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Adaptive Bio-inspired Control of Humanoid Robots – From Human Locomotion to an Artificial Biped Gait of High Performances

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1. Introduction

Biped locomotion, in the sense of gait stability and maintenance of dynamic balance, represents one of the most complex known natural motions. Anthropomorphic locomotion is performed by a synergy of large number of body muscles. Among them, of special importance are leg muscles. Human anatomy and physical capabilities of human body determine the kinematical and dynamic performances of the gait. Stability, harmony of motion, repeatability, smoothness of trajectories, rigidity of foot landing, etc., are the attributes that characterize human gait. In that sense, performances of biped gait differs from person to person, depending on different factors such as: physical and physiological capabilities, age, professional deformation (e.g. ballerina, athletic, fashion model, etc.), some pathologic conditions but sometimes also on psychological condition of the person, etc. In this paper, the focus of research attention will be directed towards the physical capabilities (and their modulation) of human body to perform regular biped walk as a model to be used for synthesis of artificial gait for biped robots. Sophisticated synergy of muscle activities of the whole body determines characteristics of biped locomotion and its stability performances.

During walking, running or jumping, leg muscles and ligaments are being strengthened or relaxed alternately according to the physical phases of locomotion. As consequence, landing foot produces corresponding ground reaction forces through foot contact/impact to the ground, that transmit to the corresponding leg joints. In that sense, the term *leg impedance* represents a measure of how much a body structure resists motion when subjected to a given external force(s). It relates forces with corresponding velocities acting on a bio-mechanical system. The mechanical impedance is a function of the frequency of the applied force and can vary greatly over frequency. At resonance frequencies, the mechanical impedance will be lower, meaning less force is needed to cause a structure to move at a given velocity. Leg impedance has an important role in human locomotion. By modulation of leg impedance in a natural way, it is possible to produce different kinds of biped locomotion as well as to damp corresponding impact/contact forces that represent perturbation to the system and can cause in-stability. Advanced humanoid robots use electric motors in the joints to produce biped locomotion and suppress perturbing impact forces.

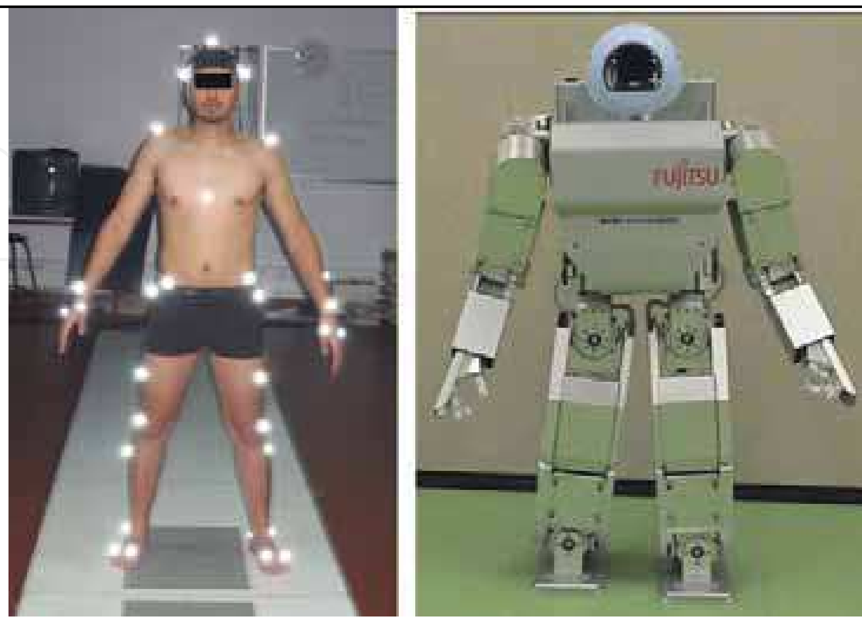

Fig. 1. Biological and artificial biped locomotion system – biped robot (Fujitsu, 2009) as an imitation of human body

2. Advances Beyond State-of-the-Art

Currently many research groups in the world are working on biped robots. The main thrust of the current research can be categorized into three parts: optimization of leg and foot trajectory, stable locomotion control, and hardware design. For optimization, reducing impact in foot landings and reducing torque and energy requirements of joint actuators are primary concerns (Rousell et al., 1998; Bruneau et al., 1998; Rostami et al., 1998). Different designs of biped robots are also explored by many research teams (Sony, 2006; Kim & Oh, 2004). However it has been regarded that walking, especially dynamic walking, is a very difficult problem to be tackled until the recent development of a few biped robots with the capability of dynamic locomotion such as for example: Wabian (Ogura et al., 2006), Asimo (Honda, 2009), Hoap-3 (Fujitsu, 2009), QRIO (Qrio, 2009), etc.

The problem of realizing a walking action in humanoid robots involves two components: generation of the basic walking pattern and the compensation required to maintain the robot's balance. Summarizing research results and practical experience of many research teams concerning implementation of different control strategies for dynamic biped locomotion, the impedance control was promoted as the most frequent strategy applied with contemporary humanoid robots. Park proposed (Park, 2001) an impedance control and corresponding switch-mode impedance modulation in particular phases of biped gait as well as in particular directions of locomotion. Both legs are controlled by impedance, where the desired impedances at the hip and swing foot are specified. The impedance parameters

(damping factors) were changed depending on the gait phase. Stiffness of the legs was assumed invariable.
Lim H-O, Setiawan and Takanishi have proposed (Lim et al., 2004; Lim et al., 2001) a position-based impedance control for biped humanoid robot locomotion. The impedance parameters of the biped leg were adjusted in real-time according to the gait phase. In order to reduce the impact/contact forces generated between the contacting foot and the ground, the damping coefficient of the impedance of the landing foot is increased largely during the first half double support phase. In the last half double support phase, the walking pattern of the leg changed by the impedance control is returned to the desired walking pattern by using a polynomial. Also, the large stiffness of the landing leg is given to increase the momentum reduced by the viscosity of the landing leg in the first half single support phase. For the stability of the biped humanoid robot, a balance control that compensates for moments generated by the biped locomotion is employed during a whole walking cycle.
The adaptive impedance control of biped robots with leg impedance modulation is proposed in the article. It controls the impedance of the swing foot as well as the hip link. The impedance control method has been successfully used for the robot manipulators (Hogan, 1986) which interact with their environment. In locomotion, a biped robot is in contact with the ground, sometimes with one foot and other times with two feet. Only in running or jumping there are phases when humans or robots have no contacts with the ground and then they have to be considered as “flyers” (Potkonjak et al., 2005). Moreover, impedance control for bipedal locomotion is similar to the control method that a human uses for his locomotion. When a human wa1ks, he does not explicitly control the trajectory of his upper body but rather controls the muscle strength of his legs that support the upper body (Park, 2001). He also rather controls the trajectory of the swing foot in order to avoid obstacles such as bumps or in order to land the foot in a safe area, for example, avoiding a pot hole. In typical human locomotion, the leg muscles are repeatedly hardened and relaxed depending on the gait phase (Leonard et al., 1995). Just before the contact of the swing foot with the ground, the leg muscle is relaxed to regulate and reduce impact, resulting in a very soft contact with the ground. Borrowing this idea from human locomotion, the authors suggest that the parameters used in the impedance control are also appropriately modulated depending on the gait phase of the biped robot. Flying phase (running or jumping) will not be considered in this paper although it represents an interesting problem how the legs prepare themselves for landing and contact with the ground.
The main contribution of this paper concerns with design of a novel, biologically-inspired, adaptive impedance control applied to biped robot locomotion. Leg impedance modulation is performed in an anthropomorphic way, implementing the biological principles of leg adaptation based on gait conditions and proprioceptive feedbacks on dynamic reactions at biped robot legs. Impedance modulation does not depend on gait phases only but also on the real gait conditions and dynamic reactions changing in real-time. The impedance parameters (leg stiffness and damping) are adjusted in real-time (continually) as humans do it. Thus, this paper covers in details how the adaptive impedance control is implemented, how to identify the variable parameters in order to achieve the high (but not optimal in the sense of energy efficiency) dynamic performances of the system. Generation of the artificial bio-inspired (anthropomorphic) gait is also concerned in the paper, using experience obtained from the capture of motion experiments with biological system. Stabile walk is enabled by implementation of a regulator based on the feedback on dynamic reactions

(Rodić, 2008). The efficiency of the control strategy proposed in the paper is verified by extensive simulation.

3. Biped Robot Model

Human body for its complex motion uses synergy of more than 600 muscles. It has more then 300 degrees of freedom (DOFs) (Vukobratović et al., 1990). Some of these particular motions are essential for the human activities (gait, work, sport, dancing, etc.) while the others give it a full mobility. In this paper, a 36 DOFs biped locomotion mechanism of the anthropomorphic structure (Fig. 2) will be considered as a mechanical representative of a human body.

Let us consider the biped robotic system of the anthropomorphic structure illustrated in Figs. 2a and 2b. Let the joints of the system be such to allow n independent motions. Let these joint motions be described by joint angles forming the vector of the generalized coordinates $q=[q_1 \cdots q_n]^T$. The terms 'joint coordinates' or 'internal coordinates' are commonly used for this vector in robotics. This set of coordinates describes completely the relative motion of the links. The basic link (such as the pelvis in this case, Fig. 2a) is allowed to perform six independent motions in 3D-space. Let the position of the basic link be defined by the three Cartesian coordinates (x, y, z) of its mass centre and the three orientation angles (φ-roll, θ-pitch and ψ-yaw), forming the vector $\underline{X}=[x\ y\ z\ \varphi\ \theta\ \psi]^T$. Now, the overall number of DOFs for the system is $N=6+n$, and the system position is defined by

$$Q=\left[\underline{X}\ q\right]=\left[x\ y\ z\ \varphi\ \theta\ \psi\ q_1 \dots q_n\right]^T \tag{1}$$

It is assumed that each joint has an appropriate actuator. This means that each motion q_j has its own drive – the torque τ_j. Note that there is no drive associated to the basic body coordinates $\underline{X}$. The vector of the joint drives is $\tau=[\tau_1 \cdots \tau_n]^T$, and the augmented drive vector (N-dimensional) is $\mathrm{T}=[\underline{0}_6\ \tau]^T=[0 \cdots 0\ \tau_1 \cdots \tau_n]^T$.

