Contribution to the Study of Humanoid Robots Anthropomorphism

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Abstract: Rapid development of humanoid robots brings about new shifts of the boundaries of Robotics as a scientific and technological discipline. New technologies of components, sensors, microcomputers as well as new materials, have recently put up the barriers to real time integrated control of some very complex dynamic systems such as humanoid robots are, which already today possess about fifty degrees of freedom and are updated in microseconds. In relation to this, the work raises also some new fundamental questions concerning the necessary anthropomorphism of humanoid robots, and how to achieve sufficiently high degree of anthropomorphism with a reasonable number of degrees of freedom. On the example of humanoid robot, concrete measures are proposed how to achieve the desired degree of anthropomorphism of humanoids.

Keywords: humanoid robot, antromorphism, zero-moment point, semi-inverse method

1 Introduction

1.1 How to assess the robot's anthropomorphism?

Current development of robotics indicates that the spectrum of robotic activities will significantly expand in the near future. Rapid development of humanoid robots brings about new shifts of the boundaries of Robotics as a scientific and technological discipline.

New technologies of components, sensors, microcomputers, as well as new materials, have recently shift the barriers to realtime integrated control of some very complex dynamic systems such as humanoid robots are, which already today possess about fifty degrees of freedom, and are updated in microseconds.

For a long time already, robots have not been present only in industrial plants, at the time their traditional workspace, but have been increasingly more engaged in the close living and working environments of humans. This fact inevitably leads to the need of "working coexistence" of man and robot and sharing their common working environment. The fact that no significant rearrangement of the humans' environment because of the presence of robots could be expected, robots will have to further "adapt" to the environment previously dedicated only to man. However, in the time to come it will be inevitable to accept the necessity of cooperative activities of man and robot, and make a step in the direction of increasing comfort of their joint action. Besides, it is expected that the robots cooperating with humans will have an operation efficiency as close as possible to that of humans. The working and living environment, adapted to humans, imposes on robots with their mechanical-control structure at least two classes of tasks: manipulating various objects from the human environment and robotic motion in a specific environment with the obstacles of the type of staircases, thresholds, multi-level floors, etc. One of the ways of approaching these tasks is to make robots look more like humans, i.e. anthropomorphic[1]. Hence, the necessary degree of the robot's anthropomorphism may be more concretely conceived as the degree of similarity of its motion and global behavior, whereby the similarity should not be only visual, but some other aspects of anthropomorphism also have to be satisfied. In this work we will confine ourselves only to considering the anthropomorphism of the artificial bipedal gait.

In relation to this, the work raises also some new fundamental questions. One of them is surely the relationship between the degree of anthropomorphism and number of degrees of freedom (DOFs) of the robotic mechanical structure, which could be formulated in the following way: How complex should be the robotic structure (i.e. how many DOFs should robot possess and which they are) in order it would be capable of attaining the desired (high enough) degree of anthropomorphism? It is clear that the mechanical complexity of the human skeleton is practically impossible, and perhaps senseless, to mimic, either from the viewpoint of mechanics or control. Besides, it is not a priori clear what are the DOFs that predominantly influence the degree of anthropomorphism. Hence, a thought-out and factuality-based answer to this delicate question is needed.

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[1] In the frame of the Belgrade School of Robotics, still in the sixties of the previous century, we began the study of bipedal locomotion mechanisms, at the time called 'active anthropomorphic mechanisms'.

Another question is related to the anthropomorphism of the gait itself that is to be performed by the humanoid mechanism under real conditions. There are two aspects that should be borne in mind. The first is, how to synthesize a gait with the highest possible degree of anthropomorphism, and second, how to preserve the synthesized gait anthropomorphism in the course of its realization in the presence of disturbances, i.e. how to realize "the most anthropomorphic" compensation of disturbances?

A fundamental question is how to more precisely define the anthropomorphism of an artificial gait and how to quantify it. Instead of giving a definite answer to this delicate question we will define some relevant attributes of anthropomorphism that are, in our opinion, dominant, so that we will focus our attention on them:

The amplitudes of particular DOFs of humanoid robots should be kept within the possible moderate range, whereby a decisive influence has the robot's trunk, both in the frontal and sagittal plane. Lower consumption of driving energy is therefore in correlation with smaller movements at robot's joints, namely of those realizing the compensational motion in the stage of forming nominal dynamics, i.e. the dynamic balance under ideal conditions of the synthesized artificial gait.

