Double benefit: a Stuttgart-based Max Planck team is investigating the biomechanics of running birds, for example, on two-legged robots. The findings also help the researchers to improve the movement of robots.

PHOTO: WOLFRAM SCHEIBLE FOR MPG

RUN, ROBOT!

TEXT: DAVID HOLZAPFEL

Walking and running without stumbling is still a challenge for two-legged robots, especially on uneven terrain. It could be easier for them in the future, however. A team led by Alexander Badri-Spröwitz, Research Group Leader at the Max Planck Institute for Intelligent Systems, has designed a walking robot inspired by running birds. In the future, such machines could be used on construction sites, in agriculture, or even in space missions.

Alexander Badri-Spröwitz puts the robot on the treadmill. He keeps hold of it with one hand. The two legs of the machine stomp in the rhythm of their electric motors. It looks as if it wants to free itself from the researcher's grip. Badri-Spröwitz switches on the treadmill. He types on a laptop. The robot twitches in a somewhat uncoordinated way, dragging its left leg. "He's a little shy today," the scientist says, looking at the screen. Next try. The machine is running. A little awkwardly it moves step by step over the treadmill – at least for a few seconds. Then it starts limping. Badri-Spröwitz fiddles with the left leg of the robot. Then he finds the problem; the knee motor is not pulling properly. A small adjustment, BirdBot starts again – and this time it does not limp.

BirdBot is the name of the robotic leg system developed by Badri-Spröwitz and his team at the Max Planck Institute for Intelligent Systems in Stuttgart. The researchers combine biology and robotics in the field of biomechanics. They want to understand nature better. And learn from it. According to Alexander Badri-Spröwitz, BirdBot could be the prototype for a new type of running robot. More energy-efficient than previous robots, in future they could carry heavy loads on construction sites, for example. Instead of large machines with a lot of weight and powerful wheels, light-footed robots may soon run over fields. They could pick apples or help with the grape harvest. Badri-Spröwitz also sees potential applications in space travel. "We believe that a robot can be supplied with enough energy by mobile solar panels to explore the moon or Mars, or help build a lunar station." Two-legged robots are lighter than four- or six-legged ones, require less space – for example, between trees or shelves – and can usually reach higher if they are equipped with arms as humanoid robots. However, the BirdBot mechanism can also be used in multi-legged machines.

Biologists have known for a long time that animals run, jump, fly, and swim in a very energy-efficient manner. Since there has been life on our planet, evolution has found countless solutions to all kinds of challenges. In doing so, nature has already solved many