Similarly, with human beings muscles represent biological power-trains. Pairs of muscles by their synchronized contractions and extensions move the bones of the skeleton at its joints in an articulated manner. Bearing in mind the previous mechanic assumptions, the dynamic model of the biped mechanism (humanoid) has the general form (Vukobratović et al., 1990; Park, 2001):

$$\begin{aligned} H(Q,d)\ddot{Q}+h(Q,\dot{Q},d) &= \tau + J^T(Q,d)\,F \\ h(Q,\dot{Q},d) &= h_{ccf}(Q,\dot{Q},d)+h_g(Q,d) \end{aligned} \tag{2}$$

or decoupled

$$\begin{aligned} H_{\underline{X},\underline{X}}\ \ddot{\underline{X}}+H_{\underline{X},q}\ \ddot{q}+h_{\underline{X}} &= \underline{0}_6+J_{\underline{X}}^T\ F \\ H_{q,\underline{X}}\ \ddot{\underline{X}}+H_{q,q}\ \ddot{q}+h_q &= \tau+J_q^T\ F \end{aligned} \tag{3}$$

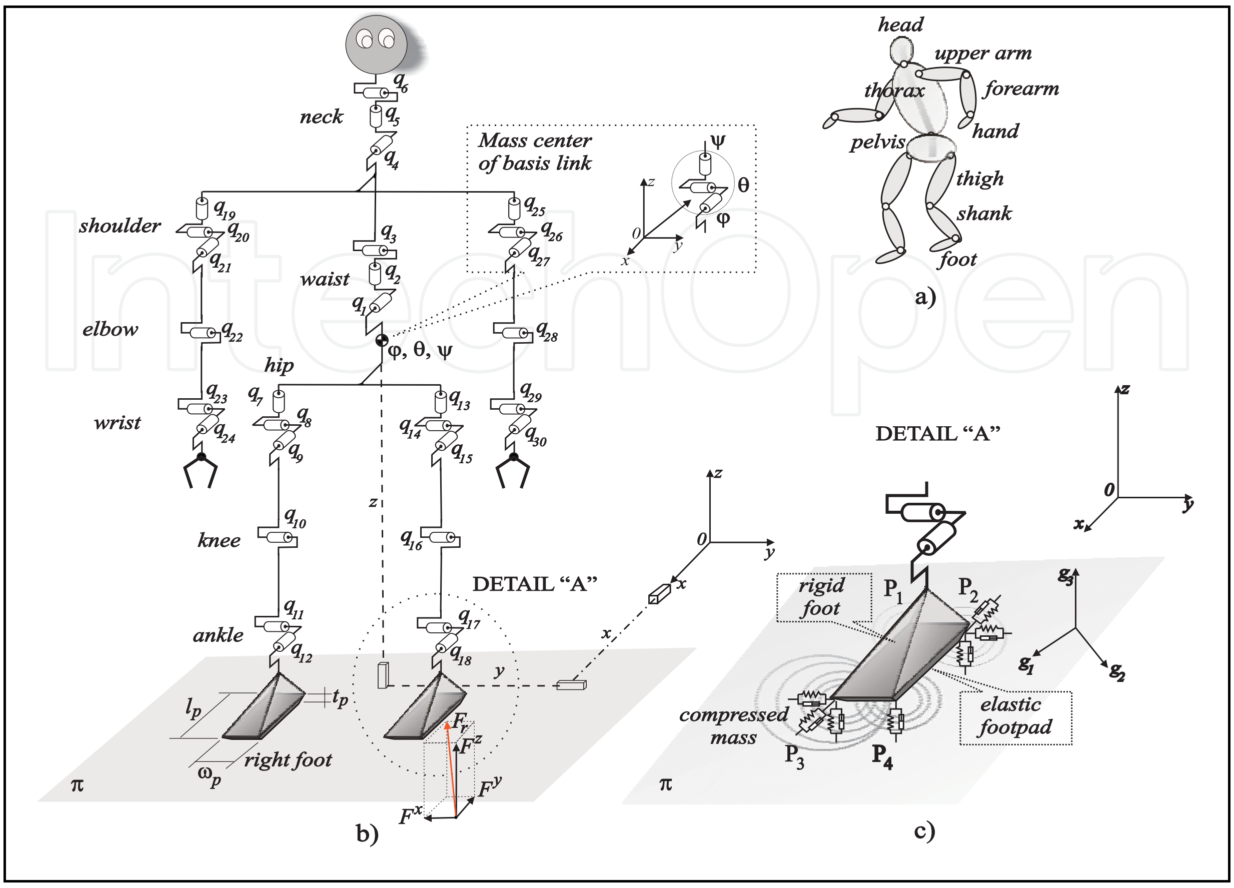

Fig. 2. Spatial model of a biped robot interacting with dynamic environement: a) Multi-body biped robot with two-link torso, b) Kinematic scheme of a 36 DOFs biped robot mechanism considered in the paper, c) 6 DOFs compliance model of a ground support

Dimensions of the inertial matrix and its sub matrices are: $H(N\times N)$, $H_{\underline{X},\underline{X}}(6\times 6)$, $H_{\underline{X},q}(6\times n)$, $H_{q,\underline{X}}(n\times 6)$, and $H_{q,q}(n\times n)$. Dimensions of the vectors containing centrifugal, Coriolis' and gravity effects are: $h(N)$, $h_{\underline{X}}(6)$, and $h_q(n)$. Vector $h(Q,d)$ consists of two vectors: the vector of centrifugal and Coriolis' forces $h_{ccf}(Q,\dot{Q},d)$ and the vector of gravity forces and torques $h_g(Q,d)$. Dimension of the vector of ground reaction, external load and disturbance forces is $F(m\times 1)$. Dimensions of the Jacobian matrix and its sub matrices are: $J(m\times N)$, $J_{\underline{X}}(m\times 6)$, $J_q(m\times n)$. Vector $d(l)$ represents a parameter vector including geometry (links' lengths, positions of the links' mass centers), as well as the corresponding dynamic parameters (links' masses, moments of inertia) of the robotic system.

3.1 Modeling of Contact Dynamics

Let us consider the link of the biped mechanism that has to establish contact with some external object. In the case considered, it is the foot that moves towards the ground, strikes it and stays in contact (e.g. walking, running or climbing the stairs). An external object may be immobile (like ground), or mobile, like part of some other dynamic system (mobile platform (Vukobratović et al., 2004), conveyer, boat, tram, etc.). To express mathematically the forthcoming contact, the motion of the considered link should be described by an appropriate set of coordinates. Since the link is a body moving in the 3D-space, it is necessary to consider six coordinates. Let this set be $\underline{g} = [g_1, \cdots, g_6]^T$ and let call them functional coordinates (Fig. 3a). Functional coordinates are introduced (Potkonjak et al., 2005) as relative ones, defining the position of the link with respect to the ground (object) to be contacted.

A consequence of the rigid link-object contact is that the link and the object perform some motions, along some axes, jointly (Fig. 3b). These are constrained (restricted) directions (e.g. g_3, g_5, Fig. 3b). Let there be m such directions. Relative position along these axes does not change. Along the other axes (e.g. g_1, g_2, g_4, g_6, Fig. 3b) relative displacement is possible. These are unconstrained (free) directions. In order to get a simple mathematical description of the contact, $\underline{g}$-coordinates are introduced to describe the relative position. Zero value of a coordinate indicates the contact along the corresponding axis. So, the motion of the external object (to be contacted) has to be known (or calculated from the appropriate mathematical model), and then the $\underline{g}$-frame fixed to the object (the plane π in this case, Fig.3) is introduce to describe the relative position of the link in the most proper way. Thus, in a general case, the $\underline{g}$-frame is mobile. As the link is approaching the object, some of $\underline{g}$-coordinates reduce and finally reach zero. The zero value means that the contact is established. These functional coordinates (which reduce to zero) are called restricted coordinates and they form the sub vector $\underline{g}^c$ of dimension m. The other functional coordinates are free and they form the sub vector $\underline{g}^f$ of dimension $6-m$. Now, one can write:

$$[\underline{g}^c, \underline{g}^f]^T = K \cdot \underline{g} \tag{4}$$

where K is a 6×6 matrix used to rearrange the functional coordinates (elements of the vector $\underline{g}$) and bring the restricted ones to the first positions. In order to arrive at a general algorithm, the foot motion has to be described in a general way and, once the expected contact is specified, relate this general interpretation to the appropriate $\underline{s}$-frame.

The general description of the leg motion assumes three Cartesian coordinates of a selected point of the foot link plus three orientation angles: $\underline{s}_f = [x_f \; y_f \; z_f \; \varphi_f \; \theta_f \; \psi_f]^T$, the subscript "*f*" standing for "foot link". These are absolute external coordinates defined with respect to the $Oxyz$ reference coordinate system (Fig. 3a).

The relation between the foot links coordinates $\underline{s}_f$ and the leg position vector q_l is given by:

$$\underline{s}_f = \underline{s}_f(\underline{X}, q_l, d) \tag{5}$$

$$\dot{\underline{s}}_f = \dot{\underline{X}} + J_l(q_l, d)\,\dot{q}_l \tag{6}$$

$$\ddot{\underline{s}}_f = \ddot{\underline{X}} + J_l(q_l, d)\ddot{q}_l + A_l(q_l, \dot{q}_l, d) \quad (7)$$

where q_l is a corresponding 6×1 vector of leg's (right one or left) joint coordinates, $\underline{X}$ is a 6×1 position vector of the hip (basis) link of robot mechanism defined in (1), $J_l = \dfrac{\partial \underline{s}_f}{\partial q_l}$ is a 6×6 Jacobian matrix of the foot link with respect to the basis link, and $A_l = \dfrac{\partial^2 \underline{s}_f}{\partial q_l^2}\dot{q}_l^2 = \dot{J}_l\dot{q}_l$ is a 6-dimensional adjoint vector.

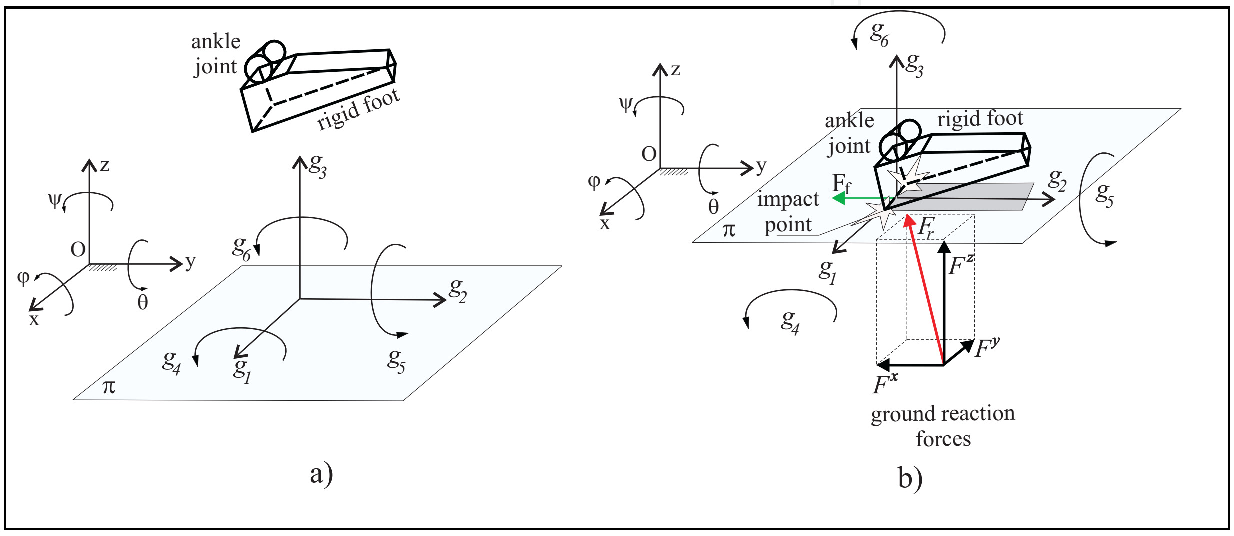

Fig. 3. a) Functional coordinates of a foot contact; b) Rigid frictional impact along the foot edge

