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Compliant Actuation for Energy Efficient Impedance Modulation

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Abstract— **Energy efficient compliant actuation is the missing ingredient and key enabler of next-generation autonomous systems, domestic robots, prosthetic devices, orthotic devices, and wearable exoskeletons, to name a few. For all these devices, one would wish to develop actuators enabling wide range impedance modulation with low energy cost. Using conventional and biologically-inspired compliant actuation, previous research led to functional devices but with high energy cost. Here we introduce a minimalistic compliant actuator to realize impedance modulation with low energy cost. Using this actuator we demonstrate stiffness augmentation in human-machine collaboration. We argue that the non-biologically-inspired actuation concept presented here may effectively complement a biological system, by restoring or extending its functionality, with negligible energy cost.**

I. INTRODUCTION

Compliant actuators, used to implement stiffness modulation, are characterized by passive and often tunable force-deflection characteristics. This can be achieved using closed-loop control [1] or through introduction of elastic elements, material or geometric non-linearity and control redundancy by design [2]. Actuated compliant mechanisms have been used widely especially in modern robotics applications. Compliance is vital to maintain a desirable interaction between the robot and its environment and is essential to achieve robust and adaptive behavior [3]–[7].

A biologically-inspired mechanism to realize stiffness modulation is through the use of antagonistic actuation. A typical antagonistic actuator employs two non-linear springs concurrently to modulate the apparent joint stiffness; analogous to how biceps and triceps muscles modulate the stiffness of the elbow joint. Previous studies have shown that humans are able to modulate the stiffness of their limb, and that in tasks involving unstable dynamics, stiffness modulation is essential [8]–[10]. However this control modality has been recognized as energetically expensive. Recent studies have indicated that a similar argument carries over to the vast majority of actuators designed to realize impedance modulation in artificial systems, including but not limited to actuators using the biologically inspired antagonistic principle [11].

A number of practical applications indicate the desirable technical specifications of an ideal compliant actuator: (1) a compact design; (2) stiffness modulation over a large range; (3) sustaining constant stiffness with minimal (ideally zero) power drain; (4) high modulation bandwidth (i.e., rapid stiffness change); and (5) minimal power required to change stiffness, even under load. Changing stiffness rapidly under load with minimal power is particularly challenging. Changing stiffness under load requires adding or subtracting mechanical energy, and to do so rapidly requires non-zero power. Thus some of these requirements may seem contradictory; nevertheless they are important. While a number of previously designed actuators enable stiffness modulation over a large range without requiring energy to hold a given stiffness setting [12], [13], despite these recent advances, it is non-trivial to design actuators that comply with all the above requirements.

In this paper we introduce a non-biologically inspired compact compliant actuator that enables a large range of stiffness modulation at high speeds with low energy cost. To focus on the main challenge, this actuator separates the modulation of stiffness from the production of continuous mechanical power, which is relegated to a conventional actuator. We posit that direct propagation of external loads to the motor used to modulate the output stiffness of the actuator is the main reason for the high energy required in previously designed actuators. Our minimalistic design embodies geometric features to ensure that the external load is supported by the structure of the actuator instead of the motor used for stiffness modulation. This makes it possible to render a large range of stiffness modulation for low energy cost, not only when the actuator is at its natural equilibrium configuration but also when it is externally loaded and considerably deflected from its equilibrium configuration.

Using this actuator we demonstrate low-energy stiffness augmentation in human-machine collaboration related to isometric postural stabilization and a weight bearing task. Based on the reported experimental results we argue that the present actuation concept could be used to effectively complement a biological system, by restoring or extending its function, with low energy cost.

II. STIFFNESS MODULATION

In the human musculo-skeletal system antagonistic muscle groups enable stiffness modulation around the joints. A minimalistic model of this “compliant biological actuator”

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involves two motors to change the apparent stiffness of the joint and to provide the torque required to generate motion (see Fig.1a). In this minimalistic model, the motors are connected in series with the non-linear compliant elements which have quadratic force-displacement characteristic [14], [15]. The dimensionless joint stiffness K, motor force $\mathbf{F} = [F_1, F_2]^T$ and joint torque τ, of this actuator, are given by the following relations:

$$K = K_0 + (x_1 + x_2), \quad F_{1,2} = (K \pm 2(q - q^*))^2 \quad \text{and} \quad \tau = -K(q - q^*) \tag{1}$$

where K_0 is the smallest joint stiffness, q denotes the link position while $q^* = \frac{1}{2}(x_2 - x_1)$ denotes the equilibrium position of the joint. When the motors are activated and $x_1 \neq x_2$, joint torque is generated. When the motors are activated and $x_1 = x_2$, the stiffness of the joint is changed with zero joint torque.

