Design of a 21-DOF Humanoid Robot to Attain Flexibility in Human-Like Motion

Hanafiah Yussof, Mitsuhiro Yamano, Yasuo Nasu, Masahiro Ohka

Abstract—**This paper presents a design of a 21-DOF humanoid robot from the perspective of DOFs and joint angle range characteristic to identify elements that provide flexibility to attain human-like motion. Description and correlation of physical structure flexibility between human and humanoid robot to perform motion is presented to clarify the elements. The investigation is focusing in joint structure design, configuration of DOF and joint rotation range of 21-DOF humanoid robot *Bonten-Maru II*. Experiments utilizing this robot were conducted, with results indicates effective elements to attain flexibility in human-like motion.**

I. Introduction

DEFINING a humanoid robot is a lot like defining what it means to be human. Humanoid robots are fundamentally different from any other robots we have yet seen because they resemble human physical characteristics. Commonly, they are expected to coexist and collaborate with humans in built-for-human environments where human work and live.

It is apparent that to work with humans, humanoid robots must be able to recognize and perform human-like motion. In the past decade, we have seen enthusiastic efforts by robot researchers to develop anthropomorphic humanoid robots, ones that can think intelligently and mimic human action. Many of them have concentrated on bipedal locomotion [1], modeling human learning capabilities [2] and understanding human intelligence [3], while others has focused more on entertainment [4]. One property of humanoid robots that is not often discussed is the definitions of physical structure design of these humanoid robots and how the design factor contributes to the ability of attaining human motion. Certainly, we would like humanoid robots to be more 'humanized' and

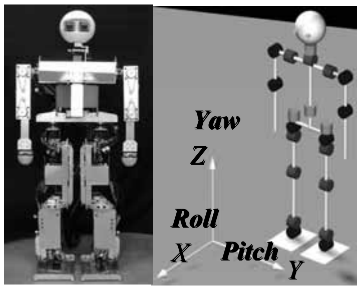

Fig. 1. Humanoid robot *Bonten-Maru II* and configuration of DOFs.

able to achieve high degrees of flexibility and redundancy so that they could mimic human motion in a smooth, safe, and reliable way. Eventually, flexibility in robotic research leads to the manipulability of the robot's manipulators. Manipulability provides a quantitative measure of the closeness of a manipulator to singularity. Manipulability is normally evaluated and defined by indexes or functions, therefore manipulator can move within optimum trajectory without colliding external objects. In this situation, Ming [5] has proposed joint availability function in robot control algorithm to detect the joint limit, while Nakai [6] proposed shape definition evaluation method of the robustness and manipulability in metamorphic robot.

However in this report we focus on the approach to analyze humanoid robots structure design [7], instead of defining manipulability index solutions. We concentrate in the joint structure design to clarify elements that provide flexibility to attain human-like motion, which is related to the aspect of mechanical design. At first, we study human physical flexibilities to clarify elements that produce abilities to perform motion. Then we correlate with humanoid robot flexibility to perform motions and determine the elements in joint structure design needed to attain human-like motion. In this research, we utilized a 21-DOF (Degrees-of-Freedom) humanoid robot named *Bonten-Maru II* in experiments and analysis. Figure 1 shows a photograph of *Bonten-Maru II* and the configuration of its DOFs. Our goal is to lay the foundations in development of humanoid robots with the ability to attain human-like motion.

II. Human and Humanoid Robot Physical Structure

In humanoid robotic research, to perform human-like motion, we must first understand the physical structures of human and ability to carry out motions.

The physical structure of a human is a very complex system of muscles and bones that together comprise what is called the musculoskeletal system. The bones give posture

A part of this study was supported by fiscal 2006 grants from the Ministry of Education, Culture, Sports, Science and Technology (the Japan Scientific Research of Priority Areas 438 "Next-Generation Actuators Leading Breakthroughs" program, No. 16078207).

Hanafiah Yussof is a PhD student at the Department of Complex Systems Science, Faculty of Information Science, Nagoya University, Furo-cho Chikusa-ku Nagoya 464-8601 Japan (phone: +81-52-789-4251; e-mail: hanafiah@nuem.nagoya-u.ac.jp)

Mitsuhiro Yamano is a Research Associate at the Department of Mechanical Systems Engineering, Faculty of Engineering, Yamagata University, Jonan 4-3-16 Yonezawa Yamagata 992-8510 Japan (phone: +81-238-26-3238; e-mail: yamano@yz.yamagata-u.ac.jp)

Yasuo Nasu is a Professor Emeritus at the Faculty of Engineering, Yamagata University, Japan. His address is Rinsenji 2-2-35-2, Yonezawa, 992-0062 Japan (phone: +81-238-22-3044; e-mail: rin_nasu@ybb.ne.jp)

Masahiro Ohka is an Associate Professor at the Department of Complex Systems Engineering, Faculty of Information Science, Nagoya University, Furo-cho Chikusa-ku Nagoya 464-8601 Japan (phone: +81-52-789-486; fax: +81-52-789-4800; e-mail: ohka@is.nagoya-u.ac.jp)

1-4244-0565-3/06/$20.00 ©2006 IEEE.

and structural support for the body and the muscles provide the body with the ability to move (by contracting, thus generating tension). To serve their function, bones must be joined together by something. The point where bones connect to one another is called a joint, and the joints are secured mostly by ligaments (along with the help of muscles). Muscles are attached to bone by tendons. Bones, tendons, and ligaments do not possess the ability (as muscles do) to make the body move: muscles are very unique in this respect.

