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Efficient lightweight series elastic actuation for an exoskeleton joint

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Introduction

Thanks to its low output impedance and excellent torque controllability, series elastic actuators (SEA) have been widely applied to bipedal robots and wearable robots such as orthotic/prosthetic devices, since its first introduction to robotics world [1]. For portable active wearable devices such as exoskeletons, the pursuit of highly efficient and lightweight actuation never stops.

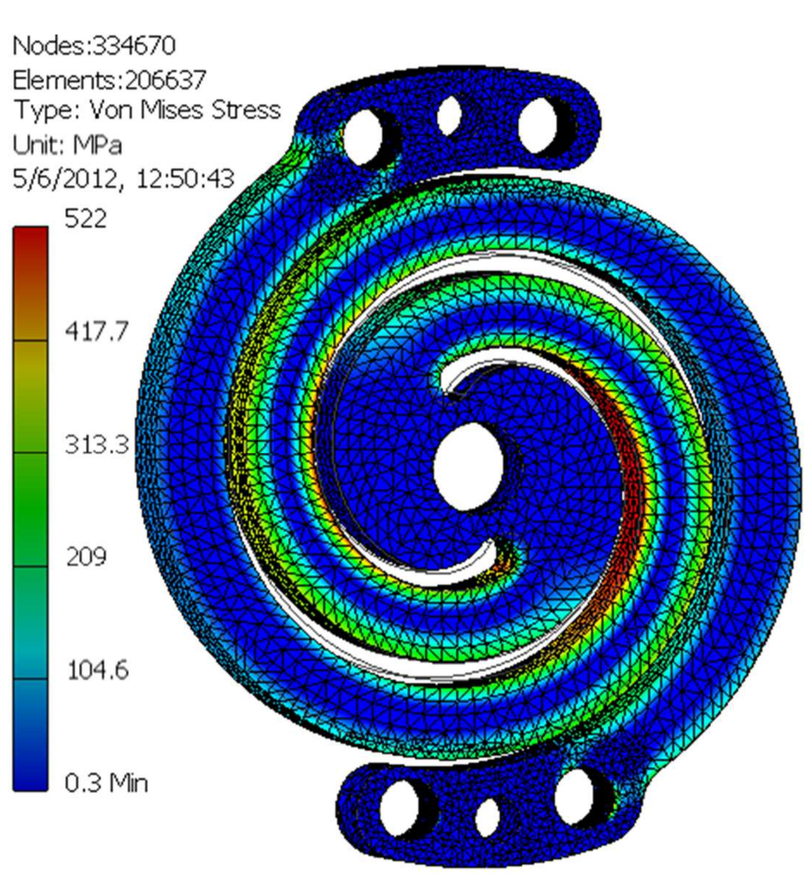
Actuation Design

To achieve high efficiency and low weight, the selection of each component in the drivetrain becomes very critical:

- The Hacker A60 motor we use is optimized for efficiency and torque density (see table below). Mass-normalized motor constant is proposed to be used for comparing motors.
- We use ballscrew as the reduction for its high torque density and efficiency (comparing to harmonic drive). Backdriveability enables regenerative braking and saves energy.
- DirectFET® MOSFET is used for its ultra low on-resistance (better efficiency) and low profile.
- To obtain lightweight series spring, we made a double spiral spring from a single piece of high grade titanium. The spiral spring was designed and optimized. The spring stiffness was predicted accurately (calculated to be 800Nm, measured 814~820Nm, less than 2.5% prediction error)

Table.1 Motor comparison using mass-normalized motor constant ($\text{IND}_{\text{mtr}} = K_m/M$, $K_m = K_T/\sqrt{R}$). Motor constant K_m determines the ability of a motor to transform electrical power to mechanical power.

Motor	Torque const K_T, Nm/A	Resistance R, Ω	Mass M, kg	IND_{mtr}, $Nm/\sqrt{W}/kg$
Moog BN23-23PM-03[1]	0.054	0.715	0.596	**0.11**
Emoteq HT03801 [2]	0.9	13.26	0.850	**0.29**
Hacker A60 8S V2	*0.044*	*0.026*	*0.595*	***0.46***



