# High Power Series Elastic Actuator Development for Torque-Controlled Exoskeletons

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*Abstract*— **This paper presents the development procedures of a high power series elastic actuator that can be used in torque-controlled exoskeleton applications as a high-fidelity torque source. In order to provide a high torque output while containing its weight, the main objective was to satisfy dimensional and weight requirements within a compact structure. A three-fold design approach was implemented: i) The torsional spring was designed using finite element analyses and its stiffness profile was experimentally tested via a torsional test machine, ii) thermal behavior of the actuator was experimentally examined to ensure sufficient heat dissipation, iii) the fatigue life of the spring was computed to be 9.5 years. Having manufactured the actuator, preliminary torque-control experiments were conducted. As the result, a high-fidelity torque control was achieved with a control bandwidth of up to 12 Hz.**

## I. INTRODUCTION

The potential benefits of the compliance, e.g., actuators with low mechanical output impedance, can be exploited in the form of high fidelity torque control. These force-controlled compliant robots enable enhanced interaction capabilities and are inherently safe for human-robot interaction. Furthermore, the series elasticity emulates the series tendons in muscular structures, and therefore, it is highly efficient in terms of mechanical energetics [1]. In the light of these facts, SEAs (Series Elastic Actuator) appear to be a very conceivable choice to power torque-controlled exoskeleton systems when considering safety, dependability and sustainable physical human-robot interaction. With this motivation, we designed a SEA unit with a high torque-to-weight ratio. Despite the conventional approach that is based on basic finite element analysis, we propose an integrated approach that combines meticulous mechanical design, particularly for the torsional spring, fatigue characteristics and the thermal behavior of the unit [2].

This paper aims to report the further refinements and experiments over our previous work presented in [2]. Section II explains the hardware design and torque control, together with the results. Section III concludes the paper.

## II. METHODS

### A. Hardware Design

*1) Mechanical Design:* The SEA unit is comprised of a frameless brushless motor (Kollmorgen, TBM-7631/7615), a strain wave gear (Harmonic Drive CSG-25, 1:100) and a 2-spoke torsional spring that acts as a torque sensor; see Fig. 1. Two 23-bit encoders (Avago Tech., AS38-H39E-B13S) were integrated to measure the motor angle and the torsional deflection. Technical specifications of two units with different torque output capacities are provided in Table I. The torque-to-weight ratios of the units are 52 and 33 Nm/kg, which are comparable to state-of-the-art SEAs; for instance, see [3].

*2) Torsional Spring:* The conventional torsional spring design is based on empirical topology search that is followed by FEA simulations. Our past experiences showed that this approach is prone to unexpected material behaviour; e.g., instead of spring spokes, the screw holes may dominantly effect the spring stiffness. Moreover, it may not be possible to determine the elastic/plastic region boundaries.

To this end, we backed up finite element analyses with spring break-up experiments via a torsional test machine. In these experiments, the torsional spring specimens were subject to gradually increasing torques until they completely break-up. In doing so, the elastic region and plastic regions boundaries were clearly defined; we were able to validate that the spring will behave linearly within the torsional deflection of 0-2 degrees. Moreover, the experimental value of the stiffness matched well with our finite element simulations, adequately confirming the proposed spring topology. Fig. 2(a)-(b) depict the experimentally obtained torque-angle curves and a spring sample before and after the break-up.

Furthermore, the fatigue life of the springs are not chiefly investigated in the literature. Using the actual hip joint torque data from exoskeleton-supported able-bodied walking experiments reported in [4], we determine the fatigue life of the spring via Palmgreen-Miner cumulative fatigue damage theory. The damage values under this specific loading is determined to be $2e^{-7}$; see Fig. 2(c). This damage value indicates that the loading could be applied for $5e^{6}$ cycles that correspond to 83333 hours (approx. 9.5 years) of continuous operation if the spring material is AL-7075.

TABLE I

COEX-SEA ACTUATOR SPECIFICATIONS

| Specification | Unit | Unit-A | Unit-B |
|---|---|---|---|
| Max. Angular Velocity | RPM | 26.33 | 44.09 |
| Max. Continuous Torque | Nm | 164 | 94 |
| Peak Torque | Nm | 460 | 304 |
| Weight | kg | 3.15 | 2.85 |
| Dimensions (r x L) | mm x mm | 53.25 x 152.3 | 53.25 x 125 |
| Stiffness | Nm/deg | 91 | 91 |
| Torque Resolution | mNm | 3.9 | 3.9 |

