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A NEW ROTARY SERIES ELASTIC ACTUATOR TO ASSIST IN FLEXION AND EXTENSION OF THE KNEE JOINT DURING PHYSICAL THERAPY

Wilian M. dos Santos
Glauco A. P. Caurin
Adriano A. G. Siqueira
University of São Paulo at São Carlos, Mechanical Engineering Department, Robotic Rehabilitation Laboratory, Mechatronics Group, Av. Trabalhador São-carlense, 400 - São Carlos, SP, Brazil
Center for Robotics of São Carlos and Center for Advanced Studies in Rehabilitation, University of São Paulo, SP, Brazil
http://www.crob.usp.br/, http://www.fm.usp.br/nap_near/
wilianmds@sc.usp.br; gcaurin@sc.usp.br; siqueira@sc.usp.br

Abstract. *Wearable robots, like prostheses, active orthosis and exoskeletons need of actuators able to meet certain requirements as low output impedance, backdrivability, precise and large torque generation, and a compact and lightweight design. This paper presents 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. The device includes a DC motor, a worm gear and a customized torsion spring. Since the elastic element is the most important component in the design of the SEA, an analysis procedure based on Finite Element Method (FEM) is used in order to meet the requirements for the specific application. With a total weight of 2.53 kg, it is possible to directly mount the actuator on the frame of a knee orthosis. 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.*

Keywords: *series elastic actuator, rehabilitation robotics, robotic orthosis and interactive robots.*

1. INTRODUCTION

This paper presents a new rotary SEA designed to be used in an active orthosis to assist in flexion/extension of the knee joint during physical therapy. To effectively assist human motions and at the same time ensuring patient safety, the device must satisfy certain requirements such as ability to absorb impacts, precise and large torque generation with a bandwidth that approximates of muscle movement and to be able to assume a characteristic of backdriveability in other to achieve a very low mechanical impedance comparable to humans required to move smoothly and quickly the point of contact in compliance with the patient's actions. Conventional actuators do not meet these requirements that are critical to such applications. A simple and effective solution initially proposed by Pratt and Williamson (1995) are the Series Elastic Actuators (SEAs) where elasticity is intentionally introduced in series between a gear-motor and the load. This configuration allows to decouple 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 by multiplying the measured spring deflection by the spring constant.

The SEAs are able to provide large torque and allows the implementation of impedance control (Hogan (1985)) which can be used as a rehabilitation strategy to adjust the level of interaction between the device and the patient. For example, if we want a active orthosis provide support torque only when needed then during the rest of the time 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 Kong *et al.* (2009). This consists of a geared DC motor, a spring torsion conventional and two rotary potentiometers used to detect the position of the output shaft and the deformation of the spring. In this configuration presented the spring was directly installed between gear-motor and the human joint therefore it must support large torque. Conventional springs that support large torque are also very stiff for given application. The very stiff spring deteriorates compliance of the control system making it difficult to obtain an accurate torque control. Moreover, the nonlinearities of a very stiff spring are not negligible. From these considerations a new rotary SEA model was proposed by the same authors in Kong *et al.* (2010). In this new configuration, the spring is inserted between the worm gear and the output gears, thereby enabling the use of a spring with a low stiffness. The disadvantage of this configuration is that the nonlinearities associated to output gears compromises the fidelity of measured torque resulting uncertainties in the system.

A solution adopted by some researchers is the conception arrangement of linear springs so as to obtain a torsion elastic element, (Yoon *et al.* (2003); Tsagarakis *et al.* (2009)). This approach allows insert an elastic element 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 this way. Another solution is the development of custom elastic element, (Lagoda *et al.* (2010); Carpino *et al.* (2012)). In addition to allowing the elastic element 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

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angle relationship, that can compromise the accurate torque estimation and consequently control performance.

Starting from these considerations a new rotary SEA for knee joint assist is presented in this paper. The device consists of a DC motor, a worm gear set and a customized torsion spring obtained through simulation based on finite element method. Torque controller is implemented to ensure secure interaction with the patient and enable new strategies for rehabilitation.

This paper is organized as follows: Section 2. describes the design requirements; Section 3. presents in detail the mechanical design; Section 4. presents the results of the implementation of torque controller and Section 5. presents the discussions and conclusions.

