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Toward Motor-Unit-Recruitment Actuators for Soft Robotics

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Abstract— **Among the many features of muscles, their softness, (the ability to deform to accommodate uncertainty in the environment), and their ability to continue functioning despite disturbances, even partial damage, are qualities one would desire to see in robotic actuators. These properties are intimately related to the manner in which muscles work since they arise from the progressive recruitment of many motor units. This differs greatly from current robotic actuator technologies. We present an actuation platform prototype that can support experimental validation of algorithms for muscle fiber recruitment-inspired control, and where further ways to exploit discretization and redundancy in muscle-like control can be discovered. This platform, like muscles, is composed of discretely activated motor units with an integrated compliant coupling. The modular, cellular structure endows the actuator with good resilience in response to damage. It can also be repaired or modified to accommodate changing requirements in situ rather than replaced. Several performance metrics particular to muscle-like actuators are introduced and calculated for one of these units. The prototype has a blocked force of 2.51 N, a strain rate of 21.1 %, and has an input density of 5.46 $\times 10^3$ motor units per square meter. It consumes 18 W of electrical power during a full isometric contraction. The actuator unit is 41.0 mm^3 in size. The force during isometric contractions as it varies with activation is evaluated experimentally for two configurations of modules.**

I. INTRODUCTION

Part of the genius of skeletal muscle as an actuator is its discrete, cellular structure. Soft, "artificial muscles" are being increasingly viewed as a potential solution as the robotics community grapples with the challenges of unstructured environments [1]. While there are several good recent works on soft robotics [2], [3], a discrete, modular paradigm for actuation represents a largely untried frontier. The modular actuation unit presented in this paper, shown in Figure 1 represents a first step toward exploring the implications of a cellular muscle-like architecture in an engineering context. It will support experimental investigations into recruitment strategies. The key principles involved are discrete activation, integrated compliance, and a hierarchical arrangement.

Compliance was the earliest characteristic to be explored in producing more human-like robots. Beginning with Pratt's seminal work in the 1990s [4], which showed the importance of series elastic elements in robotic actuation, much effort has been focused on novel uses and implementations of series elastic actuators. One extension of particular interest in duplicating muscle-like performance is variable-impedance actuation [5], [6]. Vanderborght et al. [7] provides a good review. In nearly every case the implementation involves some type of mechanism with a deformable component connecting a traditional servomotor to the load.

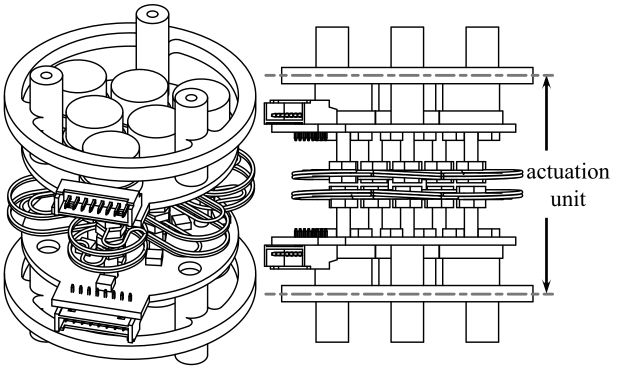

Fig. 1. Single degree-of-freedom actuation unit consisting of discretely activated elements coupled to the mounting feature by a compliant element. This actuation unit is a "building block" for constructing designer muscle-like actuators with a hierarchical structure. Such actuators are controlled by setting an activation level, or the number of active elements in the "on" state, a process known as *recruitment*.

The fact that skeletal muscle is composed of numerous actionable units arranged in a hierarchical manner, though distinctive, has received less attention than compliance. Notable exceptions include the work of Dittrich [8], and Huston et al. [9]. Both of these works present a type of actuator that is made up of numerous "sub-actuators." This endows the overall actuator with great robustness to failure because if one unit fails, the remaining units can carry the load. Instead of resulting in a loss of a *degree of freedom*, failure of an electromechanical part results in a *loss of performance*, a preferable failure mode.

