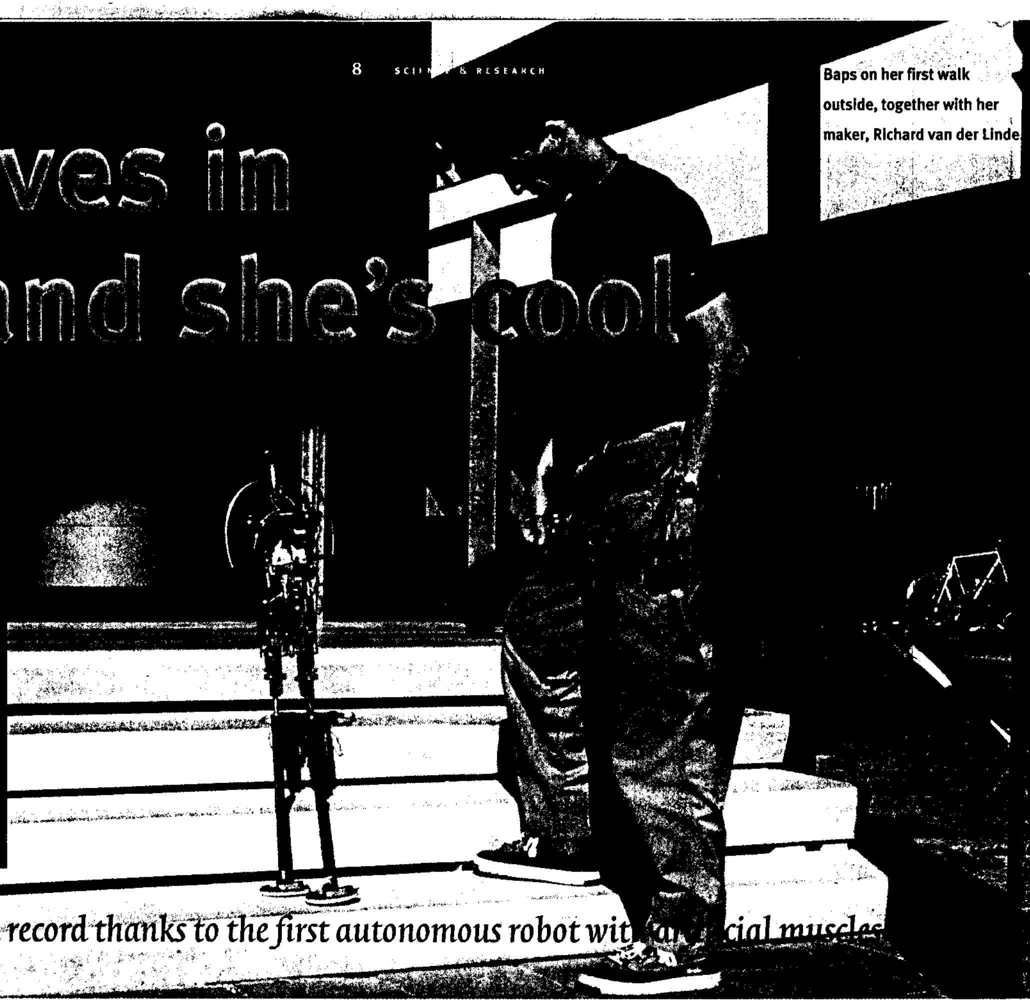
HARM IKINK

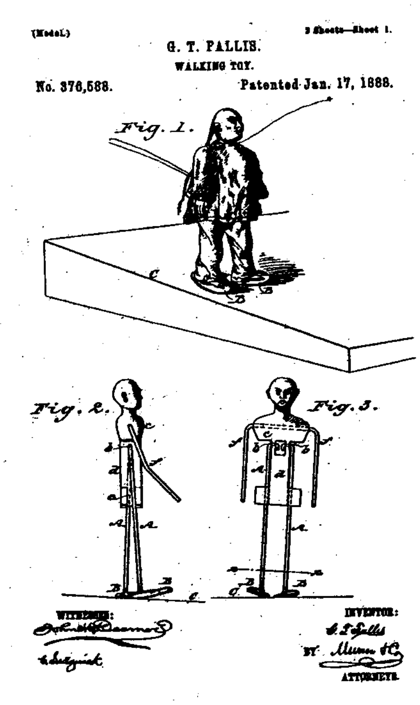
# Baps lives in Delft, and she's cool

Baps is the autonomous, biped robot developed by Richard van der Linde at the Man-Machine Systems & Control section at the department of mechanical Engineering at Delft University of Technology. Baps is the world's first autonomous, biped robot driven by artificial muscles whose mechanical power consumption is less than a human's. The project is being funded by the Netherlands Technology Foundation STW. A worldwide patent application has been filed for the principle on which the walking robot from Delft is based.