2. DESIGN REQUIREMENTS

The design requirements were based on gait data defined in Kirtley (2006). Considering that the maximum power exerted by the knee joint is approximately 0,739 W/kg, with a maximum torque of 0,365 Nm/kg, and that active knee orthosis should be able to supply 30 % 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 not less than 15 Nm. The minimum large torque bandwidth was determined by the Power Spectral Density (PSD) of knee joint torque. Account that more than 95 % of the PSD of knee joint torque is in the frequency range between 0 and 5 Hz a minimum bandwith 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 large torque bandwidth taking into account that low impedance and stiction are desired. According to Robinson *et al.* (1999) the higher the spring constant value the greater the large torque bandwidth however low impedance and stiction need that the spring constant is 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, Sergi *et al.* (2012). A stiffness of 200 Nm/rad is defined as target value for the design. This was achieved through the theoretical analysis considering the desired large torque bandwidth, Robinson (2000).

The minimum impedance must assume values as low as possible so that contact force is minimal when no torque is requested. Thus the measured torque resolution should be below 0.6 Nm. The actuator dimensions and weight must be reduced allowing assembly directly in the frame of a wearable orthosis for knee.

3. MECHANICAL DESIGN

The mechanical design was conceived in order to obtain a compact and lightweight architecture. All housing parts were made of aluminium for the purpose of reduce 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) custom 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.

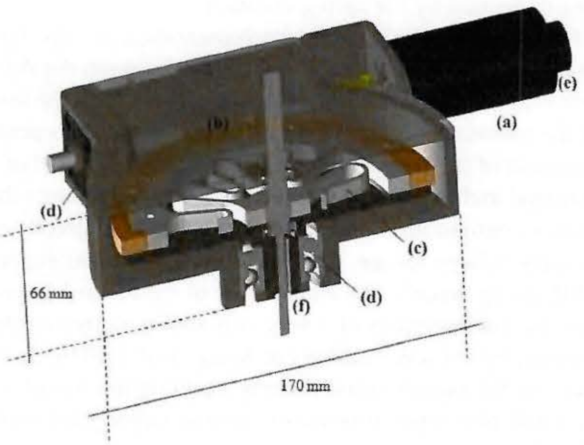

Figure 1. Cross section of the rotary SEA showing drivetrain components

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 2.), 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

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adjust the operating range of motor order to fulfill the requirements for velocity and torque. Thereby the SEA can operate in a velocities range of +/- 55 rpm and if the efficiency of the gears is not considered this 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, Kong *et al.* (2010). For this reason, a safety factor of 1.81 to the torque requirement is considered.

All information relevant to the control system, i.e. motor rotation, actuator output, and spring deflection estimate, are obtained by two encoders. A magneto-resistant incremental encoder 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 with a resolution of 2000 pulses per revolution in quadrature decoding mode is used to mesure 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.

3.1 Custom 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, this characteristics are not found in commercially available torsion springs. For this reason, a new topology torsion spring was developed. In Figure 2 is shown schematic perspective view of the torsion spring. This 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), which has a Young's modulus of 205 GPa and a yield strength of approximately 1320 MPa after a heat treatment process.

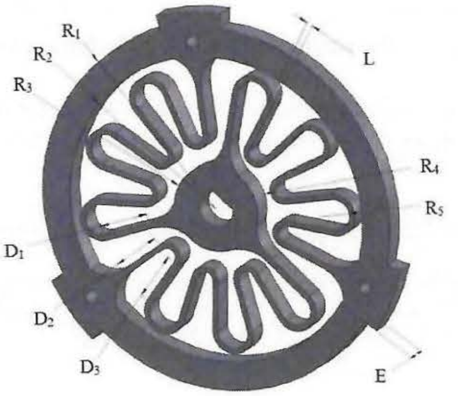

Figure 2. Schematic perspective view of the custom torsion spring

The stress distribution and deformation of spring was analyzed by the FEM using ANSYS® software, to assure 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.

