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REVIEW

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Comparison of water and terrestrial jumping in natural and robotic insects

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Abstract

Jumping requires high actuation power for achieving high speed in a short time. Especially, organisms and robots at the insect scale jump in order to overcome size limits on the speed of locomotion. As small jumpers suffer from intrinsically small power output, efficient jumpers have devised various ingenuous schemes to amplify their power release. Furthermore, semi-aquatic jumpers have adopted specialized techniques to fully exploit the reaction from water. We review jumping mechanisms of natural and robotic insects that jump on the ground and the surface of water, and compare the performance depending on their scale. We find a general trend that jumping creatures maximize jumping speed by unique mechanisms that manage acceleration, force, and takeoff duration under the constraints mainly associated with their size, shape, and substrate.

KEYWORDS
jumping insects, jumping mechanisms, jumping on water, robotic insects

INTRODUCTION

Insects, relatively small organisms with sizes ranging from millimeters to centimeters, often employ jumping as a method to traverse long distances quickly. This mode of locomotion is particularly effective for escaping from predators. By propelling themselves away from danger, insects significantly reduce the risk of being caught. To uncover the unique mechanisms behind effective jumping, researchers have proposed several hypotheses based on their observations and the principles of mechanics. These include the co-contraction and semilunar process in locusts,[1–3] the energy storage and release mechanism in fleas,[4–8] and the coxal and femoral protrusions-based locking mechanism in froghoppers.[9–13] Drawing inspiration from these jumping insects, various robots have been developed to enhance their locomotion range, thereby overcoming size limitations.[14–39] Jumping enables these robots to navigate and pass over obstacles larger than their size, effectively expanding their operational capabilities.

Jumping performance is primarily determined by the takeoff speed. As jumpers get smaller, their leg length decreases, which in turn reduces the push-off duration. Consequently, smaller jumpers require higher acceleration than larger ones to achieve an equivalent takeoff speed.[40] However, both biological muscles and engineered actuators are subject to a force-velocity trade-off, limiting the maximum takeoff speed.[41] This limitation is related to the power output (force times

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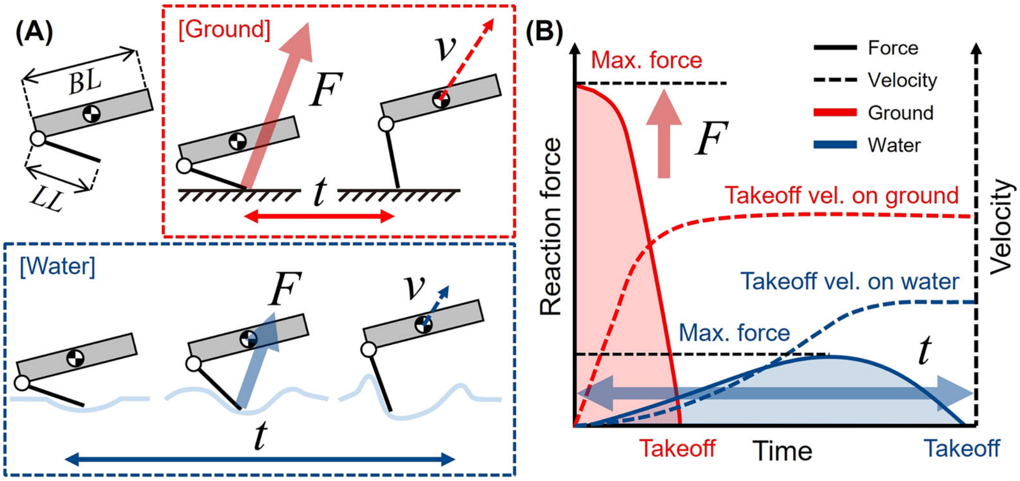

FIGURE 1 (A) Jumping phases of terrestrial and water jumpers. "*BL*" and "*LL*" represent the length of the body and the length of the leg, respectively. (B) Schematic plot of the force–time and velocity–time curves during the jumper's takeoff from the ground and water surface, where *F*, *v*, and *t* indicate substrate reaction force, takeoff velocity, and takeoff duration, respectively.

velocity), indicative of how quickly energy can be released by the muscle or actuator (Figure 1A). As jumpers become smaller, their power output diminishes, leading to a greater discrepancy between the actual output power of the muscle or actuator and the power required for effective jumping. This issue is especially challenging for small creatures and miniaturized robots, making it difficult for them to jump effectively using their tiny muscles or actuators.[42, 43] To overcome this limitation, small insects and robots often employ catapult mechanisms to amplify their output power.[44–57] These mechanisms involve slowly deforming elastic materials to store energy using their low power muscles. Then, this stored energy is rapidly released, resulting in a high-power output for jumping. This process allows for effective jumping despite the inherent power constraints in smaller biological muscles and engineered actuators.

Several semi-aquatic organisms have adapted to jump on the water surface (e.g., pygmy mole crickets,[58] springtails,[16, 59] long-legged flies,[60] fisher spiders,[61, 62] and water striders[63–66]), employing different strategies compared to jumping on land. Unlike the ground, which provides a firm support allowing for large force application by the legs, water surfaces cannot withstand such forces. Instead, various forces at the interface between the insect legs and the water surface, including drag, buoyancy, added inertia, and the capillary force, can provide thrust (Figure 1A).[67] Previous studies have shown that these forces are intimately related to morphological and dynamical scales, which can be described by dimensionless numbers like the Weber ($\mathrm{We} = \rho U^2 L/\sigma$), Reynolds ($\mathrm{Re} = \rho UL/\mu$), and Bond ($\mathrm{Bo} = \rho g L^2/\sigma$) numbers.[63–70] Here, ρ, μ, and σ are, respectively, the density, the viscosity, and the surface tension coefficient of water, and U and L are, respectively, the characteristic velocity and length of the organism. Building on these principles, various bioinspired water-jumping robots have been developed, confirming the scale-dependent principles of jumping on water surfaces.[63, 68–73]

In this review, the characteristic properties of various jumping insects and robots are collected and compared to explain the different mechanisms of jumping on the ground and the surface of water to achieve high jumping performance. A general scaling law can be applied to the jumping locomotion by comparing the jumping speed over a range of masses and the length scale of the systems. Various mechanisms to overcome the power limits of muscles and actuators are found and the different strategies for achieving the maximum momentum from rigid ground and the surface of water are explained (Figure 1B). Biological observations and the modeling and design efforts in engineering have shown that the jumping systems are optimized in a common manner, with various constraints imposed by the environments.

PHYSICS OF THE JUMPING MODES

Jumping performance is determined by the takeoff speed. The energy generated by muscles or actuators is converted to kinetic energy for jumping: $E = 0.5mv^2$, with m being the mass and v the jumping velocity. The jumping speed can be obtained by the simple energy conservation equation if we know the input energy generated by the muscles or actuators. As the kinetic energy is changed to the gravitational potential energy mgh, with h being the jump height, we see that $h = 0.5v^2/g$ can be expressed using the specific energy ($e = E/m$) as $h = e/g$, and thus h is independent of mass and the size of the jumper. However, this simple scaling does not work when the jumper has a mass-specific power (W/kg) limit, specifically in a small scale that does not have enough time to generate high power (force times velocity) by actuation. On the ground, the actuation power limit from limited actuation time can be compensated by using elastic materials with high contraction rates, so that the reaction force from the ground can be as high as the actuation force. Therefore, the system can get the high impulse (force F times reaction duration t) from the rigid ground and generate high momentum (mass times velocity: $Ft = mv$) for jumping, as shown by the graph in the red color in Figure 1B. However, on the water surface, the reaction force is not guaranteed to be as high as the actuation force, but is rather limited by fluid-mechanical forces. Different from jumping on the ground, jumping on water requires a long interaction before takeoff so as to obtain sufficiently high impulse with limited reaction force.

The major reaction forces acting on the insects jumping off the water surface consist of the surface tension force and the form drag.[65,70] These forces are strongly related to scale of the system. The surface tension force is much larger than other forces in a small scale, and the form drag gets larger as the system size and leg speed increase.[65,69] The surface tension force is a static force that is independent of the leg speed, but is determined by the volume of the dimples on the water surface made by the legs. Therefore, the water surface can be considered as a spring for small systems. As the actuation energy is conserved by the water surface, the jumper reaches the same height on the ground and the water surface.[63] Recently, larger insects and robots have been reported to jump on the water by drag-dominant propulsion.[65,69] The form drag is a hydrodynamic force determined by the speed and projected area of the legs, and thus larger jumpers can jump much higher by high actuation power. However, these hydrodynamic forces are lower than the reaction force on the ground. Jumping insects and robots are evolved and designed to achieve longer takeoff duration for higher momentum transfer, as shown in Figure 1B.

JUMPING MECHANISMS IN NATURE AND ROBOTICS

There are two primary schemes for momentum generation that jumpers can use for jumping: the catapult mechanism or direct leg extension. The catapult mechanism is typically employed by relatively smaller creatures with short legs. This jumping process consists of three phases. The first is the energy storage phase, where the muscle or actuator slowly deforms an elastic component, storing energy in it. During this phase, the body is latched, preventing the release of stored energy. The second is the push-off phase, where the latched body or the stored energy is released, initiating the push-off. In this phase, the legs push against the substrate, subject to a reaction force that accelerates the body. The final phase occurs when the leg tips lose contact with the substrate, leading to takeoff. Essentially, the catapult mechanism involves deforming the elastic body and using the stored elastic energy for jumping.

In contrast, the direct scheme, typically used by relatively larger creatures with long legs, uses muscle or actuator output for jumping. Instead of pre-storing energy, this method involves directly extending crouched legs to push against the substrate. In this section, we review jumping mechanisms in both insects and robots, categorized by terrestrial jumping and water jumping, and further subdivided by the systems employing either the catapult mechanism or the direct actuation method (Figure 2). Moreover, it is noteworthy that among insects using the catapult mechanism, some achieve jumping through unconventional means, employing parts of their body other than legs. We further review these intriguing legless jumping insects. The specifications, substrates, and performance of natural and robotic insects are summarized in Tables 1 and 2, respectively.