Baps on her first walk outside, together with her maker, Richard van der Linde

## *An energy efficiency world record thanks to the first autonomous robot with artificial muscles*




This 1888 patent already shows the ballistic walking principle. A simple wire figure is configured to produce a walking motion. A slight incline provides the necessary activating power to maintain the motion.

Richard van der Linde has always been very keen on robots. He modeled his mechanical engineering studies around them, got his degree on the subject, and soon, when he gets his doctorate with the design of a new type of robot, the cliché of the dream come true will be at the tip of everybody's tongue. Even so, the dream had a touch of nightmare about it as does all experimental research. 'There isn't a single aspect of Baps that didn't have us stumped at one time or another', Van der Linde recalls. 'The next few months will be extremely important for gathering experimental data to support the theoretical part of my thesis. That's the problem when you come up with something new. As long as you haven't made anything yet, you can't have any data.'

**Ballistic** ¶ Baps – apart from being a reference to Van der Linde's girlfriend Barbara – stands for Biped with Adjustable Pneumatic Springs. Which is something altogether new. Although biped robots have existed for some time (the Japanese have developed a spectacular example), none of them are based so strongly on the concept of human walking as Baps is.

Taking his cue from fellow researchers, Van der Linde has dubbed the concept «ballistic walking». As early as 1836, researchers demonstrated that the cadence of human walking closely resembles the movement of a single leg suspended like a pendulum. In other words, humans tend to walk at the inherent frequency of their mechanical systems. An important advantage of this principle of walking is that it minimizes power consumption.

In the literal sense, ballistic walking is walking with a free, unpowered movement. Many toys – of which Van der Linde has a small collection in his office – are based on this principle. It may be an exaggeration to call it walking, but even so, the toy figures and animals go waddling down a slight incline under gravitational power. After some detective work Van der Linde discovered that the first patent on the ballistic walking motion was in fact granted for a toy application, and dates as far back as 1888.

Van der Linde: 'All we did was to extend the concept to a robot design that is still very simple at heart, but which resembles a human being rather better than the simple toys you see here.'

**Japanese 'toys'** ¶ At the start of the project, in 1996, Van der Linde was afraid that other research groups, such as the famous Leg Laboratory at the Massachusetts Institute of Technology (MIT) would overtake him, but that didn't happen. As it was, competition came from a very unexpected direction. 'We have seen enormous developments in the world of robots since we started research on this subject in Delft', Van der Linde says. 'Japan in particular has made real progress. However, they tend to have a different way of doing things than we have.'

Awe-struck, Van der Linde talks about the Humanoid, a real walking, human-like robot constructed by Honda. The presentation of the robot, in late 1997, was a bombshell. Van der Linde is still impressed every time he looks at the film clips he downloaded from the Internet.

The images are spectacular. With its American football player looks, the Honda robot is overwhelming in appearance. Its performance is even more impressive. If you did not know better, you would swear you were looking at a person in a robot suit. Arms, legs, head, they all seem to move like a human's.

**Climbing stairs** ¶ 'The humanoid was a total surprise for all the people working on robots', Van der Linde says. 'It is said that Honda secretly spent an estimated amount of some 400 million US dollars on the development of the robot. The result is fantastic. It can even climb stairs.'

It also plays soccer, as Honda's latest promotional films reveal. The Robocup soccer championship for robots (the European version of which took place in Holland from 29 May to 2 June this year) has already reserved two special divisions for humanoids. At the Melbourne Robocup, last September, there were even three humanoid divisions.

The human-like behavior of Honda's Humanoid is the result of a mechanical design that strongly resembles the kinetics of the human body, powered by electric motors and controlled by powerful computers. Its smooth movements are the result of motion capture techniques in which the control computers received their instructions based on data from a video analysis of human beings in motion. Advanced electric motors coupled to sensor systems enable the robot to reconstruct the movements.

**Simplicity and elegance** ¶ Although Van der Linde was impressed by the products of Honda's robotic experts, he remained undaunted. The result – a walking robot – may be the same, but there is an enormous difference in concept between Baps and the Humanoid. It is the difference between simplicity and complexity, between elegance and brute force.

The Humanoid, with its limbs full of sensors and electric motors, is very complex and heavy. Both these aspects hinder the robot's full autonomy. Its power consumption equals that of an electric fire, and the batteries it carries on its back are drained in fifteen minutes.

