Journal of Intelligent and Robotic Systems **41:** 65–84, 2004.

Human and Humanoid Dynamics

From the Past to the Future

M. VUKOBRATOVIC
"M. Pupin" Institute, Belgrade, Serbia; e-mail: vuk@robot.imp.bg.ac.yu

V. POTKONJAK
Faculty of Electrical Engineering, University of Belgrade, Serbia; e-mail: potkonjak@yahoo.com

S. TZAFESTAS
National Technical University of Athens, Greece; e-mail: tzafesta@softlab.ntua.gr

(Received: 26 May 2004)

Abstract. The questions when and why one needs to use mathematical models, and especially the models of dynamics, represent a still unresolved issue. A general answer would be that dynamic modeling is needed as a tool when designing structure of the system and its control unit. In this case we talk about simulation. The other application is in on-line control of the system – the so-called dynamic control. While for simulation one should generally use the best available model, the control can be based on a reduced dynamics, depending on a particular task. This article considers humans and humanoid robots and addresses a rather important question: what are dynamic effects that one should take care of when modeling and simulating a human or a humanoid? The article suggests the key topics for work and tries to justify them. As a final result a *General Human/Humanoid-Dynamics Simulator* is seen.

Key words: humanoid dynamics, humanoid robot, dynamic control, active exoskeleton, zero moment point, balanced motion.

1. Mathematical Models: Where and Why?

We start our discussion with a rather general question: how much is mathematical description really necessary for a successful solution of problems in different fields? Although it seems obvious, the answer is not simple. Let us consider a non-technical field – economy. Mathematical models are present in a scientific analysis but they are less common in practical work. Managers and even creators of economic policy often rely on their experience and the "feeling" of the problem. One may say that this comes out from the lack of qualified mathematical description of complex rules that govern such systems. Perhaps even worse situation is in some fields that are close to our current interest – biology and medicine. Extremely complex problems faced in these fields are tough to describe mathematically. Mathematical modeling is entering biology and medicine but the wide application is still far. However, this fact did not prevent the growth of these sciences. In technical disciplines, as our primary interest, mathematical models describe the operation rules quite successfully. Engineers and even students know that mathematical description of their problems is inevitable. However, experienced engineers still can sometimes "feel" the solution. So, one could state that the *knowledge* about the system is always necessary but it can be of different kind: *mathematical models*, *expert knowledge* (experience: facts and rules collected by learning), or a combination. Further, one may state that the knowledge is needed to design a system and to control it. In this article, we are interested in two fields: biomechanics of human motion, and robotics. The article primarily addresses the *mathematical approach* but at the same time recognizes the significance of *expert approach* and suggests it whenever it is useful.

In biomechanics of humans, we are definitely not interested in "designing systems" but we are interested in analyzing the behavior in order to detect potential malfunctioning and assist or improve the control. One direction leads to medicine (diagnosis and rehabilitation) and the other to sport (improving results). In both directions one meets mathematical models and expert knowledge. In diagnostics, expert approach is preferred while in rehabilitation the devices to be applied are often designed and controlled by using mathematical apparatus. The latter will be explained below since it is closely related to the other field of our interest – robotics. In different sports, it is rather common to analyze and plan the motion by using mathematical models of kinematics and dynamics. What analysts are looking for are more efficient movements and finally better results. Currently, several program systems developed for this application are available.[*]

Robotics is a good example of how a scientific (mathematics-based) approach and a practical (experience-based) approach can exist and grow separately. Practical robotics came out from real industrial problems that needed solutions. At the beginning, it was manipulation of workpieces and machine loading–unloading, later came process operations (like welding and spray painting), etc. Experienced engineers found the solution in a mechanical system powered by hydraulic or electrical actuators that could replace human workers at these jobs. The first systems of this kind[**] did not look like humans and were not based on mathematics and dynamics theory. The term *manipulator* seems to be appropriate for such systems. Later, as manipulators became more complex, the term robot was introduced. At a certain moment, designers of industrial manipulators/robots felt the need to model robot kinematics in order to plan and generate complex manipulation trajectories. However, for a long time they did not need true dynamics. Design and control were based on experience and simplified models. A wider application of dynamic models in on-line robot control started about ten years ago.

[*] When searching for *"biomechanics software"* the Yahoo engine finds 171 matches. Search for *biomechanics and software* (logical AND) gives 51,100 matches. From this offer we select sites: www.motionanalysis.com, and www.vicon.com.

[**] The first robotic devices were patented in 1954: in Great Britain by C. W. Kenward and in USA by G. C. Devol. The latter system, supported by J. F. Engelberger, was the first widely used industrial manipulator (a simple robot) manufactered by the first robotic company UNIMATION.

Independently of industrial needs, scientists have worked on anthropomorphic systems. These devices were supposed to have legs and arms, to walk and manipulate like humans did. If one would pose the question why researchers did that, the answer could be found in the article "How Far Away is Artificial Man".* The authors stated that the idea that led robotic scientists from the very beginning was to create a copy of themselves – an artificial man called *robot*. It was seen as the essence of the entire robotics. As serious scientists always do, "roboticists" started from mathematical modeling of robot kinematics and dynamics. Two-leg walking was considered with the aim of generating a stable gait. Arm and hand motions were modeled in order to allow manipulation. Regarding the mathematical description, full kinematics and dynamics were involved from the very beginning of work in this direction. Since some practical output was required from robotic projects, the researchers looked for some realistic applications. Rehabilitation devices appeared to be suitable products: prostheses were made for leg, arm and hand, and orthosis for arm and legs (active exoskeleton). Different types of multilegged machines were designed while trying to solve the transport on a rough terrain.

A reasonable question is: when and why these two directions of work, industrial and scientific, have finally met? It was not long ago that industrial robotics faced the tasks where very fast and precise motion was required. To control fast motion of heavy elements, it was necessary to take care of different dynamic effects. At the same time, the designers of robotic mechanism and control felt the need for designing tools that could assist in fast, flexible and more efficient work. This meant simulation and finally CAD for robotic systems. For complex robotic systems, experience and expert knowledge could not be a substitute for mathematical models. Thus, simulation appeared to be an inevitable step in design and, along with optimization techniques, has allowed development of CAD.

The aim of this article was to highlight the problems important for the dynamics of humans and humanoids and propose guidelines for research in this field. We do this by suggesting and justifying some research topics.

2. Robot Dynamics: History and Problems

As stated above, robot dynamics was first introduced to analyze the behavior of anthropomorphic active mechanisms. These works gave the initial stimulus to the development of robot theory. In view of its many specific features one may say that robot dynamics constituted a new field of applied mechanics.

Modeling of biped gait resulted in mathematical description of kinematics, dynamics and stability of two-leg walking robot [6, 25]. It was then that "zero-moment point" (ZMP) was first recognized as being essential for the synthesis of a stable (balanced) gait. Newton's and Euler's equations were used to describe

* Authors: T. Fukuida, R. Micelini, V. Potkonjak, S. Tzafestas, K. Valavanis, and M. Vukobratovic; published in IEEE Robotics and Automation Magazine, IEEE Robotics and Automation Magazine, March 2001 issue, pp. 66–77.