Jumping insects

Terrestrial jumping insects

Catapult mechanism

The flea beetle (Coleoptera: Chrysomelidae) (Figure 3A) weighs 0.64–12.16 mg, has a body length of 1.7–4.9 mm, and has relatively short hind legs, which are 43%–75% of their body length. Their takeoff velocities are 0.83–2.93 m/s, with a push-off duration of 1.1–7.7 ms.[46,47] This rapid push-off indicates that these insects use a catapult mechanism. The primary muscles responsible for this rapid takeoff jumping are the metafemoral extensor muscles, which are in the swollen femur. This muscle group is attached to the metafemoral extensor tendon (MET), which is a hard cuticle with a unique shape. The core principle of energy storage is the co-contraction of an antagonistic muscle pair. During this process, the relatively small flexor muscle holds the flexed leg configuration, using its lever advantage (Phase 1). The contraction of large extensor muscles with short lever arms extends resilin-bearing ligaments and stores elastic energy in them (Phase 2). Sudden relaxation of the flexor muscles triggers energy release and leg extension, which in turn leads to jumping (Phase 3).[46–48]

The froghopper (Auchenorrhyncha: Aphrophoridae) (Figure 3B) weighs 3.2–32.9 mg, has a body length of 4–9.5 mm, and has relatively short hind legs, which are 60%–66% of their body length. Their takeoff velocities are 3.8–4.7 m/s, with a push-off duration of 1–1.5 ms.[10] This rapid push-off indicates that these insects use a catapult mechanism. The primary muscles responsible for this rapid takeoff jumping are the trochanteral depressor muscles, which are in the thorax. Burrows[9–11] proposed that the underlying principle of the froghopper's jumping involves co-contraction with a novel locking mechanism. Before jumping, the insects flex their hind legs and place them between the thorax and middle legs. In this cocked posture, the coxal and femoral protrusions engage with each other, and this engagement holds the hind legs in this cocked position. When the trochanteral depressor muscle contracts even more, it stores elastic energy in its tendons and thoracic pleural arches. These are parts of the thorax's skeletal structure and are made up of chitinous cuticle and rubber-like resilin. When the contraction of the depressor muscle exceeds a certain threshold, the locking mechanism is passively disengaged, which triggers the jumping. The additional locking mechanism enables them to store additional energy, which results in high-performance jumping.[9–13]

The planthopper (Auchenorrhyncha: Dictyopharidae and Auchenorrhyncha: Issidae) (Figure 3C) weighs 5.7–22.9 mg, has a body length of 6.6–9.3 mm, and has relatively short hind legs, which are 36%–91% (Flatidae: 36%–54%, Issidae: 65%, Dictyopharidae: 82%–91%) of their body length. Their takeoff velocities are 2.8–5.8 m/s, with a push-off duration of 0.78–2 ms.[50,51] This rapid push-off indicates that these insects use a catapult mechanism. The primary muscles responsible for this rapid takeoff jumping are the trochanteral depressor muscles, which are in the thorax. The core principle of energy storage is similar to the froghopper's jumping mechanism using the thoracic pleural

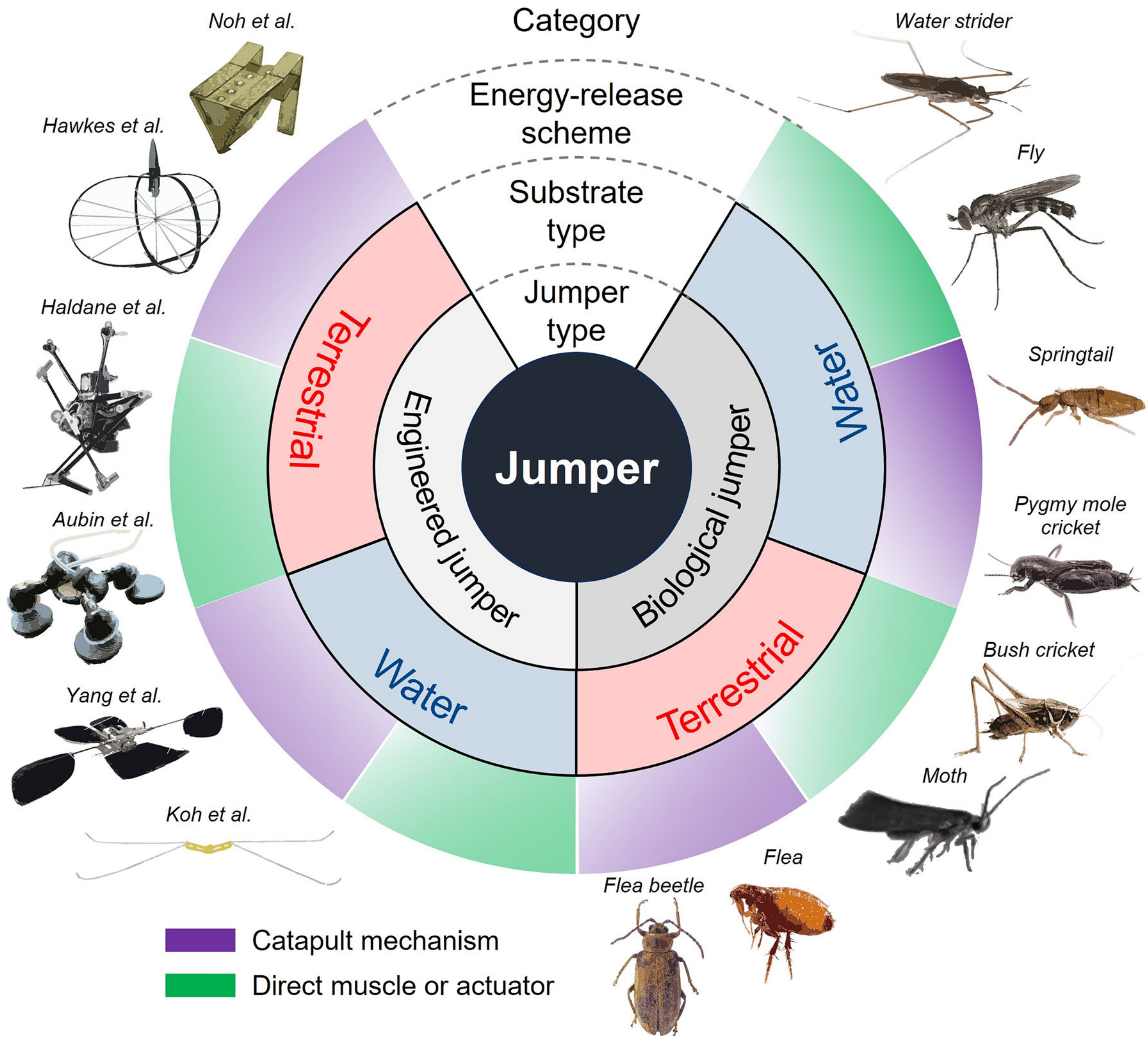

FIGURE 2 Categorization of jumpers.

arches. However, planthoppers have weak femoral protrusion, and the locking mechanism for this insect is unclear.[49–51]

The leafhopper (Auchenorrhyncha: Cicadellidae), whose organs used for jumping is shown in Figure 3D, weighs 0.86–19 mg, has a body length of 3.5–9 mm, and has relatively long hind legs, which are 82%–98% of their body length. Their takeoff velocities are 0.88–2.9 m/s, with a push-off duration of 2.75–5.64 ms.[53] Although leafhoppers share similarities in weight and size with froghoppers and planthoppers, they stand out with their longer legs and a more prolonged push-off duration. Although the push-off is prolonged, it is still too rapid to be solely driven by direct muscle contraction; therefore, they also use the catapult mechanism. The primary muscles responsible for this rapid jumping are the trochanteral depressor muscles, which are in the thorax. Leafhoppers do not have a locking mechanism; therefore, they use co-contraction of the depressor and levator muscles and their moment balance in fully elevated hind leg position to prevent leg extension. The lever advantage of the depressor muscle increases as the legs depress. Therefore, a burst of depressor muscle contraction in the later phase of the co-contraction triggers the jumping. Their long leg morphology and absence of a locking mechanism yield a different jumping mechanism and consequently lower jumping performance compared to froghoppers and planthoppers. However, their energy expenditure is only about a third of the froghoppers.[52–54]

The flea (Siphonaptera) (Figure 3E) weighs 0.7 mg, has a body length of 1.8 mm, and has relatively long hind legs, which are 154% of their body length. Their takeoff velocities are 1.9 m/s, with a push-off duration of 1.2 ms.[6] This rapid push-off indicates that these insects use a catapult mechanism. The primary muscles responsible for this rapid takeoff jumping are the trochanteral depressor muscles, which are in the thorax. The underlying mechanism behind the jumping ability of fleas remains unclear, with Bennet-Clark et al.[4] and Rothschild et al.[7,8] proposing two distinct hypotheses. According to the hypothesis of Bennet-Clark et al.[4], fleas use the over-center property of the trochanteral depressor muscles. When the legs are elevated, the depressor muscles pass over the pivot point of the coxa-trochanter joint and apply an elevation moment. This holds the legs in an elevated position, and further contraction of the muscle compresses resilin that stores elastic strain energy. At a certain point,

TABLE 1 Specifications, jumping substrates, and performance of organisms.

Name (Genus species)	Substrate	Mass (g)	Body length (mm)	Leg length (mm)	Speed (m/s)	Duration (ms)
Catapult mechanism						
Flea beetle (*Longitarsus gracilis*)[46]	Ground	0.00275	3	1.91	2.7	1.4
Flea beetle (*Psylliodes affinis*)[46]	Ground	0.00128	2.23	1.62	2.93	1.1
Froghopper (*Lepyronia coleoptrata*)[10]	Ground	0.0176	7.2	4.39	4.6	1.5
Froghopper (*Philaenus spumarius*)[10]	Ground	0.0123	6.1	4.03	4.7	1
Planthopper (*Engela minuta*)[50]	Ground	0.0057	6.6	5.87	5.8	1.2
Planthopper (*Issus coleoptratus*)[49]	Ground	0.0215	6.7	4.38	5.5	0.78
Leafhopper (*Aphrodes makarovi*)[53]	Ground	0.0184	8.5	7.14	2.9	2.75
Leafhopper (*Graphocephala fennahi*)[53]	Ground	0.013	9.0	8.19	1.85	4.5
Pygmy mole cricket (*Xya capensis*)[57]	Ground	0.0083	5.6	7.34	5.4	1.8
Pygmy mole cricket (*Xya capensis*)[58]	Water	0.0092	5.6	7.34	2.2	5.8
Flea (*Archaeopsylla erinacei*)[6]	Ground	0.0007	1.8	2.77	1.9	1.2
Locust (*Schistocerca gregaria*)[1]	Ground	2	47.2	43.9	3.2	25
Springtail[59]	Ground	0.00015	1.7	1.04	1.3	2
Springtail[59]	Water	0.00015	1.7	1.04	0.6	2.5
Trap-jaw ant (*Odontomachus bauri*)[74]	Ground (legless)	0.0121	11.9	–	0.24	–
Click beetle (*Athous haemorrhoidalis*)[75]	Ground (legless)	0.0294	11	–	2.26	–
Direct muscle contraction						
Moth (*Udea olivalis*)[55]	Ground	0.0191	10.8	14.8	1	24
Moth (*Xanthorhoe fluctuata*)[55]	Ground	0.0174	10	12.9	1	18
Bush cricket (*Conocephalus dorsalis*)[56]	Ground	0.013	17	20.1	1	21
Bush cricket (*Meconema thalassinum*)[56]	Ground	0.0174	18	22.5	1.4	22.5
Water strider (*Aquarius paludum*)[63]	Water	0.0372	12.4	22.1	1.3	25
Water strider (*Gigantometra gigas*)[65]	Water	0.375	35.2	120	1.6	68
Water strider (*Ptilomera tigrina*)[65]	Water	0.134	17	47.9	1.2	30
Fly (*Hydrophorus alboflorens*)[60]	Water	0.0047	4.4	7.48	1.64	11.6
Spider (*Dolomedes triton*)[61]	Water	0.475	–	–	0.88	12
Spider (*Dolomedes triton*)[61]	Water	0.233	–	–	0.72	12

the trochanteral depressor anchored to the coxa pulls the depressor tendon, and the tendon passes over the pivot point in the opposite direction. This reverses the moment applied to the legs, depressing the legs and triggering the jumping.[4–6]

The locust (Orthoptera: Acrididae) (Figure 3F) weighs 2 g, has a body length of 47.2 mm, and has relatively long hind legs, which are 98% of their body length. Their takeoff velocity is 3.2 m/s, with a push-off duration of 25–30 ms.[1–3] This jump is made possible by a catapult mechanism. The primary muscle responsible for this jumping is the extensor tibiae muscle, located within the femur. The semi-lunar process found in the distal femur serves as the main energy storage element. When the locust's hind legs are fully flexed, it exhibits co-contraction, leading to the deformation of the semi-lunar process, which in turn stores strain energy. Additionally, the locusts make use of the long lever arm of the flexor muscle when their legs are fully flexed, ensuring the legs remain in a flexed position. Upon triggering the jump, the legs rapidly extend, releasing the stored energy.