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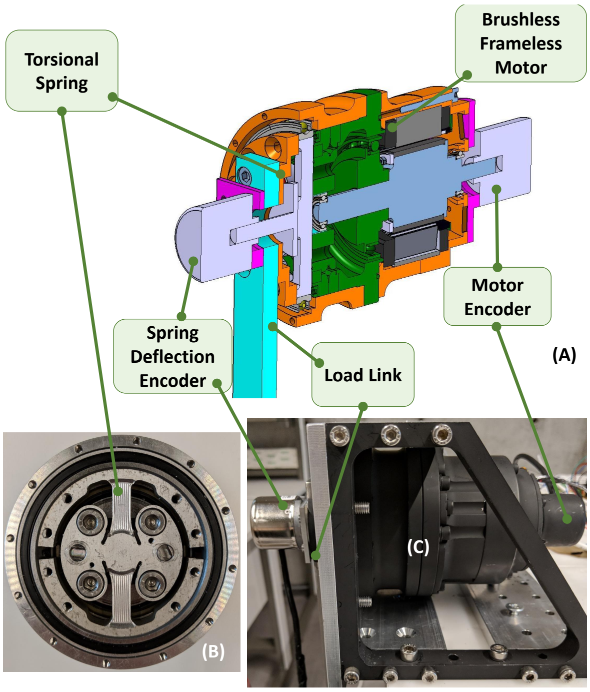

Fig. 1. (A) CAD drawing of the SEA unit. (B) The torsional spring mounted at the output. (C) The actual SEA unit for the experiments.

*3) Thermal Management:* Another important characteristics of the mechanical design is to see how the system emits the heat generated by the motor. To that end, we use the actual hip joint torque data from exoskeleton-supported able-bodied walking experiments reported in [4] and observed the thermal behavior experimentally via a thermocouple and an IR camera. The maximum heat accumulated during this experiment was recorded to be 33 $^\circ C$, in ambient temperature of 22 $^\circ C$ with natural convection, after 25 minutes of motion.

## B. Torque Control

Having completed the design procedures, we conducted preliminary experiments using the robust torque control technique proposed in [5]. As the result, the actuator unit provided a control bandwidth up to 12 Hz; see Fig. 3. Although the performance was satisfactory, tracking performance of the controller will be further enhanced via the use of other robust control techniques. During the experiments, the output link was subjected to a stiff environment, i.e., it was blocked with the obstacle that has a non-stiff material between link and the environment.

# III. DISCUSSION

In this paper, we succinctly explained the development and torque control implementation of our SEA unit to actuate our next generation exoskeleton robots. The units have relatively high torque-to-weight ratios and their mechanical behaviour is well tested. The preliminary experiments showed that its torque control performance is promising. In our next work, we will report our SEA-powered exoskeleton systems.

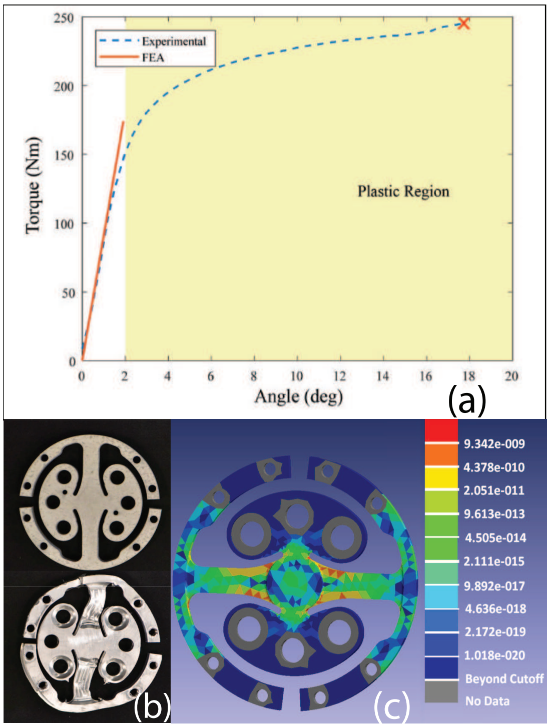

Fig. 2. a) Actual torque-angle curve of the spring. b) A torsional spring specimen. c) Von misses stress(MPa) distribution of the spring under 1Nm torque loading for the fatigue calculation.

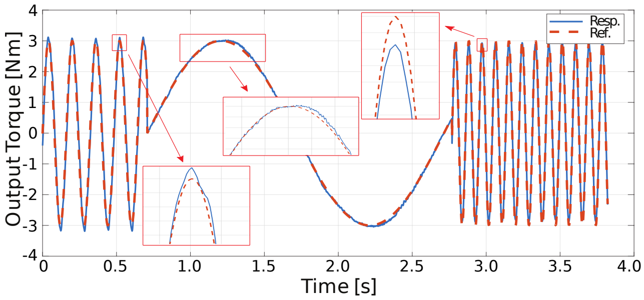

Fig. 3. Sine input response of the torque controller, respectively for 6.2 Hz, 0.5 Hz, and 11 Hz.

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