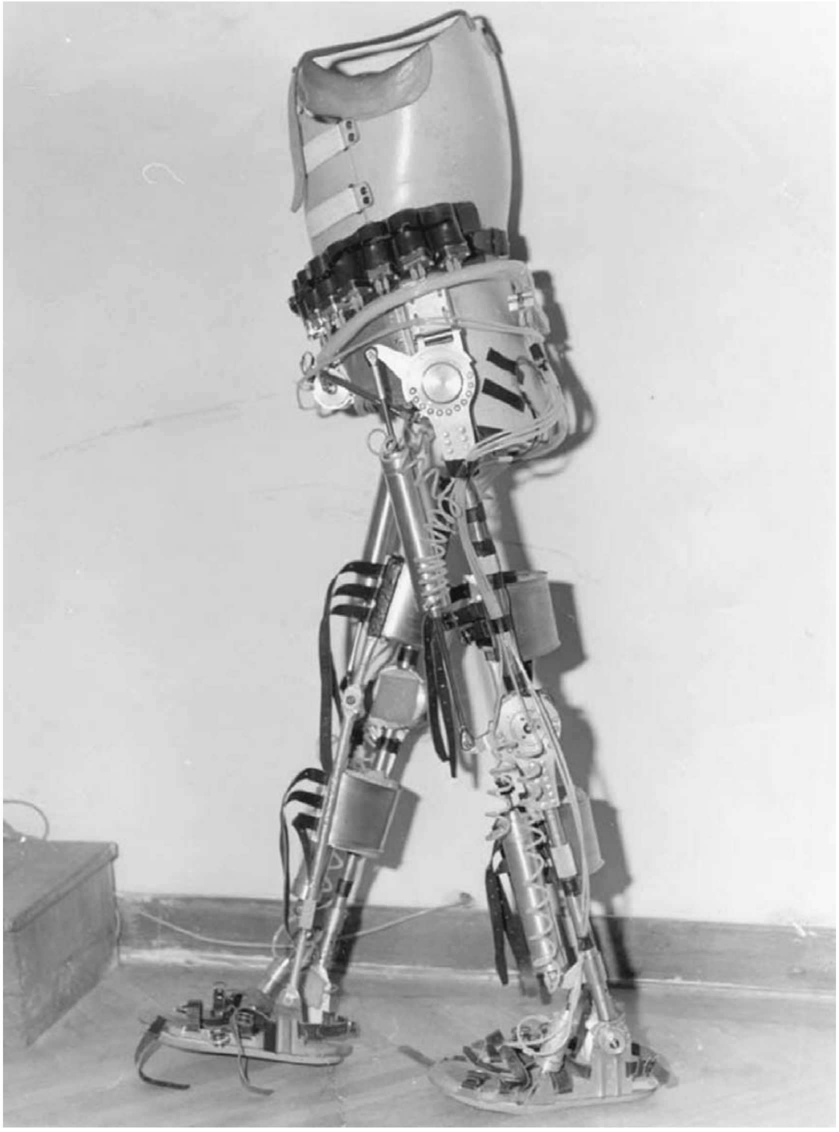


Figure 1. Active exoskeleton for paraplegics (“M. Pupin” Institute, 1972).

system dynamics. This research prepared the theoretical background for humanoid robotics. As a practical output, a lower-extremities exoskeleton was made to allow paraplegics to walk [24] (Figure 1).

Independently, dynamic model was formulated for robotic arm and generalized to arbitrary spatial open linkage [16, 29]. The model utilized Rodrigues’ formulae to solve relative rotation between links and Newton–Euler approach to solve dynamics. It was a computer-aided model that eliminated mistakes that might appear when preparing models “by hand”.

2.1. ROBOT ARM – INDUSTRIAL ROBOTICS

Successful work in arm kinematics and dynamics gave rise to sophisticated industrial robotics. After the above-mentioned fundamental results, research in dynamics followed several directions. Some of them used different kinematic and dynamic approaches (Denavit–Hartenberg parameters for geometry and kinematics; Lagrange's equation and Appel's equations for dynamics; symbolic form of models) to make the computation time shorter. However, one may consider computation time as a matter of computer technology – it reduces rapidly for any kind of mathematical model. The other researchers tried to move the boundaries of knowledge in this field by introducing new dynamic effects, and thus generalizing the existing dynamic models. Here we list the problems that occupied attention of researchers and specify just some initial results (and references).

The fact that many robot tasks involved the contact of the end-effector and the robot environment led to the first research on contact dynamics [12, 27, 28]. Robot environment was considered in the form of a geometric constraint (stationary and nonstationary). The friction between the robot and the environment was included. Collision problems were discussed and the solution for nonelastic impact was found.

After solving the dynamics of rigid robots, the attention of researchers has turned to elastic effects. The problem of flexible links was considered first in [17, 21, 26].

The next source of elastic effects is the transmission of torque (often termed as "flexible joints"). The initial results in this field were presented in [10, 15]. They provided the foundations for further investigations.

With contact tasks, the most interesting deformation effects are those observed in the vicinity of contact points. Hence, for exact modeling of contact, the elastodynamics in the contact zone has to be taken into account. The first successful dynamic model was offered in the so-called "impedance control" algorithm [5, 7]. A thorough presentation of dynamic-environment control problems was given in [2, 23].

Special attention is to be paid to the problem of collision. It is an omnipresent effect since no contact can be made so precisely to avoid impact. The first study of impact with robotic systems was given in [1]. The nonelastic impact between the robot and the object in grasping was solved. In [27], the collision of the robot end-effector and a geometric constraint was elaborated. The impact was still considered nonelastic. To get a better insight, the collision can be modeled through elastodynamics. One way of doing this was by means of the lumped mass approach [20].

The final problem to be mentioned in this survey is redundancy. In the early research in this field, redundancy was considered as a problem of kinematics (avoiding obstacles, avoiding singular positions, etc.). Later research, however, saw redundancy as a possibility to improve robot's dynamic performance [4, 11].

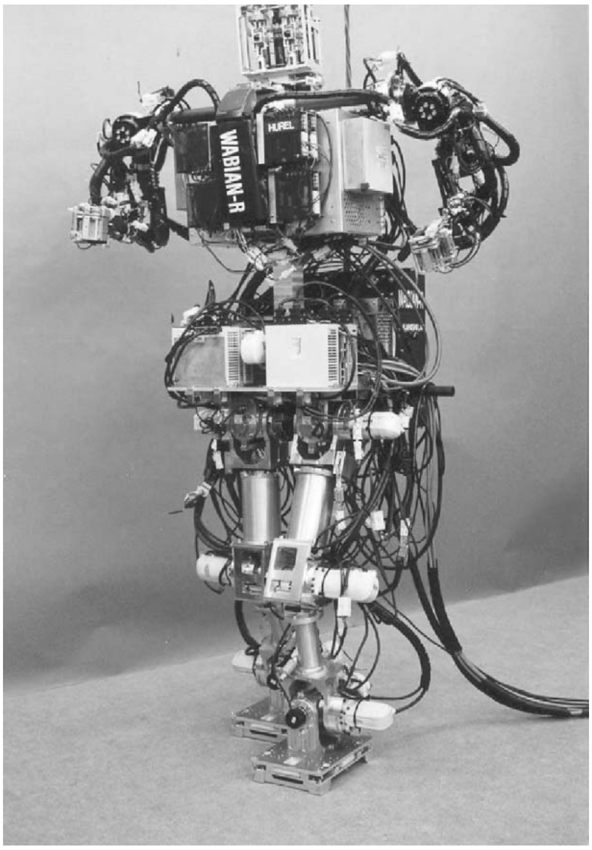


Figure 2. WABIAN – humanoid robot built at Waseda University.