The trap-jaw ant (Odontomachus) (Figure 3G) weighs 12.1–14.9 mg and has a body length of 11.9 mm.[74] These ants are renowned for their mandible strikes, primarily used for prey capture. Among trap-jaw ant lineages, particularly in *Odontomachus*, this striking mechanism is also used for escape jumps.[74,76] They achieve a takeoff velocity of 0.24 m/s, relying on a catapult mechanism for this purpose. Although the catapult mechanism is a common trait among trap-jaw ants, the specific structures involved in this process vary across different genera.[77] Gronenberg[78] proposed a hypothesis to explain the catapult mechanism in *Odontomachus*. To prepare for a mandible strike, the mandible opener muscle first opens the mandibles and slightly adjusts the ventral hump of each mandible to fit into a corresponding notch on the mandible socket. This positioning allows the opened mandibles to stay in place due to the mandible hump catching in the notch, while the contraction of the large muscle closer to the mandible stores the energy necessary for jumping. The jump is initiated when the small trigger muscle acts, slightly moving the ventral hump out of the notch, leading

TABLE 2 Specifications, jumping substrates, and performance of robots.

Name	Substrate	Mass (g)	Body length (mm)	Leg length (mm)	Speed (m/s)	Duration (ms)
Catapult mechanism						
EPFL 7g[23]	Ground	7	50	100	5.9	19
Flea robot 1[14]	Ground	1.104	20	31	4.2	8
Flea robot 3[15]	Ground	2.25	30	60	7	8
Continuous Jumping Robot (MSU jumper)[24]	Ground	20	65	40	3.34	–
Locust inspired jumping robot - TAUB[31]	Ground	23	135	160	9	23
Grillo 3[27]	Ground	22	50	66.8	1.7	40
MiniWheg 9[25]	Ground	190	104	104	2.6	–
Tribot[32]	Ground	9.7	58	44	1.65	–
JumpRoACH[19]	Ground	99	120	95	5.39	15
Flapping-wing-assisted jumping robot[20]	Ground	23.5	130	80	4.27	23
No-latch frog-inspired jumping robot[18]	Ground	100.7	100	160	4.9	30
Insect-scale jumping robots[37]	Ground	1.68	23.1	3.5	4.2	3.5
Moobot[30]	Ground	6	50	44	3.5	–
Untethered 216 mg insect-sized jumping robot[17]	Ground	0.216	24	12	2.1	–
Soft jumping robot[81]	Ground	0.08	56	28	1.12	21
Locust inspired stable jumping robot[29]	Ground	60	100	126	2.8	20
Jumper with magnetically actuated gearbox[26]	Ground	0.0252	3.1	3.1	2.3	0.75
Springtail-inspired robot[16]	Ground	0.1	20	11	3	–
Engineered jumper[28]	Ground	30.37	300	300	28	9.2
Water strider robot (surface tension)[63]	Water	0.068	20	50	1.7	25
Water strider robot (drag)[69]	Water	3	320	130	3.6	45
Water jumping robot[71]	Water	0.51	15	5.5	0.09	2.1
Water jumping robot (drag) 1[72]	Water	11	250	125	1.95	–
Water jumping robot (drag) 2[73]	Water	10.2	260	130	2.1	–
Water-walking device[70]	Water	0.004	13	6.5	1	3
Direct actuation						
Micro Jumping Robot(Chemical)[39]	Ground	0.314	7		1.25	–
Salto-1P[34]	Ground	98.1	150	144	4.95	57
Salto[33]	Ground	100	150	150	4.44	60
3.4-mm Flea-sized robot[35]	Ground	0.012	3.4	0.3	1.74	10
Soft combustion insect-scale robot[36]	Ground	1.6	29	7	2.5	0.24

to the rapid closure of the mandibles. This action propels the ant into the air, facilitating an escape jump.

The click beetle (Coleoptera: Elateridae) (Figure 3H) weighs 29.4 mg and has a body length of 11 mm.[75] This insect jumps to recover its posture when it is overturned. Its takeoff velocity is 2.26 m/s, and its push-off duration is 0.6 ms. These quantities indicate that this insect uses a catapult mechanism. Instead of using legs, this insect uses the rapid bending of the so-called "jack-knifing" to propel its body. Evans[75] proposed a hypothesis that explains this insect's jumping mechanism. First, when the insect is in a reversed posture, it arches its back, then the middle of the body is raised. At this point, the posterior end of the peg on the ventral side of the prothorax contacts the mesosternal lip on the anterior side of the mesosternum. The friction generated between these two parts maintains the beetle's arched posture as it contracts its large dorsal intersegmental muscles to prepare for the jump. This contraction stores energy in the cuticles, apodemes, and possibly other elastic components, although the exact energy storage components remain unclear. Triggering the jump involves the peg moving upward off the mesosternal lip and rapidly sliding along the mesosternum, causing a swift jack-knifing action. This action flips the beetle's body curvature, rapidly elevating its center of mass and launching it into the air.

Direct muscle contraction

The moth (Lepidoptera) (Figure 4A) weighs 4.6–19.1 mg, has a body length of 6.8–10.8 mm, and has relatively long hind legs, which are 129%–152% of their body length. Their takeoff velocities are

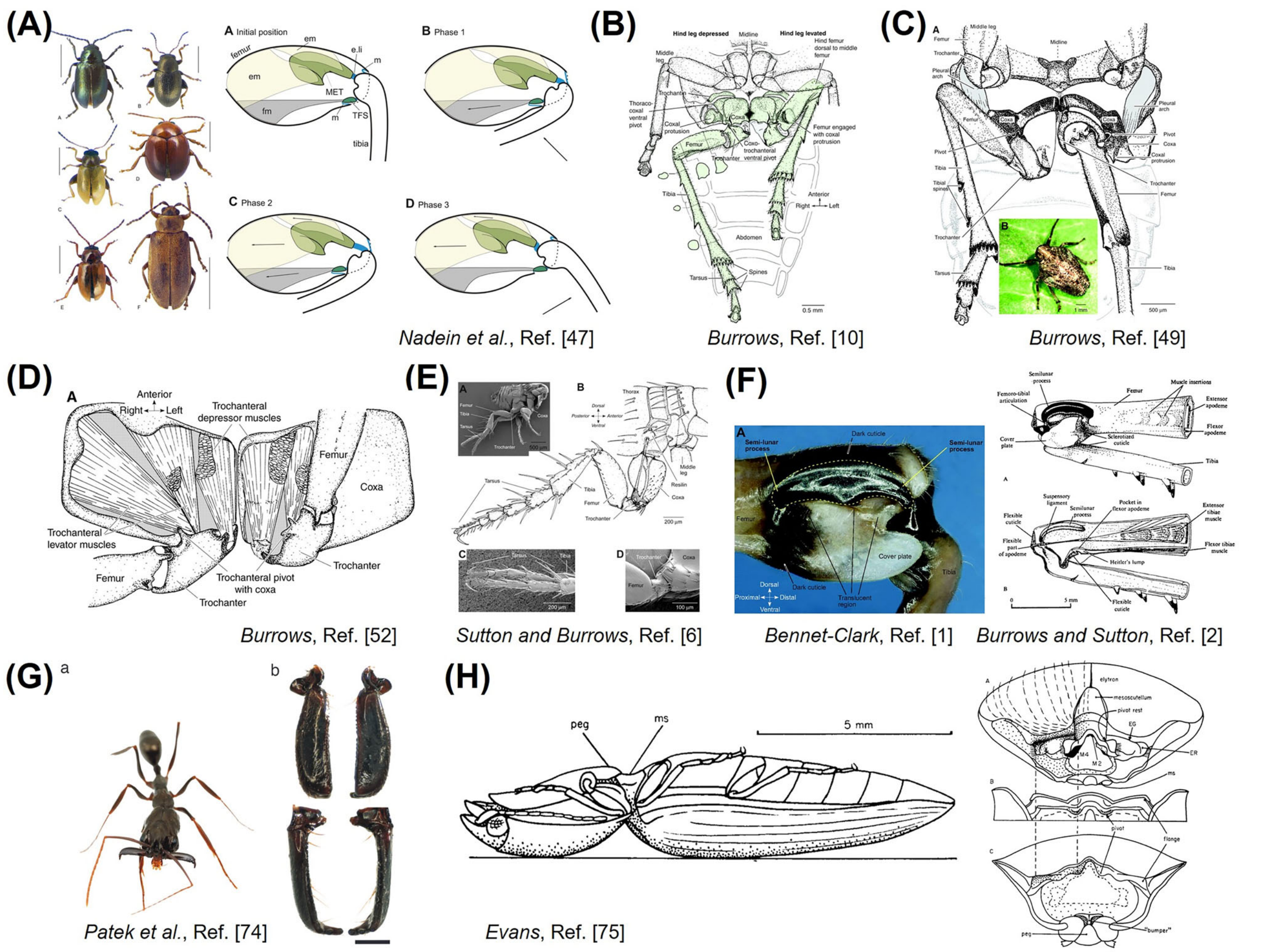

FIGURE 3 Terrestrial jumping insects with catapult mechanism. (A) Flea beetle. Images reproduced with permission from Ref. 47. (B) Froghopper. Image reproduced with permission from Ref. 10. (C) Plant hopper. Image reproduced with permission from Ref. 49. (D) Leafhopper. Image reproduced with permission from Ref. 52. (E) Flea. Image reproduced with permission from Ref. 6. (F) Locust. Images reproduced with permission from Refs. 1, 2. (G) Trap-jaw ant. Image reproduced with permission from Ref. 74. (H) Click beetle. Image reproduced with permission from Ref. 75.

