drivetrain.

Passive compliant actuators have a number of advantages with respect to the stiff actuators [15], [16]. First, the compliant actuator exhibits the impedance of a spring when the system is excited above the bandwidth of the controller. When there is no passive compliant element in the actuator system, the reflected motor inertia is felt. Due to the high transmission ratios applied in the actuators, these reflected inertias are often high. Secondly, the spring-like element filters the non-linearities in the transmission such as friction and backlash. This reduces the impact of the non-linearities on the control. Next, knowledge of the stiffness and the spring deflection results in an estimate of the force, which makes the use of expensive force cells obsolete. The compliant element transforms a force control into a position control. Force control by a stiff actuator is less stable, since small displacements can have high force effects as opposed to compliant actuators. Next, the ability to store energy in the spring should not be forgotten. This allows the use of smaller motors since they no longer have to be sized for the peak powers.

A drawback of introducing compliance in an actuator is the reduction of bandwidth of the system due to the compliant element. For assisting human motion, which is a low-bandwidth activity, this is not a problem. It is a matter of shaping the design to reach a sufficient bandwidth.

A common conception regarding compliant actuators is that the compliant element also unconditionally improves the safety with respect to impacts. This is a partial misconception as the spring also stores energy when absorbing an impact. This energy should not be released in an uncontrolled way to avoid a hazardous situation. Yet in combination with a suitable controller the compliant element is capable of increasing the safety of the system [17].

A well-known implementation of passive compliance in the drivetrain is the Series Elastic Actuator (SEA) [16] where a spring is placed directly in series with the actuator. The stiffness of the spring is fixed in this case. More advanced designs are capable of varying the stiffness of the spring by separating the equilibrium position and the pretension of the spring. Examples are the VS-joint [18] or the MACCEPA [19]. An overview can be found in [13]. The compliant actuator design in this work is based on the MACCEPA principle. The pretension of the spring can be set independently and it changes the stiffness of the overall actuator system.

Most compliant actuators in research that assist the lower limbs are only designed for the knee [20], [21], [22], [23]. There, only a single joint has to be aligned with the human joint and they do not have the difficulties with adjusting the lengths of the links to those of the limbs. Hence the adaptability of the designed actuator to fit different persons is not taken into account in these works. For an exoskeleton to become a practical and possibly commercial product it must be adaptable to the wearer's physique. The actuator should allow room for an extendable structure that is usually present in commercially available orthoses, while keeping the overall width to a minimum. This work presents a compliant actuator system which is modular and can be built into commercially available orthoses at all desired joints.

Our novel modular actuator is intended for use in assistive exoskeletons that can help people with muscle weakness by an assistance-as-needed strategy. To attain this goal, the adjustable range of mechanical compliance, the modularity, the compactness, the sensors and the integrated real-time control and communication are important features.

This paper is built up as follows: Section II describes the actuator design. First an overview of the design criteria is given. Next the working principle, mechanical compliance, drivetrain and sensors are worked out. In section III the first experiments regarding the compliance are presented and discussed. In the final section IV the conclusions are drawn.

II. ACTUATOR DESIGN

The modular actuator is initially developed as a modular component to build a six degree of freedom two-leg exoskeleton that actuates hip-, knee-, and ankle flexion/extension. The primary use of the actuator is to support sit-to-stand activities for an adult. The secondary purpose is to assist in walking. A design effort was made to extend the capabilities of the actuator to cover both objectives. The modular application of the actuator to build a six degree of freedom wearable exoskeleton is treated in another paper of Junius [24]. Fig. 1 shows the actuator module as a part of the sit-to-stance exoskeleton prototype. Fig. 2 gives a view of the actuator module in detail.

