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Bionics and systems theory approach to the investigation of human gait

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Advantages of system-theoretic, bionics, and cybernetics approach to the investigation of human gait have been proved. The complete motion act has been considered in multi-level hierarchical organization. As an example, two sequential levels have been analyzed: gait techniques and gait tactics. Gait heading control has been considered in brief. Natural sources of the so-called locomotion rhythms have been explained.

Keywords: biomechanics, kinesiology, human locomotion, bionics, modelling, simulation

1. Introduction

It is natural locomotion that human being acquires during the first months of life. In spite of the apparent easiness bipedal gait has to be considered as an extremely complex task. There are at least two reasons for that. Firstly, body structure involves a great number of degrees of freedom and exhibits typical inherent instability. Secondly, the foot sole (the supporting surface) is so small, and additionally reduced due to specific elasticity and subtle muscles action, that biped's centre of gravity, projects itself during predominant part of the motion cycle outside this surface. This means that the states of static equilibrium practically do not exist and the problem concerns a dynamic stability assured by complex control actions within the neuromuscular system. It is advanced control systems theory, cybernetics and bionics that provide the clue to deeper understanding of the problem.

The considerations concern two levels isolated from the whole multi-level motion task, gait techniques and gait tactics, and will be illustrated by the results of investigation of a simple model.

2. Cybernetics and bionics approach

A significant part of investigations of natural locomotion makes use of sheer statistics. Selected phenomena, such as step length, stepping frequency, muscles action, etc., are measured by use of various means in numerous groups of "representative" subjects. No reference to any model is made. The results obtained in this way, though of wide scope (concerning many details) have limited depth, i.e., do not explain many of the natural phenomena.

Alternatively, the investigation may begin with an experiment in the micro-world of elementary units of muscles (muscle fibres) and nerve cells and proceeds (by gradual extending of investigated structure) towards complete motion acts realised within the whole organism. This procedure (often referred to as "direct"), by some researchers seen as the only reliable, makes use of the inductive pattern of reasoning and prioritizes original structure in which, de facto, the motion takes place.

Still other way ("adversary" to the previous one) uses close interrelations between function, structure and motion goal that become more and more evident along with extending of the structure [11]. Thus, the following conclusion may be drawn: Since in a complete organism some global function is performed and some global goal reached, this organism has to involve a mechanism that makes it feasible. Moreover, this mechanism may be initially seen in a nature other than the original but better recognized, more easily measured, etc., i.e., in the world of models. This way evidently makes use of deductive reasoning and is typical of bionics and cybernetics.

The model is, in fact, the "minimum" structure capable of performing given function. It should be noticed that modelling (building models) and simulation (investigation of models) stick deeply to natural pattern of reasoning per analogiam human being widely uses in everyday life. The model strictly depends on the purpose of investigation. Once the adequate model (simple but sufficiently related to the original phenomenon) has been defined, simulation provides new information concerning the natural phenomenon. Common use of efficient computers and user friendly software packages makes these procedures easy for those researchers who, though well acquainted with the original subject, have no special knowledge in computer programming [10, 11].

In this understanding modelling relates to theory, whereas simulation corresponds with experiment. Any rational research on human locomotion calls for careful balancing between experiment and theoretical backgrounds. One may conclude that experiment not supported by theory becomes blind, whereas theory not verified by experiment is limp.

3. Cause–effect approach

Cause–effect approach opens the way to problem drawing and understanding [10]. Physical systems consist of elements, each representing elementary cause–effect relation. The element can be specified in terms of an independent variable or input (the cause), dependent variable or output (the effect) and some formal relation between the two, the latter predicting how the input gets converted (transformed) to the output. The elementary cause–effect relation may be schematically depicted as has been shown in Fig. 1. The arrows show the direction of action flow that makes the diagram oriented.