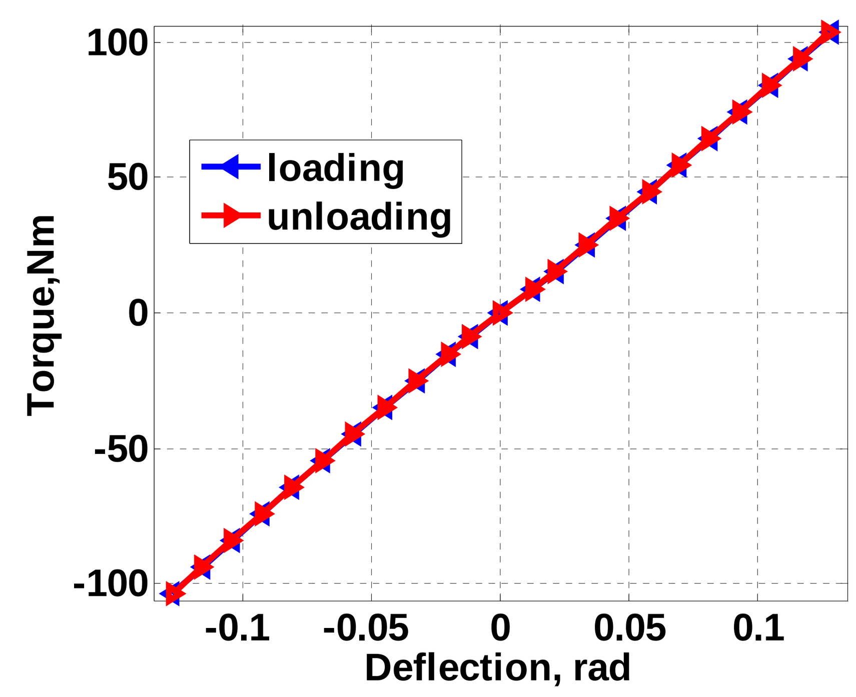


Fig.1 Left: finite element analysis results of the double spiral spring; right: spring stiffness validation

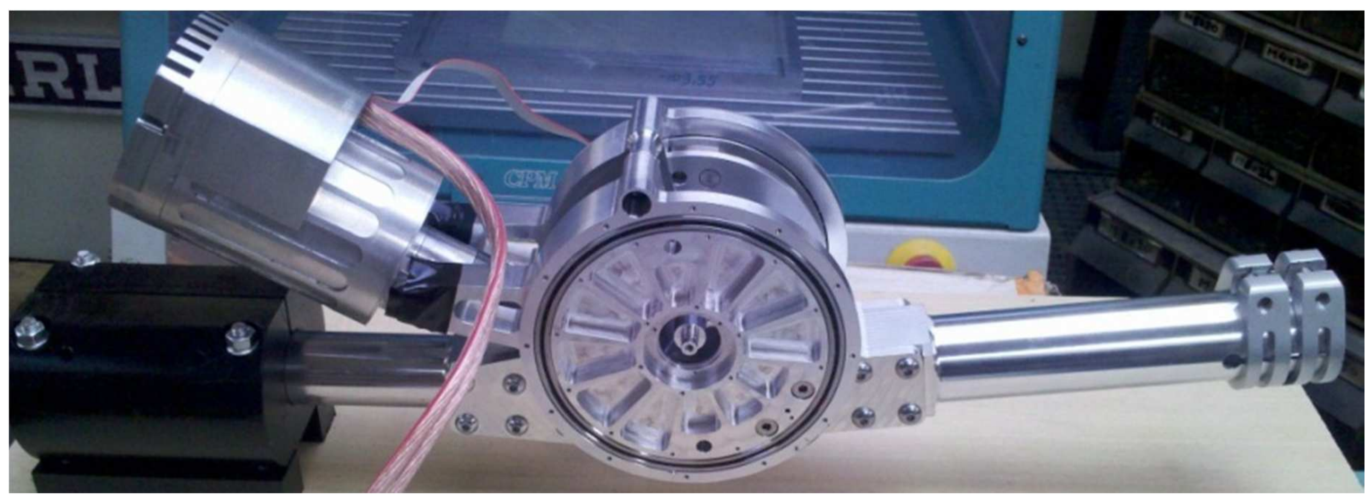


Fig.2 Exoskeleton knee joint: the joint (excluding the segment tubes) weighs 2.9kg; electronics responsible for low-level control and EtherCAT communication are contained inside the center of the joint; motor drive electronics are embedded inside the actuator.

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 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.

