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It took a while to discover the secret, but two-legged robots can at last get around as gracefully as humans. Philip Ball reports

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BODY:

THEY'RE everywhere. From the Imperial Walkers of Star Wars to the alien tripods from War of the Worlds , there's something about walking robots that captures the imagination. Maybe it's that they look alive. Maybe it's that machines with two legs look human. Whatever the reason, they have given engineers a headache for decades: making robots that walk well has been an enormously difficult trick to pull off.

Until now, that is. It seems walking robots are finally up and running. Surprisingly, we may have toy-makers to thank for this. In 1938, the American inventor John Wilson filed a patent for a toy that, when placed on a gentle slope, would walk on two pivoted legs with a comical waddling motion that served to lift the swinging foot clear of the ground. Wilson's "Walkie" waddled its way to success, and its descendants can be found in toyshops to this day. These gizmos don't need batteries or clockwork. Gravity alone is enough to set the legs in motion.

We humans don't waddle like the Walkie because we can bend our knees to ensure our swinging feet clear the ground. But the toy-makers' observation has nonetheless proved a vital one for engineers trying to recreate the human gait. Until recently, robot designers had a tendency to pack their devices' legs with ever more motors and stricter controls to direct the movements of the joints. That approach led to machines like Asimo, built by Honda. They are remarkable feats of engineering, but they walk with a slow, plodding gait that is nothing like a human's.

What the Walkie showed was that natural walking can arise from the way gravity acts on a body supported by freely hinged legs, not from precise motor control of the legs' movements. In short, walking is not active but passive. "I am appreciating more and more the insights that the toy inventors had," says walking-robot researcher Andy Ruina of Cornell University in Ithaca, New York. "I think they perhaps deserve more credit."

Biomechanics expert Thomas McMahon at Harvard University was the first to bring the Walkie insight to the laboratory. In the early 1980s, McMahon and his student Simon Mochon proposed that a leg behaves like a pendulum, swinging freely or "ballistically" under the influence of gravity, until the body's weight brings the foot into contact with the ground. What's more, they realised that this means taking a step should cost no energy once the body is in motion. "It explained why little leg muscle activity is needed during the swing," says locomotion expert McNeill Alexander of the University of Leeds, UK.

Encouraged by McMahon's ballistic-walking idea, mechanical engineer Tad McGeer, then at Simon Fraser University in Burnaby, British Columbia, wondered whether a passive walker could emulate the entire gait cycle - because of the legs' motion and gravity rather than under the influence of motors. His calculations showed that this would work, provided that the knee joint was placed a few per cent above the halfway point of the limb, which is precisely where the human leg is jointed. In a series of landmark papers in 1990, McGeer showed that a passive machine, with or without knees, could walk stably downhill with a human-like gait.

Ruina was introduced to this work by roboticist Marc Raibert of the Massachusetts Institute of Technology's then-famous Leg Lab. From that moment, Ruina was hooked on passive walking robots. By 2001, his students Steve Collins and Martijn Wisse had figured out how to make a simple biped out of rods and hinges that could stroll casually down a slope, using carefully designed feet and arms to maintain balance despite its side-to-side pitching. Their walkers showed that McGeer's ideas could be extended to increasingly lifelike robots. "Simplicity and low power are the big advantages," Ruina says.

It is only now, however, that McGeer's ideas are getting their full due. "It has taken 10 to 15 years for the impact to really sink in," says mechanical engineer and walking expert Art Kuo of the University of Michigan, Ann Arbor. Many roboticists thought passive walking was "too simple to work" on level ground. But last year, three separate teams unveiled two-legged robots with remarkably natural-looking gaits that exploit the principle of passive walking (Science , vol 307, p 1082).

These robots mark a huge step forward for the field, as they greatly simplify leg design and control and, crucially, reduce power consumption. Passive walkers get along with far less energy than actively controlled robots like Asimo, which has electric motors that continuously drive the flexing of 26 different joints. This requires so much power that Asimo's 40-volt battery, which takes 4 hours to charge, provides only 1 hour of continuous walking.

On level ground, passive walking still requires some power to make up for the energy lost each time a foot hits the floor and the body's downward motion is reversed. But here, the robot designers took their cue from natural processes. Humans pump their gait by pushing off their back foot at the start of each step. Ruina's team designed a bipedal robot with an analogous capability, provided by a spring in each lower leg that is stretched by a small motor and flexes the ankle joint when released .

They unveiled their robot at the February 2005 meeting of the American Association for the Advancement of Science in Washington DC. The Cornell walker has jointed legs a metre long, a compact torso and a slab-shaped head decorated with two eyes. Set in motion on flat ground, the device has a relaxed human-like gait far removed from the artificially deliberate steps of traditional bipedal robots and sci-fi archetypes like C-3PO. In terms of energy consumption, it is on a par with human walking, and about 15 times more efficient than Honda's Asimo.

The Cornell walker had two companions at the Washington meeting. One, modelled on an early version of the Cornell machine, was devised by a team at the Delft University of Technology in the Netherlands, where Wisse now works. The Delft team named its robot "Denise" - a pun on "the knees" - to distinguish it from earlier machines with no knees. Powered by compressed-air actuators in the hips, it is not as energy-efficient as the Cornell walker but is more stable thanks to an ankle design that borrows from the principles of skateboard suspensions. While the Cornell robot can be thrown off balance by small irregularities in the floor, being started wrongly or being touched, Denise can compensate by adjusting its footfall. "When Denise pitches to the right," Ruina says, "the whole machine rotates slightly about a vertical axis, causing the next step to be slightly to the right."

