A muscle-like recruitment actuator with modular redundant actuation units for soft robotics

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Abstract

Human muscles contrast sharply with traditional robot actuators in that they consist of several motor units, connected in series and parallel, which can be progressively recruited. Some roboticists have explored this idea in robotic actuators, striving for improvements such as the ability to withstand partial damage, inexpensive repeatability by discrete open loop control, the potential of modular actuators, etc. These systems, however, become rather complex or rely on less widely used actuation techniques such as piezo-actuators or SMAs to produce a compact implementation. This paper presents a novel design of a modular redundant actuation unit which can be combined in various combinations to form compliant actuators with varying characteristics. The actuation unit consists of discretely activated solenoids with an integrated compliant coupling. This paper presents the working principle and the physical implementation in detail. Failure of a single motor unit will merely lead to a loss in performance rather than failure of the actuator. Since each motor unit is discrete, neither power electronics nor control require analog signals. Isometric experiments display the actuation characteristics and demonstrate the repeatability. The platform can

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be used in future work to further explore the virtues of exploiting discretization and redundancy in muscle-like control.

Keywords: Discrete actuation, Modular motor units, Soft robotics,
Redundant actuation

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1. INTRODUCTION

Reproducing the properties of biological muscle is a longstanding research effort since actuator limitations heavily influence the capabilities of robots. Stiffness properties of muscles is one of the earliest characteristics that has been
5 studied. The seminal work of Pratt et al. from the 1990s [1] showed the virtue of elastic elements in series with the drive train and ever since numerous roboti-
cists have focused on novel uses and implementations of series elastic actuators (SEA). An important extension of this work towards muscle-like actuators is
the work on variable impedance actuators (VIA) [2, 3]. Vanderborght et al. [4]
10 provides a good review with classification of actuators that can vary stiffness and damping characteristics so as to exploit and modify the natural dynamics of
a system. In addition, dedicated control architectures for safety [5] and energy efficiency [6] are developed. A number of materials and techniques have been
explored for their use in artificial muscles, such as pneumatic artificial muscles
15 [7], electroactive polymers (EAP) [8] [9], shape memory alloys (SMA) [10], etc.

Apart from its compliance, the hierarchical structure of skeletal muscle is also distinctive, though this aspect has received less attention. A skeletal muscle consists of multiple motor units, each consisting of a number of muscle fibers. Each motor unit can be activated through its motor neuron: as such a muscle
20 with more motor units is able to control force output in a finer manner. The activation of motor units to produce a force is called *motor unit recruitment* and differs markedly from generating an analog signal proportional to the desired force output [11] [12]. Actuators with a discrete cellular structure include the work of Dittrich [13], MacNair and Ueda [14] and Huston et al. [15]. Both

25 of these works present a type of actuator that is made up of numerous sub-
 actuators. This redundancy increases the robustness of these actuators. Failure
 of an electromechanical component will only lead to a loss in performance instead
 of a loss of a complete degree of freedom (DOF), since the remaining undam-
 aged units can continue to perform the task. The cellular structure opens the
 30 possibility for modularity in the actuators which represents an untried frontier
 in engineering. In Mathijssen et al. [16] the series-parallel elastic actuation con-
 cept was proposed whereby multiple springs in parallel can be variably recruited
 by multiple dephased intermittent mechanisms and only one motor. Cho et al.
 [17] introduced and validated a segmented cellular architecture of SMA wires.
 35 Ueda et. al [18] focused on distributed stochastic control of an actuator system
 consisting of many cellular SMA units. Schultz and Ueda [19] validated their
 multilayer strain amplification mechanism on a camera positioning mechanism
 based on piezo actuators. For mathematical simplicity, each active element of
 the actuator in Schultz and Ueda’s actuator was identical and interchangeable.

40 Most mechatronic devices composed of modular units are in the context of
 self-organizing systems [20] [21], distributed manipulation [22] or modular ac-
 tuators for multi-DOF systems [23]. Using modular components to precisely
 configure the actuation system for a particular performance characteristic for a
 given joint axis has been less studied. Most actuators are size selected rather
 45 than built-to-order. This work presents a modular *actuation unit* which can be
 combined in series and parallel combinations. Each actuation unit contains 12
motor units which can be discretely activated similarly to motor units in the
 human body. Since this actuation unit is based on activation of individual mo-
 tor units, it generates contractions under the motor unit recruitment paradigm.
 50 This paper begins to explore the idea that the central nervous system deliber-
 ately chooses activation patterns with motor units of different characteristics
 [24]. The actuation unit pictured in Fig.1 has a compliant coupling mecha-
 nism specifically constructed so as to produce different operating characteristics
 from physically identical active elements, which was first introduced in [25]. We
 55 present here a new spring design with an improved manufacturing process, bet-

Figure 1: Single degree of freedom actuation unit consisting of discretely activated elements coupled to the mounting boss by a spring. 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*.

ter repeatability and greater ease of assembly. An experimental validation of the spring models is reported in the paper, showing a good match between our mathematical models and physical device behaviors. Furthermore, we present the results of isometric experiments on actuators that consist of different arrangements of actuation units. Finally, we have quantified variability over the various choices of activation patterns for two representative configurations.