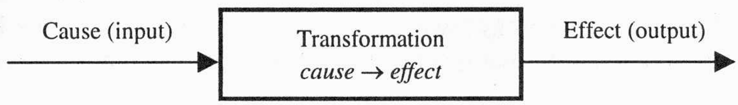

Fig. 1. Graphical representation of cause–effect (input–output) relation

The whole system can be defined by the configuration of interconnections among a number of elements, wherein certain outputs from some elements become inputs to the other elements. The procedure starts with the revealing of elementary cause–effect relations within the system, grouping them in the so-called Cause–Effect Table that allows us to specify a set of separate links, which, when drawn and connecting spots of identical marking (inputs and outputs), form a system structural diagram. In these terms the general scheme for body controlled motion takes form as shown in Fig. 2.

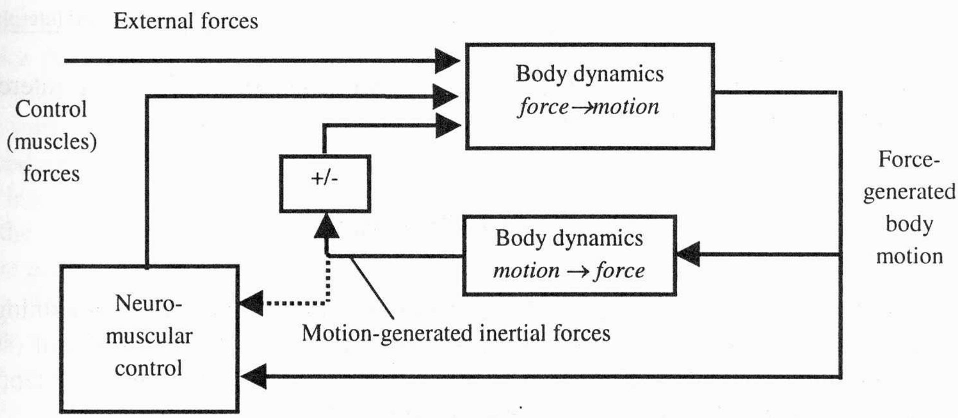

Fig. 2. Basic structural diagram of body motion control system

4. System theoretic approach

System theoretic approach provides a row of specific effective procedures and tools. A system is actually understood as a set of objects (elements, components) interrelated and combined in such a way as to make a whole. The well-known statement that the whole is more than the sum of components means that the system would exhibit new properties that cannot be explained in terms of components themselves.

A complex system is assumed to have multi-level organisation [11]. Generally speaking, the levels differ by a scale, the latter concerning not only dimensions and space but also other factors important for the action to be performed, such as time, information, structure engaged, goals to achieve, etc. Thus, the levels are arranged in a hierarchical order, according to the scale. Higher, more comprehensive levels assign goals for the lower ones, whereas lower levels enable reaching the higher level goals.

Table 1 presents possible five-level organization of human natural locomotion.

Table 1. Suggested multi-level organization of human natural locomotion

Locomotion level	Level goal	Means at disposal
Locomotion policy	attainment of global goal	long-term motivation
Locomotion strategy	reaching the destination point	short-term motivation
Gait tactics	maintaining heading and speed of locomotion	ground reaction averaged forces
Gait (stepping) techniques	maintaining stability, avoidance of falling down, synchronizing lateral and longitudinal stepping	choice of step length & width and time of putting down stance foot
Body motion mini-techniques	body motion coordination, energy costs limitation	muscles action, changes of joint angles, complex foot–ground interplay

Gait (stepping) techniques and gait tactics, two sequential and strictly interconnected levels, will be analyzed in brief.

5. Gait techniques

It is obvious that at some level of organization stepping rules and maintaining of dynamic stability dominate. Let us localize these functions at the level of gait (stepping) techniques. In our earlier works (see for example [4]) the simplest stepping model was introduced. The following assumptions were made:

a) the entire mass of a biped is concentrated in a single point, the centre of gravity (C.G.),

b) the biped's C.G. coincides with the point of rotation of mass-less, stilt-type legs (the contact between the leg and the ground is considered to be a single point and the moment-less pivot),

c) there is no double support phase during the locomotion,

d) there is no slippage at the supporting point,

e) the ground surface is smooth and level.

