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# Design and control of an active knee orthosis driven by a rotary Series Elastic Actuator ☆

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A B S T R A C T

Active orthosis is one of the main research topics in the field of motor recovery. This paper deals with the design and control of an active knee orthosis driven by a customized rotary Series Elastic Actuator (SEA). The proposed actuator includes a DC motor, a worm gear and a customized torsion spring. Since the elastic element is the most important component in SEA design, a finite element analysis of the spring is performed to meet the specific requirements for knee assistance. Torque and impedance control are implemented to ensure secure interaction with the patient and to enable new strategies for rehabilitation. The torque controller, cascaded with an inner motor velocity control loop, is based on $\mathcal{H}_\infty$ criterion to achieve good system performance with relation to parametric uncertainties and external disturbances. The impedance control is implemented using a PD position controller in cascade with the torque controller, where the outer position controller determines the desired torque according to position and velocity errors and impedance parameters. A variable impedance control strategy is then implemented to show the possibility to regulate the impedance of the knee joint during walking. Experiments considering the interaction between the subject and the active orthosis are performed to evaluate the proposed controllers.



## 1. Introduction

The use of robotic devices for rehabilitation of neurological patients is increasing rapidly due to the importance of functional exercises that stimulate motor cortex and promote motor recovery (Ferris, Sawicki, & Domingo, 2006). Studies suggest that rehabilitation of post-stroke patients was intensified with robot-assisted therapy (Kwakkel, Kollen, & Krebs, 2008; Prange, Jannink, Groothuis-Oudshoorn, Hermens, & Ijzerman, 2006). The advantages of robotic therapy compared with traditional ones also include the ability to evaluate patient progress constantly through objective measures, and the possibility of customizing the treatment according to the patient's level of commitment.

In general, robotic therapy includes a combination of exercises involving passive, active-assisted or active-resisted movements. This combination of exercises can be obtained through the use of impedance control, proposed by Hogan (1985), which allows to configure the dynamic interaction between the device and the patient. For example, an active orthosis can provide support torque during gait training in a assist-as-needed basis. During remaining part of the gait, the orthosis need to present a low impedance behavior, so as to be fully compliant with the patient's actions. The impedance control can also be used to impose a controlled resistance to the patient movement aiming to strengthen muscle groups.

To effectively assist human motion and, at the same time, guarantee patient safety, rehabilitation robots must satisfy certain requirements such as precise and large torque generation, with a bandwidth that approximates muscle movement. It is also essential to ensure a backdrivable behavior, characterized by a low mechanical impedance. Traditional stiff and high-precision actuators do not meet these critical requirements (Ham, Sugar, Vanderborght, Hollander, & Lefeber, 2009; Santis, Siciliano, Luca, & Bicchi, 2008). A simple and effective solution, initially proposed in Pratt and Williamson (1995), is the Series Elastic Actuator (SEA) concept, where elasticity is intentionally introduced in series between a gear-motor and the load. This configuration allows decoupling the gear-motor inertia and other nonlinearities from the

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output and isolates the drivetrain from shocks introduced by the load. Another important feature is that the elastic element can be used as a torque sensor considering the linear relationship between spring deflection and torque.

A rotary SEA to assist the movement of lower limbs was presented in Kong, Bae, and Tomizuka (2009). It consists of a geared DC motor, a helical torsion spring and two rotary potentiometers used to detect the position of the output shaft and the deformation of the spring. In the proposed configuration, the spring is directly placed between the gear-motor and the human joint, therefore subjected to large torques. Helical torsion springs able to support large torques are usually stiff for the considered application. Stiff springs are less sensitive to small torques, resulting in lower torque control accuracy. Moreover, their nonlinearities are not negligible. The spring constant values for gait assistance usually lie in the range from 100 to 300 N m/rad (Carpino, Accoto, Sergi, Tagliamonte, & Guglielmelli, 2012), with the maximum torque in the range from 10 to 100 N m (Kong, Bae, & Tomizuka, 2012; Lagoda, Schouten, Stienen, Hekman, & van der Kooij, 2010; Sergi, Accoto, Carpino, Tagliamonte, & Guglielmelli, 2012; Stienen et al., 2010).

From these considerations, a new rotary SEA model was proposed by the same authors in Kong et al. (2012). In this new configuration, the spring is inserted between the worm gear and the output gears, thereby enabling the use of a spring with low stiffness. The disadvantage of this configuration is that the nonlinearities associated with the output gears compromise the fidelity of measured torque, increasing the uncertainties in the system.

A solution adopted by some researchers is to propose an arrangement of linear springs so as to obtain a torsion elastic element (Tsagarakis, Laffranchi, Vanderborght, & Caldwell, 2009; Yoon et al., 2005). This approach allows the insertion of elastic elements with low stiffness directly between the gear-motor and the load. However, a linear behavior in the torque versus angle relationship is difficult to be obtained. Another solution is the development of customized elastic element (Carpino et al., 2012; Lagoda et al., 2010). In addition to allowing the elastic element to be connected to the load in a direct-drive configuration, this approach may reduce some problems such as residual deflection, hysteresis and a non-linear behavior in the torque versus angle relationship that negatively affect accurate torque estimation and consequently control performance.

