JJMIE
Volume 5, Number 4, Aug. 2011
ISSN 1995-6665
Pages 285 - 289
Jordan Journal of Mechanical and Industrial Engineering

Conceptual Design of a Single DOF Human-Like Eight-Bar Leg Mechanism

O. Al-Araidah*[,a] , W. Batayneh[b], T. Darabseh[c], S. M. BaniHani[d]

[a]Industrial Engineering Department, Jordan University of Science and Technology, Irbid, 22110, Jordan
[b]Mechanical Engineering Department, Jordan University of Science and Technology, Irbid, 22110, Jordan
[c]Aeronautical Engineering Department, Jordan University of Science and Technology, Irbid, 22110, Jordan
[d]Mechatronics Engineering Department, The Hashemite University, Zarqa 13115, Jordan

Abstract

Legs are the most important elements for accomplishing human physical work including transportation or displacement. The article presents a mechanical reproduction of the human walking apparatus. Using design rules, a final mechanism configuration is achieved such that the crank is a binary link connected to a binary ground link. The resulting linkage is a single degree-of-freedom (DOF) eight-bar mechanism. The mechanism exemplifies the shape and movement of a human leg. The mechanism is simulated and tested to verify the proposed synthesis.

*Keywords:*kinematic synthesis; DOF; Biped walking; Leg mechanism

1. Introduction

Legs are the primary means to satisfy relocation needs for human and many types of animals and insects. Moreover, legs help protect other parts of the body by keeping them far from ground. In the literature, Weber and Weber [1] studied the human walking apparatus and showed that the skeletal system constitutes a mechanism that can potentially be reproduced mechanically. The human leg has a cylindrical shape with the driving mechanism and controllers located at the upper part of the leg. Many researchers studied the walking apparatus and showed that walking patterns are measurable, predictable and repeatable. Hence, mechanical reproductions of walking mechanisms prove useful in the development of humanoids for applications ranging from toys to space exploration.

This article presents a closed loop one degree of freedom (DOF) eight-bar human-like leg mechanism. Like it in a human, the proposed leg design includes a hip, a knee and ankle joints, in addition to a clear femur and fibula. Proportions of the mechanism are appropriately scaled to approximate the human leg. Moreover, the resulting movements of the leg proportions approximate that of a typical person walking. The approximate mechanism precision points represent the human-type walking gait, known as the ovoid path [2]. Figure 1 illustrates an approximation of the desired path. The path is composed of a straight-line, line H1H2H3, portion that represents the times when the foot contacts the ground. Points H1 and H3 represent the extreme points of the path where distance H1H3 represents the horizontal stride. The arched portion H3H4H1 represents the motion of the foot to assume a new position through which the foot has no contact with the ground. To this end, the authors followed a typical design procedure to develop, simulate and test design alternatives.

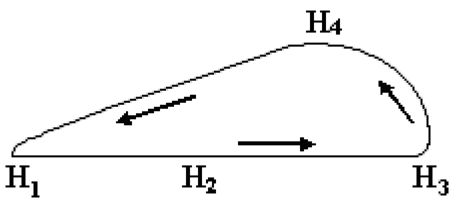

Figure 1: An approximation of the desired walking gait.

The rest of the paper is organized as follows: Section 2 presents a review of related literature. Section 3 describes the mechanism and presents kinematic synthesis of the mechanism. Section 4 provides simulation results obtained from testing the mechanism. Concluding remarks are presented in the final section.

2. Literature Review

Many researchers studied the human walking apparatus and produced motion diagrams representing the movement. A mechanical reproduction of these mechanisms and their movement were useful in various fields such as the development of human prosthetics, human mimicking robots, and advancements in research areas such as biomimetics, military combat, cinematography, toys, and terrestrial and extraterrestrial exploration [3-4].

* Corresponding author. e-mail: alarao@just.edu.jo

In the literature, researchers developed various open and closed kinematic chains for human-like walking machines. While open kinematic chains are generally more flexible and easier to design, their large number of degrees of freedom (DOF) makes them more expensive and harder to control. On the other hand, most of the existing closed chain configurations are generally bulky and do not look like a human leg. The closest approximation of human-like leg with a closed kinematic chain uses a six-bar mechanism [5]. Batayneh, et al. [5] presented a single DOF Watt I six-bar mechanism that typifies the human's motion. The proposed mechanism includes a hip, femur, knee, and fibula. Shieh et al. [6-7] proposed a two-stage optimization process of a two DOF leg mechanism. In the first stage, leg dimensions are optimized with respect to the design objectives, which include minimizing leg size and actuating forces. In the second stage, spring elements with various placement configurations are considered for further reduction of the actuating forces. Sangwan et al. [8] introduced a design for a self-excited biped walking mechanism consisting of two legs that are connected in series at the hip joint through a motor. Each leg has a thigh and a shank connected at a passive knee joint that has a knee stopper restricting hyperextension similar to the human knee. Mukherjee et al. [9] studied the stability of the previous bipedal gait and verified their work by comparing the results with human gait.