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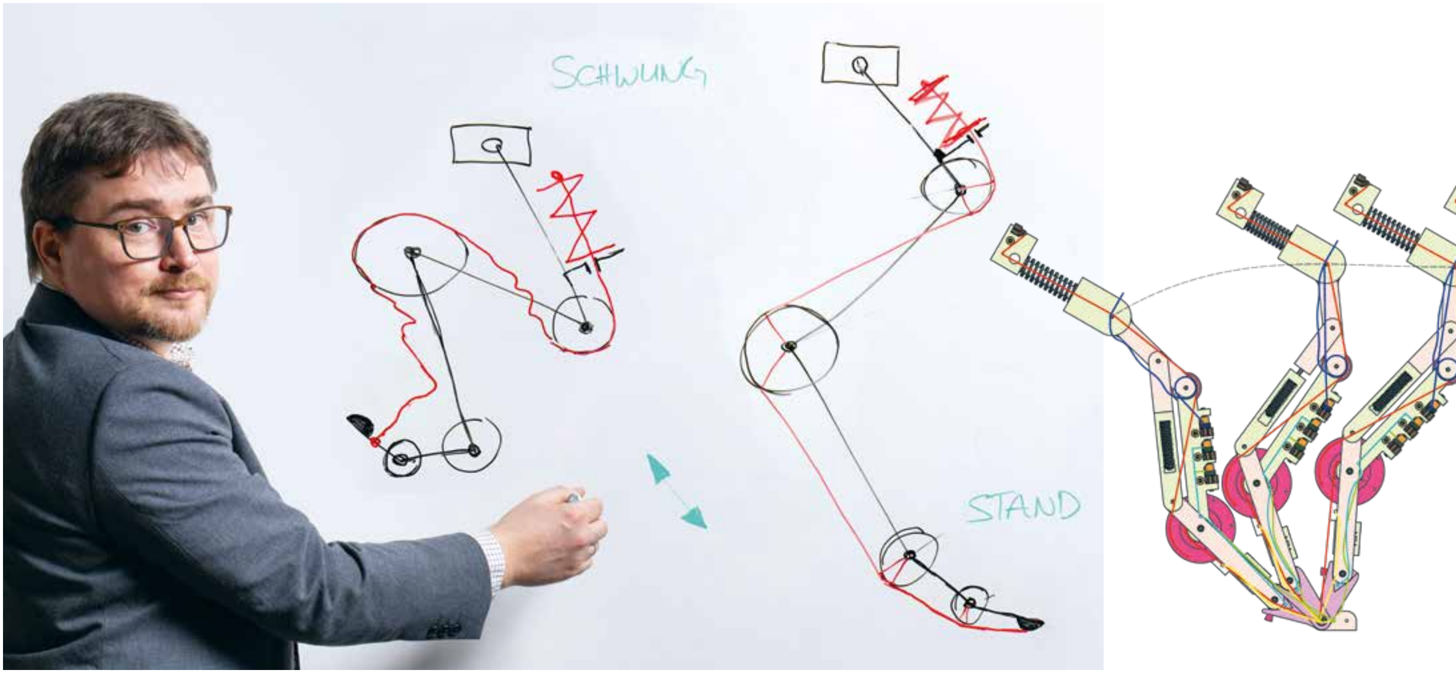


PHOTO: WOLFRAM SCHEIBLE FOR MPG

It is exciting. Alexander Badri-Spröwitz sketches the crucial innovation for BirdBot. This is the fact that a tendon (red) extends from a spring on the thigh, over all joints to the foot of the robot. When standing (sketch on the right), the tendon and spring are taut, so a motor is not required to carry the weight. When BirdBot lifts its leg (sketch and graphic on the left), it folds its foot backwards. Then the tendon and spring relax, and the robot can lift the leg with relatively little effort.

of the problems we face in developing technology today. We just need to look carefully.

Take, for example, the ostrich and the emu. Running birds like these are mechanical marvels. They sometimes weigh over 100 kilos and yet run at speeds of up to 55 kilometers per hour through the Savannah. This represents an early success of evolution, because as long as 66 million years ago a Tyrannosaurus Rex, weighing six to seven tons, ran with an almost identical leg structure.

But science knows surprisingly little about how the animals move in detail. There is a lot of research on this, but there are also a lot of questions. Biomechanical engineers describe movement sequences and measure forces and joint movements. "But much is still unclear," says Badri-Spröwitz. How do the muscles work? How do they use energy? "We are a long way from explaining why these animals are so energy-efficient."

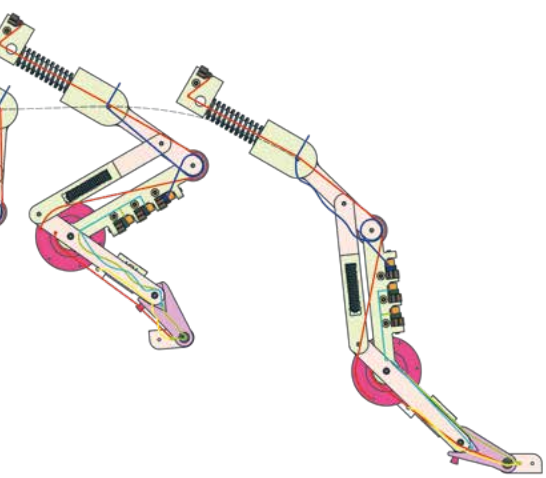
From Emu Carcass to Robot Model

And there are some developments that seem at first glance to be curiosities. Unlike humans, many birds fold their feet backwards as they pull their leg up toward the body. But nature does nothing by chance. So why do these animals do this? Is this foot movement perhaps particularly energy-efficient when walking and running? BirdBot should provide answers to such questions.

