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Stiffness Modulator: A Novel Actuator for Human Augmentation

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Abstract— **Stiffness modulators are devices that promote a novel means of actuation; they provide stiffness modulation without deliberately doing mechanical work. These type of compliant actuators may be used for human augmentation to complement co-contracted antagonistic muscles and as such reduce muscle activity and metabolic energy cost. Despite the theoretical appeal of this concept, its implementation remains elusive in practical applications. This is particularly true for human augmentation which requires a portable stiffness modulator. In this paper, we present a compact, lightweight, and self-contained stiffness modulator. Using this device, we demonstrate stiffness augmentation of the human knee joint in a sit to stand task. The experimental results indicate that the proposed device is able to assist a human by reducing muscle activity while drawing minimal battery power.**

I. Introduction

Exoskeletons are robotic devices developed to aid recovery after physical injury and to augment human strength and endurance [1], [2]. One of the core technologies used to develop exoskeleton devices is provided by compliant actuators [3], [4]. These actuators are similar to antagonistic muscle pairs surrounding biological joints in that they can (i) generate the force required to initiate, maintain, and terminate an ongoing motion, and (ii) provide the stiffness to achieve stabilization [5], safe human-robot [6] and stable body-environment interactions [7].

Most compliant actuators are either series elastic or variable stiffness actuators. The former enables intrinsically stable force augmentation [3], while the latter enables intrinsically stable force and stiffness augmentation [4].

In order to initiate or maintain a given motion, for example locomotion, the force and the required mechanical work necessitates the use of a sufficiently powerful actuator. In particular, the size of the actuator is defined by the mechanical requirement of the task, which cannot be reduced by optimizing the actuator design. This is why effective force augmentation, realized with a series elastic actuator, or combined force and stiffness augmentation, implemented using a variable stiffness actuator, typically requires a sturdy structure, a heavy motor, and a large battery in exoskeleton applications. As a result, devices that aim to augment the user often constrain the autonomy of the user. While light and strong structures, compact motors, and high energy density batteries are expected to advance this field, the fundamental issue with force augmentation as well as the combined force and stiffness augmentation stems from the physical requirement of the task, and not the technological bottleneck affecting compliant actuation. This appears to be one of the main reasons why portable force augmentation of humans using series elastic, variable stiffness, or other means of actuation, remains challenging in practical applications.

According to the physics of compliant actuation, energy is required for both force and stiffness augmentation. However, the energy required for force augmentation is largely independent of the actuator, while the energy required for stiffness augmentation strongly depends on the design of the actuator. For example in antagonistic actuators, the power required for stiffness augmentation is a monotonically increasing function of the stiffness [8], which indicates why high stiffness is metabolically expensive in a biological actuator [9]. On the other hand, in intrinsically efficient variable stiffness actuators [10], [11], and in inherently low power stiffness modulating actuators [12], [13], the power may even be theoretically independent of the stiffness [8]. Based on this observation, it appears desirable to explore *stiffness augmentation as a portable means of actuation* for human augmentation.

In this paper, we present a *stiffness modulator*; a novel compliant actuator dedicated to human augmentation which provides intrinsically low-powered stiffness modulation without deliberately doing mechanical work. Similar to some recently developed variable stiffness actuators [10], [14]–[16], the proposed device provides inherently stable and theoretically infinite range of stiffness modulation. However, compared to previously developed series elastic and variable stiffness actuators, the proposed stiffness modulator does not require a powerful motor typically used for force augmentation. This enables a portable, lightweight and energetically autonomous design suitable for human augmentation.

A compliant actuator of this type may be used in parallel with a human limb to complement the biological joint stiffness modulation, thereby reducing co-activation of antagonistic muscles and the associated metabolic energy cost. Following this idea, we use the proposed device to demonstrate an energetically autonomous human augmentation in a natural sit to stand task. Consistent with our empirical prediction, the experimental data confirm a significant reduction in mean muscle activity due to the stiffness adaptation of the actuator. This result demonstrates the utility of the proposed

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actuator, and justifies the use of stiffness modulation as a portable means of actuation for human augmentation.

