Efficient Lightweight Series Elastic Actuation for an Exoskeleton Joint

Shiqian Wang*, Cor Meijneke*, Arthur Ketels**, Herman van der Kooij*, ***
*Biomechanical Engineering Dept., Delft University of Technology (TU Delft), Mekelweg 2, 2628CD Delft, the Netherlands
shiqian.wang@tudelft.nl, C.Meijneke@tudelft.nl
**Speciaal Machinefabriek Ketels v.o.f., Bosscheweg 28, 5151BD Drunen, The Netherlands
arthur@smfk.nl
***Biomechatronics and Rehabilitation Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands
h.vanderkooij@utwente.nl

1 Introduction

Series elastic actuators (SEA) have been widely applied to bipedal robots and orthotic/ prosthetic devices since its first introduction to robotics world. Comparing to conventional 'stiff' actuation, SEA has the advantages in terms of low output impedance, high force fidelity, and energy storing capability [1, 3]. For portable rehabilitation devices such as exoskeletons, the demand on highly efficient and lightweight actuation imposes great challenge.

The purpose of this paper is to discuss the possible way of choosing components and optimizing the design for a series elastic actuator so that we can achieve a better design in terms of efficiency maximization and weight/size reduction.

2 Design requirements

This portable rehabilitation device is designed to support lower limb disabled patient to walk on level ground. We are targeting at a user group with maximal body weight 100kg, and a walking speed of 0.8 m/s. According to the previous gait study [4], the requirements on an exoskeleton joint is briefly listed out in Table I.

TABLE I. DESIGN REQUIREMENTS FOR AN EXOSKELETON KNEE JOINT

Range of motion*	1.5° extension, 120° flexion
Joint mass	<3 kg
Peak torque	100 Nm
Peak Power	150 W
Series spring stiffness	800Nm/rad
Small torque bandwith@2Nm	20 Hz
Large torque bandwidth@100Nm	4 Hz
Output torque resolution	1 Nm
Closed-loop control update frequency	1000Hz

*differs joint by joint. In this paper knee joint is used as an example.

3 Joint design and parameter optimization

All the component selections have two objectives: high efficiency and lightweight. The optimization of the overall drivetrain is not discussed here due to space limitation.

A. Motor selection

For motor selection, efficiency and torque density are the quantities of interest. Copper loss is the main loss in a brushless DC motor. Motor constant K_m is a figure of merit used to compare the relative efficiencies and output power capabilities of different motors, which defines the ability of the motor to transform electrical power to mechanical power. We use the mass-normalized motor constant as a measure to select the motor. We chose Hacker A60 7S V2 motor, with a motor constant 0.28 $Nm/\sqrt{W}$ and IND_{mtr} of 0.46 $Nm/\sqrt{W}/kg$. Comparing to other motors from e.g. Emoteq (high torque frameless series) or Moog, the selected motor is 1.5~7 times better in terms of this measure.

B. Transmission selection

High torque density, high efficiency, and good back drivability are our requirement on transmission. In wearable robots, harmonic drives are often used thanks to its relative high torque density and easy integration with rotary motors [5]. However harmonic drive suffers from low efficiency and poor backdrivability; similar story holds for lead screw, if no special development effort is implemented [3]; planetary gear is ruled out due to its low torque density. We've chosen ballscrew for its excellent torque density, high efficiency, and good backdrivability.

C. Spiral spring design

Spiral spring made from a single piece material is a continuation of the idea from A.H.A, Stienen [6] and C. Lagoda [2]. This new design aims to improve in torque density, connection backlash elimination, and stiffness estimation.

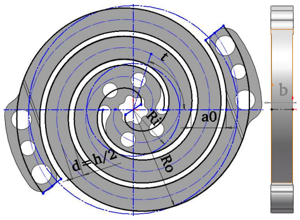

Figure 1: double spiral spring: R_i = root diameter; R_o= outer diameter; a_0 = space between coils of one spiral; h = spiral thickness; b=spring width; L (not shown) = spiral length; t = parametric angle (t=0 is the root, t = 2π is one revolution); n (not shown) = active spiral coils (revolutions, denoted as n_0 when no load is applied. here each spiral has n_0 = app.1)

A spiral spring contains two Archimedean spirals. The edges of the spiral spring are two curves equally offset a certain distance from the centerline. This double spiral spring was made from a single piece of high grade titanium for its low mass index ($\rho E/S_f^2$). The spring geometry is optimized to reduce mass. Given the design space we have, we fixed the parameters such as $R_i = 18.5mm$ and $R_o = 41.5mm$. We formulate the objective function as

$$\min\ f\left(b,h,a_0\right) = \rho bhL = \rho bh \frac{\pi\left(R_o^2 - R_i^2\right)}{h + a_0}$$

Subjected to constraints:

$$\begin{cases} n_0 = \left(R_o - R_i\right) / \left(h + a_0\right) \geq 1 \text{ active coil number } \geq 1 \\ \sigma_{\max} \leq S_f / C_{s,\sigma} \text{ max. stress below fatigue strength} \\ \theta_{\max} \leq \theta_{wound} / C_{s,touch} \text{ no touching at max. deflection} \\ K = K_d \text{ desired stiffness } K_d = 800\text{Nm/rad} \end{cases}$$

where $C_{s,\sigma}$ and $C_{s,touch}$ are safety factors.