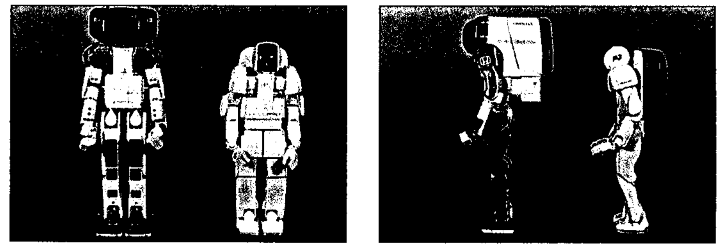
Van der Linde compares the robot's power consumption to a human's: 'We can walk about a 1,6 kilometres on the energy provided by one slice of wholemeal bread. The Humanoid's 4000 watt power consumption means that it will not even cover one hundred metres on that amount of energy.'

So, the Honda robot uses sixteen times as much power to move as a human does. This can only be partly explained by its higher weight, since the Humanoid weighs only two to three times as much as a man. In fact, the electric motors are more efficient than muscles. So why the enormous difference in power consumption?

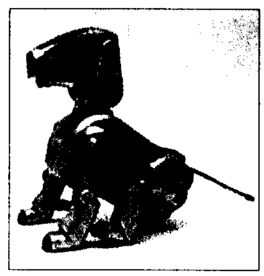
Van der Linde: 'It's because Honda's robot, like practically all walking robots, is based on a completely unnatural design. The concept has nothing in common with the concept underlying the way we humans walk. Now if you use the ballistic principle, you find that you don't really need all that power just to keep walking.'

The scientist compares it with the motion of a swing. By giving a small push at just the right moment, a mother can make her child swing in a wide arc. If she were to try to set the swing in motion by turning the shaft from which the swing is suspended, she wouldn't get very far.

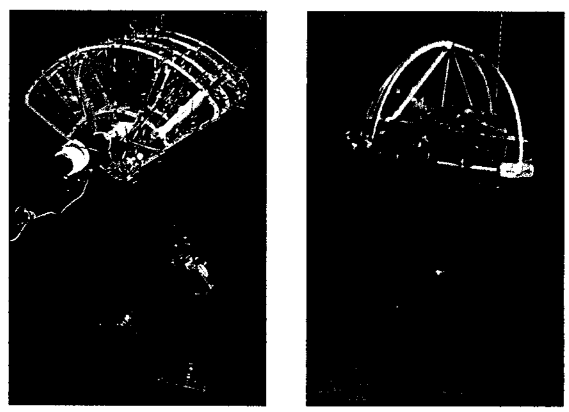
'What you see is that, since its pendulum properties practically make the swing move by itself, all you have to do is add enough power to sustain the motion.'



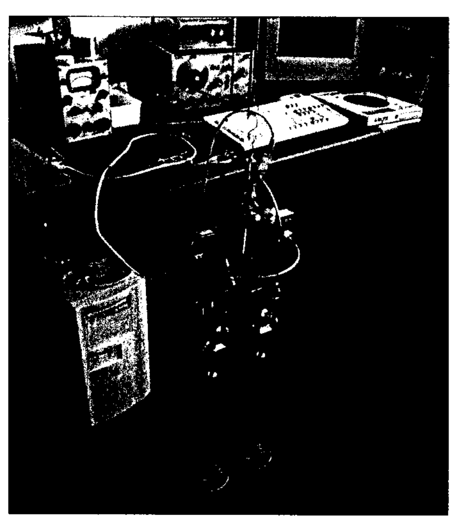
Honda's first autonomous humanoid walking robots. P2 (on the left) weighs 200 kg and consumes about 4000 W. Its younger brother, P3 (on the right), weighs a good 130 kg.
(http://www.honda.co.jp/english/technology/robot/index.html)