II. Stiffness Modulator

Stiffness modulators are tunable springs that generate a restoring force upon displacement. These devices consist of a motor, a compliant element, and a kinematic mechanism that couples the motor position at the device's input to the stiffness at its output, see Fig.1.

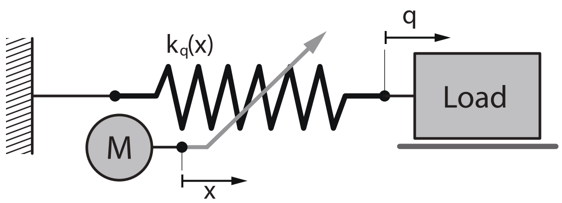

Fig. 1. Schematic representation of a stiffness modulator where x is the motor position, q is the output position (displacement of the load) and $k_q(x)$ is the output stiffness.

A. Model

The general mathematical model of a stiffness modulator is given by its potential energy function as well as the physical constraints that limit the motor position x and the output displacement q:

$$V = V(q,x), \quad x \in [0,1] \quad \text{and} \quad |q| \leq q_{\max}(x). \quad (1)$$

The potential energy function depends on the internal kinematic mechanism and the compliant element, while the physical constraints come from the limited motion range of the motor, and the stress limit of the compliant element.

Imposition of the following design conditions:

(i) zero output force at the equilibrium position

$$\partial V(q,x)/\partial q|_{q=0} = 0,$$

(ii) symmetric output force-displacement relation

$$\partial V(q,x)/\partial q = -\partial V(-q,x)/\partial q,$$

(iii) controllable output stiffness

$$k_q(x) = \partial^2 V(q,x)/\partial^2 q,$$

(iv) zero input force at the equilibrium position

$$\partial V(q,x)/\partial x|_{q=0} = 0,$$

(v) large output stiffness

$$\lim_{x\to 0} k_q(x) \to \infty,$$

(vi) finite motor force

$$\max_{x\in[0,1],|q|\leq q_{\max}(x)} \partial V(q,x)/\partial x < \infty$$

lead to a class of mechanisms characterized by theoretically infinite stiffness range, achievable using finite static motor forces [17].

The simplest mathematical model of a stiffness modulator characterized by the six conditions (i)-(vi) is given by:

$$V(q,x) \propto \frac{q^2}{x}, \quad x \in [0,1] \quad \text{and} \quad |q| \leq q_{\max}(x) \propto x. \quad (2)$$

According to this model, the output stiffness $k_q(x) = \partial^2 V/\partial q^2$, and the static force imposed by the compliant element to the motor $f_x(q,x) = -\partial V/\partial x$ obey the following analytical relations:

$$k_q(x) \propto \frac{1}{x} \quad \text{and} \quad |f_x(q,x)| \leq \max_{x\in[0,1]} |f_x(q_{\max}(x),x)| \propto 1. \quad (3)$$

The canonical model of a stiffness modulator (2) and (3) provides an ideal description of a device which possesses the six design features (i)-(vi) stated in this section. However, this model does not provide a guideline for the design of a functional device. In other words, there may be a number of different designs that could satisfy the six conditions (i)-(vi). In the next section, we present the model of one such design.

B. Canonical Stiffness Modulator

A canonical stiffness modulator, which is based on a variable length torsional leaf spring design, is shown in Fig.2. The kinematic mechanism of this design consists of motorized rollers that translate along the leaf spring. On one end, the rollers prevent the spring to twist. On the other end, the spring is connected to the output of the stiffness modulator which rotates when being loaded. As the rollers move, they change the active length of the leaf spring. Consequently, the torsional stiffness of the spring and the rotational stiffness of the output link change.

The simplest model of this design is given by [18]:

$$V(q,x) = \frac{Gah^3k}{2}\frac{q^2}{x}, \quad x \in [0,L], \quad |q| \leq q_{\max}(x) = \frac{\sigma_Y}{Gh}x \quad (4)$$

where G is the modulus of torsional rigidity, a and h denote the width and the thickness of the spring, $k \approx 1/3$ is the geometric correction factor of a torsionally loaded thin ($a/h > 10$) rectangular spring, x denotes the position of the roller, L is the total length of the spring, σ_Y is the yield stress and q is the torsional angular deflection of the spring, see Fig.2.