When speaking about the relationship between the magnitude of compesational movements and energy consumption we should notice that our initial investigations of the model of gait dynamics with the imposed flat-foot contact showed somewhat lower energy consumption in comparison with the "natural" gait, where the foot-ground contact is realized in three phases (heel strike, flat foot and deploy phase). Let us notice that the robot SONY [1] realizes its gait via flat-foot contact with the ground.

The number of prescribed Zero-Moment Points (ZMP) [2]-[5] and their distribution within the support polygon, either in the single-support or double-support gait phase influences the robot's anthropomorphism.

And the last, but not least important, attribute concerning the functional anthropomorphism of humanoid robots is related to the importance of the choice of mechanical DOFs, such as active segmentation of the foot and trunk, as well as the robot's active rotation about the vertical axis.

The above remarks concerning the anthropomorphism of humanoid robots testify to its significant complexity. The possibility to determine the degree of this integral performance as a solution of the high-complexity optimization problem involving numerous constraints seems to be rather unlikely. Hence we think it more practical to use the approach in which, instead of attempting to find an integral criterion of anthropomorphism, one considers a set of its particular attributes (for example, those mentioned above). Then, taking into account the maximal possible particular attributes of humanoid robots one will arrive at the maximum of its possible overall anthropomorphism, even when it has not been explicitely defined.

1.2 Basic characteristics of bipedal systems

All of the biped mechanism joints are powered and directly controllable except for the contact of the foot and the ground, which is the only site at which the mechanism interacts with the environment. This contact is essential for the walk realization because the mechanism's position with respect to the environment depends on the relative position of the foot with respect to the ground. The foot cannot be controlled directly, but can in an indirect way – by ensuring appropriate dynamics of the mechanism above the foot. Thus, the overall indicator of the mechanism's behavior is the point where the influence of all the forces acting on the mechanism can be replaced by one single force. As mentioned above, this point was termed Zero-Moment Point (ZMP). Recognition of the significance and role of ZMP in biped artificial walk was a turning point in gait planning and control..

The motion of a humanoid robot should be as anthropomorphic as possible. Hence, it is necessary to synthesize the most anthropomorphic motion under ideal conditions (in the absence of disturbances), which we call nominal. Then, such motion should be realized by the real system, so that the deviations from the nominal should be as small as possible, and corrections made in the most anthropomorphic way. In this work, to our knowledge the first one intending to call attention to the problem of anthropomorphism of humanoid robots, we will confine ourselves to the analysis of the synthesized nominal motion.

For the gait synthesis (defining trajectories of all the mechanism joints) of crucial importance is the semi-inverse method [3]-[6], in which, upon prescribing the ZMP and trajectories for a part of mechanism joints, trajectories of the remaining joints are calculated and thus the dynamic balance of the overall humanoid robot is ensured. The motion of the mechanism was synthesized by the semi-inverse method in the following way:

> The legs' motion was copied from a human subject's motion and adopted as the motion of the mechanism legs;
>
> The trunk's motion was determined in the way ensuring dynamic equilibrium of the mechanism as a whole during the half-step, i.e. in the period considered, the point within the support polygon that in the given moment represents the ZMP is characterized by the equalities $Mx = My = 0$.

If we want to consider the entire locomotion system of humanoid robot, we ought to take care of the anthropomorphism of its two basic subsystems that are stronly coupled: the legs' subsystem and the subsystem of the upper part (trunk). Evidently, different motions of the legs can cause different compensational motion of the trunk. Hence, the variation in the motion of the legs can influence the form of the synthesized trunk motion. Since the legs' motion has been copied from a human, the requirement for anthropomorphism is inherently satisfied. However, since the copied motion can never be faithfully reproduced by a humanoid system the question arises as to how the simplification of legs' motion can influence the trunk motion, i.e. how much abandoning (blocking) of the motion at particular DOFs at the main leg joints (the hip, knee, and ankle) can influence the anthropomorphism of the upper part of the system. Besides, there is an essential difference in the complexity of the human foot and the foots of humanoid robots that have been realized up to now and another very interesting question is how much the anthropomorphism of the trunk motion is influenced by the complexity of construction of the foot of humanoid robot.