In fact, the neurological input to a muscle is not an analog signal, but an *activation level*, or the number of discrete on-off units that are in the "on" state. The way the brain controls the motor system by setting the number of units active at a given instant in time is referred to in physiology as *recruitment*[10]. This is a fundamental idea in movement science, but there are only a few engineering works that consider this idea, such as [11], [12]. This work presents a platform in which discrete activation, compliance, and a hierarchical structure go hand-in-hand. Its discrete cellular structure makes the hardware well–suited to build *ex vivo* experiments to test neurologically inspired control schemes.

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II. CONCEPTS AND KEY TERMS

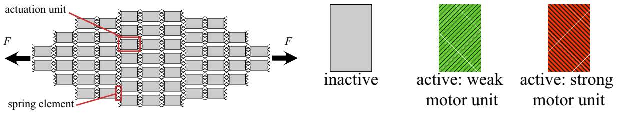
Although examples of mechatronic devices composed of modular units exist, most are in the context of self-organizing systems [13] or distributed manipulation [14]. Other than those described in Section I, the authors are not aware of applications where modules are combined in such a way as to meet a performance characteristic for a particular joint axis. To formalize these notions, the following terms are introduced or borrowed (with some license) from Biology, and their specific meanings in the context of this paper delineated:

- **cellular [15] muscle-like actuator**: a motion or force producing device composed of more than one actuation unit and containing more than one motor unit.
- **actuation unit**: this is a manufacturing distinction. It refers to the smallest possible unit that can be conveniently added, removed or reconfigured to adjust the muscle-like actuator's characteristics.
- **motor unit [10]**: this is computational or communication distinction. It refers to the collection of force-producing devices that can be independently activated or deactivated by a single communication line.

Actuation units' and motor units' physical boundaries may coincide, but are not required to. Various interpretations (or implementations) are shown in Figure 2. Each paradigm can be associated with a biological interpretation, depending on what physiological unit (individual muscle fiber, fascicle, etc.) is considered to be an "actuation unit." The implementation in this paper, to be described in Section V, has each motor unit corresponding to one solenoid. Each actuation unit has multiple solenoids, so it is an example of the paradigm in Figure 2c. Models corresponding to the remaining paradigms could be constructed with similar hardware but different software and signal routing decisions.

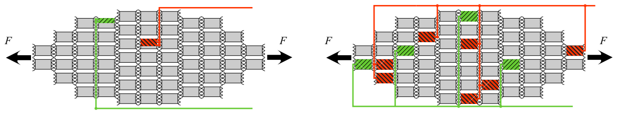
The functional model of an actuation unit of the particular type described in this work is explained in Figure 3. This is an example of the paradigm in Figure 2c. When an active element contracts, it deforms the compliant connecting material, which results in a force at a central mounting feature. As will be described in subsequent sections, this compliant connecting material is critical to operation, and is considered to be part of the actuation unit, not merely a mechanical coupling. Adjacent actuation units connect to this mounting feature and ultimately, to the robotic link itself. The force at the mounting feature, F, is a function of the number of motor units active and the contraction of the actuation unit, x. If an actuation unit experiences an extension ($x < 0$), plungers of the inactive units will rest against a mechanical stop, and the unit will behave as a spring with maximum stiffness (all of its springs in parallel). These units are designed to be used in an antagonistic configuration. As such, they will have at least a small preload, and completely inactive motor units will always be in this high-stiffness mode. This stiffening-when-overextended behavior helps prevent run-away under high loads.

A unit's force supplied can be described by Equation (1):



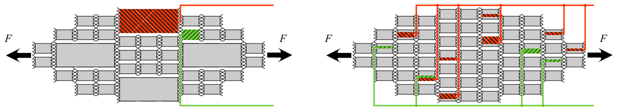
(a) A muscle-like actuator consisting of actuation units

(b) legend



(c) There are more signal lines than actuation units. Each actuation unit has multiple active elements. Each motor unit is contained within a single actuation unit.