According to (4), the canonical stiffness modulator has the following features:

(i) The angular displacement of the device under constant load $\tau \in [0, \tau_{\max}]$ (where $\tau_{\max} = \sigma_Y a h^2 k$) is given by:

$$q_\tau(x) = \frac{\tau}{Gah^3k}x. \quad (5)$$

This relation shows that the maximum deflection of the spring is independent of the slider position $q_\tau(x)/q_{\max}(x) = \tau/\tau_{\max}$.

(ii) The stiffness under any load $\tau \in [0, \tau_{\max}]$ is:

$$k_q(x) = Gah^3k\frac{1}{x}. \quad (6)$$

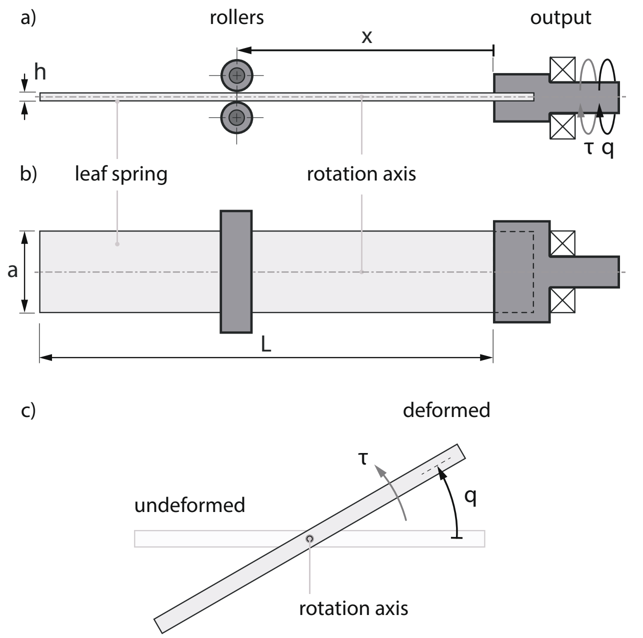

Fig. 2. Variable length torsional leaf spring design. a) Side view. b) Top view. c) Front view. τ is the torsional moment (load) applied to the spring. q is the angular displacement of the spring. x is the active length of the spring. The active length is changed by two position controlled rollers. As the length of the spring changes, the torsional stiffness of the leaf spring also changes.

This relation shows that the device is theoretically able to achieve infinite stiffness $k_q(x \to 0) = \infty$, the minimum stiffness $k_q(x = L) \propto 1/L$ is limited by the size L of the leaf spring, and that the output stiffness is a monotonic functions of the active length of the spring x.

(iii) The static motor force of this design is given by:

$$f_x(q, x) = \frac{1}{2} Gah^3 k \frac{q^2}{x^2}. \tag{7}$$

This relation shows that the motor force is zero at the undeflected configuration $f_x(q = 0, x) = 0$ and that the motor force remains limited irrespective of the deflection q and the stiffness setting x i.e., $|f_x(q, x)| \leq \max_{x \in [0,L]} |f_x(q_{\max}(x), x)| = ahk\sigma_Y^2/2G$. These features lead to intrinsically low power stiffness modulation [8]. Additionally, according to (5) and (7) the motor force is constant under constant load irrespective of the stiffness setting.

In summary, the simplicity of this stiffness modulator may enable a lightweight, self-contained, and energetically autonomous implementation. In the following section, we present one such implementation.

III. Portable Stiffness Modulator

A single joint stiffness modulator has been designed and fabricated as shown in Fig.3. The device resembles the canonical design presented in the previous section. The device is compact, lightweight, and self-contained (Table I). These features make it suitable for human augmentation [1], [19], [20]. In the following section, we detail the design of this stiffness modulator.

TABLE I

Technical specifications of the portable stiffness modulator

Mass of the mechanical structure	680g
Size (Length × Height × Width)[a]	$295 \times 72 \times 45$mm
Output angular displacement[b] $q \in [q_{\min}, q_{\max}]$	$[0, 1.75]$rad
Stiffness range[c] $k_q \in [k_{q\,\min}, k_{q\,\max})$	$[3.12, \infty)$Nm/rad
Minimum power for changing stiffness[d] $p_{\min}$	0.3W
Maximum efficiency $\eta_{\max}$	75%
Mass of the electronics	250g
Operating voltage V	11.4V
Current range $I \in [I_{\min}, I_{\max}]$	$[0, 4]$A

[a]Main body of the device.
[b]At minimum stiffness setting $k_q(x = L) = k_{q\,\min}$.
[c]Infinite stiffness means that the output link is kinematically locked.
[d]When there is no load $\tau = 0$. See the supplementary video.

