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Damage resilience of manufactured and biological actuators

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Abstract

Designing resilient actuators is a challenge for industry, in part because an index for resilience has yet to be established. In this work, several definitions of resilience are analysed and, on the basis of this, an index quantifying resilience for actuators is proposed. This index does indeed allow for the resilience computation of a wide range of manufactured and biological actuators to be compared. The two manufactured actuators chosen as iconic models are a hydraulic cylinder and a bio-inspired McKibben muscle, and these are shown not to be resilient by design. In addition, two biological actuators likely to be resilient were also analysed. The pulvinus resilience index shows that it is partly resilient depending on damage location. But the most promising is the skeletal muscle, which has been shown to be highly resilient. Finally, the bio-inspired roots of resilience are discussed: resilience may originate from multi-scale structural design.

Keywords: Resilience; Actuator; Bio-inspiration; Damaged actuator; Bio-inspired muscle; Bio-inspired pulvinus

1. Introduction

In industrial machines, input motion is created by an actuator, which converts non-mechanical energy (chemical, electric, hydraulic, thermal, etc.) into mechanical power. Thus, when an actuator fails in an industrial setting, this jeopardises the functioning of the mechanism. To secure critical motions, the current industrial standard is to duplicate crucial parts to avoid catastrophic failure. This is particularly true for drones and helicopters where flying commands that orient blades are duplicated [33]. This strategy is called redundancy and comes with drawbacks. Redundant systems are heavier, more expensive, less compact, and consume resources and energy. In the context of sustainable development, redundancy is no longer a gold standard and new design strategies are emerging. One of the most recent is the digital twin that helps predict risks of catastrophic failure [18].

Another option to secure critical motions is to rely on resilient-by-design actuators [20]. Resilience is a trendy concept that is not well defined in the context of industrial systems. It conveys the idea that the system may resist disturbances without catastrophic loss of performance. To define resilience of an industrial system, one may leverage existing definitions of resilience from different research fields. Table 1 summarises a number of definitions found in science and engineering, together with their different nuances. Some of the definitions focus on resistance to, mitigation of, external disturbances whereas others deal with recovery after a disturbance. The latter definition matches the concept of self-healing material in engineering [26] which is not considered in this analysis. Here, the focus is set on resilience as resistance to, mitigation of, external disturbances. Despite numerous definitions found in literature, none of them was given specifically for industrial systems or actuators. The definition given in computer sciences (Table 1, line 2) may be adapted to define mechanical resilience as the *faculty of an actuator to maintain its motion capabilities when disturbed or damaged (and respectively a system for its function)*.

With regards to resilience, this definition may be used to optimise the design of a new class of actuators. Design for resilience has not been investigated much by industry. To create resilient actuators, an efficient method is to leverage those that can be found in Nature. Among the most promising is the skeletal muscle. It allows the motion of mammals, fish and birds (vertebrates) even when it is slightly damaged. In fact, most athletes notice that during training, muscle damage is barely felt and performance remain constant. It is after a period of rest, however, that muscle soreness then appears. This delayed onset of muscle soreness corresponds to micro-damage within the muscle (Myofibril breaks and accumulation of lactic acid) [22]. In

Field	Definition	Ref.
OXFORD DICTIONARY	(1) The ability of people or things to recover quickly after something unpleasant, such as shock, injury etc. (2) The ability of a substance to return to its original shape after it has been bent, stretched or pressed.	
COMPUTER SCIENCES	(1) Continue to operate in presence of compromised nodes, and endure and overcome internal attacks. (2) Maintain functions and structure in the face of internal and external change.	[7] [2]
RESILIENCE SCIENCE	The extent to which a system can maintain its structure, function, and identity in the face of disturbance.	[17]
ENGINEERING RESILIENCE	Ability of systems to anticipate and adapt to the potential for surprise and failure.	[14]
CIVIL ENGINEERING	Capability to recover from external stresses to an equilibrium.	[3]
MANUFACTURING SYSTEMS	The intrinsic property of a system to resist, and/or recover from, and/or adapt to a new and improved state in a time much smaller than the overall lifetime of the system, under known and unknown stochastic or random perturbation(s).	[20]
BIOLOGY	The ability to quickly and completely recover after deviation from normal physiological state or damage caused by a stressor or an adverse health event.	[30]
ECONOMY	The ability of an economy or a society to minimize welfare losses for a disaster of a given magnitude.	[11]
SUPPLY CHAIN	The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations - ideally, a better state than prior to the disruption.	[29]

Table 1: Definitions of resilience in science and engineering.

this sense, muscle is resilient given that even when damaged an athlete is able to continue training without a catastrophic loss of performance.

In a similar vein, plants also exhibit versatile actuators likely to be resilient. Pulvini move plants leaves to follow the sun’s path and avoid herbivores. Early observations show that even when a significant part of the pulvinus is excised, the leaf motion still occurs [21]. This shows that pulvinus is also a resilient actuator.

In these two biological examples, resilience should emerge from a combination of structural and control properties. Resilience by command (software) has been successfully conceptualized and mimicked numerically [1, 5, 16, 34, 35]. Bio-inspired algorithms based on artificial intelligence, have been implemented for multi-actuator systems [5].

However, little attention has been paid to the structural properties of these biological actuators that may favour resilience. To address this, firstly an index quantifying resilience to damage for actuators is proposed and discussed. Secondly, this index is then applied to a hydraulic cylinder, a skeletal muscle, a pulvinus and a McKibben bio-inspired muscle. These applications result in efficient descriptions of the resilience of manufactured and biological actuators. The index further shows that loss of performance is dependent on where the damage is located. This allows for a definition of the global resilience of a system or an actuator to be given. Lastly, practical considerations are discussed, specifically bio-inspired design laws to create a resilient industrial actuator.