Section 2 discusses the most important concepts and key terms with regard to this paradigm. The actuation unit implementation is discussed in Section 3. More specifically the implementation of solenoids, springs and straps (mechanical stops), close packing of motor units, and custom drive circuits is discussed. The results of different actuator configurations composed of the actuation units are presented in Section 4. Section 5 concludes the paper and potential future work is proposed.

2. KEY TERMS AND WORKING PRINCIPLE

Beyond those described in Section 1, the authors are not aware of applications where modules are combined based on a performance characteristic for a particular joint axis. Section 2 recaps the key terms for modular actuation introduced in [25], discusses the importance of compliance, and introduces the functional model of the actuation unit shown in Fig. 1.

75 *2.1. Key terms modular actuation*

The following terms are introduced or borrowed (with some license) from biology, and their specific meanings in the context of this paper delineated:

- **Cellular [26] muscle-like actuator:** a motion or force producing device composed of more than one actuation unit and containing more than one
80 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 [11]:** this is computational or communication distinction.
85 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. Several paradigms are delineated in [25] and shown in Fig. 2. A schematic of the paradigm implemented in this paper is shown in Fig. 2a
90 and Fig. 2b. Each actuation unit consists of multiple motor units, which can be activated independently. The implementation, to be described in Section 3, has each motor unit corresponding to one solenoid in series with a compliant element. Each actuation unit has multiple solenoids in parallel.

2.2. Compliance enables discretization

95 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 [27]. The same reasoning is valid for modular actuators where actuation units are connected in series and parallel. The compliance between these units is indispensable to the
100 operation of a modular actuator. This can be understood by a thought experiment: take two units tied together in parallel with no compliant interface but instead a rigid end cap. The contraction of one unit would then result in the

Figure 2: Different paradigms for actuation units and motor units, adapted from [25]. (a) shows a muscle-like actuator composed of discretely activated actuation units coupled by compliant elements. (b) - (e) show different paradigms, with in each example one strong and one weak motor unit active. The paradigm implemented in this work is shown in (b), where each actuation unit consists of multiple motor units. The signal lines to inactive motor units have been omitted for clarity.

same contraction of the other unit. Any other case would violate the compatibility condition of mechanics of materials [28]. This is indicated in Fig. 3. By
 105 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 displacements to be equal, the compliant material imposes a mathematical relationship between displacement and the force contribution of that fiber. In skeletal muscle, the fibers are instead connected together by
 110 endomysial connective tissue [27], which is elastic. In modular actuation units, this elastic force-displacement relationship can be exploited and specified so as to obtain desirable properties for the muscle-like actuator as a whole.

Figure 3: The compliant element is crucial to allow different contraction patterns amongst actuation units. The three most left configurations do not include a compliant element. The third figure indicates the inconsistency, which is resolved by the compliant element in the fourth figure.

2.3. Working principle of an actuation unit

The working principle of an actuation unit of the type described in this work
 115 is explained by means of the functional model in Fig. 4. This is an example of the paradigm in Fig. 2. The implementation is further explained in Section 3.

Each functional part of the actuation unit schematic is indicated in Fig. 4a. For clarity, the schematic consists of only 2 parallel solenoids which function as the motor units; in practice, any number may be present. Since a solenoid
 120 is a unidirectional actuator, the actuation unit is unidirectional as well. Both solenoids are fixed to a printed circuit board (PCB) and connected to a leaf spring. Since the displacement is the same, the stiffness of the spring distinguishes between strong and weak motor units. The stiffness of each spring is

named k_w and k_s respectively. The stroke L_x of the solenoid is indicated as well.
 125 When the plunger is pulled away from the coil, a strap becomes taut and prevents the plunger from separating from the coil. Each strap is fixed to the PCB and to the middle of one of the springs. The ends of the springs opposite of the plunger are fixed to the mounting boss. When a solenoid contracts it deforms the spring, which results in a force at the mounting boss. Each combination of
 130 a solenoid and a spring can, as such, be considered an SEA. Adjacent actuation units connect at the mounting boss and ultimately, to the robotic link itself. The working principle of an actuation unit will be explained via Fig. 4b-4c.