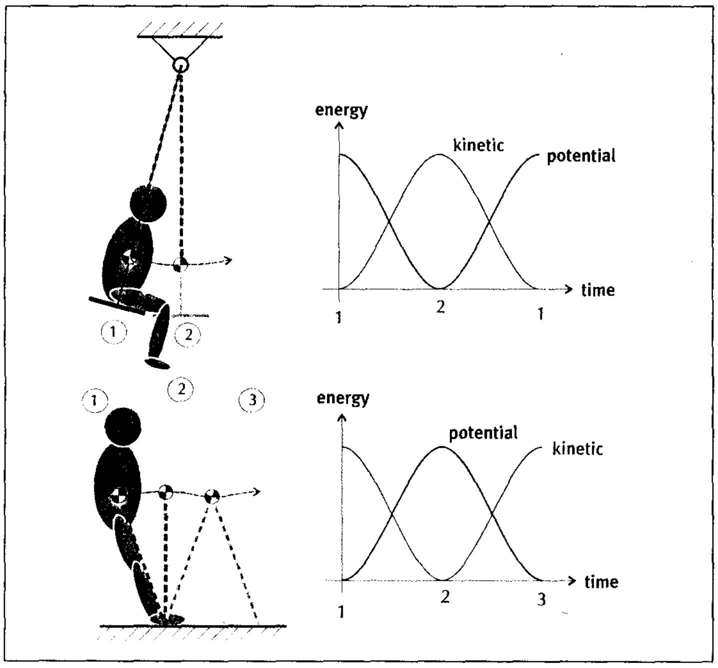
Walking on four legs is much simpler than walking on two legs. This is clearly demonstrated by the weight and size of the Sony Aibo robot dog, which weighs only 1.2 kg and runs 1.5 hours on a battery weighing 180 g with a capacity of 2900 mAh, putting the power consumption at 12 W. Aibo costs only US $ 2400.
(http://www.aibo-europe.com)



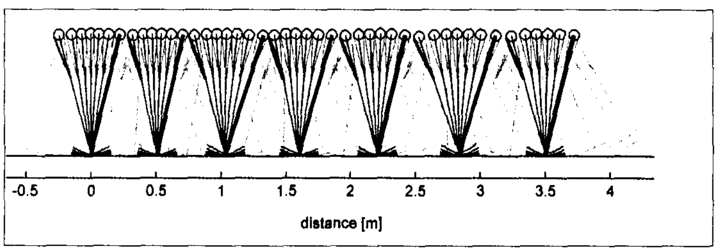
The «Spring Flamingo» and «Biped Hopper» robots were created at the MIT Leglab. These fantastic creatures can walk and run, respectively. The latter can even turn somersaults. However, neither of these robots can work without the umbilical cord connecting them to their surroundings and providing them with power.
(http://www.ai.mit.edu/projects/leglab)



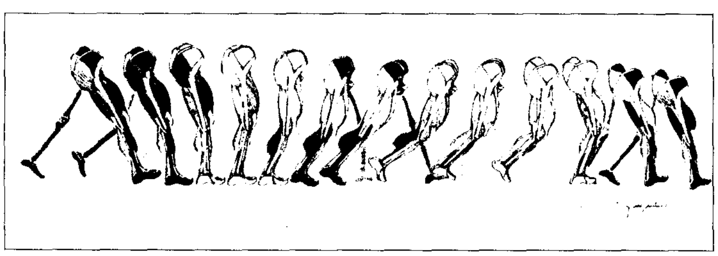
Baps (Biped with Active Pneumatic Springs), the autonomous robot designed by Richard van der Linde, hangs in the startup position, connected through the Internet to a startup computer by means of an umbilical cord. Baps weighs only 3 kg. Once the built-in computer has received its instructions, the connection can be severed, leaving Baps free to move on her own.




The natural frequency of a mechanical system is the frequency at which the system prefers to oscillates. The natural frequency become apparent when left to move freely, as with a child on a swing. Once a certain oscillation pattern has been established in which both the frequency and the amplitude remain constant (referred to as a limit cycle), potential energy (derived from height) and kinetic energy (derived from speed) can alternate in a practically perfect cycle. This results in a very efficient mechanical motion. Humans and Baps both use this principle. The walking motion could be considered as an inverted swing, but a number of aspects make walking considerably more difficult than swinging, including switching between legs, rolling the foot, stability, pushing off, and linked movements.




A 7-step simulation of a model comprising three masses (two legs and a torso) and 6 spring/damper elements (four muscles in the hips, and two in the stance leg). The model is representative for Baps. The thickness of the lines representing the legs and hip muscles are a measure of the stiffness or activity. A slight disturbance was introduced at the first step. Within seven steps Baps manages to return to her own walking pattern (the limit cycle) by creating a balance between the dissipated energy and the added energy (muscle activity).



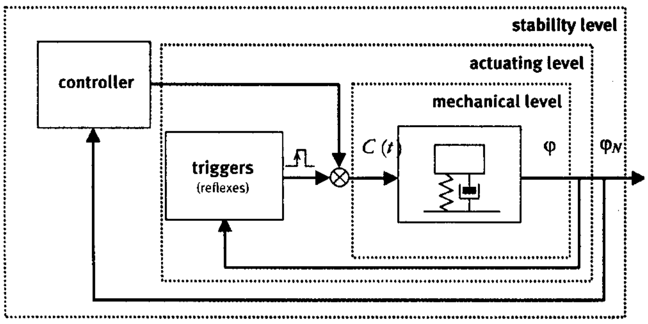
The muscle activity of the major muscle groups in the lower human limbs during normal walking. This clearly shows the phasic activity, with the muscles tensioned only part of the time. (Source: Human Walking, Verne T. Inman, Henry J. Ralston, F. Todd, Williams & Wilkins, Baltimore/London 1981.)