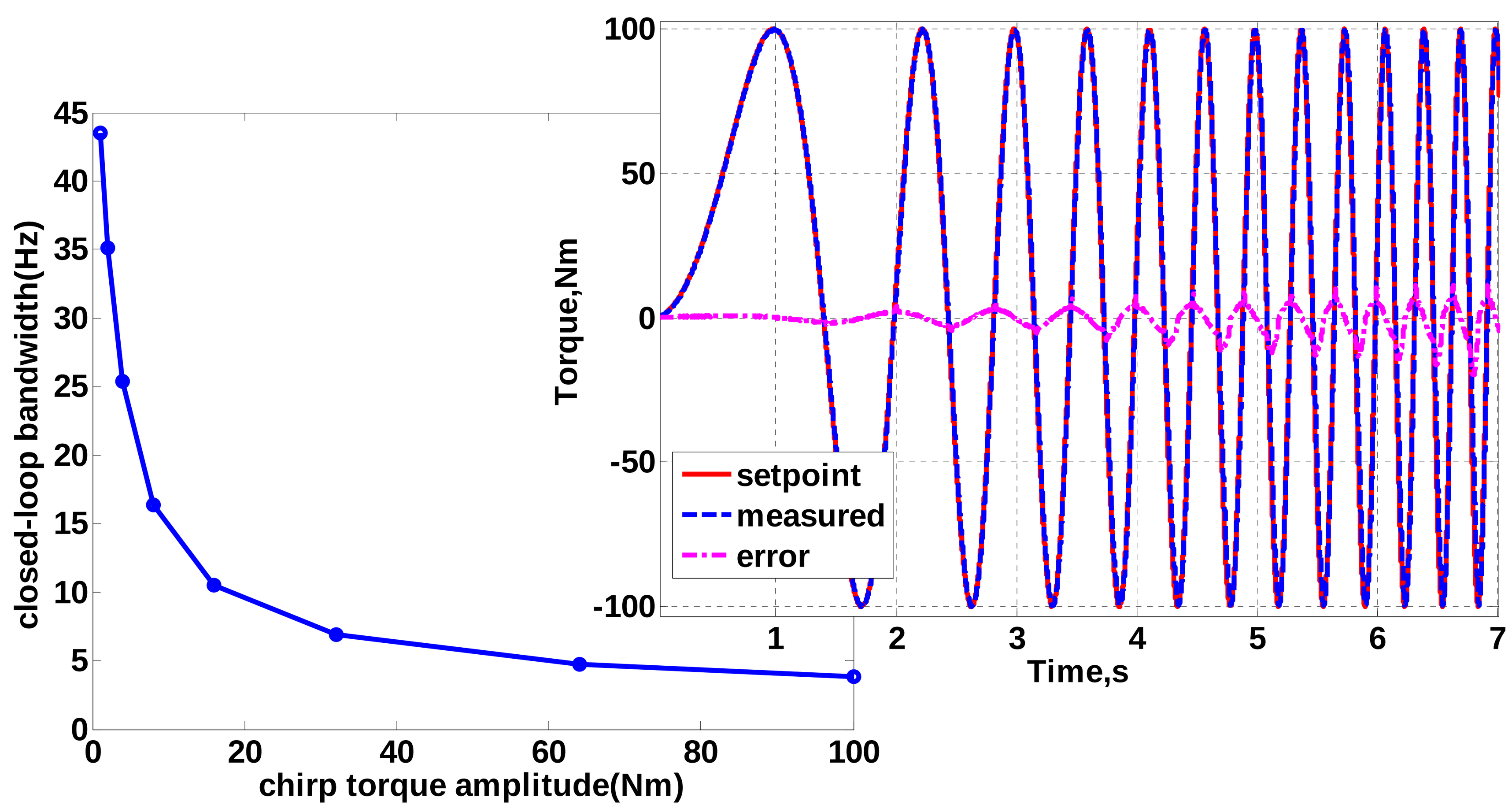


Fig.3 Left: closed-loop bandwidth at different torque amplitudes; right: torque tracking. The bandwidth is related to gear ratio, in final exoskeleton joints, the gear ratio is lower, thus higher bandwidth

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.

Reference

[1] G. A. Pratt and M. M. Williamson, "Series elastic actuators", IEEE Int. Conf. on Intelligent Robots and Systems, 1: 399-406, 1995
[2] C. Lagoda,et.al., "Design of an electric series elastic actuated joint for robotic gait rehabilitation training", IEEE Int. Conf. on Biomedical Robotics and Biomechatronics, 2010

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