Biomimetic robotics: self-propelled physical models test hypotheses about the mechanics and evolution of swimming vertebrates

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Abstract: Biologists are beginning to combine biomimetic and robotic methods to generate and test biological hypotheses about animal function and evolution. Notable progress has been made studying aquatic vertebrate systems and their locomotor mechanisms, with self-propelled physical models improving our ability to simulate complex behavioural and mechanical systems. As biomimetic robots gain popularity as model simulations, it is essential to characterize explicitly the investigator's scientific intent and method of evaluating the robot in regards to testing hypotheses. Intent and evaluation can be characterized using Webb's seven-dimensional hyperspace for biorobotic model simulations. After reviewing this hyperspace approach, it is used to discuss three different kinds of biomimetic, swimming robots that differ in their accuracy, concreteness, and specificity with regard to their biological targets. Although each robotic system occupies a different position in Webb's hyperspace, because of the investigators' choice of biological target and method of evaluation, explicit justification of the robot's position makes it clear that no single position is better than another. Thus, biomimetic robotics is a flexible modelling methodology, addressing different kinds of biological questions and, in addition, providing engineers with plausible biological mechanisms and a library of implemented biorobotic designs.

Keywords: biomimetics, robotics, biorobotics, modelling, swimming, propulsion

1 INTRODUCTION

As robotic engineering has grown in sophistication, the field has attracted the attention of biologists who seek to build biomimetic robots for the purpose of testing biological hypotheses [**1**]. This new biological method has been dubbed 'biorobotics' [**1**] or the more explicit 'biomimetic robotics' [**2**]. Biomimetic robots – physical models operating in real environments – are fast becoming the tools of choice for simulating complex biological systems that produce behaviours such as navigation, social foraging, predator-prey interactions, human-like cognition, and evolution [**1**, **3–11**]. One reason for this attraction is that in contrast to computer simulations, physical robots cannot violate the laws of physics, even if those laws are unspecified by the investigator. The performance of a physical robot is immediately informative about what works and what does not.

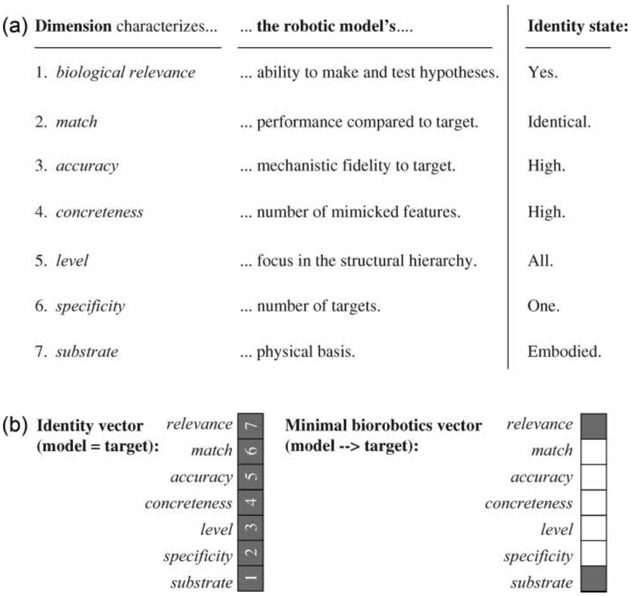
Biomimetic robots are particularly powerful tools for the study of complex biological behaviours. One such behaviour is aquatic propulsion in vertebrates. Although computational fluid dynamics can estimate hydrodynamic forces acting on a body from its kinematics [**12**], the resulting external forces are not coupled with the body's internal muscular and elastic forces. Instead, the vertebrate propulsion problem is a hydroelastic one, where physically coupled fluid and body forces interact to produce body motion. Though attempts have been made to couple fluid forces with the flexible, anisotropic, and inhomogeneous bodies and fins of vertebrates, computer simulations tend to produce poor swimmers [**13**] or tightly constrained operating parameters [**14**]. In contrast, even simple fish-shaped pieces of rubbery material can produce a range of realistic swimming performance [**15**].