- If an actuation unit experiences an extension ($x < 0$) as in Fig. 4b and Fig. 4c, both active and inactive motor units contribute to the force at the
 135 mounting boss. An inactive motor unit will behave as spring due to the taut strap. Each spring whose strap is engaged will have a stiffness equal to a fraction f of the stiffness of the spring, i.e. $f k_w$ or $f k_s$ ($0 < f < 1$), depending on the connection of the strap to the springs, which determines the number of springs that can extend. The connection of the strap differs
 140 from that in [25]. An active motor unit will contribute with a stiffness equal to the full stiffness of the spring, i.e. k_w or k_s . In Fig. 4b both units are inactive and behave like a spring with stiffness $f k_w$ and $f k_s$, since part of the spring is being cut off and unstrained. In Fig. 4c both the inactive and active unit contribute to the force at the output F_a .
- If an actuation unit experiences a contraction ($x > 0$), the inactive motor
 145 units will float and generate no output force F_a . The active motor units will contribute a stiffness equal to the full stiffness of the spring, i.e. k_w or k_s

The schematic in Fig. 4 shows only 2 solenoids, each having a different spring
 150 stiffness k_w and k_s . In a more general case, each actuation unit consists of N motor units, of which $\frac{N}{2}$ motor units have a spring stiffness k_s and $\frac{N}{2}$ motor units have a spring stiffness k_w . All solenoids are identical; functionally they act as a displacement source. The characteristics of the spring element a given

Figure 4: Actuation unit concept schematic; only a single strong and a single weak motor unit are shown for clarity. The important conceptual parts are indicated in (a), which shows an inactive unit under zero load. The springs are at their resting length. In both (b) and (c) the displacement x is negative, subsequently referred to as an extension. As a result, both the active and the inactive motor units contribute to the output force F_a . The strap of the strong motor unit in (c) becomes limp due to the active motor unit and the extension. The contraction in (d) results in 2 limp straps and as a result only the active motor units contribute to the output force F_a .

solenoid is connected to determines whether it is a strong or weak motor unit.

155 The spring path to the mounting boss 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. Ideally, the geometry is chosen such that

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

160 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 actuation units described in this paper the aim was $r = 1/\sqrt{2}$. 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
165 inputs while producing only a modest reduction in blocked force.

The output force of an actuation unit F_a depends on how many and which type of motor units (weak or strong) are activated. The number of active motor units is named M , and the number of strong and weak active motor units M_s and M_w , respectively. F_a also depends on the displacement x of the mounting
170 boss and the stroke of the solenoid L_x . Taken together, F_a can be described by Eq. (2). For $x \geq 0$ Eq. (2) consists of 1 term, which represents the contribution of the active motor units. The inactive motor units do not contribute since the straps are not taut for $x \geq 0$, which is the case in Fig. 4c and Fig. 4d. The additional term in Eq. (2) for $x < 0$ represents the contribution of the inactive
175 motor units. Since the straps are taut here, the extra factor f must be taken into account.

$$F = \begin{cases} (L_x - x) (M_w k_w + M_s k_s), & x \geq 0 \\ (L_x - x) (M_w k_w + M_s k_s) - x \left(\left(\frac{N}{2} - M_w \right) f k_w + \left(\frac{N}{2} - M_s \right) f k_s \right), & x < 0 \end{cases} \quad (2)$$

It should be noted that selecting a specific activation pattern also results in a change in stiffness of the actuator. Depending on which motor units (strong

or weak) and how many are activated, and which straps and how many are
180 taut, the stiffness of the actuator will change. Rigorous study of this property
is beyond the scope of this article and will be addressed in a future work.

3. ACTUATION UNIT IMPLEMENTATION

In this section the physical implementation of the actuation units is dis-
cussed. The general schematic of an actuation unit, discussed in the previous
185 Section 2.3, consists of one PCB and N solenoids with $\frac{N}{2}$ strong and $\frac{N}{2}$ weak
motor units. As defined in Section 2.1, the term *actuation unit* is a *manufac-*
turing distinction. In this work, two PCBs with 6 solenoids each (3 weak and 3
strong motor units) are combined to form an actuation unit. A spring element
is placed in series with each plunger, and connected to the mounting boss. The
190 spring stiffness of the weak and strong motor units is respectively defined as
 k_w and k_s . The following main parts of an actuation unit will be discussed in
the subsections hereafter: solenoids which should be arranged optimally, springs
and straps, and the custom drive circuit.

3.1. Solenoids

195 The contractile element of the motor unit is a miniature solenoid; each ac-
tuation 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
200 units. Performance specifications of the solenoid are listed in Table 1. Each
solenoid can be independently activated, making it a convenient analog to a
biological motor unit. Active materials such as electroactive polymers [9] and
shape memory alloy (SMA) [10] could also be used.

The solenoids consist of two parts, the coil and the plunger. If sufficient
205 current is present in the coil, the plunger will be drawn into the coil until it
reaches the ferrous rear end of the coil. If there is insufficient current present,

Table 1: 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
Weight	1.7	g

the plunger will float ($x > 0$) or rest against the strap ($x \leq 0$) as shown in Fig. 4. The coils are soldered to a custom PCB which manages electrical connections to each solenoid, while structurally coupling them together rigidly. The unoccupied
210 space between the solenoids for the outer ring is used for the mounting holes. A tab is added on one side to accommodate a Molex Picoblade 8-pin connector. A rigid standoff mounted to the printed circuit board allows the connection of additional modules in series.