In this paper the *compliance model* of the ground support is considered in a form of *full impedance* (inertia, damping and stiffness effects including). In that goal, a relatively complex 36 DOFs model of the biped system (Fig. 2a and 2b) is considered. Biped system considered interacts with a dynamic environment performing anthropomorphic gait. Contact dynamics is identified in a form of a 6 DOFs compliance model as presented in Fig. 2c (Park, 2001). To simulate locomotion of the biped robot, its environment should be modelled accurately so that it can provide reasonably realistic interaction forces from the ground. Typically, biped robots have elastic pads at their soles for shock absorption. These pads allow small motions of the feet on the ground. Plastic collision models such as the one proposed in (Fujimoto & Kawamura, 1995) cannot simulate contact transitions such as a foot bouncing from the ground during a foot landing. In this paper, a 6 DOFs environment model based on non-linear (Marhefka & Orin, 1996) and linear compliant models (Kraus & Kummar, 1997) is used. This model allows simulations of small movements of the feet on the ground, caused by their elastic pads and provides more realistic reaction forces.
Humans wear very often soft, elastic, tracking shoes with rubber pads on the foot sole, to ensure a comfortable and free motion (walking, running, jumping, dancing, etc.). Analogously, the biped locomotion mechanisms (humanoid robots) use elastic pads attached to the feet soles. These elastic elements damp the impact effects that are transmitted

onto the structure of the system. Human/humanoid joints are especially sensitive to the dynamic loads. In the instant when the landing foot touches on the ground, a large impact force can be generated. Active control of such impact force would require robot's controllers and actuators to have very wide bandwidth and be capable of generating a large instantaneous power (Park, 2001). It is not realistic to have controllers with a wide bandwidth and huge powerful actuators, which add more weight to the biped robot. That is the reason why many biped robots are equipped with some kind of shock-absorbing elastic pads, which in turn cause small movements of the foot landing on the ground, and may destabilize the locomotion.

4. Biological Aspects of Human Gait

Aiming to the analysis of human biped gait, the extensive experiments in the capture motion laboratory have been carried out. For this purpose, a middle-age male subject, *190 cm* tall, *84 kg* weight, of normal physical constitution and functionality, played the role of an experimental biological system whose parameters are identified by direct body measurements, photometry and implementation of the anthropometry empirical relations given in (Zatsiorsky, 1990; De Leva, 1996). The following variables are captured (acquired) in the experiments: (i) body motion (joint angles), (ii) hip joint and foot sole cycloids (heel and toe trajectories) defined in the Descartes coordinate system, and (iii) ground reaction forces/torques on the footsole reduced to the coordinate system attached to the supporting surface. The mentioned measurements are used in an appropriate way to analyze the biological principles of human locomotion characteristic for a regular and stable human gait. The following parameters of biped gait are assumed as relevant: (i) *walking speed* V , (ii) *step size* s , (iii) *lifting height of the swinging foot* h_f , and (iv) *step period* T . The step period is determined from the relation $T = s / V$, under the assumption that within one step there is no variation of the forward speed V. Additionaly to capturing of the foot cycloids, the motion of the hip link is also captured. This bobbing motion is described by corresponding hip joint cycloids as well as trajectory of the hip link mass center. Forementioned cycloids are of crucial importnace for the anlysis of human gait charcateristics as well as for the synthesis of biped gait generator. For the needs of reserach in this paper, a generator of artificial biped gait was synthesized based on the experimental results obtained from the capture motion system, and the antrpopomorphic parameters of the examined biological system.

Regular biped gait consists of several characteristic gait phases that alternate periodically (Park, 2001). Hence, depending on whether the system is supported to a single or double legs, two macro-phases can be distinguished, viz.: (i) single-support phase (SSP) and (ii) double-support phase (DSP). Double-support phase has two micro-phases: (i) *weight acceptance phase* (WAP) when the heel strike happens, and (ii) *weight support phase* (WSP). Single support phase includes the *swing phase* (SP). Gait phases can be recognized also by analysis of the ground reaction forces during walking.

4.1 Foot Impact and Leg Impedance Modulation

Analysis of the foot-ground contact phenomena is essential for the research of human locomotion. The ground reaction forces (Fig. 4) that appear in contact surface of the human supporting foot, have significant dynamic influence to the body joints (Rodić, 2008): ankles, knees, hips, waist, even neck. In that sense, a foot impact is suggested to be related to pain and injury of joints, so the repetitive loads could be linked to the development of different pathologic conditions with human patients. Amplitudes of contact forces can vary significantly depending on type of locomotion (walking or jumping) as well as on gait parameters (speed, step size, lifting height of swinging leg) and ground support parameters (compliance, unevenness of surface profile, etc). With biped robots, large ground reaction forces can cause system instability as well as mechanical damages of the structure. Due to the quoted reasons, importance of leg impedance studying with human beings and biped robots is evident. A contribution to one such study will be provided in this paper.

Three time instants are of interest during a biped gait (Fig. 4): t_1 - time of heel strike to the ground (begin of the WAP phase), t_2 - time when the landing toes reach the support (begin of the WSP phase), and t_3 - time when the supporting foot leaves the supporting plane (beginning of the SP). In t_1 and t_2 time instants, the heel centre and the toe centre points reach zero speeds in the *z*-direction perpendicular to the supporting surface. In these time instants the local impacts occur producing corresponding energy dissipation. These phenomena significantly influence the stability of the system during the walk. Another critical time instant is the time when a leg leaves the ground, i.e. when the body is supported by single leg (stance phase). The way how the impact forces can be suppressed (damped) will be solved in this paper by the leg impedance adaptation. These research targets will be considered in the following sections of the paper.

By the extensive experimental measurements in the capture motion laboratory, with a complementary measuring of corresponding neuro-muscular activities with human patinets (Dalleau et al., 1998), it was discovered that an impedance of leg muscles (i.e. parameters) varies significantly in real-time during different locomotion activities such as: walking, running, jumping, climbing stairs, balancing on a mobile platform, etc.

Natural leg impedance varies not only with changing gait phases (e.g. WAP, WSP, SP) but also within duration of a single phase depending on different dynamic and kinematical gait parameters. It was proved by the experiments.

The same person changes the own leg impedance in different way depending on: forward speed of motion, lifting height of swinging leg, step size, ground support compliance, foot-ground conditions, etc. By measuring neuro-muscular activities during human locomotion it was identified that man hardens instictively leg muscles just before the foot impact in order to supress (damp) a shock to the ground suport. Since the impact period lives too short (it was measured to be just *5-30 ms*), an instantaneous modulation of the leg stiffness and damping characteristics is imposible (Dalleau et al., 2004). The damping factor of leg muscles in WAP phase is usually significantly larger (e.g. especially during fast walk and jump) than in the WSP phase. Using the proprioceptive[1] feedback as well as tactile

[1]It is the sense that indicates whether the body is moving with required effort, as well as where the various parts of the body are located in relation to each other.

information about the ground reaction forces/torques existing on the footsole, neural system commands to the leg muscles to change impedance. After the initial strengthening of leg muscles, a phase of their relaxation subsequently succeeds. The level of relaxation (decreasing stiffness and damping) depends on amplitudes of the ground reaction force F_z in the WSP phase (see the interval $t \in (t_2, t_3)$ shown in Fig. 4).

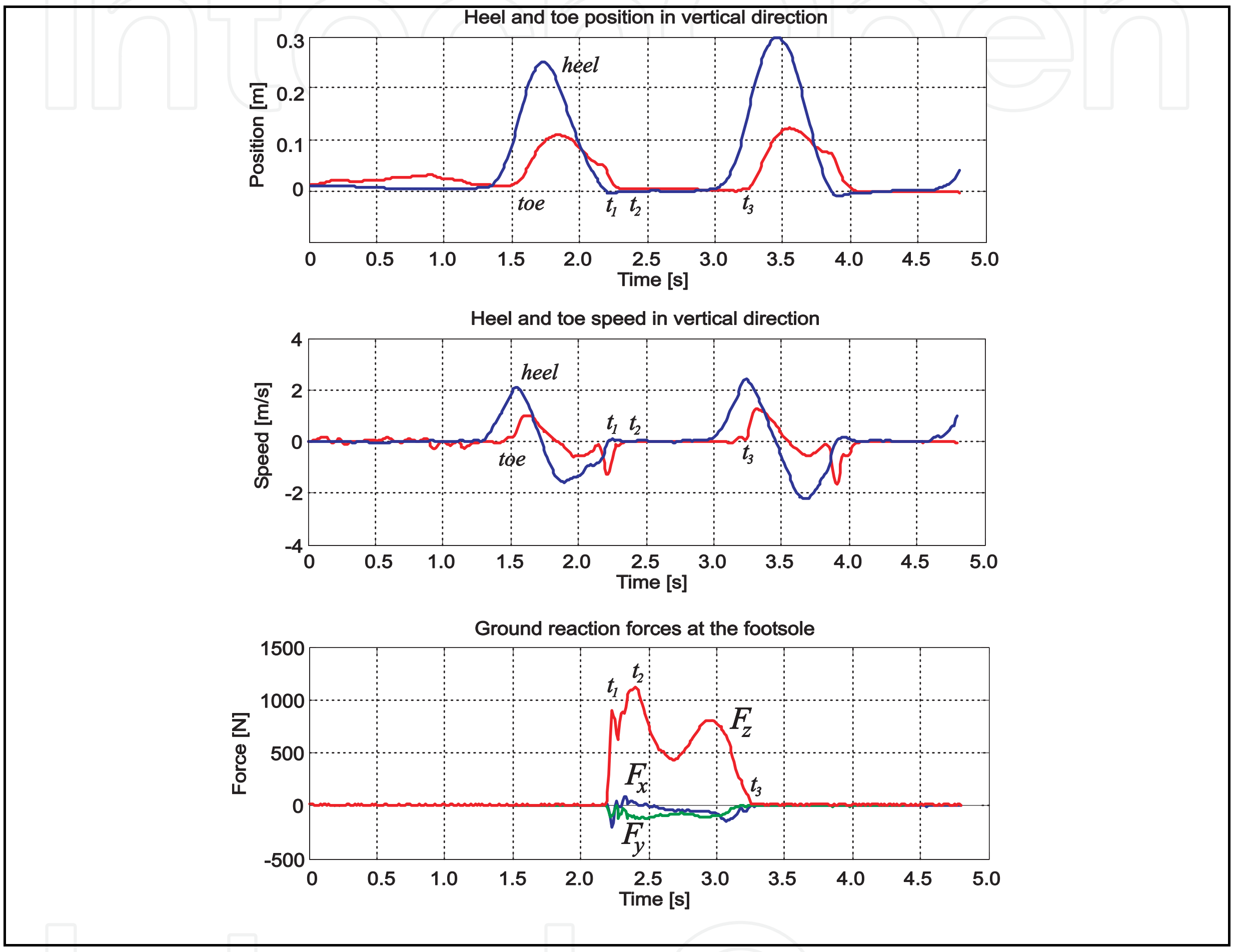

Fig. 4. Experimentaly measured indices of a human gait: (i) heel and toe (foot) cycloids, (ii) speed of the landing foot, (iii) ground reaction forces acting to the foot sole in the sagital-F_x, lateral-F_y and vertical-F_z direction

When the contact force magnitude F_z transcends the reference value corresponding to the body weight, the leg musles are consequently relaxed proportionally. Concerning the gait speed of a biped system, it was identified that the damping factor of the leg muscles is being deceresed with increasing of the speed of motion. Changes of a ground compliance (from the rigid to the soft) cause consequently changes in leg imedance, too. A soft, i.e. more compliant supporting surface (e.g. carpet, sandy terrain, etc.) needs additional muscles strengthening as well as viceversa – increasing of the ground rigidity needs relaxation of leg muscles in order to adapt to the originated changes. Forementioned biological principles, acquired from biomechanical experiments, will be elaborated in the next Sections of the paper for the synthesis of new adaptive impedance control algorithm.

