Torque Control Characterization of a Rotary Series Elastic Actuator for Knee Rehabilitation

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***Abstract*—This paper presents the evaluation of a rotary Series Elastic Actuator (SEA) designed to assist in flexion/extension of the knee joint during physical therapy. The proposed device includes a DC motor, a worm gear and a customized torsion spring. Since the elastic element is the most important component in the SEA design, an analysis procedure based on Finite Element Method (FEM) is used in order to meet the specific requirements of knee assistance. With a total weight of 2.53 kg, it is possible to directly mount the actuator on a knee orthosis frame. Torque controller is implemented to ensure secure interaction with the patient and enable new strategies for rehabilitation. The design specifications as well as the controllers performance are verified by experiments.**

I. INTRODUCTION

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 of muscle movement, and the ability to absorb impacts. It is also essential to ensure a backdrivable behavior, characterized by a low mechanical impedance. Conventional actuators do not meet these critical requirements. A simple and effective solution, initially proposed by [1], was the 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 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.

Series Elastic Actuators are able to provide large torque and allow the implementation of torque and impedance control [2], which can be used as a rehabilitation strategy to adjust the level of interaction between device and patient [3], [4]. For example, support torque can be provided by the SEA (properly attached to an orthosis) only when needed during gait training. During the rest of the gait, the SEA should take a low impedance behavior, so that the orthosis is fully complacent with the patient's actions.

A rotary SEA to assist the movement of the lower limbs was presented in [5]. It consists of a geared DC motor, a conventional spring torsion 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 supporting large torques. Conventional springs able to support large torques are very stiff ones. However, stiff springs deteriorate compliance of the control system, making it difficult to obtain an accurate torque control. Moreover, their nonlinearities are not negligible. Taking into account these considerations, a new rotary SEA model was proposed by the same authors in [6]. In this new configuration, the spring is inserted between the worm gear and the output gears, thereby enabling the use of a spring with lower stiffness. The disadvantage of this configuration is that the nonlinearities associated with the output gears compromises the fidelity of measured torque, increasing the uncertainties in the system.

A solution adopted by some researchers is to propose a given arrangement of linear springs so as to obtain a torsion elastic element [7], [8]. This approach allows the insertion of elastic elements with low stiffness directly between the gear-motor and 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 [9], [10]. In addition to allowing the elastic element to be connected to the load in a direct-drive configuration, this approach can help to overcome some problems like residual deflection, hysteresis and a non-linear behavior in the torque versus angle relationship, that can compromise accurate torque estimation and consequently control performance.

Regarding these concept options, a new rotary SEA is presented in this paper where a customized torsion spring is proposed. The torsion spring is obtained through simulation based on Finite Element Method (FEM) and an optimization procedure is conducted to satisfy the specific requirements of knee assistance. Torque controller is implemented to ensure safe interaction with the patient and enable new strategies for rehabilitation.

This paper is organized as follows: Section II describes the design requirements; Section III presents in details the mechanical design of the SEA and the customized torsion spring optimization; Section IV presents the results of the implementation of torque controller and Section V presents the discussions and conclusions.

II. DESIGN REQUIREMENTS

The design requirements were based on gait pattern data described in [11]. Considering that the maximum power exerted by the knee joint is 0.739 W/kg, with a maximum torque of 0.365 Nm/kg, and that active knee orthosis should be able to supply 60% of the peak torque from the gait pattern of

978-1-4799-2722-7/13/$31.00 ©

a healthy person with approximately 70 kg, the new robotic device must provide a torque assistance up to than 15 Nm. The minimum torque bandwidth was 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 is the most important component in the design of a SEA, therefore it must be carefully designed. The elastic constant is defined considering the minimum torque bandwidth taking into account that low impedance and stiction are desired. According to [12] the higher the spring constant value, the greater the torque bandwidth. However, low impedance and stiction need that the spring constant be as low as possible. The spring constant values for assist movement of the knee joint usually lies in the range from 100 to 300 Nm/rad, [3]. A stiffness of 200 Nm/rad is defined as target value for the design. This was achieved through theoretical analysis considering the desired torque bandwidth, following the procedures described in [13].

