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Transforming Biological Patterns into Robot Concepts

Teresa Zielińska
Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics, Nowowiejska 24, 00-665 Warsaw

Abstract: Biology not only provides inspiration in the design of walking machines, but also suggests detailed design solutions. Concise information on legged locomotion in the animal world is presented, and the relationships between engineering solutions and the biological world are shown. The construction of animal legs is briefly described and the most commonly used leg structures for walking machines are discussed, including references to biological patterns. Examples of bio-inspired walking machines developed by our team are given and several concepts of bio-inspired robots are discussed. The general aim of the article is to show how knowledge of the animal world inspires innovative design solutions for robots intended for practical applications.

Keywords: walking machine; design; biological template; hexapods; quadrupeds; bio-robotics

1. Introduction

Invention of electric motor by M.H. Jacobi in the first part of the XIX century marked a significant step in the development of biologically inspired robotics. The fist prototypes of the electrically powered moving machines having human appearance were presented at the beginning of the XX century. Walking machines being developed since the mid of the XX century are an obvious example of biological inspiration. It is clear that biological legged locomotion is an efficient form of displacement over rough terrain. The surface may be uneven, soft, muddy and generally unstructured. Such environment is easily accessible to animals, but not to wheeled vehicles, therefore legs demonstrate a significant advantage. The capabilities of legged robots are constantly enhanced, mainly due to the advances made in computer technologies, however, how to design legged robots as efficient and agile as animals, is still an unresolved problem.

Designers of legged machines must make many choices, which determine the technical features of the developed devices. The most important are the decisions pertaining to:

- the mechanical structure and leg configuration (number of legs, their kinematic structure, joint design),
- actuating and drive mechanisms (motor types and their power),
- placement of motors and the way that motion is transmitted from motors to leg joints,
- basic types of gait (speed of motion, number of legs supporting the body during each phase of the chosen gait, duty factors, leg transfer sequences etc.).

Autor korespondujący:
Teresa Zielińska, teresaz@meil.pw.edu.pl

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An important problem is the specification of the control system (control software and hardware as well as their architectures), e.g. [29, 30, 36]. The autonomy of actions depends on the motion control principles. The information about the current machine state must be provided by internal sensors (proprioceptors). Adequately selected external sensors (exteroceptors) must provide information about the state of the environment. Sensory data must be processed and fused delivering the information used by the control software, which is responsible for the machine's ,,intelligence". The distribution of the on-board motors and electronics as well as placement of cables and sensors should be such as to avoid overheating and mutual interference. The placement of machine parts determines the location of the center of mass, what is relevant to the postural stability. Such stability is associated with the range of possible gaits and possible step lengths. During the design process, the estimation of power consumption, taking into account the machine's weight, payload, motion conditions (soft, hard terrain, inclined terrain, etc.) is very important. These data are also needed for the design of motion transmission systems and for the selection of sufficiently powerful actuators. The answer to the above technical problems is provided not only by engineers by also by biologists, neurologists or even specialists in social sciences. Biology provides inspiration, helping to release design creativity in search for novel solutions. Neurology inspires the development of control systems. Social science supports the work on robot-user interfaces and the design of human companion robots. Our paper attempts to illustrate how biology is utilized by designers of walking machines.

The paper is organized as follows. The properties of animal gaits are summarized first, presenting the method of gait description. Postural stabilization is discussed next. Animal leg structures and postures are described subsequently, considering the ways of postural stabilization. Robot leg design concepts are presented and illustrated by examples. Several biologically inspired foot concepts are presented. Finally, the role of compliance in biological and robot locomotion is summarized and examples are provided. The paper ends with concussions. Since biological legged locomotion is one of the most effective over rough terrain, our attention is focused on walking machines.

2. State of the Art. Biological and Artificial Legged Locomotion

2.1. Gait of Animals and Walking Machines

Biological patterns are commonly used as an inspiration for the selection of gait and motion synthesis. In this section we summarize the main features of biological gait. Locomotion of insects is mainly statically stable. It is described by simple rules directly relating the sequence of leg transfers with the motion speed. Static stability means that, at every instant of time, the vertical projection of overall body mass center onto the ground remains inside the polygon, the vertices of which are formed by the footprints of the supporting legs. The features of periodic statically stable gaits of insects were identified over forty years ago by Hughes and Wendler, and then summarized by Wilson [19]. They are described by five simple rules:

- the legs on one side of the body are moved one after another, and such order goes from the back to the front of the body, no leg will be transferred before the leg behind is placed on the ground,
- the transfer time is constant for every leg and does not depend on the walking speed,
- opposite legs in the same body segment are never moved simultaneously,
- time of the leg support phase (when the leg is in contact with the ground) decreases when the walking speed increases, what implies that with the increase of walking speed walking frequency increases,
- the time intervals between lifting of two adjacent legs on the same side of the body are similar, but those intervals change when the walking frequency changes.

At higher speeds, and when avoiding obstacles, insects retain dynamic, not static motion stability. The locomotion of legged amphibians and reptiles is statically stable too. Many mammals, including human beings, move maintaining dynamic, not static, postural stability. Only during the slowest gait, named quadruped crawl, four-legged mammals utilize a statically stable gait. Dynamic stability is the result of the balance of forces and torques acting on body parts of a moving animal or robot. Due to such equilibrium the body reproduces the desired trajectory of motion while maintaining the desired configuration.

Synthesis of statically stable periodic gaits is not difficult. Motion description of walking hexapods uses gait diagrams obtained from the observation of insect motion. The gait diagrams represent the timing pattern of leg transfers. The gait diagrams are also commonly used when describing the gait of quadrupeds. Figure 1 shows the diagram of the quadruped crawl, which is the slowest gait used by four-legged animals. Legs are transferred one after the other. There are also intervals in which all legs support the body. Such gait was implemented in several walking machines developed by our research team [35].

When designing statically stable gaits, not only the sequences of leg transfers, but also the leg motion ranges must be properly selected, however it is rather an easy task. When the mechanical structure and masses of all body parts are known, it is not difficult to calculate the position of the overall mass center. The leg back stance position and gait stride must be such that the vertical projection of the mass center is inside the supporting polygon, thus assuring static stability. Despite relative simplicity of periodic gait design, planning of leg movement sequences avoiding obstacles is still a valid research problem. Still there is an ongoing search for effective methods that combine real-time environment perception and motion planning.

