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Review

Review of bioinspired aquatic jumping robots

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ABSTRACT

In natural, aquatic and amphibians creatures have evolved exceptional impulsive-based, momentum-based, and mixed water–air cross domain locomotion capabilities through long-term natural selection, providing significant reference and inspiration for the design of aquatic jumping robots. In recent years, inspired by nature and biology, researchers have turned to jumping as a potential mode of locomotion for aquatic robots, aiming to improve their adaptability across water–air environment. However, the performance of these robots remains significantly limited, far from meeting practical application requirements, due to issues like inadequate propulsion efficiency, high structural resistance, and excessive weight. This paper summarizes the key features of bioinspired aquatic jumping robots, including their bioinspired structural designs, jumping mechanisms, and actuators, while evaluating their jumping performance. Finally, the current challenges are analyzed, and future prospects for development are discussed.

1. Introduction

Locomotion from water to air is crucial to the survival of many animals, such as to capture prey, evade predators, save energy for swimming or breathing [1]. These animals can produce enough thrust to leave water mainly due to their morphology and physiology, such as paddle-like feet [2], elastic energy-storing tendons and muscle fascia, and powerful muscle contractions [3,4]. These animals have catapult-like hindlimb [5], which facilitates stored elastic recoil energy from various parts of their skeleton-muscle–tendon system [6], which can be released simultaneously with muscle contraction to complement an aquatic jumping. Due to the large paddle surface area of feet, the ballistic leaping is realized; however, a slower velocity may not allow the animal to generate enough kinetic energy to overcome drag force or break surface tension. These explain why some animals of the same species cannot jump out of the water [7], while others can due to their strong energized capability. Studying the biomechanics of aquatic jumping may help understand how animals can transfer from one medium to another to survive and reproduce and provide clues in bioinspired robot design and fabrication [8].

According to previous research, biologists divide aquatic jumpers into three categories: impulsive jumper, mixed jumper, and momentum jumper [1].

In comparison with other forms of locomotion, swimming [9] is limited to exploration in a single environment, and jumping demonstrates a remarkable level of terrain adaptability [10]. In recent years, a succession of remarkable biomimetic terrestrial jumping robots [11–16], have been developed, while the development of aquatic jumping robots remains exploratory. In the study of impulsive aquatic jumping robots, creatures such as water strider [17], water-dwelling frog [18], flying squid [19], and Chinese rice grasshopper [5] are frequently employed as research subjects. These creatures achieve brief aquatic jumps by means of rapid muscle contractions. They are characterized by their relatively small body sizes [20], allowing them to generate greater kinetic energy; Momentum aquatic jumping robots rely on high swimming speeds and optimal pitch angles to break through the water surface and glide in the air, similar to the behaviors observed in bionic flying fish [21] and dolphin [22]; Mixed jumpers, such as silver carp [23], archer fish [24], and crocodile [25] can combine the above two jumping modes.

Aquatic jumping is a complex process influenced by various factors, including biological morphology, muscle energy density, jump kinematics, and the fluid properties of water [26,27]. During this movement process, aquatic and amphibious creatures not only rely on their morphological features but also relate to their

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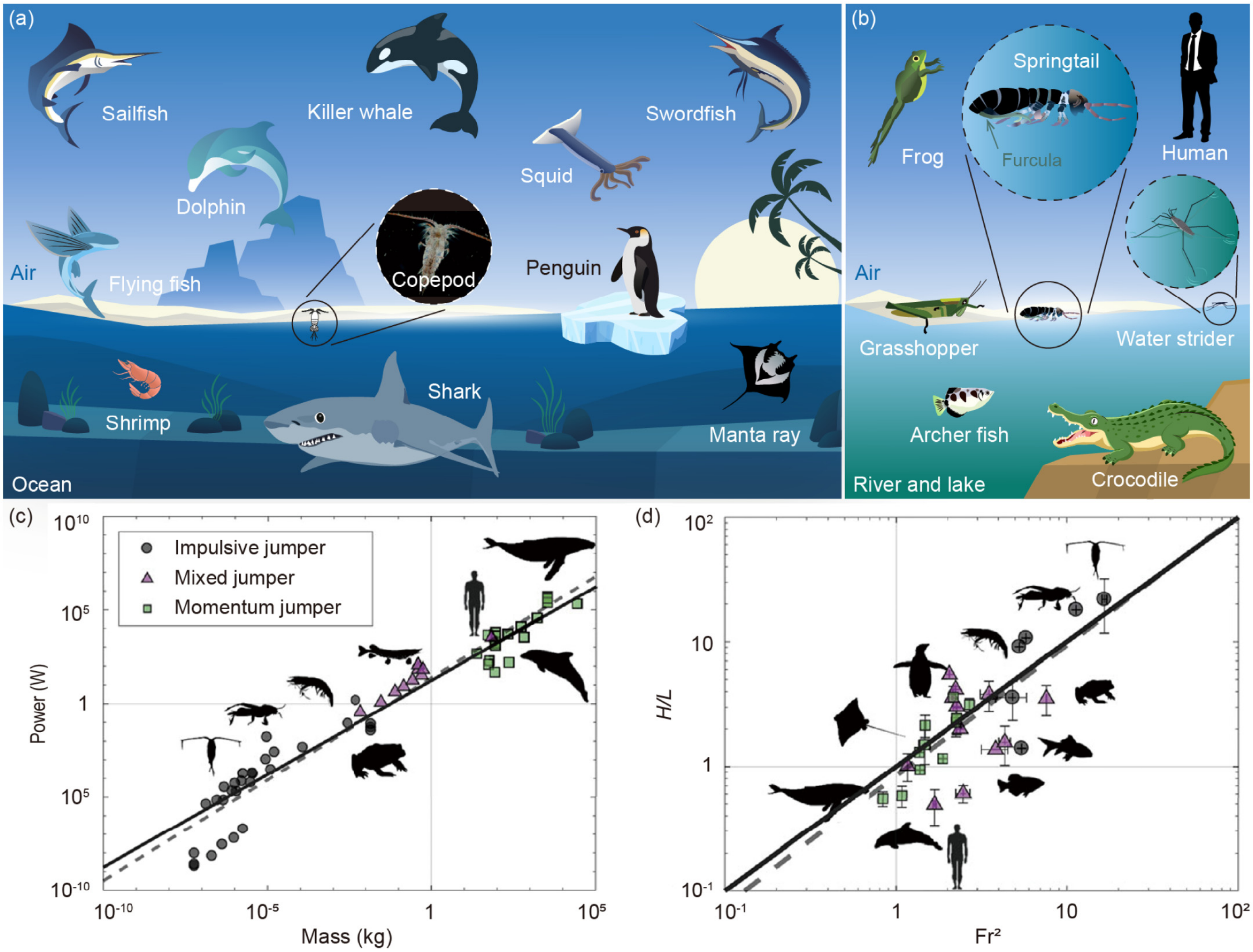

Fig. 1. Aquatic jumping creatures and three jumping modes. (a) Aquatic jumping creatures living in the ocean. (b) Aquatic jumping creatures living in the river or lake. (c) Relation between power production and mass [1], Copyright©2019, Journal of the Royal Society Interface. (d) The normalized jumping height as a function of Froude number [1], Copyright©2019, Journal of the Royal Society Interface.

internal biomechanical systems [28,29]. These biomechanical systems can participate in the entire process of creatures leaping out of the water and utilize the resistance and pressure of water to generate sufficient kinetic energy [30].

When jumping on land, the ground is usually hard, whereas water is a fluid with a certain viscosity and fluidity, so there is greater resistance when moving in water. These differences in physical properties make aquatic jumping more challenging [31] in the following aspects: (i) aquatic creatures, amphibians, or aquatic jumping robots are dragged by surrounding water during jumping, causing an "adding mass"; (ii) water, as a fluid, is much softer compared to solid ground, providing significantly less reactive force; (iii) still water cannot resist any amount of tensile or shear force, no matter how small.

Aquatic and amphibious creatures helps clarify the direction of biomimetic research into their robots. Researchers can select the most suitable biomimetic subjects based on the different jumping methods of these creatures, allowing for more targeted design and research. Additionally, this paper organizes and classifies existing bioinspired aquatic jumping robots, aiding researchers in understanding current research progress and challenges. This classification work not only helps identify gaps and challenges in the research but also provides valuable insights for designing more efficient robots.

The remainder of this work is organized as follows: Section 2 presents some representative aquatic and amphibious creatures that were searched for and classified by their jumping types, summarizing their aquatic jumping behaviors. Section 3 presents the impulsive aquatic jumping robots. Section 4 reviews the momentum aquatic jumping robots. Section 5 analyze the challenges of aquatic jumping. Section 6 prospects the future prospects. Section 7 draws the conclusion.

2. Jumping behaviors of aquatic creatures

Aquatic jumping is a survival mechanism for aquatic and amphibious creatures (Fig. 1(a)–(d)). This form of movement may be used for evading predators, catching prey, social interactions, entertainment, and even cleaning parasites. In 2019, Chang et al. [1] have classified the jumping behavior of these creatures in water into three modes (Fig. 2): (i) impulsive jumper; (ii) momentum jumper; (iii) mixed jumper.