5. Adaptive Control of Biped Locomotion

A good biped robot control scheme should have the following capabilities (Park, 2001). First, the desired trajectory of the swing foot should be tracked as accurately as possible in order to avoid obstacles in the way the human feet do it precisely. On the other hand, tracking of the upper body is not so much rigorous as that of the swing foot. However, maintaining a good balance and posture of the upper body is important having in mind that it carries a vision system (e.g. stereo cameras) on the head as well as robot arms should to perform different service tasks that requests posture stability. Second, footing on the ground should be safe and stable. An efficient control scheme would prevent the swing foot from being bounced from the ground during its landing on the support surface (ground). Foot bouncing from the ground, during foot landings, could cause instability in locomotion and thus should be ultimately avoided. Third, a biped robot should be also able to adapt to various conditions in the locomotion environment so that it can walk with a dynamic balance, for example, on a carpeted floor, on a compliant sandy surface, on a surface with pebbles as well as on a flat rigid floor.

The novelties presented in this paper are addressed to building of an adaptive control of biped robot mechanisms with bio-inspired, continual (real-time) leg impedance modulation. It is unique that it controls the impedance of the swing foot as well as the impedance of the hip link. The impedance control method has been successfully used for the robot manipulators (Hogan, 1986) which interact with their environment where manipulators perform their constrained motions. In biped locomotion, humanoid robot is periodically in contact with the ground, sometimes with single foot and other times with double feet. Moreover, impedance control for bipedal locomotion should to be similar to the natural method that human being uses for locomotion. When a human walks, he/she does not explicitly control the trajectory of his upper body, but rather controls the muscle strength of his legs that support the upper body. Human also rather controls the trajectory of the swing foot in order to avoid obstacles such as bumps and sills or in order to land the foot in a safe area, for example, avoiding a pot hole. In typical human locomotion, the leg muscles are repeatedly strengthen and relaxed depending on gait phases (Leonard et al., 1995). Just before the contact of the swing foot with the ground, the leg muscles are strengthen to regulate and reduce impact, resulting in a very soft contact with the ground. Borrowing this idea from human locomotion, the parameters used in the impedance control should be also appropriately modulated depending on the gait phase having in mind that the gait phase indicators can be identified in real-time as described in previous section.

5.1 Impedance Control

The impedance control law is derived under the assumption that there exist contact sensors at the feet soles and force/torque sensors at the ankles so that the controller knows when a foot reaches the ground and how much the contact force/torque is generated at the feet. Both feedbacks (sensor information) are necessary for building a regulator of dynamic balance to be described in the next section, too.

This paper proposes that the impedance of the swing foot should be specified with respect to the ground. During the SPs and WAPs, the impedance of the tip of the swing foot depends on the entire kinematical chain, which passes through the hip and terminates at the ground contact point of the support foot of other leg. This paper also proposes a way of adaptive modulation of the set of leg impedance parameters to be used for the swing foot depending on its locomotion phase, i.e. whether it is in the SP, WSP or in the WAP. The higher damping ratio, as it will be demonstrated, is used in WAPs than that in SPs and WSP in order to absorb the impact energy in foot landings. Also, the leg in its WSPs, supporting the weight of the biped robot and propelling the hip and the upper body forward, is controlled based on the impedance model of the hip and upper body with respect to the foot on the ground. The impedance model is selected so that the hip link follows its predetermined trajectory and moves forward. It should be stressed out that the impedance of the hip link in the WSP phase depends on the entire chain up to the ground contact point or the supporting foot. The relation defining the impedance control algorithm of biped robots are presented in the text to follow.

The impedance control is applied at the level of the inertial frame rather than the joint space, as the desired behavior of the biped robot at the global coordinate is needed. For that purpose, the model of biped robot mechanism (3) is used to design the control algorithm of the overall biped mechanism including hip link and swing foot impedance control as well as posture control of the upper body and robot arms. The vector form of the integrated control algorithm has the following form:

$$\tau = H_{q,\underline{X}}\ddot{\underline{X}}^* + H_{q,q}\ddot{q}^* + h_q - J_q^T F \tag{8}$$

where, the particular variables are explained previously in Section 2, while $\ddot{\underline{X}}^*$ and $\ddot{q}^*$ represent the corresponding 6×1 and $n\times 1$ control accelerations to be determined in the text to follow. Vector $\ddot{\underline{X}}^*$ concerns with control of hip (basis) link motion while $\ddot{q}^*$ concern with biped robot joint motions including legs, trunk and arms displacements. Then, the vector of control joint accelerations $\ddot{q}^*$ has the following sub-vectors that correspond to the particular kinematical chains (legs, arms, and trunk) of biped mechanism.

$$\ddot{q}^* = \left[\ddot{q}_{tr}^* \ \ddot{q}_{rl}^* \ \ddot{q}_{ll}^* \ \ddot{q}_{ra}^* \ \ddot{q}_{la}^*\right]^T \tag{9}$$

where "*tr*", "*rl*", "*ll*", "*ra*" and "*la*" stands for trunk, right leg, left leg, right arm and left arm successively. Now, suppose the desired impedance of the hip (basis) link (Fig. 2a) reduced to the centre of it, is expressed in a form:

$$M_b\left(\ddot{\underline{X}} - \ddot{\underline{X}}_0\right) + B_b\left(\dot{\underline{X}} - \dot{\underline{X}}_0\right) + K_b\left(\underline{X} - \underline{X}_0\right) = \underline{0}_6 \tag{10}$$

where, M_b, B_b, K_b are the desired mass, damping ratio, and stiffness of the hip link, respectively. Impedance of the hip link in the SSP depends on the entire leg chain up to the ground contact point centre (case of foot multi-point contact) of the supporting foot. In order to achieve the desired impedance (10), acceleration of the hip link $\ddot{\underline{X}}^*$ should be:

$$\ddot{\underline{X}}^* = \ddot{\underline{X}}_0 - M_b^{-1}\left\{B_b\left(\dot{\underline{X}} - \dot{\underline{X}}_0\right) + K_b\left(\underline{X} - \underline{X}_0\right)\right\} \tag{11}$$

The obtained vector $\ddot{\underline{X}}^*$ is used in calculation the control law (8). Suppose that the desired impedance of the leg in the swing phases and the weight acceptance phases is expressed as:

$$M_l\left(\ddot{s}_f - \ddot{s}_f^0\right) + B_l\left(\dot{s}_f - \dot{s}_f^0\right) + K_l\left(s_f - s_f^0\right) = -\left(F_l - F_l^0\right) \tag{12}$$

where superscript "0" denotes the desired (reference) value, M_l, B_l, K_l are the desired mass, damping ratio and stiffness of the swinging leg, and F_l is the resultant ground reaction force at the considered leg (i.e. foot link). In order to make it possible to shift the load from the one leg to another one, as the second leg gradually takes the weight of the biped robot mechanism in the WAP, reference forces/torques $F_l^0 = \left[F_{l,x}^0\ F_{l,y}^0\ F_{l,z}^0\ 0\ 0\ 0\right]^T$ at the foot sole is selected. In the SPs the contact force $F_{l,z}^0$ is set to zero, while in the WAP and WSP it varies its amplitude. The vertical ground reaction force $F_{l,z}^0$ is assumed to have a trapezoidal profile, while the longitudinal $F_{l,x}^0$ and lateral $F_{l,y}^0$ components depend on the estimated friction between foot sole and support surface. The referent torques (roll, pitch and yaw) at the foot can be set to zero.

During the SP, the impedance of the tip of the swinging foot depends on the entire kinematical chain, which passes through the hip and terminates at the ground contact point of the support foot. In order to achieve the desired impedance in (12) foot acceleration should be:

$$\ddot{s}_f = \ddot{s}_f^0 - M_l^{-1}\left[B_l\left(\dot{s}_f - \dot{s}_f^0\right) + K_l\left(s_f - s_f^0\right) + \left(F_l - F_l^0\right)\right] \tag{13}$$

Having in mind the non-linear relation (7), which maps the leg coordinates q_l from joint space to the Descartes coordinates of the corresponding foot $\underline{s}_f = \left[x_f\ y_f\ z_f\ \varphi_f\ \theta_f\ \psi_f\right]^T$ in task space, then (7) can be re-written in a form:

$$\ddot{q}_l = J_l^{-1}(q_l, d)\cdot\left[\underline{\ddot{s}}_f - \underline{\ddot{X}} - \dot{J}_l(q_l, d)\,\dot{q}_l\right] \tag{14}$$

The explicit relation between the leg impedance and the corresponding joint coordinates is possible to be derived by combination of (13) and (14). The resulting relation has the form:

$$\ddot{q}_l = J_l^{-1}(q_l, d)\cdot\left\{\ddot{s}_f^0 - M_l^{-1}\left[B_l\left(\dot{s}_f - \dot{s}_f^0\right) + K_l\left(s_f - s_f^0\right) + \left(F_l - F_l^0\right)\right] - \underline{\ddot{X}} - \dot{J}_l(q_l, d)\,\dot{q}_l\right\} \tag{15}$$

The control vector of joints' accelerations for the right leg $\ddot{q}_{rl}^*$ or the left leg $\ddot{q}_{ll}^*$ (valid for SPs and WAPs), that produce the imposed leg impedance (12), is calculated from (15). In that case, $\ddot{q}_{rl}^* \equiv \ddot{q}_l$, i.e. $\ddot{q}_{ll}^* \equiv \ddot{q}_l$. Similarly, combining the relations (11) and (14), the new relation can be derived as:

$$\ddot{q}_l = J_l^{-1}(q_l, d)\cdot\left\{\underline{\ddot{s}}_f - \left[\underline{\ddot{X}}_0 - M_b^{-1}B_b\left(\underline{\dot{X}} - \underline{\dot{X}}_0\right) - M_b^{-1}K_b\left(\underline{X} - \underline{X}_0\right)\right] - \dot{J}_l(q_l, d)\,\dot{q}_l\right\} \tag{16}$$

The control vector of joints' accelerations for the right leg $\ddot{q}_{rl}^*$ or the left $\ddot{q}_{ll}^*$ (valid for WSPs), that produce the imposed hip link impedance (10), is calculated from (16).