0.7–1.2 m/s, and because of their relatively long hind legs, they show a prolonged push-off duration of 8–24 ms.[55] In contrast to the aforementioned insects that use catapult mechanisms, they propel the body using both pairs of middle and hind legs and direct muscle contraction. Similar jumping mechanisms using four legs are seen in lacewings,[79] snow fleas (*Boreus hyemalis*),[80] and a certain species of fly (*Hydrophorus alboflorens*).[60] This approach distributes ground reaction forces over a larger area and a longer duration, which in turn enables these insects to jump on compliant substrates, such as delicate leaves, snow, and water surfaces.

The bush cricket (Orthoptera: Tettigoniidae), whose leg is shown in Figure 4B, weighs 602 mg, has a body length of 23.2 mm, and has relatively long hind legs, which are 158% of their body length. Their takeoff velocities are 2.12 m/s, with a push-off duration of 32.6 ms.[56] The primary muscle responsible for this jumping is the extensor tibiae muscle, located within the femur. Although the bush cricket's morphology is similar to that of the locust, its jumping mechanism is distinct. The bush cricket exhibits a shorter co-contraction duration, and the semi-lunar process remains undeformed during this period. Also, the bush cricket possesses a longer lever arm of the flexor muscle when the legs are fully flexed. Using this lever advantage, this insect primarily relies on direct muscle contraction for jumping. Some portion of the energy is stored in the extensor apodeme and elastic elements of the extensor muscle during brief co-contraction.[56]

Insects jumping on water

Catapult mechanism

The pygmy mole cricket (Orthoptera: Tridactylidae) (Figure 5A) weighs 8.3–9.2 mg, has a body length of 5.6 mm, and relatively long hind legs, which are 131% of its body length. Their takeoff velocity is 5.4 m/s, with a push-off duration of 1.8 ms. This rapid push-off indicates that these insects use a catapult mechanism. The primary muscles responsible for this rapid takeoff jumping are the extensor tibiae muscles, which are in the large femur. Like the locusts, the pygmy mole cricket has a

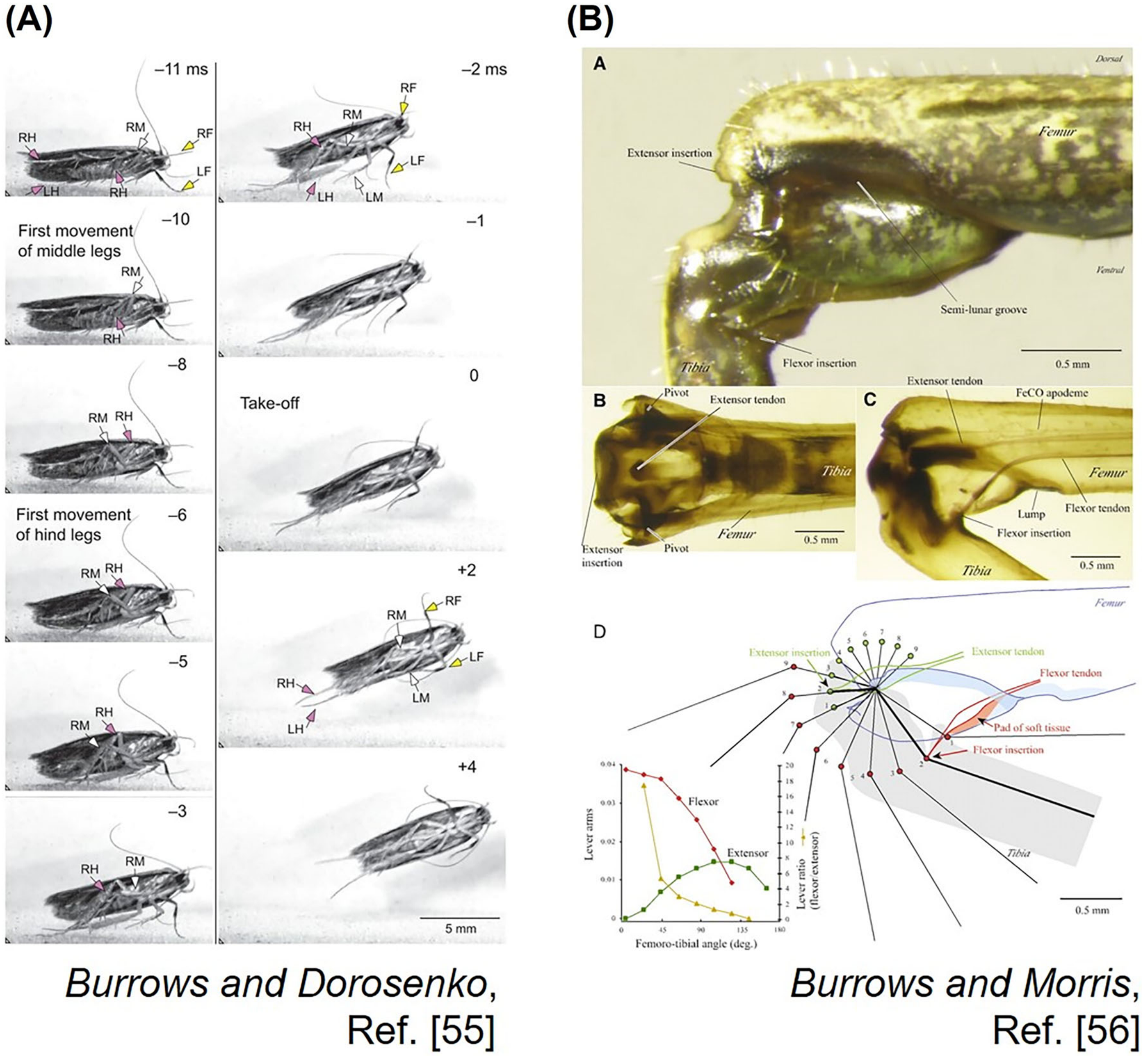

FIGURE 4 Terrestrial jumping insects with direct muscle contraction. (A) Moth. Image reproduced with permission from Ref. 55. (B) Bush cricket. Image reproduced with permission from Ref. 56.

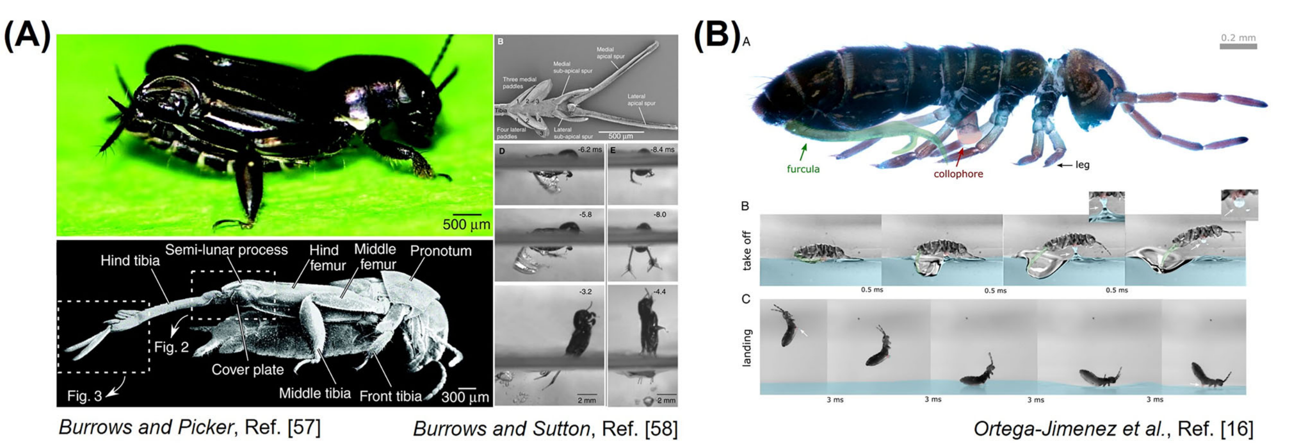

FIGURE 5 Water-jumping insects with catapult mechanism. (A) Pygmy mole cricket. Images reproduced with permission from Refs. 57, 58. (B) Springtail. Image reproduced with permission from Ref. 16.

semi-lunar process on the distal femur, which stores elastic energy during co-contraction in the energy storage phase. Contrary to the general trend where longer legs correlate with prolonged push-off durations, this long-legged insect shows rapid push-off.[57,58] Another fascinating ability of this insect is its capability to jump from water surfaces, aided by its tibial paddles and spurs. The takeoff speed is 2.2 m/s with a push-off duration of 5.8 ms. The force for propelling these water jumps stems from the drag force generated by the rapid strike of their air-carrying tibia.[57,58]

The springtail (Hexapoda: Entognatha: Collembola) is shown in Figure 5B. It has a body length of 1.7 mm and a jumping appendage known as the furcula, which is 61% of its body length. On the ground, its takeoff speeds reach 1.3 m/s, with a push-off duration of 2 ms, thanks to a catapult mechanism. The furcula is attached to the ventral side of the abdomen by the posterior hinge. Ordinarily, it remains stowed on the ventral side of the abdomen, held securely by the ventral wall and hamula. During a jump, it rapidly pops out and strikes the substrate.[16,59] Remarkably, the springtail can also jump on the water surface with a takeoff speed of 0.6 m/s and a push-off duration of 2.5 ms. The force propelling these water jumps comes from the surface tension of the water surface.[16,59]

Direct muscle contraction

A small water strider (Hemiptera: Gerridae), shown in Figure 6A (*Aquarius paludum*), has a weight of 37.2 mg and a body length of 12.35 mm. Its relatively long middle and hind legs measure 179% of its body length. When jumping on the water surface, it achieves takeoff velocities of up to 1.3 m/s, with a push-off duration of 25 ms. This jump is made possible by using the surface tension of the water. The water strider employs both its middle and hind leg pairs in the locomotion. As it jumps, the insect rotates its long legs inward, applying force at a relatively low descending speed, just beneath the threshold needed to break the water's surface. Rather than exerting a large impulsive force on the water, the water strider uses a more sustained, yet gentle, force over a longer duration to propel itself using the surface tension of water.[63–65] In contrast, large water striders,[65] such as *Gigantometra gigas*, use a different mechanism. Weighing 375 mg with a body length of 35.2 mm and having relatively long middle and hind legs that measure 340% of their body length, they achieve takeoff velocities of up to 1.6 m/s with a push-off duration of 68 ms. Unlike their smaller counterparts, large water striders use both the surface tension of water and the drag force for jumping. During the push-off phase, their air-carrying middle and hind legs break the water surface, pushing water downward to generate a reaction force through drag.[63–65]

The fly (Diptera) (Figure 6B) has a weight of 4.7 mg and a body length of 4.4 mm. Its relatively long middle and hind legs measure 170% of its body length. When jumping on the water surface, it achieves takeoff velocities of up to 1.6 m/s, with a push-off duration of 11.6 ms. This jump is made possible by using the surface tension of the water and wing flapping of 148 Hz. Similar to the water strider, the fly employs both its middle and hind leg pairs in the locomotion. As it propels itself, the fly rotates its legs inward, ensuring they do not penetrate the water's surface.[60] The simultaneous wing flapping as the legs move enhances the jump's efficiency. Because of the combination of a consistent, gentle force on the legs over an extended duration and the contribution of wing flapping, the insect does not rely on an energy storage mechanism for its jumping capability.