The actuator module has an integrated controller hardware and an integrated motor driver. The sensor signals are locally acquired and processed. This results in a minimal amount of cables on the exoskeleton. The actuator unit requires a power cable carrying 36 V / 3 A to the motor driver and a 5 V supply for the electronics, which can be derived from the 36 V. The real-time data communication network is scalable and works with the EtherCAT protocol. This requires simple Ethernet cables in a daisy chain topology between the multiple actuators. The low amount of cables increases the reliability and facilitates the detection of disconnected cables. It also reduces the overhead of communication. Update rates of an EtherCAT network are typically between 1 and 30 Khz. All sensor signals and real-time control signals can be transmitted over the scalable real-time network. This highlights the modularity of the designed compliant actuator.

A. Design Requirements

The drivetrain needs to deliver appropriate angular speeds and torques to be deployable in lower limb exoskeletons. In sit-to-stance activity, the actuator speed is not crucial and a small motor with very high gearing could be used. To extend the versatility of the actuator to human walking, the target speed has is based on kinematic gait data. The maximum rotational speed in natural walking at a natural cadence of 105 steps per minute is about 59 rpm [25], where the knee is the most demanding joint.

The developed exoskeleton will promote participation of the user, motivating the human to use his own muscles as much as possible. It does not need to produce the full biomechanical torque. In sit-to-stance activities, which is the primary objective, the aim is to generate 30 % of the biological instantaneous flexion/extension torques of an average adult with a weight of 80 kg. Our intent is an assistance-as-needed strategy. In the work of Junius [24] the torque requirements of the actuator are discussed in detail, starting from biomechanical simulations for different levels of muscle weakness. With this assistance level of up to 30 %, the goal is to bridge the capability gap, i.e. the gap between the capabilities of the user and the task requirements. This is essential to maintain neuromotor

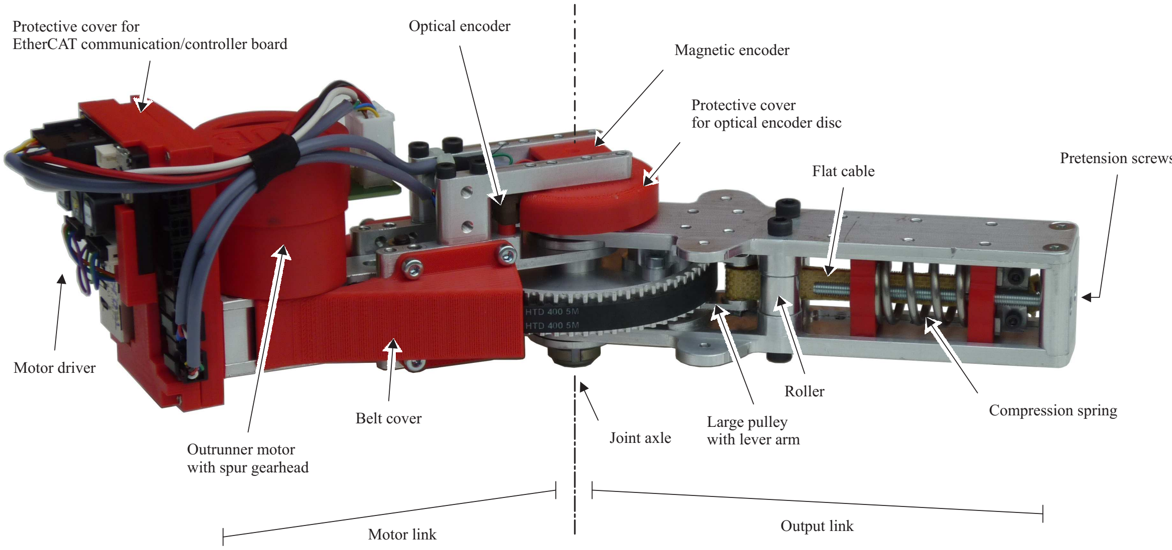

Fig. 2. Components of the compliant actuator. The pulley, lever arm and compression spring which form the mechanical compliance are clearly visible on the photograph. This actuator module has a total weight of 1.4 kg, including the integrated electronics and protective covers.

function and prevent disuse [26]. Afschrift et. al. [26] have obtained the biological flexion/extension torques for a sit-to-stance activity from experimental biomechanical data and inverse dynamic modeling. From this data one can derive that for a 80 kg person, 30 % of assistance corresponds to a peak torque of about 15 Nm for the hip and the knee, while only to 6 Nm for the ankle. A maximum torque of 15 Nm is the target value for this actuator module.