Finally, when the control accelerations $\ddot{q}_{rl}^*$ and $\ddot{q}_{ll}^*$ in the vector (9) are determined (by relations (15) and (16)), providing the desired hip link and leg impedance of the biped robot, the rest of the control accelerations in the control law (8) should be determined, too. Bearing in mind that the upper body (trunk) of biped robot and robot arms have to ensure the accurate positioning (speed) and posture stability, necessary for task performance and advance vision, the control accelerations $\ddot{q}_{tr}^*$, $\ddot{q}_{ra}^*$ and $\ddot{q}_{la}^*$ can be determined as corresponding PD-regulators in a form:

$$\ddot{q}_{ch}^* = \ddot{q}_{ch}^0 - K_d\left(\dot{q}_{ch} - \dot{q}_{ch}^0\right) - K_p\left(q_{ch} - q_{ch}^0\right) \tag{17}$$

where the subscript "*ch*" denotes one of the following kinematical chains: trunk "*tr*", right arm "*ra*" or left arm "*la*". K_p and K_d are corresponding positional and differential control gain matrices of dimension 6×6. The choice of the control gains K_p and K_d depends on desired characteristics of the system (stability, time of response, frequency, etc.), used actuators for biped displacements, size of the robot, etc. The structure (size), mass and inertia moments of a biped robot system determines its frequency characteristics. In that sense, the control gains in (17) could be chosen in such a way to ensure system to be stable and to avoid the resonant frequency. That is accomplished by appropriate setting of the frequency ν [*Hz*] and the relative damping factor ζ of the regulator. Bearing in mind the previously said, the control gains are calculated as to follow:

$$\begin{aligned} &K_p = diag\{k_p^i\}, \quad k_p^i = \omega_n^{i^2}, \quad i = 1,\ldots,6 \\ &K_d = diag\{k_d^i\}, \quad k_d^i = 2\zeta^i \omega_n^i, \quad i = 1,\ldots,6 \\ &\zeta^i = const, \quad \nu^i = const, \quad \omega_n^i = 2\pi\nu^i \end{aligned} \tag{18}$$

Set of parameters, including the basis (hip) link impedance (M_b, B_b, K_b) and the swing leg impedance (M_l, B_l, K_l) parameters defined in (10) and (12), is determined using relations (19). Inertial (mass) parameter matrices of the hip and leg impedance are assumed constant, and depend on the lump mass of biped mechanism. Corresponding particular damping ratio and stiffness matrices can be calculated from the relations:

$$\begin{aligned} &K_b = M_b \cdot \omega_b^2 = const, \quad B_b = M_b \cdot 2\zeta_b \cdot \omega_b = const, \\ &\omega_b = 2\pi\nu_b, \zeta_b = const, \nu_b = const \\ &K_l = M_l \cdot \omega_l^2 \cdot diag\{k_{l,1} \ldots k_{l,6}\}, \quad B_l = M_l \cdot 2\zeta_l \cdot \omega_l \cdot diag\{b_{l,1} \ldots b_{l,6}\}, \\ &\omega_l = 2\pi\nu_l, \zeta_l = const, \nu_l = const; \end{aligned} \tag{19}$$

where $k_{l,i}, b_{l,i}$ are so called the *adjustment factors* (for $i = 1,\ldots,6$ particular directions of motion) used for modulation of leg impedance parameters B_l, K_l defined in (19); ς_b, ς_l are damping factors and ν_b, ν_l are corresponding frequencies of the controller. Bearing in mind that walking conditions and gait parameters can vary significantly in real-time, impedance parameters could be varied according to the real conditions as well as according to the biological principles considered in the previous section.

5.2 Impedance Modulation

Humans adapt leg impedance parameters in real-time during a walk by changing corresponding impedance characteristics in the range from the low values (corresponding to the slack muscles) to the high values (corresponding to the stiff muscles). Magnitudes of the

leg impedance parameters (B_l, K_l) depend on actual walking conditions (ground surface characteristics, compliance of the support, foot-ground contact characteristics, etc.) as well as on gait parameters (speed, step size, lifting height of foot, etc.). The leg impedance parameters can be modulated by an appropriate variation of the corresponding adjustment factors $k_{l,i}, b_{l,i}$ given in (19). The adaptive knowledge-based algorithm for leg impedance modulation was designed based on the experimental results obtained by motion capture of human gait as well as by the complementary simulation tests with the 36 DOFs model of biped robot gait. Aimed to this goal, the gait speed is varied in the range $V \in [0.5, 2.0]$ [*m/s*], step size within $s \in [0.30, 0.85]$ [*m*] and lifting height of the swing foot within the range $h_f = [0.05, 0.40]$ [*m*]. Compliance of support surface (stiffness coefficient) is varied, too. Three characteristic compliant parameters are considered as representatives: (i) stiff one $k_{z0} = 10^5$ [*N/m*], (ii) moderately compliant $k_{z0} = 4 \cdot 10^4$ [*N/m*], and (iii) compliant $k_{z0} = 10^4$ [*N/m*]. Experimentally acquired knowledge (concerning the principles of impedance modulation) enables building of the corresponding empirical algorithm for impedance parameters modulation. Flow-chart of the bio-inspired algorithm for real-time impedance modulation is presented in Fig. 5.
The procedure for identification of the adaptive (time-variable) impedance parameter values $K_l(t), B_l(t)$ is performed in two stages. First, determination of the constant-value adjustment factors $b^o_{l,i}, k^0_{l,i}$ (*i=1,…,6*) is done. Obtained constant-value factors $b^o_{l,i}, k^0_{l,i}$ can be assumed as the quasi-optimal, non-adaptive values due to the fact that they ensure the best possible performances to be achieved with implementation of constant-value adjustment factors. The identified set of adjustment factors provides a kind of satisfactory dynamic performances of biped system for variable walking conditions. Variable adjustment factors $k_{l,i}, b_{l,i}$ have to be identified in the second stage of the tuning procedure to ensure high dynamic performances of the robot. The values of the variable adjustment factors should be sought in the vicinity of the constant-value $b^o_{l,i}, k^0_{l,i}$ factors. Real-time modulation of the adjustment factors $k_{l,i}(t), b_{l,i}(t), t \in (0, \infty]$ ensures adaptive bio-inspired control of biped robot locomotion in a way similar as the humans do it. Both stages of the procedure for tuning algorithms for impedance modulation is performed beyond plenty of experimental and simulation tests seeking for the best system performances through one iterative procedure. For this purpose, different qualitative and quantitative criteria for assessment of the results, achieved by implementation of the developed adaptive impedance control algorithm, are introduced such as: accuracy of foot trajectory tracking Δs_f, posture stability in sense of tracking accuracy of the hip link cycloids Δs_h, robustness to external perturbation and environment uncertainties, criterion of the minimal peak impact force amplitudes $F_{l,z}$, minimal ground reaction force deviation from the reference values $e_F = F_{l,z} - F^0_{l,z}$, criterion of low joint torque amplitudes τ_l and energy consumptions related to the leg joints, etc. The established criteria mainly concern with stability, dynamic performances and energy issues of the control system assessment.

Concerning the first stage of the procedure for identification impedance adjustment factors, the best setup of the constant-value adjustment factors $b_{l,i}^{o} > 1, k_{l,i}^{0} > 1$ (for *i=1,…,6*) are identified for the 'moderate-case' locomotion characterized by the gait speed $V_{MC}^{ref} = 1.00\ m/s$, foot lifting height $h_{f}^{ref} = 0.15\ m$, landing speed of the swing foot $\dot{z}_{f}^{ref} = -1\ m/s$, and surface compliance of $k_{z0}^{ref} = 4 \times 10^{4}\ N/m$ stiffness coefficient. The identified constant-value adjustment factors $b_{l,i}^{o}, k_{l,i}^{0}$ enable calculation of the so called *basic impedance parameter setup* B_{l}^{0}, K_{l}^{0}, by applying the relation (19). The basic parameter setup B_{l}^{0}, K_{l}^{0} represents a reference set of parameters to be used for assessment of biped system performances obtained by implementation of the adaptive impedance control algorithm.

Impedance parameters $K_{l}(t), B_{l}(t)$ of biped legs should be changed during walk from phase to phase (SP, WAP and WSP) as well as to be varied continually in real-time within a particular phase. It was experimentally discovered that a biped robot has to change its leg impedance in the swing phase depending on: (i) landing speed $\dot{z}_{f}^{\min}$ of the swing foot, (ii) forward speed of robot V_{MC}, and (iii) estimated value of the foot-ground compliance. In that sense, two characteristic indicators are introduced: (i) rate indicator $\eta = V_{MC} / V_{MC}^{ref}$ that takes into account the relationship between the actual forward speed of biped mechanism V_{MC} and the reference speed V_{MC}^{ref} that corresponds to $V_{MC}^{ref} = 1.00\ m/s$ assumed as the moderate value; (ii) compliance indicator κ that represents a quotient $\kappa = k_{z0} / k_{z0}^{ref}$ of the foot-ground contact stiffness k_{z0} and the reference stiffness k_{z0}^{ref} that corresponds to the assumed moderately rigid surface $k_{z0}^{ref} = 4 \times 10^{4}\ N/m$; Additionally, it was explored that the damping adjustment factor $\tilde{b}_{l}$ of a biped robot leg should to be changed according to the cubic polynomial $P(\dot{z}_{f}^{\min}) = -0.172\left|\dot{z}_{f}^{\min}\right|^{3} + 1.120\left|\dot{z}_{f}^{\min}\right|^{2} + 2.570$ identified empirically.

At the end of the SP as well as during WAP, humans instinctively strengthen leg muscles to suppress the impact. As large as the landing speed amplitude $\dot{z}_{f}$ of the foot is, the foot impact is more powerful and vice versa. Impact forces at the swing foot can be absorbed significantly by enlargement of the appropriate leg impedance parameters (e.g. damping coefficient B_{l}). During an impact, adjustment factor $\tilde{b}_{l}$ changes its value according to the empirical rules given by the algorithm presented in Fig. 5. The magnitude of the damping adjustment factor $\tilde{b}_{l}$ can be multi-enlarged (depending on actual walking conditions) in comparison to the value to be applied during the WSP phase. It is proportional to the landing speed quotient $\dot{z}_{f} / \dot{z}_{f}^{ref}$ (where $\dot{z}_{f}^{ref} = -1\ m/s$) as well as inverse-proportional to the compliance indicator $\kappa = k_{z0} / k_{z0}^{ref}$. During the SP and WAP the stiffness adjustment factor of leg impedance is kept invariable, i.e. $\tilde{k}_l = k_l^0 = const$.