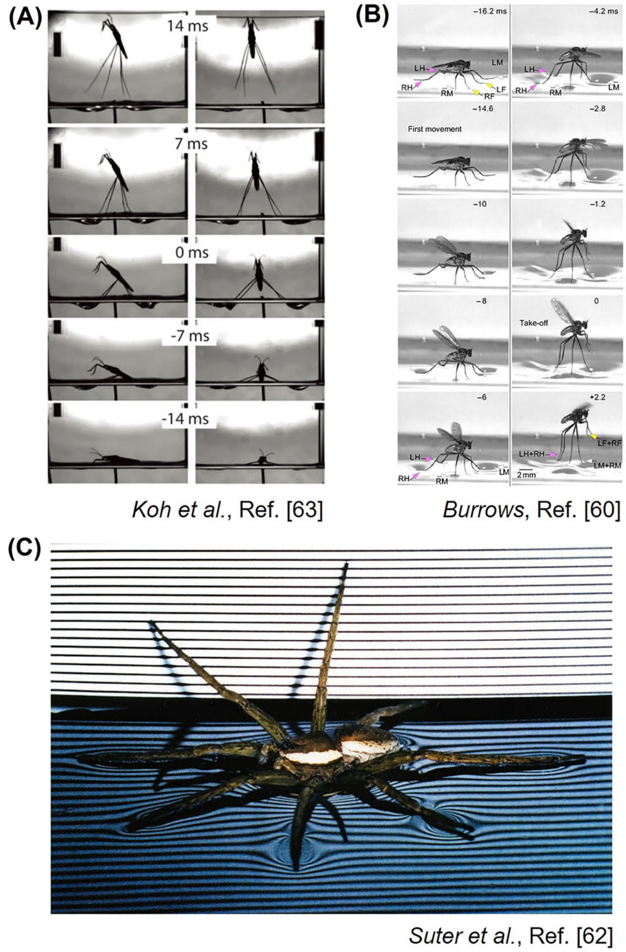

FIGURE 6 Water-jumping insects with direct muscle contraction. (A) Water strider. Image reproduced with permission from Ref. 63. (B) Fly. Image reproduced with permission from Ref. 60. (C) Fisher spider. Image reproduced with permission from Ref. 62.

The fisher spider (Arachnida: Araneae) is shown in Figure 6C. The fisher spider has a weight of 475 mg and jumps on water with takeoff velocities of up to 0.88 m/s and a push-off duration of 12 ms. This jump is made possible by using the drag force. Similar to the springtail and pygmy mole cricket, the spider rapidly strikes its air-carrying legs. The drag is the dominant force for the jump, but as the spider gets smaller, the effect of the surface tension increases.[62]

Jumping robots

Terrestrial jumping robots

As discussed above (see "Physics of the Jumping Modes", pg. 2), terrestrial jumpers can use a guaranteed ground reaction force due to

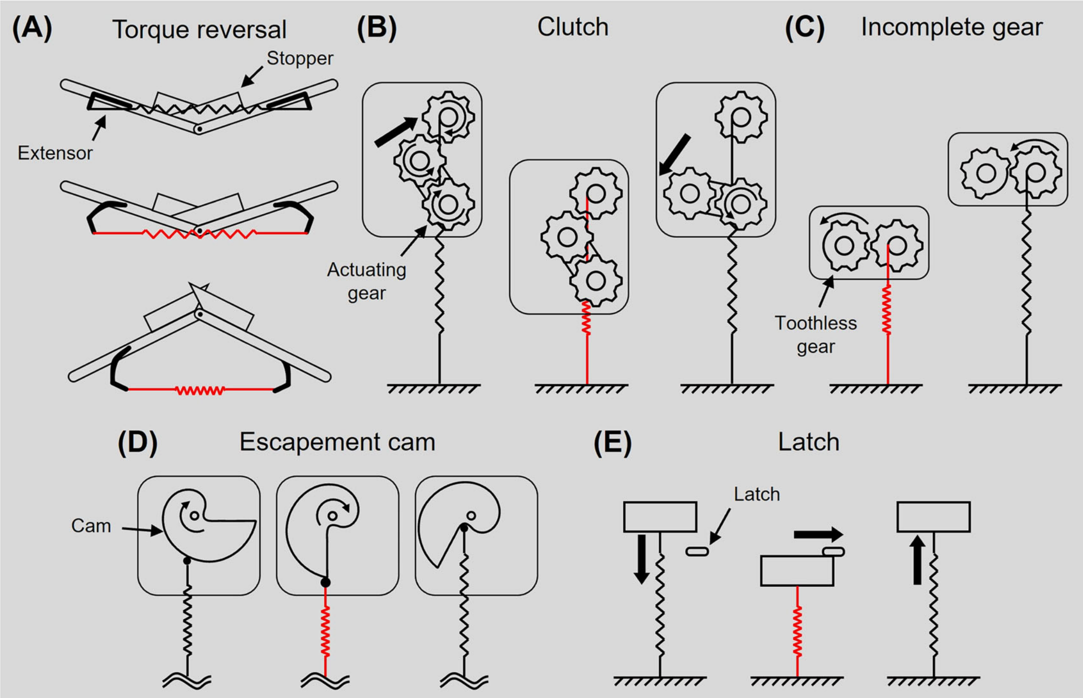

FIGURE 7 Energy-release methods of catapult mechanism. (A) Torque reversal. (B) Clutch. (C) Incomplete gear. (D) Escapement cam. (E) Latch.

the rigidity of the substrate. Thus, the foremost design strategy of the terrestrial jumping robot is to achieve large impulsive force. In this section, we review the terrestrial jumping robot's specifications and performances and their jumping mechanisms. The catapult mechanism is far more widely adopted in jumping robots than the direct actuation scheme. We first categorize the robot systems based on the mechanical components used in the catapult mechanism or the energy release method. Then we discuss the direct actuation method and exceptional means to overcome the power limit of the actuator exploited in the small-scale robots.

Catapult mechanism

To construct an artificial jumper based on the catapult mechanism, incorporating a lock-and-release mechanism is crucial. This mechanism must hold stored elastic energy during the energy storage phase and then rapidly release the energy during the push-off phase. Various methods exist and we delineate representative mechanisms below, including torque reversal, clutch, machine element–based release, and latch mechanisms, as shown in Figure 7.

The flea serves as the model for the torque reversal mechanism (Figure 7A). The central principle of this mechanism is the moment direction reversal, which is induced by the over-center movement of the extensor spring. When the legs are flexed, activating the extensor spring generates a flexion moment. This occurs due to the unique positioning of the extensor spring relative to the joint's center. At this stage, further contraction of the extensor spring stores elastic energy. Then, if the extensor spring moves over the leg joint, the moment's direction reverses suddenly, leading to rapid leg extension and the release of stored energy. The extensor spring can be moved either by structural deformation or the actuation of an additional trigger spring.

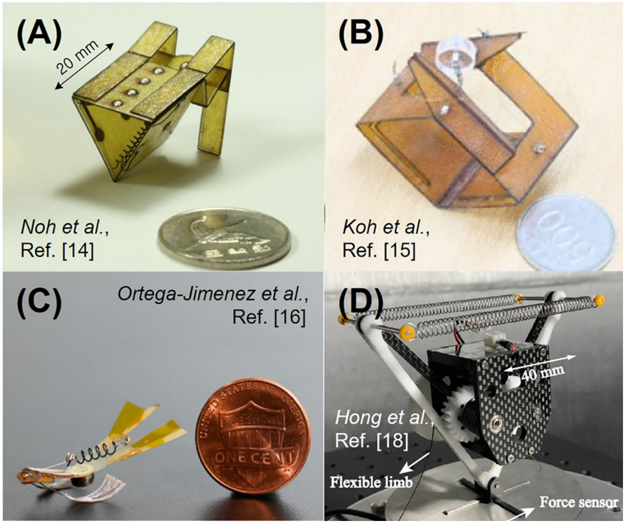

FIGURE 8 Terrestrial jumping robots with torque reversal catapult mechanism. (A) Flea-inspired robot 1. Image reproduced with permission from Ref. 14. (B) Flea-inspired robot 2. Image reproduced with permission from Ref. 15. (C) Springtail-inspired robot. Image reproduced with permission from Ref. 16. (D) Frog-inspired jumping robot. Image reproduced with permission from Ref. 18.

Noh et al.[14] developed a jumping robot that weighs 1.1 g, has a body length of 20 mm, and leg length of 31 mm (Figure 8A). It achieves a takeoff speed of 4.2 m/s with a push-off duration of 8 ms. Koh et al.[15] developed a jumping robot that weighs 2.25 g, has a body length of 30 mm, and has 60 mm leg length (Figure 8B). It achieves a takeoff speed of 7 m/s with a push-off duration of 8 ms. Ortega-Jimenez et al.[16] developed a jumping robot that weighs 0.1 g, has a body length of 20 mm,

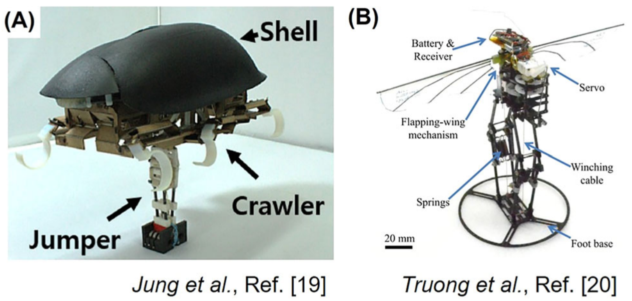

FIGURE 9 Terrestrial jumping robots with clutch mechanism. (A) JumpRoACH. Image reproduced with permission from Ref. 19. (B) Flapping-wing-assisted jumping robot. Image reproduced with permission from Ref. 20.