Self-propelled robots that mimic specific aspects of vertebrate anatomy and behaviour have made important advances, demonstrating the importance of vortex shedding [**16**] and fin actuation parameters [**17**, **18**]. In his own laboratory, the author has built three different kinds of vertebrate-mimic robots to test different aquatic propulsion hypotheses. Because of his familiarity with the design process and the shortcomings of these biomimetic robots, they are examined here, with apologies to readers seeking a more comprehensive review of the field. The goals of the current paper are two-fold:

(a) to present to an engineering audience a characterization scheme for biomimetic robots, and, using that characterization scheme;
(b) examine recent work in aquatic biomimetic robotics that demonstrates the different kinds of hypotheses that can be tested.

2 A SEVEN-DIMENSIONAL HYPERSPACE FOR BIOMIMETIC MODELS

Webb [**1**] proposed seven dimensions by which any model simulation can be characterized and evaluated. The seven dimensions are based on the range of scientific opinions about what constitutes a good model simulation (Fig. 1). As such, this seven-dimensional hyperspace offers a tool for any worker in biomimetics. Many robotics researchers offer a single justification for their models, such as the ability to produce and test biological hypotheses (dimension 1: biological relevance) or qualitative similarities between the performance of their robotic model and the biological target (dimension 2: match). Few acknowledge that modelling itself is considered by some to be of little or no scientific value. With this background, Webb challenges researchers to explicitly justify their use of robots to make and test biological hypotheses. As a tool for the task, she offers the seven-dimension biomimetic modelling hyperspace, which is reviewed and modified slightly below.



(a)

Dimension characterizes...	... **the robotic model's....**	**Identity state:**
1. *biological relevance*	... ability to make and test hypotheses.	Yes.
2. *match*	... performance compared to target.	Identical.
3. *accuracy*	... mechanistic fidelity to target.	High.
4. *concreteness*	... number of mimicked features.	High.
5. *level*	... focus in the structural hierarchy.	All.
6. *specificity*	... number of targets.	One.
7. *substrate*	... physical basis.	Embodied.

Fig. 1 Webb's seven-dimensional hyperspace for characterizing biomimetic models. (a) Seven dimensions, with the identity state (model = target) for each; (b) Vectors represented graphically, with binary states (grey = identity; white = other) given for the identity vector and for Webb's minimal biorobotics vector

The names of three of the seven dimensions have been altered here (Fig. 1): dimension 4 – 'concreteness', was originally 'abstraction'; dimension 6 – 'specificity', was originally 'generality'; and dimension 7 – 'substrate', was originally 'medium.' Concreteness and specificity are used here to reverse the direction of the dimension with respect to the 'identity state', that is, the biological target, the animal itself and the origin in the seven dimensions hyperspace. Thus, if a robotic model is an exact match of the biological target, it has achieved the identity state in all seven dimensional (Fig. 1(a)); showing biological relevance (dimension 1); an identical match to target performance (dimension 2); a high degree of accuracy (dimension 3); a high amount of concreteness (dimension 4); replication of all structural levels (dimension 5); specificity of one particular target (dimension 6); and substrate of physical embodiment (dimension 7).

By Webb's definition of biorobotics [**1**], two of the seven dimensions – biological relevance (dimension 1) and substrate (dimension 7) – must possess the identity states in order for the robotic model to be considered a biorobotic one (Fig. 1(b)). This leaves open a wide range of modelling options in the five other dimensions.

Two apparent deficiencies in this seven-dimensional hyperspace approach should be recognized. First, the scale and quantitative nature of some of the dimensions are unspecified. This is by necessity dictated by the experimental situation. For example, match (dimension 2), can be quantified by measuring the performance of the robot model and the target in a similar manner. As performance changes, so will the metric. The second apparent deficiency is the lack of a criterion for what constitutes having achieved the identity state for a given dimension [**19**]. True identity can only be achieved by building an exact replica of the biological target, the animal itself. From a practical perspective then, the binary judgment of 'identity' has to be justified case-by-case. By forcing researchers to make those justifications explicit, Webb's hyperspace does the service of offering any scientist access to the rationale behind a given robotic model simulation [**20**]. Three different systems and their justifications and results are presented in the next section.