Many researchers used motor/motors as actuators while others tend to use other kinds of actuations. Verrelst et al. [10] designed a biped walking mechanism actuated using pneumatic muscles. Hosoda et al. [11] studied antagonistic pneumatic actuators that can be utilized to achieve locomotion for different cases. In [12], the authors presented a five DOF design for a three dimensional bipedal walking robot with human-like morphology and gait. Yavin [13] considered the modeling and control of a three DOF walking four-bar open chain linkage robot. Capi [14] introduced an optimal scheme for a biped robot that has two legs with two DOF each; one translational DOF achieved by a DC motor attached at the body of the robot, and the other DOF is the rotational motion at the ankle joint. Companies such as Honda Motors, Kawada Industries and Sony played a major roll in the competition towards developing legged robots [15-19]. Hurmuzlu et al. [20] studies different existing bipedal robots including "Honda's P3 robot" and cited that most of these existing robots need development in terms of walking patterns and in terms of stability. Mousavi and Bagheri [21] presented a mathematical interpolation of a seven-link robot. The authors presented a simulation study of the biped robot for both nominal and un-nominal gaits. Barai and Nonami [22] presented a two-degree-of-freedom fuzzy controller for hydraulically actuated six leg robotic mechanisms. The proposed designs generally focus on creating the desired walking gait while overlooking the shape of the leg. This article utilizes observations of previous works in designing a closed-loop 8-bar human-like leg mechanism.

3. Mechanism Description and Kinematic Synthesis of the Linkage

A planar one DOF eight-bar mechanism is shown in Figure 2a. For convenience, an alternative sketch of the mechanism is shown in Figure 2b. The proposed path generator $O_AAO_BBCDEFH$ where, B is a coupler point on O_BBC, D is a coupler point on CE, and H is a coupler point on FE that represents the nickel joint. The rotation of the short crank O_AA provides forward/backward motion. The mechanism could be provided with a turning capability about its vertical axis using a second DOF motion. In this design, the lengths of the linkages are selected such that $CE = O_BF = H`H$ and $O_BC \geq FE$. Moreover, $CD` \leq CE/3$ measured from C, $B`$ is located midway on segment $O_BC$ and $H`$ is located midway on segment EF.

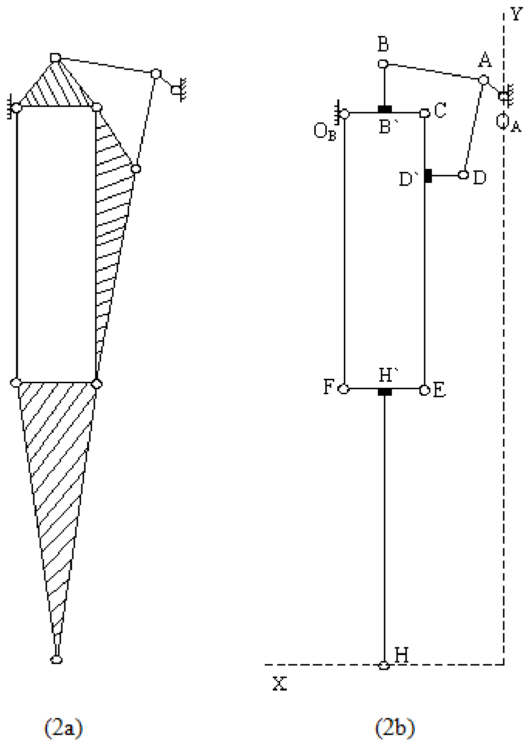

Figure 2: Configuration of the proposed leg mechanism.

Four precision points are selected to reflect the desired motion, and the complex number method is used to synthesize the mechanism. Figure 3 shows the general notated configuration in addition to the individual closed loops.

Equations (1) through (4) illustrate the standard form equations for resulting closed loops.

