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# A call for a performance-driven approach for soft robotics research

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Soft robots offer physical adaptability and collision robustness, but they find limited applications due to lower speed, precision, and controllability compared to rigid systems. We advocate for a performance-driven approach to develop hybrid soft-rigid robots with animal-like agility. Recent research demonstrates that soft robots incorporating fast-acting muscles, energy-storing tendons, and shape-morphing skeletons can achieve capabilities approaching their biological and rigid counterparts.

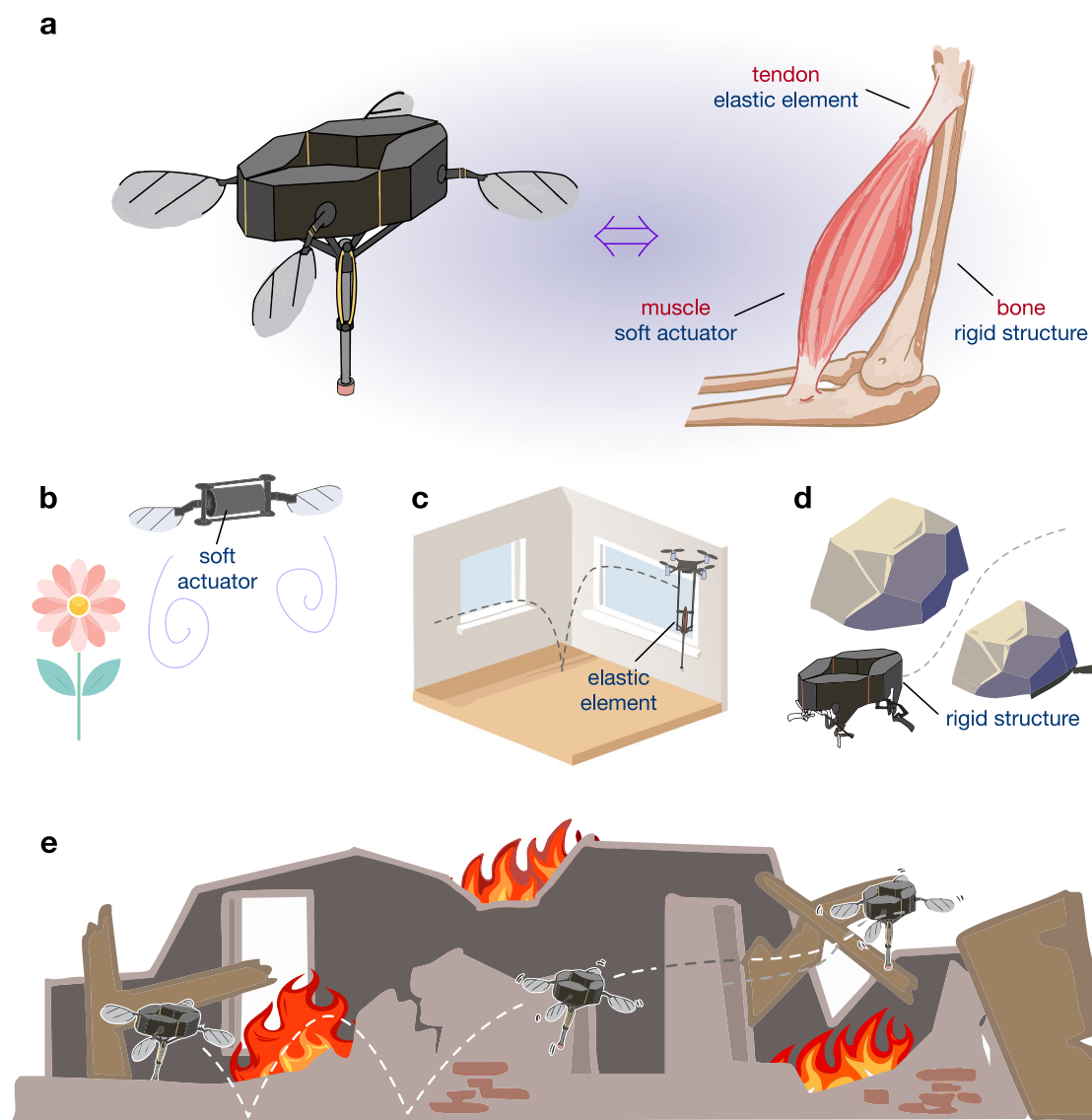
The soft robotics community has witnessed rapid growth in recent years, featuring exciting new actuators, sensors, and systems. A salient feature of soft robots, as suggested by their names, relates to the use of low-elastic modulus materials in the construction of primary robot components, including actuators, linkages, and end-effectors. This confers novel capabilities for robot systems, such as continuous deformation to physical constraints (i.e., adaptability) and inherent safety to collisions (i.e., robustness), in complex natural environments to increase their appeal for real-world deployment. Popular examples of biological models that have inspired soft robots include inchworms<sup>1</sup>, octopuses<sup>2</sup>, and elephant trunks<sup>3</sup>, among others. The similarities between these soft robotic and biological systems with respect to their material composition, form, and function have led to advances in foundational understanding and technological innovations with bidirectional synergy between them<sup>4,5</sup> and have resulted in unique applications, ranging from wearable haptics<sup>6–8</sup>, deep-sea sampling of delicate animal species<sup>9</sup>, to microfluidic chips for chemical analysis<sup>10</sup>, and various flexible and thin medical devices<sup>11</sup>.