Over the past few decades, numerous research teams have drawn inspiration from biological systems to develop a range of bioinspired aquatic jumping robots. For example, if the goal is to achieve efficient water surface jumping similar to that of a water strider [32], one could reference its mechanism of utilizing surface tension to jump. If the aim is to combine aquatic jumping

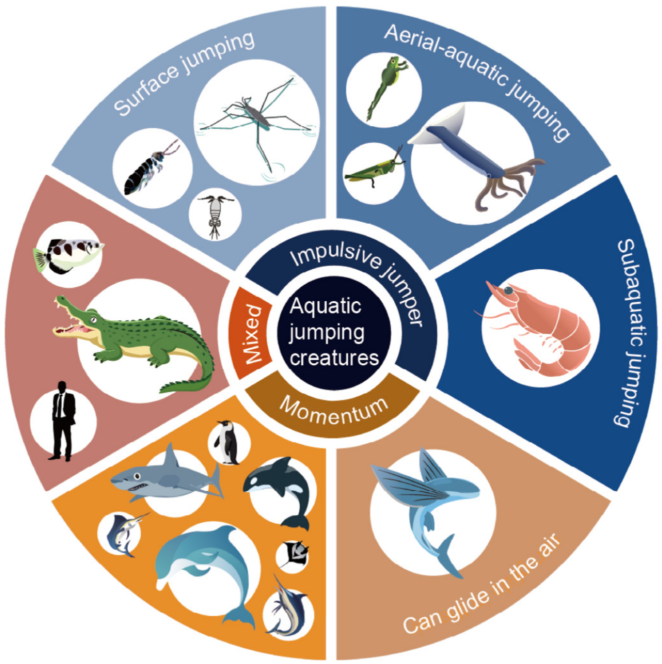

Fig. 2. Three movement modes of aquatic jumping creatures.

with aerial gliding for multimodal movement, a detailed study of the movement techniques of flying fish would be beneficial [33]. The Chinese rice grasshopper can immediately jump away as soon as it touches the water surface [5]. Additionally, the jumping capabilities of aquatic species such as sailfish, crocodiles [25,34,35] and shrimp [36,37] offer potential inspiration for the design of aquatic jumping robots, although no robots have been specifically designed or developed based on these species thus far. A comprehensive investigation of the jumping mechanisms of various aquatic species, combined with a systematic classification of their movement patterns, can enable future researchers to make more informed and precise decisions when selecting appropriate research subjects.

2.1. Impulsive aquatic jumping creatures

Impulsive aquatic jumping creatures, often characterized by their diminutive size, possess specialized adaptations that facilitate rapid and explosive propulsion through aquatic environments. They are characterized by efficient transient energy conversion and their principle of motion relies heavily on the explosive force of high speed impacts on the water surface. Impulsive jumpers are characterized by their quick jump, in which they initially start at rest close to the free surface and then flap their appendage with a single stroke [1]. Such creatures usually possess well-developed hindlimb muscles or other specialized propulsive structures to accumulate energy in the water and convert it into vertically oriented leaping kinetic energy instantly. This form of exercise is characterized by efficient energy use and rapid explosive power output, enabling high speeds and heights to be achieved in a short period of time, but is usually accompanied by greater energy expenditure.

Based on the differences in the movement processes of creatures during water jumping in water and air, as well as their starting positions for the jumps, they can be categorized into three jumping modes (Fig. 3(a)): (i) surface jumping behavior refers to the locomotion of creatures that leap on the water surface without being submerged. This jumping behavior relies not only on the structural characteristics of the creatures, such as a lightweight body and hydrophobic limbs, but is also influenced by surface tension. A typical representative of this behavior is the water strider [38], the springtail [39,40] and the Chinese rice grasshopper [5] which can jump continuously across the water surface; (ii) aerial–aquatic jumping behavior refers to the act of an organism jumping while fully or partially submerged in water, with the aim of escaping from the water into the air. This behavior may serve to evade predators or to capture prey. Water-dwelling frogs [2] and flying squids [41] are typical representatives of this behavior; they use their powerful muscles to either push off the water surface or expel water, generating reactive force to propel themselves out of the water; (iii) subaquatic jumping behavior refers to creatures being completely submerged in water while consistently remaining underwater during jumps. This means their movement only interacts with a single medium (water), unlike the previous two behaviors that involve interactions with both water and air. Shrimp are a typical example of this behavior, as most shrimp jump in water to evade predators [36,37].

Regardless of the mode of jumping behavior, it is closely related to water, which serves as its medium. The aquatic jumping behavior of creatures is not limited to a single mode [42], and this classification merely provides a preliminary division of jumping under conventional conditions. For example, shrimp can also leap into the air when close to the water surface, which is closely linked to the depth of their aquatic habitat and their living habits. This paper will not delve into extensive biological explanations but will focus on aquatic jumping behaviors with both water and air as mediums.

Water striders (Fig. 3(b)), small aquatic insects typically found in calm or slow-moving water, have a body mass of only a few tens of mg [43]. The lightweight body of them reduces the likelihood of sinking, and long slender legs distribute their weight better to prevent submersion while generating greater jumping force. Averaging 10–15 mm in length, water striders are capable of swiftly skating and leaping on the water [38]. This remarkable agility is primarily due to the dense array of microsetae on their legs, which maximizes the exploitation of water surface tension, ensuring buoyancy and facilitating rapid motion [44,45]. Furthermore, the robust musculature in their middle and hind legs enables rapid contraction and extension, generating sufficient thrust to propel them off the water. Consequently, water striders can reach a maximum speed of 1.5 m/s while skating and jump to heights exceeding 140 mm, all while supporting loads up to 15 times their own body weight [46].

Springtails (Fig. 3(b)), often characterized by their explosive jumping abilities, have traditionally been perceived as lacking in controlled takeoff and landing maneuvers. However, recent findings reveal that semiaquatic springtails can execute highly directional jumps, rapidly reorient themselves midair, and achieve near-perfect landings on water surfaces, demonstrating a remarkable level of control during locomotion [39]. During their aerial phase, these springtails adopt a distinctive U-shaped body posture, which optimizes aerodynamic forces and allows them to reorient in less than 20 ms — the fastest self-righting maneuver ever recorded in the animal kingdom. This rapid righting ability not only enhances their aerial stability but also contributes to efficient energy use during their leaps [47]. Moreover, these springtails reach horizontal velocities of up to 28 cm/s (280 BL/s), showcasing their impressive speed relative to their size. Their jumps generate a complex vortical wake, characterized by flow velocities of up to 50 cm/s and vorticity levels as high as 150 BL/s [48]. These findings underscore the unique biomechanical adaptations of semiaquatic springtails, highlighting their sophisticated aerial maneuverability and the aerodynamic principles

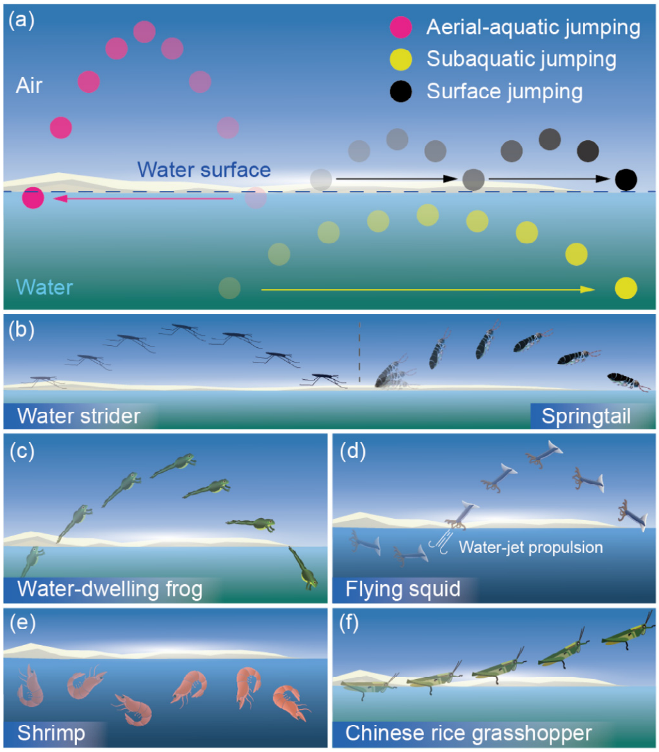

Fig. 3. Impulsive aquatic jumping creatures. (a) Three impulsive jumping modes. (b) Surface jumpers: water strider and springtail. (c) Aerial–aquatic jumper: Water-dwelling frog. (d) Aerial–aquatic jumper: flying squid. (e) subaquatic jumper: shrimp. (f) Aerial–aquatic jumper: Chinese rice grasshopper.

underlying their rapid and controlled movements across air and water interfaces.

Water-dwelling frogs (Fig. 3(c)) are quintessential amphibians known for their exceptional jumping abilities. Notably, they are capable of leaping from a floating position on the water surface to heights of up to 50 cm, often to capture flying insects above the water [2]. This impressive jumping performance is driven by the rapid contraction and violent extension of the hind limb muscles of frog, which instantaneously convert stored potential energy into kinetic energy. The force generated by the powerful thrust of the hind limbs propels the frog body out of the water, relying on both muscular strength and a streamlined body shape to minimize drag and optimize propulsion efficiency. The role of elastic energy storage within the plantaris longus tendon is critical in determining jumping performance [49]. They with shorter plantaris tendons may need to compensate by developing greater absolute muscle cross-sectional areas to achieve comparable levels of jump power [50]. Additionally, variations in the surface area of the frog webbed feet influence propulsion: greater webbing surface area increases drag between the feet and the water, thereby generating more propulsive force and minimizing backward slippage during aquatic jumping. These morphological and biomechanical adaptations are essential for maximizing jumping efficiency.

Flying squid (Fig. 3(d)) has an extremely high swimming speed in the ocean, capable of generating powerful bursts of acceleration, particularly during predation or escape responses [41]. They utilize water-jet propulsion to launch themselves out of the water, covering distances of approximately 26.4 to 33.5 m through the air before re-entering the water [51]. This form of propulsion enables the squid to generate substantial thrust in a brief period, allowing them to overcome significant drag forces and fluid viscosity [52,53]. The maximum speed of flying squid has been recorded at 11.2 m/s, equivalent to 43.9–49.7 BL/s, which is notably higher than the typical maximum of 25 BL/s achieved by most fish [54]. Flying squid employ multiple propulsion mechanisms, including the expulsion of water from their mantle cavity, which provides a rapid jet thrust [55], as well as the oscillation of their flexible carpal fins and rapid undulations of their paired fins [56,57]. These dynamic adaptations enable the squid to sustain high-speed movements both in water and during aerial gliding.