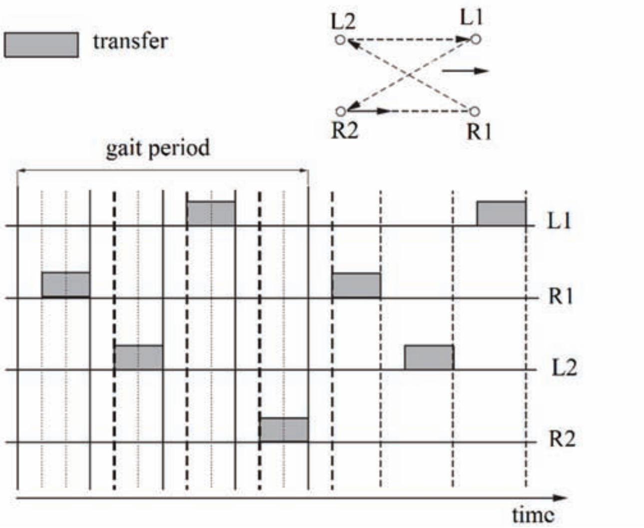

Fig. 1. Gait diagram for a quadruped crawl, L denotes the legs on the left hand side of the body and R – the legs on the right hand side, dashed vertical lines mark the beginnings of leg transfers
Rys. 1. Diagram chodu czteronożnego, L oznacza nogi po lewej stronie ciała, R – nogi po prawej stronie, przerywane linie pionowe oznaczają początki fazy przenoszenia poszczególnych nóg

The dynamic gait of quadruped mammals cannot be described as simply as those of insects. Leg transfer sequences, support time of each leg and the time intervals between leg transfers do not change in such a regular way as it is in the case of insects. The methods of designing dynamically stable gaits are more complex. Many of them take into account the ZMP (Zero Moment Point) criterion [18] in motion synthesis. Real-time postural adjustments are needed to equilibrate the acting forces and torques. Body dynamics is crucial in this case. A broad range of different approaches is employed [13, 17, 22, 27].

2.2. Animal Legs

Legged machine locomotion imitates animal locomotion. It is obvious that such locomotion is easier to achieve when the structure of the robot imitates its biological counterpart (insect, quadruped mammal or a human being). Majority of multi-legged walking machines are hexapods and quadrupeds. The leg structures and postures are similar to those of reptiles,

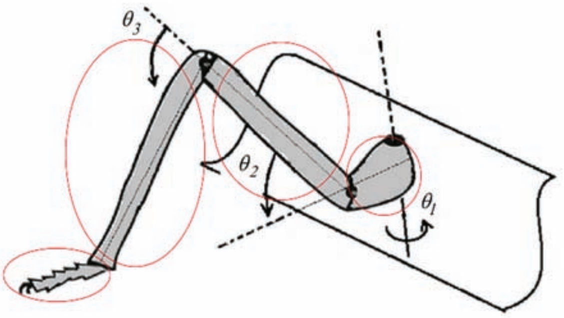

Fig. 2. Typical structure of the insect leg. The ellipses mark the main segments
Rys. 2. Typowa struktura nogi owada. Główne segmenty zaznaczono elipsami

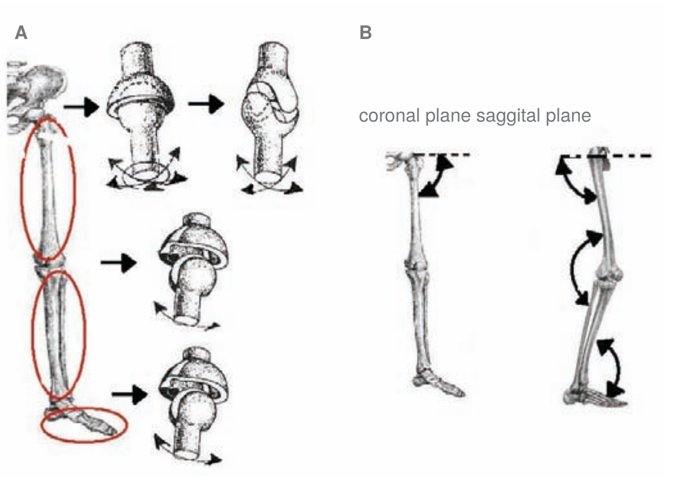

Fig. 3. Simplification of a human leg. Ellipses mark the main segments
Rys. 3. Uproszczona struktura nogi człowieka. Główne segmenty zaznaczono elipsami

amphibians or insects. Humanoids obviously resemble humans. In this section we briefly describe biological patterns, which are relevant to walking machine design.

Pairs of legs of insects and legged vertebrates not only differ structurally, but contribute to the body movement in a different way. Animals use legs not only for walking, but also for jumping, swimming, catching of pray, as well as for food collection. Their legs have a large work space and the leg-ends are complex multi-functional structures.

Despite of the differences in the leg proportions and the differences in the leg postures, there is one representative model, which is commonly used by walking machine designers. This model of the insect leg is shown in Figure 2. The leg has four main segments (hip, thigh, shank and foot) and three degrees of freedom (DOF). Two first DOF are located near the trunk and are responsible of up-down and backward forward movement, the third DOF is responsible for leg extension.

The legs of vertebrates consist only of 3 main parts: thigh, shank and foot. Taking into account the dominant motion ranges, the human leg can be described as a 4DOF structure with: knee and ankle joints with 1DOF each, and hip joint with 2DOF. Figure 3 shows a human leg and its simplification into a 4DOF system.

The legged amphibians and reptiles use the sprawling legs posture, what results in a larger support polygon and trunk being lower over the ground, compared to the legged mammals. Figure 4A presents an amphibian and reptile posture, with sprawling legs (side view and frontal view). Figure 4B shows the mammalian posture. Here, for better illustration, besides the side view, the frontal view of a horse and of a human are shown. Figure 4C presents the side and frontal view of the insect posture. More detailed description of the animal leg structures and postures can be found in [21].

2.3. Legs of Walking Machines

As it was already emphasized, designers of walking machines often refer to the patterns exhibited by insects and legged vertebrates. The research on machines that move quickly, maintaining dynamic stability, is gaining momentum. The precursor of this type of research is M. Raibert. He started by first building a one-legged hopping machine and subsequently moved to bipedal, and four-legged jumping machines [11].

Being inspired by insects, and having in mind statically stable gaits, very often the legs of six-legged and four-legged machines are constructed as serial mechanical chains with three revolute DOF's (Figure 5A). The first two degrees of freedom (closest to the trunk) are separated by a short link – equivalent of the hip bone. The third degree of freedom is located in the knee. When small servomotors are used as actuators two of them are placed side by side in the hip joint, what results in a very short length of the first link (Figure 5B).

Some motor placements impose limits on the motion ranges, and then only one or very few postures are achievable. In general, when only revolute motors are applied, postural changes are nominally possible, but structures with linear actuators or with prismatic DOFs fix the leg posture. Figure 5C illustrates a 3DOF structure with two prismatic joints and one revolute. The reptile posture of this leg cannot be changed. The leg presented in Figure 5D has three revolute joints, however the application of two linear actuators does not permit postural modification from the insect type. The pantograph system is often used in walking machines, however its mechanical linkage must be designed carefully, so that the leg end closely follows a straight line during the support phase. Moreover, a pantograph introduces postural limitation. Figure 5E shows a leg with a pantograph having one revolute and one prismatic joint providing the leg lift. The leg is designed for a fixed insect posture. Figure 5F presents the design with two sliders. Here the posture is similar to a human bent leg.

Multi-legged walking machines usually utilize the sprawling posture, what is beneficial for a statically stable gait over rough terrain. Besides that only a fixed walking posture is usually used. However the observation of insect and decapod locomotion (e.g. crabs) shows that they change the leg posture significantly, especially when crossing over obstacles. Translation of this feature into the technical realm requires special design solutions enabling postural modifications.