According to the first three assumptions the biped, in fact, uses only one leg at time; the legs simply appear (stance leg) and disappear (swing leg) at the moment of changeover.

Simple model of biped stepping motion is shown in Fig. 3.

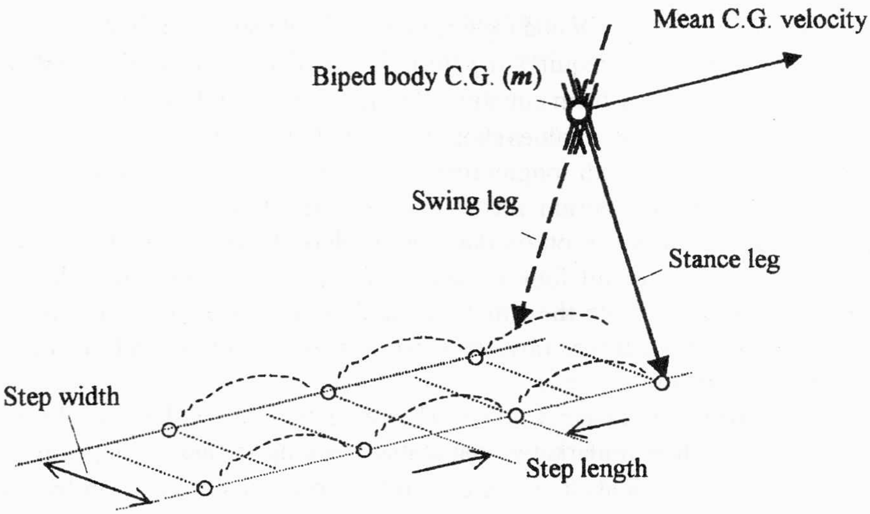

Fig. 3. Simple model of biped stepping techniques

By these assumptions the motion control can be reduced to a step control: a proper choice (in time and in space) of the foot/ground contact points. Within each step biped's body can be considered as a free inverted mathematical pendulum. The factor that initiates the motion within each step is the kinetic energy transmitted from the preceding step. The stepping motion takes place in two planes: longitudinal (sagittal) and lateral (frontal). In the longitudinal component motion, the initial energy suffices for the body to pass over the upright position. This makes it possible for the body to move progressively. This is not the case in frontal motion when initial energy does not allow the C.G. to pass over the supporting point and only lateral oscillations appear.

In the course of simulation studies, simple control laws meeting the stability and repeatability requirements of the stepping motion have been found. The general form of the control law that meets the stability (repeatability) requirements is:

$$\phi_i = -\lambda\,(\phi_{i/f})', \tag{1}$$

where: ϕ – body tilt ($\phi \equiv \delta$, pitch angle; $\phi \equiv \gamma$, bank angle) measured from vertical at the supporting point; ϕ_i – initial (just after feet changeover) tilt angle; ϕ_f – final (just before feet changeover) tilt angle; $(\phi_{i/f})'$ – initial/final (at the moment of feet changeover) tilt angular velocity; λ – control coefficient (λ_δ – for longitudinal motion; λ_γ – for lateral motion).

The following conditions have to be met:

$$\lambda_\delta < \left(\frac{l}{g}\right)^{-1/2}, \qquad \lambda_\gamma > \left(\frac{l}{g}\right)^{-1/2}, \tag{2}$$

where l is the leg's length.

In this nomenclature $(\delta_f + \delta_i)l$ and $(\gamma_f + \gamma_i)l$ approximate step length and step width, respectively. The simulation requires *a priori* choice of the values of δ_f and γ_f. The values of δ_i and γ_i will result from equation (1). Since stepping frequency depends on the coefficients λ_δ and λ_γ, their values should be strictly selected to assure compliance of stepping frequencies for both longitudinal and lateral component motions. Simulation runs proved that stable motion was established after first few steps (reaching an attractor – closed trajectory – seen on the motion phase plain) [2, 3]. It was remarkable that *a priori* choice of all four values δ_f, δ_i, γ_f, and γ_i, even when they corresponded to those obtained from the simulation making use of the control law (1), did not lead to stable solution. It was obvious since in that case the model, in fact, operated in an open loop mode.