2. An index to quantify resilience

Actuation and resilience		Pulvinus	
$f(t)$	Force during a cycle	θ	Leaf inclination angle
$v(t)$	Velocity during a cycle	Hydraulic cylinder/McKibben muscle	
V	Initial volume of material	P	pressure
η	Relative damaged volume V^*/V	Q	Feeding flow rate
χ	Resilience	Q_l	Leak flow rate
R	Redundancy of the system	a	Leak typical diameter
χ_s	Resilience of a system	e	Diameter of the input pipe
Muscle		l	Length of the pipe
f_0	Skeletal muscle maximum force	w	Housing thickness
v_0	Skeletal muscle maximum velocity	L	Housing length
α	Actin-Myosin kinetical parameter	d	Housing diameter

Table 2: Definition of parameters. (*) indicates quantities relative to a damaged actuator or system.

We aim to define resilience to damage, χ , with respect to the motion capability of an actuator for a given level of damage. Moreover, such a definition must suit a large variety of actuators and systems, from biology to industry.

The motion of an actuator or function of a system may be described by different quantities, such as maximal stroke, velocity of actuation, maximal strength, maximal instantaneous power, yield, etc. In fact, a different measure of motion capability may be given depending on the targeted motion. For the sake of generality, the power produced by an actuator during a typical cycle, $\int_{cycle} f(t) v(t) dt$ is considered (where $f(t)$ and $v(t)$ are the time variations of force and velocity during the actuation cycle).

The definition of resilience must also take into account damage level. Here, again, the definition of damage level must be clarified. The damage of a system or an actuator may be described by different quantities such as crack depth, volume of plastic deformation, loss of material, loss of internal fluid, corrosion, fatigue, wear, etc. Although, an index of damage may be created for each of these quantities, it could not be applied to every type of actuator. For instance, material corrosion may be useful to describe the ageing of the piston of a hydraulic cylinder, but it cannot be applied to skeletal muscle made of liquid and soft solid. For the sake of generality, no specific damage was considered in particular, but rather all types of damage were gathered within a single quantity: the damage volume V^* . Specifically, the ratio between the damage volume, V^* , and the total volume, V , is considered to represent the damage level, $\eta = V^*/V$.

With these two conditions, one may propose the following expression for resilience to damage of a single actuator,

$$\chi = \frac{\int_{cycle} f^*(t)v^*(t)dt}{\int_{cycle} f(t)v(t)dt} \frac{1}{1-\eta}. \quad (1)$$

For an undisturbed actuator, χ is 1. When damaged, the resilience of an actuator may be greater than one, indicating that the damage volume has little influence on the actuator's capabilities. Indeed, this case would represent oversized actuators. Conversely, minor damage involving catastrophic loss of performance will generate extremely low scores of resilience ($\chi \rightarrow 0$). $\chi = 0$ indicating an out-of-order actuator.

This definition stands for a single actuator and may not be applied directly for a system combining a number of actuators. Specifically, to define resilience for systems made of redundant actuators, one may first define redundancy,

$$R = \frac{N}{n}, \quad (2)$$

where n is the minimum number of actuators needed to perform the motion and N the total number of actuators in the system. With this definition, the resilience of a system reads,

$$\chi_s = R\chi. \quad (3)$$

The definitions above of resilience directly show that redundancy is an efficient way to enhance the resilience of a system. Indeed, χ_s may be much larger than χ if the redundancy is large.

To show the broad spectrum of this definition of resilience, four reference cases are presented: two manufactured actuators – a hydraulic cylinder (conventional industrial actuator), and the McKibben muscle (bio-inspired actuator); and two biological actuators, – the biceps (skeletal muscle) and the pulvinus (plant muscle), see figure 1.

3. Computing resilience of four reference actuators

3.1. The hydraulic cylinder (industrial actuator)

The index of resilience is computed on an industrial actuator, a simple effect hydraulic cylinder, figure 1c. This actuation technology is widespread in industry, for instance for hydraulic bike brakes, glasshouse window and trunk openers, lifting operations, etc. Now, a simple hydraulic car jack is considered, figure 2. This car jack is composed of a steel body of thickness w , length L and diameter d , a piston fitted with a toric seal, and a pressure source feeding through an input pipe (length l , diameter e). Experience shows that such hydraulic cylinders may deteriorate due to wear of the toric seal [23]. This triggers a leak from the seal, which is idealized as a cylinder of diameter a , cross-section πa^2 and depth w . The volume of this small cylinder represents the damaged volume $V^* = \pi a^2 w$. The power of the hydraulic cylinder fv (force times velocity) is given by the power of the hydraulic feeding PQ (pressure times flow rate),

$$fv = PQ. \quad (4)$$

An oil flow rate, Q , is fed from the constant pressure source through the input pipe and a flow rate Q_l is lost by the leak. Thus both should flow in a viscous regime (low Reynolds number, $Re < 1$),

$$Q = \frac{\pi P e^4}{128 \nu l} \quad \text{and} \quad Q_l = \frac{\pi P a^4}{128 \nu w}. \quad (5)$$

The damage level η may be computed with reference to the total volume of the hydraulic cylinder, $V = \pi d^2 L$. This leads to the expression of the typical leak dimension,

$$\eta = \frac{a^2 w}{d^2 L} \quad \text{leading to} \quad a^2 = \eta \frac{d^2 L}{w}. \quad (6)$$

One can now express the resilience of the hydraulic cylinder,

$$\chi = \frac{f^* v^*}{fv} \frac{1}{1-\eta} = \frac{P(Q-Q_l)}{PQ} \frac{1}{1-\eta} = \frac{1}{1-\eta} \left(1 - \eta^2 \frac{d^4 L^2 l}{e^4 w^3} \right). \quad (7)$$