(d) There are more actuation units than signal lines. Each signal line activates some collection of actuation units, forming a motor unit.



(e) Each motor unit consists of one actuation unit. To have motor units of different strengths, actuation units must have different characteristics.

(f) Motor units are dispersed among several actuation units. There is no geometric correspondence between the concept of actuation and motor units.

Fig. 2. Different paradigms for actuation units and motor units. (a) shows a muscle-like actuator composed of discretely activated actuation units coupled by compliant elements. (c) - (f) show the potential manifestations of strong and weak motor units; each example shows one strong and one weak motor unit active, with the remaining motor units inactive. The signal lines to inactive motor units have been omitted for clarity.

$$F = \begin{cases} (\ell_0 - x)\sum\limits_{i=1}^{M} k_i, & x \geq 0 \\ (\ell_0 - x)\sum\limits_{i=1}^{M} k_i \quad - \quad x\sum\limits_{j=1}^{N-M} k_j, & x < 0 \end{cases} \tag{1}$$

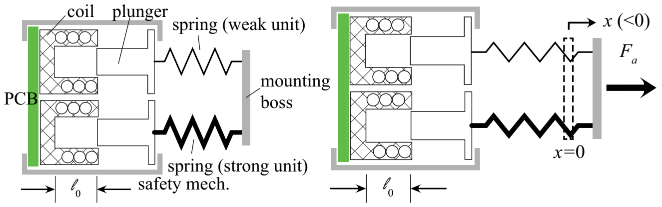
where k_i, k_j are the spring constants from each motor unit to the mounting feature, x is the position of the mounting feature and ℓ_0 is the maximum plunger travel. N represents the total number of motor units, and M is the number of motor units active.

III. COMPLIANCE AND DISCRETE ACTIVATION

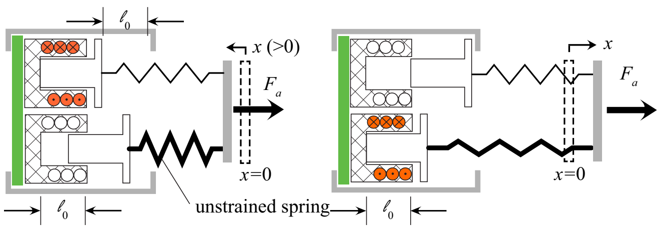
A. *Compliance enables discretization*

Skeletal muscle fibers are arranged in parallel in sufficient numbers to generate the required force. A single muscle fiber does not necessarily run the entire length of the muscle, so series connections are also important [16]. A muscle contraction involves a shortening of certain muscle fibers and not others. As would be expected from a biological system, each muscle fiber does not contract by the same amount. If a bundle of fibers were to be tied together at their ends with a rigid end cap, a contraction of a single fiber while leaving the length of the other fibers unchanged would violate the compatibility condition of mechanics of materials [17]. In skeletal muscle, the fibers are instead connected together by endomysial connective tissue [16], which is elastic.

By connecting a contractile unit (analogous to a muscle fiber) through a compliant connection, rather than a rigid one, the compatibility condition is satisfied. Instead of requiring



(a) actuation unit schematic (b) inactive: spring behavior



(c) active: contraction (d) active: high external load

Fig. 3. Actuation unit concept schematic; only one strong and one weak motor unit are shown for clarity. (a) shows an inactive unit under zero load. The springs are at their resting length. When inactive, as in (b), any external load will cause a negative displacement x, the plungers will rest against the mechanical stop. When one or more units are active ((c) activates a weak motor unit) and the external load is not excessive, the actuation unit will contract. Plungers of inactive motor units will "float," keeping their springs at resting length. Under high external loads, inactive plungers are pulled against the mechanical stop, ((d) activates a strong motor unit) the displacement will be negative, but compared to (b), the force will be higher for a given displacement. In all four scenarios, the unit exhibits springlike behavior, but the stiffness depends on the number of strong and weak motor units active.

displacements to be equal, the compliant material imposes a mathematical relationship between displacement and the force contribution of that fiber. In modular actuation units, this force-displacement relationship can be exploited and specified to obtain desirable properties for the muscle-like actuator as a whole.