2.2. ANTHROPOMORPHIC ROBOTS – HUMANOIDS

Research in humanoids did not have so fast progress as industrial robotics had. This has been a consequence of the fact that industrial robots were recognized as key systems in advanced manufacturing automation and hence were supported by high investments. At the same time, work on humanoids has been almost considered as mere enthusiast's concern. Among few centers where such research has been permanently conducted we point out Waseda University. The efforts resulted in building the famous WABOT and WABIAN humanoids [19] (Figure 2). It was not long ago when the researchers and robot society in general came to the conclusion that humanoids represented a highly prospective direction of work. It was finally "discovered" that humanoids open a huge field of work, potentially very profitable – service and personal robotics. In the already mention article "How Far Away is Artificial Man", the authors argue for a coordinated international effort towards a robot with *human-like motion, intelligence and communication*. For its impact to the way people look at robotics, it is necessary to mention the HONDA humanoid [18] (Figure 3).

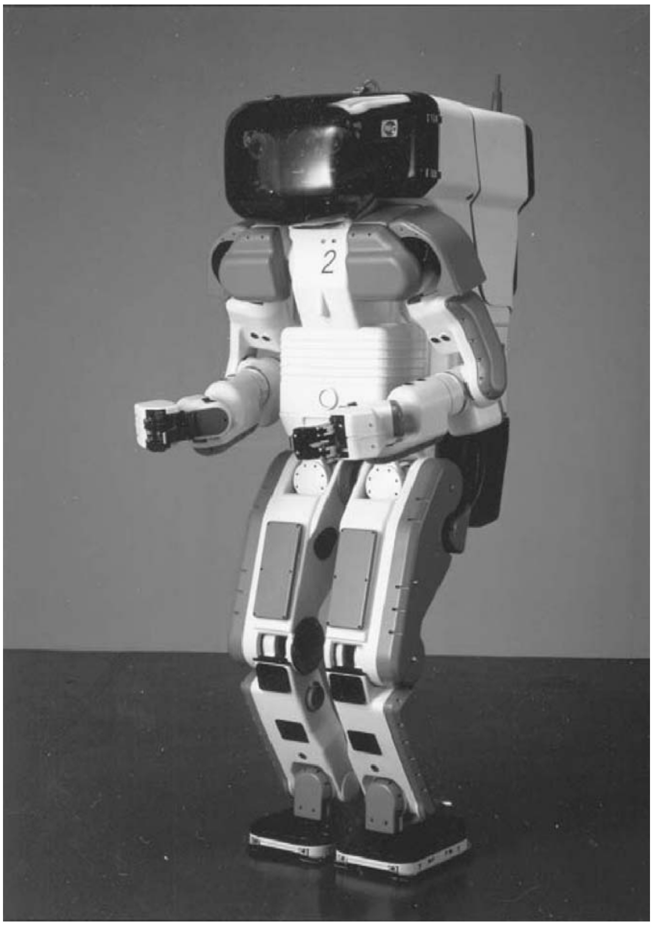


Figure 3. HONDA humanoid robot.

Kinematics and dynamics of anthropomorphic robots are much more complex than it is the case with industrial robots. Industrial robot arm usually possesses up to six degrees of freedom (DOFs) while a humanoid may have more than fifty. Redundancy is rarely present in industrial arms while in humanoids it is likely. Synthesis of a stable bipedal gait is a rather complex problem, present exclusively with humanoids. For these reasons, much effort and time has been spent to solve theoretically the motion of a rigid-body anthropomorphic mechanism and develop real robotic systems. The major problems considered were [22]:

– formulation of a dynamic model that relates joint torques (vector τ, with zeros for unpowered joints) and joint motions (vector q); and
– synthesis of a stable gait.

Dynamics is described by a set of linear second-order differential equations. They allow the solution of both direct ($q \rightarrow \tau$) and inverse ($\tau \rightarrow q$) dynamics. The

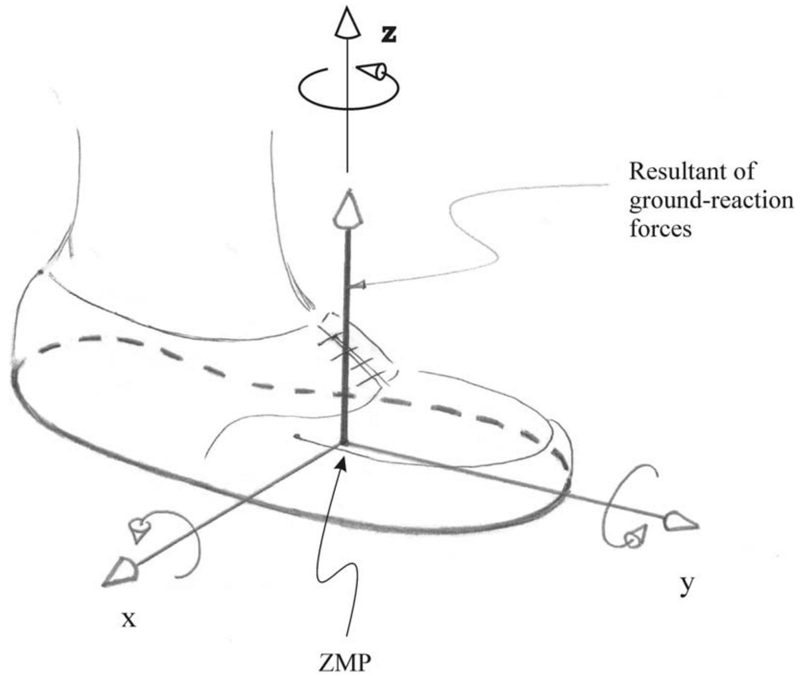


Figure 4. Zero-moment point (ZMP).

ground reactions and friction force are important effects in the system dynamics. The open-chain model is used in single-support phase and the closed-chain model for the double-support phase. As an example, we show the form used for single-support phase,

$$H(q)\ddot{q} + h(q, \dot{q}) = \tau,$$

not aspiring to elaborate the robot mathematics in detail.