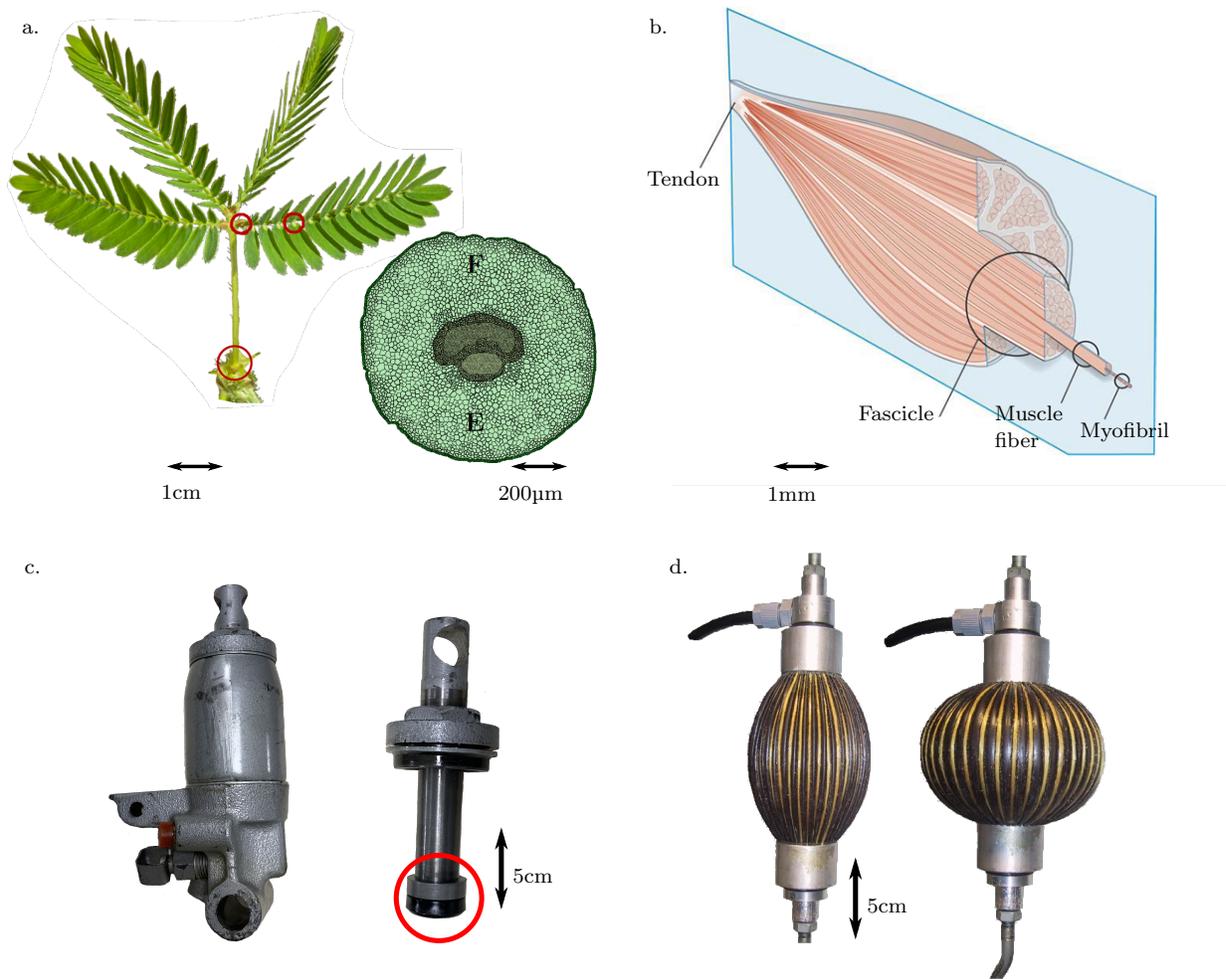


Figure 1: Actuators of reference. a. A leaf of (*Mimosa Pudica*), adapted from Tadrict et al. [24]. Pulvinus locations are encircled in red. inset: Cross-section of pulvinus with motor cells in light green. b. Diagram of a skeletal muscle showing highly structured muscle fibres (at multiple scales), adapted from Gillies [9]. c. Car jack hydraulic cylinder. Inset: Piston and rubber seal (red circle) where damage may occur. d. Pneumatic McKibben muscle.

The force-velocity relationship of the hydraulic cylinder is plotted in figure 2a. In log-log scale, the damaged force-velocity curve shifts down (black to red curve). For a given damage level, the available power is changed by the same factor for any force.

When the hydraulic resistance of the leak is similar to the one of the input pipe, the resilience of the hydraulic cylinder collapses and reaches 0 (figure 2a). Interestingly, resilience is independent of the force or velocity of the motion. This is a small artefact of this model, where the pressure source is considered ideal and the fluid incompressible. Here, with $P = 10^5 \text{Pa}$, $d = 30 \text{ mm}$, $e = 3 \text{ mm}$, $l = 10 \text{ mm}$, $\nu = 1$, $w = 5 \text{ mm}$ and $L = 140 \text{ mm}$, $\chi = 0$ corresponds to a damage level $\eta = 0.0013$. This poor resilience to damage shows that hydraulic cylinders are sensitive to wear. Therefore this situation requires monitoring and maintenance operations. Prudently, to avoid such catastrophic failures, most hydraulic cylinders are designed with security margins.