The modularity and versatility are of major importance. The actuator is intended to be used as a universal component and should thus have symmetric connecting points and a symmetric range of motion (see Fig. 3) to be functional in both legs of an exoskeleton. The range of motion is designed such that it is large enough for the hip-, knee- and ankle rotations while both links of the actuator are mounted aligned with the human limbs. The actuators are designed to stay backdrivable in case of a power shutdown so that the wearer can still move and stabilize himself. To overcome the static friction when the device is not powered we have to apply less than 0.8 Nm.

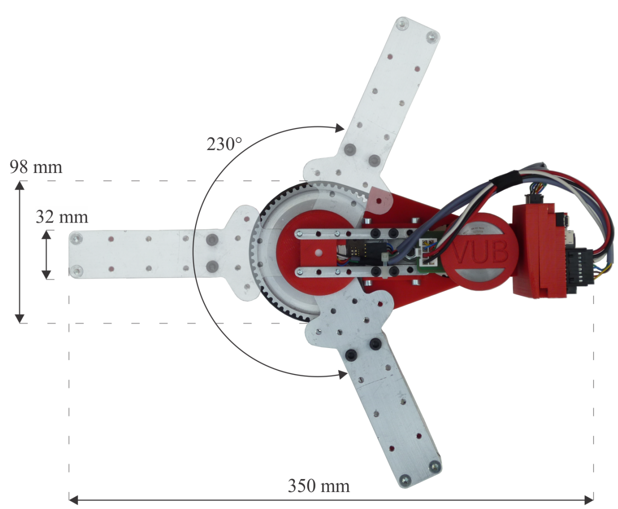

Fig. 3. The actuator has a range of motion of 230°. Because of its symmetry and symmetric range of motion, the universal module can be used to actuate both left and right joints in a two-leg exoskeleton. Further this large range of motion is sufficient to cover flexion/extension angles for the hip, knee and ankle while both links of the actuator are mounted aligned with the human limbs. The outer dimensions are indicated on the figure. The outer width of the actuator is 112 mm .

B. Working Principle

Fig. 4 schematically shows the principle of the rotational joint with adaptable compliance. The motor link and the output link are connected at the joint axis. A lever arm which is pulling a cable also rotates about this same axis. A motor drives the rotation of the lever arm relative to the motor link, thus setting the equilibrium point of the compliant mechanism. When using an electric motor, a suitable gear reduction is needed. For compactness and a low-weight, it is interesting to merge the lever arm and the final gear/pulley into a single component. The torsional compliance is created when the lever arm pulls an elastic element on the output link. In the wheeled MACCEPA principle [19], the spring is pulled by a cable that runs between two rollers and is fixed to the furthest end of the spring. The other end of the spring can be linearly displaced to adapt the pretension and thereby the torsional stiffness characteristic of the joint.

C. Mechanical Compliance

Although the benefits of compliant actuators in human-robot interaction have been studied, the optimal actuator stiffness is not well-defined [27]. The right stiffness is considered strongly dependent on the application and the individual wearer's physique and needs. Therefore and for a modular use of our actuator, an adjustable stiffness is desirable. The actuator dimensions are sized to obtain a