Soft robotics research over the last decade has taken a function-driven approach in which new materials, designs, and methodologies are aimed at achieving unique capabilities that are challenging or absent in traditional robotic systems. Although this approach has already enabled demonstrations of capable soft robots in human-centered applications, such as healthcare and wearables, the emphasis on unconventional functions often creates specific goals and metrics for soft systems that may not be as broadly applicable to the diversity of robotic systems and may isolate this community from other subfields. To illustrate, present-day soft robots find it difficult to perform conventional robotic tasks, such as precise manipulation<sup>12</sup> and agile locomotion<sup>13</sup>. Very few soft robots have demonstrated the speed, bandwidth, and controllability comparable to the state-of-the-art rigid-driven systems<sup>14–16</sup>. Such robots are capable of agile running<sup>17</sup>, hopping<sup>18</sup>, and flying<sup>19</sup> and are almost exclusively constructed of motors,

rotary gearing mechanisms, and rigid linkages. This unsatisfactory limitation is in sharp contrast to the capabilities demonstrated by organisms that include several soft components, such as muscles, tendons, and compliant exoskeletons, in addition to rigid elements, such as bones<sup>20</sup>. Using this architecture, a cheetah (*Acinonyx jubatus*) can outrun the fastest quadrupedal robot<sup>21</sup> by over seven times, in addition to making over 10 m long jumps and aggressive braking and turning using power-dense muscles, energy-storing tendons and flexible spines - all primarily soft components. Several of these musculoskeletal mechanisms with unique properties that allow animals to outcompete state-of-the-art rigid-driven robots in terms of system performance are yet to be fully realized as engineering analogs. Therefore, we see an opportunity to advance the development of soft robots that are capable of performing animal-like power- and energy-dense tasks in real-world environments<sup>22</sup>, in addition to embodying well-studied characteristics, such as adaptability and robustness. In this perspective, we advocate for a performance-driven approach to soft robotics, building on ongoing efforts to integrate high-performance soft robotic elements with bio-inspired musculoskeletal principles to yield systems that are competitive or even superior to the state-of-the-art rigid systems.

In order to achieve this ambitious goal and from a practical viewpoint towards real-world deployment, we believe it is appropriate to evaluate soft robots against the state-of-the-art rigid systems using a common set of task-specific performance criteria. We believe that this approach will bring four important benefits. First, this approach provides industry with increased options to select the most suitable robot for each application. Second, it can potentially drive performance-orientated efforts within the soft robotics community to accelerate their integration for real-world tasks. Third, it will substantially expand soft robotic applications to underexplored areas, such as aerial and legged robotics<sup>23,24</sup>. Fourth, the emphasis on task-specific performance will motivate the community to tackle major technical challenges with far-reaching impacts across all robotics subfields<sup>25</sup>. Although

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**Fig. 1 | Musculoskeletal system and its soft robotics analogs.** The bio-inspired design represents one promising approach among various potential strategies for performance enhancement in soft robotics. **a** Comparison between an integrated soft-rigid robot design and a biological musculoskeletal system, highlighting the functional parallels between their key components. **b** Soft actuators mimic muscles by providing high power density for forceful and rapid movements<sup>50</sup>. **c** Elastic elements function like tendons, enabling efficient energy storage and release to support

impulsive motions, such as jumping and rapid acceleration<sup>74</sup>. **d** Rigid structures serve as artificial bones, offering mechanical support while allowing for controlled flexibility, essential for maintaining adaptability in dynamic environments<sup>110</sup>. **e** The integration of these elements enables practical advantages in real-world applications, where robots can simultaneously achieve high performance while maintaining adaptability and robustness in complex environments.

there are emerging efforts in these directions underway, we encourage further research.