B. Strategic compliance properties for unit function

The piezoelectric cellular actuator [15], [18], is an example where the compliant material is deliberately structured in a hierarchical mechanism–within–mechanism or *nested* configuration so that it acts as a displacement amplifier. The compliance mitigates the fact that the active material, piezoelectric ceramic, has a strain rate of just 0.1% [19].

Strain amplification is just one example of how the compliant material linking the active material can be exploited. Each active element of the piezoelectric cellular actuator was identical and interchangeable from the perspective of its result at the actuator output. This greatly simplified the control of the device and avoided concerns about the hysteresis of piezoelectric materials [20]. This was for mathematical simplicity and represents a departure from biology in that skeletal muscle has motor units of different characteristic (in terms of size and actuation speed). The central nervous system deliberately chooses activation patterns that make use of these differences [21]. This paper begins to explore this idea starting from the hardware perspective. The actuation unit pictured in Figure 1 has the compliant coupling mechanism specifically constructed so as to produce *different operating characteristics from physically identical active elements*.

All solenoids are identical, and functionally they act as a displacement source. The characteristics of the spring element a given solenoid is connected to determines whether it is a *strong* or *weak* motor unit. The spring path to the mounting feature is stiffer for the strong motor unit than for the weak, resulting in a higher force for the same solenoid displacement. It is easy to generalize this concept to actuators which posses finite numbers of actuation levels greater than 2; there would simply be more grades of stiffness. The geometry is chosen such that

$$k_{weak} = r\ k_{strong},\ r \in \mathbb{R}/\mathbb{Q}, 0 < r < 1 \qquad (2)$$

where k_{weak} and k_{strong} are effective spring constants from the active material to the load and r is an irrational proportionality constant. For the actuator in Figure 4 this was selected to be $1/\sqrt{2}$. This prevents the contribution of small numbers of strong motor units from being identical to that of larger numbers of weak motor units, conserving a greater richness of potential control inputs while producing only a modest reduction in blocked force.

IV. MUSCLE-LIKE ACTUATOR PERFORMANCE METRICS

When comparing muscle-like actuation technologies it helps to have a set of metrics by which to compare their relative merits. Existing ones are reviewed and some new ones specific to modular actuators are introduced in this section.

The force developed by a skeletal muscle varies with extension. Exactly where along the stroke the maximum force capability occurs is dictated by numerous bio-mechanical factors, but in general it is near the beginning of the stroke [10] and decreases with controlled length contraction. For this reason, in actuators it is called the *blocked force* F_{block}. The *stress* the actuator can apply $\sigma_{block} = F_{block}/A$, where A is the cross-sectional area, is also of interest.

Another important metric is the *strain* ϵ, or how much the actuator can contract normalized by its uncontracted length. The area and volumetric *input density*, η_A and η_V, or number of inputs per unit area or volume, is important because it quantifies the granularity of the control, and sheds light on the relative benefits of various spatial arrangements. Finally, steady state power consumption, P_{ss} should be considered when evaluating any actuator type, and biologically inspired actuators are no exception.

V. IMPLEMENTATION

The role of a muscle motor unit is played by a miniature solenoid; each actuation unit contains twelve. This solenoid is produced by the Line Electric Company, S. Glastonbury, CT, USA, and claims to be "the world's smallest solenoid". The form factor of this solenoid is the same as a TO-5 transistor package and is particularly suited to the construction of compact actuation units. Performance specifications of the solenoid are listed in Table I. Each solenoid can be

TABLE I

TO-5 SOLENOID PERFORMANCE SPECIFICATIONS. PEAK FORCE ASSUMES THE PLUNGER IS AT 80% OF FULLY CONTRACTED

Quantity	Value	Unit
Stroke Length	2.54	mm
Peak Force	1.6	N
Steady State Force	1	N
Response time (max)	0.5	ms
Cross Section	65.4	mm^2
Coil Resistance	6	Ω