During a WSP, biped robot behaves as an inverted pendulum. A body mass displacement happens in this phase, causing variation of the corresponding ground reaction forces at the foot sole. Consequently, corresponding impedance adjustment factors $k_{l,i}, b_{l,i}$ should be determined with respect to the contact force magnitudes $F_{l,z}$ as well as to their rates of changing $\dot{F}_{l,z}$. Algorithm uses force error $e_F = F_{l,z} - F_{l,z}^0$ as well as rate of force error $e_{dF} = \dot{F}_{l,z} - \dot{F}_{l,z}^0$ as the indicators necessary for stiffness adjustment factor $\tilde{k}_l$ and damping adjustment factor $\tilde{b}_l$ modulation (Fig. 5). Depending on the signs (less/equal/greater than zero) of e_F and e_{dF} errors, the proposed empirical algorithm calculates corresponding particular stiffness adjustment factors $\tilde{k}_l^I$ and $\tilde{k}_l^{II}$. The valid value takes one that satisfies criterion given by the relation $\left|\tilde{k}_l^{II} - k_l^0\right| > \left|\tilde{k}_l^I - k_l^0\right|$, (see Fig. 5). Identified stiffness adjustment factor $\tilde{k}_l$ takes a value within the range $\tilde{k}_l \in \left[k_l^{min}, k_l^{max}\right]$. Damping ratio and stiffness factor are related each other according (19). Changes of stiffness adjustment factor $\tilde{k}_l$, as one of leg impedance characteristics, causes consequently changes of the damping ratio factor $\tilde{b}_l$ as presented in Fig. 5. When the amplitude of the ground reaction force $F_{l,z}$ in z-direction increases over its reference value $F_{l,z}^0$ (i.e. $e_F = F_{l,z} - F_{l,z}^0 > 0$) then the leg muscles should be relaxed. Accordingly, stiffness of robot leg mechanism should be decreased proportionally and vice versa for $e_F = F_{l,z} - F_{l,z}^0 < 0$.

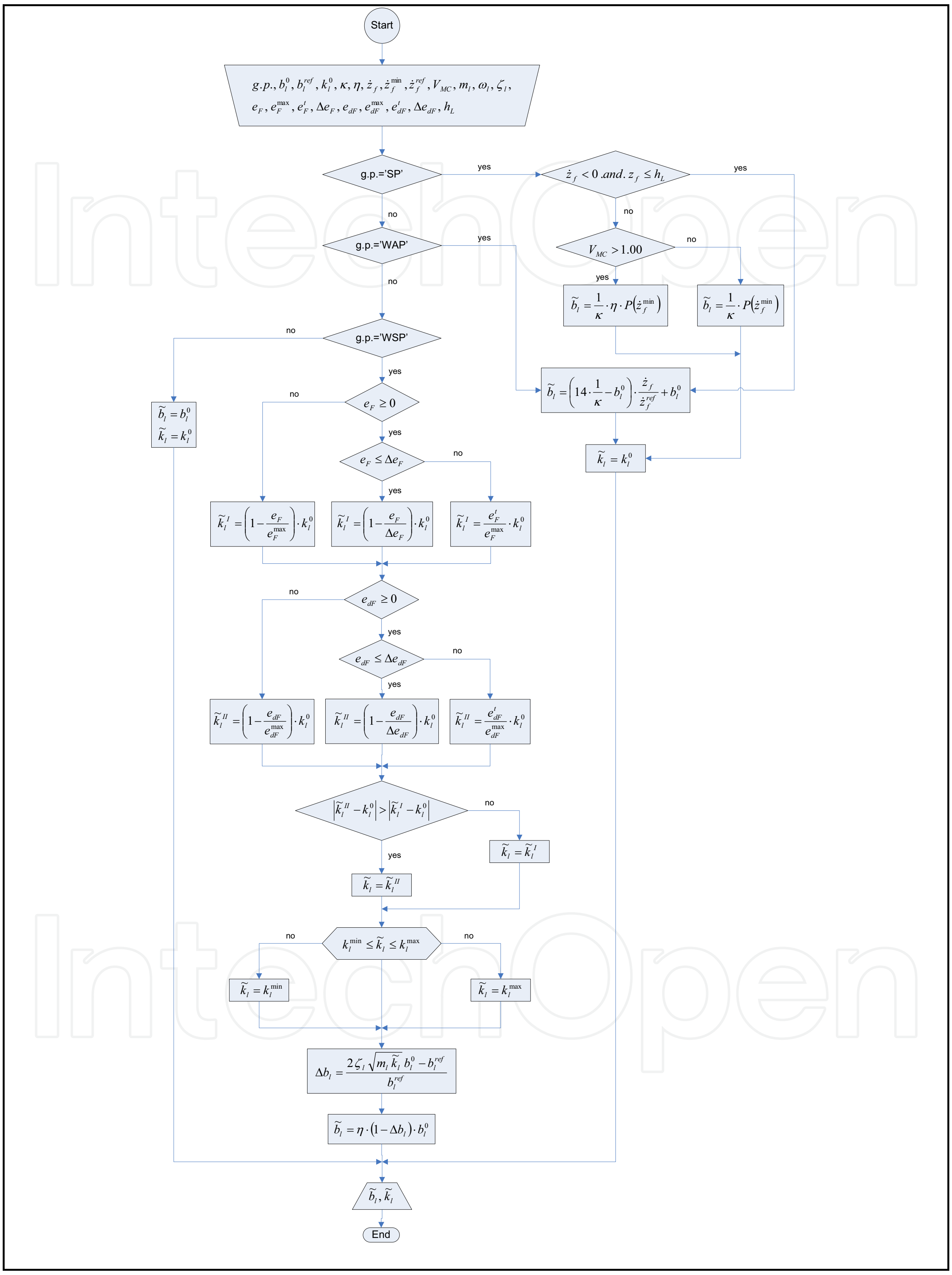

Fig. 5. Flow-chart of the algorithm for determination of adaptive impedance parameters in a way that emulates natural leg impedance modulation with human beings

The following signatures in the flow-chart diagram (Fig. 5) are used: "*g.p.*" is the acronym for gait phase; m_l represents leg mass as impedance parameter; $\zeta_l = 1.00$ is the assumed damping ratio of a leg mechanism; $\nu_l = 3.00\,Hz$ is the assumed frequency of a leg mechanism; $\omega_l = 2\pi\nu_l$ is the angular frequency of a leg mechanism; $b_l^{ref} = m_l\, 2\zeta_l\, \omega_l\, b_l^0$ is the reference damping ratio including the basic damping adjustment factor b_l^0; $\dot{z}_f^{\min}$ is the extreme negative landing foot speed (e.g. $\dot{z}_f^{\min} \sim -1.70\; m/s$); $h_L = 0.01m$ is the assumed landing height threshold; $e_F^{\max}, e_F^t$ are the maximal force error (assumed to be as large as body weight) and corresponding threshold of sense (assumed to be *25 %* of $e_F^{\max}$) successively; and $e_{dF}^{\max}, e_{dF}^t$ are the maximal rate of contact force error (assumed to be *7000 N/s*) and the corresponding threshold of sense (assumed to be *25 %* of the $e_{dF}^{\max}$ value).
Adaptive impedance control algorithm presented in this section will be tested and verified through extensive simulation experiments under different real walking conditions. The results of evaluation of the proposed control strategy are presented in Section 7.

6. Simulation Experiments

Biped robot locomotion is simulated to enable evaluation of control system performances. For this purpose, the spatial 36 DOFs model of biped robot (presented in Fig. 2) and adaptive impedance control (defined by relations (8)-(17)) are simulated by implementation of the HRSP software toolbox (Rodić, 2009). Biped robot parameters used in simulation experiments are specified in (Rodić, 2008). Parameters of a 3D compliant model of robot environment, applied in simulation tests, are assumed as in (Park, 2001). Concerning the leg impedance parameters modulation, three qualitatively different cases are considered and evaluated by the simulation tests: (i) non-adaptive control "NA" with invariable leg impedance parameters (case without modulation of parameters), (ii) quasi-adaptive "QA", switch-mode impedance modulation depending on particular gait-phases, and (iii) continual adaptive "AD" real-time impedance modulation. Concerning the first case, inertial impedance matrices defined in (10) and (12) are imposed as the constant 6×6 diagonal matrices $M_b, M_l = \Re^{6\times 6} = const$ that have the values $M_b = diag\{40\}$ and $M_l = diag\{10\}$. Particular damping ratio and stiffness coefficient of the hip link from (19) are assumed to be constant-value matrices, too. The following values $B_b = diag\{1508\}[Ns/m]$ and $K_b = diag\{14212\}[N/m]$ (when choose $\zeta_b = 1$ and $\nu_b = 3\,[Hz]$) are assumed. Their values are kept invariable in the simulation experiments. The leg impedance parameters K_l and B_l from (19) are variable in general case. They are determined on-line by use of the algorithm presented in Fig. 5. Exception of that is in the cases when choose the constant leg impedance in some of the particular simulation tests, i.e. when the adjustment factors from (19) use to have the constant unit values $b_{l,i} = 1,\, k_{l,i} = 1,\, i = 1,\ldots,6$. Then, assuming $\zeta_l = 1$ and $\nu_l = 3\,[Hz]$, the following constant-value impedance parameters are obtained to have the values $B_l = diag\{377\}[Ns/m]$ and $K_l = diag\{3553\}[N/m]$. Control gain matrices K_p and K_d of the PD regulator (17) of trajectory tracking are imposed to have the invariant values $K_p = diag\{1421\}[s^{-2}]$ and $K_d = diag\{76\}[s^{-1}]$ assuming that $\nu^i = 3.00$ [Hz] and $\zeta^i = 1.00$. Imposed gain matrices are used in simulation experiments as the invariable constant-value matrices.

In order to evaluate the control performances of the new-proposed, adaptive impedance algorithm, three different simulation examples are considered in the paper depending on type of control algorithms applied: NA, QA or AD as explained in the previous paragraph. The simulation examples are performed under the same simulation conditions such as: (i) walking on a flat surface, (ii) compliant, moderate rigid ground surface with $k_{z0} = 4\times10^4$ $[N/m]$ stiffness coefficient, and (iii) a moderate fast gait including forward gait speed of $V = 1\,[m/s]$, step size of $s = 0.7\,[m]$ and swing foot lifting height of $h_f = 0.15\,[m]$. Biped robot locomotion in the simulation examples (cases) is checked on stability, quality of dynamic performances and other relevant performance criteria such as: accuracy of trajectory tracking (hip link and foot trajectories), maximal amplitudes of ground reaction forces and joint torques, energy efficiency, anthropomorphic characteristics, etc. Simulation results obtained in three verification simulation tests are mutually compared in order to assess the quality of the applied control strategies. Simulation examples presented in Fig. 6 prove that the best dynamic performances, regarding to the smoothness of the realized ground reaction forces during a flat gait, are obtained in the Case "AD" (adaptive control). That is the example when the continual leg impedance parameter modulation was applied. The worst performances were obtained as expected in the Case "NA", where there is no adaptive control and when the impedance parameters have exclusively the constant, non-adaptive values. The Case "QA" regards to the quasi-adaptive switch-mode modulation of leg impedance parameters. It provides a moderate quality of system performances. The minimal force peak amplitudes and deviations from the referent values are in the Case "AD". The peaks are well damped by introducing of the continually modulated impedance, with an on-line modulation of the leg stiffness and damping ratio. The results presented in Fig. 6 prove that the new-proposed bio-inspired algorithm of adaptive impedance with continually modulated leg stiffness and damping ensures the best system performances with respect to other candidates - Case "NA" and Case "QA". The labels in the figure marked as "rf" and "lf" will be used in the paper to indicate the right, i.e. the left foot.