In the context of this perspective, we focus on locomotion agility, a system-level performance attribute that is often underexplored within the soft robotics community. Locomotion agility encompasses movements, such as running, hopping, landing, sharp turning, or acrobatic maneuvers in flight<sup>26</sup>. Qualities that contribute to agility include speed (how quickly a robot can traverse a distance), acceleration (the ability to exert large forces and torques), and precision (the ability to closely follow a trajectory). To achieve agile locomotion at the system level, the underlying subsystems, including actuators, transmission, and bodies, must collectively provide high force output, rapid power generation, and reliable and repeatable motions, while factors, such as efficiency and stability influence agility indirectly through their effect on overall locomotion performance.

Animal musculoskeletal systems embody these properties, resulting in highly agile performance. Figure 1a illustrates a sample musculoskeletal

system and a bio-inspired design that takes advantage of key corresponding elements. It consists of power-dense muscles that can exert large forces and torques (Fig. 1b) and energy-efficient tendons that can quickly store, dissipate, and release energy (Fig. 1c) embedded within hybrid soft-rigid skeletons that simultaneously modulate dynamic environmental interactions and withstand physical demands (Fig. 1d). In addition to locomotion agility, these elements also lead to superior movement economy<sup>27</sup>, real-world adaptability<sup>28</sup> and natural robustness<sup>29</sup>, in animals compared to primarily rigid-driven robots<sup>20,30</sup>. We believe that this represents an opportunity to further improve soft robotic designs and build systems that embody the biomechanical principles of agility. Building on historical examples of compliant musculoskeletal robotic structures<sup>31–35</sup> that support the feasibility of our claims, one promising research direction to achieve this vision is to develop muscle-like soft actuators, tendon-like transmission, and flexible skeleton-like body morphologies resulting in a hybrid soft-rigid robotic architecture.

In the rest of this article, we highlight recent examples of high-performing soft robots which already possess some of these characteristics and describe their design and operation principles. In the following three sections, we specifically analyze the properties and functions of three soft elements in these systems that resemble fast-acting muscles, energy-storing tendons, and shape-morphing skeletons respectively as promising concrete evidence supporting our thesis above and describe their contributing roles in increasing performance. We conclude by highlighting some opportunities for the soft robotics community to further develop the fundamental tools and components that enable agile locomotion performance. In the long term, we envision that this new class of soft or soft-rigid hybrid robots will replace entirely rigid systems in most out-of-laboratory robotic applications by emulating animal-like agility, adaptability, and robustness (Fig. 1e).

### Muscle-like actuators for fast and precise movement

From the perspective of locomotion agility, animals outperform rigid-driven robots due to several unique properties of the musculoskeletal system. Vertebrate muscles are highly dynamic, controllable, power-dense, and long enduring, which support agile locomotive behaviors, such as flapping flight and impulsive leap. Muscles also exhibit intrinsically tunable compliance that allows disturbance and impact dissipation, which enables robust locomotion in complex terrains<sup>36</sup>. In contrast, it remains difficult for existing robots to simultaneously embody animal-like agility and robustness. In our view, the development of soft actuators that resemble vertebrate muscle properties represents an exciting opportunity to close the gap between robot and animal locomotion performance.

Compared to engines and motors, soft actuators typically have superior adaptability and robustness but lag behind in actuation speed and precision. Emerging soft technologies, such as piezoelectric polymers<sup>37</sup> that are fast and precise, unfortunately output weak forces. Pneumatic or hydraulic actuators<sup>38,39</sup> are safe and adaptive, but require external pumps and valves, exhibit large hysteresis, and have a speed, precision, and efficiency inferior to electromagnetic motors. Magnetic actuators<sup>40</sup> have demonstrated multiple actuation modes using a single input, but they are limited to small sizes (< 10 g) and confined spaces where high fields or currents can be applied. Thermal driven actuators<sup>41,42</sup> have demonstrated high force density, but their actuation speed is often limited by the thermal diffusion process. In our view, the development of power-dense soft actuators is an underexplored yet highly impactful research direction. The achievement of fast and impulsive motion depends on the increase of actuator power density. Combustion-driven soft actuators<sup>43,44</sup> exhibit high force density (15 N/g), moderate bandwidth (10–100 Hz), and they lead to impulsive locomotion, such as high jumps and fast hopping.

