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Research paper

Design and evaluation of a torque-controllable knee joint actuator with adjustable series compliance and parallel elasticity

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ABSTRACT

Compliant actuators are increasingly being designed for wearable robots (WRs) to more adequately address their issues with safety, wearability, and overall system efficiency. The advantages of mechanical compliance are utilized in a new actuator designed to exploit inherent gait dynamics. Unlike any other orthotic power unit, it combines Variable Stiffness Actuator (VSA) and Parallel Elasticity Actuation (PEA) unit into a single modular system. This way, the actuator has the potential to provide the benefits of VSA when net-positive work is necessary and efficiently store energy during energetically conservative tasks. A novel real-time torque controller allows the two units to work together throughout the gait cycle. The design aspects and experimental evaluation of the actuator and its low-level torque controller are presented in this paper. The actuator characterization, carried out in two benchmarking environments, highlights the actuator's high torque density and favorable energetic performance, providing evidence for its applicability in a standalone or multiple-joint lower limb orthoses.

1. Introduction

Human walking, as well as other activities of daily life (ADLs), requires a complex interplay between neural and musculoskeletal systems. This interplay, among other things, enables humans to adapt to new situations when confronted with task and/or environmental constraints. To interact with humans in such a constrained daily environment, wearable robots (WRs) need to be flexible, adaptable, and, most importantly, safe. One of the hallmarks for achieving that goal is compliance.

Compliance plays an essential role in human adaptations to external environmental changes and achieving stable gait [1]. Moreover, it has multiple advantages over a traditional stiff actuation [2] used in the field of human-robot interaction. Nevertheless, compliance has not found its way into commercial WRs, which still use direct drive actuation due to its high bandwidth and controllability. A different trend can be seen in research prototypes, where the introduction of an elastic element into a drivetrain led to different realizations and applications of series elastic actuators (SEAs). These include MINDWALKER [3] and IHMC [4] lower body exoskeletons, iT-Knee [5] knee joint orthosis, and stationary gait rehabilitation robots LOPES [6] and ALTACRO [7].

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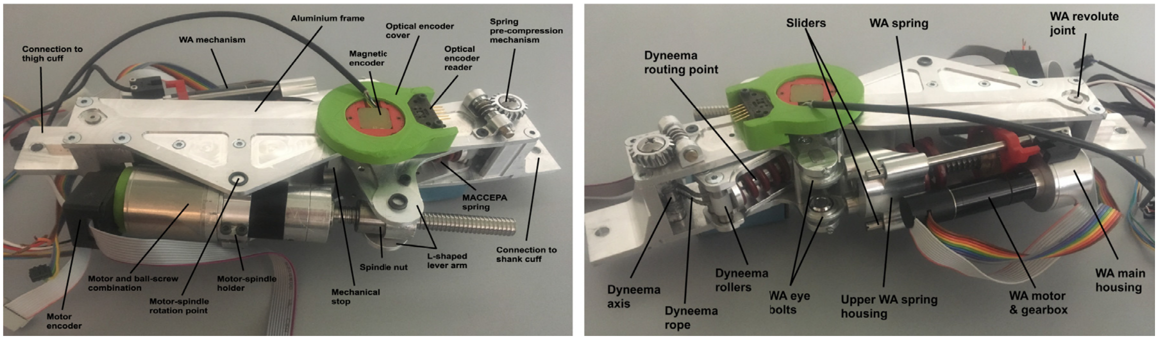

(a) The knee actuator - front side (b) The knee actuator - back side

Fig. 1. A modular compliant knee joint actuator consisting of parallel and series elasticity units, thus combining the advantages of both. Parallel elasticity is realized as a quasi-passive mechanism consisting of an EC motor, spindle, and a spring. Series elasticity is realized as a MACCEPA (VSA) due to its simplicity, compactness, robustness, and favorable output characteristic. Such an approach has the potential to lead the actuator to a better energetic performance. The actuator's range of motion is 5° in the extension and 90° in flexion limited by mechanical stops.

In order to overcome their bandwidth limitations and improve their force/torque performance, several modifications have been proposed to traditional SEAs [8,9]. However, the SEAs' energy storage capability and output dynamics depend on the resulting fixed spring constant whose choice remains bound to a certain application/control strategy, severely limiting its applicability. The introduction of VSAs [10] overcame that and enabled the embodiment of characteristics found in biological systems in a new generation of mechatronic systems. Actuation units that exploit variable stiffness include MACCEPA [11], CompAct-VSA [12], AwAS-II [13], ARES [14], and BAFSA [15]. However, despite their indisputable benefits, many VSAs reported in the literature never came to be used in WRs since their energy-saving benefits usually come at the cost of a higher complexity, size, and/or weight. That is not the case with ARES, recently used in ATLAS exoskeleton and the MACCEPA. Ever since its introduction, the MACCEPA concept has been successfully used to develop actuation systems for different applications, including walking exoskeleton [16], stationary gait rehabilitation robot [7], ankle orthosis [17], and ankle-knee prosthesis [18].

Apart from a series compliance unit, WRs can also benefit from a PEA unit. This unit, placed parallel to an actuator's drivetrain/joint, reduces its motor peak torque requirements and, consequently, its power consumption by offloading the motor [19]. Such a configuration is especially useful in a case when a biological joint resembles the behavior of a spring, as is the case with the knee joint's early stance gait phase. Several efforts where this concept was exploited in the knee joint orthoses [20–22] and prostheses [23,24] can be found in the literature. In order to avoid compromising the joint's movement dexterity, all these devices share the employment of a spring (dis)engagement mechanism and a quasi-passive design that exploits mainly elastic, spring-like behavior of the knee joint but has cannot actively input energy into the system.

However, regardless of its realization and adjustability properties, compliance is not sufficient to ensure safe, robust, and biologically relevant actuation in human-robot interaction and needs to be complemented by the appropriate control strategies [25] on two levels. On a low level, the control needs to ensure that a motor reaches any given setpoint to result in a desired user's behavior, previously defined on a high level. As discussed in [26] and [27], low-level controllers used in the literature vary substantially depending on the application and functionality of the actuator. Nevertheless, some trends, dominated by a predefined gait trajectory control [28] and a force/torque control [26] can be identified. The most prominent realizations of both approaches can be found in [29], where the authors compared a torque-tracking performance of different torque controllers under realistic experimental conditions. However, despite such efforts, it is not clear which, if any, combination of a high- and low-level controller is the optimal in any given scenario.

All these WRs' components discussed above are embodied in the actuator presented herein in detail (see Fig. 1), designed as a research platform to investigate the effects of its varying output stiffness on the users' biomechanics and energetic performance across and not within different daily activities. This is made possible by introducing the following novelties:

1. Its overall design is guided by a modularity requirement, leading to an actuator that can be used as a standalone or part of a multiple-joint lower limb orthosis. This modularity also allows the actuator to be used in different assistive and structural configurations (passive degrees of freedom), thus analyzing the effects these have on both the actuator and the user.
2. It utilizes a spindle-driven MACCEPA concept realization tailored for use in a human knee joint orthosis. The simplicity and controllability of the MACCEPA concept are combined with wearability and safety requirements to deliver a compact and a high-power actuator with desirable inertia distribution and the potential for increased energetic efficiency.
3. Its non-linear output characteristic is exploited to devise a robust low-level controller in analytic form, allowing joint stiffness and torque control to be realized in real-time. In addition, this controller can be used with other realizations of the MACCEPA concept.