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Research Issues in Natural and Artificial Biped Locomotion Systems

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Abstract

This paper presents a review on biological and robotic biped locomotion systems. The main purpose is to study the achievements attained in the last years and to develop a deeper insight towards future research. In the past decade a significant progress in the cooperation between biology and robotics has been made as researchers recognise the synergies in the two scientific areas. This cooperation stimulated the development of experimental legged vehicles and adequate control algorithms. The ultimate purpose of this article is to contribute toward the productive interaction between these two fields.

1. Introduction

Today robotics is a well-known area of research and development. More and more aspects of modern life involve the use of sophisticated and intelligent machines capable of operating in locations or under conditions hazardous to human health, ranging from areas of the factory floor to the ocean depths and outer space. The necessary specifications for such welfare robot that can be used in this area are as follows:

1) autonomous and energy efficient.
2) mobile and able to move quietly and gently.
3) adaptable to the environmental conditions.
4) multi-functional.

There are many classes of robot locomotion, the most conventional being wheeled, tracked, “snake-like”, and legged locomotion (see the survey in [1]). Hybrid wheeled/articulated mobile robots have also been investigated [2]. Nowadays, wheels are the dominant form of mechanical locomotion. One reason is that rolling on wheels is smooth. On prepared surfaces wheels provide translation without any extraneous motion. More recently, there has been a growing body of literature on snake or slug-like locomotion [3]. However, none of these methods result in human-like mobility. In contrast, systems which employ multiple limbs for locomotion, commonly referred to as legged systems, tend to provide a greater mobility in rough terrain while not requiring a continuos support path. Another advantage is to provide an active suspension mechanism which separates the body’s path from that of the toes. Nevertheless, legged vehicles may suffer impacts at each footfall and incur on additional accelerations as part of the walking cycle. In animals, where legged locomotion is the norm, because of its advantages on rough terrain, compliant bodies and highly developed senses are well adapted to the shocks and accelerations of legged locomotion. The walking machines, however, are not yet so well developed. It is the goal of current research to build robots which preserve the advantages of legs and, simultaneously, walk smoothly.

Legged machines are, commonly, classified as either “static” or “dynamic” according to the technique adopted to maintain equilibrium. Static machines commonly have four or six legs and must keep at least three feet on the ground at all times to provide a broad base of support. They must select gaits which ensure that the walker’s centre of mass remains within this base and, in addition, they must move slowly so that inertial effects from reciprocating limbs do not disturb the balance. Dynamic machines, in contrast, do not require a broad base of support and do not suffer the speed restrictions of static machines. Dynamic stability is essential for systems with less than three legs and useful in vehicles with more legs. However, it introduces a much more complicated control problem because requires a permanent active control of the legs to assure stability.

This paper concentrates on biped locomotion systems. Three problems normally associated with biped locomotion are generation, stabilisation, and trajectory transition. In spite of the excellency using legs for locomotion we are in a primitive stage in understanding the control principles subjacent to human walking and running. Some pertinent questions that seem without answer are: how animals keep balance? how do we calculate the control signals to the actuators allowing the robot to keep a standing posture, walk or run arbitrarily? and which is the coordination principle present in locomotion?

These questions have motivated a growing community of researchers whose fascination for building and understanding machines that can balance, strike purposively and coordinate multiple actuated degrees of freedom has begun to lay the foundations of a scientific framework in this area. In the literature there are two typical approaches to the biped locomotion problem. On one side, several legged walking machines have been built providing insight to plausible control and mechanical structures in human locomotion. On the other side, the theories and algorithms guiding the biological research suggest specific models to apply and verify experimentally.

In this line of thought the remainder of the paper is organised as follows. Section 2 discusses, briefly, the principles underlying the human locomotion. Section 3 reviews the progress on experimental biped walking with its own set of applications, techniques and problems.

2. Biological Aspects of Human Locomotion

The essence of locomotion is to transport the section of the head, arms, and trunk from an initial position to a desired position throughout the action of the lower limbs. The movement of the musculoskeletal system is produced by the contraction of muscles and moderated by environmental aspects. Therefore, the resultant motion depends on two factors: (1) those influencing the muscular contraction, including the structural and functional characteristics of the neuromuscular system; and (2) those related with physical phenomena, such as gravity, friction, and reaction forces.

The locomotion, either in humans or in robots, consists of a periodic process. The major determinants of human gait are [4]: pelvic rotation, pelvic tilt, knee and hip flexion, knee and ankle interaction, and lateral pelvic displacement. All the determinants of gait minimise the forces that tend to impede effortless motion. In essence, humans attempt to keep their centre of gravity in a path requiring the least expenditure of energy. It is usual in literature to divide bipedal locomotion into a "stance" phase, in which one of the legs bears the body weight, and a "swing" phase, in which this leg is moved to another point of contact.