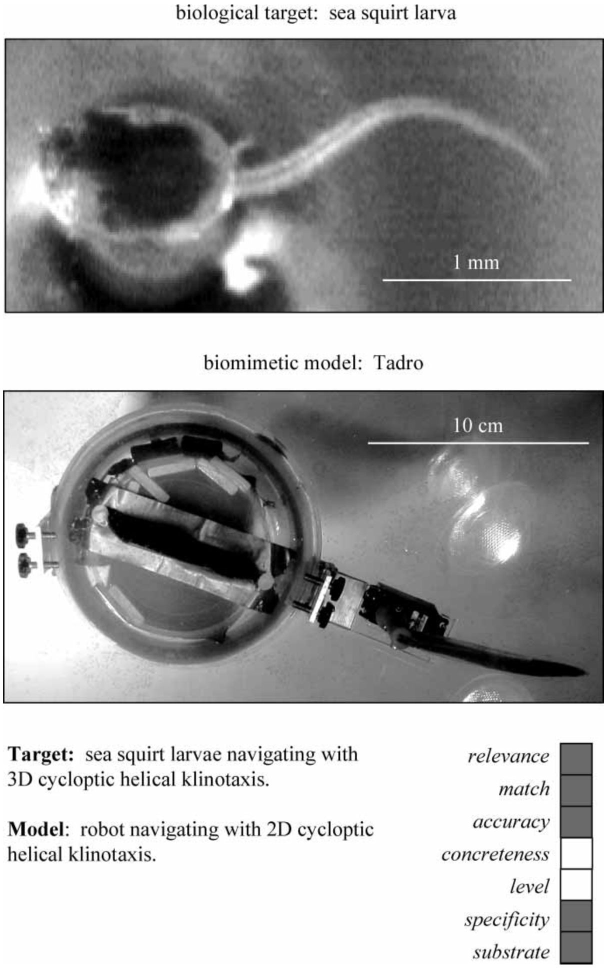
3 APPLYING WEBB’S BIOMIMETIC HYPERSPACE

3.1 Tadro – a tadpole robot navigating with two-dimensional cycloptic helical klinotaxis

Of the three examples in this section, this is the only robotic system that was designed to mimic a single biological target, the tadpole larva of sea squirts (Fig. 2). In reality, the sea squirt tadpoles (members of the Phylum Chordata) are small swimmers with a propulsive, undulatory tail and a single eyespot. In their brief larval stage in the ocean, they swim away from their substrate-bound parents, first towards the light, located at the surface of the water, and then away from it, back towards the bottom, where they adhere and metamorphose into an adult after having been dispersed by surface currents. Laboratory experiments on sea squirt tadpoles posited two important hypotheses: (a) orientation towards or away from the light is an active process and (b) light navigation is mediated by a simple neural circuit that alters the turning angle of the tail in direct proportion to the intensity of the light hitting the single eyespot [**21, 22**]. The tadpoles swim in a three-dimensional corkscrew trajectory called ‘helical klinotaxis’ (HK). Because only a single eyespot is used by the tadpoles, this special case was named as ‘cycloptic’ HK (cHK).

To test the two hypotheses about light navigation, a robotic tadpole, ‘Tadro’, short for ‘tadpole robot’ [**7, 23**] was designed and built. To mimic the biological target, Tadro was built with a single eyespot (a photoresistor) and a flapping propulsive tail whose orientation to the hull of Tadro could be altered by a motorized potentiometer. In response to the changes in voltage across the photoresistor, the motorized potentiometer, wired in an analogue circuit as part of a window comparator, altered its position to match the voltage drop. When placed in either gradual or abrupt light gradients, Tadro navigated towards the light source and orbited around it. These results supported the hypotheses that cHK is an active process and that cHK navigation can be mediated by an extremely simple neural circuit. In spite of Tadro’s success, two important differences existed between Tadro and its biological target: (a) Tadro performed cHK in two dimensions, at the water’s surface, rather than in three dimensions submerged, and (b) Tadro was two orders of magnitude larger (Fig. 2).

In terms of Webb’s biomimetic hyperspace, the Tadro system meets the baseline criteria for employing biorobotic methodology: it tests biological hypotheses (dimension 1) and it is embodied physically (dimension 7). Beyond that, the production of the cHK navigation behaviour earns the Tadro a close, but not perfect match (dimension 3), because it operates in two dimensions and not three. Tadro’s accuracy (dimension 4) was judged to be high because the exact mechanisms hypothesized for cHK in the real tadpole were modelled. Specificity (dimension 5) is one, since a single biological system was targeted.



Target: sea squirt larvae navigating with 3D cycloptic helical klinotaxis.