2 Description of the mechanical structures of the mechanisms used in the work

In this section we describe the kinematic schemes of mechanical configurations of robots of different degree of complexity that were used in the present work. The basis for deriving the mechanism's mathematical model is a programme for forming the dynamic model of a branched, open or closed, kinematic chain whose links are interconnected with joints having only one DOF. The structure of the basic mechanism having 36 DOFs, used in the present work, is shown in Fig. 1.a. The first kinematic chain represents both legs (links 1-27), the second chain extends from the pelvis and comprises the trunk and the right hand (links 28-33) and tht third extends from the left shoulder to the left forearm (34-36). Particular links correspond to the real mechanism links (link 9 to the shank, link 12 to the thigh, link 30 to the trunk ,…), and are presented in Fig. 1 by full lines. However, some links were needed only for the purpose of modeling the joints with more DOFs. Namely, the joints with more DOFs are modeled as sets of more joints having only one DOF each and are connected by links having mass, moment of inertia and length equal to zero (in Fig. 1 being presented by broken lines). Thus, for example, the hip joints, which are in reality spherical joints with three DOFs, are modeled as a set of three one-DOF joints whose axes are mutually orthogonal. Thus the right hip is modeled by a set of of simple joints 13, 14 and 15 (with the unit vectors of rotation axes $\boldsymbol{e}_{13}$, $\boldsymbol{e}_{14}$ and $\boldsymbol{e}_{15}$), and the left hip by the set of joints 16, 17 and 18 (unit vectors $\boldsymbol{e}_{16}$, $\boldsymbol{e}_{17}$ and $\boldsymbol{e}_{18}$). The links connecting these joints (for the right hip the links 13 and 14, and for the left links 16 and 17 were needed only to satisfy the mathematical formalism of kinematic chain, on which the programme is based) were presented by broken lines, to indicate their "fictitious" nature. The other links (those that are not part of the joints with more DOFs) correspond to the real characteristics of the links of an average human body.