III. MECHANICAL DESIGN

The mechanical design was conceived in order to obtain a compact and lightweight architecture. All housing parts were made of aluminum for the purpose of reduced weight. The final assembly of the rotary SEA consists of a) Maxon Motor RE 40, graphite brushes, 150 Watt DC motor, b) worm gear set (M1-150 of HPC Gears International Ltd.) with reduction ratio of 150:1, c) customized torsion spring, d) angular contact bearings, e) magneto-resistant incremental encoder, and f) opto-electronic incremental encoder. The overall dimensions are shown in Fig.1 and the resulting mass is 2.53 kg, allowing direct mounting of the actuator on the frame of a knee orthosis.

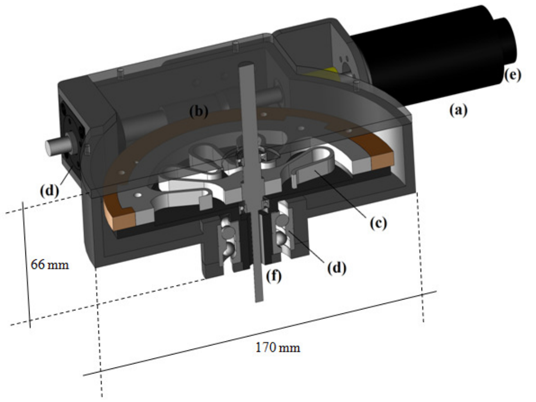

Fig. 1. Cross section of the rotary SEA showing drivetrain components

The choice of gear-motor was made based on the characteristics of the knee joint considering of gait pattern of a healthy person. The angular velocities of the knee joint are in the range of +/- 50 rpm and the maximum torque required for the project is 15 Nm (see Section II), while the maximum continuous torque and the maximum speed of the selected motor are respectively 0.181 Nm and 8200 rpm. Therefore a worm gear set with reduction ratio of 150:1 is used to adjust the operating range of motor in order to fulfill the requirements for velocity and torque. Thereby the worm gear output can operate in a velocities range of +/- 55 rpm and, if the efficiency of the gears is not considered, can provide a maximum continuous torque of 27.15 Nm. However, the friction between the gear significantly reduces the efficiency and the torque amplification ratio is not necessarily the same as the ratio speed reduction, [6]. For this reason, a safety factor of 1.8 to the torque requirement is considered.

All relevant information to the control system, i.e. motor rotation, actuator output, and spring deflection estimate, are obtained by two encoders. A magneto-resistant incremental encoder Maxon with a resolution of 4096 pulses per revolution in quadrature decoding mode is used to measure the motor rotation and allows to estimate the position of the worm wheel and a opto-electronic incremental encoder Maxon HEDS 5540 with a resolution of 2000 pulses per revolution in quadrature decoding mode is used to measure the actuator output. The spring deflection estimate is obtained by the difference between the position of the worm wheel and the actuator output. The theoretical output torque resolution is given by $k_s(2\pi/2000)$, where k_s is the spring constant.

A. *Customized torsion spring*

To meet the requirements of the proposed application the elastic element should be compact, lightweight, and able to withstand high torque with low intrinsic stiffness. However, these characteristics are not found in commercially available torsion springs. For this reason, a new topology torsion spring was developed. Figure 2 shows schematic perspective view of the torsion spring. It is composed of two rings interconnected by flexible elements defined by finite element analysis. The material selected for analysis and fabrication was chromium-vanadium steel (AISI 6150), with a Young's modulus of 205 GPa and a yield strength of approximately 1320 MPa after a heat treatment process.

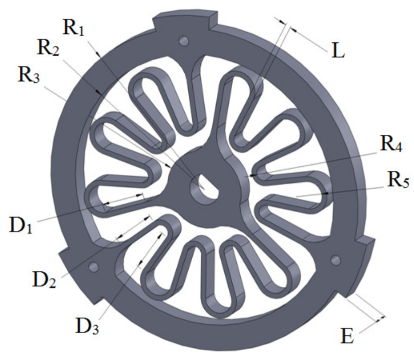

Fig. 2. Schematic perspective view of the customized torsion spring

The stress distribution and deformation of spring was analyzed by the FEM using ANSYS® software, to ensure that the maximum stress is less than the yield stress of the material when subjected to the maximum torque. The analysis consisted in fixing the inner ring of the spring while tangential forces equivalent to torque were applied on the outer ring. The stiffness is calculated by the ratio between the torque applied and the corresponding angular deformation obtained in the simulation. In the first analysis it was observed that the stress concentration is located in the inner corner radius, R_4, Fig. 3.