In addition to high power density, agile locomotion also requires a fast response to reflex stimuli and control signals. Although it is difficult to precisely command the input power of combustion-driven systems, electrically driven actuators have shown high bandwidth and precise motion control. We view dielectric elastomer actuators (DEAs) as promising artificial muscles that enable fast, controllable, and robust locomotion. DEAs behave as a soft capacitor that undergoes deformation under an applied electric field. Although DEAs are a well-established class of soft actuators, prior research has predominantly prioritized metrics, such as energy density and strain, often at the expense of speed and power density. However, recent advances demonstrate that DEAs can achieve muscle-like power density (> 1.5 kWkg<sup>-1</sup>) and strain ( $\approx$  15%) as well as a resonance frequency of 1 kHz<sup>45,46</sup>. In recent years, DEAs (Fig. 2a, b) have enabled a wide range of challenging and competitive robotic demonstrations.

Under feedback control, DEA-driven aquatic robots<sup>47,48</sup> could autonomously follow complex trajectories. Another fish-like DEA robot<sup>49</sup> could operate in the Mariana Trench under extreme pressure and temperature. Based on DEA properties, we believe it is possible for future aquatic soft robots to embody both capabilities, which would be difficult for similar-sized rigid-driven systems.

To demonstrate how DEAs can enable agility and robustness simultaneously in soft robotic systems, our team has developed a new class of

DEA-driven aerial robots<sup>50</sup>. Soft DEAs embedded in rigid carbon fiber frames analogous to an insect thorax drive pairs of flapping wings at 400 Hz under high-rate (10 kHz) feedback control, and the robot can demonstrate a suite of challenging maneuvers (Fig. 2a). Specifically, this robot can achieve 20 body lengths per second flight speed, follow complex 3D trajectories, perform multiple body flips in flight, recover from in-flight collisions, and most impressively, endure critical damage to actuators and wings. In fact, our robot's speed and flight precision outcompete that of similar-sized rigid-driven systems because DEAs can operate under aggressive commands. This represents an example in which the robustness of soft actuators increases robot agility, which is an important result that highlights competitive capabilities in soft systems.

Hydraulically amplified electrostatic<sup>51,52</sup> (HASEL) actuators are another class of soft artificial muscles that exhibit notable controllability and power density. Similar to DEAs, HASELs can be easily built on the milli- (< 1 g<sup>53</sup>) and meso- (10–100 g<sup>54</sup>) scales, and recent developments<sup>55,56</sup> have demonstrated dynamic legged locomotion under HASEL actuators (Fig. 2f). Furthermore, these soft actuators have been shown to integrate well with rigid backbones similar to biological architectures, such as muscle-tendon-bone configurations in mammals or hydraulic hinges in spiders for efficient force transmission and precise position control<sup>57</sup>.

These examples (Fig. 2a–c) illustrate that robustness and agility are not conflicting properties in soft actuator powered robotic systems, much like muscles in animals<sup>58</sup> and highlight the promising progress toward achieving animal-like agile aerial and terrestrial locomotion. Furthermore, emerging studies demonstrate that many of these actuators are capable of self-sensing<sup>56,59</sup> or can easily integrate sensing mechanisms<sup>60,61</sup> that provide feedback for closed-loop control similar to that of animals<sup>62</sup>. In addition to performing slow and safe tasks, soft actuated robots have the potential to demonstrate fast, precise, and sophisticated maneuvers using power-dense and controllable soft actuators.

Beside these potential benefits, electrostatic soft actuators, such as DEAs and HASELs face major technical challenges, such as requiring high driving voltage (hundreds to thousands of volts), exhibiting low transduction efficiency due to electrode resistive loss, suffering short lifetime due to dielectric breakdown, and having limited size (< 10 g) and net force. Recent developments in new elastomer and electrode materials, fabrication processes, and circuit designs have shown promising progress. Inspired by the hierarchical skeletal muscle structure, thin DEA films can be rolled into cylindrical shells and then bundled into a bulk actuator that spans 40 cm in length and exerts tens of Newtons in force<sup>63</sup>. High-speed spin coating and the use of low viscosity elastomers have reduced DEA operation voltage to 500 V without compromising power density<sup>45,64</sup>. Furthermore, sub-gram boost electronics<sup>65</sup> were developed to convert a DC battery input into a high frequency (> 300 Hz) and high voltage (600 V) output. This recent progress has enabled fully autonomous terrestrial<sup>66</sup> and aquatic locomotion<sup>48</sup> at the gram-scale, with ongoing work towards autonomous aerial locomotion. To catch up to animal-level performance and autonomy at a larger scale, it requires interdisciplinary efforts in multiple directions, including the design of custom boost circuit components and investigation of soft actuator nonlinear dynamic behaviors.