A. Design

The design of the stiffness modulator aims to achieve a good balance between structural integrity, functionality, and weight. The mechanically minimalistic main frame consists of two high-strength aluminum alloy parts connected via two stainless steel linear guides (Fig.3a). These parts were designed to serve structural and functional roles while having a small footprint.

The mechanism responsible for stiffness modulation is based on the canonical design detailed in Section II-B. It uses a single leaf spring (Full hard SUS301, length $L = 160$mm, width $a = 20$mm, and thickness $h = 1$mm) as the compliant element. On one end, the leaf spring is constrained by a roller-slider support, while on the other end it is connected to the output link, see Fig3a. The roller-slider support (Fig.3b) prevents the twisting of the end of the spring, and is guided by stainless steel linear guides. The connection between the roller block and the guides is realized via linear ball bearings to minimize friction. The roller block is moved by a ball screw (Thomson Linear Miniature Precision Ball Screw, diameter $d = 6$mm and lead $p = 2$mm). As the rollers move, the active length of the leaf spring changes which then also changes the output stiffness of the device. At the output, the spring is connected to a custom made gearbox ($1.85 : 1$ gear ratio). This gearbox keeps the angular displacement of the leaf spring within safe limits while allowing large angular displacement at the output link. The gearbox contains two helical gears which align the output link of the device with the human limb. It is important to note that the spring remains within its undeformed envelop upon deformation. These features allow the device to provide effective stiffness modulation without being bulky or heavy, see Table I.

The drivetrain requires low power to hold stiffness and is also efficient when changing stiffness. The drivetrain consists of a low voltage DC motor (Maxon DCX 22 L Series, 9V) and the ball screw. The motor drives the ball screw via $1 : 1$ ratio spur gears. Energy losses are minimized by the roller support between the slider and the spring which in turn