Shrimp (Fig. 3(e)) can jump in the water, typically using a subaquatic jumping behavior called “tail flip” to achieve rapid movement, primarily to evade predators. This ability is facilitated by their strong abdominal muscles, which allow them to quickly contract and extend, generating significant thrust. Additionally, they perform a strike motion with their raptorial limbs by storing energy in the elastic elements of their exoskeletons and releasing it instantaneously [36,37]. As a result, they can respond to danger very quickly and initiate a tail flip immediately upon sensing a threat. Moreover, their flexible body structure allows them to effectively perform the tail flip, swiftly changing direction and moving. They achieve ultrafast motion through latch-mediated spring actuation (LaMSA), a process that utilizes intricately coordinated springs and latches to temporarily store and then rapidly release elastic energy to propel motion [36,37]. In comparison to a snapping shrimp belonging to a simple pivot or slip class, those possessing a cocking joint can generate remarkably fast movement of the dactyl due to the latch-based energy storage and instantaneous release function [58]. Specifically, both the cocking joints utilize a torque reversal latch, and the resulting tip speed of the dactyl in the closing phase reaches approximately 32 m/s in water [59].

Chinese rice grasshoppers (Fig. 3(f)) usually rest on aquatic plants, such as rice, and can easily fall into the water when disturbed by strong winds. Upon accidentally falling into the water, they immediately jump to escape the water surface. They use their front and middle legs to push the water downwards, then they powerfully strike the water with the long tibiae of their hind legs, propelling themselves quickly out of the water surface at an angle [5].

Planktonic copepods display quick escape behavior when reacting to hydrodynamic disturbances [60,61]. *Acartia* spp. typically react to hydrodynamic disturbances within 4 ms, using several power strokes of their swimming legs. Each stroke and recovery lasts about 7 ms, with peak speeds frequently surpassing 500 mm/s, and speeds between strokes seldom dropping below 100 mm/s. The initial escape acceleration typically surpasses 100 m/s^2.

2.2. Momentum aquatic jumping creatures

Momentum aquatic creature typically exhibit characteristics of large size and mass, such as certain large fish or marine mammals. They possess robust muscular systems and good stamina, allowing them to generate sufficient momentum in water for high-speed, long-distance jumps, crucial for swiftly capturing prey or evading predators. Momentum jumpers first build up momentum [33,62], typically far from the water surface, by continuously stroking their limbs, to reach a steady swimming speed prior to exiting the water [1]. Through sustained momentum accumulation, these creatures are able to achieve smoother leaps out of the water, reducing energy loss and the effects of air drag. Momentum aquatic jumping creatures demonstrate the ability to achieve complex locomotion through progressive energy transformation [63], a mechanism that not only allows them to quickly reach the speed required to leap out of the water, but also provides them with the agility and endurance to do so in the air or across two environments.

These creatures are often capable of jumping at different depths within the water column, adapting to complex aquatic environments. Beyond hunting purposes, their jumping behavior may also serve defensive or social display functions; for instance, some dolphins and whales surface jump for communication or to assert dominance over rivals. These traits enable momentum aquatic creature to play diverse and vital roles within their ecosystems.

Dolphins are well-known for their remarkable intelligence and agility, which are often showcased through their dynamic aquatic jumping behaviors that also serve as a form of social communication. As typical members of the cetacean family, dolphins are highly proficient swimmers, capable of reaching speeds up to 11.1 m/s, equivalent to approximately 6 BL/s [62]. They are also capable of jumping over 5 m above the water surface, often executing complex aerial maneuvers such as flips and spirals [3,63]. The aquatic jumping capabilities of dolphins are largely attributed to their anatomical adaptations, particularly their flattened, horizontal caudal fins and vertically oscillating tails, which allow for exceptional control in pitch maneuvers. Different from fish that only swim, which primarily use lateral oscillation in the horizontal plane for high yaw maneuverability, dolphins employ vertical tail movements to navigate efficiently and execute sharp turns. Moreover, their flexible flippers and spinal flexibility further enhance their ability to maneuver in the horizontal plane, allowing them to maintain both speed and agility during complex movements [62]. These anatomical features not only enable high-speed swimming and jumping but also facilitate a variety of dynamic behaviors crucial for foraging, social interaction, and predator avoidance.

Flying fish are highly skilled at evading underwater predators, they accelerate to jumping out of the water, using their enormously exit speed to glide through the air [33]. They generate thrust by creating undulatory waves along their bodies and utilizing their caudal fins as oscillating propulsors, which enables rapid acceleration [4,64,65]. This dynamic propulsion allows them to reach burst swimming speeds of up to 10 m/s, or approximately 20–30 BL/s, providing the momentum necessary to breach the water surface [33]. Once airborne, flying fish can maintain speed and prolong their glide by employing a ''taxiing'' maneuver, where the caudal fin continues to oscillate against the water surface, further enhancing their velocity. The pectoral fins are then deployed for sustained gliding over long distances [21]. This gliding is facilitated by their streamlined body design and wing-like pectoral fins, similar to gliding during flight. During gliding, flying fish adjust their body posture and utilize the reactive forces of water to maintain stability and directional control. Finally, flying fish gently re-enter the water, typically head or belly first, to minimize impact and water entry. This jumping behavior is primarily used for hunting, escaping predators, and in reproductive behaviors, potentially for courtship displays and attracting mates, as well as for social communication. This remarkable capability to switch rapidly between aquatic propulsion and aerial gliding makes flying fish a compelling subject for studies on adaptive locomotion and biomechanical efficiency [66].

Penguins are required to leap out of the water for breeding and to rest on sea ice around Antarctica, where they maintain their body temperature and migrate. With their short hindlimbs and limited climbing ability, they must launch from the sea onto ice of varying thickness. Although the heights they achieve above the water surface are relatively modest, ranging from 0.2 to 0.46 m, their recorded exit speeds surpass the typical 2 m/s, reaching between 2.5 and 3 m/s. This increase in velocity is closely correlated with the speeds necessary to overcome gravitational forces at these heights. It has been observed that flipper of penguin activity ceases some distance below the water surface, suggesting that buoyancy plays a crucial role in achieving the higher exit speeds [67].

Manta rays exhibit a distinctive aquatic jumping behavior characterized by their rotational swimming posture [68]. As they approach the water surface, they increase both their rotational speed and swimming velocity, enabling them to breach the surface impressively. These jumps can reach heights of 1.5 to 4 m and are sometimes accompanied by aerial flips, with a notable splash upon reentry. These behaviors serve several purposes, including foraging, mating, evading, communication, protecting the cubs, and removal of parasites. Manta rays propel themselves vertically upward with significant speed, often landing with their ventral side facing downward. Despite their precision, they occasionally experience rebound and twisting effects before reentering the water [69].

In addition to the aforementioned organisms, such as sharks [70,71], whales [72,73], sailfish, swordfish, and others are also capable of executing impressive leaps from the water.

2.3. Mixed aquatic jumping creatures

Mixed jumping refers to aquatic creatures combining multiple techniques or strategies during their jumping process to enhance their movement efficiency and adaptability to the environment [70,84,85]. This jumping method is based on the flexibility of the body structure and functions of animals, effectively integrating two main types of jumping techniques: impulse jumping and momentum-based jumping. In practical life, aquatic creatures of this type often do not rely solely on a single jumping technique. Instead, they flexibly choose and combine these two techniques based on specific circumstances and behavioral needs, to meet various survival challenges and behavioral requirements [73]. Humans, archer fish [86], and crocodiles [25] are notable examples of mixed jumpers.

The archer fish is a species of freshwater fish inhabiting tropical regions, renowned for its distinctive predatory abilities [86]. Its most notable characteristic is its capability to shoot down airborne insects or small animals perched on trees by precisely controlling and expelling jets of water from below the surface. This skill highlights the exceptional visual acuity and oral precision of them [87,88]. Additionally, they can swim rapidly underwater to build momentum and then use swift body movements to leap out of the water. It also employs its tail, along with its anal, pectoral, and dorsal fins, to generate sufficient thrust from a stationary position for both predation and evasion of predators [24,89]. Such leaping behavior may facilitate capturing insects near the surface or enable rapid escape from threats. During the breeding season, this jumping behavior might also function as a courtship display to attract mates.

Crocodile is renowned for their remarkable jumping abilities, which are enabled by two primary mechanisms: static attack jumps and momentum-accelerated jumps. Static attack jumps depend on the powerful tail muscles and overall body strength of the crocodile. In this mechanism, the crocodile captures prey near the edge of water by rapidly leaping from the water and delivering a strong tail thrust [25,90,91]. In contrast, momentum-accelerated jumps utilize the momentum gained while swimming. As the crocodile approaches the surface of water, it propels itself upward with a swift tail swing and a powerful thrust [34,35]. This technique enhances both the height and distance of the jump, thereby improving agility in capturing prey.

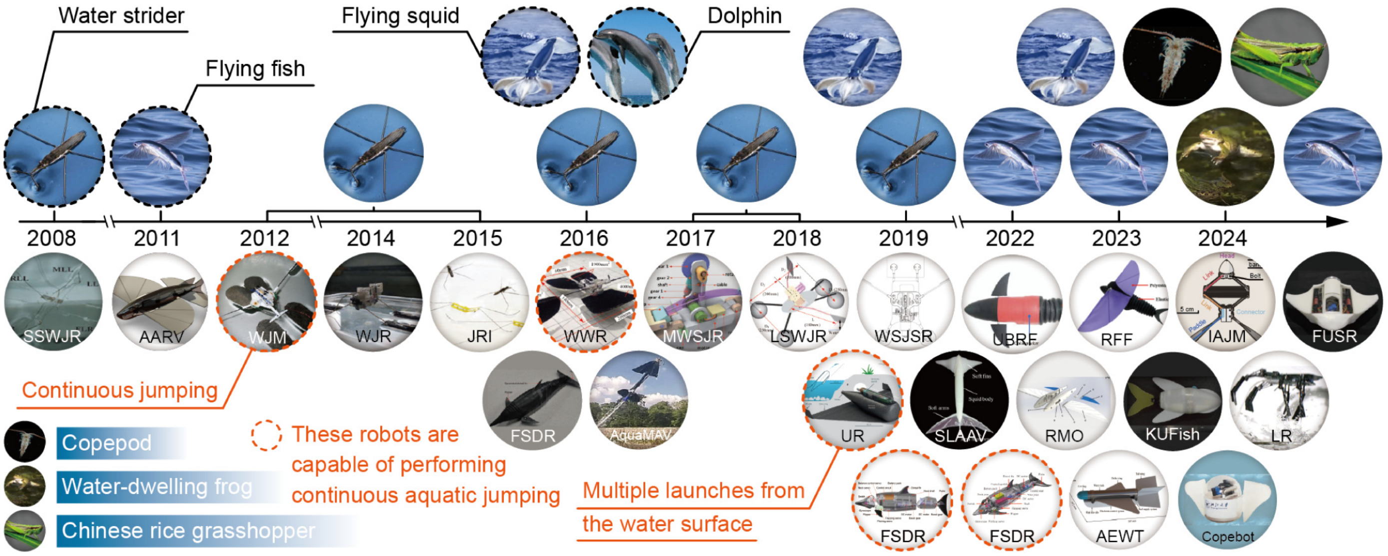

Fig. 4. The chronicle of aquatic jumping robots from 2008 to 2024. The figure presents a chronological sequence of representaive bioinspired aquatic jumping robots, enabling a visual assessment of their advancements and modifications over the yeans. Furthermore, it highlights achievements reached during this progression.