**Downhill** ¶ The feasibility of the ballistic principle for biped walking robots has been demonstrated in various experiments. An important pioneer in the field was the American researcher, Ted McGeer, at the Simon Fraser University in British Columbia, Canada. Around 1990 he conducted extensive research into ballistic biped robots that, like the waddling toys, walk downhill.
The ballistic principle offers the advantages of a very low power consumption and a very simple mechanical construction. The major drawback is that the walking motion is determined by the system's inherent properties such as mass distribution and rigidity of the components.

**Artificial muscles** ¶ In Baps, Van der Linde has managed to overcome the major limitations of the ballistic principle. The crux lies in the use of devices known as McKibben artificial muscles. Van der Linde was the first person in the world to combine the principle of the ballistic robot with artificial muscles. The pneumatic «muscles», named after their inventor, consist of special rubber tubes inside sleeves that become stiffer when the air pressure inside them is increased. Up to a certain level their mechanical action is analogous to the way human muscles work, enabling them to feed energy to the system to compensate for the friction in the mechanical ballistic system. This enables Baps to walk on flat surfaces. Another major function of the pneumatic muscles is to change the natural frequency of the robot's legs by increasing or decreasing the basic pressure. The result is that the robot can walk more quickly or slowly.
'Another advantage of these muscles is that they come quite close to the way their human counterparts work', Van der Linde says. Humans have ligaments that temporarily store part of the motion energy. These artificial muscles do the same. It is the combination of mechanisms in the human walking system exchanging potential and kinetic energy that makes it so efficient. The design of Baps closely mimics that.'
Back in 1997, using compressed air from the laboratory network, Van der Linde demonstrated the suitability of McKibben muscles for Baps, but it wasn't until this year that a pneumatic system became available that could control the robot's muscles. It was developed by science graduate Jan van Frankenhuyzen, and manufactured at the faculty's in-house instrument workshop by John Dukker and Ad van der Geest. The pièce de resistance of the pneumatic system is a miniaturized switching block, a masterpiece of micromechanical instrumentation that contains the pressure regulators. Small $CO_2$ cartridges supply the energy, in the form of gas pressure, to power the muscles.

**Reflexes** ¶ The introduction to the ballistic robotics of artificial muscles may have been a major innovation, but Van der Linde took things a step further in the control of those muscles. His system is based on the concept that a major part of the walking motion of human beings is based on reflexes. In other words, the control of the motion does not take place in our brain, but at a lower level of the nervous system.
An article in which he described the concept of reflex-based control of the walking motion, in the leading Biological Cybernetics periodical, generated a lot of interest among neurobiologists. Researchers at the universities of Twente (The Netherlands) and Aalborg (Denmark) recently published results that confirm the fact that human walking involves a major reflex action.
Van der Linde uses two reflex actions to control the muscles of Baps. First, the muscles (in human terms, the leg and hip extensors) are activated when the swinging motion is initiated. In addition, the pneumatics of Baps ensure that the stance leg stiffens just before the foot of the swinging leg touches the ground.
'The biological analogy is the extension of the foot of the stance leg, in biomechanical terms called plantar flexion. The effect has been confirmed by the Researchers in Twente and Denmark.'
The great thing about using the reflex principle is that it actually determines the walking characteristic itself. In simulations with reflex-controlled muscles Van der Linde has managed to create specific walks, from Charlie Chaplin's shuffle to John Travolta's macho swing.