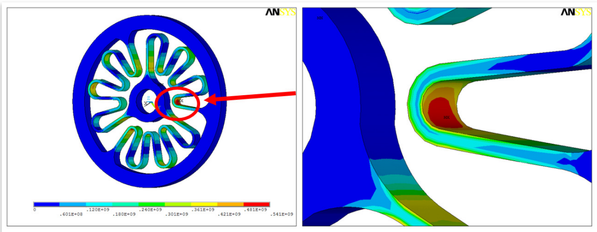

Fig. 3. Static simulation for stress distribution

In order to find the lowest stress value for a given stiffness, the following methodology based on a finite element analysis was adopted. The value of radius R_4 was varied from 2.5 to 3.5 mm with a step of 0.05 mm for each thickness (E) from 5 to 8 mm with a step of 0.5 mm. The values of D_1, D_2 and D_3 were varied proportionally to the R_4 whereas the values of R_1, R_2, R_3, R_5 and L were kept constant in order to not change of the proposed topology. Figures 4 and 5 shows the results of the methodology adopted. Analyzing Figure 4 we note that a linear approximation can be used to characterize the directly proportional relationship between spring geometry parameters (R_4 and E) and spring constant. When analyzing the Fig. 5 a similar behavior is observed between the geometric parameter R_4 and von Mises stress, however, in an inversely proportional way. It can also be observed that the inversely proportional relationship between geometry parameter E and Von Mises stress is characterized by an exponential function.

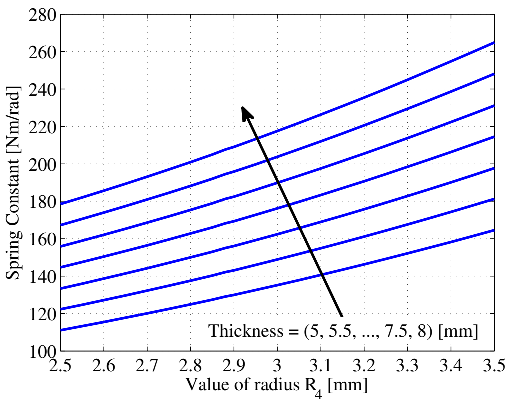

Fig. 4. Geometry parameters vs. spring constant

The geometry parameter values of the torsion spring that had lower stress for the desired stiffness of 200 Nm/rad are shown in Tab. I. The maximum von Mises stress obtained by simulation is 541 Mpa. Thus a safety factor of 2.4 is considered.

TABLE I. CUSTOMIZED TORSION SPRING PARAMETERS (MM)

D_1	D_2	D_3	E	L	R_1	R_2	R_3	R_4	R_5
17.60	17.05	17.15	8	2	62.5	52.5	15	2.8	5.3

The customized torsion spring, shown in Fig. 6, has been manufactured using the Wire Electrical Discharge Machining

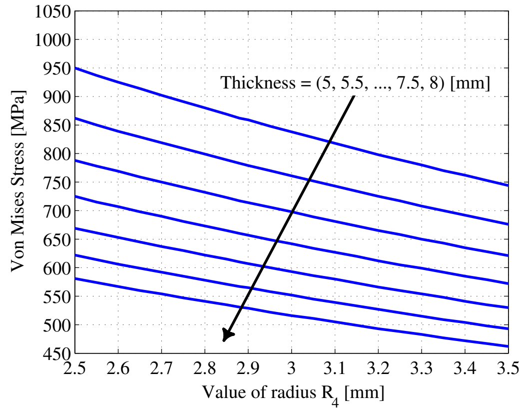

Fig. 5. Geometry parameters vs. Von Mises stress

(WEDM) process. The mass of the spring is 0.384 kg with a thickness of 8 mm and maximum diameter of 125 mm.

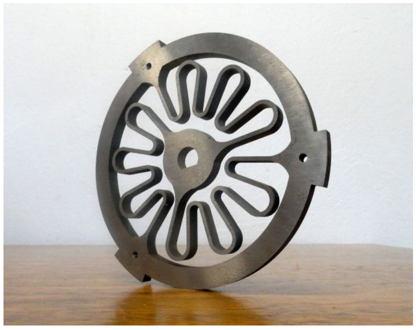

Fig. 6. Customized torsion spring

Experimental characterization of the spring stiffness was performed by coupling on the output shaft of the SEA in a torque sensor (Gamma SI-65-5 from ATI Industrial Automation, Inc.). The SEA was programmed to follow a position profile consisting of a sequence of steps (amplitude 0.14 deg, duration 10 sec) in both loading and unloading conditions, while the torque was measured by the sensor. Figure 7 shows the obtained results.