2.4. Other water–air cross-domain locomotion creatures

In addition to the aforementioned creatures that can perform aerial–aquatic leaps, there are other creatures capable of aerial–aquatic movement. For example, the gannet can dive from the air into the water, achieving cross-domain movement.

Aerial plunge-diving is a highly specialized foraging strategy employed by gannets, characterized by its speed and high efficiency, with prey capture success rates exceeding 50% [92]. Gannets possess morphing wings capable of generating propulsion both in air and underwater. During a dive, their wings partially fold with the hand wings positioned backward to reduce drag [42]. Upon locating prey while hovering at altitude [32,93,94], they initiate a rapid descent using gravitational potential energy, coordinating wing folding with precise control of their neck, feet, and tail to adjust their dive trajectory [95]. They enter the water at high speed, resembling arrows striking a target, to capture their prey underwater with accuracy [96]. After seizing their prey, gannets quickly return to the surface, aided by the buoyancy of their air-filled, hydrophobic feathers [97], as well as propulsion from flipper movements and regular intermittent body oscillations [98].

3. Impulsive aquatic jumping robots

The design intention of impulsive aquatic jumping robots are to enable them to generate sudden energy release when on the water surface, underwater, and partially submerged, achieving water-to-air cross-domain jumps. Jumping in water requires the end effector of robots to create a reaction force against the water, allowing it to obtain the kinetic energy needed for jumping. Under the same force, the kinetic energy generated in water is typically lower than that on land because water is a fluid, and the robot encounters resistance while splashing, with water adhering to it and increasing its mass (except for robots that jump using liquid surface tension), which affects jumping performance. This type of robot has the following characteristics:

(1) *Waterproof design:* Most jumping robots powered by motors and equipped with circuitry need waterproof designs to prevent water ingress that could cause damage.
(2) *Jumping mechanism:* They usually uses springs or other energy storage devices to quickly release energy.
(3) *Stability and control:* It needs to maintain stability both on the water surface and in the air, and be able to precisely control the direction and distance of their jumps.
(4) *Water adaptability:* The design must consider the buoyancy and resistance of water to ensure effective aquatic jumping.

(5) *Light weight:* This design enables them to achieve jumping with lower inertia and a higher energy efficiency ratio.

In recent years, many researchers have conducted in-depth studies on water striders, flying squids, copepods, frogs, flying fish, and dolphins, leading to the development of a series of impulsive aquatic jumping robots (Fig. 4). Water striders and copepods inhabit the water surface, with their superhydrophobic legs adapted to surface movement; flying squids achieve underwater jumping through a water-jet propulsion movement pattern; and water-dwelling frogs have evolved webbed feet that provide greater lift in the water. These creatures offer valuable insights for the design of related robots (Fig. 5).

3.1. Inspired by water striders

Water striders (Fig. 5(a)) can easily jump on the water surface, primarily due to their light body weight and superhydrophobic legs, which allow them to be supported by surface tension at the tarsal joints (the proximal segment of the foot of arthropod). The speed of the water striders and coordination enable them to leave the water surface with high velocity and at precise angles through coordinated leg movements. In recent years, researchers have drawn inspiration from these characteristics of the water strider, particularly its light weight, superhydrophobic leg design, and continuous jumping ability, to develop a series of biomimetic robots [20,28]. The motion modes of these robots are primarily divided into two categories [46]: (i) skating on the water surface; (ii) aquatic jumping.

In 2003, Hu et al. designed a robot called Robostrider (RoboS [99]), measuring 9 cm in length and weighing only 0.35 g. The robot is powered by an elastic thread (spring constant of 310 dynes/cm) that runs through its body and is connected to the driving legs via a pulley. In 2007, Ji et al. proposed a robot (WSR [100]) that, after optimization, uses Hydrophobic Teflon coated wire legs and a carbon fiber plate for the body. Utilized a T-shaped actuating mechanism composed of three piezoelectric

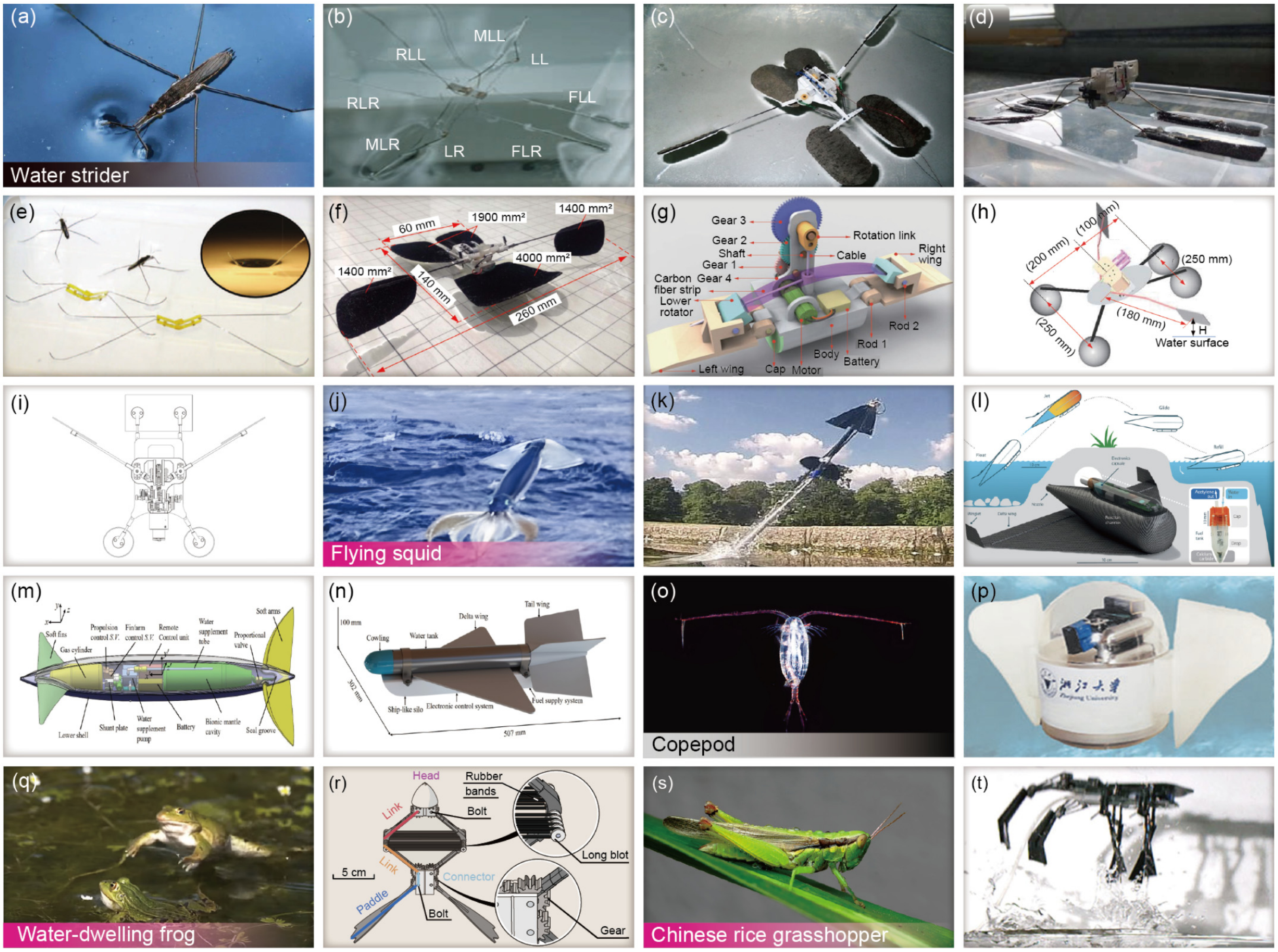

Fig. 5. Bioinspired impulsive aquatic jumping robots. (a) Water striders. (b) SSWJR [74], Copyright©2008, IEEE RAS & EMBS BioRob. (c) WJM [75], Copyright©2012, ACS applied materials & interfaces. (d) WJR [76], Copyright©2014, IEEE ICIA. (e) JRI [20], Copyright©2015, Science. (f) WWR [17], Copyright©2016, Bioinspiration & biomimetics. (g) MWSJR [77], Copyright©2017, IEEE RA-L. (h) LSWJR [7], Copyright©2018, IEEE RCAR. (i) WSJSR [78], Copyright©2019, China Patent. (j) Flying squid, Copyright©2019, IEEE. (k) AquaMAV [79], Copyright©2016, IEEE/ASME TMech. (l) UR [80], Copyright©2019, Science Robotics. (m) SLAAV [19], Copyright©2019, IEEE ICRA. (n) AEWT [81], Copyright©2023, IEEE ROBIO. (o) Copepod [82], Copyright©2024, Nature Climate Change. (p) Copebot [83], Copyright©2023, Soft Robotics. (q) Water-dwelling frog, Copyright©2017, BBC. (r) IAJM [18], Copyright©2024, IEEE RA-L. (s) Chinese rice grasshopper. (t) LR [5], Copyright©2024, PNAS.

unimorph as actuators. In 2010, Wu et al. designed a Water Dancer II (WDII [101]). The weigh is 3.3 g and body length is 180 mm. The WRII was powered by two motors, utilizing surface tension to achieve variable speed movement and turning, with a maximum speed of 20 cm/s.