Loop1:

$$Z_1(e^{i\alpha_j}-1)+Z_3(e^{i\theta_{3j}}-1)+Z_4(e^{i\theta_{4j}}-1)+Z_6/2(e^{i\theta_{4j}}-1)=0, \quad J=2,3,4$$
$$Z_1(e^{i\alpha_2}-1)+Z_3(e^{i\theta_{32}}-1)+Z_4(e^{i\theta_{42}}-1)+Z_6/2(e^{i\theta_{42}}-1)=0$$
$$Z_1(e^{i\alpha_3}-1)+Z_3(e^{i\theta_{33}}-1)+Z_4(e^{i\theta_{43}}-1)+Z_6/2(e^{i\theta_{43}}-1)=0$$
$$Z_1(e^{i\alpha_4}-1)+Z_3(e^{i\theta_{34}}-1)+Z_4(e^{i\theta_{44}}-1)+Z_6/2(e^{i\theta_{44}}-1)=0 \quad (1)$$

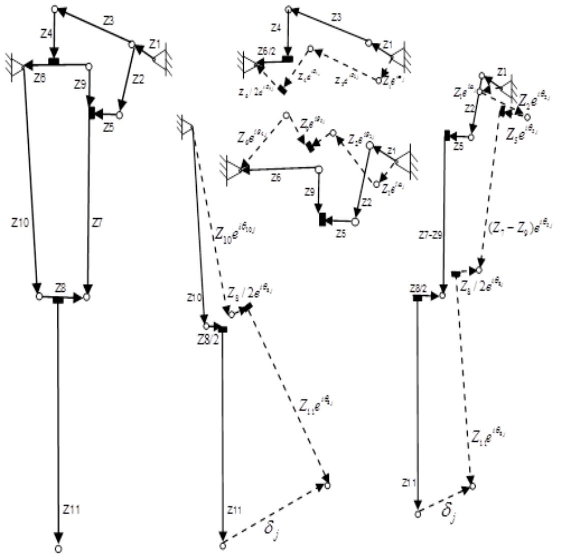

Figure 3: Notated Mechanism Configuration and Closed Loops.

Loop 2:

$$Z_{10}(e^{i\theta_{10j}}-1)+Z_8/2(e^{i\theta_{8j}}-1)+Z_{11}(e^{i\theta_{8j}}-1)=\delta_j, \quad J=2,3,4$$
$$Z_{10}(e^{i\theta_{102}}-1)+Z_8/2(e^{i\theta_{82}}-1)+Z_{11}(e^{i\theta_{82}}-1)=\delta_2$$
$$Z_{10}(e^{i\theta_{103}}-1)+Z_8/2(e^{i\theta_{83}}-1)+Z_{11}(e^{i\theta_{83}}-1)=\delta_3$$
$$Z_{10}(e^{i\theta_{104}}-1)+Z_8/2(e^{i\theta_{84}}-1)+Z_{11}(e^{i\theta_{84}}-1)=\delta_4 \quad (2)$$

Loop 3:

$$Z_1(e^{i\alpha_j}-1)+Z_2(e^{i\theta_{2j}}-1)+Z_5(e^{i\theta_{5j}}-1)-Z_9(e^{i\theta_{5j}}-1)+Z_6(e^{i\theta_{4j}}-1)=0, \quad j=2,3,4$$

$$Z_1(e^{i\alpha_2}-1)+Z_2(e^{i\theta_{22}}-1)+Z_5(e^{i\theta_{52}}-1)-Z_9(e^{i\theta_{52}}-1)+Z_6(e^{i\theta_{42}}-1)=0$$

$$Z_1(e^{i\alpha_3}-1)+Z_2(e^{i\theta_{23}}-1)+Z_5(e^{i\theta_{53}}-1)-Z_9(e^{i\theta_{53}}-1)+Z_6(e^{i\theta_{43}}-1)=0$$

$$Z_1(e^{i\alpha_4}-1)+Z_2(e^{i\theta_{24}}-1)+Z_5(e^{i\theta_{54}}-1)-Z_9(e^{i\theta_{54}}-1)+Z_6(e^{i\theta_{44}}-1)=0 \quad (3)$$