Synthesis of a stable gait is based upon the concept of ZMP, expressed by means of three conditions (see Figure 4):

$$\sum M_{x(\text{inertial and gravitational})} = 0,$$
$$\sum M_{y(\text{inertial and gravitational})} = 0,$$
$$\sum M_{z(\text{inertial and gravitational}),\ \text{in general case}} = M_{\text{foot friction}}.$$

In the original concept, the motion of some joints was prescribed (obtained by previous measurements or by learning) and this mainly referred to the motion of legs. For a nonredundant system, ZMP conditions allowed to calculate, for instance, the compensating movements of the trunk, needed to keep the stable gait. This was called *semi-inverse method* [22]. For a redundant system, additional conditions are necessary in order to compensate for the surplus of DOFs.

Thus, the "new" effects like impact, flexibility of links, joints or support, etc. came on the carpet recently. A thorough review of the state-of-the-art in humanoids would contain a huge number of references. For this reason we mention fundamental research [6, 25] and for the elaboration and realization one is referred to Web pages [18, 19] and to the proceedings of special meetings on humanoids (e.g., conference HUMANOIDS, target workshops, and special sessions on ICRA and other conferences). These are the sources of comprehensive information about what have been done in this field.

One may say that the dynamic effects that have been elaborated in industrial robotics can serve as guidelines in the generalization of humanoid dynamics. In this article we will suggest and justify the "new" effects that deserve attention of researchers.

3. Research in Dynamics: What to do and Why?

In this section we try to formulate a set of topics that seem inevitable or prospective. Although some of these problems have already been recognized and elaborated, we need to mention them in order to make the set consequent. When put together, the topics form *General Human/Humanoid-Dynamics Simulator* (GHDS). Such approach makes possible the analysis of interaction between different dynamic effects. This simulator is intended to analyze two kinds of systems:

- biomechanical human systems, and
- humanoid robots.

Human and his behavior can be modeled and analyzed for various situations. This has its application in medicine and sport. Dynamic analysis of humanoid robots has two main purposes: simulation in design (mechanical-system and control-system design), and on-line control (so-called dynamic control).

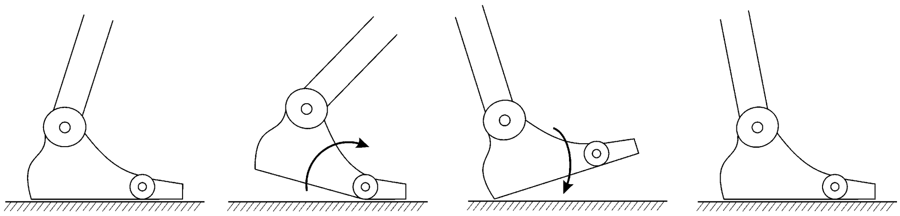
When justifying some research direction one may find that it relies on a rich experience in the topical field. An attempt to review the results and references in detail would take too much space. The only way to surmount this problem is to talk about the subject assuming that relevant references could be found when needed.

Let us arrange the suggested dynamics topics in the following groups.

3.1. OUR FIRST FOCUS IS ON THE HUMAN/ROBOT MECHANISM INCLUDING ACTUATOR SYSTEMS

The question of the number of DOFs will not be discussed since our viewpoint is simple: the more, the better. It follows from our belief that robots will never reach the diversity of human motions although they might compete with humans in some activities.*

* To perform a stationary humanoid gait, including manipulation, about 150 DOFs are engaged (this means about 300 muscles). One should point out that the mechanical complexity of



(a) (b) (c) (d)

Figure 5. Modeling the foot motion: (a) flat-foot phase; (b) deploy-phase; (c), (d) the heel touches the ground first.

3.1.1. Mechanisms used for modeling must have an anthropomorphic form, that is legs, trunk and arms. It is suggested that the structure should be *redundant*, meaning that the model can walk and perform manipulation in different manners. This will make the synthesis of motion more complex since, in addition to the stability condition, one will need additional criteria to compensate for the surplus of DOFs. If GHDS is applied to human mechanism, no justification is needed (simply, humans possess redundancy). In the case of humanoid robots, justification for this additional effort comes out from the fact that redundancy gives humans flexibility in executing tasks (avoiding obstacles, avoiding joint limits and singular positions, replacing exhausted actuators by others, improving dynamics capabilities and abilities to react in unpredicted situations) and new generation of robots should possess some of these properties. The background for the research in redundancy is rather rich, from pure robotic to pure biological studies.

3.1.2. Regarding the *foot* – it should be modeled by two links (Figures 5(a), (b)). In some phase of walking (Figure 5(a)), the foot may be considered as one link since the topical joint is inactive. However, in the next phase the joint starts to move and the two links are clearly identified.

The single-support phase ends when the "front leg" touches the ground. The correct representation requires that the heel touches first (Figure 5(c)). After this moment, it takes some time (short but definite) before the complete foot is on the ground (Figure 5(d)).

3.1.3. It is suggested to introduce *flexibility at the mechanism joints*. This means the deformation between the motor and the joint. For biomechanical systems this has no sense, while with robots, it may happen that the transmission between the motor and the corresponding joint is not completely rigid but features some elasticity (Figure 6). Each flexible joint introduces at least one additional DOF (motor angle and joint angle become geometrically independent). The associated problem is how to control this unpowered DOF.

---

advanced humanid robots exceeds 50 DOFs (according to: Human Symbiotic Robot "WENDY", www.sugano.mech.waseda.ac.jp).

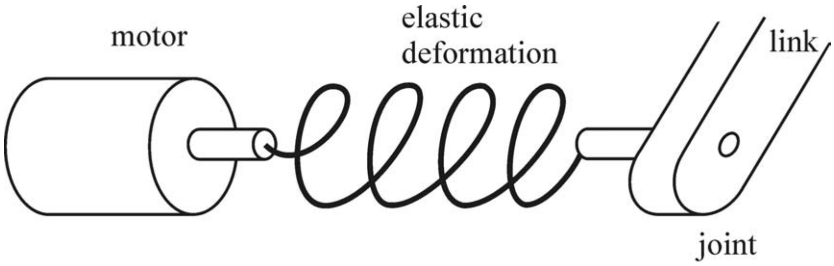


Figure 6. Flexible joint – elastic deformation in torque transmission.

It is not easy to justify the introduction of such effects. One argument is that deformation in transmission really takes place (smaller in some kind of transmission and larger with others – like harmonic drive). A counterargument is that flexible transmissions can be avoided by the appropriate design.* Another viewpoint is that joint flexibility may be introduced intentionally to absorb impact stress. If this effect is to be taken into account, one may rely upon experience and results from industrial robotics.

3.1.4. The next generalization is to introduce *external forces and torques* at selected points on the body. These external actions may be used to model some resistive effects (like walking through water) or wind. Another option is to consider the force and the torque as reactions of another mechanical system, thus allowing establishing and modeling the coupling.

3.2. THE NEXT FOCUS IS ON THE CONTACT OF FOOT/FEET AND THE GROUND (SUPPORT)

For an effective control of a biped gait, it is necessary to control the contact forces between the feet and the ground. To do this efficiently, the deformation of the two bodies being in contact has to be taken into account. Deformation may appear on the foot side and on the ground side (in this article we will use the more appropriate term *support* instead of ground). So, this topic relates the contact zone and its properties on both sides.