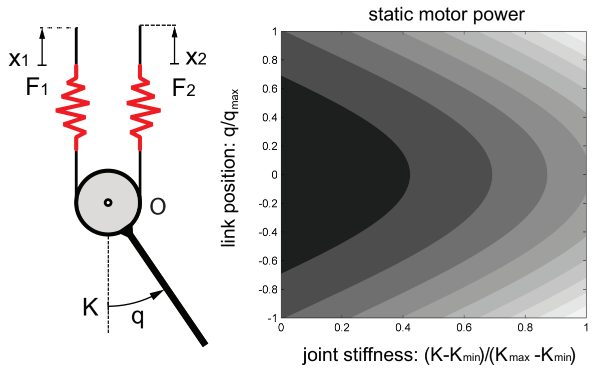

Fig. 1. a) Minimalistic model of a biologically-inspired antagonistic actuator. b) Plot showing the power required to hold a constant stiffness over the workspace of the actuator.

Regardless of the use of this actuator, to generate non-zero stiffness the motors need to apply force against the springs continuously, which leads to constant power drain[1]. This can be directly quantified by the relation between the total electrical motor power:

$$p = |F_1 \dot{x}_1| + |F_2 \dot{x}_2| + w_1 F_1^2 + w_2 F_2^2 \tag{2}$$

where $w_{1,2}$ depend on physical parameters of the motor units i.e., motor torque constant, winding resistance, transmission ratio, and drive-train efficiency respectively. The distribution of this cost over the workspace of the actuator associated with holding a constant stiffness setting (third and fourth terms in (2)) is shown in Fig.1b. This plot captures the intrinsic feature of this actuation principle, namely that holding a constant stiffness requires constant power drain.

A. *Stiffness Modulation with Low Energy Cost*

In order to explore general principles to reduce the energy required for stiffness modulation, we will now revisit the relation between the power required by the actuator p and the forces imposed on the motors due stiffness modulation (2). Assuming that we aim to establish general design guidelines for actuators supporting a variety of tasks, realizing stiffness modulation with low energy cost requires reducing the magnitude of the force felt by the motors. This means that any design where a significant portion of the output force propagates through the motors when maintaining stiffness (as with antagonistic actuators) or changing stiffness, would not be conducive to stiffness modulation with low energy cost.

One way to design actuators that are favorable for stiffness modulation is to ensure that the force generated by the compliant element is not directly transferred through the motors but instead supported by structural elements built into the actuator. In the following we present a conceptual model of a compliant actuator that is based on this design principle[1].

B. *Actuator for Energy Efficient Stiffness Modulation*

The above consideration led us to a simple variable-length leaf-spring mechanism shown in Fig.2. This mechanism is composed by the output link AB, a leaf spring BC, and a position controlled slider S which adjusts the effective length x of the spring. Following the Bernoulli-Euler beam theory, and by assuming that the leaf operates in a small-deflection regime, the output stiffness of the actuator and the input force felt by the motor are defined by:

$$K = K_0 \frac{\cos(2q)}{\left(1 - \frac{x}{L}\right)^3} \quad \text{and} \quad F = \frac{3K_0}{2L} \frac{\sin(q)^2}{\left(1 - \frac{x}{L}\right)^4} \tag{3}$$

where q denotes the link position, $K_0 = 3EIe^2/L^3$ is the minimum output stiffness of the actuator, E is Young's modulus, I is the area moment of inertia while L is the length of the spring respectively.

