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### Engineering

# Jumping robot bests biology

## Sarah Bergbreiter

A robotic jumper combines inspiration from biology with clever engineering to reach new heights. Crucial to the design is the combination of a rotary motor with a hybrid spring that maximizes stored energy density. **See p.657**

A tiny insect known as a froghopper can jump to a height of 70 centimetres, which is a staggering 115 times its body length[1]. To do this, it uses elastic structures, or springs, in its legs to power take-off velocities of up to 4 metres per second. Inspired by such insects, Hawkes et al.[2] (page 657) have developed a general framework with which to explore how both biological and engineered systems can generate and use energy to achieve the highest jump. The result is a robot that can jump almost 50 times higher than the froghopper — to a remarkable 33 metres (Fig. 1), with a take-off velocity of more than 28 metres per second.

Muscles and motors cannot generate the high power outputs necessary to propel these jumpers on their own. Instead, many biological and engineered systems use muscles and motors to store energy in spring-like structures. They then use latch mechanisms to release the spring energy to launch (actuate) the jump. This method of amplifying muscle power is known as latch-mediated spring actuation[3]. Previous modelling studies of these systems answered numerous questions about how biological jumpers overcome the power limitations of muscles and motors[4,5], but assumptions were still necessary to make the models relevant to living organisms.

To answer questions regarding the limitations of engineered jumpers, Hawkes and

colleagues were able to remove some of these previous assumptions. The first insight from their model is that engineered motors need not have the same work limitations as biological muscles. Muscles perform a single contraction (a stroke) with a finite length, which constrains their work density (the mechanical energy that they can generate relative to their mass)[4]. The rotary motors that are commonly found in engineered robots can overcome this limitation by acting as a winch to provide a force over a much larger displacement without needing a larger motor, thereby increasing work density[6]. Engineered linear motors can use ratchets for the same purpose[7,8]. Even when biological jumpers use elastic structures to launch their jumps, they are still limited by the amount of energy that muscles can store in these springs. As long as rotary motors can continue rotating, engineered systems are instead limited by the energy density (stored energy per mass) of the springs.

The second insight from Hawkes and colleagues' model regards the spring itself. The spring combines carbon-fibre beams, which can be bent like a bow, and rubber bands, which can be put under tension — giving it a very high amount of stored energy per mass. This configuration also results in the spring requiring a relatively constant compressive force to be applied over a range of distances, a feature that differs from most springs, for which the applied force grows linearly with distance compressed. Although springs
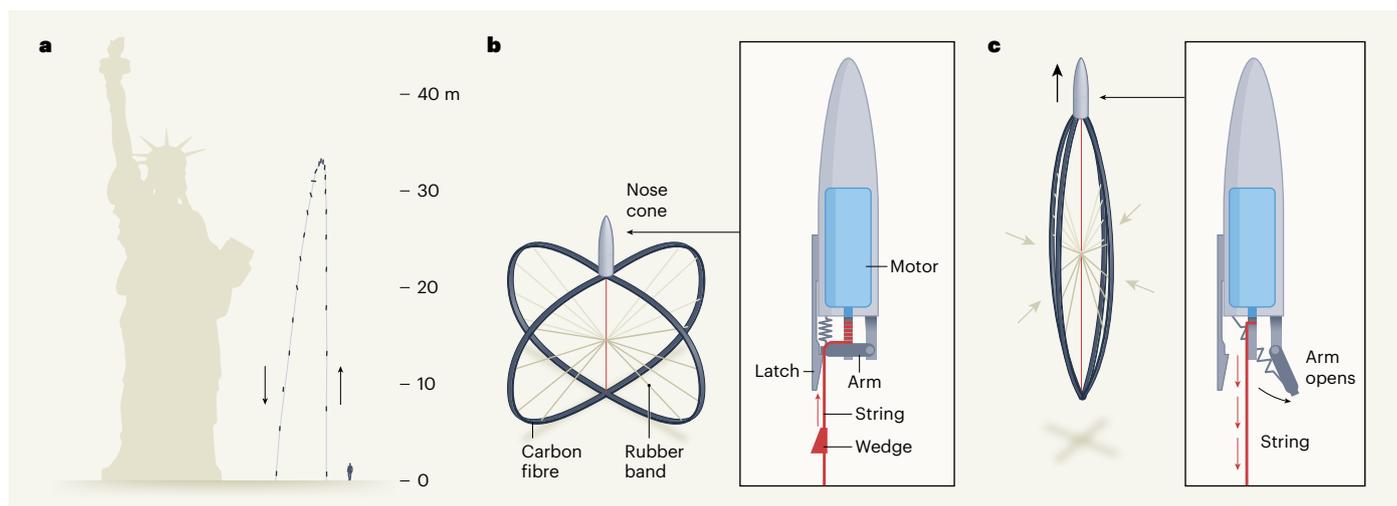


**Figure 1 | A robot engineered for high jumps. a**, Hawkes et al.[2] designed a robot that can jump up to 33 metres high — almost the height of the Statue of Liberty. **b**, The design maximizes stored energy density (energy per mass) by using a geared rotary motor to generate a high force over a relatively long distance — a feat enabled by continued rotation of the motor, which is hidden in an aerodynamic nose cone. The motor is attached through a string winched by the rotating motor to a high-energy-density spring constructed from carbon-fibre beams and rubber bands. The robot is shown in its compressed state before take-off. The arm is held in place until the wedge makes contact with the latch. **c**, Once the latch is released, the string is free to move and the stored energy is released. The robot morphs into an aerodynamic rocket-like shape to reduce drag. (Adapted from Fig. 3 and Extended Data Fig. 5 of ref. 2.)