3.2.1. In robot dynamics, the foot is generally considered rigid (consisting of either one or two bodies – Figure 5). However, in the contact zone this assumption may appear inappropriate. With the human foot (barefoot), the sole is not rigid – the skin and the subcutaneous and connective tissues are deformable. If a shoe or a robot foot is considered, then it is reasonable to expect again a *flexible sole* – some rubber layer introduced to act as a shock absorber. Such effects, elastodynamic contact, have been elaborated in industrial robotics but the experience with humanoids is limited [3, 9, 13]. For the GHDS, it is necessary to introduce this elastic layer

* One should say that HONDA has recently developed a torsion-free harmonic drive.

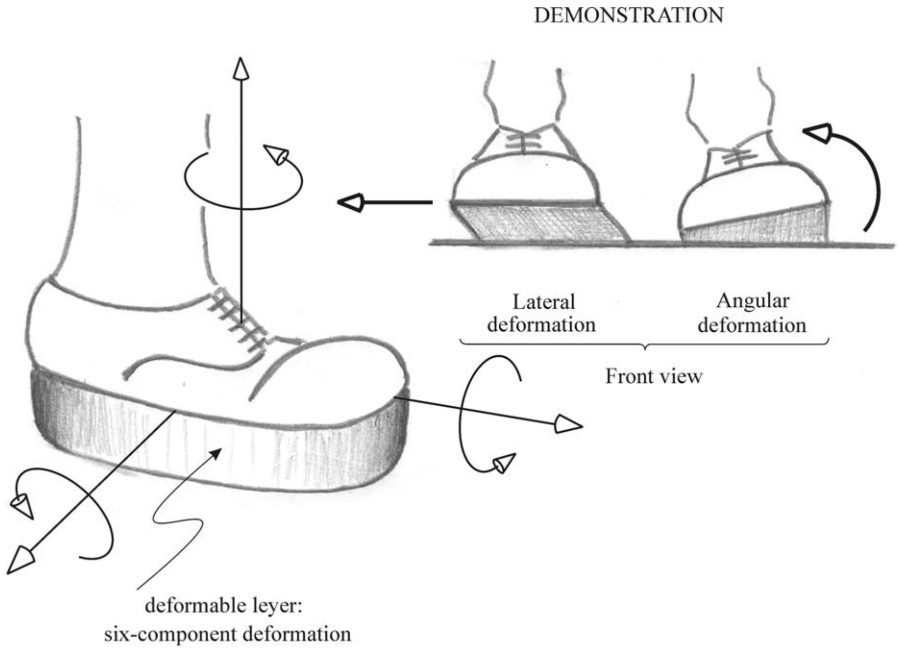


Figure 7. Deformable sole: deformation has six components; two components are demonstrated.

and it should feature six-component deformation: lateral displacements along three axes and angular displacements about these axes (Figure 7). It is generally assumed that deformation is a dynamic effect rather than just a spring and damper. Hence, we model the sole flexibility by means of appropriate impedance. One should note that the sole deformation influences the robot absolute position (lateral and angular, relative to the external frame) and robot dynamics and stability as well.

3.2.2. Now, let have a look at the surface on which the human or the robot walks. In a general case, this *support features elastic properties*: it can deform along the three axes and about them (six-component deviation – see Figure 8). Let us justify the work on this effect. One can imagine training of special forces whereby the trainees have to move on some "soft" support like a sponge or a water mattress. Simulation of these actions involves elastodynamics of the support. In another example, a sportsman on a trampoline is simulated (Figure 9). In GHDS, the deformation of the support is modeled in the same way as it was done on the foot side of the contact – introducing appropriate impedance. This deformation influences all the positions and the entire dynamics "above" it.

The introduction of elasticity in the contact zone allows the exact treatment of the *impact* that occurs when the foot touches the support. Although the elasticity eliminates the impact shock, there are still effects that need analysis (like transient response, etc.).

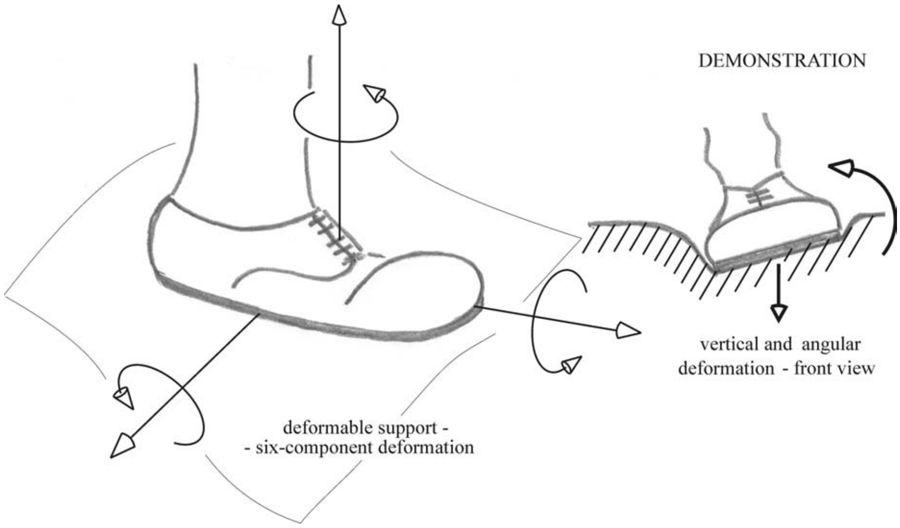


Figure 8. Deformable support: deformation has six components; two components are demonstrated.

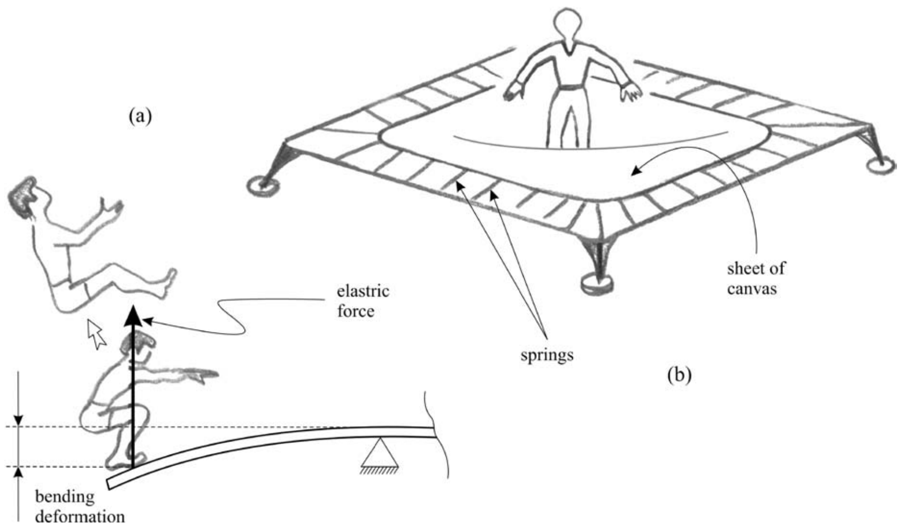


Figure 9. Sportsman on a trampoline – two examples.