The running robot itself also benefits from this. Again and again, it has been optimized according to new findings, for example, why exactly running birds move so efficiently – but there were still more questions to be answered. For example, how can the structure of birds' legs, with all their bones, muscles, and tendons, be transferred to running robots? Badri-Spröwitz has been researching this for several years. The preliminary result is now in front of him in his Stuttgart laboratory. BirdBot is around 35 centimeters high, and with its long legs, electric motors, and plastic components it looks a bit like a futuristic children's toy.

The story of the robot begins in 2014. Badri-Spröwitz sits in a laboratory at the Royal Veterinary College in London. On the dissection table in front of him lies the carcass of an emu; a massive animal – one of the largest running birds in the world. Alexander Badri-Spröwitz moves a joint on the leg of the bird, and to his surprise he sees that the other joints move too. It is like pulling multiple strings at the same time on a puppet. Because the animal is dead, and can therefore no

GRAPHIC: DLG MPI-IS & UC IRVINE



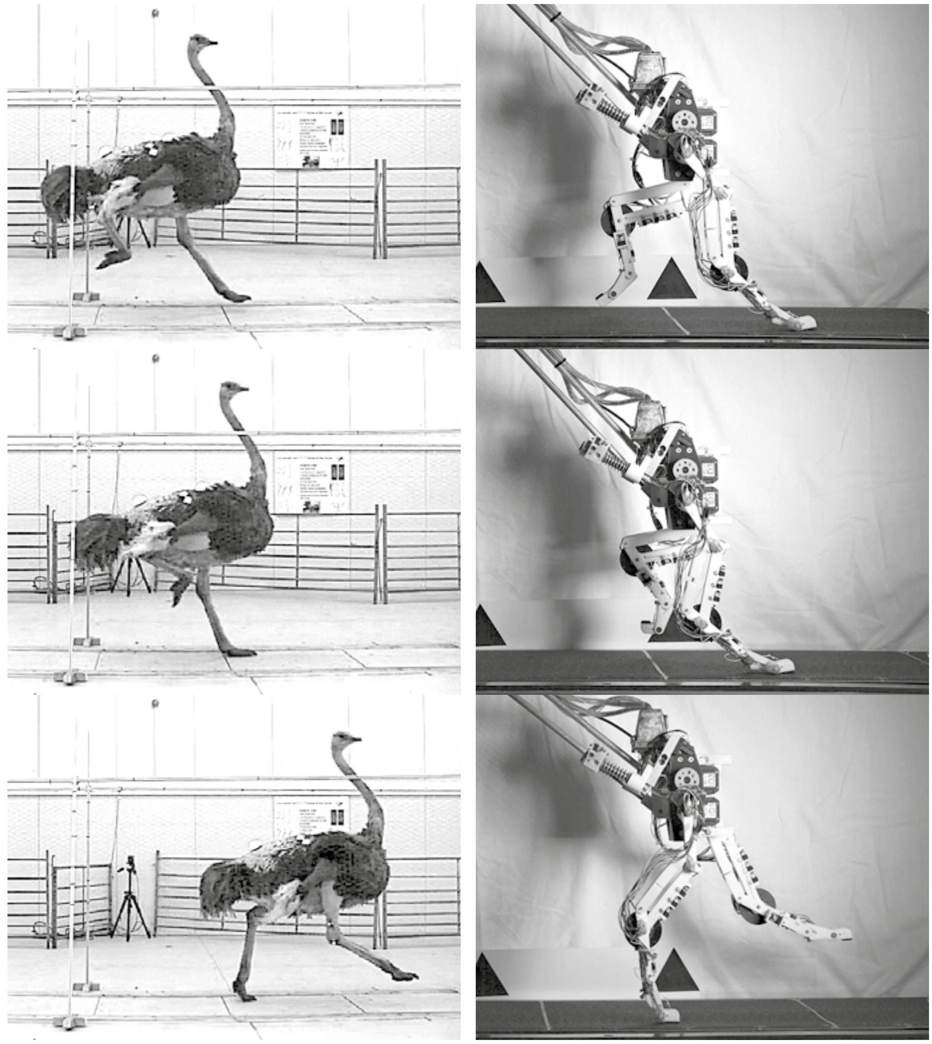


IMAGE: DLG MPI-IS & UC IRVINE AND MONICA DALEY, RVC

Inspired by an uncertain role model: BirdBot's gait is similar to that of a running bird (here: an ostrich). However, it is still unclear whether the bird also folds back its foot for the purpose of relaxing a tendon and thus saving energy when running.

longer exhibit neuronal reflexes, Badri-Spröwitz is convinced that the joints of the emus are mechanically connected to each other by tendons.