A. Biomechanics of Human Movement

The understanding of the human motion capabilities is directly related with the understanding of the anatomic and mechanical musculoskeletal structure. The activity of the trunk and lower limb in normal walking is illustrated in table I. The action taking place in the joints of the lower extremity consists, essentially, of flexion and extension. The pelvis has the double task of transmitting the weight of the body alternately, first over one limb and then over the other, while putting each acetabulum in a favourable position for the action of the corresponding femur. Unless restrained, the arms tend to swing in opposition to the legs. This is accomplished without obvious muscular action and serves to balance the rotation of the pelvis. The major muscles present in walking are shown in figure 1.

Every joint is acted upon by muscles which generate forces in opposite directions. The agonist muscle is the muscle which initiates a desired contraction while the antagonist muscle is any muscle which actively provides negative contribution to a particular function during contraction. Therefore, it is possible to control separately both the torque and the stiffness of the joint. If both, agonist and antagonist, are activated simultaneously - coactivation - the stiffness of the joint will be high and the net torque low. If the antagonists are relaxed - reciprocal inhibition - the net torque will be high. Basmajian and De Luca [4] have identified specific conditions of motor control which may be associated with these control strategies. The reciprocal inhibition seems to be present in:

1) rhythmical motor processes such as locomotion.
2) high velocity limb movements (near ballistic).

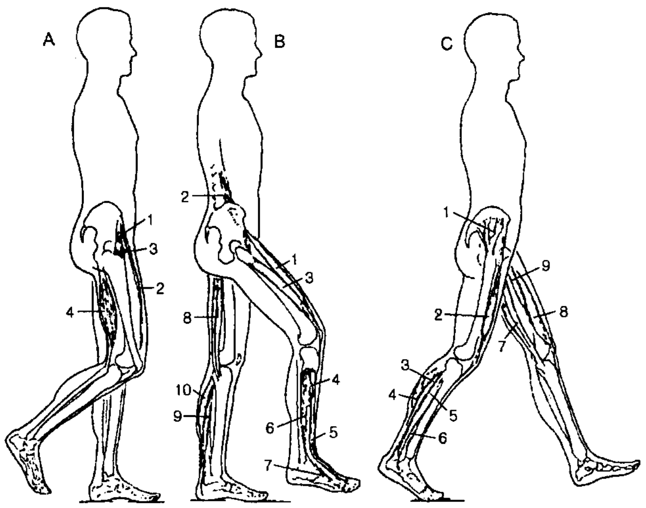

Figure 1: The muscles of the lower limb used in walking. (A) 1. tensor fasciae latae; 2. sartorius; 3. pectineus; 4. biceps femoris. (B) 1. rectus femoris; 2. iliopsoas; 3. vastus lateralis; 4. tibialis anterior; 5. extensor hallucis longus; 6. extensor digitorum longus; 7. peroneus tertius; 8. semitendinosus; 9. soleus; 10. gastrocnemius. (C) 1. gluteus medius; 2. rectus femoris; 3. soleus; 4. tibialis posterior; 5. peroneus longus; 6. peroneus brevis; 7. semimembranosus and semitendinosus; 8. vastus medialis and intermedius; 9. addutor longus.

On the other side, coactivation appears to be associated with the performance of tasks which require assurance that they be realised effectively (insurance mechanism):

1) the earlier stages of our lives.
2) unskilled movements.
3) contractions during situations, such as when balance is insecure, where a joint is required to be stiff.

B. Neuromuscular Control

The unique features of the muscular control system are not only the biological nature of its actuators but also the specific modes by which the control information is processed. The advances in electroencephalography allowed to study the correlation between different levels of neural

TABLE I : Articulation movements during the Swing and Stance Phase.

Articulation	Movements during the Swing Phase	Movements during the Stance Phase
Spine and Pelvis	*rotation toward opposite side; prevention of dropping of pelvis over unsupported side.*	*see comments under Swinging Phase.*
Hip	*flexion; outward rotation; adduction at beginning and abduction at the end of phase.*	*extension; reduction of outward rotation followed by slight inward rotation; prevention of adduction of thigh and dropping of pelvis to opposite side.*
Knee	*flexion during the first half; extension during the second half.*	*slight flexion at moment of contact followed, immediately, by extension.*
Ankle and Foot	*dorsal flexion; prevention of plantar flexion.*	*slight plantar flexion followed by slight dorsal flexion; prevention of further dorsal flexion which the body weight tends to cause; plantar flexion of ankle and hyperextension of metatarsophalangeal joints at end of propulsive phase.*

and muscular activity. At the other extreme, the local organisation of neurons, muscles, skeletal elements, and sensorial organs have been the subject of several studies [4]. These studies have revealed that a hierarchical structure is present in the locomotor systems [5], where neural, musculoskeletal and sensory systems behave cooperatively to adapt immediately to unpredictable changes of the environment. The "uncertain" variation in muscular activity during motion indicates some type of advanced control.