3.2. Motor unit arrangement by close packing

215 In order to approximate a continuous signal by recruiting solenoids, there must be a reasonably large number of motor units within the allotted space. For a given number of motor units, the best motor unit density is achieved by close-packing the solenoids, which have a circular cross section. To facilitate the design of the spring element, and to keep it symmetric, the solenoids were
220 placed in two concentric rings, with the strong motor units in the outer ring, and the weak ones in the inner ring. This is advantageous from a power standpoint, because the stronger motor units will require more current. Placing them on the outside will better allow them to dissipate heat. This is not a biologically inspired arrangement; the situation in biology is much more complicated and is
225 motivated by additional factors not represented in this design, such as routing

of nerves and blood vessels. In fact, the individual muscle fibers from various motor units are interspersed with one another [29].

The smallest non-trivial example contains 6 motor units: 3 strong and 3 weak motor units. This arrangement is illustrated in Fig. 5a. The centroids of the inner ring of solenoids lie on a circle of radius r , and the centroids of the outer ring of solenoids lie on a circle of radius R . The circumscribing circle of the outermost ring, of radius C , represents the minimum theoretical radius of any actuator of this type. They can be calculated from the number of solenoids as follows:

$$r = \frac{d}{2 \sin \frac{\pi}{n}} \quad (3)$$

$$R = \frac{d\sqrt{3}}{2} + r \cos \frac{\pi}{n} \quad (4)$$

$$C = R + \frac{d}{2} \quad (5)$$

where d denotes the diameter of the solenoid, and n denotes the number of solenoids in the inner ring. Thus the motor unit density per unit area for this configuration, σ , can be calculated as:

$$\sigma = \frac{n}{\pi C^2}. \quad (6)$$

This can be used as a metric to evaluate the relative merits of a given muscle-like solution and helps the designer answer the following question: Is the actuator getting larger in order to increase the control resolution or the actuator maximum force? It should be noted that Eq. (6) is only a theoretical value, and due to manufacturing tolerances and other design considerations, the actual value of the finished device may in fact be lower.

It turns out that this is not the most compact regular close-packed arrangement; a single ring of 6 is actually more compact [30]. A single ring of 6 solenoids would pose difficulty with regard to the spring design, however. The relative compactness of arranging the motor units in a single circle or two concentric

(a) Close-packed solenoid arrangement, two motor unit levels. Shaded region indicates area allotted to the spring element for the weak motor units.

(b) Picture of the PCB with 6 solenoids mounted on and the plungers installed.

Figure 5: Schematic (a) and picture (b) of the solenoid arrangement that was implemented in this work.

circles can be determined by comparing the quantity r_{2n}/R_n ,

$$\frac{r_{2n}}{R_n} = \sqrt{3} \sin \frac{\pi}{2n} + \cos \frac{\pi}{2n} - \frac{1}{2 \cos \frac{\pi}{2n}} \quad (7)$$

where the subscript n denotes the number of motor units in the innermost ring.

250 Note that this index does not depend on the motor unit diameter, d . Eq. (7) converges to 2 as n approaches ∞ . By means of Eq. (7) it can be shown that two concentric rings become a more compact solution once the device contains 10 units [30]. When the number of concentric rings is greater than 2, and the number of motor units becomes larger, the situation becomes more complicated, as

255 closer packings are possible [31] with the concentric rings having different numbers of motor units. In fact, it has been shown that in many cases *asymmetric* packings are the most dense [32],[33]. This would, however, make it very difficult to design a suitable spring element, and would cause undesirable off-axis bending and possible alignment issues in manufacturing and operation.

260 The space within the envelope (be it a circle of radius C or otherwise) circumscribing the motor units but not occupied by the solenoids themselves is not necessarily wasted space. In some cases, this space could be used for drive electronics, sensing, or computational elements, making the device more of an integrated solution.

265 3.3. Springs and straps

The spring element is not simply a series elastic element, but rather is crucial to the operation of the device, as it allows some solenoids to be active and others inactive at the same time. As alluded to in Section 2.2, the spring element serves several functions: it combines the various efforts of the motor units at
270 the output, presents a compliant interface with the environment, and since the solenoids correspond to a displacement source, determines which solenoids correspond to strong motor units and which correspond to weak motor units.

The selection of this spring element represents a significant engineering challenge, because it must accomplish the following objectives. It must:

- 275 • Not significantly decrease the strain rate ϵ of the actuator.
- Not interfere mechanically with other motor units when transitioned between the active and inactive states.
- Be able to be manufactured without using exotic or costly manufacturing techniques.
- 280 • Fit within (or at least not greatly exceed the dimensions of) the circumscribing circle of radius C , described in Section 3.2.