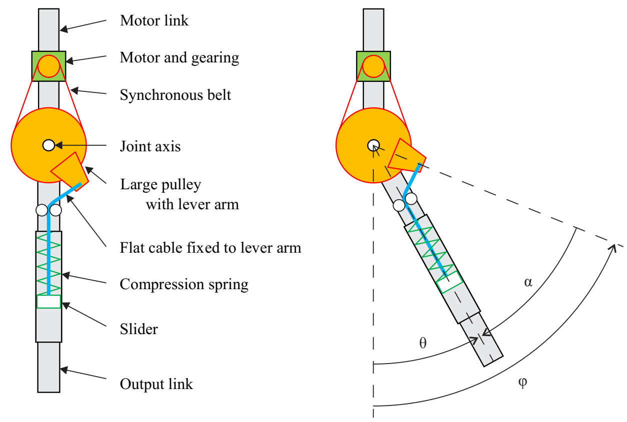

Fig. 4. Principle of the robotic joint with adaptable compliance. Left: Output link aligned with indication of the components. Right: Rotation of the output link with angle definitions. $\theta = \varphi + \alpha$

target stiffness range of about 0.50 Nm/° to 1.50 Nm/°. The lower bound is chosen such that the bandwidth remains sufficient. The upper bound is set to have rational deflection angles in the MACCEPA geometry. Unlike other MACCEPA designs, the design with a cable and rollers has a quasi-linear stiffness curve in the higher part of the stiffness range. The stiffness curves are simulated using a similar approach to that described in [28] using the following dimensions of the final actuator design and the relevant specifications of the linear spring used.

L = 72 mm (Joint axle to center of rollers)
r = 57 mm (Lever arm length)
Lo = 40 mm (Uncompressed length of the spring)
Ln = 16 mm (Fully compressed length of the spring)
k = 15 N/mm (Linear spring stiffness)

From Fig. 5 we learn that for zero pretension, the slope (stiffness) at the equilibrium is very low, but the stiffness increases for higher torques. In the pretension range above 40 %, a quasi linear torsional stiffness is obtained. This was our intension when shaping the mechanical design. A linear torsional stiffness can be very convenient when implementing a compliant control strategy.

D. Drivetrain

A compact design is obtained using a flat motor and a spur gearhead as first stage of the drive train. The spur gearhead with a parallel belt transmission was chosen for its compactness and for only loading all bearings radially.

The selected motor is a Maxon EC 45 flat 50W (24V outrunner brushless) DC motor with a rated nominal continuous torque of 82.7 mNm and a nominal speed of 5250 rpm. It has a high thermal time constant of the windings which indicates that short torque/current overloading is well tolerated. The overload capacity is particularly useful in the relatively short sit-to-stance activity. The motor speed can also be exceeded, but to a more limited extent. In comparison with their inrunner counterparts, outrunner motors produce higher torques at the cost of a lower maximum speed (ca. 10000 rpm for the selected type).

The gearing needs multiple stages to reach the required torque output of 15 Nm. The first component in the reduction is a Maxon Spur Gearhead GS 45 A with a total reduction ratio of 47:1. Next, a final reduction of 4:1 is created with a timing belt transmission. The Contitech HTD 5M belt profile with a width of 9 mm can drive the output torque of 15 Nm using a pulley with pitch diameter 95.5 mm. The pulley component has a second function: it is also the lever arm component of the MACCEPA actuator.

In Table I the torque and speed values are calculated for the motor, the intermediate gearing and the final belt reduction that drives the lever arm. The values are given for the nominal continuous operating conditions of the motor, the peak speed of the motor and the peak torque of the drivetrain. When the actuator is used for sit-to-stance assistance, the nominal speed of 28 rpm will suffice, but an elevated torque may be required. A peak output torque of 16.7 Nm for about 5 seconds is considered as a safe overload of the drivetrain. The motor driver can deliver up to 9 A peak. The weakest link is expected to be the output stage of the GS45 Spur Gearhead which will wear excessively if the torque is increased even further. If the actuator is used to assist in walking, the maximum speed becomes more important. The power supply and the motor driver of 36 V have the extra range to drive the 24 V motor to 10000 rpm. This limit in angular speed of the lever arm of 53 rpm is sufficient for the compliant actuator to operate at a slow to almost normal walking cadence.

