An Active Compliant Knee Joint for Gait Assistance: Design and Characterization

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Abstract Wearable lower-limb powered othoses represent valid tools for assisting people affected by gait disorders given their capability to actively sharing the workload of energetically expensive tasks of activities of daily living, contrarily to passive lower-limb orthoses or braces. In this abstract we present the design of an active knee orthotic joint, endowed with a novel series elastic actuator, and the experimental characterization of its torque controller. Experimental results demonstrated that the performance of the active knee joint are suitable for assisting locomotion-related activities of mildly impaired people.

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1 Introduction

Population-based studies outline an increasing aging trend in industrialized society, thus a consequent increasing incidence of age-related disorders and occurrence of gait impairments undermining people mobility, thus their productivity and, eventually, global social welfare [1]. Common cases are those people affected by stroke, multiple sclerosis, chronic patellofemoral pain syndrome, post-polio and lower-limb impairments who often show muscular weakness or hemiparesis that affect the limb stability during the stance resulting in collapse or hyperextension of the knee or drop foot syndrome. Powered orthoses assisting human articulations can improve mobility of these individuals assisting them in locomotion–related activities. Traditional knee braces are capable of rigidly supporting the body weight by locking the knee joint during the complete gait cycle or selectively during the stance phase, although requiring compensatory, unnatural and metabolically expensive movements at the hip and ankle level. More advanced braces are endowed with accurately sized springs in order to adequately comply with the human knee biomechanics mimicking shock absorption properties at early stance phase. Nevertheless, they are not capable of generating net active power for assisting demanding activities such as uphill walking, step climbing, sit-to-stand tasks. In order to efficiently inject positive energy and assist the performed task, many active orthoses and exoskeletons have been recently developed [2]. In this paper, we present the design of a novel concept for a series elastic actuator (SEA) [3] for a powered orthotic knee joint and the characterization of its low-level closed-loop torque controller. The knee module is part of a more complex system comprising knee and ankle active joints and a modular architecture allowing for easily coupling the distal active joints with the proximal active hip joint of an active pelvis orthosis [4].

2 Materials and Methods

The robotic knee joint is constituted by two linkages, interfaced with the thigh and the shank of the user, connected through a rotational joint powered by a SEA constituted of a 90 W brushless DC motor (EC-4pole 22, Maxon Motor®, Sachseln, Switzerland) with two reduction stages. The first reduction stage is a planetary gear directly assembled on the motor output shaft with a 20:1 reduction ratio (GP 22 HP, Maxon Motor®, Sachseln, Switzerland). The second reduction stage includes the elastic part of the actuator. It is composed by a 13:1 reduction ratio wormgear-wormwheel pair, with the wormgear receiving the input torque through a splined shaft connected to the planetary gear output. The wormgear is however free to shift axially with respect to the splined shaft, and is kept in a reference equilibrium position by two identical compression springs, pre-compressed and disposed in an antagonistic fashion. Thus, if the knee joint is moved from the output side, the elastic response of the axial springs will generate a corresponding elastic torque on the wormwheel, being the joint rotational stiffness $K_\theta = 2KR_P^2$ and the torque $\tau_K = 2KR_P^2\Delta x$ where K is the stiffness of the single linear spring and R_P is the primitive radius of the wormwheel. A 26-bit absolute linear encoder (RESOLUTE™, scale: RSLA A9765-0060, read head: RL26BAS001C50A, Renishaw®, Gloucestershire, England) measures the worm displacement with respect to its central equilibrium position, thus the deflection Δx of the springs. The linear encoder resolution is ± 1.5 µm, resulting in a resolution for the torque measurement of 4.23 N · mm. With $R_P = 34$ mm, the springs stiffness was chosen to be 41.4 N/mm in order to obtain the desired joint rotational stiffness of 95.7 N · m/rad (namely about 1/3 of the natural knee stiffness for a 80-kg person,