The results of simulation (see: Table 2 [4]) are comparable with those observed in the direct experiment. It is remarkable that stable stepping frequency depends just on the coefficients λ_δ and λ_γ, and, thus, on the body size l. This conclusion has proved that stepping cycle does not require any reference to sophisticated "biological clock", as some researchers lured by easiness of suchlike explanations assume, but results directly from inherent model properties.

Table 2. Main parameters obtained for the modelled gait.
Data assumed: $\delta_f = 18$ deg, $\gamma_f = 6.5$ deg, $\lambda_\delta = 0.28$ sec, $\lambda_\gamma = 0.35$ sec, $l = 1.0$ m

Model parameter	Value
Step length	0.68 m
Step width	0.29 m
Mean C.G. forward velocity	0.68 m·sec^{-1}
Amplitude of lateral C.G. motion	0.078 m
Step frequency	1.0 sec^{-1}

The characteristic stepping periodicity, referred to as locomotion rhythms [6], exhibits wide reference to many activities of contemporary man, e.g. assessment of aircraft handling qualities [8, 12].

It should be kept in mind that the basics of bipedal locomotion stick to upright body posture stabilisation. The controlled plant in this case is a body modelled as an inverted pendulum. The controlled variable is body tilt, i.e. horizontal shift of the body C.G. Due to subtle sole–ground interplay control actions are reduced to the translation of the resultant ground reaction within the envelope of feet–ground contact surface. Direct experiments prove that steady state, i.e. precise maintaining of vertical posture, does not exist. Instead of that small sway motions are detected that can be interpreted in terms of closed-loop control. The control law can be identified in the class of linear operators when control variable is a function of body tilt and its derivatives. The results obtained from modelling have shown that frequencies of dominant components of the sway oscillations are strictly grouped within the area of the locomotion rhythms.

The locomotion rhythms gain direct support in anatomy and some specific features of the natural body motion sensors localised in inner ear [9].

6. Gait economics

Gait techniques level is also responsible for locomotion economy. Some experiments show that the minimum energy costs per one step as well as per distance covered correspond to the so-called comfortable walk. The frequency at which this type of locomotion takes place lies well within the locomotion rhythms subjected, as was pointed out above, to whole body mass and size and coefficients in the control law. This phenomenon gains additional explanation when one takes into account natural frequencies of most body limbs – physical pendula, in particular lower and upper extremities. It is the resonant phenomenon that provides maximum effect at minimum costs. The resonant features of human natural locomotion were investigated in our earlier works [5, 7].

The simple model suggested above provides some means for gait resonant analysis. To do this one should take into account time changes of potential and kinetic energy: the first resulting from vertical movements of the C.G., the second – from forward speed. Both components of total energy change in the pulsating manner. Within the area of resonant the total energy remains constant (full exchange of potential energy into kinetic energy, and vice versa).

7. Gait tactics

Let us now look at the bipedal locomotion from a higher level – gait tactics. Let us assume that the operational period sufficiently exceeds duration of a single step. Then, an analysis may be accomplished by assumption that the supporting point moves in a continuous manner and the mechanical model of a biped reduces to a monoped configuration [2, 3, 4]. Also in this case the motion may be divided into two components: longitudinal and lateral. For small values of pitch and bank angles each component motion can be considered independently. The monoped's motion is subjected to the principles of the continuously controlled inverted pendulum. Simulation studies have shown that if the C.G. velocity is to be controlled, the acceleration of the supporting point should be chosen as a control variable [2].