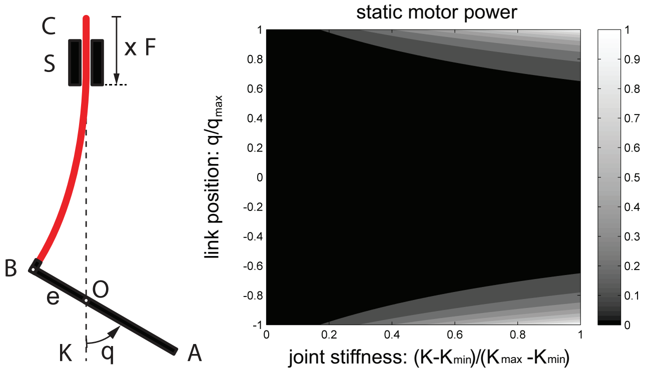

Fig. 2. a) Minimalistic model of an actuator designed for large range and low energy stiffness modulation. b) Plot showing the static power required to hold a constant stiffness setting over the workspace of the actuator.

In the following we summarize the main attributes of this mechanism proposed here for stiffness modulation:

1) By changing the effective length of the spring the output stiffness of the actuator can be modulated over a large range

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[1] Using non-backdrivable worm-gear mechanisms it is possible to maintain a given stiffness setting with zero power drain even on antagonistic actuators. However, such a design is inherently inefficient and in turn does not prevent the output forces to propagate through the motors units while stiffness is changed.

$K|_{q\approx 0} \in [K_{\min}, K_{\max}]$ where:

$$K_{\min} = \frac{3EIe^2}{L^3}\left(1 - \frac{x}{L}\right)^{-3} \quad \text{and} \quad K_{\max} \approx \infty. \tag{4}$$

Under usual design conditions i.e., $0 < e \ll L$, we can achieve almost free motion (if $x \approx 0$ then $K_{\min} \approx 0$) or emulate a rigid joint (when $x \approx L$). Importantly, this large stiffness range is realizable in a compact design due to the highly non-linear relation between the joint stiffness and the motor position given in (3).

2) In the high-stiffness domain i.e., $0 \ll x \leqslant L$, large stiffness variations are possible with small changes of the effective spring length:

$$\frac{dK}{dx} = \frac{3K_0}{L}\frac{\cos(2q)}{\left(1 - \frac{x}{L}\right)^4}. \tag{5}$$

Due to this non-linear relation, high-bandwidth stiffness modulation is achievable using low-bandwidth motors. This is why the proposed actuator can be used not only for large-range stiffness modulation but also for fast modulation with modest power required.

3) The motion range of the actuator is defined by the kinematics of the mechanism and the deformation limit of the compliant element according to the following relation:

$$|\sin(q)| = \left|\frac{\delta}{e}\right| \le \min\left\{1, \frac{2}{3}\frac{\sigma_Y}{E}\frac{L}{h}\frac{L}{e}\left(1 - \frac{x}{L}\right)^2\right\} \tag{6}$$

where δ is the deflection of the beam, σ_Y is the yield strength while h denotes the thickness of the spring. Notably, under usual design realization (where $L/e \gg 1$ and $L/h \gg 1$) the kinematically achievable motion range of the actuator $q \in (-\pi/2, +\pi/2)$ will only be limited at high stiffness settings[2] i.e., if $x \in (x_{\mathrm{cr}}, L]$. This is unlike many other compliant mechanisms where, due to the kinematics of the design, the output deflection is limited to small angles even at small or moderate stiffness settings.

4) The force required by the motor to hold a certain stiffness setting (fixed slider position) is zero when the actuator is not loaded externally (i.e., when the actuator operates at its natural equilibrium configuration $q = 0$); see (3). On the other hand, when the actuator is externally loaded i.e., $q \neq 0$, the motor force F at the actuators input remains bounded by:

$$|F| \le \max_q |F| \le \frac{3K_0}{2L}\frac{1}{\left(1 - \frac{x_{\mathrm{cr}}}{L}\right)^4} = \frac{A\sigma_Y^2}{6E} \tag{7}$$

where A denotes the cross-section area of the rectangular beam. As can be seen, the motor force is not only bounded, but with a typical design realization can be rather low regardless of the joint deflection and the actuator's stiffness setting.

Previous actuators have been designed using leaf-springs without emphasis on energy minimization [16], [17]. Actuators enabling large range stiffness modulation without requiring energy to hold a given stiffness setting have also been designed [11]–[13], [18]. However, we are not aware of any existing actuator that achieves the four above-mentioned features which are important in practice. In particular, achieving an infinite stiffness range within a compact design; low energy cost when the actuator is operated away from its equilibrium configuration; large kinematic motion range; and high-bandwidth stiffness modulation, have been recognized as difficult to achieve within a single design. In the analysis above we indicated how (and under what conditions) the presented idealized actuator could achieve all of these requirements.