It is especially important how the foot-ground contact is modeled in order to

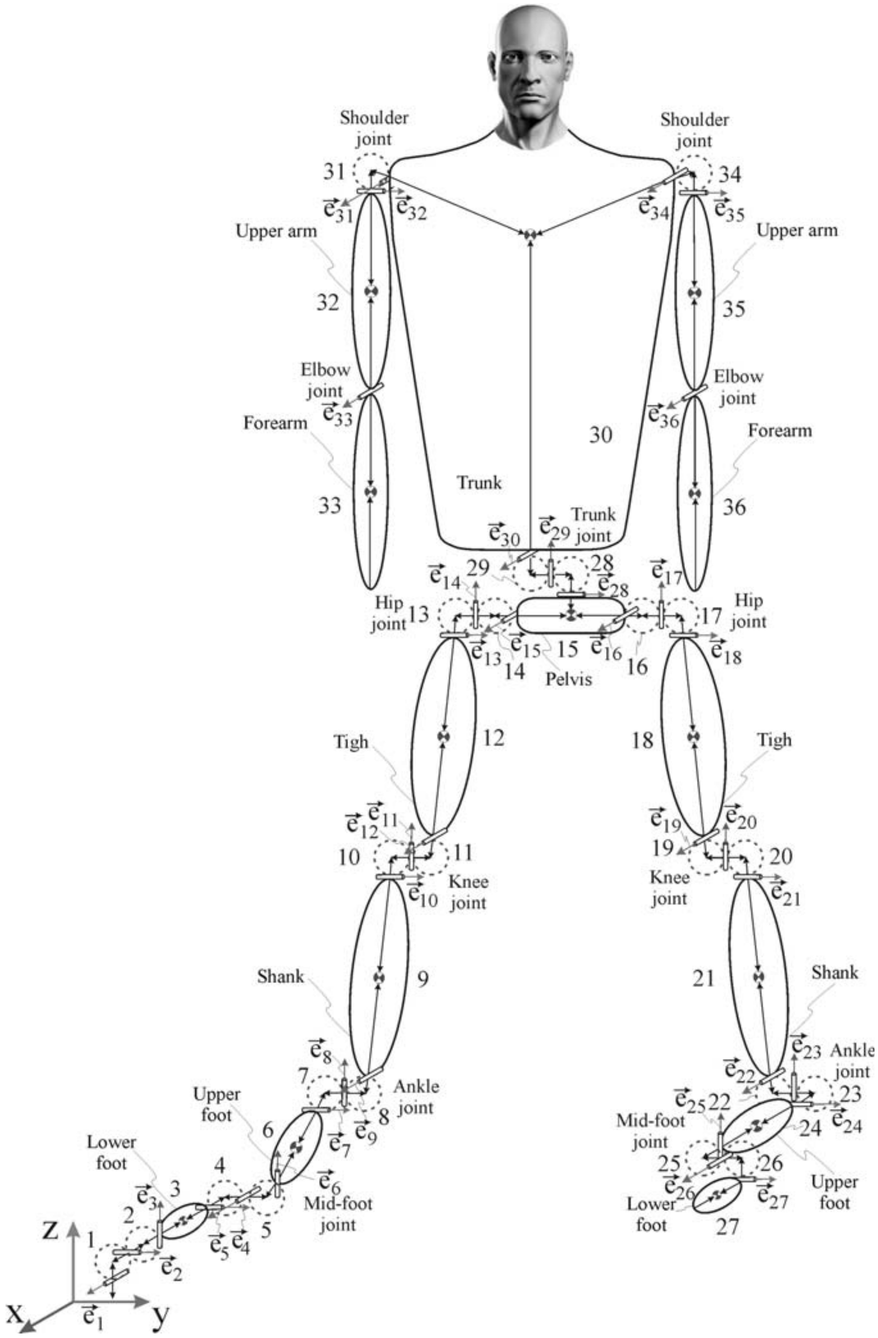

Fig. 1. Schematics of the mechanical structure of the main configuration having 36 DOFs

determine the exact position of the ZMP during the motion and observe when the mechanism is out of the dynamic balance. The loss of dynamic balance means that the mechanism collapses by rotating about one of the edges of the supporting foot, and this situation, obviously, has to be prevented. The contact of the mechanism with the ground is modeled by two rotational joints, determined with the unit vectors $\boldsymbol{e_1}$ and $\boldsymbol{e_2}$ (Fig. 1) in the horizontal plane. The mechanism motion is synthesized using the semi-inverse method in such a way that constantly ensures dynamic equilibrium during the walk [7].

The motion of all links of the locomotion system was determined on the basis of the semi-inverse method. The basic legs motion pattern was always the same and was obtained by recording the performance of a human subject (Fig. 2 shows the changes of all 27 angular coordinates of the legs during one half-step), and then, the trunk motion was synthesized in such a way to ensure the ground reaction force under the foot is in a certain predefined position, and in that point the horizontal components of ground reaction moment are equal to zero, i.e. $\mathbf{M_x}=\mathbf{M_y}=\mathbf{0}$. Each change of the dynamics above the supporting foot causes displacement of the ZMP out of its nominal position.

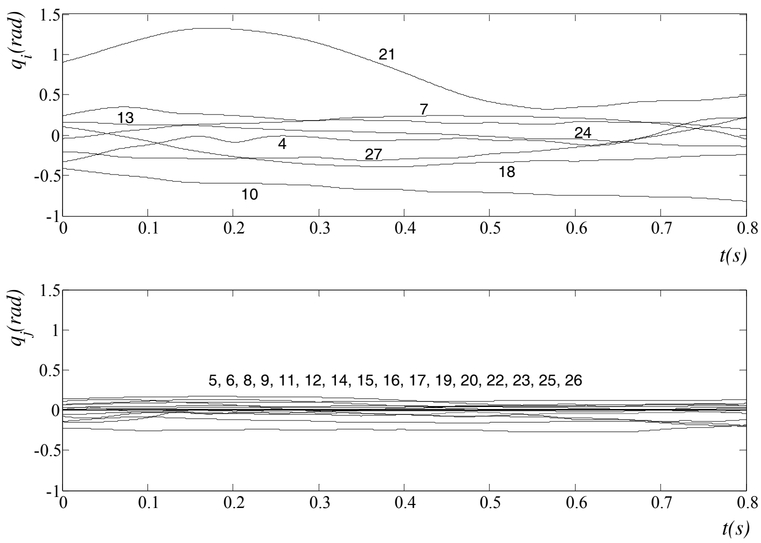

Fig. 2. Trajectories of all legs' DOFs, copied from the motion of human subject

In this way we obtained the reference motion of the mechanism. All other motions were also obtained by the semi-inverse method, whereby each motion of the legs was derived from the basic legs motion pattern, by immobilizing the particular DOFs of the legs.

In all cases, the synthesis was carried out for one half-step only. The motion in the next half-step was obtained by inverting the motion for the first half-step.