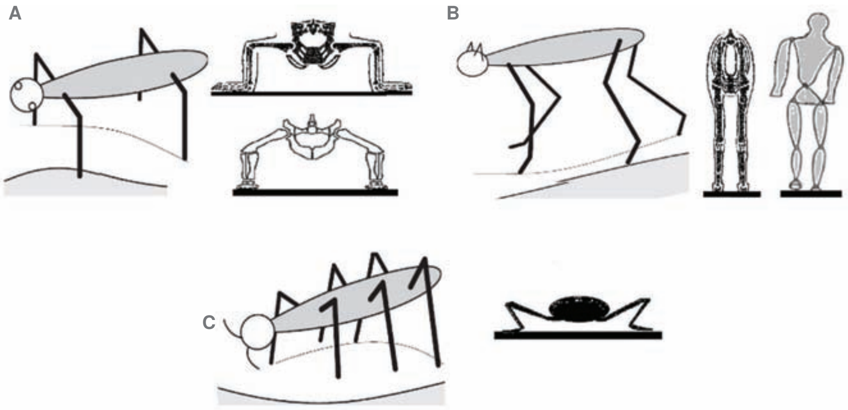

Fig. 4. Leg postures, (A) reptile and amphibian, (B) mammalian, (C) insect
Rys. 4. Typowe postury nóg, (A) gada i płaza, (B) ssaka, (C) owada

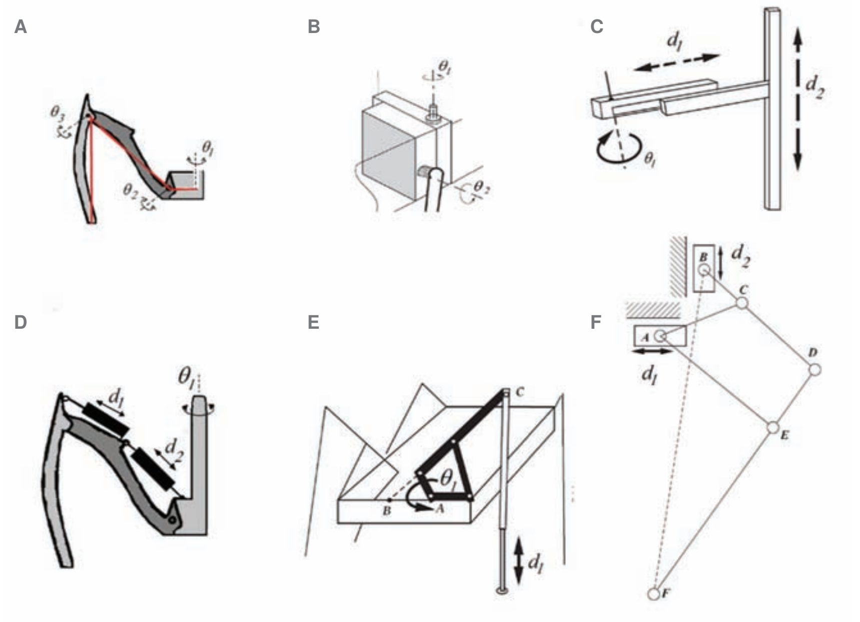

Fig. 5. Design of a walking machine leg, (A) structure imitating an insect leg, (B) design in which the equivalent of the hip bone is produced by overlapping servo motors, (C) structure with two prismatic joints and one revolute joint, fixed reptile posture, (D) structure with three revolute joints, two linear actuators limit the ability for postural change, fixed insect posture, (E) pantograph based design with revolute degree of freedom (DOF) actuating the pantograph reconfiguration and a prismatic DOF providing the leg lift, insect posture, (F) pantograph based design with two sliders actuating pantograph reconfiguration, amphibian posture

Rys. 5. Schematyczne widoki konstrukcji nóg maszyn kroczących, (A) konstrukcja imitująca nogę owada, (B) konstrukcja, w której dwa stopnie swobody stawu biodrowego napędzane są przez przylegające do siebie serwosilniki, (C) konstrukcja z dwoma przesuwnymi stopniami swobody i jednym przegubem obrotowym (typowa postura nogi gada), (D) konstrukcja z trzema przegubami obrotowymi, zastosowane dwa siłowniki liniowe ograniczają możliwość zmiany postury (postura nogi owada), (E) konstrukcja wykorzysująca pantograf, przegub obrotowy umożliwia rekonfigurację pantografu a przegub przesuwny zapewnienia podnoszenie nogi (postura nogi owada), (F) konstrukcja wykorzystująca pantograf z dwoma przegubami liniowymi umożliwiającymi rekonfigurację pantografu (postura nogi płaza)

3. Bio-inspired Design

3.1. Prototypes

In this subsection we focus on leg designs. Our research team at Nanyang Technological University (Singapore) proposed differential drive mechanism for the hip joint [20] of the robotic leg. This mechanism provides two degrees of freedom in one joint, actuated together by two motors. The motion direction depends on the difference between the number of revolution executed by each of the motors. Such solution decreases the number of mounting elements, therefore the leg workspace is large and the leg is light. This solution was applied in a four-legged machine and in six-legged machines. Figure 6 presents the leg design (the circle marks the hip joint) and the views of different leg postures. The motions and gaits using such postures were successfully tested.

Figure 7 shows our prototypes. Figure 7A illustrates the pantograph based design – in this case the leg can move only in one plane due to the limits imposed by the pantograph linkages. The leg posture, as defined by the pantograph imposed limits, can be compared to the bent leg of a human. This design was applied in four-legged machines. Another approach uses a leg with two degrees of freedom, where the motors directly actuate the joint rotation (Figure 7B) [23]. It is the most common and the simplest solution, especially when servomotors are used. This design was also applied in a four-legged machine. In the rest position the leg assumes a more upright posture than in the first case. It better resembles the regular human leg posture. The leg moves in one plane. The last design (Figure 7C) has only two hip motors without the connecting link. In this case the leg-end moves in 3D space, however not every point can be reached. This design is the simplest possible, and it is commonly used in simple hexapods – we used it too. Such structures, due to the use of inexpensive servomotors are cheap. However the change of posture is limited. In the two first cases the leg posture can be only slightly adjusted by changing the flexion in the hip and knee joints. In the last case such change is not possible. This resembles the single segmented parapodia of some pseudocoelomates [21].

As it was already mentioned, a human leg (Figure 3) can be represented as a 4DOF structure, however even in simple bipeds more active joints are usually used. Such prototypes are developed for the investigation of motion synthesis or to take part in robotic competitions (such as football games, sumo wrestling etc.) therefore more degrees of freedom assure better mobility.

Figure 8A presents a leg with six active degrees of freedom: three in the hip joint, one in the knee and two in the ankle joint. The robot shown in the photograph was designed to investigate motion synthesis using the concept of biological Central Pattern Generator [22].