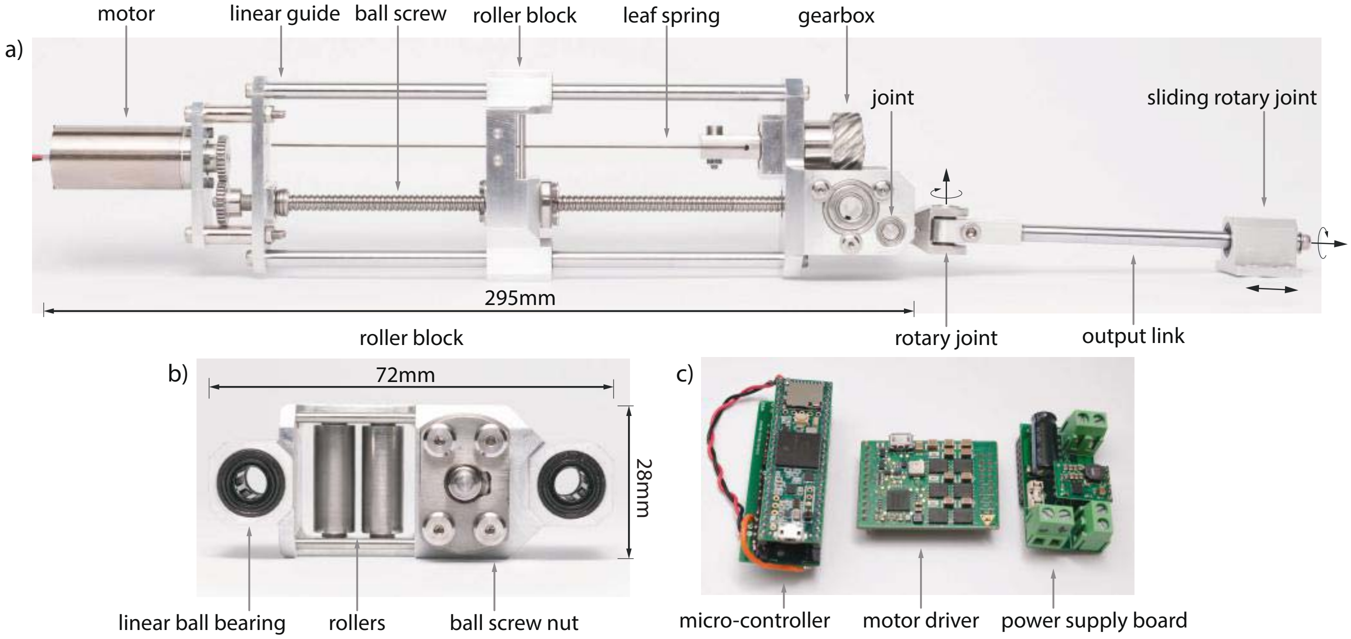

Fig. 3. Portable stiffness modulator. a) Mechanical structure. b) Roller block. c) Electronics.

eliminates sliding friction. As a result, changing stiffness quasi-statically requires approximately $p_{\min} \approx 0.3$W power when the device is not loaded. Furthermore, the maximum efficiency of the drivetrain is $\eta_{\max} \approx 75\%$. The ball screw ensures that the motion of the roller block is back-drivable and energy efficient. Although, this may suggest that holding stiffness requires considerable power, due to the analytical condition (7), the motor force required to hold stiffness remains relatively low even at high output deflections. For example, without any electrical energy input, the motor is able to hold stiffness under approximately 1.45Nm applied torque. All the above-mentioned features promote low power energetically autonomous operation.

The device is self-contained; its electronic control interface contains a micro-controller (PJRC Teensy V3.6), a motor driver (Maxon ESCON Module $50/5$) and a power supply board shown in Fig.3c. These components, together with the motor, are powered by a LiPo battery pack (Revolectrix Blend435 SILVER Label 70C Series, 3 Cells 11.4V). The feedback for the motor controller is provided by a rotary magnetic encoder (AMS AS5045). Most of these components are mounted onto the upper portion of the device in order to reduce their effect on the user.

In summary, the proposed design provides a compact, lightweight and self-contained realization of the conceptual stiffness modulator proposed in Section II-B.

B. Characterization

In this section, we summarize the experimental characterization of the presented device. The setup is shown in Fig.4a. During the experiment, we applied a constant external load ($\tau \approx 2.15$Nm). By moving the roller block, stiffness was modulated from the minimum ($x = 135$mm) to the maximum ($x = 5$mm) at a slow speed ($|\dot{x}| = 2$mm/s). The experiment was repeated ten times. In each experiment, the angular displacement of the leaf spring q, the position of the roller block x, and the current drawn by the motor I were recorded. The results are summarized in Figs.4b-d.

Figure 4b shows that the angular displacement of the leaf spring decreases as stiffness increases. The experiment is consistent with the model (5) at small displacements where it displays a linear relation between the deflection and the active length of the spring, i.e. $q \propto x$.

Figure 4c indicates that the stiffness profile of the device follows the theoretically predicted inverse relationship with respect to the rollers' position (6), i.e. $k_q \propto 1/x$.

Figure 4d shows that the electrical current I used to drive the motor, and consequently the motor force $f_x \propto I$, fluctuates around the constant value predicted by the theoretical model, i.e. according to (5) and (7), $f_x \propto \tau^2$ at constant load.

The experimental data also show differences compared to the theoretical prediction. In particular, the angular displacement remains nearly constant when the stiffness is low (see Fig.4b), and the input force of the motor fluctuates around the predicted value instead of being constant (Fig.4d). A major source of these deviations is the sliding friction in the helical gears. While this effect has been mitigated by lubrication, the friction in the gears helps the motor to hold stiffness (see Fig.4b and Fig.4d for $x \in [60, 135]$mm) while requiring high force when changing stiffness and moving the output link (see Fig.4d for $x \in [5, 60)$mm). These effects may be alleviated by a simple design modification in which the helical gears are replaced with bevel gears. However, even in the current implementation, the observed deviations do not compromise the main features of the device when used for human augmentation. We substantiate this point in