III. MECHANICAL DESIGN OF THE ACTUATOR

The conceptual actuator model has been designed and fabricated Fig.3d. The kinematic realization of the device closely resembles the minimalistic model above with the output link, leaf springs, and the position controlled slider which adjusts the output stiffness of the actuator.

Using a single leaf-spring, in the practical realization, turned out to be challenging. In particular, that solution would either severely limit the stiffness range or would considerably reduce the motion range of the actuator. For this reason, we used stacks of leaf springs to implement the compliant element for the actuator. The proposed implementation uses multiple thin springs of different thickness to allow large stiffness and large motion range. It is also important to mention that the output stiffness of the device relates to the cube of the individual spring thicknesses, and accordingly, by changing the thickness of individual leafs the passive force–deflection characteristic of the actuator can effectively be tuned.

Two stacks of leafs, designed in this way, are connected to the output link as shown in Fig.3a. The slider, used to change the effective length of the springs, is supported by two linear guides and is driven by a ball-screw mechanism. The ball-screw is actuated by a motor unit consisting of a brushless DC motor and a highly back-drivable planetary gearbox (Fig.3b). This design decision was made to ensure that the actuator is not only able to hold stiffness effectively but it can also change stiffness efficiently. Using the encoder signal from the motor, a closed-loop motor position control was implemented to set the effective length of the leaf-springs and therefore the stiffness of the actuator. The schematic of the real-time controller and the electronic implementation of the same is shown in Fig.3e. During the operation of the device, the power drained by the motor is recorded with a dedicated power measurement circuit. The motion of the output link is also measured using an off-axis magnetic absolute position sensor, built into the device.

There are two practical limitations that impede exact realization of the conceptual design shown in Fig.2a. One is due to geometric imprecision leading to non-ideal implementation of the slider cantilever support, while another is the frictional effect caused by the normal reaction force acting between the slider and the linear guides as well as the slider and the leaf springs embedded in the actuator. Both of these

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[2] If $0 < \left(\frac{3}{2}\frac{E}{\sigma_Y}\frac{h}{L}\frac{e}{L}\right) \le 1$ then $\frac{x_{\mathrm{cr}}}{L} = 1 - \left(\frac{3}{2}\frac{E}{\sigma_Y}\frac{h}{L}\frac{e}{L}\right)^{\frac{1}{2}}$ otherwise $x_{\mathrm{cr}} = 0$; see (6).