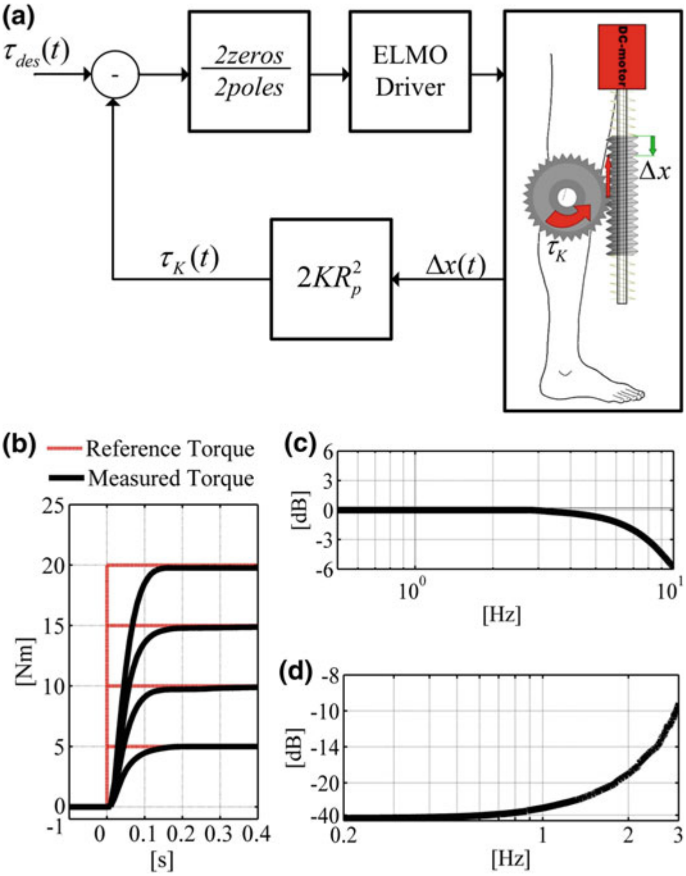

Fig. 1 Conceptual scheme of the low-level torque control of the knee orthotic joint (**a**) and results of its characterization. **b** Step response for different desired step amplitudes. **c** Amplitude Bode diagram of the transfer function from desired torque to measured torque obtained from the chirp response. **d** Amplitude Bode diagram of the transfer function from angular displacement to interaction torque normalized for the inherent stiffness of the knee joint

i.e. ~300 N · m/rad [5]). The knee SEA is able to exert up to 30 N · m of active torque. The sensor for measuring the knee joint angle is a 17-bit absolute Rotary Electric Encoder™ (DS-25 Netzer Precision Motion Sensors Ltd, Misgav, Israel). The range of motion of the knee joint –limited by mechanical stops for preventing from hyper- flexion/extension- is [–150°, 3°] (negative in flexion). The knee joint control system is based on a low-level closed-loop torque controller which relies on a 2poles-2zeros compensator operating on the error between the desired torque τ_{des} and the measured torque τ_K, and returning an electrical current controlled by means of a commercial servo amplifier (ELMO Motion Control Ltd., Petach-Tikva, Israel). A conceptual scheme of the knee joint low-level torque controller is provided in Fig. 1a. As it is explained in [3], bandwidth of a SEA system can be limited by design. Thus, the compensator was designed in order to achieve a wide closed-loop −3 dB-bandwidth, high transparency of the mechanical structure to the user movements and a passive damped behavior while providing assistive torque during locomotion-related activities. The control system is implemented on a real-time controller, a sbRIO-9632 (National Instruments, Austin, Texas, US), endowed with a 400 MHz processor running a NI real-time operating system and a FPGA processor Spartan-3 LX150. The low-level controller runs on the FPGA at a frequency of 1 kHz.

3 Experiments and Results

3.1 Step Response

Step responses were evaluated in static conditions with the knee joint being mechanically blocked at 0° and the desired torque initially set to $\tau_{\mathrm{des}} = 0\,\mathrm{N} \cdot \mathrm{m}$. The step response was evaluated over four different amplitudes in the range of $\tau_{\mathrm{des}} \in [5, 20]\mathrm{N} \cdot \mathrm{m}$; each step was repeated 10 times for assessing the reproducibility of the dynamic behavior. The averaged responses are shown in Fig. 1b. The rise time and the overshoot were 0.09 s and 0.23 N · m for the maximal step amplitude, i.e. 20 N · m.

3.2 Chirp Response

The frequency response of the torque control was characterized by commanding a desired torque along a linear chip (frequency 0–12 Hz, duration 300 s, and amplitude 3 N · m). The test was repeated for five times for improving the estimate of the Bode diagram of the system $\mathrm{G(s)} = \tau_K(\mathrm{s}) / \tau_{\mathrm{des}}(\mathrm{s})$. The resulting amplitude

Bode diagram of the chirp response is reported in Fig. 1c, and the estimated −3-dB bandwidth was about 8 Hz.

3.3 *Output Impedance*

The output impedance of the joint was tested to quantitatively assess the effort that users need to move the robot under the zero-torque condition, i.e. being $\tau_{des} = 0\,\mathrm{N \cdot m}$. Impedance was evaluated by displacing the joint in zero-torque mode by hand -with a quasi-sinusoidal flexion-extension motion- and measuring the interaction torque. The amplitude of the movement was about 20°, and the frequency varied quasi-linearly in the range 0.2–3.2 Hz. The duration of the recording –repeated five times for statistical purpose- was about 100 s. The transfer function from joint angle to actuator torque is an estimate of the output joint mechanical impedance [6]. Under the action of the torque control the joint, the output impedance for a frequency of 1 Hz was lowered by –38 dB to 1.2 N · m/rad, compared with the inherent passive impedance of 95.7 N · m/rad (as shown in Fig. 1d).

4 Discussion and Conclusions

In this work, we presented the design and the experimental characterization of a novel knee orthotic joint for a powered lower-limb assistive orthosis. Results of the experimental characterization demonstrated a fast damped behavior of the system in response to commanded torque steps of amplitude up to 20 N · m. A closed-loop bandwidth of 8 Hz ensures proper tracking capabilities of the desired assistive torque in the frequency range of human locomotion-related activities. Finally, low output mechanical impedance allows the wearer to walk naturally contrasting with the orthotic joint with minimum parasitic interaction. Future works will be focused on the assessment of the performance of the proposed active knee orthotic joint in assisting healthy and impaired individuals in activities of daily living.

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