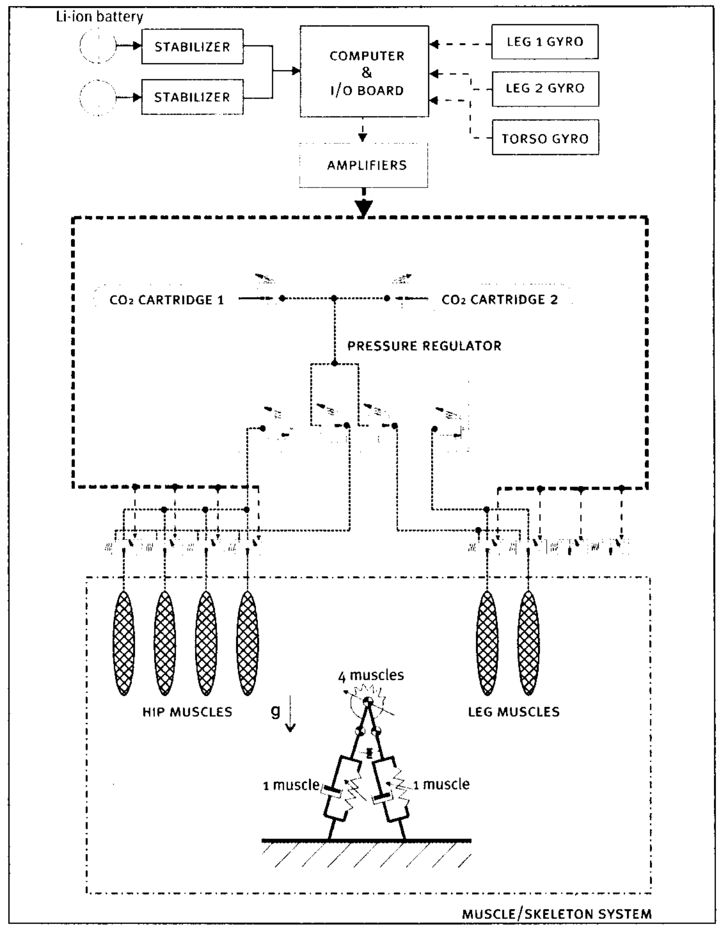
**Umbilical to the Internet** ¶ In order to create a truly autonomous robot, in addition to the muscle reflexes Van der Linde had to give Baps an additional control level. This level ensures that Baps can deal with disturbances of the



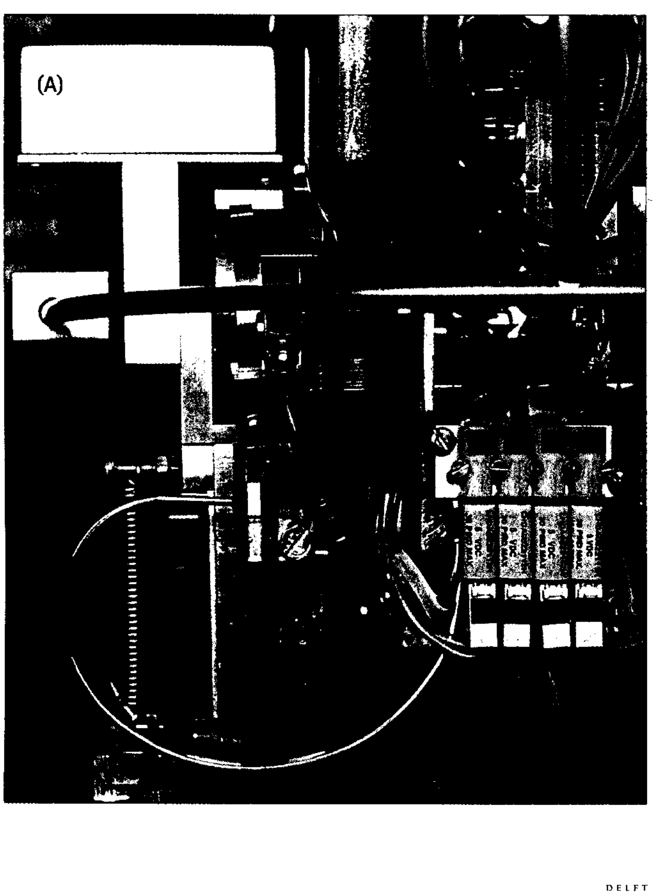

A functional flow diagram comprises three levels: motion, control, and stability. The mechanical system supplies the required proper motion. This is driven by a triggered change in stiffness which maintains the system's oscillation. If necessary, a controller changes this in order to increase the stability.