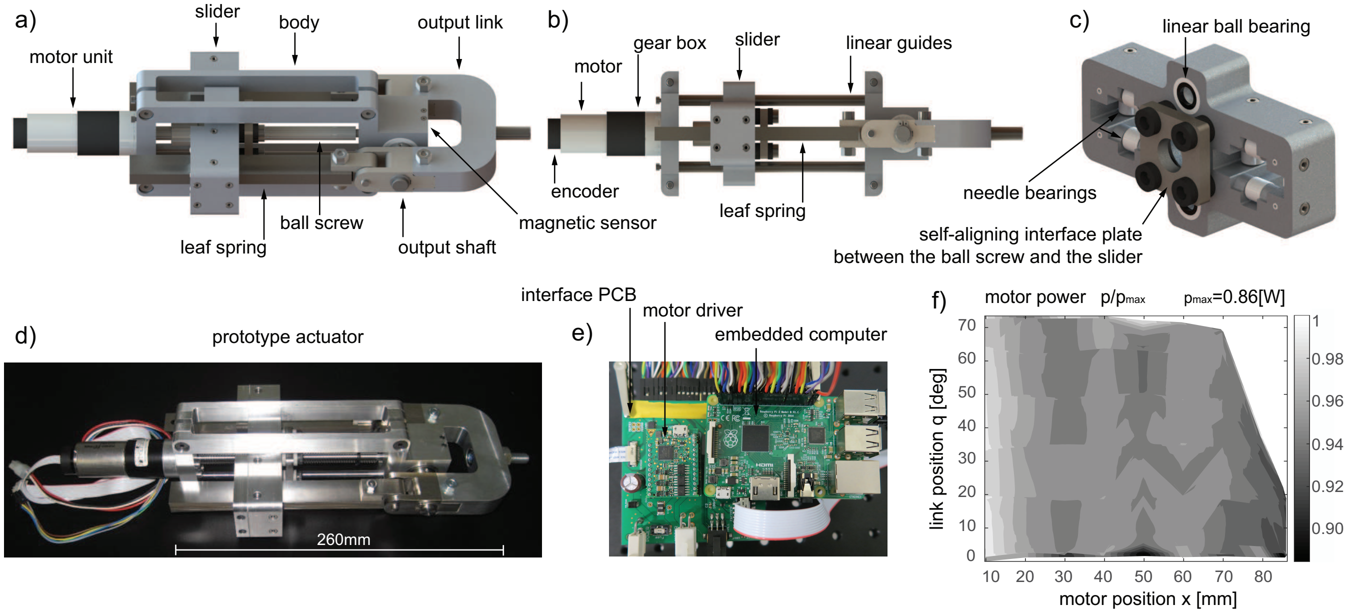

Fig. 3. a) Actuator for stiffness modulation with low energy requirement. Dimensions: W×H×L = 90×95×260mm. The two composite leaf springs (W×H= 20 × 10mm) are assembled using 5 × 1mm and 5 × 0.5mm leaves. These leaves are connected in parallel to the output link. Accordingly, the total stiffness at the output of the actuator is the sum of the individual stiffnesses of the leaves. The motor unit consists of a Maxon brush-less DC motor (Maxon EC-max 24V and 40W), 4.8:1 planetary gearbox and a $2\mathrm{mm}$ pitch ball-screw. b) Motion of the output link q [provided by absolute position sensor] and motion of the slider x [provided by the incremental encoder on the motor]. c) Design of the slider with linear ball bearings and two rows of needle bearings implementing the movable cantilever support. d) Prototype. e) Electronic control implementation using R-Pi embedded computer, Maxon ESCON motor driver and a custom made PCB. The controller was implemented in real-time with 1000Hz sampling frequency. This implementation also contains a dedicated power measuring circuit (with 0.025W resolution) used to evaluate the power drained by the device. f) Experimental power plots measured over the configuration space of the actuator.

effects increase the force felt by the motor while holding or changing the stiffness setting of the actuator. From the standpoint of energetics these are detrimental effects. These effects are mitigated in the following way: a) to reduce the geometric imperfections, the thickness of the leaves were fit to the slider and the interface between the slider and the leaf springs were precisely machined; b) to eliminate the friction between the slider and the leaves, the interface between the two was realized through needle bearings embedded into the body of the slider Fig.3c; and finally c) the friction between the slider and the linear guides was minimized using linear ball bearings Fig.3c. In this way, friction was reduced (by two orders of magnitude) compared to a design that relied on sliding bearings. These practical solutions were used to develop a working prototype of the proposed actuator. This working prototype is characterized with low static power requirement i.e., $p \leq 0.86W$ in the entire workspace of the actuator (Fig.3f).

IV. STIFFNESS AUGMENTATION

In various natural tasks, including (but not limited to) quite standing and locomotion, weight bearing is vital and postural stabilization is essential. In general, closed–loop force control and open–loop stiffness control are both viable approaches to achieve these tasks. Humans are able to utilize both of these control modalities and it has been shown that they may prefer one over the other depending on the control task [10].

It has previously been argued that the ability of humans to cope with challenging stabilization tasks under the inevitable feedback delays of a biological motor-control system is fundamentally limited [8]. Theoretical studies have also indicated why modulating the output impedance of compliant actuators through force-feedback, is not only energetically expensive, but severely limited if the passivity of the closed-loop system is to be preserved [19]. While these challenges can be avoided using open-loop stiffness control, modulating joint stiffness through biological antagonistic actuators is energetically expensive.

In this work we show how to avoid this limitation using a non-biologically inspired actuator that enables open-loop stiffness modulation with low energy cost. Experiments were conducted to test the suitability of our actuator in low-energy high-range stiffness augmentation. In these experiments the actuator was used in parallel to a human to realize a stabilization and a weight-bearing task. During the experiments, the behavior of the device was characterized by its output position q, output stiffness K and the motor power p required to modulate or hold its stiffness setting. On the other hand, the involvement of the person in achieving the task was quantified through measurement of muscle surface electromyography (EMG) [20]. The raw EMG signals show muscle activity; their magnitude provides a measure of joint stiffness and the energy consumed by the muscles. In the experiments below we use these measures to understand the contribution of the human operator and the actuator while