Here, a natural question arises: why the two deformations (one on the foot side and the other on the support side) are considered separately? There are several reasons for that. One is that the two deformations come out from different layers and may have different characteristics. The next regards the gait stability. If the walker loses its stability, the foot (together with its shock-absorbing layer) overturns about the edge being between the two deformable layers (Figure 10). In order to analyze the stability of gait, ZMP position is considered. It refers to a mobile frame (laterally shifted and inclined).

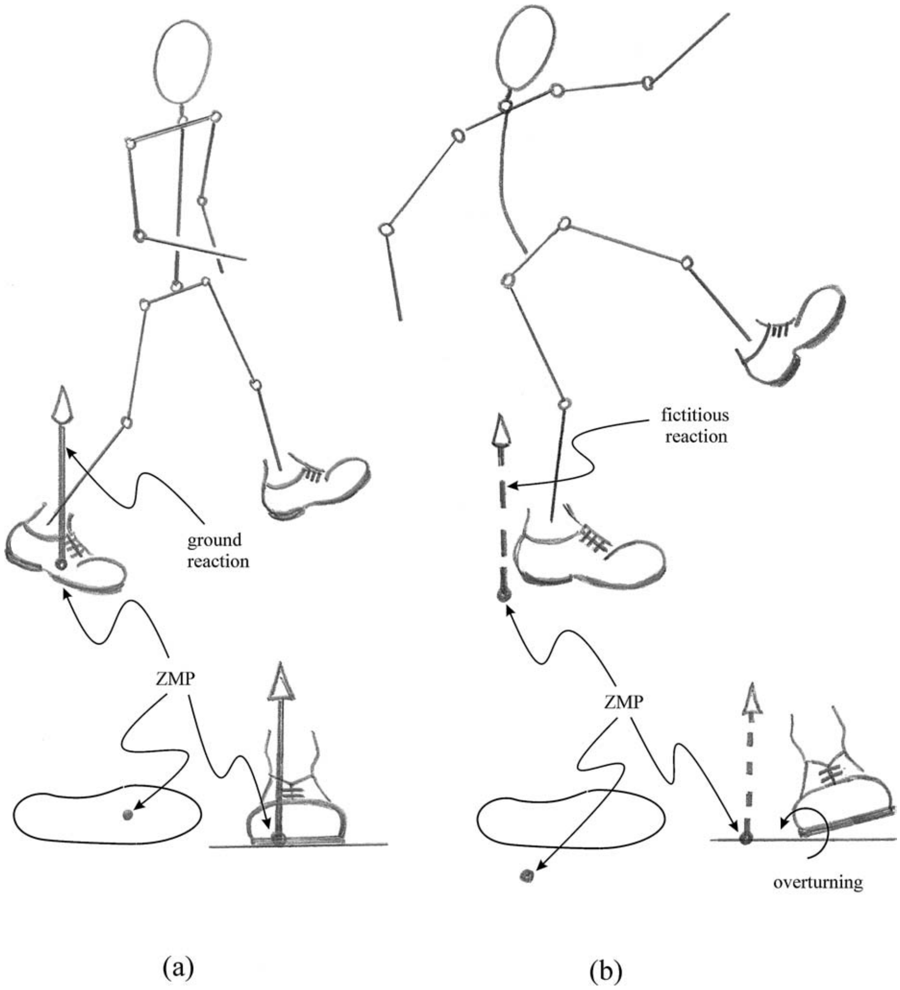


Figure 10. ZMP position: (a) for stable movement (position of the ground reaction); (b) the case of instability – overturning (fictitious point where reaction should act in order to stabilize the motion).

3.3. THE FINAL FOCUS IS ON THE SUPPORT

We have already stated that the term ground in this context should be replaced by *support*. The term ground usually means something immobile (perhaps deformable, but immobile). However, a general approach requires the option of walking on a *mobile support*. Moreover, such support is not considered as a pure nonstationary constraint but rather as a dynamic system that interacts with the walker (jumper, etc.). Thus, a mobile platform that has its own dynamics is introduced. The platform should have up to six DOFs.

Justification for this generalization comes out from real needs. Training of special forces and police includes different actions performed on a mobile platform

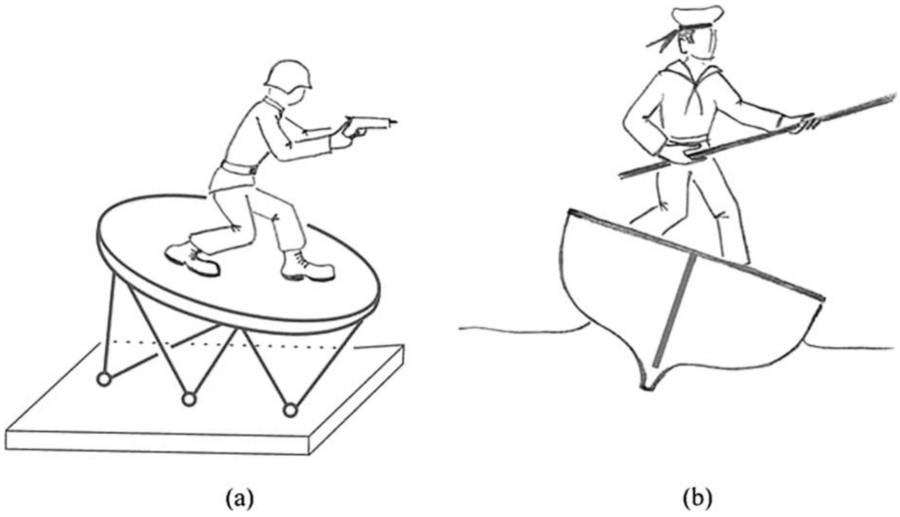


Figure 11. Mobile support – two examples.

(Figure 11(a)). Another example is the simulation of walking on a ship or, in a "worse" case, on a boat (Figure 11(b)).

It is clear that the platform can be modeled in different ways; we mention two options. A sequential (linkage) structure may be used to construct the platform. In this case, well-known algorithms used for linkages can be applied to formulate the dynamic model. The other constructive approach (perhaps primarily expected) refers to the use of special platform structures (e.g., Turin platform [14]), as shown in Figure 12. The mentioned two options may be applied even if the moving support is of some different kind (boat for instance); in this case the suggested platform mechanisms are just models of a true system.

3.4. SYSTEM INTEGRATION

In describing the effects that should be taken into account when working on humans or humanoids dynamics, we came to the configuration of the system in the *dynamics simulator* GHDS. It is shown in Figure 13.

It is important that one distinguishes between GHDS and the test bed that involves the real devices: robot, cameras, etc. [8]. A fusion of these two systems may be considered as the ultimate target.