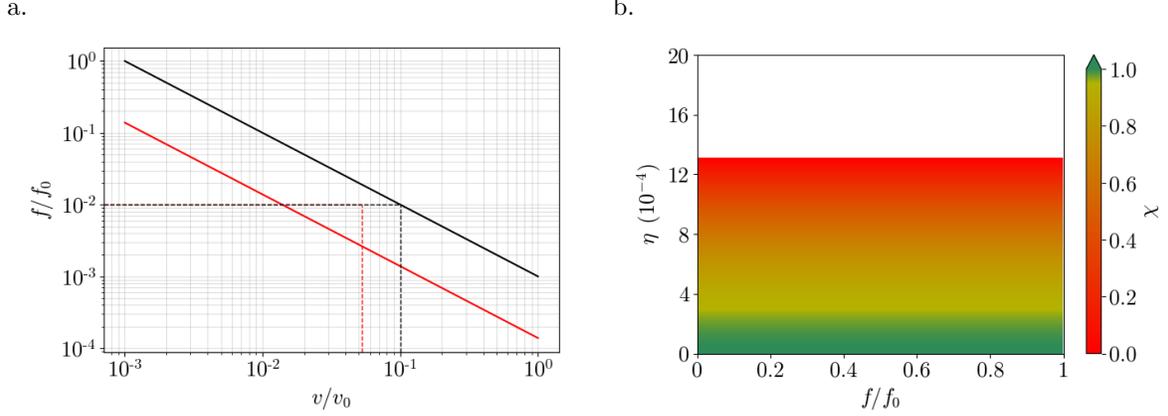


Figure 2: a. Force-velocity relationship for the hydraulic cylinder (log-log scale). Black: intact hydraulic cylinder. Red: damaged hydraulic cylinder ($\eta = 0.009$). The dotted lines represent a cycle of motion of the hydraulic cylinder. b. Colour map of the hydraulic cylinder resilience for different forces, f and damage level, η . The hydraulic cylinder has an extremely low resilience (null when damage is larger than 0.0013). For visualisation purposes, the damage level is shown between 0 and 0.002.

3.2. Biological actuators

3.2.1. The biceps (skeletal muscle)

Mammals, birds and fish (phylogenetically distant animals) rely on skeletal muscles to move, hunt or escape predators. The muscle structure for these three animal classes is quite similar [19], indicating that it has been preserved through evolution. This evolutionary history suggests that skeletal muscle may be resilient. Furthermore, intense athletic training induces delayed onset of muscle soreness (DOMS) although muscle performances are barely altered during training [22]. Muscle soreness corresponds to microtrauma of muscle fibres, specifically on the Z-layer (junction between 2 parts of the sarcomere) of sarcomeres and conjunctive tissues. This performance preservation illustrates the resilience of skeletal muscles.

The skeletal muscle is a highly-structured actuator with complex feedback-loop commands [9]. It is composed of tendons and fascicles at the macro-scale. Fascicles gather parallel muscle fibres (diameter $10 - 100 \mu\text{m}$). Muscle fibres are made of myofibril, which are, in turn, made of a series of elementary micro-scale bricks: the sarcomeres (length, at rest: $3.5 \mu\text{m}$; contracted: $2.5 \mu\text{m}$). Thus, from an engineering point of view, muscle is idealized as a sequence of series and parallel sarcomeres, Figure 1c.

Hill's seminal work [13], which gathered experimental data on frog legs, made it possible to establish the force-velocity relationship to be read as [4],

$$\frac{f}{f_0} = \frac{1 - |v|/v_0}{1 + \alpha|v|/v_0} \text{ or } \frac{|v|}{v_0} = \frac{1 - f/f_0}{1 + \alpha f/f_0}. \quad (8)$$

f_0 is the maximal force the muscle can produce. Its micro-mechanical meaning is the sum of parallel forces of single sarcomeres, considering the number of myofibres in parallel N_p , and the force generated by a sarcomere s , $f_0 = N_p s$. v_0 is the maximal velocity the muscle can actuate. Its micro-mechanical meaning is the sum of series of velocities of single sarcomeres within the fibers, considering the number of sarcomeres in series N_s , and the intrinsic velocity of a sarcomere u , $v_0 = N_s u$. The parameter α is the ratio between bio-chemical constants related to actin-myosin bound, independent of the number of sarcomeres.

Little work has been done to link muscle damage to motion performance. Leveraging on Hill's equation, Eq (8), and fatigue (chemical inhibition) data from Greenberg and Moore [10], one can compute the force-velocity curve in standard and inhibited conditions, see figure 3a. The chemical inhibition is, here, considered as a model for damage.

It is assumed that only the number of active sarcomeres is changed by the chemical inhibition ($N_p \rightarrow N_p^*$, $N_s \rightarrow N_s^*$), and that the unitary force s and velocity u are unchanged $f_0^* = N_p^* s = f_0 N_p^*/N_p$ and $v_0^* = N_s^* u = v_0 N_s^*/N_s$. The Hill's relation for a damaged muscle linking f^* and v^* reads,

$$\frac{f^*}{f_0} = \frac{N_p^*}{N_p} \frac{1 - (|v^*|/v_0)(N_s/N_s^*)}{1 + \alpha(|v^*|/v_0)(N_s/N_s^*)}. \quad (9)$$

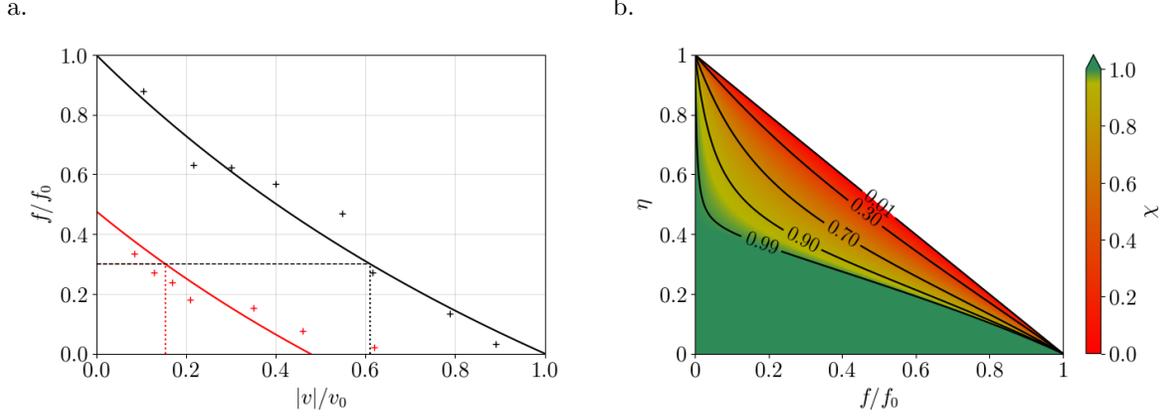


Figure 3: a. Data points are from Greenberg et al. [10]. The intact (black) and damaged (red) curves are fitted on Greenberg data varying α and N_s^*/N_s . The dotted lines represent the muscle actuation cycle for a fixed force. b. Colour map of muscle resilience for different forces (f/f_0) and damages (η). All the data is scaled between 0 and 1 for clarity.