Each of these objectives becomes more difficult to accomplish with decreasing size. To maximize the strain rate, the spring element should be as thin as possible in the actuation direction. The following Sections 3.3.1 and 3.3.2 report
285 on two custom made designs based on different manufacturing techniques: a wire form spring and a leaf spring. The wire form spring was presented in [25], but details were omitted due to the short format, they are presented here.. In Section 3.3.1 the connection issues of the lobes to form the wire form spring are discussed as well. In Section 3.3.2 the leaf spring, an improved spring design, is
290 introduced and the characterization experiments are reported. In Section 3.3.3 the implementation of the straps is delineated.

3.3.1. Wire form spring

The wire form spring consists of 3 weak motor unit springs and 3 strong motor unit springs, further referred to as weak and strong lobes. Although both lobes are custom wire forms, their design was chosen to make sure the spring would be manufacturable by conventional methods. The weak lobe is a basic oval-shaped coil, as shown in Fig. 6a. The shape is as such that it fits in one of the three shaded areas in Fig. 5a. The shaded area was arbitrarily allotted to the weak lobe. This is admittedly a heuristic, but logical based on the needs of the manufacturing process. The longitudinal axis of the oval is aligned with the radial direction of the circular PCB. The radius of the circular ends, R_w will be the same as the radius of the solenoid, based on the region available. L is chosen so that one circular end coincides with the solenoid itself, whereas the other is tangent to the outer envelope of the actuator. Then the number of coils, n_c required to get the desired stiffness k can be calculated using Eq. (8):

$$k = \frac{d_w^4 E \pi}{64 n_c \left(\frac{L^3}{3} + (1 + \nu) R_w^2 (L + \pi R_w) \right)} \quad (8)$$

where E is the elastic modulus, d_w is the wire diameter and ν is the Poisson's ratio for the material. Eq. 8 is derived from Castigliano's theorem so that the deformation of the stroke of the solenoid plunger (for the strong coil) would result in a force equal to the pull force of the solenoid coil. Castigliano's theorem is a standard method for the design of deformable structures; the interested reader may consult [34] for details and examples. Bending in the straight section of length L and torsion in all sections were considered in the straight segment; the curved segment did not consider bending. Bending in the straight section accounts for 13.7% of total deflection, a small but not insignificant amount. If the number of coils is small, the spring element will be nearly planar, giving this design a clear advantage with regard to strain rate over designs using commercial springs.

The strong motor unit's spring must not encroach within the shaded area in Fig. 5a, lie within the circle described in Section 3.2, contain the center of

the solenoid to which it is attached within the interior of the coil, and have few enough coils so as to be considered thin, i.e., it must fit conveniently within the remaining available space. The natural shape to fit the space is an oval, but with the longitudinal axis *perpendicular* to the radial direction rather than aligned with it.

Figure 6: Drawings and a picture of the wire form spring introduced in [25].

The spring constant relationships are described by Eq. (8), with R_w and L free parameters, as well as the oval's center, that can be used to select spring performance subject to the constraints. A numerical constrained optimization was conducted to determine the values that give the coil geometry with the minimum number of coils for the desired stiffness. The result, not surprisingly, is a circle ($L = 0$) tangent to the outer boundary circle and the boundaries of the shaded region ($R_w = 5.58\text{mm}$). The required n_c is 1.6.

The selected wire diameter is 25 AWG or 0.455 mm. This resulted in a theoretical strong lobe stiffness of $0.1926 \frac{N}{mm}$ and a weak lobe stiffness of $0.1352 \frac{N}{mm}$. The deflection predicted by Eq. (8) agrees with that predicted by finite element methods within 19%, indicating that the model described by Eq. (8) is useful for constructing a spring element that a spring element that will give close to the maximum holding force of the solenoid without overheating. The custom wire forms are provided by the Active Spring Company, Sibley's Green, United Kingdom.

One disadvantage is that the complete wire form spring (with 6 lobes) cannot

be manufactured in a single piece, in a single operation. In this implementation 3 wire forms, each containing one strong lobe and one weak lobe need to be connected. This was done by M1 screws and a precisely manufactured clamp, and later by a micro welding process. Although feasible and validated empirically, both techniques are unreliable and significantly increase the complexity of the wire form spring. The clamp needs to be of high precision since the wire diameter is small and is fastened by M1 screws. The micro welding degrades the metallurgical qualities of the springs. Furthermore, the repeatability of the manufacturing process (including the connection) is rather low and clear differences could be observed. Finally, the adjustment cost to produce a variant of the wire form spring is relatively high. The aforementioned issues motivated us to search for modifications that would improve manufacturing consistency and efficiency of the process. Therefore, the next Section 3.3.2 discusses a new spring design that solves the encountered issues of the wire form spring.