Model: robot navigating with 2D cycloptic helical klinotaxis.

relevance	■
match	■
accuracy	■
concreteness	□
level	□
specificity	■
substrate	■

Fig. 2 Tadro, a biomimetic robotic model of a sea squirt. Both systems employ cycloptic helical klinotaxis for swimming. Tadro was designed and built to test hypotheses about how animals navigate up light gradients

Tadro’s concreteness (dimension 4) and level (dimension 5) were intentionally designed with ’low’ and ’few’ values, respectively. A low concreteness results from the fact that only the neural and propulsive systems were modelled. Moreover, only two levels were targeted, organs and whole body. These decisions were made for an important reason: to create the simplest model possible, a single sensor connected to a single motor output. This is an example of an explicit and justified deviation from the identity state, done in support of the experimental goals.

3.2 Robot Madeleine, a robot swimming with lift-based appendages

This robotic system models multiple biological targets: any swimming tetrapod (four-footed vertebrate animal) that uses its appendages as lift-based propulsors (Fig. 3). Animals such as sea turtles, penguins, seals, and sea lions all flap their appendages when swimming, using a lift-based propulsive mechanism in locomotor mode termed 'sub-aqueous flight'. Sub-aqueous flight, with limbs oscillating perpendicular to the free-stream flow, stands in stark contrast to the drag-based, fore-and-aft paddling motion seen in the limbs of animals such as beaver and water rats [**24**]. For the biologist, sub-aqueous flyers present two puzzles. First, even though terrestrial vertebrates have repeatedly and independently evolved sub-aqueous flight, none of the living species that use this mode of swimming use all four appendages for propulsion. Sea lions use their forelimbs and seals use their hind limbs; penguins use their forelimbs and whales use what remains of their hind limbs. Second, and in contrast, giant marine reptiles, called plesiosaurs, of the Mesozoic Era (252 to 66 million years ago) used all four appendages for propulsion, based on limb shape and the arrangement of joints and muscles that would create a downward power stroke perpendicular to the free stream. Why this difference in limb use in extinct and living vertebrates? To answer this question, a robotic model simulation to create a plausible hypothesis was used.

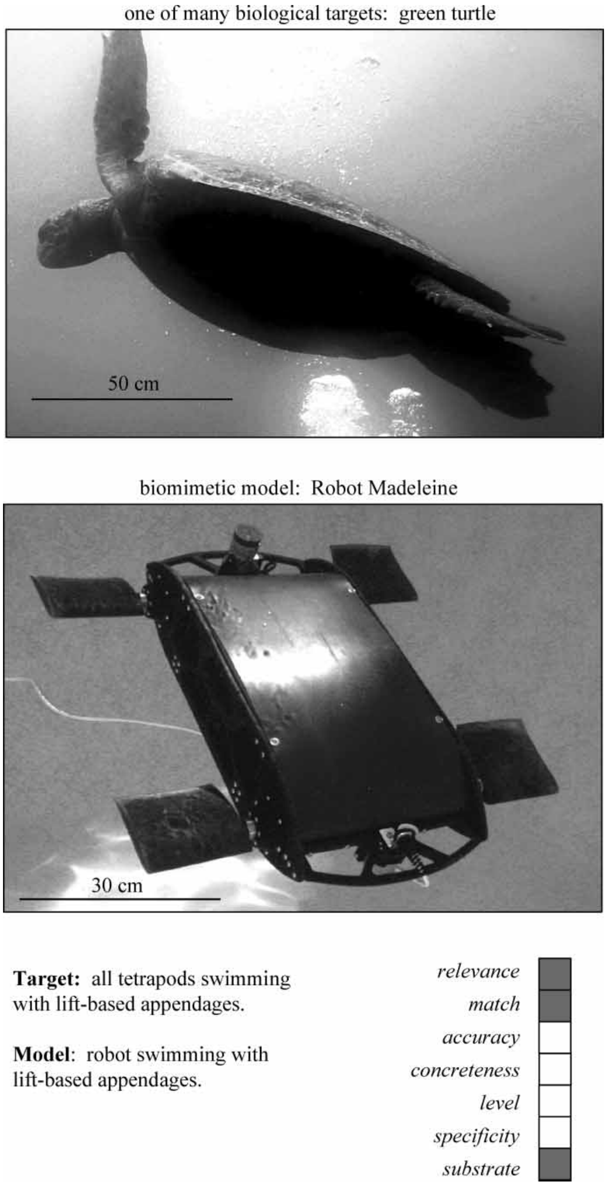


Fig. 3 Robot Madeleine – a robotic model targeting tetrapod swimmers that use a lift-based propulsive mechanism. Madeleine was designed and built to generate a plausible biological hypothesis to account for the functional differences between two- and four-flippered swimmers

Robot Madeleine was designed (Fig. 3) as a four-flippered, lift-based swimmer [**25**], mimicking no particular species. Instead, the goal was to have Robot Madeleine swim with the different limb patterns that is expected in living and extinct vertebrates. Thus the biological targets for Madeleine were vertebrate tetrapods swimming with a lift-based propulsive mechanism.