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with even higher energy densities exist, this constant-force configuration allows the most energy to be stored by a rotary motor that can continuously apply a maximum torque output to match the force needed to compress the spring.

Finally, the spring is even heavier than the motor in Hawkes and colleagues' jumping robot. This contrasts with biological jumpers, whose muscles are typically much more massive than the springs they use to directly power the jump[9]. This unexpectedly high ratio between spring and motor mass is a result of the relative energy limitations of these components: the energy density of the spring limits the robot's jump height, whereas the work density of muscle limits the amount of energy that biological jumpers can store in their springs.

A surprising feature of Hawkes and colleagues' robot is its relatively large size. The best jumpers propelled by springs in biology are typically limited to having masses of several grams or less[4,5], whereas jumpers with larger mass (such as humans) benefit from direct muscle power instead of spring actuation. But this robot has a mass of 30 grams, which makes it more than ten times heavier than the largest spring-actuated jumping organisms that inspired it[5]. This is due to the 10-gram mass of the rotary motor used in this jumper, and because the highest jumps possible for Hawkes and co-workers' robot require spring mass to exceed motor mass. Although the team did not explore further limitations, such as battery energy density, the study implies that robots larger than theirs, with bigger springs, would jump even higher.

Further research is still needed for these jumping systems to achieve their full potential. Hawkes and colleagues' robot is limited to a single jump height — just like the majority of previously reported jumping robots[6,10,11]. Resource constraints mean that these systems are not designed to control the amount of energy stored and released during each jump. But to operate in a 'real world' environment, these systems will need to be able to control their jumps. One way of doing that could involve a redesign of the latch that releases the energy during each jump, as has been proposed previously[12]. Another approach to precision jumps could come from controlling the launch angle[13]. It is also crucial that the jumps these robots perform are repeatable. Although Hawkes and co-workers' robot can reset itself and jump repeatedly, it takes two minutes between jumps to reload the spring. By contrast, other jumping robots that use different strategies to maximize power can jump again immediately on landing[14].

Hawkes *et al*. have succeeded in using biology as inspiration for their design, while circumventing the limitations of living systems through clever engineering. Instead of having a jump height limited by the amount of work a muscle can do in a single contraction, for example, the authors' robot is limited only by its spring and its battery. The robot also makes use of the fact that constant-force springs made from carbon fibre and rubber have much higher energy densities than do those made from the limited set of materials available to biological jumpers. The work therefore serves as a reminder that biologically inspired engineered systems need not incorporate biological limitations.

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## Structural biology

# Stalk twists into a hook in adhesion receptors

### Antony A. Boucard

The inner workings of a family of proteins, known as adhesion G-protein-coupled receptors, have finally been visualized at high resolution — revealing the structural basis of their self-activation mechanism. **See p.757, p.763, p.771 & p.779**

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Cells need a means of communicating with their surroundings to survive. Membrane proteins in the family of G-protein-coupled receptors (GPCRs) help cells to sense their micro-environment by responding to various stimuli, ranging from light to hormones. A subfamily known as the adhesion GPCRs (aGPCRs) has a role in sensing the interactions of cells with other cells and with the extracellular matrix (the material that surrounds cells). These receptors are unusual because many of them activate themselves. The structures of many types of GPCR in their active states have been reported, but not those of self-activated aGPCRs. A quartet of papers by Barros-Álvarez *et al.*[1] (page 757), Ping *et al.*[2] (page 763), Qu *et al.*[3] (page 779) and Xiao *et al.*[4] (page 771) now addresses this issue, and sheds light on the mechanism involved in initiating the sensing function of aGPCRs.

As biological systems evolved to become multicellular, the number of things they interacted with increased, thereby expanding the variety of external factors that could trigger a response. Cells needed to explore their micro-environments to seek nutrients, trigger defence mechanisms or form tissue, for example. This, in turn, required them to develop strategies to navigate constantly changing environmental conditions.

The advent of cells with molecular appendages that served as sensors, interfacing with the surroundings, aided cellular movement by allowing changes in cell behaviour to be stimulated in response to externally acquired information. Adhesion molecules extending from the cell membrane acquired this sensing ability, because their subcellular localization put them in the front line to probe myriad cell–cell and cell–matrix interactions. The evolution of a diverse array of these molecular sensors — the GPCRs — was key to ensuring that cells can respond to as many insults or encounters as possible.

Today, GPCRs are the largest family of membrane proteins encoded by the human genome[5]. Groundbreaking advances have revealed how GPCR structures change on contact with an external stimulus, and how they communicate these changes within cells to alter cell behaviour through the induction of signalling cascades. But, until recently[6], the membrane-spanning structures of one subfamily of GPCRs remained conspicuously unexplored: the aGPCRs. This knowledge gap is now decisively being filled with the publication of the current breakthrough studies.