3.3.2. *Novel leaf spring*

The general idea is to have a central hub, from which 6 beams emanate toward each solenoid. The spring, with 6 lobes, is laser-cut in a single piece out of a thin spring steel sheet. This process proved to be highly repeatable and precise. Furthermore, the laser cutting technique allows for easy connection to the straps, mounting boss and plungers as indicated in Fig. 7b. The challenge is to make the beams compliant enough, since the actuator diameter is small and thus the beams cannot be long, increasing the bending stiffness. Furthermore, the space is limited so the lobes cannot bend back and forth many times in the plane. In order to retain the same compact solenoid arrangement, a drop-in replacement for the wire spring was required, placing additional constraints on the design. Appropriate stiffness and extension can, however, be achieved by laser cutting U-shaped lobes out of a 0.1 mm thin 1.413 Chromium-nickel austenitic stainless spring steel plate (AISI 301). A schematic and picture are shown in Fig. 7. The precise lasers of Raytech, Brugge, Belgium allowed for a lobe width w of 2.4 mm. The density ρ of AISI 301 steel is 7900 kg/m^3 , elastic

Figure 7: Leaf spring design with 6 U-shaped lobes cut out of a 0.1 mm spring steel sheet.

modulus E of 189 GPa, yield strength σ_y of 1072 MPa and tensile strength σ_t of 1309 MPa. A schematic of the leaf spring design and illustration of the lengths of the weak and strong U-shaped lobes, L_{w1} , L_{w2} , L_{s1} and L_{s2} , is shown in Fig. 7a.

The analytical model to calculate the force produced by a lobe F_{lobe} as a function of the extension Δx , consists of standard beam bending of both of the legs of the spring as shown in Eq. (9). It is assumed that the vertical force F_{lobe} applied at the plunger connection and the bend of the U-shape. Euler-Bernoulli bending in the straight sections is assumed, and deformations in the curved sections are neglected.

$$F_{lobe} = \Delta x \frac{3EI}{L_1^3} + \Delta x \frac{3EI}{L_2^3} \quad (9)$$

375 As noted in Table 1, the maximum steady state force of the TO-5 solenoid is 1 N when fully contracted. Over a stroke length of 2.54 mm this results in a maximum linear spring stiffness of 0.39 N/mm. A safety factor of 3 is included to account for potential friction in the system. The turn of the U-shaped lobe is slightly larger than the PCB to allow for connection to the straps. Taking into
 380 account these goals and geometrical constraints, the parameters of the strong and weak lobe were tuned which resulted in the following specifications:

Figure 8: Measurements characterizing and comparing stiffness of the leaf spring with $w = 2.4$ mm. The theoretical model and the experimental data match fairly well.

- *Strong lobe:* $w=2.4$ mm, $L_{s1}=9.9$ mm, $L_{s2}=7.5$ mm. Theoretical stiffness: 0.13 N/mm.
- *Weak lobe:* $w=2.4$ mm, $L_{w1}=11.5$ mm, $L_{w2}=9.1$ mm. Theoretical stiffness: 0.08 N/mm.

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The spring stiffness of the weak and strong lobes were calculated theoretically and verified experimentally. The results are summarized in Fig. 8a. The stiffness profile and stiffness ratio between the strong and weak lobe are compared in the bar charts of Fig. 8b. From both figures it is clear that the theoretical model and the measurements match fairly well. These measurements are repeated for $w=2.8$ mm and $w=3.2$ mm. In both cases the results were similar and consistent to those for $w=2.4$ mm, reported in Fig. 8.

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3.3.3. Straps

In Section 2.3 the function of the straps is introduced. The straps in the actuation unit presented in this work are made of 4 strand braid, including 3 dyneema® strands, with a diameter of 0.25 mm. As explained in Fig. 4 the straps should be loose when the mounting boss is compressed (with respect to the neutral position), and taut when the mounting boss is extended to prevent

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Figure 9: Leaf spring experimental to determine the stiffness profile of the leaf spring.

Figure 10: Working principle and implementation of the straps.

the plungers from leaving the coils. Both cases are illustrated respectively in Fig. 10b and Fig. 10c. The assembly of the straps was performed by hand. As can be seen in Fig. 10, the straps are connected to the standoffs (red), which are fixed to the PCB, and to the bend of the U-shaped lobes. Two actuated (bottom) and unactuated (top) units in order to visualize the spring extension, which is accentuated in red in Fig. 10a.

3.4. Custom drive circuits

Custom drive circuits activate each of the 12 solenoids in the actuation unit independently. The activation is initiated by a digital signal. An activation consists of 2 phases. Initially, a high voltage (15 V) is applied across the solenoid for a short duration (20 ms). This results in a burst of current (3 A), which ensures

410 that in the worst-case scenario (isometric contraction) the solenoid plunger will still reach the ferrous rear plate of the coil. This closes the magnetic flux gap, increasing the total force. After this short burst, the voltage drops (2.5 V) and a steady state current of approximately 0.5 A ensures the plunger is held in the solenoid coil while avoiding overheating of the coil.