In 2008, Shin et al. designed a small-scale water jumping robot (SSWJR [74]) capable of vertical jumping in water. The SSWJR (Fig. 5(b)), with a total weight of 0.51 g, achieved a maximum jump height of 26 mm in water. The SMA spring actuators that release the latch are driven by MOSFETs, and the initial force is 0.92 mN. Its maximum jump height on water was only 26% of its maximum jump height on a rigid surface.

In 2012, Zhao et al. designed an 11 g water-Jumping micro-robot (WJM [75]) that was capable of continuous aquatic jumping, reaching a maximum height of 140 mm. The WJM (Fig. 5(c)) used a motor-driven gear mechanism to deform a spring and store energy. Although this robot weighed approximately 1100 times more than a water strider, it effectively performed continuous impulsive aquatic jumping tasks in water.

In 2014, Yan et al. designed a water-jumping robot (WJR [76]) with excellent aquatic jumping performance through structural optimization. The WJR (Fig. 5(d)) not only glided on the water surface but also performed aquatic jumping. With a body length of 105 mm and a weight of 5.5 g, it used a DC motor as its actuator, achieving a water jumping height of 223 mm.

In 2015, Koh et al. built a 68 mg at-scale jumping robotic insect (JRI [20]) and verified that it impulsive aquatic jumping with maximum momentum transfer. The catapult mechanism of the JRI used composite materials and planar shape memory alloy (SMA) as actuators. The driving forces for their jumping robot can be varied by changing actuator stiffness and leg length. In their models, the initial energy stored in the actuator is 0.304 mJ and the jumping kinetic energy of the robot jumping on water is 0.095 mJ (31.3%), whereas the vibration kinetic energy is 0.193 mJ (63.5%). The research reveals the hydrodynamic phenomena behind semi-aquatic arthropods during water-surface jumping and offers new insights for replicating this ability in artificial systems (Fig. 5(e)).

In 2016, Yang et al. designed a water-walking robot (WWR [17]) mimicking the jumping abilities of water striders, carefully engineering sits center of gravity to ensure stable jumping. The robot weighs approximately 10.2 g and is capable of continuous jumping on the water surface with a cycle time of 4.2 s, achieving a maximum jump height of 120 mm and a distance of 410 mm.

The robot is powered by springs, and different spring stiffnesses of 0.08, 0.09, and 0.10 N/mm were tested. Experimental results indicate that the spring with a stiffness of 0.10 N/mm achieves the best jumping performance. The DC motor rotates continuously, resulting in the continuous jumping of the robot. The direction of the actuating legs hitting the water surface can be conveniently adjusted by changing the jumping angle between the swing base and the base.

In 2017, Jiang et al. designed a 12.5 g miniature water surface jumping robot (MWSJR [77]) to mimic the aquatic jumping of water striders. The robot was designed with a carbon fiber strip (CF) for energy storage, two wings to flap the water surface, a hollow body to initially support the MWSJR (Fig. 5(g)), and an intermittent gear train to accumulate and release energy. By adding super hydrophobic materials to the body and two wings, the robot achieved a 20% to 40% increase in aquatic jumping. Finally, experiments showed that the robot could achieve an aquatic jump height of 9.5 cm. As the MWSJR did not possess self-recovery capability, continuous jumping functionality had not yet been achieved.

In 2018, Yan et al. designed a large-scale robot (LSWJR [7]) weighing up to 650 g, utilizing torsion springs as actuators. The core of the research involved constructing a dynamic simulation model of the robot using ADAMS dynamic analysis software and analyzing the key factors affecting its jumping performance and posture. By adjusting the structural parameters, the jumping height of LSWJR was optimized. This work focused on optimizing the parameters of LSWJR (Fig. 5(h)), and aquatic jumping experiments have not yet been conducted.

In 2019, Yan et al. developed a water surface jumping and sliding robot (WSJSR [78]), which included key components such as a water surface support system, main support frame, drive system, pitch adjustment mechanism, and energy storage spring. This robot (Fig. 5(i)) was capable of performing both jumping and sliding movements on the water surface, using a combination of motor and springs for propulsion. Additionally, it was equipped with sensors, making it suitable for tasks such as exploring unknown or monitoring water quality.

3.2. Inspired by flying squid

The flying squid (Fig. 5(j)) uses water-jet propulsion for rapid underwater ejection to take off continuously on the water surface [102,103]. Underwater soft robots can effectively utilize this approach to achieve comprehensive omnidirectional motion [6]. Some robot designs leverage this principle, generating thrust through sudden bursts, thus enabling cross-medium jumps between water and air [79]. The body proportions and mantle cavity size of squid can inform the design of impulsive aquatic jumping robots powered by water-jet propulsion, in terms of size, layout and volume of the tank [81,104].

In 2016, Siddall et al. introduced a jet-propelled AquaMAV (Fig. 5(k)) capable of leap-glide jumps from water, as well as a planar trajectory model that can accurately predict escape trajectories in water [79]. The 100 g robot can leap from beneath the water surface, unfurl its wings, and glide over the water, achieving speeds above 11 m/s. By mimicking the water-jet propulsion of squid, the AquaMAV uses CO_2 powered water jet for aquatic propulsion, driven by custom-shaped shape-memory alloy gas release mechanisms. In this study, the ejection speed of the AquaMAV is sufficient for it to continue gliding in the air after launch. However, due to open-loop control, even minor disturbances can cause changes in the pitch of the vehicle.

In 2019, zufferey et al. present an untethered robot (UR [80]) that is capable of multiple launches from the water surface and of transitioning from jetting to a glide (Fig. 5(l)). The 160 g robot could achieve a flight distance of 26 m using 0.2 g of calcium carbide. Aquatic jump-gliding power is generated by reacting calcium carbide powder with environmental water to produce combustible acetylene gas, enabling the robot to quickly attain flight speed from the water. This mode of movement is similar to the water-jet propulsion of flying squids, featuring a high energy efficiency for propulsion and enabling continuous impulsive aquatic jumping.

In 2019, Hou et al. demonstrated a prototype [19] weighing 1.12 kg and with a total length of 78 cm, featuring pneumatically driven soft fins and arms that can be folded and spread. The soft morphing SLAAV has three modes: slow underwater swimming, cross-medium jetting flight, and aerial gliding. The pneumatic system powers both the jet propulsion and the soft morphing actuators. This work presents the experimental demonstration of slow underwater swimming jet propulsion for the SLAAV (Fig. 5(m)). Additionally, it verifies the advantages of the soft-bodied squid prototype with a variable structure design through wind tunnel and underwater towing experiments. In 2023, Wang et al. developed a squid-inspired water-jet structure (CM-jet structure [105]). They designed two series of experiments compared the thrust performance of C-jet and CM-jet structure actuators, and theoretical models for both structures were developed based on these findings. This work provides a design for a propulsor that broadens the direction of water-jet acceleration for aquatic impulsive jumping.

In 2023, Wang et al. developed and fabricated a novel aerial–aquatic water-jet thruster that utilizes butane and oxygen to realize explosive water-jet propulsion. An unit butane cell and oxygen can sustain over 50 explosions without the need for component replacement [81]. we designed the prototype model (AEWT) as shown in Fig. 5(n).

3.3. Copebot inspired by copepod

In 2023, He et al. introduced the design and development of combustion-driven underwater soft robot prototypes (Fig. 5(p)), called the “copebot”. Mimicking copepods (Fig. 5(o)), this robot can precisely reach predefined nearby locations with a single curved leap. Due to an enhanced thrust force transmission system that generates a significant initial acceleration peak (850 body length$\cdot$s^{-2}), the copebot is eight times faster than earlier combustion-driven underwater soft robots and capable of executing a full 360° rotation during aquatic jumps [83].

3.4. IAJM inspired by frog limbs

In 2024, Dong et al. designed the first frog-inspired (Fig. 5(q)) aquatic jumping mechanism [18], known as the impulsive aquatic jumping mechanism (IAJM). The mechanism (Fig. 5(r)) was inspired by the amphibious frog (*Euphlyctis hexadactylus*) from Southeast Asia [28]. The mechanism includes a 1-DOF four-bar linkage, a streamlined head, frog-inspired paddles, and an energy storage unit made of rubber bands. The prototype, constructed from polylactic acid with a total weight of 37.6 g, derives its energy from the elastic potential generated by the deformation of rubber bands, providing 2.17 J of energy. Experimental results demonstrated that, under this energy, the IAJM achieved a jumping height of 3.85 m on land, while in water, the height was limited to 60.5 cm, reflecting an energy loss of 85.62% during aquatic jumping.