And the researcher sees something else. If he angles one of the dead emu's legs as if the bird were walking, then the foot folds backwards. Could this mechanism explain why such a large animal can not only run very fast, but also stand effortlessly for hours? Badri-Spröwitz has become curious. He now has a theory that he can investigate.

A mechatronic model of the running bird's legs should help him with this. In September 2017, Badri-Spröwitz and his PhD student Alborz Aghamaleki Sarvestani begin constructing BirdBot. Biomechanics translate nature into technology, but they need to simplify it. The movement sequences of animals in which the skeleton, muscles, tendons, and fascia interact with one another are too complex. All in fractions of a second and with millimeter accuracy. "The transfer to mechatronics is difficult," says Badri-Spröwitz.

Until now, two-legged robots have usually had a motor on the knee joint that switches on when stationary and works against gravity and carries the weight of the machine. When the robot is walking, the motor turns off as the leg swings forward and turns on again just before the foot touches the ground. An energy-intensive interplay that must be precisely controlled by sensors. In order for the robot not to fall, the motor has to work and pause at the right time – i.e. switch over within a few milliseconds. This makes this type of robot error-prone. YouTube has examples of what these mistakes can look like. Between 2012 and 2015, the Defense Advanced Research Projects Agency (Darpa), a US Department of Defense research funding agency, hosted an international robotics competition, a kind of world championship for robots. The prize money was high, as was the reputation of the participants. The ro-

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bots had to master obstacle courses, climb stairs, or drive a car, for example. It did not always work. In videos accompanied by cheerful tinkling piano music, you can see, for example, how a robot reaches for a valve, misses it, and drunkenly tilts to the left. Another film shows a robot that wants to get off a quad, starts to wobble, and finally plummets to the floor. Even running does not go smoothly. There is a robot that bends its left leg forward – only to stagger on it and tip over backwards. All this is funny to watch and shows that it is not so easy to develop a mobile robot.

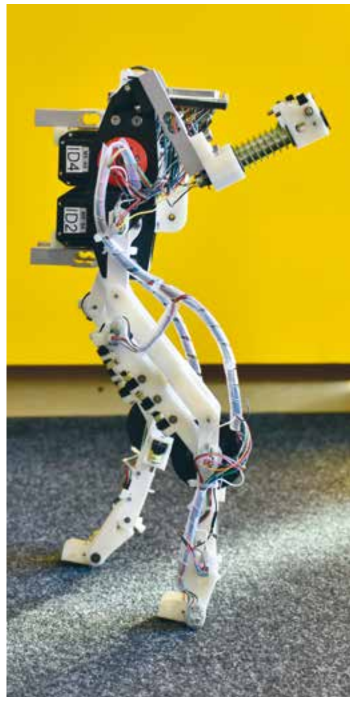

PHOTO: WOLFRAM SCHEIBLE FOR MPG

Legs instead of wheels: with the BirdBot mechanism, large robots could work on construction sites or in agriculture, for example.

The Foot as a Switch that Releases the Leg

This is why Badri-Spröwitz pursues a different approach to help a robot walk. He is guided by the musculoskeletal system of the emu, which he studied in London. He designs the foot of the BirdBot robot in such a way that it is mechanically connected to the other leg joints via cable systems made of artificial tendons and pulleys. Where other robots need a motor to stand, BirdBot uses a simple spring that carries the weight. This saves energy, but only when standing. When running, or more precisely when lifting the leg, the stiff spring would hinder the movement and actually cost more energy. Since the motor would have to work against it, it would be overloaded.