While the above mentioned examples highlight the potential of DEAs and HASELs, we believe other types of soft actuators could obtain substantial power density improvements under a performance-driven approach. For instance, through optimizing chamber geometry and elastomeric materials, researchers are developing power-dense compressed-air soft actuators toward feedback-controlled flight. Liquid-cooling may lead to higher actuation frequency in thermally driven shape memory actuators. Applications that require high operation frequency and precision may inspire the next-generation soft actuators.

### Tendon-like mechanisms for efficient energy management

Although power-dense artificial muscles can enable agile movements, including flight and running, these actuators alone cannot support



**Fig. 2 | High-performance soft robots.** Examples of systems that leverage muscle-like fast actuators, tendon-like energy storage mechanisms and flexible bodies for animal-like agility. **a** Driven by DEAs, miniature flying robots<sup>46,50</sup> are capable of high agility maneuvers, such as figure-8 motion or barrel rolls midflight. Similarly, **b** low-voltage stacked DEAs<sup>64</sup> and **c** PVDF-powered<sup>160,161</sup> legged robots demonstrate rapid planar locomotion. **d–g** Elastic elements of various forms enable high efficiency hopping<sup>56,74</sup>, record-breaking jump height<sup>88</sup> and deployable gliding via compliant

origami structure<sup>162</sup>. **h** Arthropods like cockroaches<sup>28</sup> have tough yet compliant exoskeletons which enables novel locomotion through confined spaces. Robots inspired by these principles are able to dorsoventrally<sup>28</sup> or laterally deform passively<sup>111</sup> to adapt to physical environmental constraints while maintaining high-speed locomotion. Subfigure **a** adapted from<sup>45</sup> and<sup>50</sup>; **b** adapted from<sup>64</sup>; **c** adapted from<sup>161</sup>; **d** adapted from<sup>74</sup>; **e** adapted from<sup>88</sup>; **f** adapted from<sup>56</sup>; **g** adapted from<sup>162</sup>; **h** adapted from<sup>28</sup>; **i** adapted from<sup>111</sup>.

impulsive motion, such as high jumps. In nature, the dynamic interaction between the musculoskeletal elements not only provides structural support, but also allows efficient energy management, leading to safe and smooth braking, rapid acceleration, dynamic stiffness control, and energy-efficient

cyclic operation<sup>67,68</sup>—all features essential to agile movement in spatially variable environments. For this, animals often feature specialized components, such as tendons<sup>69</sup> and apodemes<sup>70</sup> with specialized high toughness high modulus materials, such as resilin<sup>71</sup>. The design, incorporation, and

control of tendon-like soft, energy modulating elements represent another crucial avenue for achieving high performance in soft robotic systems. Specifically, tendon-like mechanisms bring two benefits: efficient energy management and agile impulsive movements.

In biological systems, energy redirection is evident in animals that rapidly change direction during locomotion or perform evasive maneuvers<sup>72,73</sup>. In robotics, the Hopcopter exemplifies this concept by redirecting stored kinetic energy to enable rapid acceleration or changes in travel direction<sup>74</sup>, mimicking evasive maneuvers seen in animals (Fig. 2d). Using the ground reaction force, the hybrid robot stores elastic energy in its passive telescopic leg upon impact. This energy is then strategically released in a controlled manner in a different direction during takeoff, enabling instantaneously large accelerations. This redirection allows the Hopcopter to achieve high accelerations more than ten times the force of gravity, far exceeding what its aerial propulsion system alone could achieve. This capability underscores the role of energy-storing soft structures for agile performance. In addition to enhanced agility, effective energy storage and release are crucial to improving efficiency in repetitive and cyclic tasks<sup>75–77</sup>. A remarkable example is found in large kangaroos, where exceptionally large tendons in their hindlimbs enable them to increase hopping speed without the typical increase in metabolic cost seen in other mammals<sup>78</sup>.