Figure 8B presents small humanoids developed for robotic competitions (students' work). The humanoids have 19DOF, in that 6DOF in each leg (2 in the ankle joint, 1 in the knee joint and 3 in the hip joint in each leg). Other DOFs are responsible for upper trunk rotation (1DOF), for the sway of the upper trunk (2DOF) and for the upper limbs motion (2DOF each) what makes 7DOF toge-

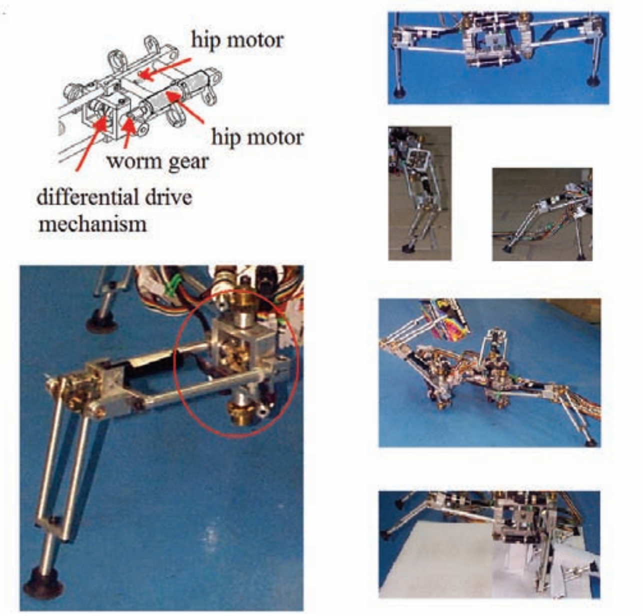

Fig. 6. Leg design with differential drive mechanism (designer J.J. Heng): schematic view, photograph of the leg (circle indicates the hip joint) and the views of the leg in different postures

Rys. 6. Konstrukcja nogi z mechanizmem różnicowym (projektant J.J. Heng): widok schematyczny, zdjęcie (okręgiem zaznaczono staw biodrowy, widoki różnych postur przyjmowanych przez nogę

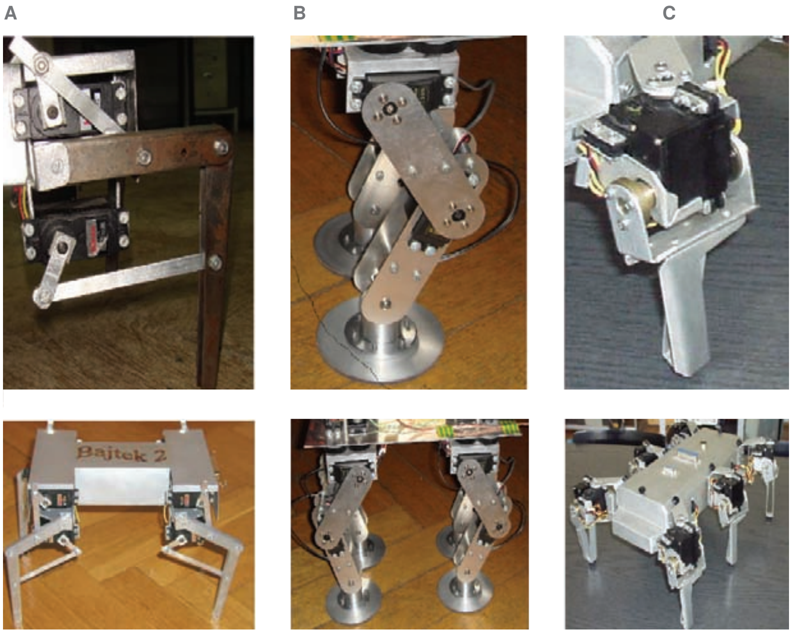

Fig. 7. Examples of simple designs, (A) leg with a pantograph mechanism applied in a four-legged machine (student's work), (B) leg with two revolute joints applied in a four-legged machine (designer M. Trojnacki), (C) one-segment leg applied in a six-legged machine (student's work)
Rys. 7. Przykłady prostych konstrukcji, (A) noga z pantografem zastosowana w maszynie czworonożnej (praca studencka), (B) noga z dwoma przegubami obrotowymi zastosowana w maszynie czworonożnej (projektant M.Trojnacki), (C) noga jednosegmentowa zastosowana w maszynie sześcionożnej (praca studenta)

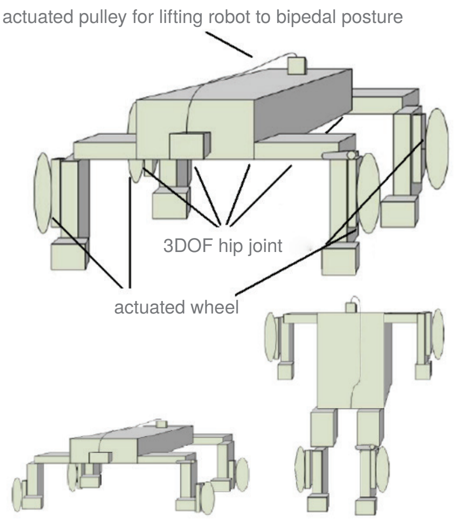

Fig. 9. Robot transformer
Rys. 9. Robot transformer

ther. Such robots are used in our research on the methods of motion synthesis, taking into account the whole body dynamics [17, 27].

For completeness of our considerations it must be added that all four postures, observed in the animal world, i.e. insect, reptile, amphibian and vertebrate type, are used in contemporary walking machines. The machines can move maintaining static or dynamic stability. The dynamic stability is often supported by different kinds of compliance, what will be discussed in the next section.

3.2. General Concepts

This subsection presents the concepts of biologically inspired robots elaborated under our supervision. These projects were developed after studying animal body structures and their motion principles. Figure 9 shows the robot transformer for transporting goods. The robot takes the four-legged posture when walking on undulating terrain (top). The robot uses the wheels for locomotion on a smooth surface (bottom left) and assumes the posture of a human for bipedal walking while carrying loads using the hands (bottom right).

Robot shown in Figure 10 was inspired by a grasshopper and a kangaroo rat. It is a small, lightweight robot dedicated

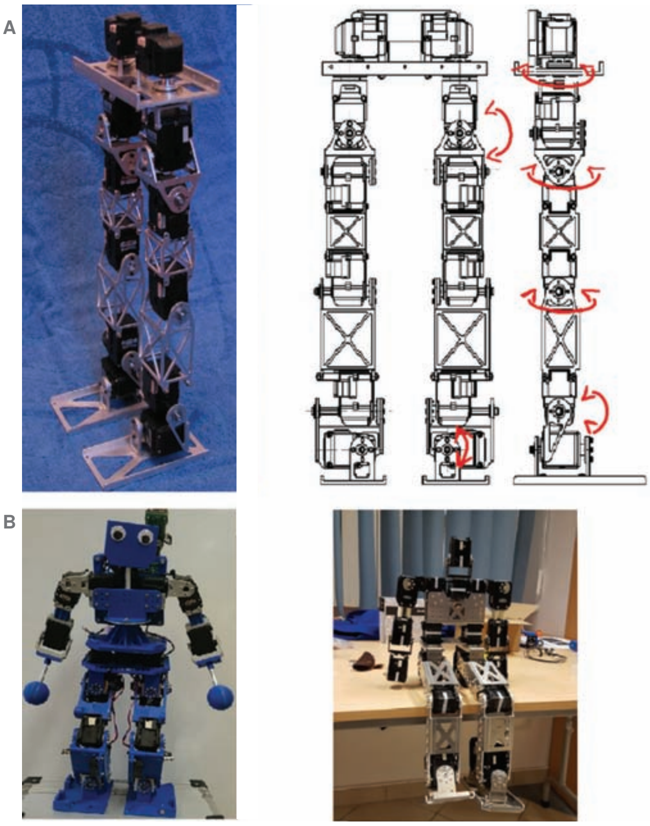

Fig. 8. Bipeds, (A) view of the robot and leg design with 6 active DOF (designer P.Kryczka), (B) photographs of a humanoid
Rys. 8. Roboty dwunożne, (A) widok robota oraz projekt nogi o 6 aktywnych stopniach swobody (projektant P.Kryczka), (B) zdjęcia robotów humanoidalnych