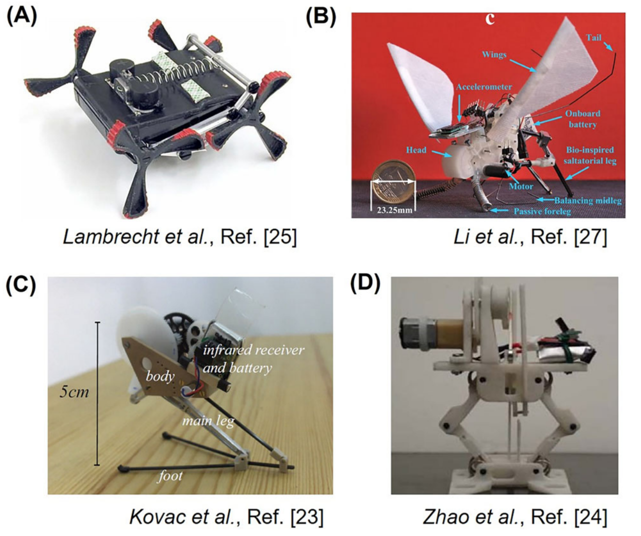

FIGURE 10 Terrestrial jumping robots with incomplete gear. (A) MiniWheg 9. Image reproduced with permission from Ref. 25. (B) Grillo 3. Image reproduced with permission from Ref. 27. (C) EPFL 7 g jumping robot. Image reproduced with permission from Ref. 23. (D) MSU jumper. Image reproduced with permission from Ref. 24.

and leg length of 11 mm (Figure 8C). It achieves a takeoff speed of 3 m/s. This robot is notable for using drag during jumping to achieve well-oriented landings. Hong et al.[18] developed a jumping robot that weighs 100 g, has a body length of 100 mm, and a leg length of 160 mm (Figure 8D). It achieves a takeoff speed of 4.9 m/s with a push-off duration of 30 ms. This robot stands out for its use of both series and parallel elastic springs, combined with a frog-inspired linkage structure, to achieve an extended push-off duration. Kurniawan et al.[17] developed a jumping robot that weighs 216 mg, has a body length of 24 mm, and leg length of 12 mm. It achieves a takeoff speed of 2.1 m/s and is distinctive for its ability to be wirelessly powered by an external transmitter coil.

In the clutch mechanism (Figure 7B), the connection between the energy storage element and the actuator is actively controlled. While connected, the actuator transmits power to the energy storage element, storing energy and simultaneously preventing its release. Upon disconnection, the actuator no longer restrains the release, enabling the rapid release of stored energy. Jung et al.[19] developed a trajectory-adjustable jumping-crawling robot called JumpRoACH (Figure 9A). It weighs 99 g, has a body length of 120 mm, and leg length of 95 mm. It achieves a takeoff speed of 5.39 m/s with a push-off duration of 15 ms. Using a planet gear–based clutch mechanism, the connection between the actuator and the energy storage component is controlled by the driving direction of the motor. Truong et al.[20] developed a flapping-assisted jumping robot that weighs 23 g, has a body length of 130 mm, and leg length of 80 mm (Figure 9B). The unique addition of flapping enhances its jumping performance.

Unlike the clutch mechanism, which actively controls the connection between the actuator and the energy storage element as needed, simpler methods exist for periodic connection and disconnection using a single machine element. These include using an incomplete gear, an escapement cam, and a one-way bearing.

An incomplete gear (Figure 7C), with a section of missing several teeth, facilitates periodic engagement and disengagement. When the teeth of neighboring gears are engaged, the motor power is transmitted to the energy storage component. When encountering the teeth-missing section, the connection is lost, allowing for rapid energy release. For example, Lambrecht et al.[25] developed a jumping-crawling robot that weighs 190 g, has a body length of 104 mm, and leg length of 104 mm (Figure 10A). It achieves a takeoff speed of 2.6 m/s. Li et al.[27] developed a jumping robot that weighs 22 g, has a body length of 50 mm, and leg length of 66.8 mm (Figure 10B). It achieves a takeoff speed of 1.7 m/s with a push-off duration of 40 ms. Hong et al.[26] developed an extremely small jumping robot that weighs 25.2 mg, has a body length of 3.1 mm, and leg length of 3.1 mm. It achieves a takeoff speed of 2.3 m/s with a push-off duration of 0.75 ms. This robot is actuated by an external magnetic field.

Kovač et al.[23] developed a jumping robot using an escapement cam mechanism (Figure 10C). Similar to Leonardo da Vinci's cam hammer, this robot stores energy as the cam radius increases and releases the energy when the radius suddenly drops (Figure 7D). The robot weighs 7 g, has a body length of 50 mm, and leg length of 100 mm. It achieves a takeoff speed of 5.9 m/s with a push-off duration of 19 ms. Zhao et al.[24] employed a one-way bearing for a jumping robot (Figure 10D). During the energy storage phase, the restoring force of the spring is blocked by the bearing in a nonrotatable direction. The energy is released when the force aligns with the bearing's rotating direction. The robot weighs 20 g, has a body length of 65 mm, and leg length of 40 mm. It achieves a takeoff speed of 3.34 m/s.

In the latch mechanism (Figure 7E), a latch holds the legs of the jumping mechanism to prevent energy release during the energy storage phase. It is then unlatched when the robot needs to jump, allowing for the rapid release of stored energy.

For example, Hawkes et al.[28] developed a jumping robot that weighs 30 g, has a body length of 300 mm and leg length of 300 mm (Figure 11A). It achieves a takeoff speed of 28 m/s with a push-off duration of 9.2 ms. Utilization of the latch mechanism and rotary motor enables work multiplication and allows the robot to outperform any other biological and synthetic jumpers. Tang et al.[30] developed a robot

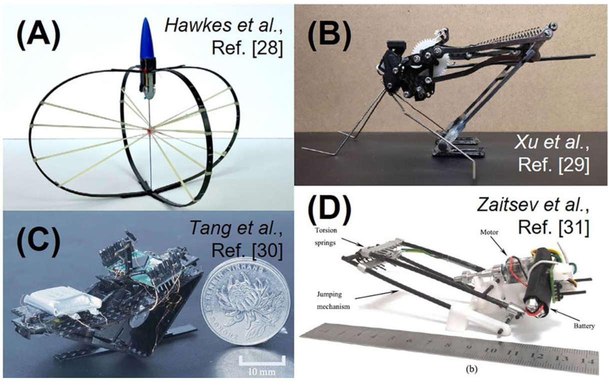

FIGURE 11 Terrestrial jumping robots with latch mechanism. (A) Engineered jumper. Image reproduced with permission from Ref. 28. (B) Locust-inspired stable jumping robot. Image reproduced with permission from Ref. 29. (C) Moobot. Image reproduced with permission from Ref. 30. (D) Locust-inspired jumping robot - TAUB. Image reproduced with permission from Ref. 31.

that weighs 6 g, has a body length of 50 mm, and leg length of 44 mm. It achieves a takeoff speed of 3.5 m/s (Figure 11C). Xu et al.[29] developed a robot that weighs 60 g, has a body length of 100 mm, and leg length of 126 mm. It achieves a takeoff speed of 2.8 m/s with a push-off duration of 20 ms (Figure 11B). Zaitsev et al.[31] developed a robot that weighs 23 g, has a body length of 135 mm, and leg length of 160 mm. It achieves a takeoff speed of 9 m/s with a push-off duration of 23 ms (Figure 11D). Zhakypov et al.[32] developed a multi-locomotion robot called Tribot, which is inspired by trap-jaw ants. The shape of the robot is threefold symmetric, with three legs, and it consists of a Y-shaped flexure hinge and shape memory alloy (SMA) coil actuators. The jumping mechanism of the robot is based on snap-through instability. The robot can jump with different takeoff angles because the direction of the ground reaction force changes depending on the configuration of the legs where the snap occurs. The robot weighs 9.7 g, has a body length of 58 mm, and leg length of 44 mm. It achieves a takeoff speed of 1.65 m/s.

Direct actuation

Haldane et al.[33,34] developed the hopping robots Salto and Salto-1P (Figure 12A). To achieve high power amplification in a no-latch mechanism, these robots adopted a series-elastic power modulation strategy inspired by the jumping behavior of *Galago* (Primates) that weighs 95–300 g, has a body length of 130 mm. The power modulation, based on an 8-bar mechanism, enables a jumping motion that is free from rotation and can generate approximately 3.6 times the power that the actuator can produce. Another feature of the robot is repetitive and agile jumping, which allows robots to perform extreme locomotion such as wall jumping. The maximum jumping height is approximately 1 m, and the robots perform repetitive jumps with a jumping frequency of 1.74 Hz. For a single jump, the push-off duration is longer than a mechanism using a latch. Salto-1P weighs 98 g, has a body length of 150 mm, and leg length of 144 mm. It achieves a takeoff speed of 4.95 m/s with a push-off duration of 57 ms. Yun et al.[35] developed a flea-size robot that weighs 12 mg and has a body length of 3.4 mm (Figure 12B). It achieves a takeoff speed of 1.74 m/s with a push-off duration of 10 ms. The robot is capable of jumping and crawling locomotion. The actuation principle is the electric arc phenomenon generated from two electrodes with pulsed high voltage (4 kV). The robot is composed of electrodes, piston chamber, and spring. The electric arc generates force by inducing expansion of the gas in the piston chamber, and the spring restores the chamber to its initial shape. The robot can take off by pushing off the ground directly with the force generated as the chamber expands. Aubin et al.[36] developed insect-scale terrestrial robots driven by the combustion of chemical fuels (Figure 12C). The soft combustion micro actuator embedded in the robot can generate forces of more than 9.5 N, which enables vertical jumping with a maximum height of 59 cm. The robot weighs 1.6 g and has a body length of 29 mm. It achieves a takeoff speed of 2.5 m/s with a push-off duration of 0.24 ms. In order for the robot to take off, the chemical fuel is ignited to release energy, and the elastomer membrane between the chamber and the feet expands to exert force on the ground.

Water jumping robots

The major difference in water jumping compared to ground jumping is that the limited fluid-mechanical force does not guarantee sufficient reaction force from the substrate. Some robot designs have been studied to address this problem and are classified into two types: surface tension–dominated jumping, which maximizes jumping momentum by increasing the takeoff duration without breaking the water surface at the small-scale robots; and drag-dominated jumping, which uses pads or paddles for larger-scale robots.

Koh et al.[63] developed a torque reversal mechanism–based water jumping robot that weighs 68 mg, has a body length of 20 mm, and a leg length of 50 mm (Figure 13A). It achieves a takeoff speed of 1.7 m/s with a push-off duration of 25 ms. Similar to the small water striders, this robot uses surface tension for the primary reaction force for the jumping. Gwon et al.[69] developed a larger robot with a similar catapult mechanism (Figure 13B). The robot weighs 3 g, has a body length of 320 mm, and a leg length of 130 mm. It achieves a takeoff speed of 3.6 m/s with a push-off duration of 45 ms. Similar to the large water striders, this robot uses drag force as the primary reaction force for the jumping.

Based on the latch mechanism, Shin et al.[71] and Hu et al.[70] developed water jumping robots (Figure 13C,D). The robot developed by Shin et al. weighs 0.51 g, has a body length of 15 mm, and a leg length of 5.5 mm. It achieves a takeoff speed of 0.09 m/s with a push-off duration of 2.1 ms. The robot developed by Hu et al. weighs 4 mg, has a body length of 13 mm, and has a leg length of 6.5 mm. It achieves a takeoff speed of 1 m/s with a push-off duration of 3 ms.