Concerning the criterion of the accuracy of trajectory tracking, the following results are obtained and described in the text to follow. In the Case "NA", when the control (impedance) parameters take the constant values then the biped robot performs trajectory tracking in a rather poor way. The better results are obtained when implement the switch-mode impedance modulation (Case "QA"). But, the best accuracy of tracking is achieved by implementation of the continually modulated impedance parameters (Case "AD") as presented in Fig. 7. In this case, the swing foot lifting height is maintained almost constant all the time at the level of $h_f = 0.15\,m$.

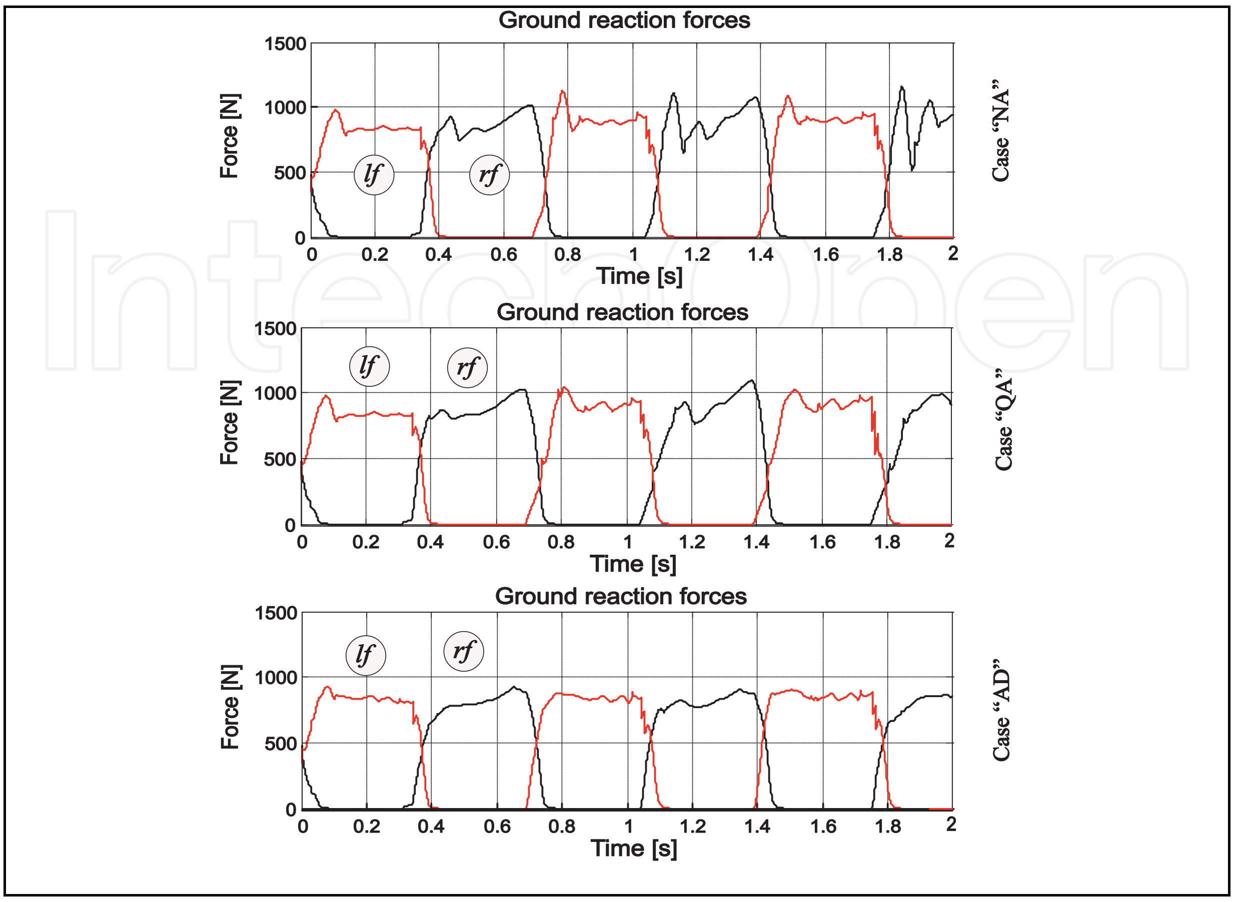

Fig. 6. Ground reaction forces for the biped locomotion obtained in different simulation examples – comparison of Cases "NA", "QA" and "AD"

The heel and toe cycloids are performed regularly and without significant deviations. That guarantees a fine locomotion and desired accuracy. Control algorithm with the continual impedance modulation of leg stiffness and damping ratio ensures that there is no foot bouncing from the ground support during locomotion (Case "AD", Fig. 7). In the Case "QA", a slight bouncing exists as presented in Fig. 7, Detail "A". Suppression of the foot bouncing is very important for the system performances, because the bouncing feet can cause system instability. Complementary to the previous results, the quality of trajectory tracking of the hip link as well as right foot of biped robot in different coordinate directions is presented in the phase-planes in Fig. 8. In both cases "QA" and "AD", a stable walking is ensured since the actual trajectories (hip and foot trajectories) converge to the referent trajectories (Fig. 8).
Although there is a certain delay in velocity tracking in the sagital direction, the foot centre tracks its nominal (referent) cycloid in a satisfactory way in the case when the continual modulation of leg impedance (Case "AD") is applied. The delay is more expressed (larger) in the case when the switch-mode modulation (Case "QA") is applied (Fig. 8). Better tracking of the foot and the hip link trajectories (in the vertical direction) are appreciable, too. The trajectory of the hip link as well as the foot centre trajectory converges to the referent cycles (Fig. 8) as locomotion proceeds. The convergence is better in the Case "AD"

than in the Case "QA". That proves the advantage of the new proposed control algorithm in the sense of achievement of a better accuracy of locomotion.

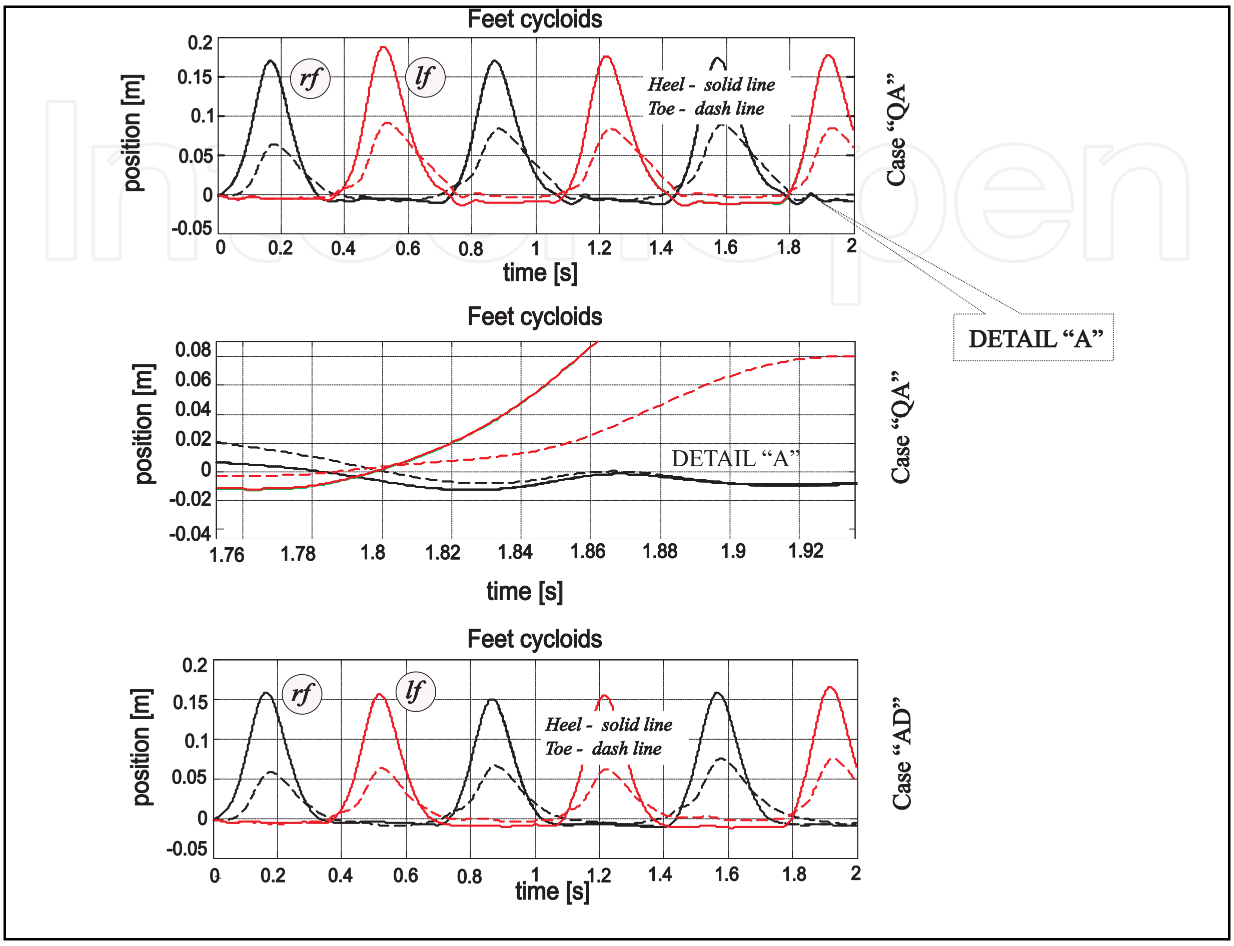

Fig. 7. Precision of foot trajectory tracking – comparison of the Cases "QA" and "AD"

The stiffness and damping ratio adjustment factors $k_{l,i}$ and $b_{l,i}$, defined in (19), are presented in Fig. 9. In the Case "QA", stiffness factor is kept constant $k_{l,i} = 1$ while the damping ratio factors (for the both legs) vary from gait phase to gait phase. In the case of continual modulation (Case "AD"), stiffness factors as well as damping ratio factors change their amplitudes as presented in Fig. 9. Variable adjustment factors provide better adaptation of the biped robot system to the variable gait as well as to different environment conditions. The hip joints as well as the knee joint endure the most effort to adapt biped gait to the actual conditions. In that sense, especially critical moments represent moments of foot impacts. Bearing in mind this fact, the variable leg impedance enables biped system to prevent enormous impact loads and serious damages of its leg joints.