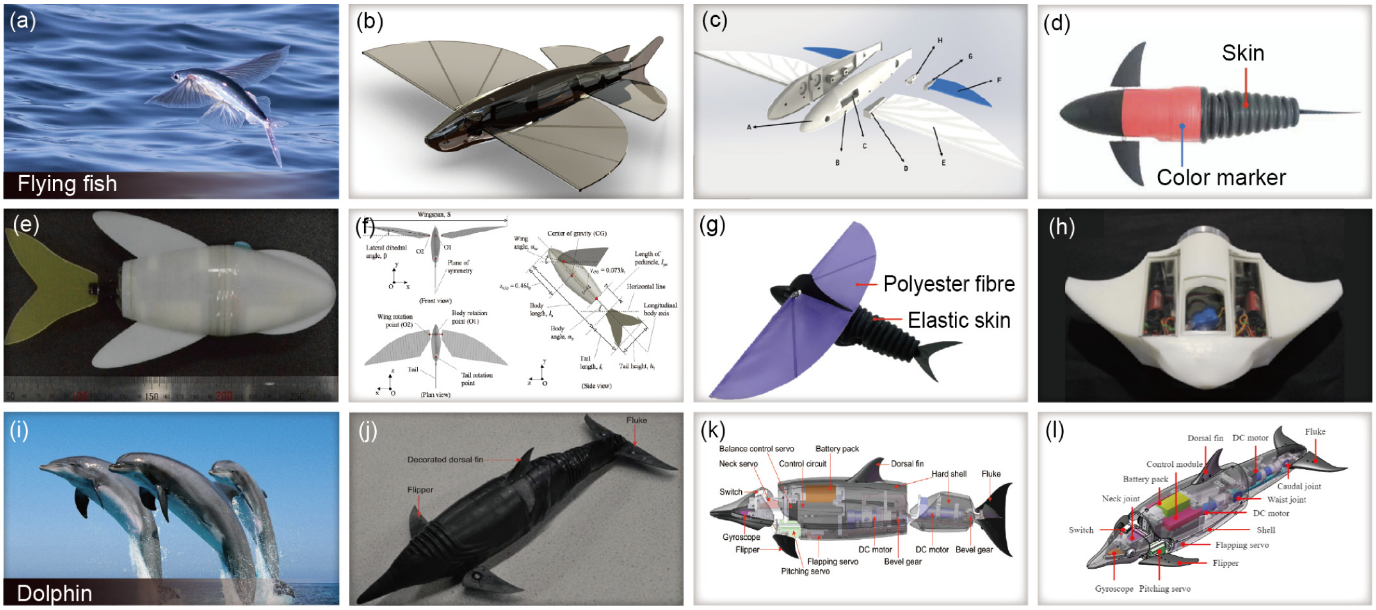

Fig. 6. Momentum aquatic jumping robots. (a) Flying fish, Copyright©2011, BBC. (b) AARV [106], Copyright©2011, OCEANS'11 MTS/IEEE KONA. (c) RMO [66], Copyright©2022, ICB. (d) UBRF [107], Copyright©2022, IEEE TMech. (e) KUFish [108], Copyright©2023, Ocean Engineering. (f) KUFish with wings [109], Copyright©2023, Ocean Engineering. (g) RFF [21], Copyright©2023, Bioinspiration & Biomimetics. (h) FUSR [110], Copyright©2024, Journal of Field Robotics. (i) Dolphin, Copyright©2021, BBC. (j) FSDR [62], Copyright©2016, IEEE TMech. (k) Mechanical structure of FSDR [22], Copyright©2019, IEEE TMech. (l) Prototype leaping robot dolphin [111], Copyright©2023, Biomimetics.

3.5. LR inspired by chinese rice grasshopper

In 2024, Song et al. designed a legged robot (LR [5]) inspired by the Chinese rice grasshopper (Fig. 5(s)) to experimentally validate biological findings. The limbs of LR (Fig. 5(t)) are made of carbon fiber sheets, while the torso is constructed from a composite structure of carbon fiber sheets and foam boards. A specialized pneumatic trigger mechanism has also been designed to control the movements of each limb. Their limbs can perform actions with different sequences and intensities, ultimately achieving various forms of surface movement, including forward, upward, and backward jumping.

4. Momentum aquatic jumping robots

Momentum aquatic jumping robots typically mimic creatures that can rapidly accelerate in water and generate significant thrust, such as flying fish [21,31,106,108], dolphins [62], and swordfish. The core design of these robots focuses on using this thrust to propel them out of the water, showcasing exceptional jumping capabilities. However, even before achieving the ability to jump, these robots generally possess excellent swimming performance, enabling them to move efficiently in water [62]. This not only enhances their jumping performance but also improves their overall maneuverability in aquatic tasks. This type of robot typically has the following characteristics:

1. *Fast swimming speed:* To enable the robot to perform an aquatic jump, it must gain sufficient underwater speed and momentum to overcome gravity when leaving the water [62]. The thrust is typically generated by the tail, which creates propulsion through rapid swinging movements to paddle the water, with the tail driven by a motor.
2. *Bionic Design:* Momentum aquatic jumping robots often mimic the form and movement patterns of natural creatures (Fig. 6). This mode of movement is better suited to aquatic environments, avoiding risks such as algae entanglement or the involvement of aquatic creatures that might be encountered by propeller-driven vessels.
3. *High robustness:* Controlling the swimming speed, water exit angle, and posture is a complex task, and these factors directly determine whether the robot can leap out of the water with optimal efficiency. Research on propulsion modeling [112,113], thrust optimization [114], and pitch and yaw maneuvering control [115] can significantly enhance the robustness and performance stability of the robot.
4. *Multimodal motion:* Before achieving the aquatic jumping, these robots may already demonstrate exceptional performance in various aquatic movement modes, including gliding, swimming, snorkeling, and turning. In floating and gliding modes, the robot can achieve prolonged, stable movement with minimal energy consumption.

4.1. Inspired by flying fish

Research on robotic fish began in the 1900s century, driven by the goal of developing underwater propulsion technologies that surpass the efficiency of traditional methods. Additionally, between 1900 and 1930, flying fish were also studied as potential models for flight systems and airplane design [116]. Biomimetic swimming and aquatic jumping methods may effectively address some of the issues caused by propellers. As a marine fish, the flying fish has evolved unique physiological structures to adapt to its oceanic environment. With a powerful tail, flying fish can achieve a burst swimming speed up to 10 m s^{-1} (about 20–30 BL/s) to aquatic jumping [33].

The current research on bionic flying fish robots [31,106,108] mainly focuses on mimicking the unique movement of flying fish as they leap out of the water and glide through the air. By precisely replicating the wing and body structures of flying fish, these robots achieve high efficiency and flexibility in cross-medium movement. When gliding in the air, the robots can conserve energy, while maintaining speed and stability when moving in water, making them highly advantageous for applications in detection, monitoring, and military operations [117]. Future development may include further optimizing the efficiency of transitioning between gliding and propulsion in water, enhancing endurance, and achieving autonomous navigation in complex and variable environments. Additionally, with advancements in material science and bionic engineering technologies, bionic flying fish robots are expected to play a role in a broader range of fields, such as marine ecological research, environmental protection, and underwater archaeology, enabling longer-distance and more intelligent task execution.

In 2011, Gao et al. explored the design of an Aerial–aquatic robotic vessel (AARV [106]) inspired by flying fish. This compact robot (Fig. 6(b)) possesses the capability to swim and glide in the air above water. Its mechanical design concept is grounded in the principles of biomimetics, with a body length of 25 cm, a body volume of 145 cm^3, and a weight of approximately 145 g. This study begins with a brief review of research on robotic fish and hydrodynamics, followed by an in-depth analysis of the mathematical theories pertinent to the project. Theoretical calculations indicate that it is reasonable to require a muscle power density of 2810 W/kg for a flying fish to swim at 10 m/s. Through experiments, analysis of water exit forces, and lift force analysis, they determined that the robot needs a small and compact design and must achieve a high water exit speed of at least 10 m/s to ensure stable flight in the air. Finally, the actuator of this robot and the control algorithm are still in the conceptual design stage.

In 2022, Saro-Cortes et al. presented an Robotic model organism (RMO [66]) inspired by flying fish, with easily adjustable design parameters, and studied the aerodynamics of their pelvic fins using wind tunnel experiments (Fig. 6(c)). The findings indicated that placing the pelvic fins directly behind the pectoral fins and using more positive pitch angles led to optimal aerodynamic efficiency but compromised stability. The optimal pelvic fin configuration varied depending on the locomotion stage of the flying fish, whether gliding, taxiing, or taking off. This research primarily focused on the gliding phase of flying fish after aquatic jumping, providing unique insights and experimental evidence into the physical principles of flying fish locomotion and design inspiration.

In 2022, Chen et al. reported an untethered bioinspired robotic fish (UBRF [107]). The robot (Fig. 6(d)) not only possesses high-speed swimming capabilities but also has high maneuverability and can perform aquatic jumping. To enhance the explosive propulsion of robotic fish, a new actuation system with high power output and compact structure was developed. The dynamic model shows that the compliant joint modulates power to the caudal fin, improving peak thrust and velocity during the return stroke. Experimental results validate this design, with the robotic fish achieving speeds of up to 3.8 BL/s. This represents a dramatic improvement over rigid joint systems, which reach speeds of 1.2 BL/s and distances of 141.2 m—a 70.6% increase. The compliant mechanism also supports high-speed swimming and high maneuverability, demonstrated by an agile front flip with a radius of 0.4 BL and an average angular velocity of 439°/s. Notably, the robotic fish can leap completely out of the water with a simple control strategy.

In 2023, Pham et al. made their first effort to eventually mimic flying fish by developing a robotic fish capable of swimming fast and leaping out of the water, named KUFish [108]. Swimming tests showed that the KUFish (Fig. 6(e)) could cover 0.68 m and leap out of the water at a exiting speed of 1.35 m/s (6.1 BL/s) within 0.68 s after release. KUFish achieved a tail oscillation frequency of 11.35 Hz using a DC motor to drive the tail-beating mechanism. This work also validated the effectiveness of the aquatic jumping robot design using the Froude number. Additionally, the established two-dimensional dynamic model accurately reflects the swimming characteristics of KUFish, demonstrating high precision. Although the robot can currently fully leap out of the water, the relatively low exit speed still does not meet the requirements for gliding in the air. The high-frequency tail oscillation may result in different aquatic jumping and reentry postures. Nguyen et al. through numerical simulations [109], identified the conditions for generating sufficient lift, overcoming drag, and providing additional vertical force. They found that the design margins of the wing and body angles are large enough to accommodate up to an 82% increase in weight. Although the KUFish cannot take off at lower airflow speeds, there may still be a chance for takeoff by increasing the wing and body angles (Fig. 6(f)).

In 2023, Chen et al. present a 26.4 cm, 360 g unique aquatic–aerial robotic flying fish (RFF [21]), featuring powerful propulsion and a pair of morphing wing-like pectoral fins for cross-domain motion (Fig. 6(g)). To further explore the gliding mechanism, a dynamic model with variable sweep angle was established. Furthermore, by modulating the morphing pectoral fins, a double DQN-based control strategy is proposed to optimize the gliding distance. Simulation results showed that the optimized control strategy achieved maximum gliding distance at various emergence angles, with a distance of 10.83 m at an emergence angle of 52.5°. The robot is capable of performing aquatic jumping, achieving 'fish leaping and wing spreading' cross-domain locomotion with an exiting speed of 1.55 m/s (5.9 BL/s) and an exit time of 0.233 s. However, because of limitations in water exiting speed, the robot has not yet achieved stable gliding in the air for an extended period after emerging from the water.