In robotics, the principle of energy recycling is also evident in systems that recover reactive power to minimize energy loss. This is particularly critical in aerial robots, where compliance can improve flight efficiency. For instance, flapping-wing robots, such as the Harvard RoboBee leverage mechanical resonance in their actuator-transmission-wing drivetrain to enhance system efficiency<sup>79</sup>, similar to wing-thorax resonance in insects<sup>80</sup>. The importance of elastic energy storage and return in legged locomotion has long been recognized, dating back to early models, such as the Spring-Loaded Inverted Pendulum (SLIP)<sup>81,82</sup> and pioneering work by Raibert on virtual spring control in legged robots<sup>83</sup>. More recently, tunable leg compliance has been shown to significantly improve locomotion in quadrupedal microrobots, such as HAMR and HAMR-Jr<sup>84,85</sup>, by allowing better energy storage and return through SLIP-like dynamics. By modulating leg stiffness, these robots achieved superior speed, stability, and adaptability, particularly at higher stride frequencies, where compliance helped mitigate slipping and body oscillations<sup>86</sup>. Similarly, the Hopcopter exemplifies efficient energy recycling through its passive elastic telescopic leg design<sup>74</sup>. Unlike traditional jumping robots that primarily use elastic elements for power amplification and most energy is dissipated upon landing<sup>87–92</sup>, the Hopcopter's passive leg design, consisting of prestretched rubber bands, can recover up to 80% of energy in each hop, demonstrating remarkable efficiency in energy recycling. Impulsive motions, such as braking or leaping also require compliant or elastic materials that can quickly dissipate or redirect energy (Fig. 2d–g). It is beneficial in scenarios where the kinetic energy from impacts is repurposed for morphological transformations to enable robots to adapt to their operating environments (Fig. 2g). For example, robots have demonstrated the ability to convert impact energy into functional transformations<sup>93</sup>, such as perching<sup>94,95</sup>, grasping<sup>96</sup>, or even squeezing through narrow spaces<sup>97</sup>.

Although elastic energy storage and return offer benefits, developing tendon-like mechanisms with engineered materials requires careful consideration and presents multiple opportunities for advancement<sup>32</sup>. Biological tendons achieve energy return rates that exceed 90% through hierarchical structures and self-healing properties<sup>98,99</sup>, engineered elastomers (e.g., rubber bands, silicone) typically exhibit lower efficiency (60–80%<sup>100</sup>) due to viscoelastic losses and material fatigue under repeated loading. Beyond efficiency, achieving high strain and high modulus simultaneously to maximize toughness in a single material remains difficult. At the system level, distributing compliance and actively tuning it<sup>101</sup> without trading off agile performance is still difficult. Supporting structural elements must be carefully designed to handle mechanical loads during impulsive movements<sup>88,102</sup>. As before, the cited examples demonstrate that hybrid rigid-soft systems are an effective solution to these limitations. In addition, new materials, stress-relieving geometrical designs, mechanisms, and

feedback controllers could be developed to further address these challenges<sup>103</sup>. More broadly, robotic systems that seek animal-like performance need to adopt a co-design approach, optimizing the interplay between soft energy-storing or energy-dissipating components and rigid load-bearing structures. Such strategies ensure that stress is effectively distributed, preventing structural failure, while producing efficient and agile locomotion performance.

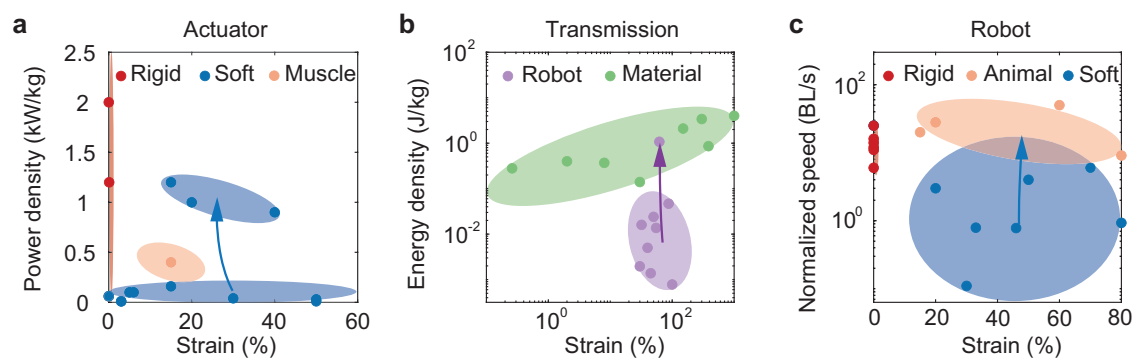
### Tough yet compliant embodiments for adaptable agility

In addition to muscles and tendons, endoskeletons and exoskeletons play crucial roles in supporting adaptive, agile, and robust animal movements. Leveraging recent progress in elastomeric materials and fabrication techniques, many soft robotic systems have taken inspiration from soft-bodied animals and demonstrated functional advantages, such as adaptability to constrained environments. However, highly flexible and deformable structures limit the speed of locomotion and therefore robot agility because they cannot exert or transmit large forces effectively to overcome inertia. We advocate for hybrid soft-rigid skeletal designs that allow forceful interaction with environments<sup>104</sup>.