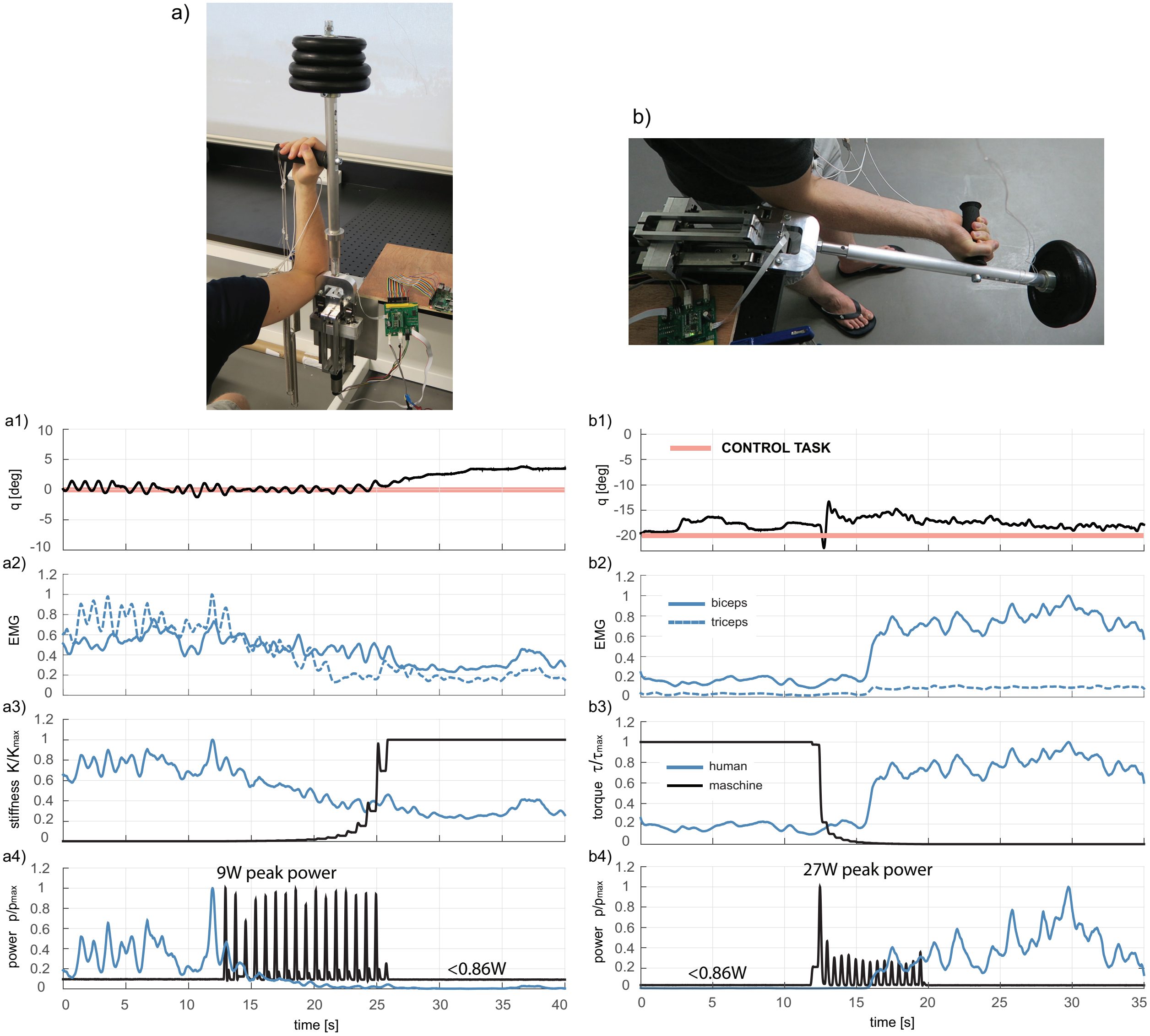

Fig. 4. a) Experimental setup for the postural stabilization task. b) Experimental setup for the weight bearing task. a1,b1) Joint angle (black line) and desired joint angle (light red line). a2,b2) Processed biceps (full line) and triceps (dashed line) EMG signals indicating muscle activity during the experiment. Processing: The EMG signals were rectified, filtered with a 5Hz - 100Hz bandpass filter, a zero-lag 1s moving-average filter and finally they were normalized. Interpretation: As a first approximation, we assume that the processed EMG signals correspond to the two position inputs x_1 and x_2 of the antagonistic actuator model shown in Fig.1a. According to this assumption, the stiffness of the human limb K, the joint torque τ, and the corresponding power drained by the muscles p are proportional to: $K \propto x_1 + x_2$, $\tau \propto x_1 - x_2$ and $p \propto (x_1 + x_2)^4$ respectively. These formulas were used to qualitatively assess the involvement of the human in the control task. a3,b3) Normalized joint stiffness provided by the actuator (black line) and the human operator (blue line). a4,b4) Normalized motor power by the actuator (black line) and estimated power consumed by the human due to task related muscle activity (blue line).

they work in parallel to achieve the same task.

In the first experiment, the person was tasked to keep the inverted pendulum in its unstable vertical configuration Fig.4a with no visual feedback. The actuator was also connected to the inverted pendulum setup and depending on its stiffness setting it could help the person achieve that task. At the beginning of the experiment, the stiffness of the actuator was set to minimum. In this case, the vertical equilibrium of the pendulum was inherently unstable and active involvement of the person was required to keep the pendulum in its upright position. In this case the task was realized by the human alone and the energy required by the actuator was negligible. In the second part of the experiment, the stiffness of the actuator was gradually increased until the muscle activity of the person monitored by the EMG recordings was negligible. Through this adaptation process, the stiffness of the robotic setup was increased to the level where the robot alone could perform the task. When stiffness changed, the actuator necessarily drained power. However, keeping the stiffness at the level required to stabilize the task by the device alone again led to negligible power consumption. This experiment illustrates how the proposed non-biologically inspired actuator can complement the human operator to achieve postural stabilization with negligible energy cost.