C. Human Posture

The ability to maintain stability is fundamental both on stance and on motion. Since the human body is not statically stable, maintaining upright posture requires continuous antigravity actions by means of coordinated adjustments of the tone of antigravity muscles. In early studies, it has been reported the concept that the nervous system is interested not only with the muscles involved in the desired motion, but also with those involved with the maintenance of posture to minimise disturbances of balance [4]. The function of human postural control is accomplished by a neural control mechanism [6], which includes the feedback information from afferent sensory inputs and the controlling coordinated motor responses.

During the last two decades, a wealth of literature on human postural control has been devoted to the responses to induced perturbations by means of force plate measurements, EMG recordings, and movement analysing systems. One of the earliest analytical studies of human postural control was performed by Nashner [7]. Subsequently, other approaches to model postural control have involved the simulation of complex motions [8,9], and the use of non-linear feedback laws [10]. Although several other attempts at applying quantitative methods have been reported [11-13], the literature has largely described the feedback properties of posture control in qualitative terms, for instance with position, velocity and force feedback. There remains a gap, however, between these models and their application in neural control of movement [14,15].

In this perspective, the regulation of static posture and the closely related, but more difficult, dynamic stabilisation of locomotion promise to be a rich area for future theoretical and experimental study.

D. Human Walking Cycle

Biological locomotion systems are characterised by their behavioural patterns with complexity of large degrees of freedom that will be stably and flexibly generated depending on the state of the environment. Walking is initiated by inclining the body forward, losing its balance as a result of cessation of activity in postural muscles. To regain balance, the swing leg must be brought ahead the centre of gravity. The stance leg, which remains at the back, helps to propel the body forward.

The division of the whole walking cycle is illustrated in figure 2. The diagram illustrates the interaction between the knee and ankle joints and the phasic action of the major muscle groups recorded by electromyography. The stance phase begins when heel strikes the ground and ends when the toe offs. During the first and late 10% segment of the stance phase both feet are on the ground. After the first 10% segment, the opposite leg is in the swing phase corresponding a period of single-support.

Human locomotion has been studied extensively and with a great diversity of efforts. Each study concerns a different task - hopping, walking and running - and each one places an emphasis on distinct behavioural objectives - walking trajectories, gait stability and associated control functions.

Various studies have used optimisation techniques in the analysis of walking. The hypothesis that walking minimises the mechanical energy [16] is one of the earliest to have been proposed; however subsequent studies show that energy is unlikely to be the quantity which is minimised [17]. Though the potential of optimal control theory to problems involving biological movement a difficulty remains associated with finding optimisation algorithms that converge numerically.

A fundamental problem in human movement that deserved the attention of many researchers is the determination of individual muscle forces that provide coordinated gaits. As result, several biomechanical models have been described for normal walking [18-22]. These models are based on explicit models of the musculoskeletal system that describe the relationships between the neural activation of muscles and the kinematics of movement, using the theories of multi-body dynamical systems and a detailed knowledge of both the anatomy and the characteristics of the muscles.