3 Analysis of the influence of particular DOFs at the locomotion mechanism joints on the anthropomorphism of the synthesized gait

As was already said, the basis for the synthesis of compensational trunk motion and later analysis of the anthropomorphism of the locomotion system motion is in fact the motion of the legs, involving active participation of different number of DOFs at particular joints. For each motion of the legs and for each prescribed ZMP trajectory, the compensational movements of the trunk were synthesized, which were then compared to each other, to analyze the influence of the degree of complexity of the mechanical configuration to the anthropomorphism of the motion.

3.1 Effect of the legs joints complexity to the anthropomorphism of the system motion

We will consider first the joints of the hips: the right hip consists of joints 13, 14 and 15, with the unit vectors of rotation $\boldsymbol{e}_{13}$, $\boldsymbol{e}_{14}$ and $\boldsymbol{e}_{15}$, whereas the left hip consists of joints 16, 17 and 18 with the unit vectors $\boldsymbol{e}_{13}$, $\boldsymbol{e}_{14}$ and $\boldsymbol{e}_{15}$. Let us consider first the DOFs that allows the system's tilting in the frontal plane – $\boldsymbol{e}_{15}$ and $\boldsymbol{e}_{16}$. Imobilization was carried out in two ways: at both joints, zero and then the mean value was fixed for the angle realized by the joint in the basic pattern before it had been immobilized.

In Fig. 3 are presented the results of the synthesis of the trunk's compensational motions. The values of the angle q^{30} (the trunk swinging left-right) are given on the abscissa while the ordinate gives the values of the angle q^{28} (the trunk swinging forward-backward). The hands are extended during the motion and immobile with respect to the trunk. The curve of compensational motion for all joints mobile (none is immobilized) was adopted as the reference one and all other cases were compared to it. In Fig. 3 can be seen that this curve is the shortest, i.e. the span of the change of the angles q^{30} and q^{28} is the smallest. When the joints 15 and 16 were immobilized at the mean values (q^{15}=-0.2457 rad, q^{16}=-0.1391 rad) the compensational movements were those represented by curve 2. It is evident that the trunk inclinations in the frontal plane are larger. These inclinations are even more pronounced (curve 3) when the the angles at the immobilized joints are zero (q^{15}=q^{16}=0 rad).

In the same way we also investigated the immobilization of the DOFs allowing rotation at the hip about the vertical axis ($\boldsymbol{e}_{14}$ and $\boldsymbol{e}_{17}$). In both cases (q^{14}=-0.0291 rad, q^{17} =-0.0243 rad – curve 4 and q^{14}=q^{17}=0 – curve 5) very close values were obtained. Both curves have significantly larger amplitudes of the trunk tilting in the frontal and sagittal plane than in the reference case, and both are significantly below the reference curve 1. In other words, the immobilization of q^{14} and q^{17}

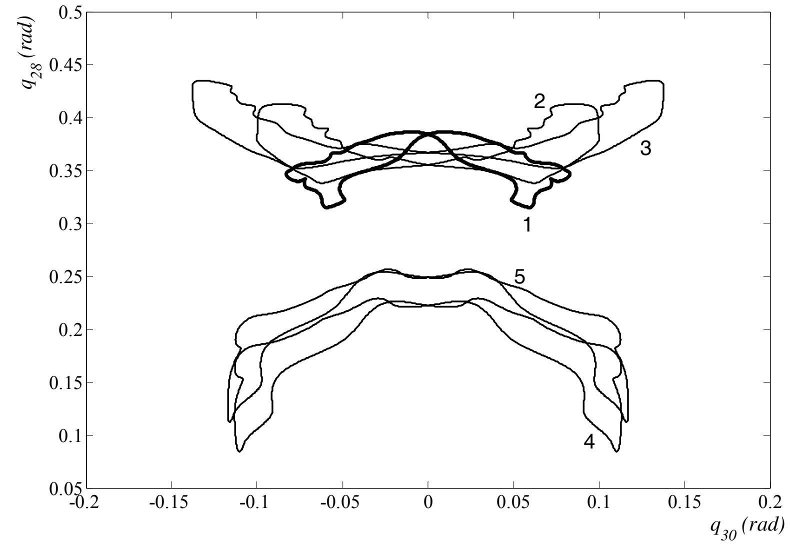

Fig. 3. Diagrams of the trunk compenasational movements in the case of immobilization of the hip DOFs: DOFs defined by the unit vectors e_{15} and e_{16} (curves 2 and 3) and by e_{14} and e_{17} (curves 4 and 5).

yielded an increase in the swinging amplitude in both planes, although the trunk was more vertical.