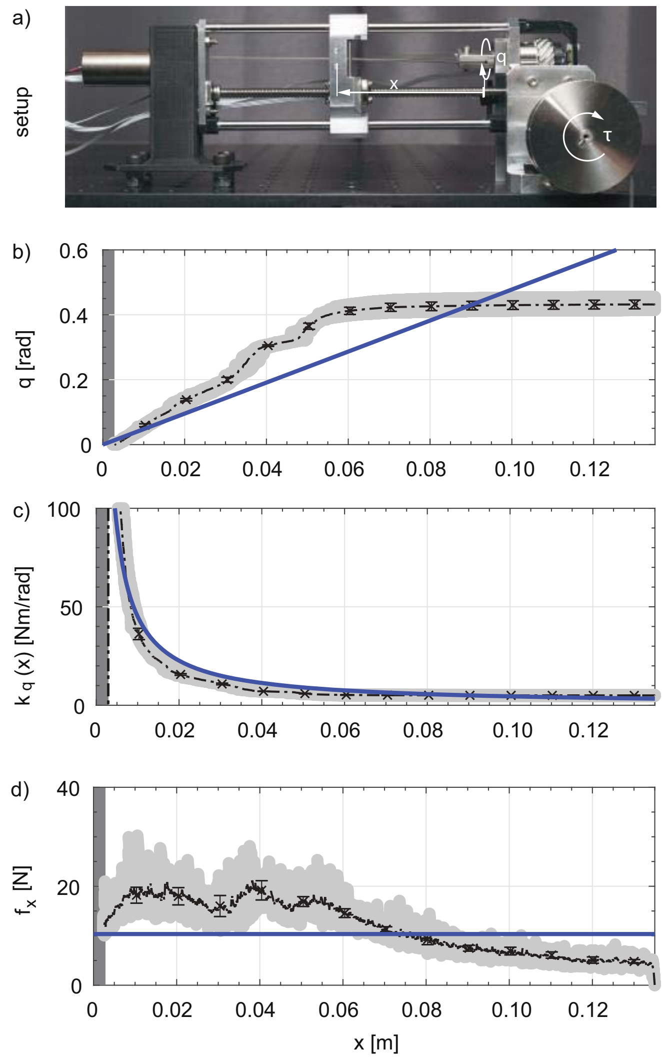

Fig. 4. Experimental characterization of the stiffness modulator. a) Setup. b-d) Experimental data. b) Angular displacement of the leaf spring q versus the position of the rollers x. c) Output stiffness k_q versus the position of the rollers x. d) Input force of the motor f_x versus the position of the rollers x. The figures show the data collected at 1000Hz over ten experiments (gray), the mean of the data (black dashed lines) and the variation in the data given by two standard deviations (error bars). The model predictions (blue lines) are based on (5), (6) and (7), and the relation between the current and the force on the ball screw is given by $f_x \approx 2\pi k_m I/p$ (where $k_m = 6.95 \times 10^{-3}$ Nm/A is the torque constant of the motor, I is the current drawn by the motor, and $p = 2$mm is the lead of the ball screw). The active length of the leaf spring is given by $x \in [5, 135]$mm.

the next section.

IV. Human Augmentation

In this section, we use the device to augment a human at the knee joint. We aim to investigate the effect of this augmentation on the activation of the leg muscles during a sit to stand to sit task, see Fig.5.

A. Exoskeleton

The device was mounted onto a post-operative knee brace, see Fig.5a,b. A commercial knee brace was chosen as the human-robot interface because it is already engineered for user comfort and can be easily interfaced with the device. The stiffness modulator and the knee brace were aligned to lessen any interference during the operation of the exoskeleton. This was afforded by the output link which has one linear degree of freedom to accommodate for axial misalignments of the joints and two rotational degrees of freedom which compensate for angular misalignments along and perpendicular to the leg of the wearer, see Fig.3a, Figs.5a,b. As a result, the output link was only affected by knee flexion and extension while misalignments between the device and the joint were largely eliminated. These features ensured smooth and comfortable operation of the exoskeleton [19], [21].