Using an incomplete gear, Zhao et al.[72] and Yang et al.[73] developed water-jumping robots. The robot developed by Zhao et al. weighs 11 g, has a body length of 250 mm, and a leg length of 125 mm (Figure 13E). It achieves a takeoff speed of 1.95 m/s. The robot developed by Yang et al. weighs 10.2 g, has a body length of 260 mm, and a leg length of 130 mm. It achieves takeoff speed of 2.1 m/s. Both of these robots use the drag as the primary reaction force for the jumping.

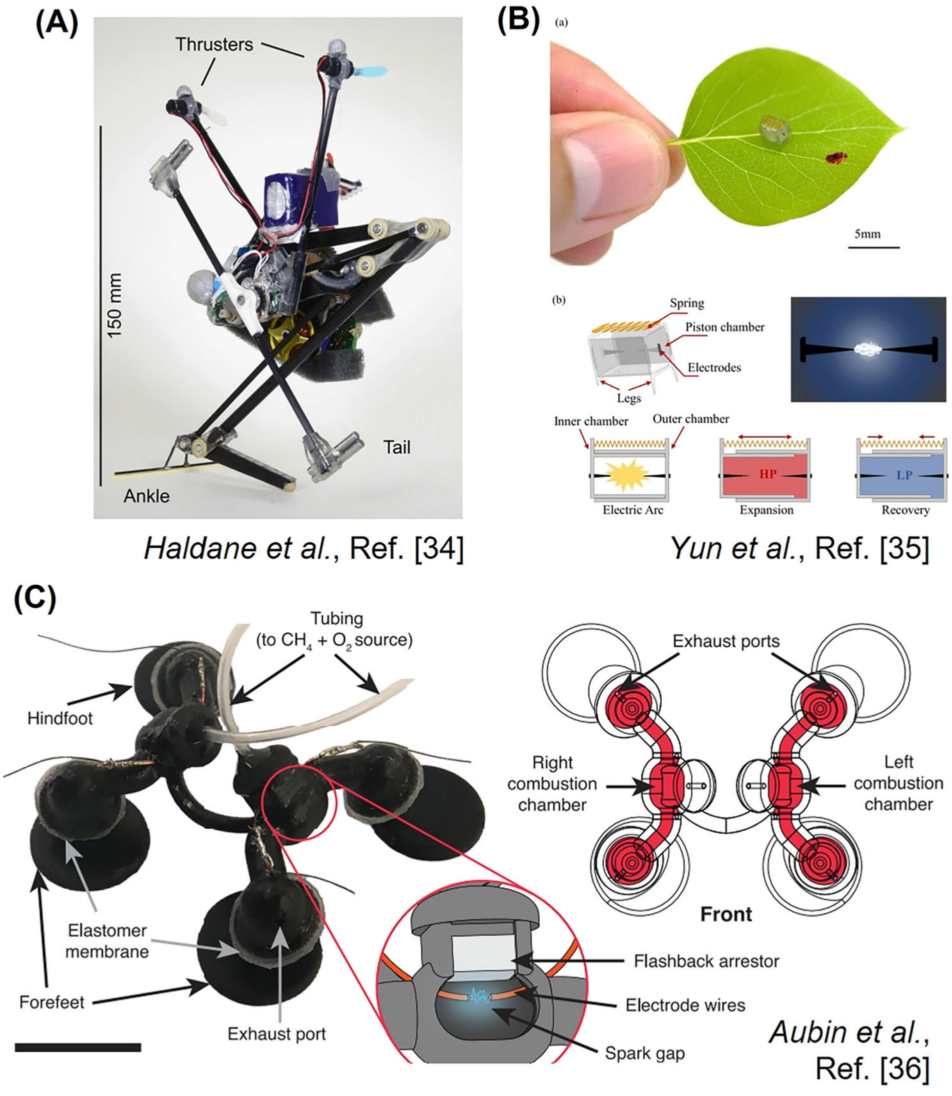

FIGURE 12 Terrestrial jumping robots with direct actuation. (A) Salto-1P. Image reproduced with permission from Ref. 34. (B) 3.4-mm Flea-sized robot. Image reproduced with permission from Ref. 35. (C) Soft-combustion insect-scale robot. Image reproduced with permission from Ref. 36.

COMPARISON BETWEEN WATER AND TERRESTRIAL JUMPING

Jumping kinetic energy

The jumping ability of a given insect would be predominantly governed by its mass and leg length because of their direct influence on actuation power and duration, respectively. Here we present the collected data of kinetic energy at takeoff versus mass and leg length of jumpers, investigate their relations, and discuss the relations' physical implications.

Figure 14A shows that the kinetic energy of jumping insects increases with the mass; for ground jumpers, it is proportional to the mass to the power of 1.15, and for water jumpers, to the power of 1.11. Similarly, Figure 14B reveals a scale-dependent tendency, where the energy of ground jumpers is proportional to leg length raised to the power of 2.42, and for water jumpers, to the power of 2.49. Similar power laws of ground and water jumpers indicate that both the scaling relations of mass and leg length to the jumping energy are insensitive to the jumping substrate.

However, both graphs show that the regression line for water jumpers is slightly lower than that for ground jumpers, suggesting differences in dynamics between the two substrates. The lower regression line means that jumping on water is less efficient than jumping on the ground. During the push-off phase of jumping, ground jumpers can get enough reaction force from the ground to accelerate their bodies; most of the work done by the jumpers during the push-off is converted to its kinetic energy at takeoff. Water jumpers, however, face limitations, as the water deforms or breaks under the force of leg push-off, and flows as a consequence. Hence, a portion of the work done by the

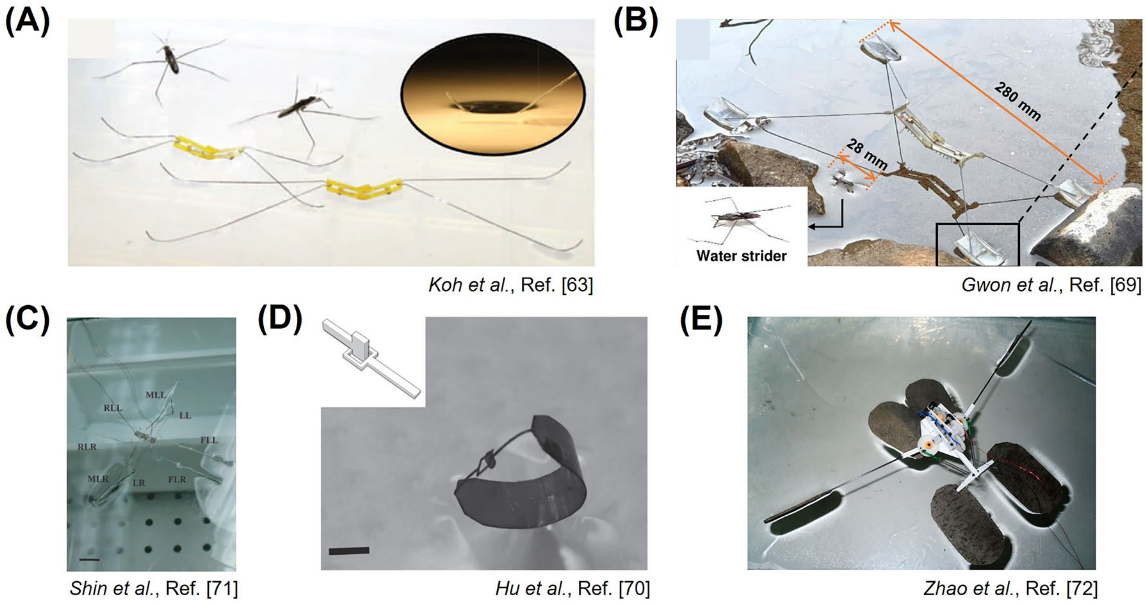

FIGURE 13 Water jumping robots. (A) Water strider robot (surface tension). Image reproduced with permission from Ref. 63. (B) Water strider robot (drag). Image reproduced under the terms of the CC BY license.[69]. (C) Small-scale water-jumping robot. Image reproduced with permission from Ref. 71. (D) Water-walking devices. Image reproduced with permission from Ref. 70. (E) Water-walking robot. Image reprinted with permission from Ref. 72.

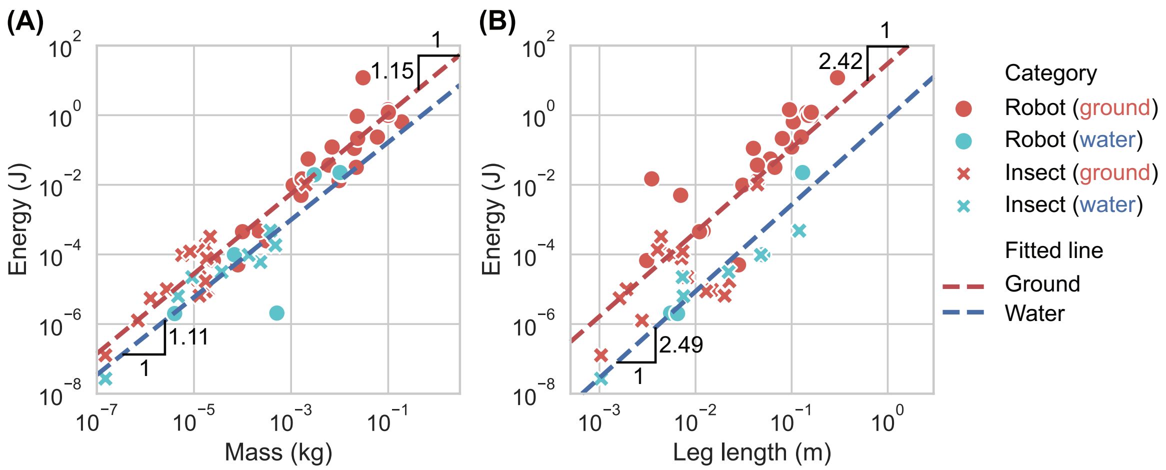

FIGURE 14 Kinetic energy of the biological and engineered jumpers. (A) Kinetic energy versus jumper mass. (B) Kinetic energy versus leg length of the jumper. All data in the scatter plots are illustrated in four colors, each color representing a combination of the type of jumpers and the type of substrates: Robot (ground), Robot (water), Insect (ground), and Insect (water).

jumpers is transferred to the kinetic energy of the water, leading to reduced jumping energy for water jumpers.

Takeoff speed of the jumping

Figure 15 illustrates the relationship between leg length–normalized takeoff speed in s^{-1} and jumping mechanism types—catapult mechanism and direct actuation—across four categories: ground-jumping robot, ground-jumping insect, water-jumping robot, and water-jumping insect. The two dashed lines represent the average speeds for ground and water jumping, respectively. The average data show that ground jumping has a 3.24 times larger relative takeoff speed than water jumping, aligning with expectations.