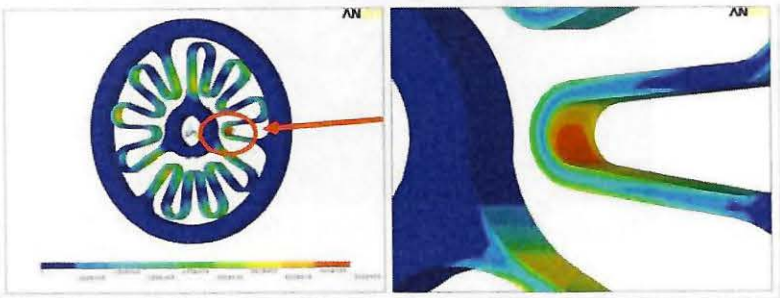

Figure 3. The static simulation for the stress distribution

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 2.5 to 3.5 mm with a step of 0.05 mm for each thickness of 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

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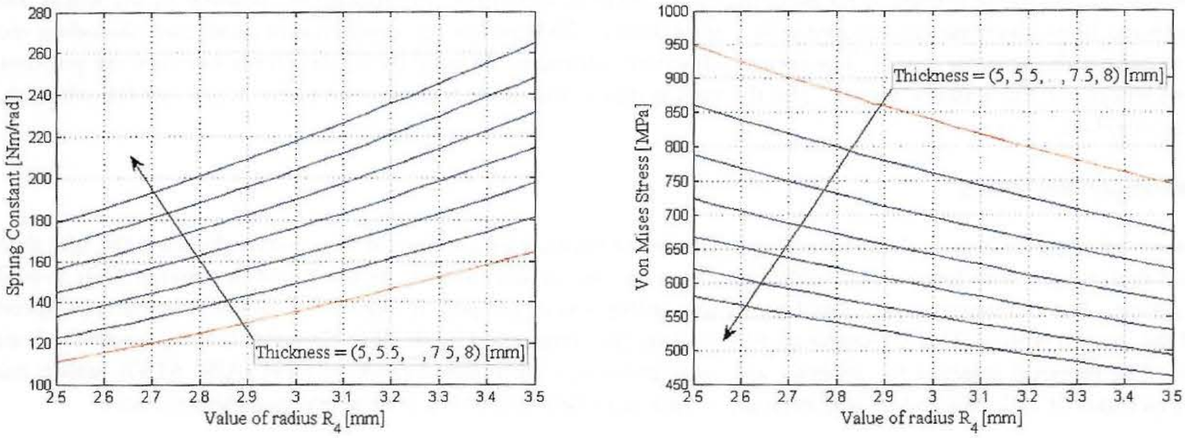
of R_1, R_2, R_3, R_5 and L were kept constant in order not to change of the proposed topology. Figure 4 shows the results of the methodology adopted. Analyzing Figure 4(a) we note that a linear approximation can be used to characterize the relationship directly proportional between spring geometry parameters (R_4 and E) and spring constant. When analyzing the Fig. 4(b) a similar behavior is observed between the geometric parameter R_4 and von Mises stress, however, in a way inversely proportional. It can also be observed that the relationship inversely proportional between geometry parameter E and Von Mises stress is characterized by an exponential function.



(a) Geometry parameters vs. spring constant

(b) Geometry parameters vs. Von Mises stress

Figure 4. Results of the simulation based on the finite element analysis

The geometry parameter values of the torsion spring that had lower stress for the desired stiffness of 200 Nm/rad are shown in Tab. 1. The maximum von Mises stress obtained by simulation is 541 Mpa. Thus a safety factor of 2.44 is considered.

Table 1. Geometry parameter values of the custom torsion spring

Parameter [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 custom torsion spring, shown in Fig. 5, has been manufactured using the Wire Electrical Discharge Machining (WEDM) process. The mass of the spring is 0.384 kg with a thickness of 8 mm and maximum diameter of 125 mm.

Figure 5. Picture of the custom 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 6 shows the analysis of the results obtained.

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 spring (compression and

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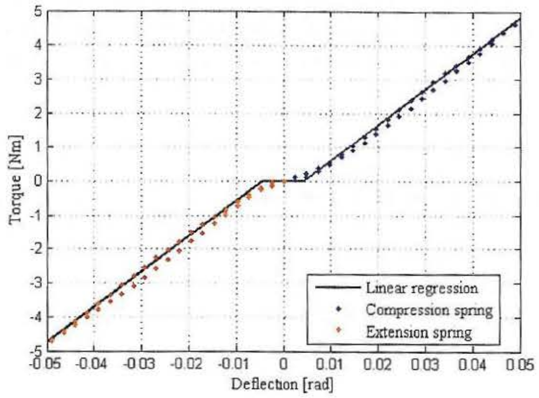

Figure 6. Characterization of the custom torsion spring

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.