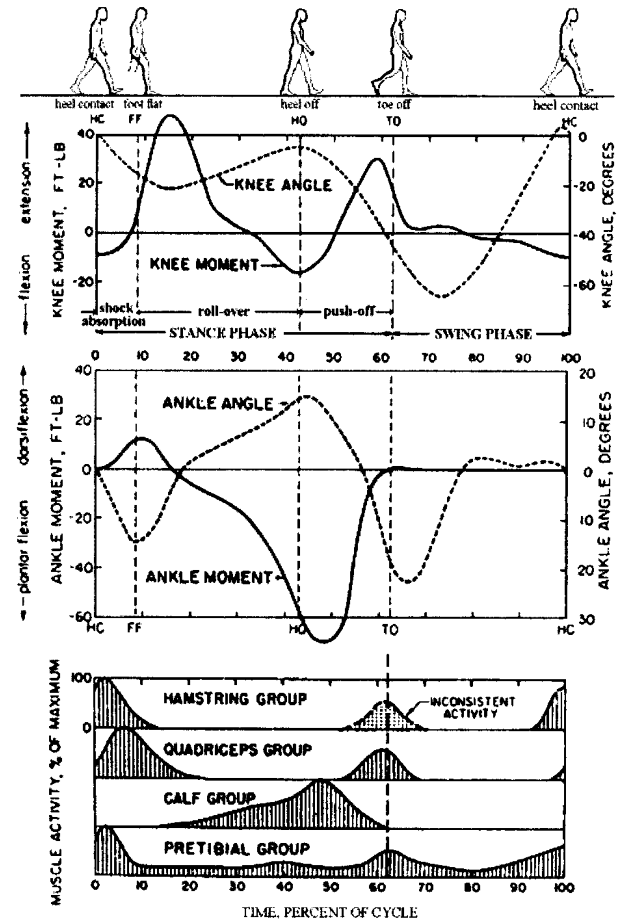

Figure 2: Normal walking: knee and ankle moments compared with muscular activity during one cycle [4].

Several researchers used simplified inverted pendulum models, or extensions thereof, to explain and predict some fundamental aspects of walking. Cavagna [23] has been an influential investigator who has used the inverted pendulum. In other studies, Hemami [24], Siegler [25], Mochon and McMahon [26], and Alexander [27] have used the inverted pendulum models to examine aspects of human walking.

3. Biped Implementation of Robotic Systems

A retrospective analysis of past walking machines shows that the design process led to the reproduction of structures, functions and principles found in nature, using technologies and techniques correspondent to each stage of development. This approach, based on heuristic methods and analogies, culminated in a rich variety of original solutions imitative of the human dexterity. The reason to believe that natural biological solutions are the optimal ones is the fact that their legs and gaits are the product of two optimising processes: the process of evolution by natural selection and of learning by experience [28].

Although bipeds have the fewest number of appendages necessary for locomotion, the dynamic equations which describe their motion are still rather complex. In addition, the inherent instability of two-legged motion increases the difficulty of the control problem [29-31]. Nevertheless, dynamic walking promises to provide higher walking speeds and greater efficiency with more versatile walking structures. In early work, biped locomotion has been studied by first studying simple models - *e.g.*, compound inverted pendulums - as approximations to bipeds and second by analysing and simulating various methods of control [32-34]. A summary of the early history of biped walking machines and extensive considerations of the major issues with dynamic balance have been presented by Tood [35], Raibert [36], and Vukobratovic [37].

A. Stability of Dynamic Systems

The analysis of dynamics and stability of bipedal gait and the development of control algorithms to regulate the motion of bipedal systems is a challenging problem which has prompted ongoing research efforts by many investigators. The control of biped locomotion models generally consists of three stabilisation problems [36,37]:

1) postural stability,
2) trajectory stability,
3) gait stability.

A common classification of dynamic systems is based on the role of active control in gait generation. On one side of the spectrum is the biped built by Mita and colleagues [38]. The biped motion is generated entirely using linear feedback control. At the end of each control cycle, the joint angular displacements are computed in accordance with the objective for the next cycle, and the controller tries to cancel the error. There is not an explicit trajectory specification between these two conditions. Yamada, Furusho and Sano [39] have, also, used an approach based on feedback control but, alternatively, with the intention of accomplishing a completely specified trajectory. Meanwhile, the stance leg is left free to turn like an inverted pendulum. Similar techniques have been used by Takanishi [40], Zheng [41] and other researchers.

In contrast, Miura and Shimoyama [42] regulate the gait without feedback, based on lookup tables with *a priori* computed joint torques executed under control. Once again, the stance leg is left free. However, as the "feedforward" gait is eminently unstable small feedback corrections are added to maintain the walking cycle. Raibert [36] developed comparable concepts that have applied successfully to running robots having from one to four legs. All these machines use some form of active control to generate the locomotion patterns.

On the other extreme, there are the passive walking mechanisms in which the effect of gravity and inertia generate, with some additional energy, the stationary patterns of locomotion. The article by Mochon and McMahon [26] demonstrates how to generate walking by passive interaction of gravity and inertia using the "ballistic walking" model. The interest of these mechanisms reside in their simplicity, alleged efficiency, and consistency with gaits present in humans and legged animals [28], without active control or energy input. McGeer [43] has studied experimentally the passive dynamic walking and the stability of a biped model with semi-circular feet. Thompson and Raibert [44] developed similar concepts applied to passive hopping and running machines, also without significant energy expenditure and requiring a simplified control algorithm.