The exoskeleton was used to assist a human in a sit to stand to sit task. In order to understand the effects of this assistance, the activation of the knee extensor (quadriceps) and flexor (hamstring) muscles were measured using electromyography (EMG) sensors. We favored small electromyography sensors over other means of measuring body energy consumption, using for example an indirect calorimetry system, because of the portability, compactness, and low power consumption of the former. In this regard, the low power consumption of EMG sensing lead to a device that is self-contained and does not need to be tethered to an external power supply.

B. Experiment

Using the exoskeleton device, we aim to augment the stiffness of the knee joint in order to reduce the muscle activity of the wearer. In this section, we present preliminary results of such human augmentation.

One healthy test subject was tasked to sit on a chair, get up and sit again, with and without the help of the knee exoskeleton, see Figs.5c,d. This task is one of the more physically demanding everyday tasks in terms of energy consumption [22]. At the beginning of the experiment, the chair was adjusted to a suitable height for the subject. The subject was then given a grace period of five minutes to acclimatize to perform the task using the exoskeleton prior to the actual testing, and was not permitted to use the armrests for support during the test.

The stiffness of the exoskeleton was initially set to the minimum ($x = 135$mm) and was gradually increased at every subsequent experiment (the active length of the spring was decreased by $\Delta x = 5$mm), see Fig.6. At each stiffness setting, the subject repeated the task eight times. The EMG signals of the quadriceps (rectus femoris) and hamstrings (biceps femoris) muscles were recorded and analyzed. In order to get a baseline for comparison, two control experiments were conducted. In the first experiment, the subject did not wear the exoskeleton. This experiment was used to obtain the baseline muscle activation for the task. In the second experiment, the subject wore the exoskeleton but with the output link disengaged. This second experiment was used to assess the effect of weight of the exoskeleton and the discomfort caused by interfacing the exoskeleton and the subject.

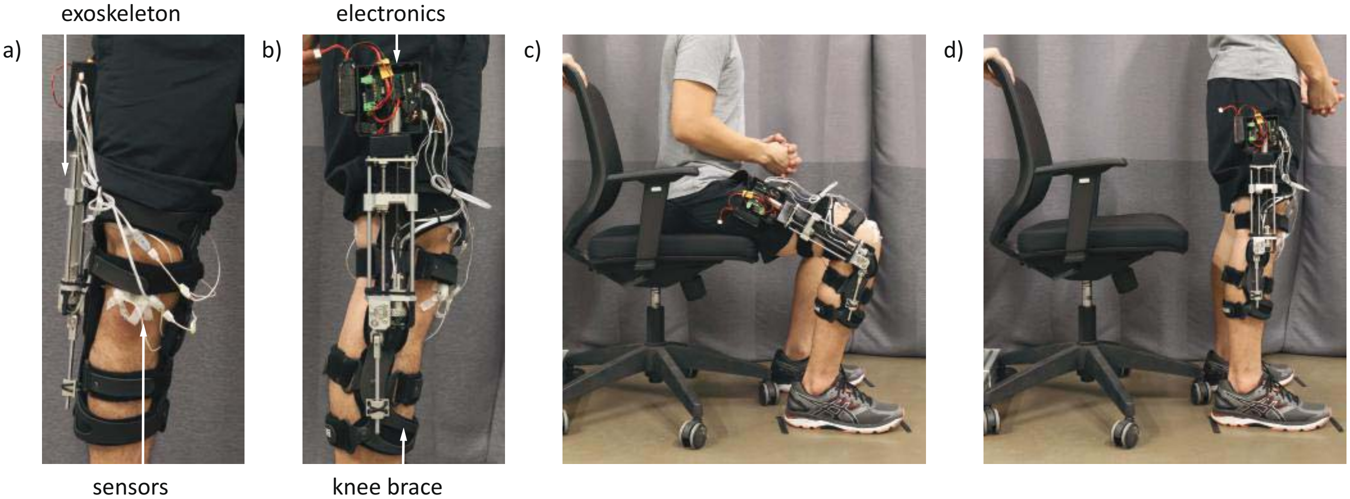

Fig. 5. Human augmentation. a-b) Knee exoskeleton. c) Sitting. d) Standing. The total mass of the portable stiffness modulator is 930g. This includes the mechanical structure, the electronics, the battery, and the sensors.