415 The custom drive circuits are activated and deactivated by means of digital I/O lines of the National Instruments USB-6501 DAQ modules. One actuation unit requires 12 digital I/O lines to independently control the 12 solenoids. The DAQ modules can be controlled by a Labview interface or matlab code.

3.5. Actuation unit performance specifications

420 Performance specifications of a single actuation unit, as shown in the sketch in Fig. 1 and in the picture in Fig. 10b, are listed in Table 2. Although the objective is not to exactly copy the human muscle, comparing to the performance specifications of mammalian muscle is still interesting. Based on [35] it can be concluded that the strain rate ϵ of the actuation unit (21.1%) is comparable
425 to mammalian skeletal muscle (20%). The maximum stress of the actuation unit (2.3 kPa), however, is a factor 40 lower compared to mammalian skeletal muscle (0.1 MPa). Performance specifications of actuators composed of these actuation units, can then be derived from the values in Table 2. In general, the maximum force is multiplied by the number of strings in parallel, the maximum
430 stroke length is multiplied by the number of actuation units in series, and P_{ss} and the mass are multiplied by the number of actuation units. To put these performance specifications into perspective, they can be compared to the nested piezoelectric cellular actuators discussed in [19]. The strain rate of the actuation unit and the cellular actuators is comparable, and respectively equal to 21.1 %
435 and 20 %. The maximum stress the actuation unit can apply is 2285 Pa, which is over 4 times the capability of the cellular actuator that can approximately apply 539 Pa.

Table 2: Actuation unit with leaf spring of $w = 2.4\text{ mm}$: performance specifications

Quantity	Value	Unit
Maximum stroke length	5	mm
Maximum force	1.55	N
Response time (max)	0.5	ms
Strain rate ϵ	21.1	%
σ_{block}	2285	Pa
Steady State Power P_{ss}	12.5	W
Mass	37	g

4. EXPERIMENTAL VALIDATION OF ACTUATION UNITS

The aim of this Section 4 is to study the isometric output force of the actuation units in several representative configurations. More specifically, a chain of 4 units in series (further referred to as 1x4 actuator) will be compared to a bundle of 2 parallel chains of 2 actuation units (further referred to as 2x2 actuator). A study on the repeatability of the output force as a function of the activation patterns is presented as well.

4.1. Experimental set-up and activation graph

The 1x4 and 2x2 actuator assemblies are shown in Fig. 11a and Fig. 11b, respectively. Both actuators were isometrically fixed between two rigid supports. A Futek LSB200 force sensor (maximum load 1lb) was placed between the actuator and one of the rigid supports to measure the output force generated by the actuator. A Futek CSG110 signal conditioner/amplifier was used along with the LSB200 force sensor to generate an analog output signal. The data acquisition was performed by a National Instruments USB-6000 DAQ module and custom Labview code.

Since the straps between each spring and the mounting feature, were set to be 2 mm when taut, the equilibrium length of the 1x4 actuator is 16 mm and 8 mm for the 2x2 actuator. Both actuators were isometrically fixed with 25%

Figure 11: Pictures of the 1x4 and 2x2 actuators.

pretension (4 mm and 2 mm, respectively). This pretension serves to return the plunger to its initial position after contraction, overcoming friction. Moreover, the pretension ensures all straps are taut to cancel strap length variations due to the manufacturing process by hand. The pretension force was measured to be approximately 0.1 N and 0.2 N, respectively for the 1x4 and 2x2 actuator. In the experimental results the pretension force is subtracted from the results. In future applications this pretension is to be expected since these actuation units are designed to be used in an antagonistic configuration.

Both the 1x4 and 2x2 actuators consist of 4 actuation units, for a total of 48 solenoids. Each solenoid can be independently activated by means of 2 National Instruments NI USB-6501 DAQ modules, along with the custom drive electronics. An example of an isometric output force graph over time is shown in Fig. 12. The activation of each individual solenoid at 100 ms intervals is clearly visible. A longer steady-state output force is maintained (for 600ms) after an additional solenoid is activated on each PCB. The data was filtered with a second-order Butterworth filter with a normalized cut-off frequency of 0.05. It is important here to note that activating each solenoid in succession is just one option. Multiple, or even every single solenoid can be activated at once. This makes for higher peak currents, however. As a result, the actuator can in principle reach any isometric output force almost instantaneously, similar

Figure 12: An isometric output force graph over time where the activation of each individual solenoid is clearly illustrated.

electric motors, which have a small electrical time constant.