Our view is supported by recent discoveries in arthropods (Fig. 2h) where rigid, jointed exoskeletons and appendages not only allow effective interaction with diverse terradynamic surfaces to enable agile locomotion, but also allow them to function as exceptional soft-bodied locomotors in confined spaces by using compliance in joints and muscles<sup>28</sup>. For example, cockroaches use tough yet compliant exoskeletons to run at speeds greater than 50 body lengths within a second<sup>105</sup>, climb up walls<sup>106</sup>, race along ceilings<sup>107</sup>, and swing stealthily under ledges out of sight<sup>108</sup>—all hallmarks at agile systems, while still being able to rapidly squeeze through crevices as small as the height of two vertically stacked pennies ( $\approx 3$  mm) compressing by more than 70% of their standing body height to remain highly adaptable<sup>28</sup>. In other cases, these exoskeletons function as effective dampers to allow cockroaches to collide into walls face-first at full speeds ( $> 1$  ms<sup>-1</sup>) to demonstrate robustness to collisions and even redirect motion to perform horizontal to vertical transitions as mechanically mediated agile maneuvers<sup>109</sup>.

These biological insights have led to the emergence of a new class of soft-bodied exoskeletal robots (Fig. 2i) that demonstrate both adaptability and agility during locomotion in confined spaces<sup>28</sup>. Unlike typical soft robots, which take advantage of material properties as the preferred solution to achieve body deformation, exoskeletal robots leverage articulated morphology for body compliance and shape change<sup>110,111</sup>. This enables such hybrid soft-rigid machines to combine the rapid, multi-gait locomotion capabilities of articulated laminate robots with passive compliance-based embodied physical intelligence of soft material systems<sup>112</sup>. For example, deformable quadrupedal origami robots, such as CLARI<sup>110</sup> are capable of achieving running speeds similar to their rigid counterparts, such as HAMR<sup>113</sup>, but also able to passively deform to locomote through gaps smaller than their body widths. Other successful recent demonstrations include omnidirectional locomotion in laterally confined spaces<sup>111</sup>, shape morphing multimodal behaviors, such as locomotion (including swimming and walking<sup>114</sup>). Beyond locomotion, these morphological principles could significantly improve perception<sup>115</sup> and manipulation<sup>116</sup>. Emerging ideas suggest that sensing body shape and actively controlling its change is crucial for the ability of these systems to remain agile<sup>117,118</sup> but might be energetically expensive<sup>119</sup>.

Achieving controlled shape change and adaptable stiffness efficiently in hybrid soft-rigid morphologies poses numerous yet-to-be-solved fabrication and design challenges. Similarly to those in biological examples, hybrid body designs likely require fine geometric features in addition to varying material properties across micro- and meso-scales to achieve performance levels similar to those in animals<sup>20</sup>. For example, biological studies of exoskeletal tissues indicate that mechanical properties can vary significantly within the structure (for example, stiffness can differ by eight orders of magnitude<sup>120</sup>), permitting the possibility that cockroaches with powerful propulsive appendages also retain the advantages of soft-bodied animals



**Fig. 3 | Performance comparison between soft, rigid, and biological systems.**

**a** Actuator output power density as a function of actuator strain. **b** Energy density of robot transmission and elastic materials as a function of strain. **c** Robot normalized speed as a function of exoskeletal strain. The robot speed is normalized by body

length. Data points correspond to representative robots and examples, with details provided in Supplementary Tables 1, 2, 3. Shaded regions enclosing each subgroup provide approximate performance boundaries of each category. Arrows indicate the potential for performance improvement on different metrics.

capable of conforming to their environment<sup>121</sup>. To achieve similar levels of variable mechanics, we believe that streamlined fabrication approaches<sup>122</sup> that can combine heterogeneous materials across size scales, such as multimaterial 3D printing<sup>123,124</sup> and stack laminate manufacturing<sup>125,126</sup> have promising potential as a start. However, the soft robotics research community needs novel principled approaches, such as the physical artificial intelligence paradigm<sup>24,127–129</sup> to rationally design high-performance hybrid soft-rigid-bodied robots. By carefully distributing passive compliance, sensing, and actuation within exoskeleton-like bodies, hybrid soft robots can embed insect-like intelligence mechanisms<sup>130</sup> and deliver the performance advantages of efficiency and agility while maintaining robustness and adaptivity.