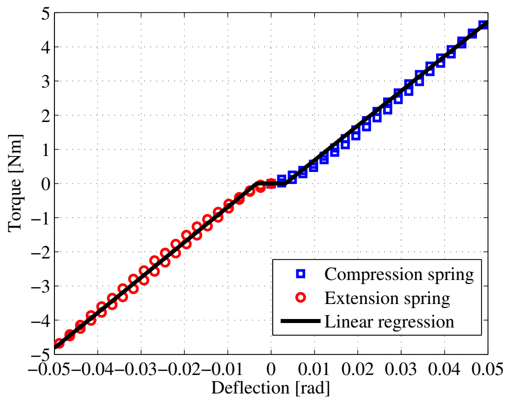

Fig. 7. Characterization of the customized torsion spring

It is possible to observe a non-negligible backlash with an amplitude of approximately 0.0088 rad occasioned by intrinsic feature of the worm gear set. A linear regression was performed in both directions (compression and extension). When the spring is compressed (positive deflection), the stiffness is equal to 106 Nm/rad, when it is extended (negative deflection), the stiffness is equal to 103 Nm/rad. The value of the spring constant determined experimentally is approximately 50 % lower than the obtained by finite element analysis. This discrepancy is probably due to the actual properties of the material being different from the nominal used in the simulation. The final assembly of the rotary SEA and a preliminary setup of a knee orthosis with the rotary SEA attached to it are shown in Figs. 8 and 9, respectively.

Fig. 8. Rotary Series Elastic Actuator

Fig. 9. Rotary SEA attached to a knee orthosis

IV. TORQUE CONTROL

The control hardware consists of a EPOS 24/5 Positioning Controller manufactured by Maxon Motor and an ordinary computer hardware equipped with a CAN communication card manufactured by National Instruments. The EPOS is a full digital smart motion controller capable of operating in position, velocity and current modes. The device also is responsible to decode the signals from quadrature encoders. The communication interface between the computer hardware and the EPOS controller is performed by CANopen communication protocol. The frequency of the control-loop is set at 200 Hz.

In traditionally adopted approach for SEA torque control, the motor is treated as a torque source. This assumption is justified since the current supplied to the motor is directly proportional to the torque. However, this approach becomes difficult to implement due to the nonlinearities intrinsic to the drivetrain such as static and dynamic friction. In [13] it is suggested to treat the motor as a velocity source rather than as a torque source. According to [14] this approach helps to overcome some undesirable effects of the gear-motor.

The block diagram of the torque control loop is illustrated in Fig. 10. The inner velocity loop was performed by the built-in EPOS velocity control and the controller parameters were automatically determined by the device. The torque controller was implemented through the programming interface Microsoft Visual Studio in the computer hardware and metrics considered to measure the performances of the controller, as described in sequence.

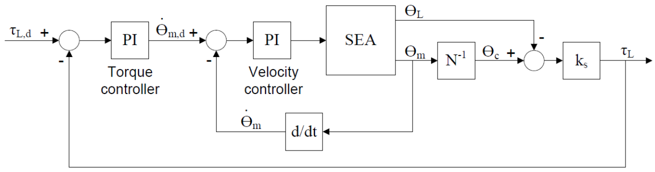

Fig. 10. Torque controller with inner velocity loop

A. Experimental characterization

The performance characteristics of the torque control system were first specified in terms of the transient response for a step input. The gains of the PI controller were defined in order to obtain faster responses with lower overshoots. Thus, the parameters of the controller were empirically adjusted to have an overshoot lower than 10% of the setpoint and a rise time lower than 0.100 s. The step response was obtained by blocking the output shaft of the SEA. This configuration implies in θ_L = 0, so the measured torque is given only as a function of the worm wheel position i.e. $\tau_L = k_s \theta_c$.