Loop 4:

$$Z_1(e^{i\alpha_j}-1)+Z_2(e^{i\theta_{2j}}-1)+Z_5(e^{i\theta_{5j}}-1)+(Z_7-Z_9)(e^{i\theta_{5j}}-1)-Z_8/2(e^{i\theta_{8j}}-1)+Z_{11}(e^{i\theta_{8j}}-1)=\delta_j, \quad J=2,3,4$$
$$Z_1(e^{i\alpha_2}-1)+Z_2(e^{i\theta_{22}}-1)+Z_5(e^{i\theta_{52}}-1)+(Z_7-Z_9)(e^{i\theta_{52}}-1)-Z_8/2(e^{i\theta_{82}}-1)+Z_{11}(e^{i\theta_{82}}-1)=\delta_2$$
$$Z_1(e^{i\alpha_3}-1)+Z_2(e^{i\theta_{23}}-1)+Z_5(e^{i\theta_{53}}-1)+(Z_7-Z_9)(e^{i\theta_{53}}-1)-Z_8/2(e^{i\theta_{83}}-1)+Z_{11}(e^{i\theta_{83}}-1)=\delta_3$$

$$Z_1(e^{i\alpha_4}-1)+Z_2(e^{i\theta_{24}}-1)+Z_5(e^{i\theta_{54}}-1)+(Z_7-Z_9)(e^{i\theta_{54}}-1)-Z_8/2(e^{i\theta_{84}}-1)+Z_{11}(e^{i\theta_{84}}-1)=\delta_4 \quad (4)$$

The above equations are constructed such that four precision points are considered. Consequently, this yields six independent equations for each loop and a total of 24 independent nonlinear equations to solve, with 43 unknowns (namely; the 11 two dimensional vectors, which represents the links used in the mechanism namely: $Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9, Z_{10}, Z_{11}$, and the links corresponding angles: α_j (corresponding to link O_AA (namely link Z_1)), θ_{2j} (corresponding to link *AD* (namely link Z_2)), θ_{3j} (corresponding to link *AB* (namely link Z_3)), θ_{4j} (corresponding to link *BB*\` (namely link $Z_4$), *CB*\` (namely link $Z_6/2$) and CO_B (namely link Z_6)), θ_{5j} (corresponding to link *DD*\` (namely link $Z_5$), *CD*\` (namely link Z_9) and *CE* (namely link Z_7)), θ_{8j} (corresponding to link *FE* (namely link Z_8), *FH*\` (namely link $Z_8/2$) and *H*\`*H* (namely link Z_{11})), θ_{10j} (corresponding to link O_BF (namely link Z_{10})) for $j=1,2,3$). All the angels are measured clockwise from the positive *x*-axis. δ_j, $j=2,3,4$, represent the precision points (for point H, which represent the motion of the foot joint), are prescribed based on desired values of the horizontal and vertical strides. Notice that increasing the number of independent equations by increasing the number of precision points will increase the number of unknowns and hence increase the complexity of the problem.

4. Modeling and Results

Matlab software package is used to solve the synthesis problem such that a horizontal (vertical) stride of no less than 15cm (5cm) is required as illustrated in the ovoid path described in Figure 1. To limit the search, the leg segments are selected proportional to that of an adult human [23] such that $O_AO_B \leq$ the 95th percentile of the thigh clearance of males ≈ 19cm, *CE* ≈ 45cm, and $O_BC \leq$ 10cm and $O_BC \geq FE$. Moreover, *CD*\` ≤ *CE*/3. These constraints guide the selection of free choice variables and are translated into the following additional equations:

$$|Z_7+Z_9|=|Z_{10}|=|Z_{11}|\cong 45cm \quad (5)$$

$$\angle Z_7=\angle Z_9 \quad (6)$$

$$|Z_1+Z_3+Z_4+Z_6/2|\cong 19cm \quad (7)$$

$$|Z_6|\leq 10cm \quad (8)$$

$$|Z_6|\geq |Z_8| \quad (9)$$

$$|Z_9|\leq |Z_7/3| \quad (10)$$

Figure 4 illustrates sample Matlab results at different crank angles where the fibula is longer than the femur such that Z_1=1.4 , Z_2=21.0 , Z_3=10.7 , Z_4= 8.4, Z_5=3.5 , Z_6=8.4 , Z_7=27.6 , Z_8=7.6 , Z_9=17.4 , Z_{10}=45.0 , and Z_{11}=76.3 . The three diagrams to the lift represent positions of the leg at specific crank angles and the one to the right illustrates the performance of the leg over a discrete range of crank angles. Other sample results obtained using Matlab are simulated using Working Model software package. Figure 5 illustrates an alternative leg model that typifies the shape of the cylindrical human leg. The model is tested by allowing a trace of the path of the foot joint as illustrated in Figure 6. The figure shows clearly that the generated path is comparable to the desired one illustrated in Figure

1. The accuracy of the path can be further enhanced by increasing the number of precision points during calculations. Figure 7 illustrates another alternative in addition to the corresponding bath. The figure illustrate that the motions of the various portions of the proposed leg typify that of the human leg. To illustrate, notice the motions of the knee and foot joints produced using small motion increments of the upper portion of the leg.