It is then assumed that the damage rates are equal for series and parallel sarcomeres $N_p^*/N_p = N_s^*/N_s$. Hill's equation with damage reads,

$$\frac{f^*}{f_0} = \frac{(N_s^*/N_s) - (|v^*|/v_0)}{1 + \alpha(|v^*|/v_0)(N_s^*/N_s)} \quad \text{or} \quad \frac{|v^*|}{v_0} = \frac{N_s^*/N_s - f^*/f_0}{1 + \alpha(f^*/f)(N_s^*/N_s)}. \quad (10)$$

This equation is fitted (least mean squares) on Greenberg data varying N_s^*/N_s and α . The parameters were found to be $N_s^*/N_s = 0.47$ and $\alpha = 2.04$. The fitted Hill's curves are plotted in figure 3a.

From this modelling and fitted values, we consider a simple actuation cycle: (i) zero velocity and increasing force from 0 to f_1 ; isometric contraction, (ii) constant force f_1 and increasing velocity to v^* , eccentric contraction; (iii) constant velocity $-v^*$ and decreasing force to 0, concentric contraction; and (iv) zero force and decreasing velocity to 0, with concentric contraction. The dimensionless powers $P/(f_0v_0)$ and $P^*/(f_0v_0)$ of the cycle read,

$$\frac{P}{f_0v_0} = \int_{cycle} \frac{f_1 |v_1|}{f_0 v_0} dt = \frac{1 - (f_1/f_0) \frac{f_1}{f_0}}{1 + \alpha(f_1/f_0) \frac{f_1}{f_0}} \quad \text{and} \quad \frac{P^*}{f_0v_0} = \int_{cycle} \frac{f_1 |v_1^*|}{f_0 v_0} dt = \frac{(N_s^*/N_s) - (f_1/f_0) \frac{f_1}{f_0}}{1 + \alpha(f_1/f_0)(N_s^*/N_s) \frac{f_1}{f_0}}. \quad (11)$$

From the powers over a cycle and the damage volume $\eta = N_s^*/N_s$, the resilience of the muscle reads,

$$\chi = \frac{1}{1 - \eta} \frac{\eta - f_1/f_0}{1 - f_1/f_0} \frac{1 + \alpha f_1/f_0}{1 + \alpha \eta f_1/f_0}. \quad (12)$$

This expression of skeletal muscle resilience depends on the level of damage η and the required level of force f . The variations of resilience depending on these two parameters is drawn in figure 3b. Resilience is close to one for low forces and low velocities. We also notice that for large forces or large velocities, resilience decreases strongly with level of damage.

This model shows that the damage rate at the sarcomere level changes the macroscopic behaviour of the muscle and its resilience.

3.2.2. The pulvinus (plant muscle)

A pulvinus is a thickening found at the base of leaves of many plants from the *Fabaceae* and *Oxilaceae* families. It allows reversible motions of leaves, for instance closure at night, or response to touch (*Mimosa Pudica*), figure 1a. Its functions vary from species to species which include orienting leaves toward the sun, protecting from herbivore attacks (*Mimosa Pudica*) and allowing the rain to reach the ground (*Samanea Saman*). Similarly to skeletal muscle, it is found in distant species on the phylogenetical tree, which indicates its robustness [24]. Since Dutrochet (1837) it is also known that ablating half of the pulvinus does not prevent the leaves from moving [6], which point to resilient behaviour.

The pulvinus from *Mimosa Pudica* is composed of 3 main structural elements organised in a cylindrical geometry, figure 1a (inset). At the centre are the vascular tissues (xylem and phloem) that provide water and extract sap. These hard tissues are surrounded by thin-walled parenchyma cells also called motor cells. A thin cuticle protects the organ from evapo-transpiration. The motor cells (diameter 25 μm) are able to expand (extensor) or to shrink (flexor) when turgor pressure is modified. This local deformation creates motion.

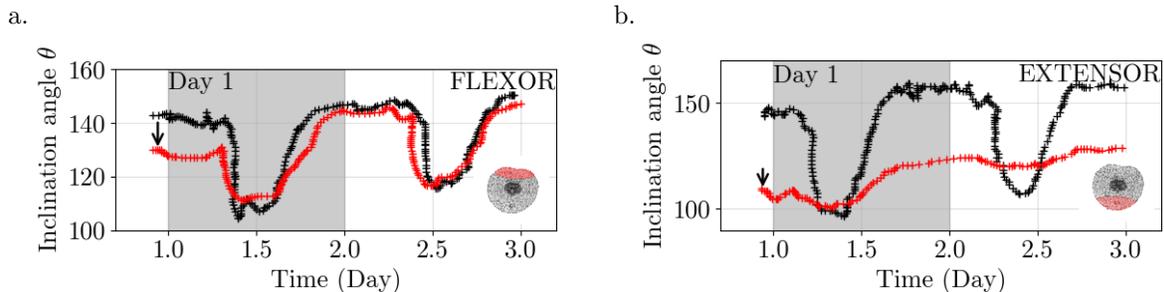


Figure 4: Angle of inclination with an intact pulvinus (black) and with the flexor excised (a. in red) or with the extensor excised (b. in red). Grey areas correspond to the first day after excision, indicated with the black arrow

No theoretical force-velocity relationship exists for pulvinus in literature. However, leveraging the work of Millet et al. [21] which reports on the evolution of the angle of inclination θ of *Phaseolus vulgaris* leaves for sound and ablated pulvinus, one can compute pulvinus resilience, see figure 4. In the figure, black points correspond to the control experiment: a sound pulvinus that follows a circadian motion, figure 4a and b. Red points correspond to the tests, excising around 30% of the pulvinus (Excised flexor, figure 4a. Excised extensor, figure 4b). The pulvinus is excised on the first day (black arrow) and its evolution over two days after excision is shown.