The other robot, called "Toddler", came from a team at MIT led by roboticist Russ Tedrake. Toddler is the smallest and lightest of the three, weighing just 2.8 kilograms and standing 43 centimetres tall. It is mechanically less sophisticated and less energy-efficient than its rivals, but in another respect it is more ambitious: it "learns" to walk by sensing the tilt of its body and other variables. An on-board computer adjusts command signals sent to electric motors that flex the robot's ankles. It can adapt to a few different types of terrain, such as carpets and tile floors.

Impressively natural as these walkers look, not everyone agrees that passive walking is the right strategy for developing robust walking robots. "Passive machines don't steer or handle obstacles," roboticist Chris Atkeson of Carnegie Mellon University in Pittsburgh points out. They are "like a car with no driver or power rolling down a hill" and they struggle with floors that are not flat or rigid. Forget trying to navigate stairs or walk through a forest. Collins takes a similar line. "I don't really see them as being very useful stand-alone products," he says. "My interests are purely in using them to better understand humans."

One lesson from passive walkers is that compliance - the softness of the joints - is important for stability. But you can have too much of a good thing. When Atkeson's group and the Delft team compared Denise's gait to that of robots with more actively controlled joints, including an electronically powered biped developed at Carnegie Mellon, they found that too much passive compliance in the hip joint can be destabilising. The strike of a foot on the ground can throw the body off balance and make it wobble.

So Atkeson and others are looking for ways to get the best of both worlds. "I think that human-like robots that are both efficient and can steer will combine elements of passive dynamic walkers and powered machines," Atkeson says. He predicts that practical bots will be powered on most if not all of their joints, though he cautions that not all roboticists share this view.

Spring in your step

If these strategies work for walking robots, might they work for humans too, to make getting around easier? It's an important issue for users of prosthetic legs, who typically expend 20 to 30 per cent more metabolic energy to walk than able-bodied people. The extra effort is especially problematic for people who suffer from vascular disease, who make up a high proportion of leg amputees in developed countries.

At the University of Michigan, Kuo and Collins are applying insights from passive-walking studies to develop prosthetic legs that are less energy-sapping. Noting that most of the work in walking goes into redirecting the body's downward motion when the forward foot hits the ground, they are starting to design artificial legs with spring-like units that can store energy and release it during the stepping cycle. "The basic idea is to store the energy from the downstroke, using a spring in the foot, and use it to propel the upstroke," Collins says.

Many existing prosthetic legs already incorporate springs and rubber bumpers in the foot or between articulating joints. But Collins thinks that he and his colleagues have hit on a more efficient arrangement. The main difference between their design and others, he says, is that the energy is returned at the time it would be supplied by the ankle during normal gait. In one device, a spring stores the energy at the heel when the foot strikes the ground and returns it at the toe during push-off.

Even more dramatic enhancements may be possible. In a paper to be published in the journal Physical Review E , Ruina and his student Mario Gomes have shown that a passive walker with spring-loaded legs can in principle walk over level ground with no energy cost at all, and so keep walking forever with no energy input. Of course, no real walker could do that; friction and air resistance will inevitably cause some energy to leak away. But the researchers were interested only in the walking action itself, so they ignored these losses in their model.

Their strategy is to eliminate energy-dissipating downward collisions of the foot with the ground. Ruina and

Gomes showed that such a collision-free gait exists for a walker made up of two rigid legs connected by a hinge and springs to a torso that tilts backwards and then forwards during each step. In the middle of the step, the walker scuffs the swinging leg along the ground, and in the model this scuffing is treated as frictionless. In practice, friction between the foot and the ground would lead to energy losses, but by giving the legs knees, scuffing could be avoided without fundamentally altering the gait.

A human walk doesn't look anything like this. But the model raises the intriguing idea that by hooking ourselves up to a system of weights and springs that produce a similar effect, we might be able to walk immense distances at very little metabolic cost. "I think it would be possible to build passive prostheses that reduce the cost of walking," Ruina says. "I don't know how clumsy they would be, but I have great confidence that such things could be built in the relatively near future."

Simple mechanical devices that reduce the energy cost of walking and running might also improve the performance of sprinters, marathon runners and high jumpers. "I do think that human performance can be augmented," says Collins. Such devices might pose a problem for sports regulators, though they wouldn't do much more than springy-soled running shoes do at present: they wouldn't use anything more than the energy the athlete's body produces by itself.

The dilemma is not likely to arise any time soon, however. "We're probably a long ways from energy-saving Nikes," Collins admits. "I think the Olympics are safe from us for quite some time."

It's the energy, stupid

Philip Ball

Why do humans walk and run when we could use any number of gaits? Andy Ruina and his student Manoj Srinivasan at Cornell University in Ithaca, New York, think they can explain. A simple mechanical model predicts that walking and running take less energy than other possible gaits (Nature , vol 439, p 72).

The researchers idealised the human body as a mass supported by two legs that swing at the hip. To allow the foot to push off and clear the ground on each swing, they included a piston at the knee that extends and retracts the leg like an old-fashioned telescope. They looked for motions that would propel the body for the least amount of piston work.

By varying the force of the pistons, the researchers were able to generate an infinite number of gaits. Out of these, they found that just three seemed to minimise energy cost. One was a standard walk, with legs swinging and the body bobbing up and down. At higher speed, the cheapest gait was a run, in which the leg flexed with each step to push the body into flight. Intriguingly, at speeds in between, Ruina and Srinivasan discovered a third gait, like an odd cross between walking and running, but they suspect it might disappear in a more realistic model that includes muscles, tendons and pivoting ankles.

Does this mean nature has designed us to be walking and running machines? Not so fast. While biomechanics expert McNeill Alexander of the University of Leeds, UK, recognises the model as "a beautiful and enlightening theory", he cautions that "it is so greatly simplified, in comparison to human walking, that it cannot tell us anything about human evolution".

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