But Badri-Spröwitz has also solved this problem and is once again guided by biology. In the Stuttgart laboratory he explains how he found the solution. Basically, most robots with legs run like humans. Put very simply, this is how it works: when we lift the leg so that it does not drag over the ground, we contract the muscles that bend the leg. The muscles that stretch the leg are relaxed. If we now swing the leg forward, it can move freely. When standing, on the other hand, the extensor muscles are active. When we walk, we switch back and forth between these two modes. Running birds, which, unlike humans, can stand without any muscle effort, apparently walk a little differently. The difference, Badri-Spröwitz suspects, could also help him solve the problem with the obstructive spring in the robot. The crucial question he asks himself is: why does the emu fold its feet back when running?

In biology, this question has not yet been conclusively answered. Badri-Spröwitz, however, has a suspicion. This is why he designed the toe of BirdBot to work as a switch to deactivate the spring when running. Through the movement of the foot, the tendon is lengthened and the tension is removed from the spring. This works in a similar way to a push puppet. These collapse when you press a button in the base. In the robot, a similar mechanism allows it to pull up the leg in the swing phase without working against the spring. The leg then swings loosely. BirdBot therefore only needs two motors per leg – one at the hip joint and one to bend the knee in the swing phase. The leg does the rest by itself. However, whether running birds really move according to a similar principle has yet to be verified by biology. According to Alexander Badri-Spröwitz, the interpretation that the folded back foot relaxes a tendon that stabilizes the emu and the ostrich when standing is new. In any case, the mechanism saves energy for the robot. “Compared to other running robots, BirdBot requires only a quarter of the energy when walking,” explains Badri-Spröwitz.

There is still a lot of work to be done by the research team. Badri-Spröwitz wants to incorporate even more biological mechanics into BirdBot in the future – for example, three toes to stabilize the robot. “The T-Rex had three big toes, the arrangement of

PHOTO: DLG MPI-IS & UC IRVINE

STRAIGHT TO THE POINT

Running birds can stand effortlessly and run quickly and efficiently despite their heavy weight. The reason for this could lie in the structure of the tendon apparatus of the legs, as a Max Planck team has found out.

Following the example of running birds, the researchers have designed an energy-efficient robot that moves with fewer electric motors and simpler control than conventional two-legged robots.

The locomotion mechanism enables the construction of larger robots than has previously been possible. Such robots could replace heavy machinery, for example, on construction sites or in agriculture.

which was probably efficient and functional for walking and hunting," he explains. "These animals could get insanely big and also walk fast on boggy ground," he says. BirdBot is still a long way from that. In an adjoining room of the Stuttgart laboratory, the researchers show what the future might look like. On the wall hangs a two-meter-long model of a BirdBot leg, made of solid wood. Robots with such long legs do not yet exist because they cannot be equipped with electric motors that could move the corresponding weight. "With our technology, however, there is no size limit for the robots," explains Badri-Spröwitz, pointing to the model. The spring and joint system takes a large part of the load from the motors.

At the Max Planck Institute, Badri-Spröwitz and his team are conducting basic research into new possibilities for robot locomotion. Meanwhile, the first companies are already launching two-legged robots on the market. For example, Atlas, a 1.5-meter tall robot weighing 80-kilograms, from the American company Boston Dynamics. It can move freely both in buildings and off-road, can pick up boxes from the floor or jump over a tree trunk when running. Unlike BirdBot, its mechanics operate hydraulically. This allows Atlas to move in a human-like way and gives it a lot of power; overloading of the motors is not an issue. But the powerful movement mechanism also makes the robot dangerous to humans. In addition, its elaborate control system is quite error-prone. Robots that run in an energy-efficient way using electric motors, thanks to the BirdBot mechanism, offer a safer and more reliable alternative. Which system is more suitable also depends on the field of application. The question remains whether we will ever see energy-efficient robots on construction sites, as harvesters or in space. Alexander Badri-Spröwitz laughs and says, "Definitely. It will not be very long."

Playground for techies: in his doctoral thesis, Alborz Aghamaleki Sarvestani made BirdBot run and analyzed its gait in experiments on a treadmill. For example, he used a high-speed camera (image center) to shoot slow-motion videos of the robot.