Detailed pictures of the final assembly of the rotary SEA are shown in Fig. 7.

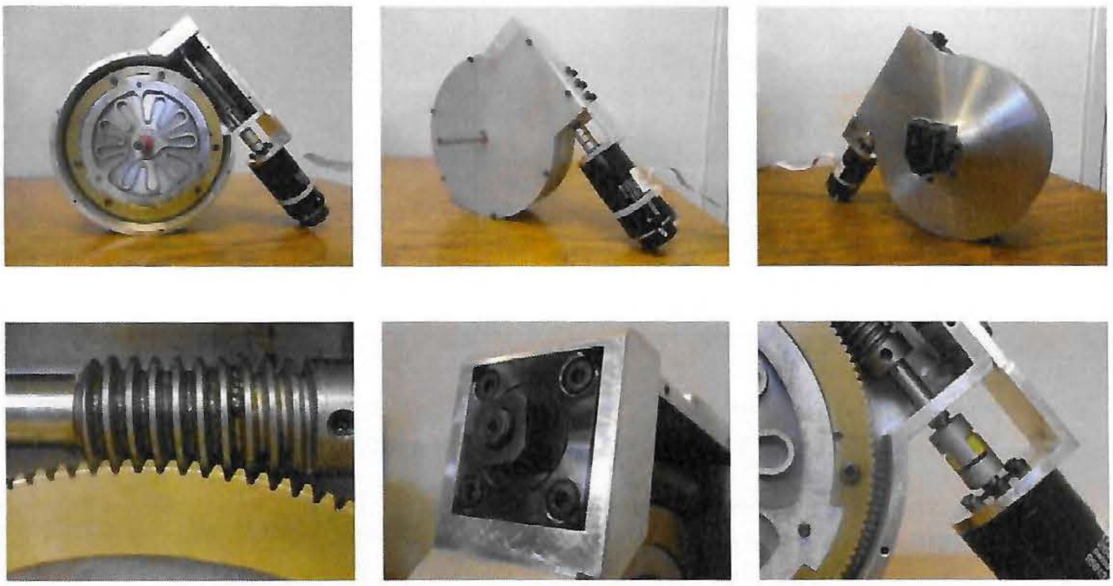

Figure 7. Pictures of the rotary Series Elastic Actuator

4. TORQUE CONTROL

The control hardware consists of a EPOS 24/5 Positioning Controller manufactured by Maxon Motor and 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 torque controller have been implemented through the algorithm, written in C language, in computer hardware. 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 Robinson (2000) is suggested to treat the motor as a velocity source rather than as a torque source. According to Wyeth (2006) this approach helps to overcome some undesirable effects of the gear-motor.

The block diagram of the torque control loop is illustrated in Fig. 8. The inner velocity loop was performed by the

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integrated velocity control of the EPOS and the controller parameters were determined automatically by the device. The torque controller was implemented through the programming interface Microsoft Visual Studio in computer hardware and metrics considered to measure the performances of the controller, as described in sequence.