The knee was considered as a next joint. When the joints 12 and 19 were immobilized (the angles were very small, $q^{12}=3.7733\times10^{-2}$ rad and $q^{19}=6.0268\times10^{-2}$ rad) the amplitudes of oscillation in the frontal plane with respect to the standard case were reduced (cf. curve 2 with curve 1 in Fig. 4), whereas the overall curve shifted, so that the mechanism trunk inclined more forward. When the DOFs correponding to the rotation about the vertical axes $\boldsymbol{e}_{11}$ and $\boldsymbol{e}_{20}$ ($q^{11}=0.1073$ rad, $q^{20}=0.1157$ rad) were immobilized, the effects (curve 3) were quite opposite to the previous case. The oscillation amplitudes in the sagittal plane were increased and the overall curve was shifted downward (the mechanism trunk is slightly straightening up). If all the considered knee DOFs ($\boldsymbol{e}_{12}$, $\boldsymbol{e}_{19}$, $\boldsymbol{e}_{11}$ and $\boldsymbol{e}_{20}$) were immobilized, the resulting effects almost completely canceled out (curve 4). Therefore, from the aspect of anthropomorphism it is not justified to realize the knee as a joint having more than one DOF.

In the case of the ankle we immobilized first the DOFs with the unit vectors $\boldsymbol{e}_9$ and $\boldsymbol{e}_{22}$, enabling the rotation about the *x*-axis ($q^9=2.1565\text{x}10^{-3}$; $q^{22}= 3.1155\text{x}10^{-3}$). Comparing the obtained compensational movements (curve 2) in Fig. 5 with curve 1 it can be seen that the immobilization of these DOFs had an insignificant effect on the amplitude of compensational movements of the trunk. However, the situation changed drastically when the DOFs corresponding to the rotations about

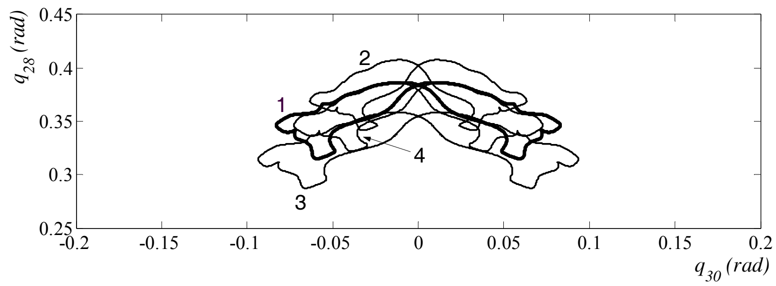

Fig. 4. Diagrams of trunk compensational movements in the case of immobilization of the knee DOFs

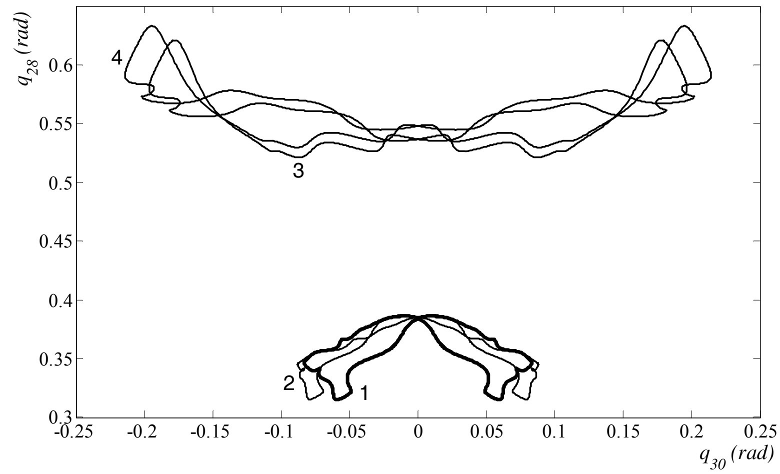

Fig. 5. Compensational movements of the trunk in the case of immobilization of the ankle joint (DOFs with the unit vectors e_9 and e_{22} – curve 2; e_8, and e_{23} – curve 3; e_8, e_9, e_{22} and e_{23} – curve 4)