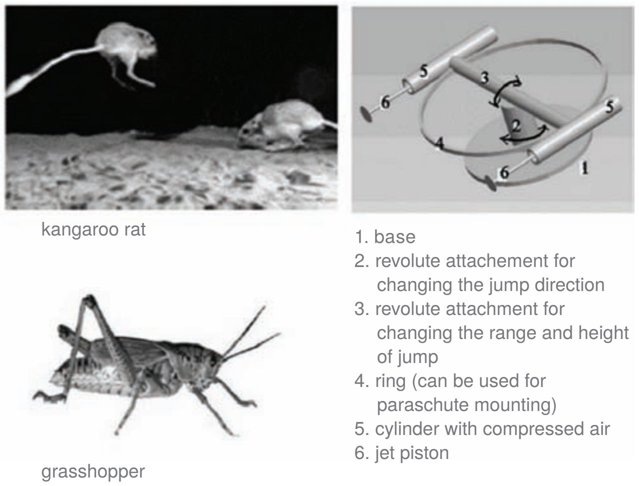

Fig. 10. Robot inspired by jumping animals
Rys. 10. Koncepcja robota inspirowany zwierzętami skaczącymi

to exploration. Up down rotation (3) of the upper ring is used to control the pitch and range of the jump, sideways rotation (2) influences the jump direction. Relatively heavier base (1) provides good landing support. The motion is obtained by a quick release of the pistons (6) in the cylinders (5).

Robot inspired by scorpion (Figure 11) was proposed to search areas of natural disasters. Robot should be able to dig through the rubble and explore underground passages. Its trunk can bend, which increases its mobility.

An interesting concept of a worm-inspired (Figure 12A) cave climber robot was proposed for exploration of rocks and caves. The robot consists of elongated segments connected by revolute joints (Figure 12B). These joints provide adaptation to the shape of the terrain. Both ends of the robots have heads containing a battery and control units. Moreover, four cameras mounted in the heads are used to explore the surrounding. Attachment to the ground is provided by the hooks (spikes) sliding out of the heads. The hooks are released by ejecting a spring and retracted with the help of an electromagnet (Figure 12C). The heads alternately attach to the wall and the robot applies peristaltic motion appropriately elongating and shortening the body segments just like a worm.

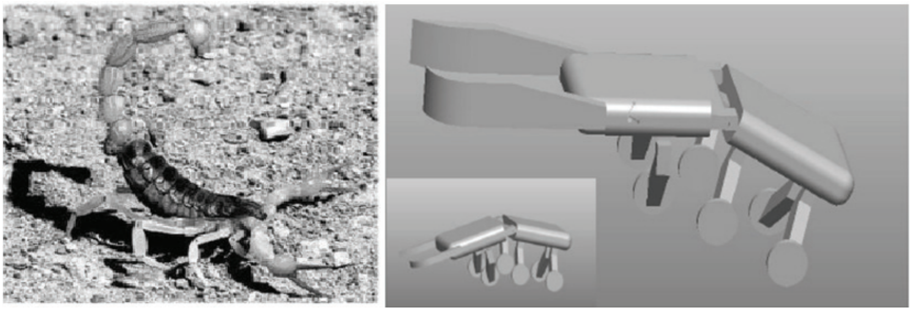

Fig. 11. Robot scorpion

Rys. 11. Robot skorpion

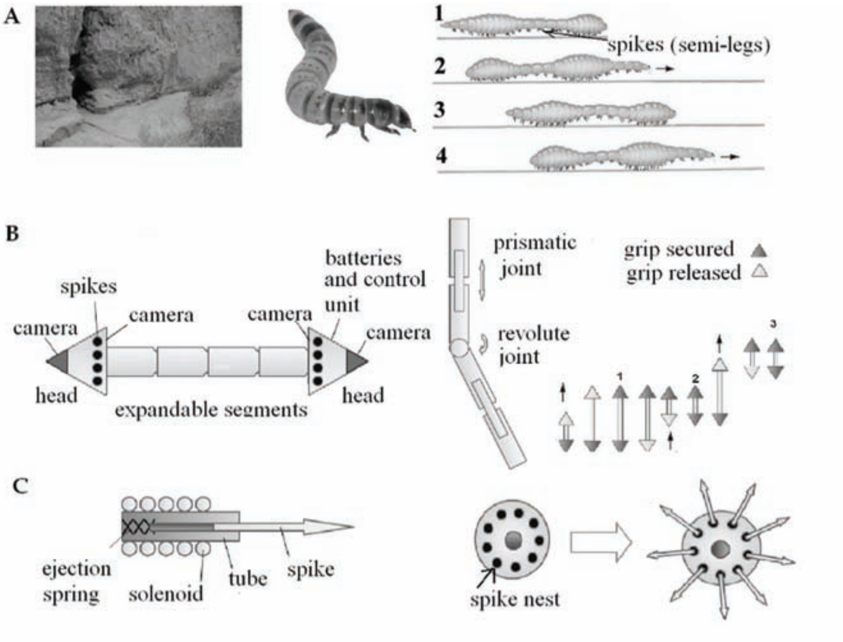

Fig. 12. Cave climber, (A) the inspiration, (B) the concept, (C) the robot heads

Rys. 12. Wspinacz jaskiniowy, (A) inspiracja biologiczna, (B) koncepcja projektowa, (C) głowice robota

Another idea is a crawling robot that moves like an inchworm. Both ends of the inchworm body have suction cups. The worm attaches the back sucker to the ground and moves the body forward. The front sucker is then attached to the ground, the rear sucker is released and the worm pulls the body to the front sucker (Figure 13A). The same motion scheme was applied in a robot that uses under-pressure to attach accordingly its ends to the ground whereas the springs push the body forward (Figure 13B).

A simple robot that moves silently along the ropes, just like a spider, has been proposed for non-invasive eavesdropping from the top (Figure 14). It is worth mentioning that similar solutions are already used for film cameras.