TABLE II

MUSCLE-LIKE ACTUATOR COMPARED TO A LINEAR MOTOR

Metric	Actuation Unit	BLMUC-79
F_{block}	2.51 N	31.4 N
σ_{block}	2285 N/m^2	21600N/m^2
ϵ	21.1 %	n/a
η_A	5.46 $\times 10^3$ motor units per square meter	n/a
η_V	293 $\times 10^6$ inputs/m^3	n/a
P_{ss}	9W	7W

independently activated, making it a convenient analog to a biological motor unit. For large systems composed of many of these actuation units, actuators following the actuation unit/motor unit paradigms in Figure 2c, (d), or (f) could be constructed by appropriate electrical routing and software means. Active materials such as electroactive polymers [22] and shape memory alloy [23] could also be used.

The solenoids consist of two parts, the coil and the plunger. If sufficient current is present in the coil, the plunger will be drawn into the coil until it reaches a mechanical stop. If there is no current present, the plunger will float ($x > 0$) or rest against a mechanical stop ($x \leq 0$). The coils are soldered to a custom printed circuit board which manages electrical connections to each solenoid, while structurally coupling them together rigidly. A rigid standoff mounted to the printed circuit board allows the connection of additional modules in series. The module presented has two concentric rings of 3 solenoids each, closely packed for the best use of space. The inner ring corresponds to the weak motor units, and the outer ring to the strong motor units.

Current is provided to the solenoids by a custom drive circuit that is activated by a digital signal. Upon activation, the circuit provides a burst of current (3A) for a short duration (nominally 20 ms). The level and duration of the current burst is set so that in the worst-case scenario (isometric contraction) the solenoid plunger will still reach the ferrous rear plate of the coil during the high-current period. This closes the magnetic flux gap, increasing the total force. After this short burst, the current drops to a steady state level of 0.5A, to hold the plunger in the solenoid coil.

The compliant mechanism connecting the solenoids to the load is composed of 3 custom wireforms provided by the Active Spring Company, Sibley's Green, United Kingdom, clamped together at the center by a custom trefoil nut, forming the mounting feature. Each wireform has two lobes, one in a circular profile with 1.5 turns, and the other, an oblong coil with 2 turns. A solenoid plunger connects to each lobe using jam nuts. When a given solenoid is activated, it acts as a binary displacement source to the corresponding lobe of the spring element, and the force applied to the load depends on the spring constant of the lobe, whether it is k_{strong} or k_{weak}. The spring element has nearly zero thickness in the actuation direction, so as to maximize strain.

VI. EVALUATION OF PERFORMANCE METRICS

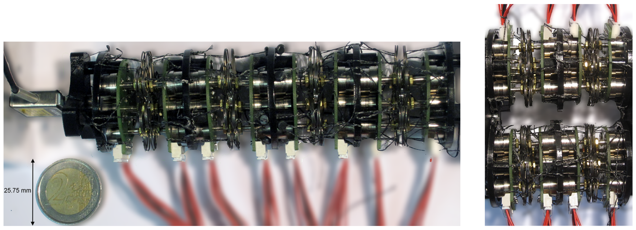
The actuation unit described in Section V represents a first prototype of the muscle-like actuation concept. The metrics of Section IV are evaluated for this example and its relative merits discussed in terms of these metrics. Its design will be compared to a commercially available linear motor, the AeroTech BLMUC-79 series (which has comparable cross-sectional area), where applicable. These are summarized in Table II. F_{block} is 2.51 N, and σ_{block} is 2285 N/m^2. This is an order of magnitude less than the linear motor, which has values of 31.4 N, and 21600N/m^2, respectively. It is expected that these numbers will become more competitive as the muscle-like technology matures, but it is reasonable to expect that some sacrifices will be made with regard to maximum force to receive the benefits of the cellular structure and integrated compliance.