In a detailed view, all four categories show that the catapult mechanism tends to achieve higher takeoff speed than direct actuation. This difference is particularly pronounced in ground-jumping insects; insects using the catapult mechanism achieve notably faster take-

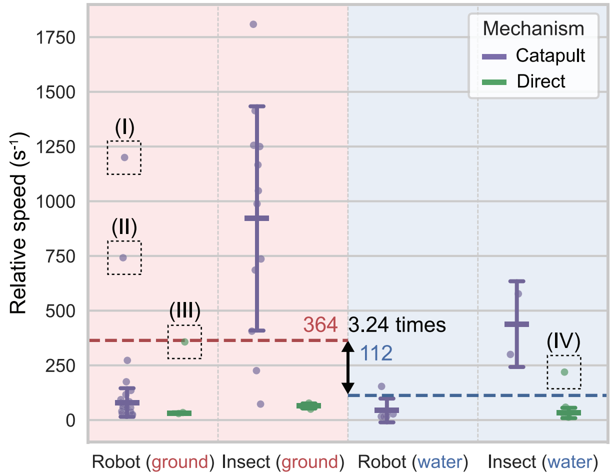

FIGURE 15 Relative takeoff speed by the type of jumpers and substrates. Outlier data are surrounded by dashed rectangles: (I) Insect-scale jumping robot;[37] (II) Jumper with magnetically actuated gearbox;[26] (III) Soft combustion insect-scale robot;[36] (IV) Fly. [60] Error bars show mean ± standard deviation.

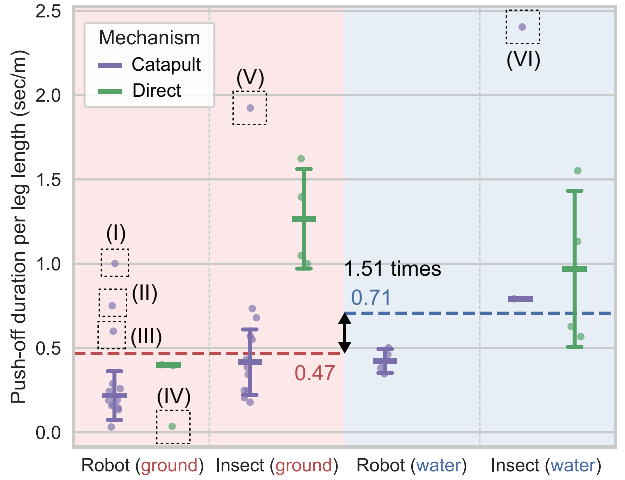

FIGURE 16 Leg length–normalized push-off duration by the type of jumpers and substrates. Outlier data are surrounded by dashed rectangles: (I) Insect-scale jumping robot;[37] (II) Soft jumping robot;[81] (III) Grillo 3;[27] (IV) 3.4-mm Flea-sized robot;[35] (V and VI) Springtails.[59] Error bars show mean ± standard deviation.

off speeds compared to those relying on direct muscle contraction. This observation suggests that the catapult mechanism is more effective in smaller-scale jumping, implying that the generally larger scale of the robot compared to the insect makes the catapult mechanism less attractive for robots. Outliers in the catapult mechanism type for ground jumping robots, marked as (I) and (II) in Figure 15, exhibit takeoff velocities comparable to the insects and have relatively short leg lengths of 3.5 mm and 3.1 mm, respectively,[26,37] aligning with the increased effectiveness of the catapult mechanism in smaller scales. An outlier in the direct actuation type for ground jumping robots, marked as (III) in Figure 15, is the robot using combustion for jumping.[36] This robot demonstrates performance akin to catapult mechanism–based insects, for it relies on the release of chemical energy rather than leg extension.

In the case of water jumping, the catapult mechanism still outperforms direct muscle contraction at the insect scale, but its effectiveness is reduced compared to ground-jumping insects. This reduced efficiency results from the catapult mechanism tending to cause water splashing during the jump, leading to energy loss. Consequently, the takeoff speed of water-jumping insects is lower than that of ground-jumping insects. An outlier in the direct actuation type for water-jumping insects, marked as (IV) in Figure 5, is the fly that uses flapping to augment jumping. This fly shows a faster takeoff speed than other water-jumping insects with direct actuation.

Duration of the push-off phase

To show the variation in push-off duration across different jumping categories, we normalized the push-off duration by the leg length of the system; this indicates the time taken to push off the unit length during the push-off phase. Figure 16 illustrates the relationship between leg length–normalized push-off duration and jumping mechanism types—catapult mechanism and direct actuation—across four categories: ground-jumping robot, ground-jumping insect, water-jumping robot, and water-jumping insect. The two dashed lines represent the average push-off duration for ground and water jumping, respectively. It shows that the push-off duration of the water jump is 1.51 times longer than that of the ground jump. In water jumping, because the water cannot withstand the large force applied by the legs, unlike the firm support provided by the ground, a different jumping strategy is needed. For ground jumps, applying a large impulsive force in a short duration is effective, while for water jumps, a strategy of applying relatively smaller forces over an extended period is more effective, as demonstrated in Figure 1B. The difference in average push-off duration indicates these different strategies.

In a detailed view, all four categories show that jumpers using direct actuation have longer push-off durations compared to those using the catapult mechanism. This is because muscle contraction rates or actuator speed are much slower than the rapid recoil of elastomers in catapult mechanisms. In addition, insects with longer legs often employ direct muscle contraction for jumping, and longer legs inherently increase the push-off duration.

The outliers in the data are noteworthy. In the catapult mechanism category for ground-jumping robots, outlier (I) uses the buckling effect of a compliant beam, which increases contact time, and it has short stroke length.[37] These result in a longer push-off duration relative to leg length. Outlier (II) employs electrostatic adhesion for locking, extending the push-off duration.[81] Outlier (III) features a bioinspired design aimed at increasing push-off duration.[27] In contrast, outlier (IV) in the direct actuation category achieves a shorter push-off duration by using arc expansion for jumping.[35] Both outliers (V) and (VI) in the ground- and water-jumping insect categories, respectively, are springtails. The springtail uses a unique jumping appendage known as the furcula, instead of its legs. It seems that using different appendages results in different push-off dynamics compared to other insects.

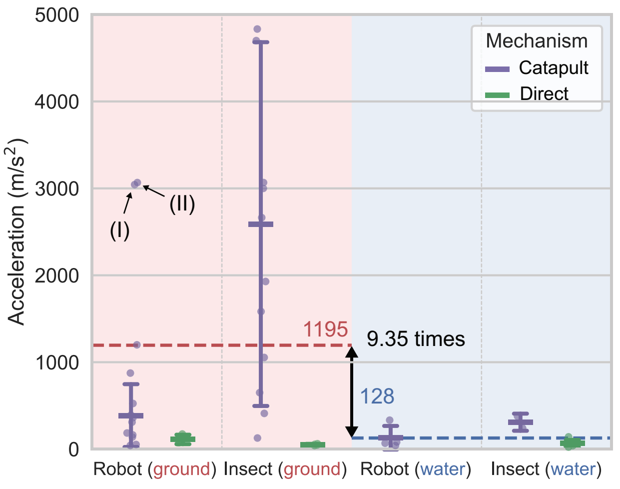

FIGURE 17 Acceleration by the type of jumpers and substrates. Outlier data are indicated by arrows: (I) Engineered jumper;[28] (II) Jumper with magnetically actuated gearbox.[26] Error bars show mean ± standard deviation.

Reaction force of jumping

Figure 17 illustrates the relationship between acceleration—calculated as the reaction force divided by the system's mass—and different jumping mechanism types. As discussed in the previous section, jumping strategies differ markedly between ground and water environments. Ground jumping involves applying a large force over a short period, whereas water jumping entails exerting a gentler force over a longer duration. The figure clearly shows that ground jumping results in higher acceleration compared to water jumping, indicating that ground jumpers experience a larger reaction force; ground jumping shows 9.35 times greater acceleration than water jumping.

From a more detailed perspective, insects employing the catapult mechanism exhibit greater acceleration than those using direct muscle contraction. This is because small insects, typically using the catapult mechanism, possess short legs and consequently require a higher acceleration for effective jumping.

In the catapult mechanism category for ground-jumping robots, outlier (I) is the jumper capable of reaching heights up to 32 m, with a takeoff speed of 28 m/s and a push-off duration of 9.2 ms.[28] This robot's extraordinary jumping performance results from a high reaction force, as indicated by its high acceleration. Another outlier (II) in this category has a leg length of 3.1 mm, similar to insects.[26] Consequently, it exhibits performance akin to catapult mechanism–based ground-jumping insects.

CONCLUSIONS

In this review, small-scale jumping creatures in nature and engineering that jump on the ground and the surface of water were analyzed and compared. Both organisms and robots have similar strategies for maximizing the jumping performance depending on their scale and their jumping substrates (ground or water surface). The jumping speed is strongly related to their substrate, being significantly higher on the ground than the water surface in a wide scale range because the fluid-mechanical force on the water surface is much lower than the reaction force from the ground. To maximize jumping speed under constraints from scale and substrate, various mechanisms are used for managing acceleration, force, and takeoff duration. Our collected data show that the jumping creatures have 9.35 times higher acceleration on the ground than on the water surface, which guarantees the high reaction force, and 1.5 times longer takeoff duration on the water surface than on ground, which can increase momentum transfer with limited fluid-mechanical force. As depicted in Figures 15–17, the data on insect jumping show a wider variation compared to that of robots. This variation highlights the diverse mechanisms employed by insects, offering a rich source of inspiration for the development of jumping robots.

Small-scale robots have the potential for operation in confined spaces inaccessible to humans and large robots. These robots can be distributed in large numbers over a vast area for use in rescue, exploration, and environmental monitoring. However, small-scale robots struggle to surmount high obstacles because the ability to overcome obstacles is limited by the size of their wheels and legs. Jumping is an effective locomotion mode for these robots. Many small-scale jumping robots have been designed based on inspiration from nature, but significant gaps remain in their locomotive capability and degrees of autonomy compared to biological counterparts.[82]

For jumping robots to autonomously perform complex locomotion, the control of jumping trajectory, repetitive jumping, stable landing, untethered energy source, and sensory integration are still challenging. As the size of robots becomes closer to that of insects, it becomes much harder to incorporate additional mechanisms or actuators. Therefore, to exploit insect-scale jumping robots in real-world applications, improvements in the degree of autonomy are crucial.

In addition, small-scale jumping robots can be robophysical platforms to simulate the locomotive behavior of organisms, providing experimental evidence for proving the mechanics of their motion. Based on the extensive data in this review, we are one step closer to establishing mathematical models that elucidate the principles of natural organisms and robots interacting with various environments. Furthermore, this work will help to formulate mathematical models of motion depending on scale of the systems, and to find design principles for optimizing the performance of the robotic insects.

AUTHOR CONTRIBUTIONS

H.-Y.K. and K.-J.C. conceived the idea. J.-S.K., S.-M.B., and B.K. collected and analyzed data. All authors discussed the results and wrote the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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