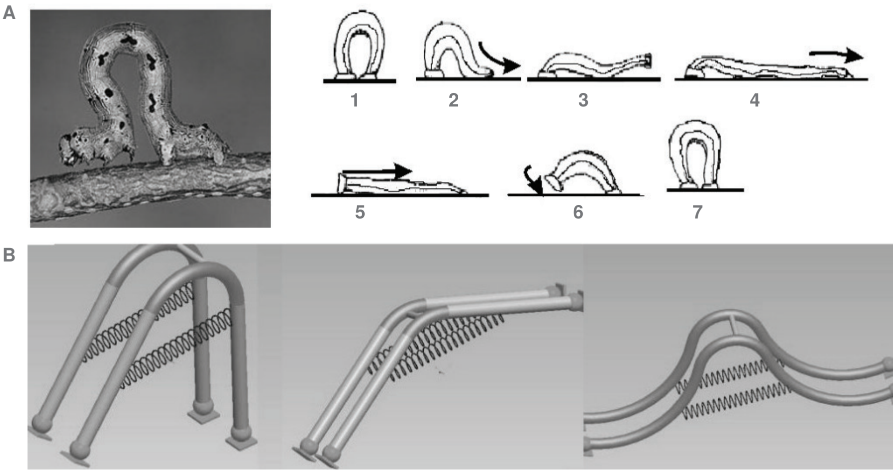

Fig. 13. Robot worm, (A) the inspiration, (B) the concept

Rys. 13. Robot robak, (A) inspiracja biologiczna, (B) koncepcja projektowa

4. Compliance in Animals Locomotion

The body and leg compliance are both instrumental in achieving efficient locomotion [4, 12]. In biology compliance is produced in many ways.

Compliance due to reshaping of the body is assisted by compliance due to changing the intrinsic mechanical properties of the body parts. It is interchangeable. In some animals the locomotion is executed by only reshaping body, as is the case with the soft-bodied animals. To this kind belong:

- acoelomates, having triploblastic body plan with three primary embryonic cell layers and body filled with liquid,

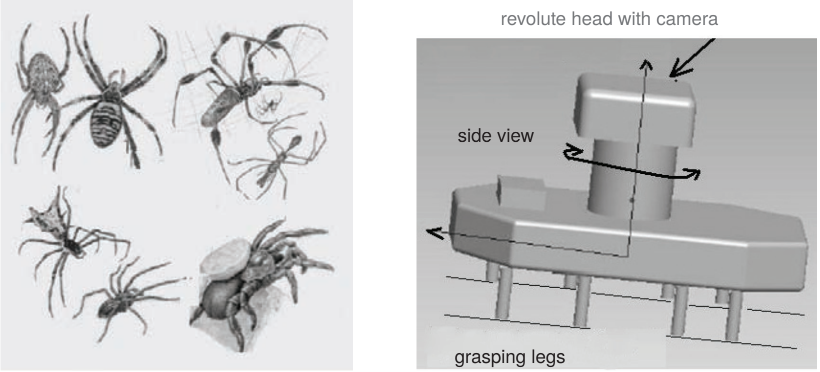

Fig. 14. Robot spider
Rys. 14. Robot pająk

- pseudocoelomates, with body musculature limited to longitudinally oriented muscles,
- and some coelomates. In soft bodied animals the fluid-filled body cavity acts as a hydrostatic skeleton resisting the outside pressure and the influence of gravity.

The muscles work as flexible actuators. Those animals can maintain a different body shape, and are very versatile in reshaping the body for the purpose of displacement. In other animals (legged coelomates) with exoskeletons or skeletons, the reshaping of the body is limited by the rigidity of the skeleton or exoskeleton. In vertebrates possession of a well-developed skeleton, the vertebral column and the controlled leg flexion and extension, produces compliance. Moreover, the mechanical properties of the feet, in some groups of animals, add to compliance too.

Biological observations show that not only repositioning of the joints, but also the leg posture influences locomotion. In unguligrade (walking on hoofs) animals the posture is characterized by significant knee flexion, and ankle joint is almost not deflected (joint angle stays close to 180°, Figure 15A). In this case during locomotion the knee angle changes in a broad range. In digitigrade (toe walking) animals the knee flexion while standing is smaller, but the ankle flexion is larger (i.e. the ankle angle is smaller than 180°, Figure 15B). In this case the take-off impulse and impact absorption are achieved by mutual adjustments of positions of both of those joints. In plantigrade (sole walking) animals the leg stays almost upright, the knee joint is not flexed, and the ankle keeps the foot at a right angle to the leg (Figure 15C).

Repositioning of the ankle joint helps the feet to adjust to the ground for smooth take-off and landing (Figure 16A). In plantigrade animals the foot, besides helping in postural adjustments, also plays an important role in locomotion. Compliant contact between the ground and the foot is assured by the foot arch (Figure 16B) [16]. The foot arch provides vertical compliance, flattening under vertical load and arching upwards when the load decreases [5]. Moreover, the arch bends along its longitudinal axis absorbing the heel or toe impact and relaxes helping to raise the foot (Figure 16C).

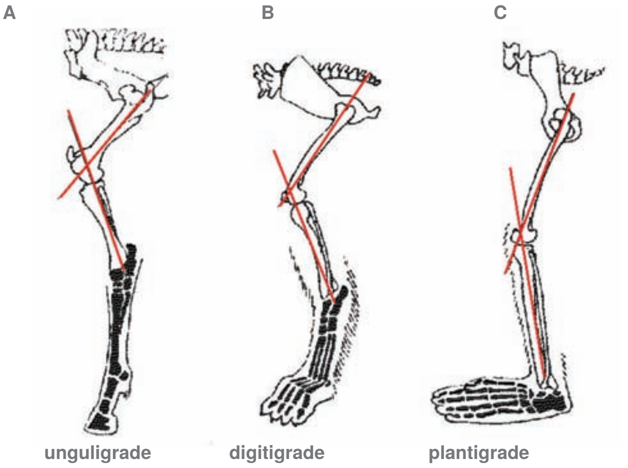

Fig. 15. Leg-end postures, (A) unguligrade, (B) digitigrade, (C) plantigrade
Rys. 15. Typowe postury nóg ssaków, (A) zwierzęta kopytne, (B) zwierzęta palcochodne, (C) zwierzęta stopochodne

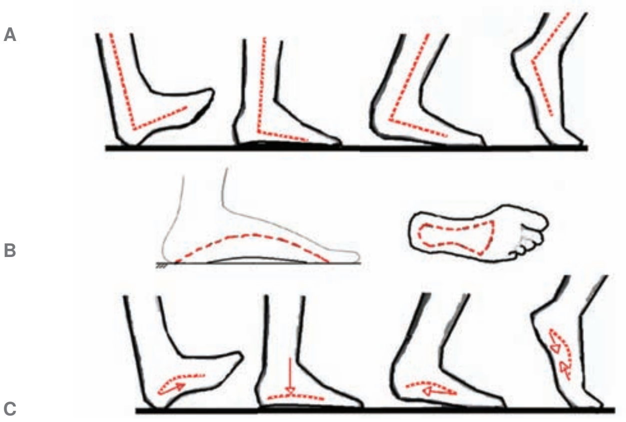

Fig. 16. Human leg, (A) repositioning of the ankle joint during walking, (B) schematic view of the foot arch, (C) work of the foot arch during walking
Rys. 16. Noga człowieka, (A) rekonfiguracja stawu skokowego podczas chodu, (B) schematyczny widok łuku stopy, (C) działanie łuku stopy w czasie chodu

5. Compliance in Robot Design

In this Section we focus on some forms of compliance. Compliance is the reciprocal of stiffness. It is defined as the measure of the ability of a structure to exhibit a deformation due to the action of external forces [37]. Compliant mechanisms are mechanisms, whose principle of operation is based on deformability.