In the following, the first day after excision (grey area) is studied to compute resilience to damage. The second day is not studied not to consider self-healing and regeneration processes.

From this data, the evolution of the angle of inclination $\theta(t)$ on day one (circadian cycle) is fitted with two half of Gaussians for smoothing purposes, figure 5a (Excised flexor) and c (Excised extensor). The evolution of force is reconstructed considering that the force is proportional to $f \propto \theta - \theta_0$, where θ_0 is the minimal angle on the circadian cycle. This corresponds to acting on the lever arm to move the leaf. The velocity is also reconstructed as $v \propto d\theta/dt$. Those two quantities are plotted in figure 5b (Excised flexor) and d (Excised extensor) and form quasicycles (some growth occurs).

Based on these quantities, the resilience index, equation (1), is computed. The resilience of each excision experiment can be estimated, by comparing black to red areas which correspond to the power over a cycle. The damage level is estimated at 30 % of the total volume. On the first day, the resilience of the extensor (excised flexor) and the flexor (excised extensor) are,

$$\chi_{extensor} = 0.25 \quad \text{and} \quad \chi_{flexor} = 0.05 \quad (13)$$

The resilience of the extensor is much larger than that of the flexor. This shows that the proposed index of resilience quantifies the biological observation found in literature (Dutrochet [6], Millet et al. [21]). The self-healing effect (regeneration) can be observed on the second day with an increasing resilience index ($\chi_{extensor} = 0.84$ and $\chi_{flexor} = 0.16$).

3.3. The “McKibben” muscle (bio-inspired actuator)

McKibben muscles are manufactured pneumatic actuators inspired from the skeletal muscle [27]. McKibben muscles are widely used for robotic arms, exoskeletons, and other bio-inspired devices. These types of muscles are made of an elongated cavity that becomes spherical when pressurised. This shortens the muscle and creates motion. Similarly to the previous actuators, McKibben resilience may be evaluated using equation (1) and some minimal modelling of its functioning.

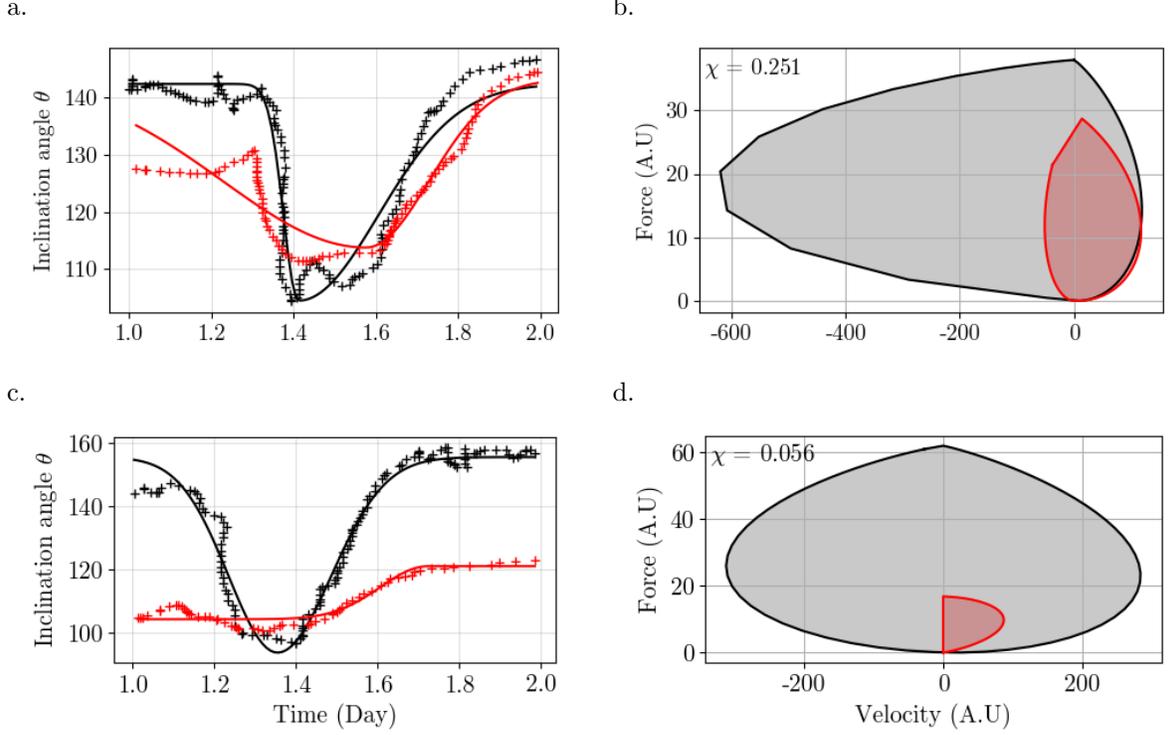


Figure 5: Angle of inclination θ for a single cycle from day 2 to day 3. The force-velocity relationship is obtained numerically after fitting the displacement curve, deriving the displacement to obtain the speed. The force is considered to be the moment of the weight of the plant. It is then proportional of the displacement.

The McKibben muscle is idealised as an ellipsoid cavity of diameter d and major axis L (volume $V = \pi d^2 L / 6$) with skin thickness w . The muscle is connected to a pressure tank P , with an input pipe of diameter e and length l . For an intact actuator, the pressure in the cavity matches the pressure of the tank. Now, if the actuator is damaged, some air may flow through this damage of typical size a (damage volume $V^* = w\pi a^2$) which may reduce the pressure inside the cavity and thus the available power of the actuator.