Madeleine was built to mimic the following aspects of vertebrate tetrapod swimmers:

(a) lift-based appendages;
(b) appendages with chord-wise flexibility comparable to that of vertebrates;
(c) length, mass, and body shape comparable to that of many sub-aqueous flyers;
(d) power density (W/kg) equivalent to that of vertebrates.

Robot Madeleine was self-propelled, carrying onboard four independently controlled servo motors, a motor controller, a computer, and the batteries to power them all. In addition, Robot Madeleine carried sensors that were logged by the computer and saved for uploading following the experiments. Those sensors included a voltage and current meter, which permits one to measure Madeleine's instantaneous power draw, and a three-axis accelerometer to measure locomotor performance. Madeleine was videotaped underwater in order to measure the velocity and parameters such as starting distance and stopping time. For experiments, a remote topside operator caused Madeleine to accelerate from rest at maximal power draw. After Madeleine reached top cruising speed, the operator decelerated Madeleine with maximum power draw. Performance was measured when Madeleine used a variety of different two- and four-flippered gaits [**26**]. Gaits were not operator-controlled during the trials; instead, they were programmed on Madeleine's onboard processor prior to each experiment.

When using four flippers, Madeleine accelerated faster than with two flippers. Madeleine also used twice as much power when accelerating with four flippers. Unexpected, however, was that Madeleine would cruise at the same peak speeds whether using two or four flippers. The cost of cruising with four flippers is that twice the power is used without any gain in performance. Though we can only speculate about the mechanism for this constant-velocity effect (destructive wake interaction at the downstream flipper?), this unexpected result was the basis for creating a novel biological hypothesis: two-flippered swimmers evolved as cruising specialists while four-flippered swimmers evolved to maximize acceleration performance.

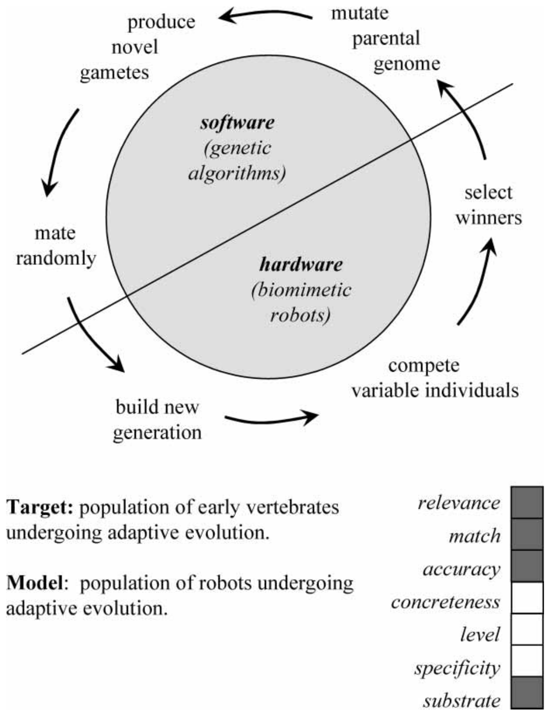
In terms of Webb's biomimetic hyperspace, Robot Madeleine meets the criteria for employing biorobotic methodology: it generates biological hypotheses (dimension 1) and it is embodied physically (dimension 7). The only other dimension considered close to the identity state is that of the match (dimension 2), since the cost of transport (power to move a given mass a given distance) of the robot is comparable, and in some cases superior, to that of the targeted group of sub-aqueous flyers [**26**]. Since only the lift-based mechanism of the flippers, flipper flexibility, overall size and shape, and power-draw features are life-like, the accuracy (dimension 3) is considered low. Abstracted neural control and force generation systems reduce the concreteness (dimension 4). The whole organism is the only level (dimension 5) modelled. By design, the specificity is high, with multiple biological targets.