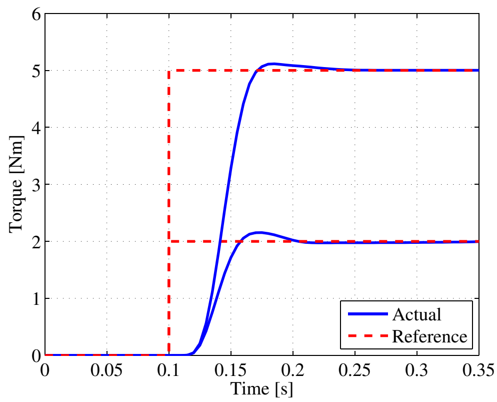

Fig. 11. Response of the system for step inputs

The responses of the system to a step input with different amplitudes (2 and 5 Nm) are show in Fig. 11. The rise time for the reference input with amplitude of 2 Nm is approximately 0.058 s while for input amplitude of 5 Nm is 0.071 s which shows a nonlinear behavior due to motor velocity saturation. The system responds with an overshoot lower than 9 % of the setpoint for all the inputs. There were no significant differences between the positive reference step input and the negative reference step input. As a preliminary validation, the SEA was commanded to track a typical knee torque profile (20 % of the knee joint torque), for a gait cycle duration of 4.4 s, with the output shaft blocked, Fig. 12.

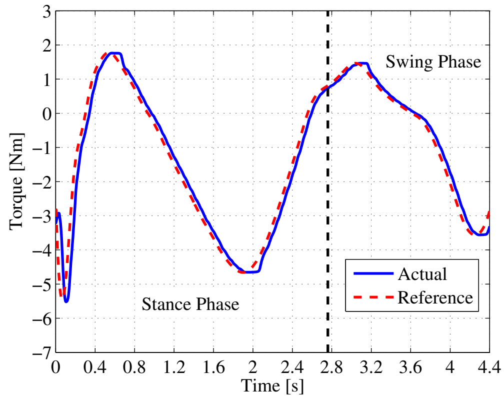

Fig. 12. Tracking of a typical knee torque profile

Torque control bandwidth of the SEA was evaluated through the frequency response function (FRF) analysis proposed in [15]. To implement the estimation method, the desired torque ($\tau_{L,d}$), seen here as input signal, was defined as a chirp signal with amplitude of 5 Nm and frequency varying from 0 to 20 Hz. Figure 13 shows the Bode plot of the closed loop transfer function computed from $H_1(\omega)$ and $H_2(\omega)$ estimators. The $H_1(\omega)$ estimator is the ratio of the input to output cross spectrum over the input power spectrum; the $H_2(\omega)$ estimator is the ratio of output power spectrum over the cross spectrum from output to input. Figure 13 also shows the coherence function $C(\omega)$, the ratio of the $H_1(\omega)$ estimator over the $H_2(\omega)$ estimator. A coherence function value near to 1 represents a good estimate of both estimators at that frequency range. From the bode plot, the torque control bandwidth of the proposed SEA is approximately 9.4 Hz, about 90% higher than the value set in the design requirements.

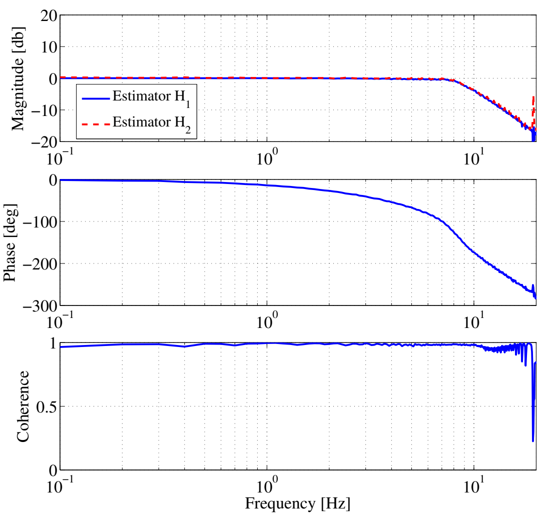

Fig. 13. Toque control response frequency

V. Conclusions

This paper presented the design of a rotary Series Elastic Actuator (SEA) to be used in an active orthosis to assist in flexion/extension of the knee joint during physical therapy. A customized torsion spring is designed through simulation based on finite element method with the aim of fulfilling a set of requirements defined in terms of admissible peak load, low stiffness and a compact and lightweight design. The value of the spring constant determined experimentally is significantly lower than obtained by finite element analysis. This discrepancy is probably due to the actual properties of the material being different from the nominal used in the simulation and the imperfections in the model and mesh used in the analysis. The resulting mass of the SEA is 2.53 kg, thus allowing direct mounting of the actuator on the frame of a knee orthosis. Torque controller is implemented to ensure secure interaction with the patient, enabling new strategies for rehabilitation. The performance characteristics of the torque control system were specified in terms of the transient response for a step input and from bode graphics. The overshoot and response time are acceptable for the specified application.

VI. Acknowledgements

This work was supported by São Paulo Research Foundation (FAPESP) under grant n^o 2011/04074-3.

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