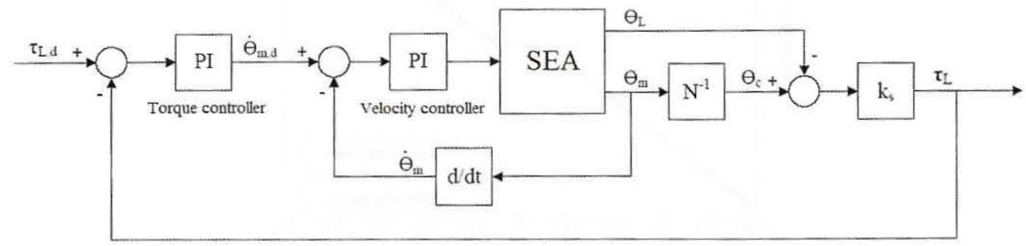
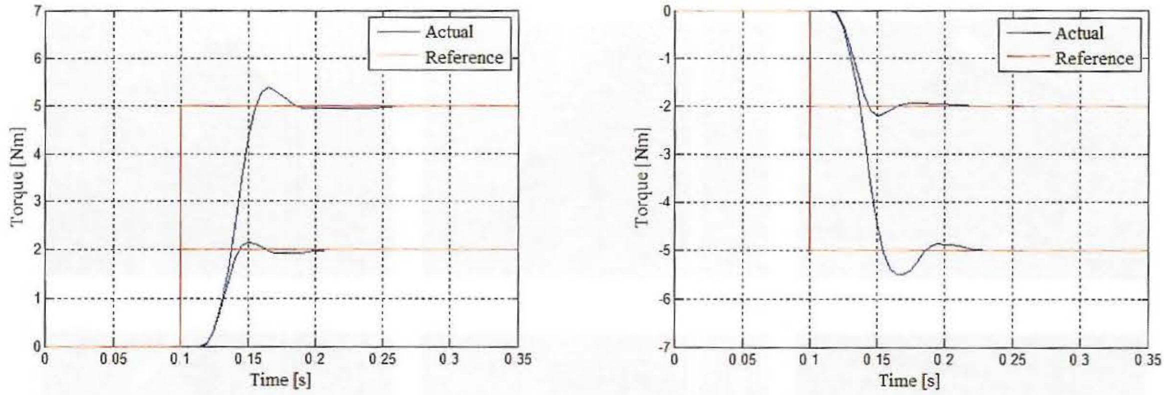


Figure 8. Torque controller with inner velocity loop

The performance characteristics of the torque control system were 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 0.060 s. The step response was obtained by blocking the output shaft of the SEA. This configuration implies in $\theta_L = 0$ soon the measured torque is given only as a function of the worm wheel position i.e. $\tau_L = k_s\theta_c$.



(a) Considering the positive reference step input

(b) Considering the negative reference step input

Figure 9. Response of the system for a step input

The response of the system to a step input with different amplitudes (+/-2 and +/-5 Nm) is show in Fig. 9. The rise time for the reference input with an amplitude of 2 Nm is approximately 0.045 s while for input amplitude of 5 Nm is approximately 0.055 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 input. There were no significant differences between the positive reference step input and the negative reference step input.

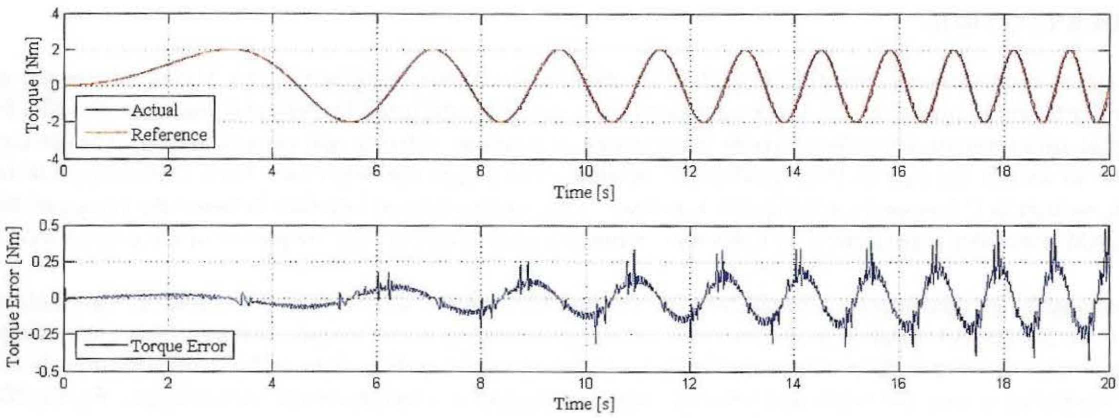


Figure 10. Desired and generated torques: the desired torque is a chirp signal

The SEA was commanded to track a torque profile consisting of a chirp function with constant amplitude of 2 Nm and frequency range of 0 to 1 Hz. Figure 10 shows the torque tracking accuracy. It may be noted that the error increases as the frequency increases. However, the error range is not significant since this is lower than the accuracy of the measured torque.

5. DISCUSSION AND 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 custom torsion spring is designed, through simulation based on finite element method, out 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 stiffness 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 and enable new strategies for rehabilitation. The performance characteristics of the torque control system were specified in terms of the transient response for a step input. The overshoot and response time are acceptable for the specified application. In future work will be performed to experimental characterization of the SEA, through the system identification techniques, to evaluate large torque bandwidth.

6. ACKNOWLEDGEMENTS

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