The current research trend is to design compliant bodies and legs of walking machines. Compliance is caused by compliant actuators, links and joints, usually due to the use of soft materials [31, 32]. Compliant actuation can be provided by artificial muscles [7], or by variable stiffness actuators [2]. The combination of soft-body with pneumatic actuation allows to reshape the body in such a way that locomotion results [33]. Such solutions closely resemble those exhibited by biological systems [6]. However, when applied in legged robots, they require rather complex control algorithms. During the support phase the leg is loaded, therefore higher joint torques are developed, and higher stiffness is required, than in the transfer phase. In the transfer phase the leg is not loaded, this results in lower joint torque, and thus lower stiffness is needed. During the support phase stiffens must prevent leg compression, when the increasing load tends to increase the joint flexion, and vice versa. In this phase the position-torque characteristics must exhibit higher stiffness, when the joints are flexed and lower stiffness when the flexion decreases.

Compliant elements or elastic materials introduce passive compliance. In this case motion control is simpler than when using active compliance, however the mechanical features of added flexible parts must be chosen very carefully, offering the required behavior in all possible configurations [8, 15]. Postural adjustment, obtained in active compliance by positioning of active joints, in this case is achieved by passive compliance. The spring and damper systems are recently often used in the legs, or in the feet of multi-legged machines and bipeds. Such elements must be selected adequately to help and not obstruct the motion dynamics. However, the simplest way is to make the whole foot of a soft or compliant material [9], or to use a soft layer as a sole. In this case the touch-down impact is absorbed, however it is difficult to obtain the take-off impulse in a similar way to the one produced by a human foot. Another solution is to produce a segmented foot with the segments connected by passive joints [14].

Presumably one of the first compliant manipulators was developed by our institute. First the anatomical structure and motions of elephant trunk were investigated (Figure 17A). The design imitated the structure of the main muscle groups (Figure 17D). Finally, the prototype was built (Figure 17B). It was planned to mount the manipulator on a walking machine (Figure 17D) [10]. Unfortunately, the large size of the then hydraulic compressors made it impossible. Another compliant manipulator (Figure 17E – design, Figure 17F – prototype) was inspired by a human spine.

Taking into account the hints that biology provides, compliant elements can be incorporated into any part of a walking machine leg. Here the controlled flexion enables postural compliance helping the motion dynamics, what can be called stiffness control, where stiffness is understood as the measure of the ability of a structure to resist deformation due to the action of external forces.

In our early design the foot of four-legged walking machine [10] was formed out of one piece of U-shaped metal providing compliance during the support phase (Figure 18A). In later research we proposed the structure with one vertical spring located bellow the ankle joint. This design was applied in a small biped (Figure 18B) [25] and in a four-legged walking machine. Theoretical and experimental studies confirmed that such a solution adequately helps the postural stability [3, 24]. This design was simple, but had limitations. The compression of the spring located in the rear part of the foot absorbed the touch-down impact, and the spring relaxation helped to enter the double support phase, unfortunately due to the rigid front part of the foot the take-off impulse at the beginning of the transfer phase did not appear. Lateral compliance was also not present. Therefore we expanded our concept [28] propo-

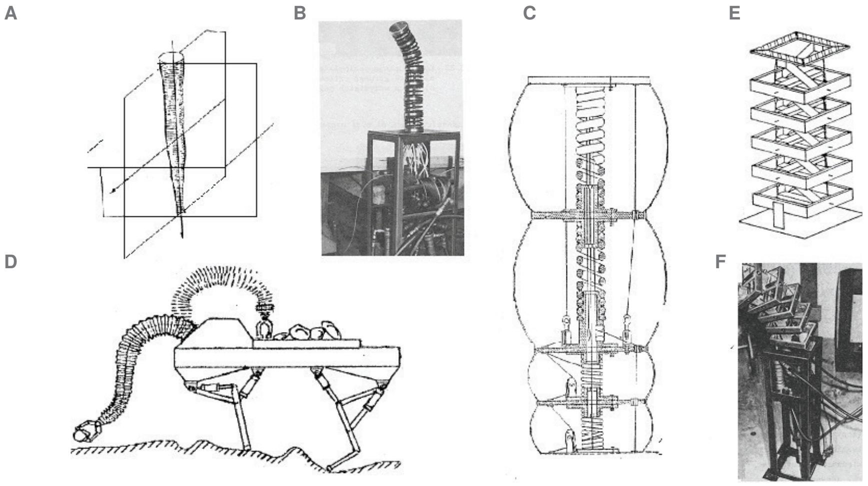

Figure 17. Compliant manipulators, (A) study drawing of elephant trunk, (B) prototype, (C) design drawing, (D) overall concept, (E) design of a spine type manipulator, (F) prototype
Rys. 17. Manipulatory podatne, (A) rysunek studyjny trąby słonia, (B) prototyp, (C) rysunek projektowy, (D) ogólna koncepcja, (E) projekt manipulatora typu kręgosłup, (F) prototyp

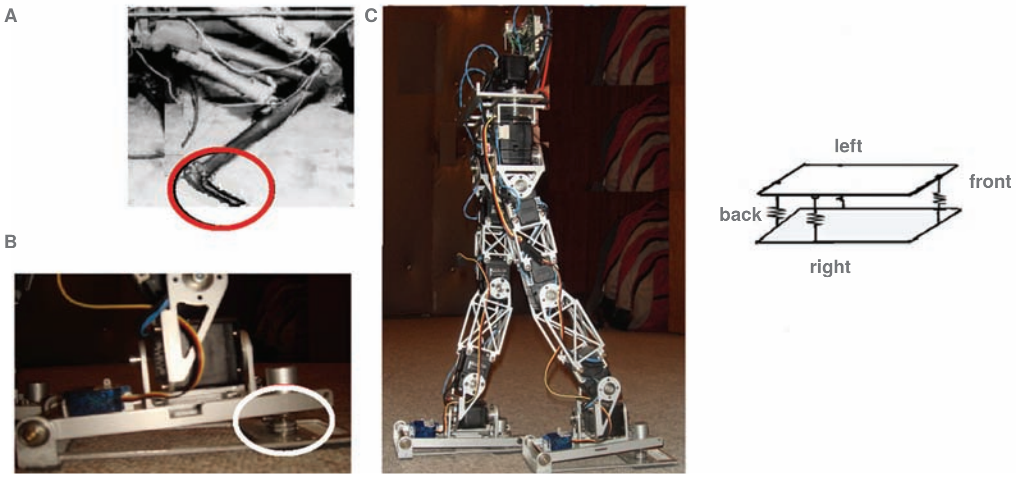

Figure 18. Legs with compliance, (A) leg-end shaped as a bending spring, (B) foot with one linear spring and the biped with such feet, (C) general idea of the foot with four springs
Rys. 18. Nogi z podatnością, (A) stopa z funkcją sprężyny, (B) stopa z jedną sprężyną liniową i robot dwunożny ze stopami zaopatrzonymi w sprężyny, (C) ogólna koncepcja stopy z czterema sprężynami