Compared to Tadro (see previous section), Robot Madeleine occupies a different position in the seven-dimensional hyperspace, as shown visually with a comparison of their vectors (see Figs 2 and 3). While both robotic simulations show a behavioural match with their biological targets, they deviate in their specificity and mechanistic accuracy. Thus one criticism of Robot Madeleine is that its low specificity and accuracy limit one's ability to model vertebrate swimmers. This seems to be a common criticism levied against biomimetic robots, one easy to make in the absence of explicit criteria for characterizing the model simulation. Using Webb's hyperspace, it can be explained that we did not set out to 'model' vertebrate swimmers in the sense of creating a replica with its identity state for all dimensions. Instead, the goal was to examine propulsion with four lift-based appendages, and low specificity in particular allows one to address the propulsive principles without the concern of imposing functional constraints unique to a particular species.

3.3 Population of Tadros undergoing adaptive evolution

Moving up from the level of individual in the structural hierarchy, this robotic system models a population of evolving early vertebrates [**8**]. An interesting pattern seen in early fish-like vertebrate fossils is that they evolved bony vertebral columns from continuous notochords. Since these species are extinct, it is a mystery how exactly evolution by natural selection worked to create vertebral columns. Because of the differences seen in living species with and without vertebral columns, biologists have hypothesized that vertebral columns are an adaptation for improved swimming performance. Ours is a specific case of a general kind of evolutionary question regarding the origin of new major organ systems, a realm of inquiry known as macroevolution.

Macroevolutionary studies require understanding of which selection pressures might have caused the evolutionary changes in question. In this case, what



Target: population of early vertebrates undergoing adaptive evolution.

Model: population of robots undergoing adaptive evolution.

Fig. 4 A robotic model of a population of hypothetical vertebrates undergoing evolutionary changes. The Tadro sea squirt robot is evolved by competing individuals with variable tails, rewarding individuals with better forage navigation performance, and then allowing the winners to have more offspring were the survival benefits experienced by individuals with tails of different stiffness? An environment was created in which a population of three Tadros, (see section 3.1), each with a different variant of tail, competed for light resources, where light is a proxy for food. These upgraded Tadros had, in addition to an interchangeable tail, a digital brain implementing the simple sensorimotor system previously explained, and a servo motor serving as both the tail rudder and flapper. The tail was built as a biomimetic model of a notochord, with denatured collagen molded and then cross-linked to build notochord-like rods used as the tails' skeletons. Stiffness of the biomimetic notochord, a proxy for vertebrae, was controlled by two traits, length and material stiffness, both of which could be determined in the fabrication process.

Using software techniques from evolutionary robotics [**27**], the genetic code for the tail length and stiffness was mutated, separated into gametes, and then recombined in novel offspring tails (Fig. 4). In each generation, the Tadros competed in 12 trials for the food proxy. The fitness function rewarded individuals who swam quickly, swam directly to the light target, stayed close to the target, and swam smoothly. The individuals with the greatest fitness were allowed to give more of their genes to the offspring of the next generation. Over ten generations, it was found that stiffer tails were associated with the enhanced ability to forage for food. This result supports the evolutionary hypothesis that vertebral columns may have evolved as adaptations for enhanced forage navigation.

In terms of Webb's biomimetic hyperspace, the population of Tadros meets the criteria for employing