Considering these concepts, a new customized torsion spring configuration for rotary SEA is proposed in this paper. The torsion spring design was optimized using Finite Element Method (FEM) simulations in order to satisfy the specific requirements to partially support the knee joint flexion/extension during physical therapy in individuals with low motor impairment. The value 15 N m, which corresponds to 60% of the peak torque from the gait pattern, is defined as design requirement for the maximum torque of the actuator. Robust $\mathcal{H}_\infty$ torque and impedance controllers are designed to ensure secure interaction with the patient and good system performance. The performance of the controllers is evaluated by frequency response analysis, where it can be verified that a suitable bandwidth was achieved. Experimental results obtained from the implementation of a variable impedance control strategy during walking are presented. The design of $\mathcal{H}_\infty$ controllers for robot-aided rehabilitation and their performance; as well as the design of the customized torsion spring are the main contributions of this paper.

This paper is organized as follows: Section 2 describes the design requirements; Section 3 presents in detail the mechanical design of the rotary SEA; Section 4 presents the torque and impedance controllers design; Section 5 presents the experimental results obtained from the active knee orthosis; Section 6 presents the conclusions.

## 2. Design requirements

The design requirements are based on body mass normalized data described in Kirtley (2006) for gait cycles. Considering that the maximum power exerted by the knee joint is 0.739 W/kg, with a maximum torque of 0.365 N m/kg, and that the active knee orthosis should be able to supply 60% of the peak torque from the gait pattern of a healthy person with approximately 70 kg, the new robotic device must provide a torque assistance up to 15 N m. The minimum torque bandwidth is determined by the Power Spectral Density (PSD) of knee joint torque. Regarding that more than 95% of the PSD of knee joint torque is in the frequency range between 0 and 5 Hz a minimum bandwidth of 5 Hz is defined as a requirement to torque control.

The elastic element must be carefully designed, since it is the most important component in the SEA. The spring constant is defined through selection procedures described in Robinson (2000). Basically, they define lower and upper bounds for spring constant based on desired large torque bandwidth and low output impedance, respectively. First, consider the simplified model of Fig. 1 which includes the equivalent inertia, $J_{eq}$, and damping, $B_{eq}$. At this point, these values consider only the inertia and damping of the motor seen through the transmission (the complete values of $J_{eq}$ and $B_{eq}$ are defined in (10) and (11), respectively). The torque applied to the load at the frequency domain, $\tau_l(s)$, is found as

$$\tau_l(s) = \frac{k_s}{J_{eq}s^2 + B_{eq}s + k_s}\tau_m(s) - \frac{k_s(J_{eq}s^2 + B_{eq}s)}{J_{eq}s^2 + B_{eq}s + k_s}\theta_l(s), \tag{1}$$

where $\tau_m$ is the torque generated by the motor, $\theta_l$ is the load position, and $k_s$ is the spring constant.

The ability of the actuator to produce large torques is limited in frequency by the maximum torque which the motor can generate. To define the large torque bandwidth, the load position is considered fixed and the torque from the motor is set to its maximum value $\tau_{max}$ (maximum continuous torque from motor datasheet). Hence, the transfer function from $\tau_{max}$ to the maximum output torque, $\tau_{l_{max}}$, is given by

$$\frac{\tau_{l_{max}}(s)}{\tau_{max}(s)} = \frac{k_s}{J_{eq}s^2 + B_{eq}s + k_s}. \tag{2}$$

The saturation frequency, i.e., the frequency at which the above system begin to fall off, is defined from (2) as

$$\omega_0 = \sqrt{\frac{k_s}{J_{eq}}}. \tag{3}$$

Therefore, the higher the spring constant, the greater the large torque bandwidth. Eq. (3) is used to define the lower bound for the spring constant. Fig. 2(a) shows the frequency responses for (2) considering three values of spring constant (100 N m/rad, 200 N m/rad, and 300 N m/rad) and the parameters of the selected motor.

To analyze the output impedance, a simple proportional controller is defined ( $\tau_m = K_p(\tau_d - \tau_l)$). Assuming a constant desired output torque ( $\tau_d = \tau_0$), the output impedance is given by

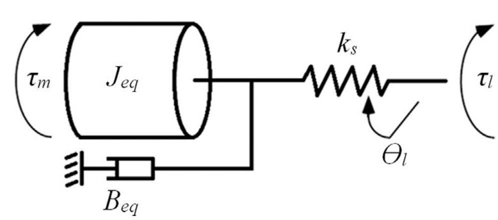


**Fig. 1.** Schematic of rotary Series Elastic Actuator.

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