Another question deserves the answer. What kinds of motions are to be modeled? One could note that we mainly used the terms *walking* or *gait*. This came out from the fact that walking was the most interesting problem and the topic that has attracted major attention for a long time. However, many other movements are of interests such as balancing on one foot (like in the case of a karate kick, Figure 14), balancing on two feet (like a policeman in Figure 10), running, jumping, etc. Skiing

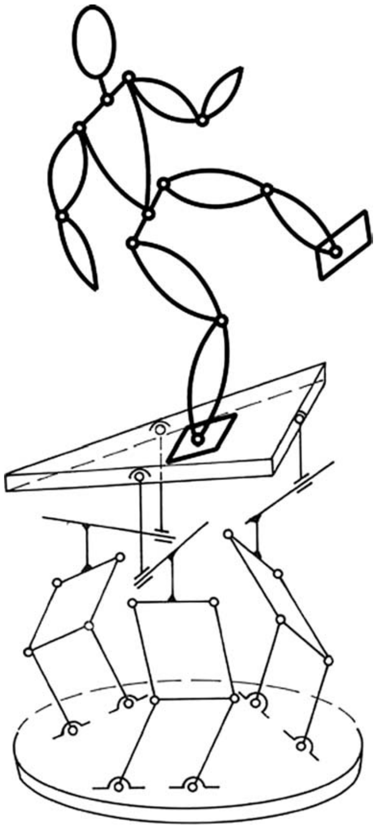


Figure 12. Turin platform system.

is another motion that might be modeled and simulated (Figure 15). It is specific due to sliding that is the key effect.

What is the form of the dynamic model that covers the introduced dynamic phenomena? The "basic" model formulated above is augmented by introducing new DOFs (due to platform motion and different flexibility effects). Let them form the vector $p = (p_1, p_2, p_3, \ldots)$. The subvector p_1 describes the position of the platform (six components) and the subvectors p_2 and p_3 (six components each) regard deformation in the contact zone (on the foot side and the platform side). Additional position coordinates should be introduced in the case of sliding. Some of these additional DOFs are powered and some are not. Following the earlier stated form of single-support-phase model, the set of differential equations is:

$$\begin{bmatrix} H_{qq}(q, p) & H_{qp}(q, p) \\ H_{pq}(q, p) & H_{pp}(q, p) \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{p} \end{bmatrix} + \begin{bmatrix} h_q(q, p, \dot{q}, \dot{p}) \\ h_p(q, p, \dot{q}, \dot{p}) \end{bmatrix} = \begin{bmatrix} \tau_q \\ \tau_p \end{bmatrix}$$

With the so augmented mechanical system, the gait is still synthesized and stability is controlled by using ZMP concept. One should note that now ZMP conditions refer now to a mobile frame (laterally shifted and inclined) as shown in Figure 10.

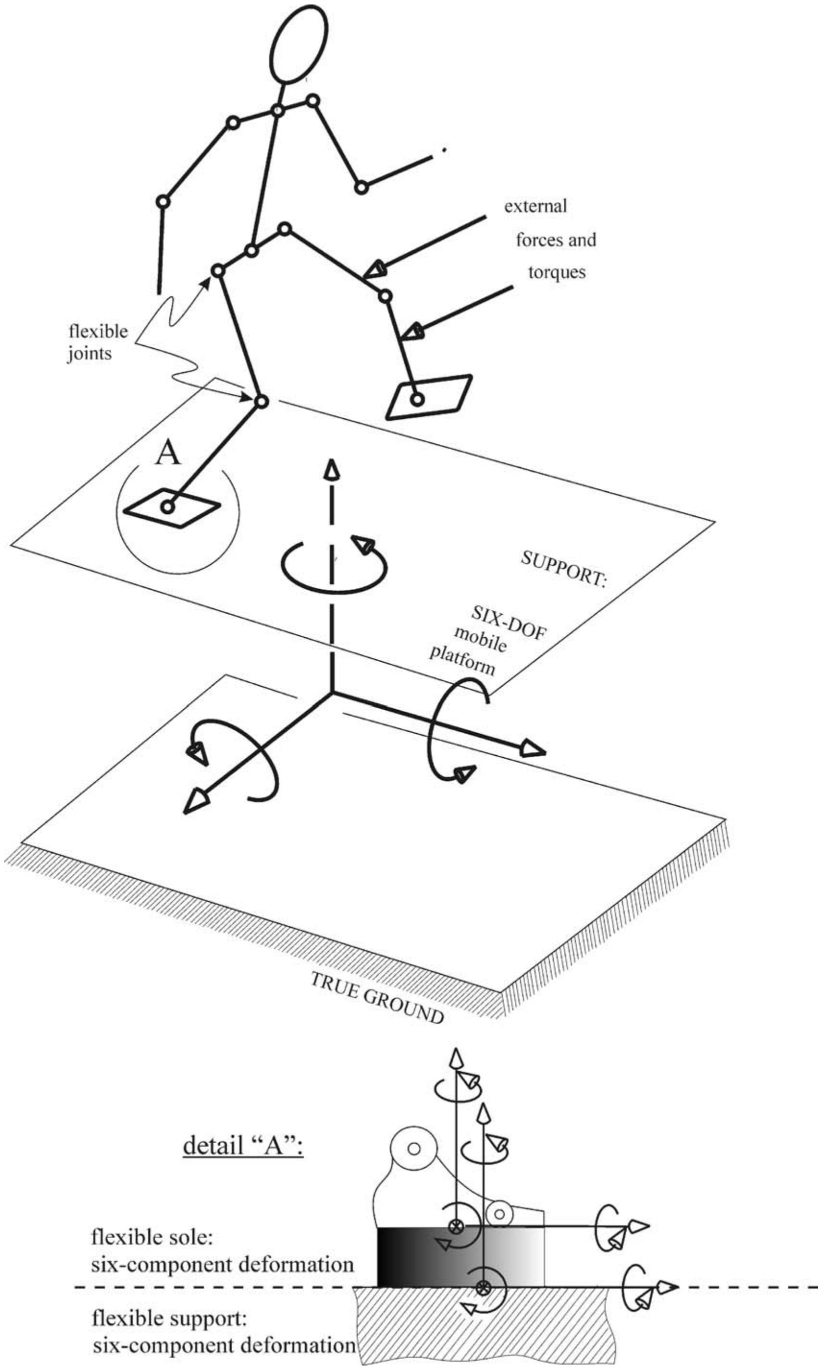


Figure 13. Configuration of the mechanical system in GHDS.

Figure 14. Example of a balanced motion on one foot – a karate kick.

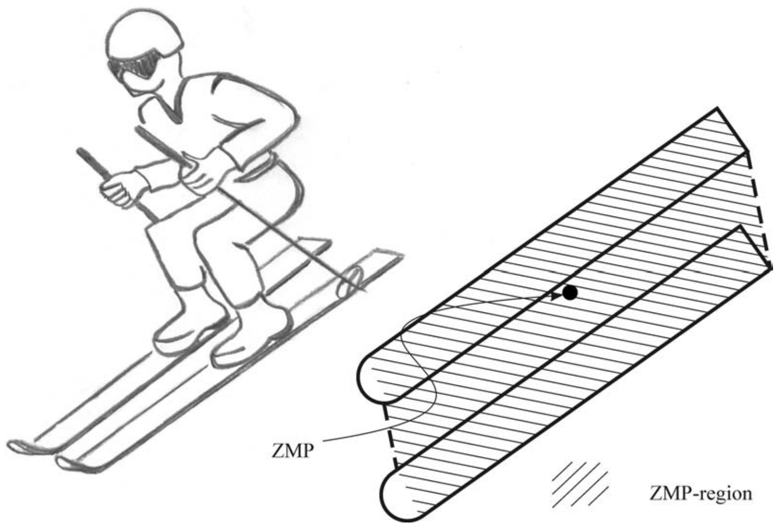


Figure 15. Skiing – balanced motion with sliding.