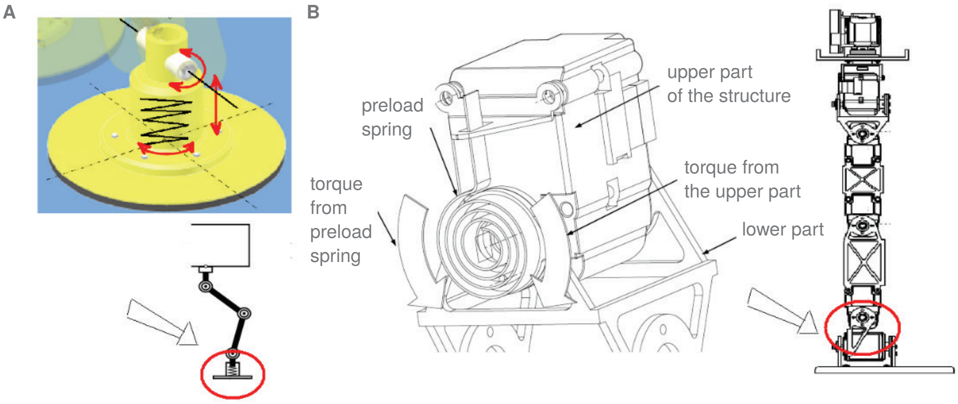

Fig. 19. Compliant parts, (A) foot with one linear spring used in a quadruped, (B) spring loaded actuator plus its localization in the ankle joint

Rys. 19. Komponenty podatne, (A) stopa z jedną sprężyną liniową zastosowana w maszynie czteronożnej, (B) siłownik z podatnością i jego lokalizacja w stawie skokowym

sing a foot with four springs (Figure 18C). The stiffness of the springs was computed taking into account that its compression and relaxation must provide the upper body sway helping the postural stability. During walk the human trunk sways in the range of ±8 degrees in the frontal plane (side sway). Similar or smaller range can be observed in the sagittal plane. These ranges depend on personal preferences, composition of the body and walking conditions. This implies that the stiffness coefficients of an artificial foot should depend on the robot structure, its mass distribution, and expected walking conditions. When selecting the spring parameters using simulations, we considered the simplified model of a human body and a human gait. The spring compression at each instant t was calculated according to a simple formula:

$$\Delta h_j(t) = Fz_j(t)/k_j \tag{1}$$

where $j \in \{\text{right; left; front; back}\}$) spring, k_j is the j-th spring stiffness coefficient, and $Fz_j(t)$ is a part of vertical leg-end force acting on the j-th spring. Taking into account the compression, the body sway was obtained by dynamic motion animation and the postural stability was checked using the ZMP criterion [27]. The anthropomorphic data of the 50-th centile man with the body height equal to 1.75 m and body mass 75 kg was used. The front spring stiffness considered as sufficient was equal to 0.05 MN/m, stiffness of the rear spring was 2 MN/m, and stiffness of left and right springs was 0.9 MN/m. Such stiffness produces a body sway in the frontal plane within the range of 1 degree and the sway in the sagittal plane (forward, backward) in the range of 3.5 degrees. The investigations confirmed that properly selected stiffness helps in maintaining the dynamic equilibrium during walking. The frontal and rear stiffness must differ, but the stiffness of the side springs must be equal.

The leg-end with a single spring was also used in four-legged walking machines. Figure 19A presents such a leg. It was used in the prototype shown in Figure 7B. As it is indicated in Figure 19A, the leg end can rotate passively around the vertical axis and around the horizontal axis of the ankle joint. The spring provides vertical compliance. The concept was investigated theoretically and tested experimentally [24]. We took into account not only the quadruped crawl, which is statically stable, but also the dynamic diagonal gait, when the body is supported by two legs located on the body diagonal. During diagonal gait a slow sway of the body around the line connecting the supporting legs, produced towards the front leg being transferred, was observed. Without compliance the sway was faster, the motion was less smooth.

As it was already mentioned, compliant elements can be incorporated into any part of the leg. Active compliance produced in the joints is a very good option. Figure 19B shows a simple concept of a spring loaded actuator designed for the ankle joint of a biped robot.

Currently the research focus is on soft-bodied robots inspired by acoelomates or plants, however classic concepts are also being modified using modern soft materials. This trend has appeared recently and is developing very quickly. The interested reader can find in [34] a roadmap showing the prospects of self-growing soft-bodied robots.

6. Conclusions

In this work we have presented the designs inspired by biology, including some forms of compliance incorporated into mechanical systems. Biological patterns have been discussed first, and next the technical solutions have been shown. It has been illustrated how biological inspirations can be transferred to the world of technology, resulting in useful solutions.

Not only legs enabling motion in unstructured terrain, but the structure and the properties of the whole body are relevant, especially when building robots performing fast movements and interacting with the environment. Artificial multi-segmented or soft-bodied structures, as well as the structures imitating the vertebral column and the bodies built of artificial muscles were and are still promising areas of research. Advances in materials science, achievements in efficient energy sources, new and miniaturized sensors are important enablers. Older ideas are now improved with the use of new technologies, and on the other hand, innovative solutions appear, such as e.g. self-growing robotic plants. It is obvious that progress depends on our creativity, but knowledge of biology and other related sciences is very important to stimulate it.

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Transformowanie wzorców biologicznych na koncepcje robotyczne

Streszczenie: Biologia nie tylko dostarcza inspiracji w pracach nad maszynami kroczącymi, ale także podpowiada szczegółowe rozwiązania konstrukcyjne. Głównym celem tego artykułu jest zilustrowanie na przykładach jak wzorce biologiczne przekształcane są w konkretne rozwiązania techniczne. Przedstawiono zwięzłe informacje na temat lokomocji nożnej w świecie zwierzęcym i pokazano związki między rozwiązaniami inżynierskimi a światem biologicznym. Pokrótce opisano budowę nóg zwierząt oraz najczęściej stosowane struktury nóg maszyn kroczących z uwzględnieniem odniesień do wzorców biologicznych. Podano przykłady opracowanych przez nasz zespół inspirowanych biologicznie maszyn kroczących oraz omówiono kilka koncepcji robotów inspirowanych światem biologicznym. Ogólnym celem artykułu jest pokazanie, w jaki sposób wiedza dotycząca świata zwierzęcego inspiruje nowatorskie rozwiązania konstrukcyjne robotów przeznaczonych do zastosowań praktycznych.

Słowa kluczowe: maszyny kroczące, wzorce biologiczne, maszyny sześcionożne, biorobotyka

prof. Teresa Zielińska, PhD, DSc

teresaz@meil.pw.edu.pl
ORCID: 0000-0002-8299-0727

She received her MSc degree in automatic control and PhD degree in robotics from Warsaw University of Technology (WUT), Poland. In 1995 she obtained habilitation from the Polish Academy of Sciences. She is a full professor at the Faculty of Power and Aerospace Engineering, WUT. She was the vice-chair of the Polish Branch of the IEEE Robotics and Automation Society (2016–2018), and the Secretary General of IFToMM Federation for Promotion of Machines and Mechanism Systems (2011–2019). In the years 2018–2022 she was the member of the Council of the National Science Centre. She is the local chair of Japan-Europe Master on Advanced Robotics – JEMARO. She published over 300 publications and holds 2 patents. Her research interest includes robotics and machine learning. Teresa Zielińska is the member of Committee for Automatic Control and Robotics of the Polish Academy of Sciences.