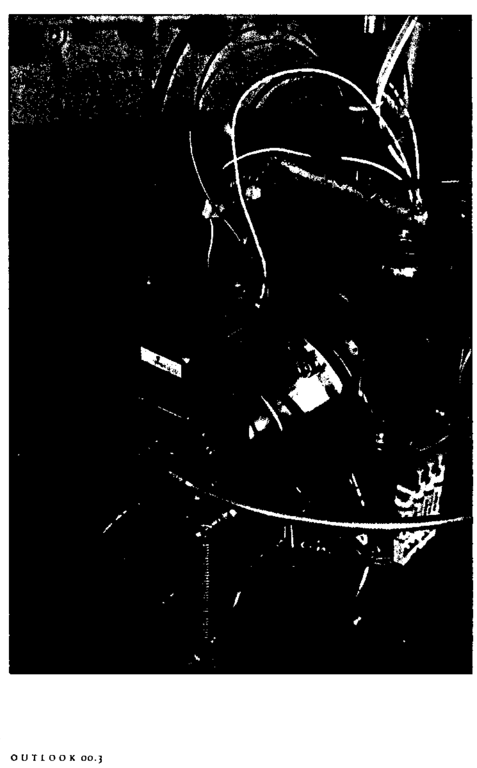
normal walking pattern. If the walking frequency changes as a result of an uneven surface or other irregularities, the extra control system activates the muscles in such a way as to ensure that Baps will return to a stable walking motion. This control level in particular requires some processing power, so Baps has an onboard computer. Baps carries her «brain» at hip level. It comprises a 133 MHz Pentium processor with 32 MB of RAM and 48 MB flash memory storage capacity. The Linux software was custom-written for this application. The electronics are powered by a pair of lithium-ion batteries of the type used in video cameras. A short length of cable dangling from the robot is the umbilical cord. This is used to connect Baps to a network so Van der Linde can use another computer to feed initialization and activation commands to her. Once Baps is on her own legs, the umbilical connection can be cut, she can go her own way.

The network connection even makes it possible to create an umbilical cord spanning the world. Van der Linde can use the Internet to issue commands and retrieve measuring data.



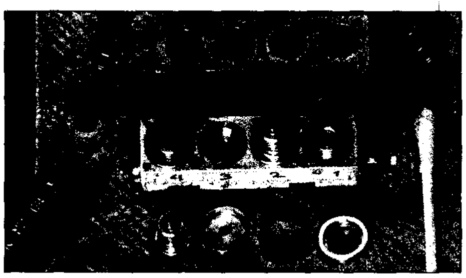

The mechatronic circuit diagram of Baps, showing the electric (red), pneumatic (blue), and mechanical (black) circuits. All these components are carried onboard Baps, affording the robot full autonomy. A lot of trouble has been taken to make all the components as small as possible. Most of the pneumatic switching logics even had to be developed in-house.



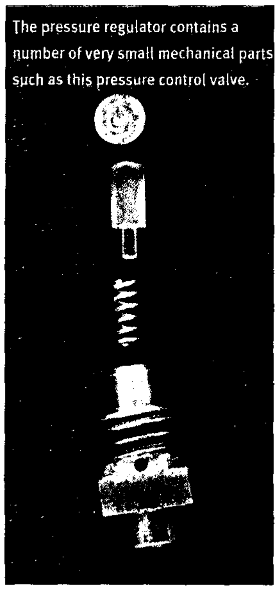



(A) Detail view of the pneumatic circuit, showing a $CO_2$ cartridge (top centre), and four valves in front of the pressure regulator.

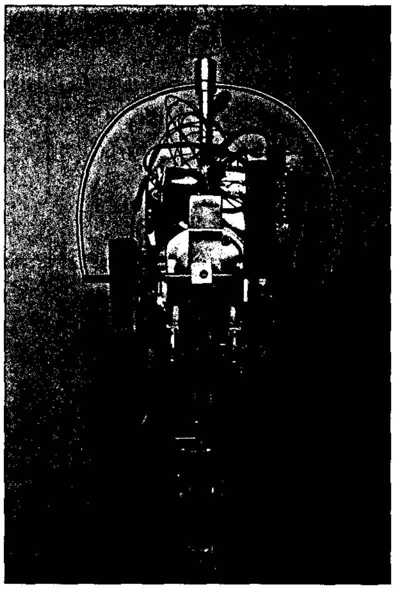
(B) Each leg carries a gyroscope sensor (the labelled box) to determine the orientation and speed of Baps. A third gyroscope is hidden among the other components in the torso.



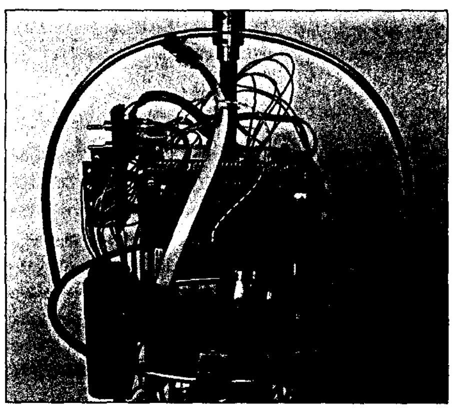
Disassembled pressure regulator specially developed for Baps by Jan van Frankenhuyzen. The miniaturized regulator reduces the pressure from 10 bar to an accurately controlled muscle pressure (2 - 3 bar).