η_A is 5.46 $\times 10^3$ motor units per square meter and η_V is 293 $\times 10^6$ inputs/m^3. This is calculated based on the actual cylindrical envelope of the prototype unit, which is lower than the theoretical values calculated from close-packing. The strain rate is 21.1 %, which compares favorably with human muscle [24]. Comparing this value to the travel of the linear actuator is not a valid comparison, since its travel length depends only on the length to which the linear motor is manufactured.

The power consumption of the prototype is 9W if all 6 units are active. The linear motor consumes 7W during an isometric contraction at the maximum continuous current allowed, the same order of magnitude. One drawback of the muscle-like actuator is that it consumes a fixed amount of current per solenoid, even if the applied load is not large. This should not pose a barrier to adoption, however, because the situation is the same with stepper motors, which are used widely. The prototype uses the same amount of holding current for each motor unit; the overall power consumption could be reduced by using less current for the weak units.

VII. EXPERIMENTAL RESULTS

Four actuation units containing 12 solenoids each were assembled. The spring element lobes were configured so that the 3 solenoids in the inner ring correspond to weak motor units, and the 3 solenoids in the outer ring correspond to strong motor units. Two configurations were evaluated (shown in Figure 4: a series chain of 4 units (a), and a bundle formed of two series chains placed in parallel (b). Each solenoid can be activated from a Mathworks Matlab interface. This interface communicates over the serial port with an Arduino microcontroller running custom firmware, which generates the digital input to the drive circuit, causing current to flow in the coil of the corresponding solenoid.



(a) 4 actuation units in series

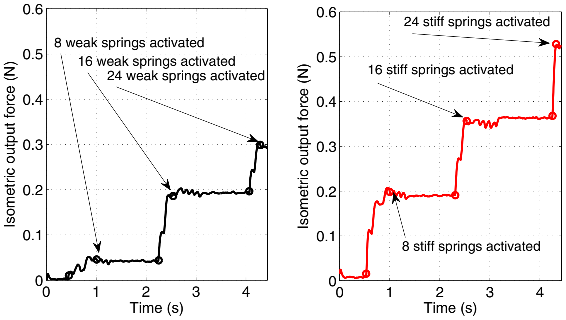
(b) 2 chains of 2 actuation units in parallel

Fig. 4. Actuation units in two constant length configurations. The central mounting feature is connected to a load cell to measure isometric contraction force with varying activation levels.

Each configuration is connected to a rigid bracket through a Futek (Irvine, CA, USA) LSB-200 load cell with a range of 4.5 N, which measures the force applied by each setup. The signal from the force sensor is amplified by a Futek CSG110 signal conditioner, and its output recorded. The other end is mounted to another bracket, such that the configuration is fixed at its resting length. Activation of any motor unit(s) will result in an isometric contraction and deformation of the spring elements.

With a total of 48 motor units, it is impractical to present all possible activation patterns. The following simple examples were deliberately chosen to illustrate the functionality of the device. Motor units were activated in homogenous (all strong or all weak) collections of 8. Richer patterns consisting of combinations of weak and strong motor units can also be chosen with no modification to the hardware. Each test proceeded as follows: 8 units were activated, followed by an interval of approximately 2 s, then 8 more were activated, followed by another interval, then the remaining 8 were activated. This was performed for the strong motor units and the weak motor units on each of the setups in Figure 4. Figure 5 shows how the force varies with activation in time for a representative trial activating the weak (a) and strong (b) motor units. In each force history four different force levels (including zero) can be distinguished. The force converges to steady state within 200ms and remains constant until the activation level is changed. As indicated by the arrows and annotations, each consecutive level has 8 more motor units active than to its predecessor. Activation of each of the 8 solenoids was staggered slightly to avoid high peak currents. The data was filtered with a second-order Butterworth filter with a normalized cut-off frequency of 0.05.