In the second experiment, the same setup was connected horizontally to a desk, and the person was asked to keep the position of the output link constant Fig.4b. Unlike the first experiment, in this case the actuator was operated away from its equilibrium configuration and the task required output force to be exerted. At the beginning of the experiment the device provided maximum stiffness. Under this condition, the output link was deflected (Fig.4b1). Despite the high stiffness and nonzero joint angle, maintaining this configuration required negligible energy by the actuator and no involvement by the human operator. Subsequently, the stiffness of the device was gradually decreased to its minimum value. During this adaptation process, the actuator consumed power, but keeping a constant stiffness setting at the end of the adaptation was again negligible. When the stiffness was decreased, keeping the output link at its original position required direct involvement of the human operator. In particular, the EMG recordings show higher activation of the agonist (biceps) muscle, indicating that, unlike the previous stabilization task, fulfillment of this task required considerable joint torque. This experiment illustrates how the proposed non-biologically inspired actuator can complement the human operator in weight bearing where it provides low-cost high-stiffness augmentation even if it is deflected from its equilibrium configuration.

Designing artificial systems capable of augmenting humans with low energy cost has significant potential benefit. Recent studies have demonstrated this using unpowered passive exoskeletons [21] and simple active exoskeletons with off-board power [22]. Extending these ideas requires autonomous devices capable of providing biologically relevant augmentation – stiffness modulation – with low energy cost. This has been recognized as challenging. One of the main reasons for this stems from current actuation principles that may introduce stability issues and high energy cost. In this study we aimed to demonstrate that those limitations are not fundamental; it is possible to realize stiffness augmentation with low energy cost. We demonstrated this using a simple non-biologically inspired compliant actuator. We foresee this actuation principle being a key component of next-generation robotic systems, autonomous prosthetics, orthotics and exoskeleton devices, aiming to augment human strength and endurance in a biologically compatible fashion.

V. CONCLUSION

By considering the power required for stiffness modulation, design of an actuator capable of large range stiffness modulation was sought, found, demonstrated and investigated. This actuator was shown to enable large-range stiffness modulation in conjunction with large-range output motion and was capable of holding a given stiffness setting with minimal power drain. The usefulness of the underlying design concept, and the actuator itself, was demonstrated through human-machine collaboration in challenging postural stabilization and weight bearing tasks. The experimental results confirm that the non-biologically inspired actuation concept presented here may effectively complement a biological system, by restoring or extending its functionality, with negligible energy cost.

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