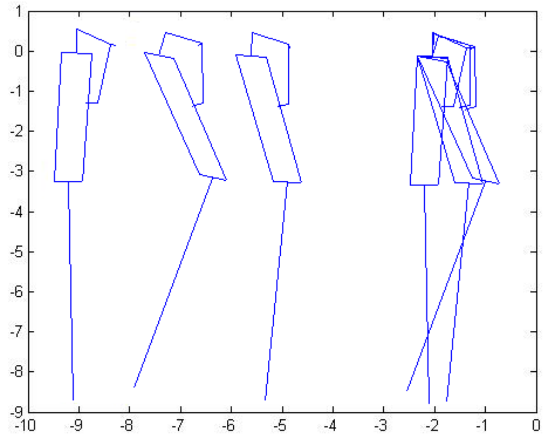

Figure 4: Sample Matlab results of the mechanism.

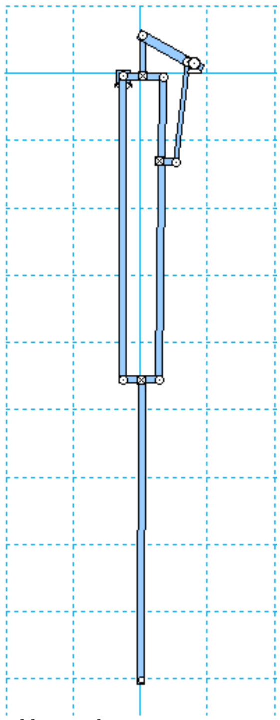

Figure 5: Simulated leg mechanism.

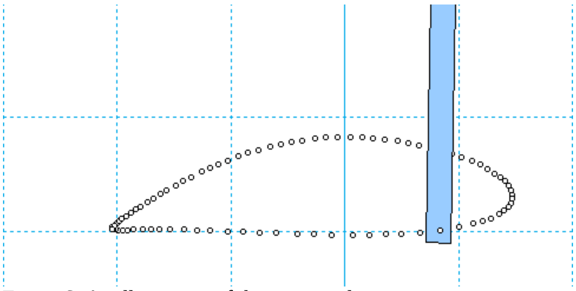

Figure 6: An illustration of the generated gait.

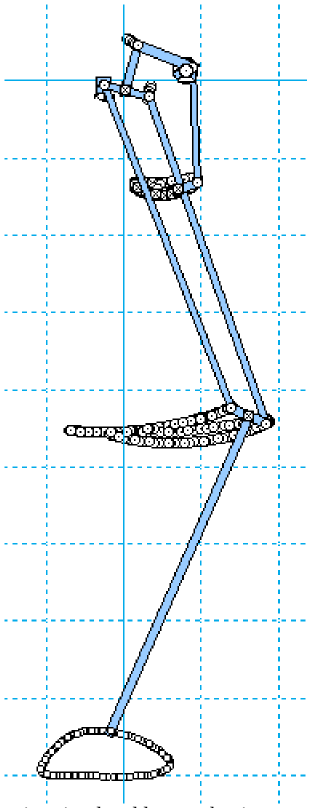

Figure 7: Alternative simulated leg mechanism.

5. Concluding Remarks

The paper presents an eight-bar single DOF path generator that typifies the shape and motion of a human leg. Considered design specifications include the slenderness of the leg and the shape of the walking gait. Moreover, the actuator of the mechanism is located in the upper portion of the linkage similar to it in a human leg. The proposed mechanism is suitable for the fabrication of legged robots. Proportions of the linkage are estimated utilizing anthropometric measures of the human leg. Matlab and Working Model software packages are used to simulate and validate the usability of the mechanism. The proposed mechanism demonstrates that a one DOF closed loop mechanical linkage can be designed to the shape and movement of the biped human walking apparatus.

References

[1] Weber W., Weber E., Mechanics of the human walking apparatus. Springer; 1992.

[2] Al-Araidah O., Analysis and design of two-degree of freedom pantograph type leg mechanism. Masters Thesis, Department of Mechanical Engineering, Eastern Mediterranean University, TRNC, Turkey; 1998.

[3] M. Gracia, A. Chatterjee, A. Ruina, M. Coleman, "The simple walking model: stability, complexity, and scaling". Journal of Biomechanical Engineering, Vol. 120, 1998, 281-288.