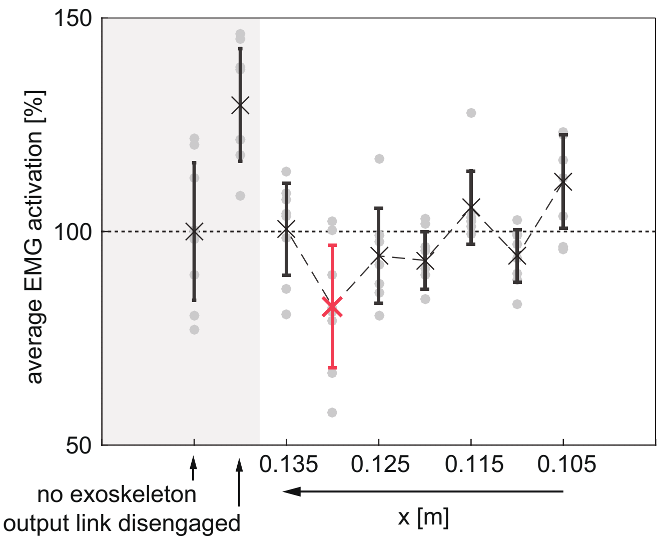

Fig. 6. Experimental data. Average muscle activation versus the stiffness setting of the exoskeleton. The figure show the data collected over eight trials per stiffness setting (gray), the mean of the data (black dashed lines), and the variation in the data given by two standard deviations (error bars). Processing: The raw EMG signals from each muscle group were rectified and filtered through a 50Hz low pass filter. A moving average filter (over 0.1s) was then applied to obtain the envelope of each EMG signal. This signal was used to characterize the activation of the considered muscle group. The activation of the two antagonistic muscle groups were summed, averaged over the period of each sit to stand to sit task and then normalized. The obtained data was used as a surrogate for the energy required by the subject.

Figure 6 summarizes the experimental results. The plot shows that there exists a roughly quadratic relationship between the muscle activity of the test subject and the stiffness setting of the exoskeleton. In particular, we observe that, as the stiffness of the exoskeleton increases, muscle effort initially decreases before it starts to increase. At the optimal stiffness setting ($x = 130$mm), a 17.5% reduction in the averaged muscle activity level was obtained as compared to when the exoskeleton is not worn by the test subject. By comparing the actual experiments in which the exoskeleton was active to the control experiments in which it was disengaged, we observe that the effect of stiffness augmentation is able to outweigh all other cumulative effects including the weight of the exoskeleton and other, often critical, interfacing issues which in many cases hinder effective human augmentation with robotic exoskeleton devices [23]. Finally, we note that the motor was found to draw only 0.13A during the experiments, which made the total power consumed by the device less than 2W. This means that the battery included in this lightweight device (mass $\leq$ 1kg) could last more than 12 hours when used for low power stiffness augmentation (power $\leq$ 2W).

Overall, the results of these experiments support our proposition that the presented portable stiffness modulator is capable of reducing the level of muscle activation with minimal energy cost. This justifies further exploration of the design as well as the actuation concept proposed in this work.

V. Conclusion

We propose stiffness modulation as a portable means of actuation for human augmentation. By avoiding force augmentation, seen in more typical compliant actuators, a compact, lightweight and self-contained stiffness modulator was developed. This device provides a large range of stiffness modulation and is energetically autonomous. Preliminary experimental results indicate that the device used as a knee exoskeleton is able to significantly reduce muscle activity in a natural sit and stand task. This result supports the proposition that stiffness modulation may be used to portably and effectively augment a human. The obtained results also bring into question the importance of providing mechanical work in exoskeleton designs for able-bodied human augmentation.

The proposed device may be useful in a number of different applications (i) to provide better stabilization, disturbance rejection, and to improve endurance through stiffness augmentation [24], (ii) to assist in everyday tasks including sit to stand transition [25], and (iii) to speed up recovery from joint weakness after limb injury or lack of joint stability after surgery. However, the proposed device may be ineffective in supporting paralyzed patients due to its minimalistic design. Future work involves the improvement of the proposed device through better mechanical and electronic components as well as the investigation of the underlying biomechanical effects in greater detail.

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