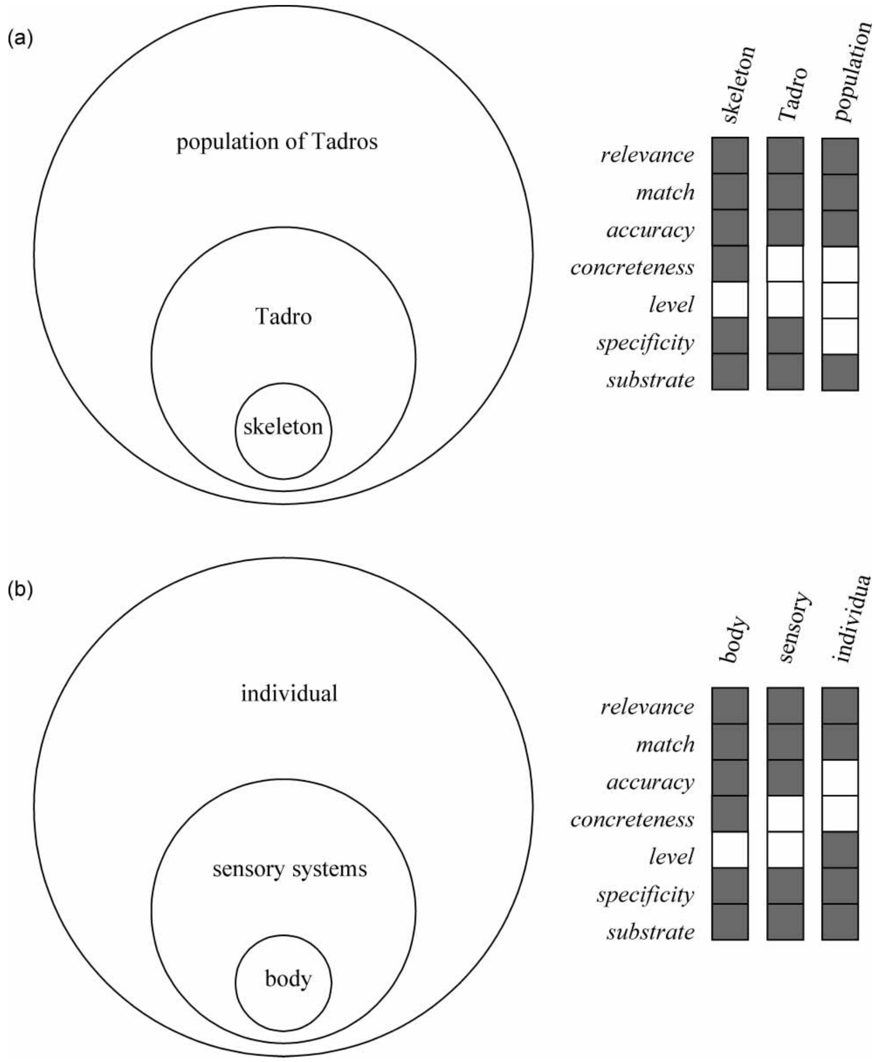


Fig. 5 Most robotic models are a hierarchy of models: (a) The modelled population of Tadros includes the Tadro model and a biomimetic model of the skeleton, each with its own vector; (b) a hypothetical case of a single individual with hierarchically nested models of body, sensory systems, and the whole individual

biorobotic methodology: it tests biological hypotheses (dimension 1) and it is embodied physically (dimension 7). Because the Tadro population evolved in a manner consistent with patterns seen in the fossil record of early vertebrates, the match is considered (dimension 2) to be life-like. The very different kind of performance metric used here to establish a match is to be noted here; it is not locomotor behaviour but rather evolutionary behaviour of the robotic system. Furthermore, since realistic evolutionary mechanisms – selection, mutation, mating – are employed, the accuracy is considered (dimension 3) to approach the identity state. By design, concreteness (dimension 4) is low, with only the tail and its skeleton evolving when, in all likelihood, the entire body would have evolved. Specificity (dimension 6), by design, is high, since any number of early fish-like vertebrates could be seen as targets.

While the focus was on the level (dimension 5) of the population, that level is really only one of several included in this robotic simulation. In addition, the whole body and the organ-level tail were modelled; these levels are nested hierarchically, each with its own position in the seven-dimensional hyperspace (Fig. 5(a)). This specific case highlights the general fact that most robotic model simulations are likely composites of hierarchically-nested model simulations, and the dimensional vectors provide a visual reference for the different positions that each level can occupy in the hyperspace (Fig. 5(b)).

4 CONCLUSION

Biomimetic robotics is a powerful new method for generating and testing biological hypotheses. As shown in the three examples reviewed here, robotic model simulations can be used to study different aspects of aquatic propulsion in vertebrates:

(a) the autonomous navigation behaviour of individuals (Tadro, section 3.1);
(b) the functional consequences and evolutionary significance of changes in limb-based propulsive behaviour (Robot Madeleine, section 3.2);
(c) the evolutionary behaviour of populations as driven by changes in the axial body and its propulsive machinery (Tadro population, section 3.3).

All three model simulations feature self-propelled aquatic robots designed to mimic different suites of vertebrates, anatomy, physiology and behaviour. Model simulations can be characterized within Webb's seven-dimensional biomimetic hyperspace, which, by requiring explicit justification of the intent and method of evaluation used by the researcher, is a tool that helps to formalize and articulate the emerging methodology of biomimetic robotics.

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