[4] V. Vakili, L. Shu, "Toward biomimetic concept generation". Design Theory and Methodology Conference, Pittsburgh, PA, 2001.

[5] W. Batayneh, O. Al-Araidah, C.A. Mattson, A. Ismail-Yahaya, "Design and implementation of human-like biped walking mechanism". 3ed International Conference in Mechatronics, Kuala Lumpur, Malaysia, 2008.

[6] W.B. Shieh, L.W. Tsai, S. Azarm, A.L. Tits, "Multi-objective optimization of a leg mechanism with various spring configurations for force reduction". NSF Technical Research Report, University of Maryland, Harvard University and Industry, 1996.

[7] W.B. Shieh, L.W. Tsai, S. Azarm, "Design and optimization of a one-dof six-bar leg mechanism for a walking machine". Journal of Robotics Systems, Vol. 14, No. 12, 1997, 871-880.

[8] V. Sangwan, A. Taneja, S. Mukherjee, "Design of a robust self-excited biped walking mechanism". Mechanism and Machine Theory, Vol. 39, 2004.

[9] S. Mukherjee, V. Sangwan, A. Taneja, B. Seth, "Stability of an underactuated bipedal gait". Biosystems, Vol. 90, 2007, 582-589.

[10] B. Verrelst, B. Vanderborght, J. Vermeulen, R.V. Ham, J. Naudet, D. Lefeber, "Control architecture for the pneumatically actuated dynamic walking biped “Lucy”". Mechatronics, Vol. 15, 2005

[11] K. Hosoda, T. Takuma, A. Nakamoto, S. Hayashi, "Biped robot design powered by antagonistic pneumatic actuators for multi-modal locomotion". Robotics and Autonomous Systems, Vol. 56, 2008, 46-53.

[12] S.H. Collins, A. Ruina, "A Bipedal walking robot with efficient and human-like gait". IEEE International conference on robotics and automation, Barcelona, Spain, 2005.

[13] Y. Yavin, "Modeling and control of a walking four link robot". Mathematical and Computer Modeling, Vol. 35, 2002.

[14] G. Capi, S. Kaneko, K. Mitobe, L. Barolli, Y. Nasu, "Optimal trajectory generation for a prismatic joint biped robot using genetic algorithms". Robotics and Autonomous Systems, Vol. 38, 2002.

[15] K. Hirai, M. Hirose, Y. Haikawa, T. Takenaka, "The development of Honda humanoid robot". IEEE International Conference on Robotics and Automation, Leuven, Belgium, 1998.

[16] M. Hirose, Y. Haikawa, T. Takenaka, K. Hirai, "Development of humanoid robot ASIMO". IEEE/RSJ International Conference on Intelligent Robots and Systems, Maui, USA, 2001.

[17] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, T. Isozumi, "Humanoid robot HRP-2". IEEE International Conference on Robotics and Automation, New Orleans, USA, 2004.

[18] Y. Kuroki, T. Ishida, J. Yamagushi, M. Fujita, T. Doi, "A small biped entertainment robot". IEEE/RAS International Conference on Humanoid Robots, Piscataway, NY, 2001.

[19] H. Hirukawa, F. Kanehiro, K. Kaneko, S. Kajita, K. Fujiwara, Y. Kawai, F. Tomita, S. Hirai,. K. Tanie, T. Isozumi, K. Akachi, T. Kawasaki, S. Ota, K. Yokoyama, H. Handa, Y. Fukase, J. Maeda, Y. Nakamura, S. Tachi, H. Inoue, "Humanoid robotics platforms developed in HRP". Robotics and Autonomous Systems, Vol. 48, No. 4, 2004.

[20] Y. Hurmuzlu, F. Genot, B. Brogliato, "Modeling stability and control of biped robots-a general framework". Automatica, Vol. 40, 2004, 1647-1664.

[21] P. Mousavi, A. Bagheri, "Mathematical simulation of a seven link biped robot on various surfaces and ZMP consederations". Applied Mathematical Modelling, Vol. 31, 2007, 18-37.

[22] R. Barai, and K. Nonami, "Optimal two-degree-of-freedom fuzzy control for locomotion control of hydraulically actuated hexapod robot". Information Science, Vol. 177, 2007, 1892-1915.

[23] Eastman Kodak Company, Ergonomic Design for People at Work, Volume1, Lifetime Learning Publications, Belmont, CA., 1983.