the *z*-axis ($\boldsymbol{e_8}$, and $\boldsymbol{e_{23}}$, q^8=-8.3048x10^{-2}; q^{23}=2.3525x10^{-3}) were immobilized. The amplitude of compensational movements in the frontal plane (curve 3) was more than doubled, whereas the trunk inclination forward also changed significantly. Curve 4 corresponds to the case when all the above DOFs, i.e. $\boldsymbol{e_8}$, $\boldsymbol{e_9}$, $\boldsymbol{e_{22}}$ and $\boldsymbol{e_{23}}$ were immobilized simultaneously. It is evident that the effects of imobilization of joints 9 and 22 were small (curve 3), being practically identical to those shown by curve 1. Therefore, an unambigous conclusion is that the ankle joint DOFs corresponding to the rotations about the z-axis (unit vectors $\boldsymbol{e_8}$ and $\boldsymbol{e_{23}}$) increased very significantly the degree of of the motion anthropomorphism

The foot has not been adequately treated in the literature. It has been mainly modeled and practically realized as being one link, in the best case as two links, connected to a joint having only one DOF and composed of rigid links. The natural human foot is a far more complex flexible structure. In this work, the foot was modeled as being composed of two links (Fig. 6) connected by a spherical joint (unit vectors of rotation: $\boldsymbol{e_4}$, $\boldsymbol{e_5}$ and $\boldsymbol{e_6}$). In Fig. 6, link 3 represents the lower foot and link 6 the upper foot.

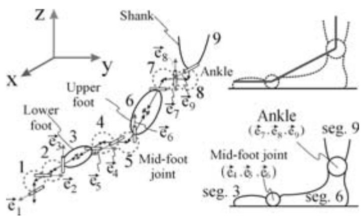

Fig. 6. Model of the mechanism foot

As first, the DOFs corresponding to the rotation about the vertical axes $\boldsymbol{e_6}$ and $\boldsymbol{e_{25}}$ were immobilized (fixed at the mean values of the angles q^6=0.0341 and q^{25}=-0.0089) and then the compensational movements were synthesized (curve 2 in Fig. 7, curve 1 representing again the reference case). The amplitude of the compensational movements increased in the frontal plane and decreased in the sagittal plane. Then, the trunk compensational motion was synthesized (curve 3 in Fig. 7) for the immobilized DOFs corresponding to the rotation about the *x*-axis ($\boldsymbol{e_5}$ and $\boldsymbol{e_{26}}$). As can be seen, curve 3 is quite close to the reference curve 1, so that it can be concluded that the effect of the motion at joints 5 and 26 on compensational movements (the shape and position of curve 3) is very small and practically negligible in a regular gait.

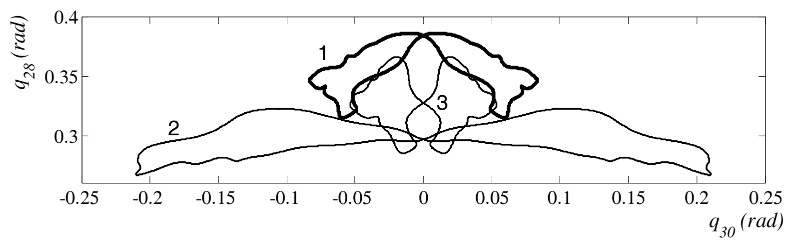

Fig. 7. Diagrams of the trunk compensational movements in the case of immobilization of the foot DOFs by the unit vectors ellowing rotation about the vertical (e_6 and e_{25}) and horizontal (e_5 and e_{26}) axis

Concluding remarks

In order to expand the engagement of humanoid robots to some new, previously unimaginable, applications, it is necessary to make robots participate in the working and living environment of humans in a most direct way, which will inevitably lead to a "functional coexistence" of man and robot. It is especially important to point out that the common living and working environment to be shared by them, is presently adapted mainly to man, and it cannot be expected that this will be significantly changed to suit the needs of robots. Hence, the problem of anthropomorphism (all aspects of which we are not aware of yet), as well as the new approach to modeling of human and humanoid motion, are becoming the research topics that gain more and more in their importance.

The anthropomorphism of humanoid robots has certainly much more aspects than considered in this paper, which deals only with the problem of gait anthropomorphism. However, to our knowledge, this is the first attempt to treat the anthropomorphism of humanoid robots in a systematic way, the dynamically balanced gait being certainly the basic requirement to be met by humanoid robots.

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