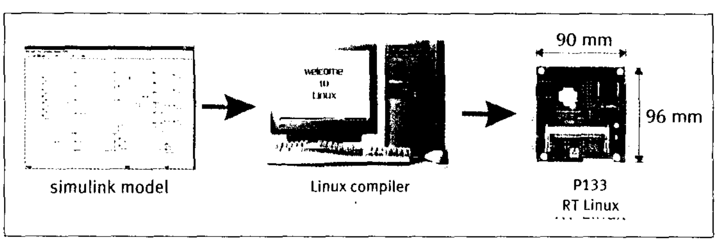
The pressure regulator contains a number of very small mechanical parts such as this pressure control valve.



Side view of Baps showing three of the six leg muscles. The outermost muscles are hip muscles, the muscle in the middle is the leg extensor. A thin stainless steel band connects the hip muscles to the hip, acting like a ligament.



Baps has a brain comprising a mini Pentium computer running the Linux operating system. The computer is powered by two Li-ion batteries. The connector at the top provides the link with the Internet.




For experimental purposes it is useful to be able to test various control strategies in a minimum of time. For this reason the software for Baps is created using a generic method. First, a neural controller is developed using MATLAB/SIMULINK software. The resulting C code is then compiled into an RT Linux program, which is then uploaded to the mini Linux computer in Baps through the Internet connection.

**Rehabilitation technology** ¶ The first steps taken by Baps are in fact the birth of the world's first autonomous, biped robot driven by artificial muscles and with a low weight and an even lower power consumption. Whereas the human body uses about 2 W/kg for walking, Baps makes do with less than half that amount. And compared with the Honda robot, Baps is amazingly efficient. A conservative estimate puts the power consumption of the Japanese product at 16 W/kg, Van der Linde says. Her very low power consumption makes Baps highly suitable for applications in the rehabilitation and entertainment fields. Businesses from both sectors are represented in the supervising committee of the Netherlands Technology Foundation STW, which funds a major part of Van der Linde's research. Low energy needs are important for rehabilitation aids if they are to stress the user as little as possible. Further research with Baps is expected to provide insights that will improve the design of ortheses and prostheses. The entertainment industry, theme parks in particular, are interested in Baps because they have been waiting for years to find affordable autonomous robots. The simple, low-power design is a major step in the right direction. In addition, her low weight makes Baps inherently safe in interaction with visitors.

**Bob** ¶ Work is already well under way on a new generation of Delft walking robots. Baps has recently received company from Bob, the brainchild of Van der Linde's graduate student, Martijn Wisse, who will soon take over the project from Van der Linde. Bob will have knee joints and a torso, and the plan is to include a simple control system, so that it is inherently more stable and will require less computing power. The aim is to make things even lighter and with an even lower power consumption. Van der Linde is confident they will succeed.

'We have been working on this for four years now, and by now we have established a very good reputation. Baps and Bob will help us show the world that this is a group to be reckoned with.'

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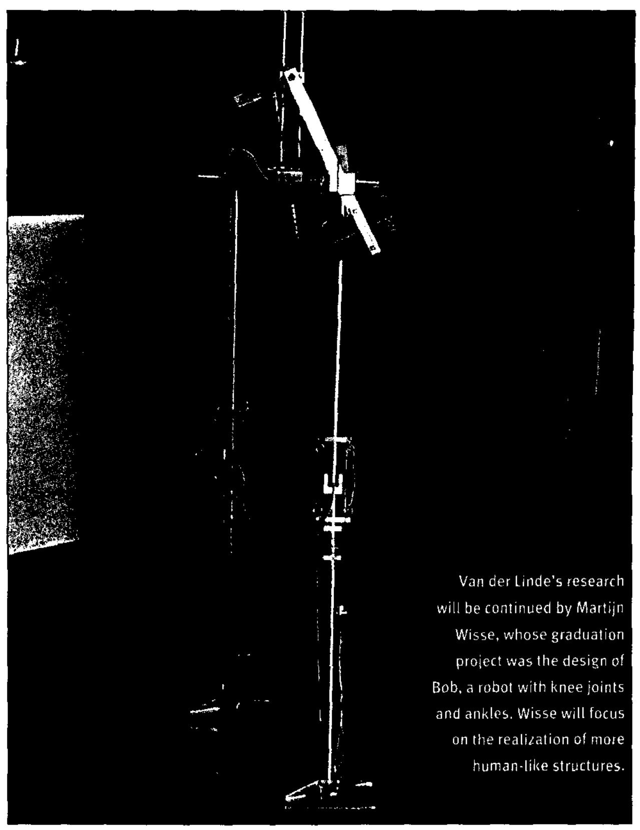

Van der Linde's research will be continued by Martijn Wisse, whose graduation project was the design of Bob, a robot with knee joints and ankles. Wisse will focus on the realization of more human-like structures.