E. Sensors & Control

The mechanically compliant actuator requires two angular position measurements for good controllability [21]: one before and one after the compliant element in the drivetrain. In Fig. 4, three angles φ, α and θ are defined which are

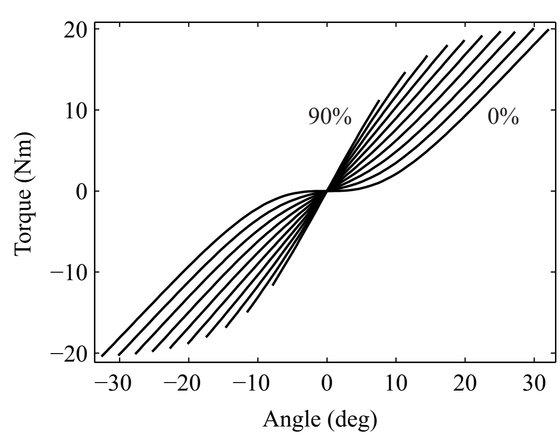

Fig. 5. Simulated torsional stiffness characteristic. Pretension in steps of 10%. The slope (stiffness) increases with higher pretension settings. Above 40 % pretension of the spring, a quasi linear torsional stiffness is obtained. The decrease in maximum torque for high pretension settings is due to the geometry of the MACCEPA mechanism. The end of the curve is when the spring is fully compressed.

TABLE I

DRIVETRAIN SPECIFICATION

	Motor			Gearing	
		Maxon EC 45 flat 50W		Maxon Spur Gearhead GS 45 A	Contitech HTD 5M
				$n = 47:1$, $\eta = 0.76$	$n = 4:1$, $\eta = 0.95$
Nom. motor	Current: 2.32 A		Torque: 82.7 mNm	Torque: 2.95 Nm	Torque: 11.2 Nm
	Voltage: 24 V		Speed: 5250 rpm	Speed: 112 rpm	Speed: 28 rpm
Peak torque (150%)	Current: 3.70 A	$k_T = 33.5$ mNm/A	Torque: 124 mNm	Torque: 4.40 Nm	Torque: 16.7 Nm
Peak speed (no load)	Voltage: 35 V	$k_V = 285$ rpm/V	Speed: 10000 rpm	Speed: 213 rpm	Speed: 53 rpm

related through $\theta = \varphi + \alpha$. The angle φ is defined from the motor link to the lever arm. The deflection angle α is defined from the lever arm to the output link. The joint angle θ is defined from the motor link to the output link. Since they are directly related, only two out of three angular positions must be measured and the choice of which angles to equip with sensors is free. A careful consideration on the choice of encoder measurements is however required. The resolution in angular position and angular speed and the ability to have a safe nulling depend on this choice. Table II helps to select the most interesting encoder configuration.

Given a good model of the torsional stiffness (see section II-C), a measurement signal of the angle α can provide an indirect measurement of the output torque. This is only true on the condition that the measurement of α has a good nulling and that the torsional stiffness is well calibrated for the pretension setting of the spring. For the joint angle θ, good initial nulling is also required as well as a precise derivative $\dot{\theta}$. The joint velocity signal is particularly interesting for the implementation of compliant controllers such as impedance controllers that require active damping and for control strategies of the full exoskeleton. Initial nulling of θ can be performed in a safe way by passing the index pulse. When the motors are not powered they are easily backdriveable so that the person in the exoskeleton can be asked to move each actuator for initial nulling.

The lever arm angle φ is controlled by the electric motor. The position measurement of φ is needed as the feedback signal for a simple position control loop. Our experience tells that a PI-controller performs well and there is no need for a derivative action, or more specifically no need for a precise velocity measurement of $\dot{\varphi}$. On the other hand, it is difficult to obtain an initial nulling on φ. In order to pass through the index pulse of an encoder at the initialization, the lever arm would have to be moved by the actuator. This results in unknown applied torques, which is considered as unsafe when the exoskeleton is fit to a person.