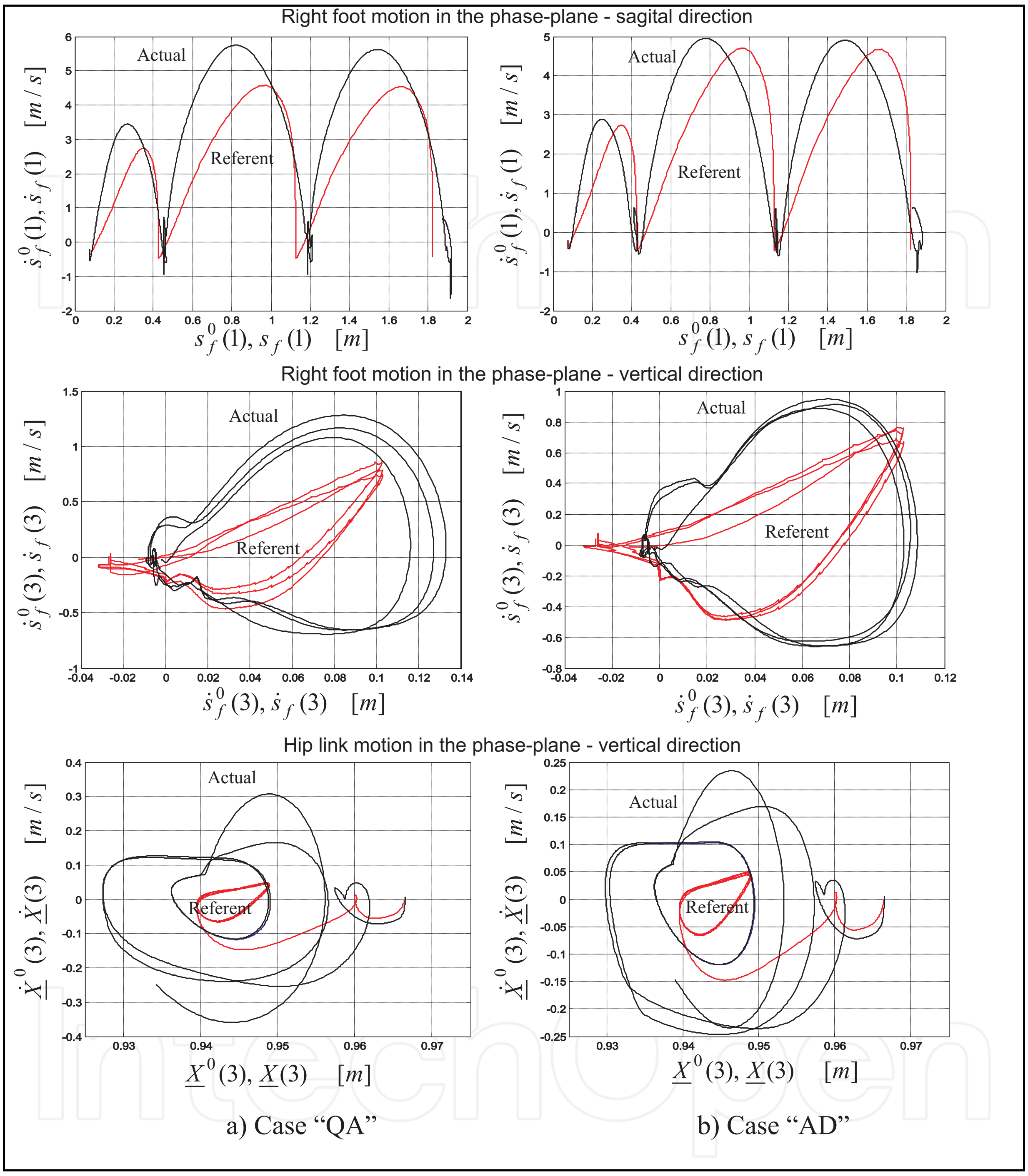

Fig. 8. Precision of biped robot trajectory tracking shown in phase-plane – comparison of the Case "QA" and Case "AD"

Performances of the adaptive impedance control with continually modulated leg impedance parameters can be validated by the analysis of some additional numerical indicators, too. The appropriate criteria indicators, related to the extreme dynamic reactions as well as to the energy efficiency, are imposed such as: (i) the relative average magnitude of the ground reaction forces' deviation η_F with respect to the referent "NA" case; (ii) extreme relative peak amplitude of dynamic reactions η_{Peak} with respect to the "NA" case, and (iii) indicator of the relative energy efficiency η_E with respect to the referent "NA" case. Systematized indicators of performance quality are shown in Tab.1. According to this table, it is evident that an adaptive control with real-time modulation of leg impedance parameters ensures significantly better characteristics than non-adaptive and quasi-adaptive cases of control.

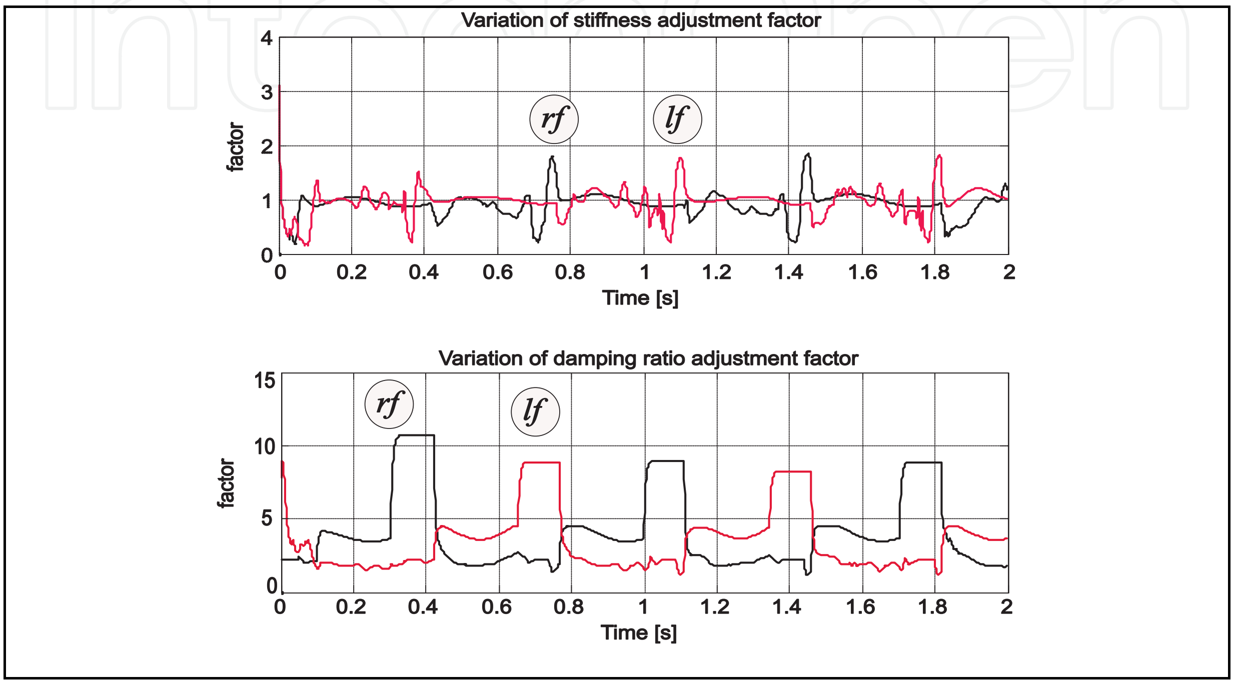

Fig. 9. Leg impedance modulation – the stiffness and the damping ratio adjustment factors for the Case "AD"

Comparative pair	η_F %	η_{Peak} %	η_E %
QA : NA	-23.82	-8.82	-1.13
AD : NA	-66.45	-47.05	-30.93

Table 1. Table of criteria indicators depicting the quality of control performances against the indices of dynamic reactions deviations, extreme payload and energy efficiency

7. Conclusion

Stable and robust walking on irregular surfaces and compliant ground support as well as walking with variable gait parameters request advanced control performances of biped robots. In general case, walking conditions are unknown and cannot be anticipated confidently in advance to be used for trajectory generation. As consequence, path generator produces biped trajectories for non-perturbed locomotion such as: flat gait, climbing stairs, spanning obstacles, etc. In the case of a perturbed locomotion, robot controller is charged to manage the dynamic performances of the system and to maintain dynamic balance. In that sense, we speak about the robustness of control structure to the gait parameters variation as well as to the external perturbations concerning uncertainties (structural and parametric) of

the ground support. Bearing in mind previous facts, promising control architecture capable to cope with the fore mentioned uncertainties is the adaptive impedance control with continually modulated impedance parameters.
Main contribution of the article is addressed to a synthesis of the bio-inspired, experimentally-based, adaptive control of biped robots. Aimed to this goal, the adaptive bio-inspired algorithm designed for real-time modulation of leg impedance parameters are proposed in the paper. Proposed control structure is robust to variation of gait parameters as well as uncertainties of the ground support structure. The proposed control algorithm was tested through the selected simulation experiments to verify the obtained control system performances. Developed control algorithm is valid and can be applied for control of any biped robot of anthropomorphic structure regardless to its size, kinematical and dynamic characteristics. It was proved through the simulation experiments that the biological principles of leg impedance modulation are valid with artificial systems such as biped robots, too.

8. References

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This book book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of contemporary robotics and autonomous systems. The volume is organized in four thematic parts according to the main subjects, regarding the recent advances in the contemporary robotics. The first thematic topics of the book are devoted to the theoretical issues. This includes development of algorithms for automatic trajectory generation using redudancy resolution scheme, intelligent algorithms for robotic grasping, modelling approach for reactive mode handling of flexible manufacturing and design of an advanced controller for robot manipulators. The second part of the book deals with different aspects of robot calibration and sensing. This includes a geometric and treshold calibration of a multiple robotic line-vision system, robot-based inline 2D/3D quality monitoring using picture-giving and laser triangulation, and a study on prospective polymer composite materials for flexible tactile sensors. The third part addresses issues of mobile robots and multi-agent systems, including SLAM of mobile robots based on fusion of odometry and visual data, configuration of a localization system by a team of mobile robots, development of generic real-time motion controller for differential mobile robots, control of fuel cells of mobile robots, modelling of omni-directional wheeled-based robots, building of hunter- hybrid tracking environment, as well as design of a cooperative control in distributed population-based multi-agent approach. The fourth part presents recent approaches and results in humanoid and bioinspirative robotics. It deals with design of adaptive control of anthropomorphic biped gait, building of dynamic-based simulation for humanoid robot walking, building controller for perceptual motor control dynamics of humans and biomimetic approach to control mechatronic structure using smart materials.

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