B. Experimental Biped Robots

Because of the intrinsic complexity of biped locomotion, progress has been slow in biped robot design. In 1973, the first biped walking machine, WL-5, was designed and constructed by Kato and his colleagues [29]. The machine used a static gait, in which the robot centre of gravity was kept above at least one of its large feet. Later, Miura and Shimoyama [42] built the first actively balancing robot, a biped with one motor on each leg for abduction and adduction of the hip, and a third motor to separate the legs fore and aft. The feet of the biped were like stilts, providing essentially point contacts with the ground, and the machine fell over without active control. Furusho and Sano [45] have made experiments with the BLR-G2, a biped equipped with foot pressure and ankle torque sensors to provide information about the condition of contact with the floor. The sole and ankle driving actuators undergo force/torque feedback control based on the sensor information. The BLR-G2 walked at the average speed of 0.18 m/s, or about 1.4 s/step, with a stride of about 25 cm.

Nakano *et al.* [46] proposed a light weight and dynamic biped walking robot. The robot has two legs which are a pair of flexible beams instead of a pair of usual rigid links. Light weight and saving energy are the effects of this mechanism which takes advantage of the characteristics of flexible structures. The flexible beams make light structure and act as knee joints and eliminate heavy actuators. It is found that the dynamic walking of 1.1 m/s like that of human being is attained and energy saving is confirmed.

Matsuoka was the first to build a machine that ran, where running is defined by periods of ballistic flight with all feet leaving the ground. To test his method of control, Matsuoka built a planar one-legged hopping machine [47]. The machine hopped in a place at about 1hop/s and travelled back and forth on the table. Extensive considerations in dynamic walking and running have been presented by Raibert [36]. He developed a biped locomotion robot that achieved high speed rhythmical walking (figure 3).

The problems of achieving good performance under varying conditions have led several investigators to the study of on-line gait adaptation. An anthropomorphic dynamic walking adapting to the human's living floor were developed by Waseda University [48]. The maximum walking speed is 1.28 s/step with a 0.3 m step length. The authors have developed a foot mechanism that can measure the relative position and gradient during dynamic walking. Kun and Miller [49] presented an adaptive dynamic balance scheme implemented and tested on an experimental biped. CMAC neural networks were responsible for the adaptive control of side-to-side and front-to-back balance, as well as for maintaining good foot contact. The biped is able to start and stop on demand, and to walk with continuous motion on flat surface up to a rate of 0.6 s/step, with up to 6 cm long step.

C. Promising Directions of Future Research

At present days, the walking machines described in the literature consist of laboratory prototypes used to explore ideas and particular aspects about legged locomotion. Substantial efforts are required to understand some fundamental principles of bipedal locomotion systems and to solve important practical considerations. Assuming that the goal is to develop a completely autonomous system, the legged vehicles will need to provide their own power. This is a difficult problem when the robot's general shape and dimension is similar to the human body. The solution requires an optimisation of the system architecture and the mechanical design to minimise the energy consumption.

Almost all the above referred gaits were only usable for a static environment, that is, they contained no method for traversing a varied terrain. Since biped robots are expected to walk in many different environments, it is necessary for the robot to generate gaits automatically. A practical biped needs to be more like a human - switching between different known gaits on familiar terrain [51], and learning new gaits when presented with unknown terrain [52]. A solution to this problem involves sensing, perception and spatial representation of the terrain. But, even with the complete knowledge of the terrain conditions, there remains control and planning problems to be solved, in such way that the legged robot can negotiate rough terrains [38,39]. An important aspect, often avoided, is the consideration of the reaction forces between the feet and the ground on the control algorithm. In this sense, legged robots may require the use of more advanced control strategies, such as compliant or hybrid control techniques [53,54].

As the quality and availability of electronics apparatus improves, biological studies are expected to contribute with more clear evidences of phenomenon associated with human locomotion. These results will give rise to a new generation of robotic technologies with a performance close to biological systems.

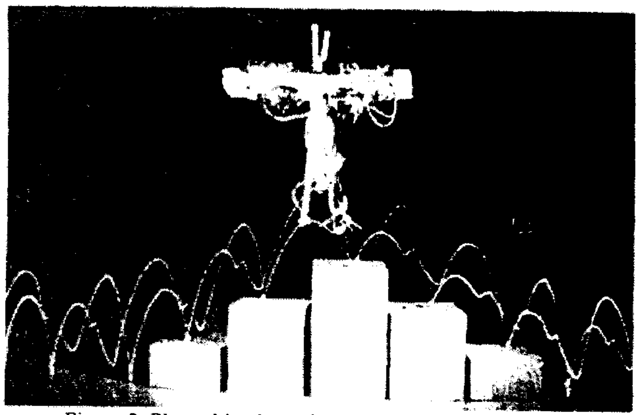

Figure 3: Planar biped running a flight of three stairs [50].

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