In 2024, He et al. created a leaping fishbot (Fig. 6(h)), a soft underwater robot inspired by flying fish (FUSR [110]), capable of aquatic jumping and gliding on the surface using a hybrid combustion–propulsion actuation system. The fishbot employs a transient driving method, where a premixed oxygen–propane gas generates a rapid thrust to propel the robot out of the water at high speed, while attached jet propellers provide continuous propulsion, allowing it to swim steadily on the water surface.

4.2. Inspired by Dolphin

As a marine mammal, dolphins (Fig. 6(h)) have evolved excellent adaptations to their environment, allowing them to swim at speeds of up to 11.1 m/s and even leap about 5 m above the water surface. The key to momentum aquatic jumping for a dolphin robot lies in its swimming speed and the precise control of its exit angle [62]. As mechatronic systems and control algorithms advance, the speed and maneuverability of robotic dolphins also improve. Developing a bioinspired dolphin robot can serve as an experimental platform for studying biological dolphins and can also be applied to practical uses such as water quality monitoring [115,118].

In 2016, Yu et al. built a fast-swimming dolphin robot (FSDR [62]) with commercially available actuators and a power supply [119], which can leaps with a length-specific speed of over 2.3 body lengths per second, and an emergence angle ranging between 35 and 60°. The FSDR (Fig. 6(j)) has a body length of 72 cm, weighs 4.7 kg, and can reach a swimming speed of up to 2.85 BL/s. It is also capable of executing an aquatic jump at a exit speed of 2.35 BL/s. In 2019, Yu et al. successfully enabled FSDR (Fig. 6(k)) to perform three consecutive momentum-based aquatic jumps in a closed pool for the first time [22]. In 2023, Yu et al. study primarily aims to quantify the leaping motion of a self-propelled bionic robotic dolphin (Fig. 6(l)) through a combination of numerical and experimental approaches. A dynamic model was developed for hydrodynamic analysis considering the variable submerged portion, with experimental data used to identify hydrodynamic parameters and validate the accuracy of model. A quantitative analysis of leaping motion was conducted, showing

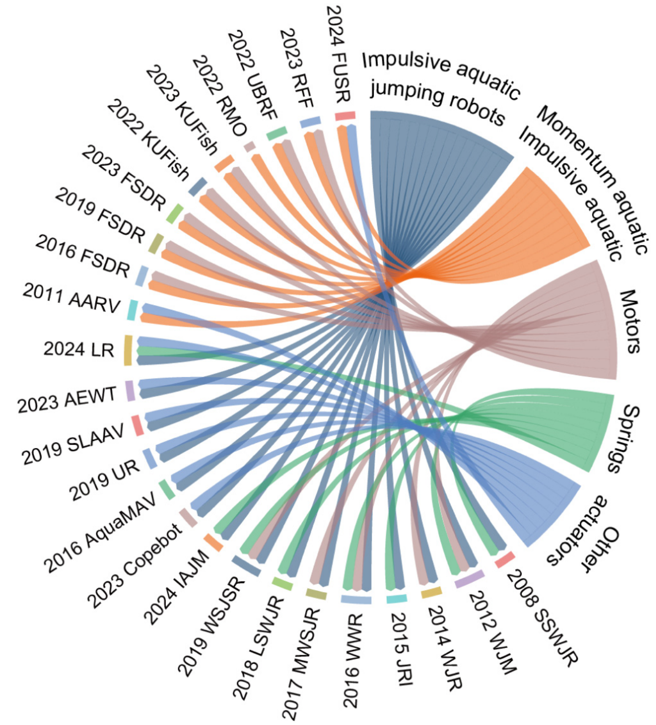

Fig. 7. Classification of impulsive and momentum aquatic jumping robots.

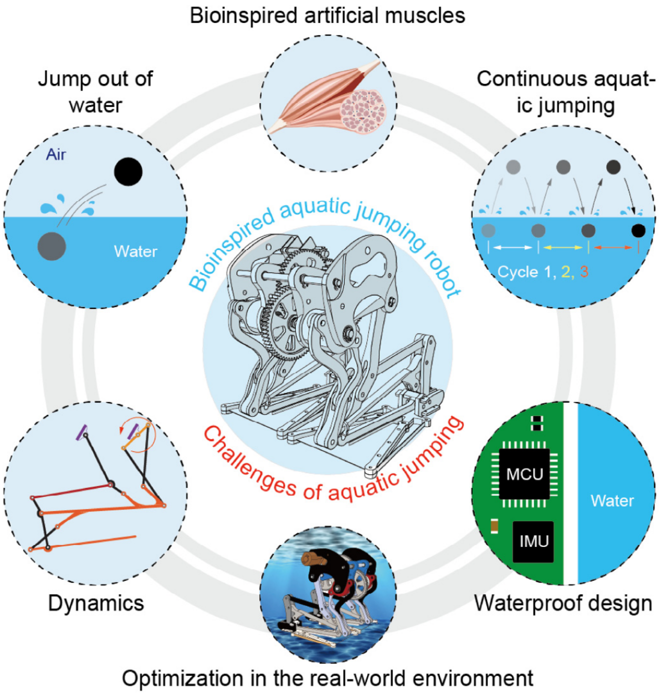

Fig. 8. The many challenges of aquatic jumping.

that as the exit velocity and angle increase, the maximum height of the center of mass also rises. Additionally, a smaller exit angle typically demands a significantly higher exit velocity to achieve full exit motion [111].

5. Challenges of aquatic jumping

Water–air cross-domain continuous jumping is a complex form of locomotion, involving motion control across distinct media and the physical mechanisms. This process requires overcoming significant physical discrepancies between the media, especially in terms of density and viscosity [120]: (i) when the robots leaps out of water, it must generate sufficient mechanical energy to viscous drag of counteract water and inertial forces, imposing stringent demands on the propulsion system and energy allocation; (ii) Upon entering the air, the robots must quickly adjust to the rapid reduction in drag and the transition in environmental conditions, which places higher demands on the attitude control system and structural stability. During the aerial phase, aerodynamic drag becomes the primary influencing force, requiring the system to achieve an effective dynamic balance amidst varying drag forces to maintain a stable flight trajectory; (iii) as the robots reenters the water, it must adapt once again to the drag of fluid environment and viscosity to minimize impact forces and avoid structural damage or system instability. In summary, the key technical challenge of water–air intermedium continuous jumping lies in a deep understanding of the physical properties of both media, optimizing fluid dynamics, structural mechanics, and motion control to ensure dynamic stability during water exit, aerial flight, and reentry.

One of the main challenges faced by bioinspired aquatic jumping robots is how to effectively jump out of the water and achieve better aquatic jumping performance. In this process, an efficient actuator is key to obtaining greater momentum. Biological muscles typically possess high energy density; therefore, designing a bioinspired artificial muscle could potentially enhance the energy efficiency ratio of the actuator to some extent. Additionally, achieving continuous aquatic jumping motions in impulsive jumping robots presents challenges, as they have stricter requirements for system compactness. At the same time, waterproof design is crucial for bioinspired aquatic jumping robots, as it directly affects their ability to operate for extended periods in water and to prevent water erosion. Theoretical research is beneficial for fundamentally addressing the optimization issues faced by robots in aquatic environments. Finally, it is essential to consider experiments in real-world environment and to continuously optimize the robots to improve their overall aquatic jumping performance (Fig. 8).

5.1. *Jump out of water*

The challenges of enabling an aquatic jumping robots to leap out of water mainly focus on the following aspects:

(1) *Power output and thrust matching:* For the robot to jump out of the water, it needs to generate sufficient upward thrust to overcome both water resistance and gravity. Given the higher density of water, efficiently converting power in the water medium into the thrust required for jumping [33].
(2) *Coordination of multi-modal movements:* Aquatic jumping robots typically need to possess the ability to propel underwater and jump out of the water. This requires the propulsion system to switch and adapt efficiently across different media (e.g., water and air), ensuring stability in flight or floating after breaking the water surface [121].
(3) *Transition between hydrodynamics and aerodynamics:* Surface tension and hydrodynamic drag change considerably as the robot crosses the water surface. Transitioning from water to air requires the robot to swiftly shift from hydrodynamic to aerodynamic forces, creating difficulties for its structural design and movement control [122].
(4) *Structural Strength and Weight:* The robot needs sufficient force and speed, often requiring high thrust and a light-

Table 1
The progression of aquatic jumping robots, encompassing classification (impulsive or momentum jumpers), capability, actuator and parameter.