TABLE II

ANGLE SENSING

	Position signal needed?	Position nulling possible by ... ?		Precise velocity signal needed?
		index pulse	absolute encoder	
φ	yes	no, unsafe	yes	no
α	yes	no, unsafe	yes	no
θ	yes	yes	yes	yes

We chose a 12-bit absolute magnetic encoder AMS AS5055 to measure φ. Since we do not require $\dot{\varphi}$, the low velocity resolution of this type of encoder is no drawback. The sensor for θ is an optical encoder USDigital EM1 with a 2” disc of 2000 counts per revolution, which is ca. 13-bit. The joint velocity signal $\dot{\theta}$ is obtained by a pulse timing algorithm based on interrupt calls on the encoder pulses, yielding a precision of less than 0.1 %. Compared to the derivative of the angle signal, this pulse timing algorithm yields a higher precision on the low rotational velocities in the exoskeleton.

The signal for the third angle α is then equal to $\theta - \varphi$. Based on the nulling of θ and the absolute sensing of φ, the signal of the angle α is also well-defined after initializing the actuator. Using only two encoders, the system is able to measure the required angular positions, the required velocity and provide safe initial nulling.

III. EXPERIMENT

An experiment setup was built where the motor link is rigidly fixed while the output link is connected to a load cell. The output link serves as a lever arm to measure the output torque by an S-beam load cell (Futek LSB200). The load cell and its connection parts are rigid so that the joint angle θ remains at 0° (aligned with the motor link). The angle of the lever arm (of the compliant actuator) is measured by the magnetic encoder with 12-bit resolution as discussed in section II-E. Both signals are logged at a frequency of 1 kHz. In this quasi-static characterization, a 0.1 Hz sine wave is set as the input for the position controller of the lever arm. The amplitude is adjusted to approximately reach the maximum required torque of 15 Nm. This has been repeated for several pretension settings as one can see in Fig. 6. One can see the nonlinear curve for lower pretension settings, but similar to the simulation, the torque can be approximated as a linear function of the angle α for pretension settings higher than 30 %. The rendered range of torsional stiffness (linear least squares approximation) is from 0.49 Nm/° to 1.42 Nm/° for 0 % to 90 % of pretension. In the actual system some dissipation losses occur. A repeatable torque drop of about 1.1 Nm is visible when the direction of rotation is inversed. Frictional losses at the sliding end of the compression spring are assumed to have the major contribution to this effect.

IV. CONCLUSIONS

A novel compliant actuator for a modular implementation in assistance-as-needed exoskeletons based on the

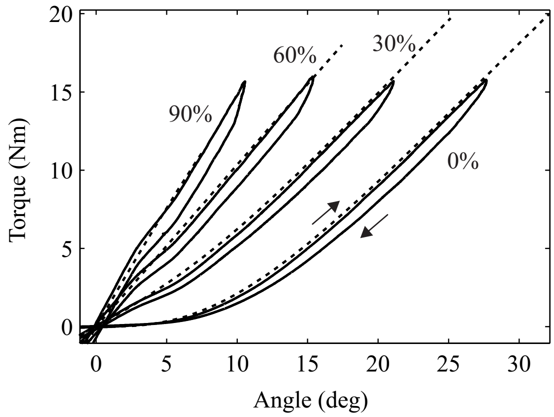

Fig. 6. Measured torsional stiffness characteristic. Curves are plot for the spring pretension settings of 0%, 30%, 60% and 90%. The forward progression direction of the curve is indicated by arrows.

MACCEPA principle is presented. The compliant actuator is capable of changing both the stiffness and the equilibrium point of the mechanism independently. The requirements and the design choices are explained. The range of joint stiffnesses is simulated and measured.

V. ACKNOWLEDGMENT

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