Similarly to the hydraulic cylinder, the power of the McKibben muscle is given by the power of the pneumatic feeding $f v = P Q$. With a similar reasoning, one obtains the resilience of the McKibben muscle,

$$\chi = \frac{1}{1 - \eta} \left(1 - \left(\frac{2}{3} \eta \frac{d^2 L \sqrt{l}}{e^2 w^{2/3}} \right)^2 \right). \quad (14)$$

The force-velocity relationship is plotted in figure 6a ($r_0 = 50$ mm, $L_0 = 100$ mm, $L = 10$ mm, $r = 5$ mm and $l = 10$ mm). In log-log scale, the curve shifts down when damage occurs (from black to red). The resilience of the McKibben muscle is plotted in figure 6b. When the damage level reaches $\eta = 0.0015$, the resilience collapses. The McKibben muscle is as sensitive to damage as the hydraulic cylinder. In fact, McKibben muscles mimic the geometry and actuation shape of skeletal muscle, showing a Hill-like force velocity relationship. However, muscle resilience has not been mimicked making it highly sensitive to minor damage.

To avoid catastrophic failures, McKibben muscle may be strengthened with reinforced self-healing fibres [25]. Such self-healing strategies are behind the scope of the present resilience analysis.

4. Resilience sensitivity to damage location : global actuator resilience

The proposed definition of resilience is not expansive. Depending on the location of the damage, different levels of resilience may be computed for an actuator. For instance, the pulvinus may be considered very

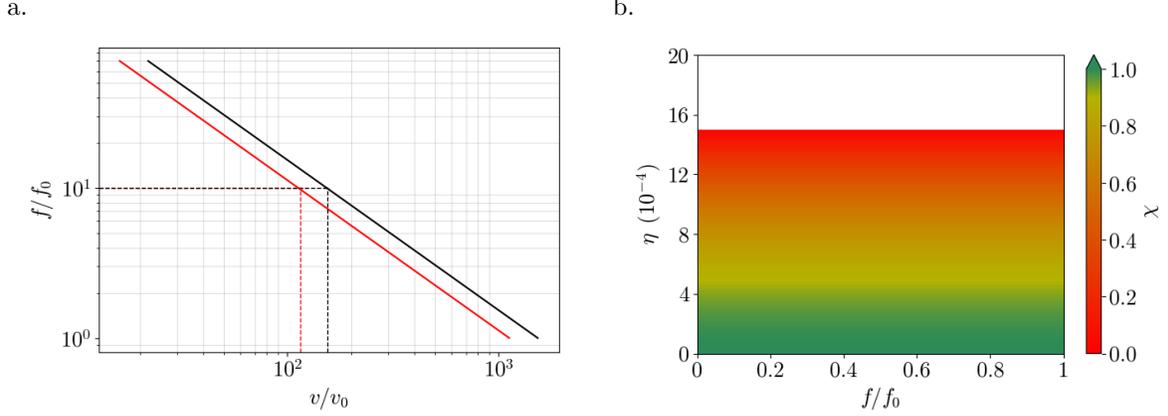


Figure 6: a. Force-velocity relationship for the McKibben muscle (log-log scale). Black: intact McKibben muscle. Red: damaged McKibben muscle ($\eta = 0.001$). The dotted lines represent a cycle of motion of the McKibben muscle. b. Colour map of McKibben muscle resilience for different forces, f and damage level, η . The McKibben muscle has an extremely low resilience (null when damages are larger than 0.0015). For visualisation purposes, the damage level is shown between 0 and 0.002

resilient when excising the flexor, but poorly resilient when the extensor is damaged. For the sake of generality, one may, for instance, consider damage in every location in the actuator and compute global resilience χ . The global resilience of the actuator would be given by the most harmful damage, where χ is minimal. The global resilience reads

$$\bar{\chi} = \min_{\Omega} (\chi), \quad (15)$$

where Ω is the set of possible damages of fixed volume.

For instance, in the case of the hydraulic cylinder, a crack on top of the cylinder, figure 7, may not change the actuator's capabilities unless used at maximal stroke. In this case, the resilience is larger than 1.

To show the importance of damage location, the resilience of the hydraulic cylinder is computed along the cylinder body and in the seal by displacing the leak position (numbers from ① to ⑥). Dimensions are given in section 3.1. A cycle from the bottom to the top of the cylinder is considered as a reference cycle. When the leak is in position ①, at the top position of the stroke, the fluid never leaks and resilience is just above 1. Conversely, for positions ② and ③, a leak occurs during the part of the cycle where the piston is above the leak position, and there is no leak elsewhere. This reduces the efficiency of the hydraulic cylinder and thus its resilience. Finally the most critical leak positions are ④, ⑤ and ⑥ where the leak occurs during the whole cycle. Those results are gathered in figure 7 that shows that resilience breaks down differently depending on the leak position. If the damage occurs on the seal or the bottom of the cylinder (④, ⑤ or ⑥) resilience breaks down independently of the stroke. Error bars represent variations of $\Delta a = 2.5\%$ of the damage typical size. This corresponds to a variation of damage level $\Delta\eta = 5\%$.

To give another example where damage location is important, a magnetic actuator made of a simple rotor and rotating stator is considered [32]. This magnetic actuator may appear resilient, because when a part of the magnetic rotor is damaged, its torque then decreases only by the damage volume. There is no catastrophic loss of performance due to this specific damage. However, the critical part of this actuator is not in the magnetic rotor, but rather in the electrical motor, the performance of which may collapse if the solenoid winding is damaged. Thus, the global resilience of the actuator needs to be studied and analysed in order to determine its critical part.

5. Discussion

As shown on the hydraulic cylinder modelling, most traditional industrial actuators are not resilient to damage. For decades, redundancy and over-sizing were the gold standards in industry. However industry 4.0 challenges to create downsized compact actuators with less raw material consumption, less energy and less weight. A resilient actuator may be key to overcoming this challenges.