Robots	Years	Class.	Performance	Actuator	Driving force	Body length	Weight	Ref.
SSWJR	2008	I.	26 mm	SMA spring	0.92 mN	15 mm	0.51 g	[74]
WJM	2012	I.	Continuous jump: 140 mm	Motor & Spring	–	150 mm	11 g	[75]
WJR	2014	I.	223 mm	DC motors	–	105 mm	55 g	[76]
JRI	2015	I.	142 mm	TRC & SMA	–	20 mm	0.068 g	[20]
WWR	2016	I.	Continuous jump: 120 mm	Motor & Spring	–	260 mm	10.2 g	[17]
MWSJR	2017	I.	95 mm	Motor & CF	–	10 cm	12.5 g	[77]
LSWJR	2018	I.	Jumping and sliding: 310 mm	Torsion spring	–	300 mm	650 g	[7]
WSJSR	2019	I.	Jumping and sliding	Motor & springs	0.92 mN	220 mm	91 g	[78]
AquaMAV	2016	I.	Exiting speed (E. S.): 11 m/s	SMA & Pneumatic	40 N	552 mm	100 g	[79]
UR	2019	I.	Continuous jump (42.8 BL/s)	Combustion	43 N	233.6 mm	160 g	[80]
SLAAV	2019	I.	E. S.: 13.64 m/s (17.48 BL/s)	Pneumatic system	15.1 N	780 mm	1120 g	[19]
AEWT	2023	I.	–	Combustion	165 N	507 mm	–	[81]
Copebot	2023	I.	E. S.: 0.6 m/s (3.4 BL/s)	Combustion	–	150 mm	2 kg	[83]
IAJM	2024	I.	605 mm	Rubber bands	77.82 N	266.4 mm	37.6 g	[18]
LR	2024	I.	E. S.: 2.8 m/s (20.7 BL/s)	Spring & Pneumatic	6.5 - 11.8 mN	135 mm	22 g	[5]
AARV	2011	M.	E. S.: 2.84 m/s (11.36 BL/s)	Motors	–	250 mm	145 g	[106]
FSDR	2016	M.	E. S.: 1.66 m/s (2.3 BL/s)	Motors	–	720 mm	4700 g	[62]
FSDR	2019	M.	Continuous jump	Motors	–	720 mm	4700 g	[22]
RMO	2022	M.	–	–	–	295 mm	–	[66]
UBRF	2022	M.	E. S.: 1.05 m/s (3.8 BL/s)	Motors	–	277 mm	380 g	[107]
KUFish	2023	M.	E. S.: 1.35 m/s (6.1 BL/s)	DC motor	–	222 mm	116 g	[108]
RFF	2023	M.	E. S.: 1.55 m/s (5.9 BL/s)	Motors	–	264 mm	360 g	[21]
FUSR	2024	M.	≈ 540 mm	Combustion	–	–	–	[110]

weight structure. The design must balance between lightness and structural integrity, ensuring that the robot can withstand the high-intensity stress during underwater propulsion and jumping without adding unnecessary weight [5].

5.2. Bioinspired artificial muscles

Existing robots mostly use springs (including SMAs), motors, and other actuators for actuation (Table 1), but there is no artificial biomimetic muscle that closely approximates biological muscles in terms of size, energy, materials, structure, or other characteristics (Fig. 7). Such biomimetic muscles would be functionally almost identical to real biological muscles, better suited to bionic structures, and capable of providing stronger driving forces for robots. To achieve the development of such actuators, the following four aspects can be pursued: (i) Conduct anatomical studies through legal means, observe biological microstructures [123,124], and explore the mechanisms of biological motion and physiological structures in depth; (ii) Develop soft materials that autonomously contract under stimulation, with smaller volume to meet the lightweight requirements of impulsive aquatic jumping robots; (iii) Conduct an in-depth analysis of the mechanical relationships in biological motion, including fields like fluid dynamics, to optimize the design of biomimetic motion systems [116]; (iv) Based on existing materials and manufacturing processes, the design incorporating rigid-flex coupling, air cavities, and embedded frameworks is beneficial for enhancing the swimming and jumping capabilities of fish-inspired robots in water [125].

5.3. Continuous aquatic jumping

There are few impulsive aquatic jumping robots capable of continuous energy storage [17,75,80], primarily due to the complexity of designing the energy storage and release mechanisms for jumping. On land, many robots achieve continuous energy storage and potential energy release using incomplete gear sets [17]. This design allows for slow energy storage but rapid energy release, making it one solution for achieving continuous jumping. However, for jumping robots that require stringent weight constraints in aquatic environments, the design and manufacturing of incomplete gear systems present the following challenges:

(1) *Increased Structural Complexity:* In addition to considering special meshing angles and transmission paths, miniaturization must also be addressed, greatly increasing the difficulty of system design and assembly [17].
(2) *Reduced Controllability:* Without adding a control system, the constant motor speed determines a fixed release time for the incomplete gears, making it difficult to adjust based on the posture of robot on the water surface, which affects the accuracy of the release of jumping mechanism. While adding a control system can enhance precision, it also increases the weight of robot, further reducing jump height.
(3) *Concentrated Stress:* Gears may experience concentrated loads during partial operation, leading to increased localized wear. To withstand these stresses, transmission components must be made from high-stiffness materials such as carbon fiber, aluminum alloy, and stainless steel. However, these materials have significantly higher densities and are unsuitable for aquatic jumping robots, as they substantially increase the weight of robot [15].

The water-jet propulsion method [42] is an effective way to achieve aquatic jumping, but in the air, the water tank cannot be replenished, and the water-propulsion system cannot continuously provide power. The most effective method for achieving impulsive aquatic continuous jumping is currently known to be mixing environmental water with calcium carbide powder to produce combustible acetylene gas [80].

5.4. Waterproof design

For aquatic robots such as dolphin [111] and flying fish-inspired models [107], waterproof design is critical. As the diving depth increases, every 10 m adds one atmosphere of pressure, requiring sealing materials to have high pressure resistance, fatigue resistance, and aging resistance. Common materials like rubber and silicone may degrade, harden, and lose elasticity after prolonged underwater use, reducing sealing effectiveness. The design must account for a multi-layer sealing system while controlling weight and size. Seals are divided into static seals (used at housing joints) and dynamic seals (for moving parts such as joints and bearings). Dynamic seals are more challenging due to friction and wear, which can lead to failure. Additionally, the enclosed design limits heat dissipation, potentially requiring additional cooling elements like cooling fins.

5.5. Dynamics of aquatic jumping robots

Currently, the theory of bioinspired aquatic jumping robots is not yet mature and faces mechanical issues such as fluid–structure interaction and fluid dynamics. If the configuration of robot (such as the angles and speeds of its legs and propellers) is unstable when emerging from the water [18], the non-uniform distribution of the water flow may cause the robot to lose balance or deviate from its trajectory. Therefore, the robot needs to reasonably adjust its configuration through fluid–structure interaction effects and maximize the utilization of the reaction force generated by hydrodynamics to enhance its jumping height. The fluid part can be described using the Navier–Stokes equations to model fluid motion, while the solid part can be characterized by elasticity theory or rigid body dynamics to describe the structural response. These two components are coupled through the boundary conditions between the fluid and solid (such as pressure, velocity, and displacement). In studying fluid dynamics issues, it is essential to determine whether the fluid flow is laminar or turbulent, and whether the flow is stable, taking into account the physical properties of water such as density and viscosity during modeling. Finally, experimental validation is necessary, comparing experimental results with numerical simulations to ensure the accuracy of the model [126].

5.6. Optimization in the real-world environment

The optimization strategies for the jumping dynamics and propulsion systems of bioinspired aquatic jumping robots in real-world environments include, but are not limited to: (i) Enhancing energy management and conversion efficiency by using lightweight materials and high energy density elasticity storage mechanisms to improve jumping performance; (ii) Establishing fluid dynamics models to optimize the jumping behavior under different water flow conditions; (iii) Introducing adaptive control algorithms to adjust jumping parameters in real-time; (iv) In terms of propulsion systems, recommending the use of variable geometry propeller designs and multi-mode propulsion technologies to improve propulsion efficiency and flexibility.

6. Future prospects

Currently, there are no designs for mixed jumping robots. As apex predators, crocodiles demonstrate an impressive ability to integrate two distinct modes of aquatic locomotion [25]. Designs inspired by these large reptiles are expected to enhance continuous impulsive and momentum-based aquatic jumping capabilities [91]. Such designs could incorporate mechanisms that mimic the hydrostatic properties of crocodile musculature, enabling optimized thrust generation and stability during both submersion and aerial phases. This system is anticipated to utilize sophisticated algorithms for real-time decision-making and adaptive behaviors, improving the ability of robot to navigate complex aquatic environments. Additionally, advanced actuators capable of delivering rapid bursts of energy will be essential for achieving the thrust and speed during jumping.

Crocodiles have a large torso and relatively short limbs, which suggests that when designing such robots, we can primarily concentrate the transmission and energy storage devices in the torso, without the need to strictly focus on the overall integration of the system as in traditional impulsive aquatic jumping robots. This approach also allows for the installation of more powerful actuators and control systems in the torso area. A larger, high-speed brushless motor can be used as the prime mover, along with a gearbox. The oscillating mechanism of tail can reference the Scottish yoke mechanism, which allows a single motor to achieve high-speed oscillation of the tail, providing the robot with strong propulsion for jumping in water. Additionally, the design of the tail materials should also be considered. To quickly produce the bioinspired tail, 3D printing technology can be used to create molds, into which silicone of varying hardness can be injected to obtain the desired bioinspired tail. A binocular vision sensor can be installed on the head of the robot as “eyes” to enhance the amount of information gathered from the environment. Binocular vision uses the principle of binocular disparity, enabling accurate assessment of the distance and depth of objects, thereby improving the understanding of the surrounding environment. Additionally, binocular vision can enhance obstacle detection capabilities and spatial positioning accuracy, allowing for more effective navigation and task execution in complex environments. By identifying and analyzing the shape, color, and motion of objects, the binocular vision system can provide richer environmental information, enhancing autonomous decision-making abilities.

Ultimately, the integration of these technologies is expected to significantly enhance the stability, agility, and operational functionality of mixed aquatic jumping robots, and find applications in diverse fields such as environmental monitoring, search and rescue operations, and biological research.

7. Conclusions

In this article, we seek a series of bioinspired designs for aquatic jumping robots from the perspective of aquatic jumping creatures. Firstly, we categorizing these creatures into three types. A review of relevant biological studies provided a detailed overview of the reasons behind their jumping behavior, the mechanics of the jumping process, and their jumping capabilities. Subsequently, a further classification of aquatic impulsive creatures was conducted, focusing on their modes of interaction with water during the jumping process. Once again, the research on impulsive aquatic jumping robots and momentum aquatic jumping robots in recent years has been described, primarily covering aspects such as jumping ability in water, actuators, and size parameters, along with a table created for comparative analysis. Finally, the potential challenges faced by such robots were analyzed, and future development directions were explored, aiming to provide some assistance for the advancement of these robots.

CRediT authorship contribution statement

Tao Zhang: Writing – review & editing, Writing – original draft. **Jiawei Dong:** Writing – review & editing, Writing – original draft. **Qianqian Chen:** Investigation, Data curation. **Xiongqian Wu:** Data curation. **Shuqi Wang:** Writing – review & editing, Data curation. **Yisheng Guan:** Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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