4.2. Isometric output force experiments

The isometric output force experiments consist of activating a certain number of motor units on each of the 8 PCBs. This is performed for both the 1x4
480 and 2x2 actuator. The results are shown by means of 2 bar charts in Fig. 13. With a total of 48 motor units, it is impractical to present all conceivable activation patterns. The first 2 bars in Fig. 13a for example present the activation of 1 weak motor unit on each PCB. Since each of the 8 PCBs has 3 weak motor
485 units, there are 3^8 or 6561 different, though redundant, activation patterns possible. By means of a random generator, 10 different activation patterns were fired and each bar in Fig. 13 shows the mean isometric output force of 10 different activation patterns. The constant force due to the pretension is subtracted from the results in order to compare the results between different experiments.
490 The standard deviation is shown in red on top of each bar.

The bars in Fig. 13a show the results of the activation of 1 weak motor unit on each PCB, 2 weak motor units, 1 strong motor unit, and 2 strong motor units. It is clear that the ratio between the activation of 1 weak (strong) motor unit and the activation of 2 weak (strong) motor units on each PCB is approximately
495 0.5, which is to be expected since the force in parallel is doubled. The same goes for the ratio between the activation of a certain number of solenoids on each

(a) Activating a certain number of motor units on each PCB.

(b) Increasing the number of activated motor units on each PCB increases the output force.

Figure 13: Isometric output force experiments of 1x4 and 2x2 actuators.

PCB of the 1x4 actuator and the 2x2 actuator. In Fig. 13b the output force is further increased by activating additional motor units on each PCB.

It is interesting to note that the results obtained are in accordance with the spring experiments shown in Fig. 8a. Activating 1 weak motor unit on each PCB, for example, results in an isometric output force of approximately 0.2 N and approximately 0.3 N for 1 strong motor unit.

4.3. Open loop repeatability study

Actuators consisting of a number of discrete motor units can benefit from their high repeatability without intensive control algorithms. The standard deviation in the experiments of Fig. 13a and Fig. 13b is, however, not totally negligible. The authors expect that repeatability will improve drastically with a more uniform manufacturing process, since currently the assembly is done by hand. A specific pattern for 1 weak motor unit on each PCB was activated 10 times. The same was done for an alternate activation pattern still consisting of weak motor unit on each PCB. The experiments were repeated for a strong motor unit as well. All experiments were done on the 1x4 actuator. The results are shown in Fig. 14. The standard deviation of a specific activation pattern in Fig. 14 is negligible which proves the high repeatability of a specific activation pattern. Therefore, it can be concluded that the standard deviations in Fig. 13

are due to the assembly by hand.

Figure 14: Redundant patterns do give a different output force due to manufacturing imprecision. However, this figure shows that activating a specific activation pattern multiple times is very repeatable.

5. CONCLUSION AND FUTURE WORK

In a robot, the word “actuator” traditionally denotes a single servomotor or similar device. Human muscle, to the contrary, consists of several motor units, connected in series and parallel, which can be progressively recruited. In this paper, we present a novel design of a modular redundant actuation unit which can be combined in various combinations to form compliant actuators with characteristics derived from the intended function, much as muscle fibers are organized in human muscles. Inspired by the distinctive hierarchical structure of skeletal muscle, the compliant actuation unit presented in this paper is not only compliant, but also possesses a *cellular structure*. As such, multiple motor units cooperate to drive a single output. This paper presents the working principle and discusses the physical implementation in detail. The isometric experiments show the actuation characteristics and prove the high repeatability of the actuators composed of these actuation units. The platform can be used in future work to further explore the virtues of exploiting discretization and redundancy in muscle-like control.

The actuation unit presented in this work consists of 12 motor units which can be activated independently. Each motor unit consists of a miniature solenoid to initiate contraction, and a compliant element. This work describes in detail the actuation unit implementation, which was particularly challenging due to the relatively small dimensions of the actuation unit. This includes close-packing of the solenoids in each actuation unit, as well as the design of a custom spring with 3 weak and 3 strong lobes. The design of a wire form spring and a leaf spring are discussed in detail.

Two representative actuator configurations are evaluated experimentally, a chain of 4 units in series and a bundle of 2 parallel chains of 2 actuation units. Numerous other configurations are conceivable. The experiments corroborate the working principle and analytical models of the actuation units. Study of the repeatability of the output force as a function of the activation patterns showed high repeatability of the muscle-like actuator.

This actuator module has applications in humanoid robotics, rehabilitation robotics, anthropomorphic arms, etc. and gives roboticists the ability to produce “designer muscles” by combining these units in serial and parallel combinations to achieve specific properties. The authors, and their respective research groups, have particular interest in this actuator type for implementation in anthropomorphic arms with actuators build into the lower arm structure. Additionally, they are particularly useful in areas where high redundancy is needed, such as aerospace applications.

Future work includes refinement of the prototype, devising a more repeatable manufacturing process, further miniaturization, and investigation of discrete-amplitude control strategies for force, displacement, and stiffness. In future designs of the actuation unit, special attention will go to improving the stress rate while remaining an equivalent strain rate.

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