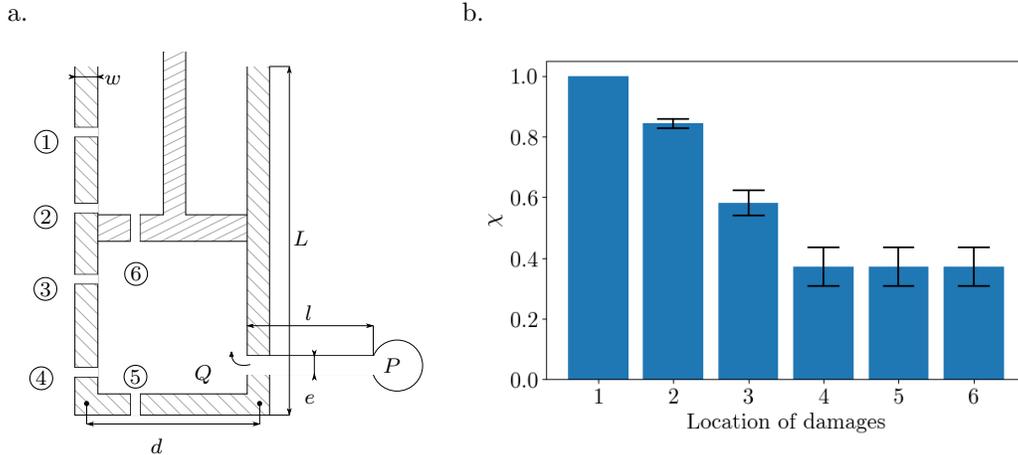


Figure 7: a. Scheme of a simple effect hydraulic cylinder. Damage is here represented by numbers, to show which damage is the most critical. b. Different level of resilience χ are plotted for each level of resilience in a. Errors were computed considering a range of variation of the leak diameter a of 2.5% around the mean value. This corresponds to a variation of damage level $\Delta\eta = 5\%$

Fortunately, resilient biological actuators may be mimicked to create industrial actuators. However, the direct copy may have drawbacks mainly because most biological actuators have evolved under multiple pressures of selection towards a specific motion as shown with pulvini. Pulvinus is more resilient on the extensor side than on the flexor side, likely because the extensor actuates critical protective motion.

Moreover, the direct mimicry of the shape, the motion capability and the force-velocity relationship, as done in the McKibben muscle, is not sufficient to produce resilience to damage. Resilience emerges from a more subtle structural design.

From a structural point of view, the skeletal muscle and the pulvinus are the aggregation of many micro-actuators in a structured (skeletal muscle) or an unstructured manner (pulvinus). This study suggests that a multi-scale structure, the structural properties shared by pulvini and biceps, is effective to create resilience. This resilience may be enhanced by feedback loops and micro-scale control. Bio-inspired series and parallel elastic actuators with their multi-scale structure may offer a promising option to create resilience [8, 12, 31]

Pulvinus control is a complex cell-centred self-regulation, still under active research [28]. The skeletal muscle is controlled by multi-levelled feedback loops and the central nervous system [15]. The feedback loops avoid shaking (control-induced oscillations) and allow precise, smooth and fast movement (these problems are recurrent in robotics). These multi-levelled control loops allow for the presence of damage to be efficiently managed. These loops are not present for the pulvinus which may explain why it is only resilient when the flexor is excised. The multi-scale structure of biological actuators, featuring series and parallel actuators, creates the necessary large number of degrees of freedom to apply bio-inspired resilience algorithms [5].

Biological actuators demonstrate self-healing capacities, which have not been considered in the present paper. In fact, for the pulvinus, self-healing is efficient to produce resilience as it is shown in figure 4a, where oscillation amplitudes are totally recovered after one day. The present analysis focuses on the first day after excision, where cells are not yet healed. Analysing self-healing properties of the skeletal muscle has not been carried out, and Hill's force-velocity relationship, equation (8), does not take self-healing into account. However we know that self-healing also occurs with skeletal muscle since athletes recover from muscle soreness within days of intense training. To create an advanced resilient actuator, a combination of these properties are required: multi-scale structure from cells to tissues, multi-levelled feedback control and self-healing.

In summary, based on definitions of resilience found in different fields, an index of resilience has been proposed. The resilience of two manufactured and two biological actuators were analysed: the hydraulic cylinder, the McKibben bio-inspired muscle, the skeletal muscle and the pulvinus. With the proposed definition, the skeletal muscle is shown to be fully resilient, the pulvinus partly resilient, and manufactured actuators not resilient at all.

The proposed index of resilience to damage has been designed to be the most general. Several other

definitions of damage level would have applied. For instance, the damaged mass ratio m^*/m may stand for the damage level as opposed to the damage volume ratio. For biological actuators, these two ratios would be almost similar given that densities of biological material are close to one (bone: $1.1 - 1.8 \cdot 10^3 \text{ kg/m}^3$, muscle: $1.1 \cdot 10^3 \text{ kg/m}^3$, adipose tissue: $0.92 \cdot 10^3 \text{ kg/m}^3$; dry wood: $0.14 - 1.3 \cdot 10^3 \text{ kg/m}^3$ – living wood density is the mean between dry wood and water densities). However, when an industrial actuator is considered, there may be more significant variations in material densities. For instance, the seal of the hydraulic cylinder is made of rubber (density: $0.92 - 2.2 \cdot 10^3 \text{ kg/m}^3$) whereas the body is made of steel (density: $8 \cdot 10^3 \text{ kg/m}^3$). Thus major damage in the seal may be underestimated when using the mass ratio as a measure of damage.

6. Conclusion

By clarifying resilience for actuators, equation (1), an index was computed on a hydraulic cylinder, a McKibben bio-inspired muscle, a pulvinus, and a biceps. Manufactured actuators are shown not to be resilient, whereas biological ones are. Depending on the location of damage, actuator resilience may be strongly affected.

This tool, equation (1), would allow to quantify in practice resilience when designing new bio-inspired actuators. This would allow for an optimisation of actuator designs with regards to resilience. Depending on the application, the proposed definition of resilience may be adapted by changing the target of equation (1) in terms of performance.

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