## Conclusion

Soft robotics is a rapidly growing field that faces unique challenges and opportunities. Building on classical work<sup>31–35</sup>, numerous recent studies have explored new designs and materials to enable new functions, which are important to broaden the knowledge state of soft-robotics and real-world applications. However, in addition and complementary to the pursuit of this function-driven approach, we believe that taking a performance-driven approach is critical<sup>131</sup> to tackle the question of “how can soft robotics have an impact in the next decade?”<sup>132</sup> head on. Although it may seem that maximizing precision or speed would always favor rigid designs, biological systems are existence proofs that high performance movement likely emerges from a synergy between rigid and soft elements. To further support these claims, we highlight a small number of example systems (Fig. 2) from the last decade in this perspective, where power-dense soft actuators, energy-storing compliant mechanisms and integrated designs of rigid and soft elements have led to high-performance robotic systems. It is important to note that our performance-driven approach does not suggest that soft robotics should compete with rigid systems in all contexts, but in many practical real-world applications, such as agile disaster response<sup>133</sup> or precision medicine<sup>11</sup>, we cannot forgo critical performance metrics in exchange for new capabilities. Additionally, the demonstrated advantages of adaptability and robustness increase their appeal for most real-world scenarios, including those described above.

Figure 3 summarizes the opportunities to improve the performance of current robotic systems with respect to actuator, transmission, and morphology designs. We refer the reader to the Supplementary Tables 1, 2 and 3 for a detailed quantitative comparison by category<sup>134–155</sup>. Power-dense actuators are essential to enable agile and fast locomotion. In the past, soft actuators, such as pneumatic artificial muscles<sup>156</sup>, electrostatic film actuators<sup>157</sup>, and dielectric elastomer actuators (DEAs)<sup>64,158</sup> often traded power density for higher strain, resulting in substantially lower performance. The arrow in Fig. 3a illustrates a new class of soft actuators that simultaneously exhibit high power density and large strain – even exceeding

that of natural muscles. In our view, this new class of soft actuators will form the foundations of performance-driven research in soft robotics. In addition to power-dense soft actuators, energy-storing transmission can enable impulsive locomotion, such as jumping and sharp braking. Figure 3b illustrates the performance gap between the energy storage capabilities of materials and the transmission of robots. Through careful material selection and mechanism design, a recent work<sup>88</sup> demonstrated high jumps that far exceeded animal performance. To enable fast consecutive leaps, future studies can investigate tendon-like mechanisms that can efficiently store and release energy. At the physical embodiment level, body deformation can improve locomotion robustness and adaptivity without adversely affecting speed and agility. Figure 3c compares the normalized locomotion speed of animals, soft- and rigid-driven robots. Early results in applying biomechanical principles to actuator, transmission, and robot body development have demonstrated agile soft robotic movements at the insect scale (Fig. 2). At sizes comparable to mammals, the efficiency and agility of soft robots remain limited due to materials and fabrication challenges of creating mesoscale (tens of centimetres) actuators and tendons. As a result, soft-driven robots, especially those on the mesoscale, still substantially underperform compared to animals and rigid-driven systems.

These comparative examples (Fig. 3) highlight not only the current limitations of soft robotic systems but also compelling research opportunities for the coming decade. Towards achieving these objectives, biological organisms offer examples where the integration of soft and rigid elements enables superior locomotion agility across multiple metrics (e.g., speed, acceleration, precision, robustness). Drawing inspiration from these biological strategies offers one promising pathway for advancing the performance of hybrid soft-rigid systems. Although we acknowledge that competing against the state-of-the-art rigid systems is currently difficult, we believe it is a direction that we cannot shy away from. As a starting point, we can organize soft robotic competitions and workshops that explore power-dense locomotion modes, such as running, flying, and hopping. Once the community has converged to several mature soft robotic platforms, we should participate in competitions (e.g., IEEE RAS Quadruped Robot Challenges<sup>159</sup>) that involve traditional rigid robots. We expect that such initiatives that demonstrate high-performing soft robots will inspire scientists from other robotics subdomains to join in to grow our community and to adapt their algorithms and design mechanisms specifically for soft systems to further augment their performance. Taking a performance-driven approach, the soft robotics community can impact the entire robotics field by creating the next generation of highly capable robots that can easily integrate into human societies as reliable partners and deliver on the promise of tremendous socioeconomic impact.

## Supplementary information

Tables of data to support the plots and metrics in the manuscript.

## Data Availability

No datasets were generated or analyzed during the current study.

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## Author contributions

All authors (Y.C., P.C., and K.J.) contributed equally to the conception, writing, and revision of this perspective. All authors discussed the ideas, participated in drafting and reviewing the manuscript, and approved the final version.

## Competing interests

The authors declare no competing interests.

## Additional information

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