4. Conclusion

Mathematical models, and especially models of system's dynamics, are a powerful tool for system design and control. This applies to any system but we focus on humans and humanoid robots. The benefits of system dynamic analysis are strongly related to the appropriate selection of the model. There is no a simple correspondence that a more complex model is always a better one. In research activities, models used for simulation should be carefully defined so as to highlight and point out the effects we are interested in while the others may be ignored. In the design one may say: "the more complex, the better". However, one should still think of the time that might be spent to calculate unnecessary (negligible or irrelevant) effects. In on-line control, the question of model complexity is expressed even more strongly. The dynamic control is generally a desirable solution if the dynamics can be calculated in real time. So, one should select very carefully the dynamic effects that are important for a particular control problem; irrelevant effects should be ignored in order to save the processor time. Although computation time reduces rapidly with new computers, some dynamic problems (like link flexibility) are still considered time-consuming.

This article tried to specify the dynamic effects that are relevant for simulation of the biomechanics of the human and for simulation and control of humanoids. The idea was to highlight the problems and topics and thus set the guidelines for further research. The authors argue for a general approach, *General Human/Humanoid-Dynamics Simulator* that can be reduced to the level needed for a particular application. The concepts of this article started from the well-known significance of simulators in different technical fields. Having in mind the benefits that simulators can bring about, it would be a natural attempt to develop a system of this kind for humanoid robotics [8]. Further improvements of simulator concept in human biomechanics and humanoid mechanics and control would strongly depend on the selection of the effects that should be taken into account. The intention of this article was to contribute to these efforts.

References

1. Chumenko, V. N. and Yuschenko, A. S.: Impact effects upon manipulation robot mechanism, *Technical Cybernetics* **4** (1981) (in Russian).
2. Ekalo, Y. and Vukobratovic, M.: Adaptive stabilization of motion and force in contact tasks for robotic manipulators with non-stationary dynamics, *Internat. J. Robotics Automat.* **9**(3) (1994), 91–98.
3. Fujimoto, Y., Obata, S., and Kawamura, A.: Robust biped walking with active interaction control between foot and ground, in: *Proc. of IEEE ICRA 1998*, Leuven, Belgium, 1998, pp. 2030–2035.
4. Hogan, N., Sharon, A., and Hardt, E. D.: High bandwidth force regulation and inertia reduction using a macro/micro manipulator system, in: *Proc. of IEEE Conf. on Robotics and Automation*, 1988, pp. 126–132.
5. Hogan, N.: Impedance control: An approach to manipulation, Parts I–III, *J. Dyn. Systems Measm. Control* **107** (1985), 1–24.

6. Juricic, D. and Vukobratovic, M.: *Mathematical Modelling of a Bipedal Walking System*, ASME 72-WA/BHF-13, 1972.
7. Kazeroni, H., Sheridan, T. B., and Houpt, P. K.: Robust compliant motion for manipulators, Part 1: The fundamental concepts of compliant motion, *IEEE J. Robotics Automat.* **2**(2) (1986), 83–92.
8. Nakamura, Y. et al.: Virtual humanoid robot platform, in: *Proc. of Humanoids 2000 Conference*, Tokyo, 2000.
9. Park, J. H. and Chung, H.: Hybrid control for biped robots using impedance control and computed-torque control, in: *Proc. of IEEE ICRA 1999*, Detroit, Michigan, pp. 1365–1370.
10. Potkonjak, V.: Contribution to the dynamics and control of robots having elastic transmission, *Robotica* **6** (1988), 63–69.
11. Potkonjak, V. and Krstulovic, A.: Contribution to the kinematics and dynamics of redundant robots via distributed positioning, *J. Intelligent Robotic Systems* **5** (1992), 229–239.
12. Potkonjak, V. and Vukobratovic, M.: Dynamics of manipulation mechanisms with constrained gripper motion – Part 1, *J. Robotic Systems* **3**(3) (1986) 321–334.
13. Silva, F. M. and Machado, J. A. T.: Goal-oriented biped walking based on force interaction control, in: *Proc. of IEEE ICRA 2001*, Seoul, Korea, pp. 4122–4127.
14. Sorli, M., Vukobratovic, M., Ferraresi, C., Kolarski, M., and Borovac, B.: Mechanics of Turin parallel robot, *Mechanism Machine Theory* **32**(1) (1997), 51–77.
15. Spong, M. W.: Modeling and control of elastic joint robots, *J. Dyn. Systems Measm. Control* **109** (1987), 309–319.
16. Stepanenko, Yu.: Method of analysis of spatial lever mechanisms, *Mechanics Machines* **23** (1970) (in Russian).
17. Sunada, H. W.: Dynamic analysis of flexible spatial mechanisms and robotic manipulators, PhD Thesis, University of California, Los Angeles, 1981.
18. The HONDA humanoid robot, `www.honda.co.jp/robot/`.
19. The WABIAN humanoid robot, `www.humanoid.waseda.ac.jp`.
20. Tornambe, A.: Modeling and controlling two-degrees-of-freedom impacts, in: *Proc. of 3rd IEEE Mediterranean Conf. on Control and Automation*, Lymassol, Cyprus, 1995.
21. Truckenbrodt, A.: Dynamics and control methods for moving flexible structures and their application to industrial robots, in: *Proc. of 5th World Congress on Theory of Machines and Mechanisms*, ASME, 1981.
22. Vukobratovic, M., Borovac, B., Surla, D., and Stokic, D.: *Biped Locomotion: Dynamics, Stability, Control and Application*, Springer, Berlin, 1989.
23. Vukobratovic, M. and Ekalo, Y.: New approach to control of robotic manipulators interacting with dynamic environment, *Robotica* **14**(1) (1996), 31–39.
24. Vukobratovic, M., Hristic, D., and Stojiljkovic, Z.: Development of active anthropomorphic exoskeleton, *Medical Biological Engrg.* **12**(1) (1974).
25. Vukobratovic, M. and Juricic, D.: Contribution to the synthesis of biped gait, *IEEE Trans. Biomedical Engrg.* **16**(2) (1969).
26. Vukobratovic, M. and Potkonjak, V.: *Dynamics of Manipulation Robots: Theory and Application*, Springer-Verlag, Berlin, 1982.
27. Vukobratovic, M. and Potkonjak, V.: *Applied Dynamics and CAD of Manipulation Robots*, Springer-Verlag, Berlin, 1985.
28. Vukobratovic, M. and Potkonjak, V.: Constrained gripper motion in assembly manipulation – Part 2, *J. Robotic Systems* **3**(3) (1986) 335–347.
29. Vukobratovic, M. and Stepanenko, Yu.: Mathematical models of general anthropomorphic systems, *Math. Biosci.* **17** (1973).