We find the optimum when $b = 10.46\text{mm}, h = 9.12\text{mm}$, and $a_0 = 13.88\text{mm}$. Each of the spiral has active coil number $n_0 = 1$. The mass of the spring is about 220gram.

The stress and stiffness are checked using finite element analysis tool (Inventor 2011) and experimentally validated The measured stiffness is 820Nm/rad, with a prediction error less than 2.5%.

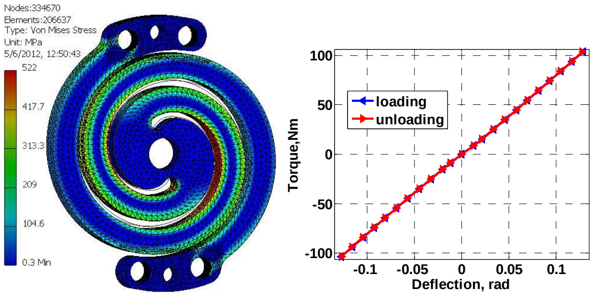

Figure 2: left: finite element analysis on the stress in the spiral spring; right: spring load-deflection curve.

4 Torque control and test results

Currently the controller implementation is similar to other series elastic actuators such as shown in [1, 2]. The major difference lies in the way of torque sensing (sensing spring deflection). Our design allows direct measurement of the spring deflection with one single encoder, eliminating the drawback (sensitive to backlash) of differential measurement using two encoders.

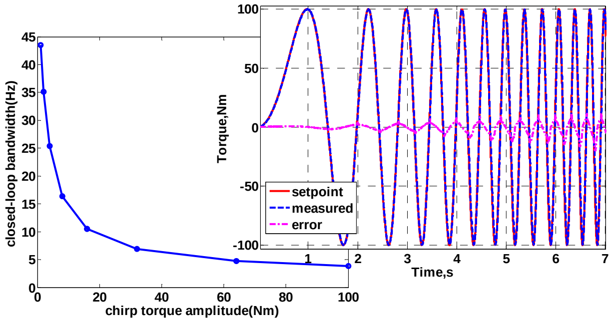

Figure 3: left: closed-loop bandwidth at different torque amplitudes; right: torque tracking. The bandwidth is related to gear ratio, in final exoskeleton joints, the gear ratio is lower, thus higher bandwidth

Figure 4: Assembled exoskeleton knee joint

5 Conclusion

We have built an exoskeleton joint prototype, capable of delivering 100 Nm peak torque, with its large torque bandwidth at 100Nm 4Hz. It weighs 2.9kg, and can be used for the actuation of exoskeleton knee and hip joints.

6 Acknowledgement

The research is supported by the EU FP7 grant no.:247959

7 Open Questions

1. Based on currently technology, what would be the minimal mass for an exoskeleton joint using SEA to support lower limb disabled patient to walk?
2. Most of the available exoskeletons don't have active hip rotation; as we all know hip rotation in human gait plays an important role as well, both from kinematic and energy point of view. Why are we ignoring it?
3. We have seen different exoskeletons and actuator being developed; shall we collect the effort and just make one fantastic exoskeleton together?

References

[1] G. A. Pratt and M. M. Williamson, "Series elastic actuators", IEEE Int. Conf. on Intelligent Robots and Systems, 1995.

[2] C. Lagoda, A. C. Schouten, A. H. A. Stienen, E. E. G. Hekman, H. van der Kooij, "Design of an electric series elastic actuated joint for robotic gait rehabilitation training", IEEE Int. Conf. on Biomedical Robotics and Biomechatronics, 2010.

[3] K.W., Hollander, R., Ilg, T.G., Sugar, D., Herring, "An efficient robotic tendon for gait assistance," J. of Biomechanical Engineering, Vol. 128 , 2006.

[4] S. Wang, W. van Dijk , H. van der Kooij, "Spring uses in exoskeleton actuation design," IEEE Int. Conf. on Rehabilitation Robotics, 2011.

[5] P. D. Neuhaus, J. H. Noorden, T.J. Craig, T. Torres, J. Kirschbaum, J.E. Pratt, "Design and evaluation of Mina: A robotic orthosis for paraplegics," IEEE Int. Conf. on Rehabilitation Robotics, 2011.

[6] A.H.A. Stienen, E.E.G. Hekman, H. ter Braak, A. M. M. Aalsma, F. C. T. van der Helm, H. van der Kooij, Design of a Rotational Hydroelastic Actuator for a Powered Exoskeleton for Upper Limb Rehabilitation, IEEE Transactions on Biomedical Engineering, vol. 57, 2010.