The simulation experiments have lead to several essential motions. It is of interest, for example, that when the increase of the C.G. velocity is demanded, the velocity of the supporting point within some initial period should decrease (e.g. by an initiative step length decrease). Alternatively, for a decrease of the C.G. velocity, initiative increase of the velocity of the supporting point (e.g. by an increase of the step length) is demanded. This phenomenon may be explained in the following way:

The control of the C.G. velocity is executed by mediation of body tilt necessary to initiate the change of the intended C.G. motion. Body tilt makes it possible to use gravity forces and related ground reaction. Thus, the very first task of the controller is to obtain a proper body tilt. A proper external force applied at the supporting point may execute this. The initiative action, because of its opposite direction with respect to the demanded change of motion, may be called counteraction. This result concerns both the longitudinal and lateral control and is common for all inverted pendulum-type plant (compare, for example, counter rotation in the case of a ski turn [1]).

8. Gait heading control

The simplest model as proposed above does not provide any means that would enable rotation of biped's body about vertical axis. Gait heading control calls for:

• departure from assumption a): the concentration of entire mass in the biped's C.G. makes it unreal to use any torque applied to the biped's body;

• acceptance of lateral separation of legs pivots (departure from assumption b)); the distance between the pivots would then correspond to the distance between hip joints;

• acceptance of double support period (departure from the assumption c)) and, in addition, acceptance of some means for application of torque at the legs pivots (at hip joints).

Now, the generation of necessary yaw torque becomes possible. Suggested model based on semi-physical inverted pendulum is shown in Fig. 4. The model has not yet been investigated in detail.

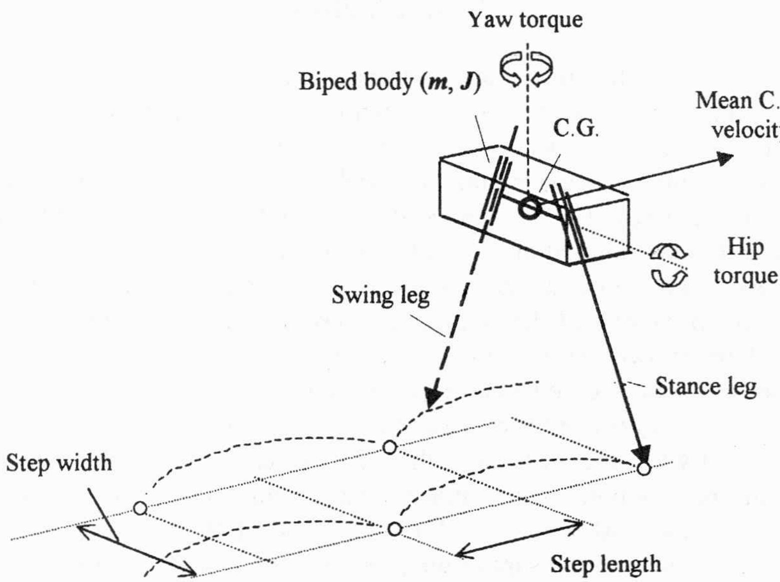

Fig. 4. Extended model enabling analysis of gait heading control

9. Concluding remarks

In this paper some predominant features of bionic, cybernetic and system-theoretic approach have been pointed at and compared with the sheer statistical and direct experiment procedures. The advantages of cause–effect analysis and problem drawing have been pointed out. Modelling and simulation aided by wide use of computers and user-friendly procedures provide powerful tool for locomotion studies. Particularly, subdivision of the full motion act into parts-levels, characteristic of system-theoretic approach, appears to be very fruitful.

Two successive levels of the model, gait techniques and tactics, have been discussed. The model reduced in this way appears to be in power to explain many essential features of the complete locomotion act. In particular, the basic control laws, hypothetically realized within the neuromuscular system, have been identified. Between the two levels: gait techniques and gait tactics, some interface means ought to be assumed, the function of which would involve synchronizing of both (lateral and longitudinal) stepping component motions (at the techniques level) as well as necessary body attitude averaging (at the tactics level).

A few words have been devoted to the gait heading control. This problem calls, however, for some departures from the basic model.

Natural sources of the locomotion rhythms have also been revealed and discussed in terms of the resonant phenomenon and gait economy.

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