Figures 6 to 8 show the force corresponding to the various activation levels over several trials. The yellow bars represent data from the actuator with 4 units in series. The green bars represent data from the actuator with 2 parallel bundles of 2 units in series. Each pair of bars represents data from experiments with the same number of motor units active. It is clear that each green bar is always higher than its yellow neighbor. In an isometric contraction with the same activation level, theoretically the force output of an actuator with 2 bundles should be double of the output force of an actuator with only 1 bundle and the data appears to bear this out over the range of activation levels.



(a) weak motor units

(b) strong motor units

Fig. 5. Force history during an isometric contraction resulting from activation and deactivation of collections of weak and strong motor units vs. time. Results are from the series case, pictured in Figure 4a. The parallel case (Figure 4b) produces similar results with a higher amplitude.

Figure 6 shows three activation levels, respectively 8, 16 and 24 weak motor units active. Figure 7 shows the same activation levels, but for the strong motor units. As a result, the output forces are higher in comparison to Fig. 7. The output force increases more or less linearly with increasing activation. Figure 8 compares the activation levels of 24 weak units active, 24 strong units active, and a combination of 24 weak and 24 strong units active.

VIII. CONCLUSIONS

Most actuators that are termed “muscle-like” are so called because they incorporate physical compliance. The compliant actuation unit paradigm presented in this paper also possesses a *cellular structure*, whereby multiple motor units cooperate to drive a single degree of freedom. This gives it additional muscle-like properties such as control by a method similar to recruitment and robustness to failure. It turns out that a compliant connection is an enabling factor for this type of discretized architecture. A actuation unit that uses miniature solenoids to initiate contraction is presented.

The discrete nature of this actuator means that some new metrics are necessary to categorize them and evaluate their performance. These metrics are introduced and evaluated for the prototype presented. With respect to several of these metrics, the actuation unit compares favorably with traditional linear motors of similar size. However, some sacrifice is to be expected in order to reap the benefits of the integrated compliance and discretized structure. The force of an isometric contraction is measured experimentally for a series chain and a series-parallel configuration.

This actuator module has applications in humanoid robotics, rehabilitation robotics, and gives roboticists the ability to produce “designer muscles” by combining these units in serial and parallel combinations to achieve specific properties. They are particularly useful in areas where high redundancy is needed, such as aerospace applications. Future work will attempt to statistically characterize and quantify the ability to tolerate damage. It will also include refinement of the prototype, further miniaturization, and investigation of

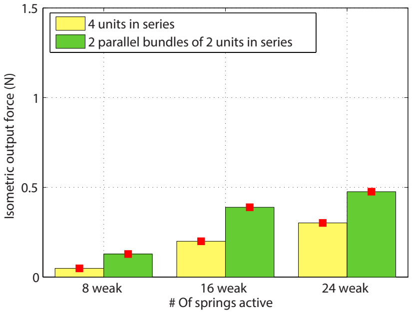


Fig. 6. Force vs. activation level: weak motor units. Error bars are one standard deviation.

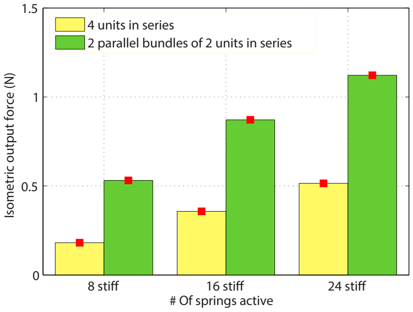


Fig. 7. Force vs. activation level: strong motor units. Error bars are one standard deviation.

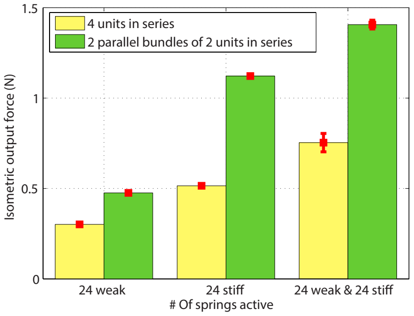


Fig. 8. Comparison of the force produced by the strong and weak motor units. Error bars are one standard deviation.

discrete-amplitude control strategies for force, displacement, and stiffness.

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