Meanwhile, a humanoid robot structure fundamentally comprises a set of manipulators designed uniquely to mimic the human physical structure. The manipulators are connected in chain by joints to form a set of bodies, and these bodies are called links. Joints form a connection between a neighboring pair of links. To describe the translation and rotational relationship between adjacent joint links, the Denavit-Hartenberg [8] method for transformation matrices is one of most useful formulations. This method systematically establishes a coordinate system for each link of an articulated chain. The trajectory of the manipulators is normally defined by solving inverse kinematics problems [9], while the manipulator's speed can be defined by employing polynomial equations in interpolation of the manipulator's end-effectors position. The force to rotate each joint is normally supplied by a DC motor that transmits torque to a drive gear at the joints using a belt, chain, or gear.

The above definition shows that joints play an important roll in performing motion for both humans and humanoids. Even for humans, despite the flexibility to perform motions by muscles contraction, the rotation of each joint involved is initially fixed to a certain number of DOFs. Humans have more than a hundreds of DOFs, but in this analysis we only consider the main DOFs at the main joints, as shown in Table I, which presents a comparison of a human's main joints with those of the humanoid robot *Bonten-Maru II*. The joints are described in three rotation axes; roll, pitch, and yaw.

III. 21-DOF Humanoid Robot *Bonten-Maru II*

In this research, we utilized the 1.25-m tall, 32.5-kg research prototype humanoid robot *Bonten-Maru II*. *Bonten-Maru II* was designed to mimic human characteristics as closely as possible, especially in relation to basic physical structure through the design and configuration of joints and links. The robot has a total of 21 DOFs: six for each leg, three for each arm, one for the waist, and two for the head. The high numbers of DOFs provide the *Bonten-Maru II* with the possibility of realizing complex motions. Furthermore, the configuration of joints that closely resemble those of humans provides the advantages for the humanoid robot to attain human-like motion. Each joint is driven by a DC servomotor with a rotary encoder and a harmonic drive-reduction system, and is controlled by a PC with the Linux OS. The motor driver, PC, and power supply are placed outside the robot. *Bonten-Maru II* is equipped with a force sensor in both arms. As for the legs, there are four pressure sensors under each foot: two under the toe area and two under the heel. These provide a good indication that both legs are in contact with the ground. The head part is equipped with two color CCD cameras (542 x 492 pixels).

TABLE 1 COMPARISON OF JOINT DISTRIBUTION IN HUMANS AND THE HUMANOID ROBOT *BONTEN-MARU II*

Joint	Quantity of DOF right/left (rotation axis)	
	Human	Humanoid robot *Bonten-Maru II*
Neck	3 (yaw, pitch, roll)	2 (yaw, pitch)
Right/left shoulder	3/3 (yaw, pitch, roll)	2/2 (pitch, roll)
Right/left elbow	1/1 (roll)	1/1 (roll)
Right/left wrist	3/3 (yaw, pitch, roll)	0/0
Waist	3 (yaw, pitch, roll)	1 (yaw)
Right/left hip	3/3 (yaw, pitch, roll)	3/3 (yaw, pitch, roll)
Right/left knee	1/1 (pitch)	1/1 (pitch)
Right/left ankle	3/3 (yaw, pitch, roll)	2/2 (pitch, roll)

IV. Human Physical Flexibility

Human flexibility is defined by Gummerson [10] as *"the absolute range of movement in a joint or series of joints that is attainable in a momentary effort with the help of a partner or a piece of equipment."* This definition means that flexibility in humans is not something general but is specific to a particular joint or set of joints. For example, rotation of an arm at the yaw rotation axis does not come from a single arm-joint rotation, but a combination of rotation of the shoulder, elbow, and wrist joints and contraction of the arm's muscles. In other words, it is a myth that some people are innately flexible throughout their entire body. Being flexible in one particular area or joint does not necessarily imply being flexible in another. Furthermore, according to Health for Life [11], flexibility in a joint is also *"specific to the action performed at the joint."* Meanwhile, according to Kurz [12], there are three types of flexibility in humans according to the various types of activities involved in athletic training:

- *Dynamic flexibility* - (also called *kinetic flexibility*) is the ability to perform dynamic (or kinetic) movements of the muscles to bring a limb through its full range of motion in the joints. Dynamic flexibility in humans is very subjective. Ability to perform dynamic movement can be improved by engaging in training activities such as dynamic stretching which improves muscle contraction.
- *Static-active flexibility* - (also called *active flexibility*) refers to the ability to assume and maintain extended positions using only the tension of the agonists and synergists while the antagonists are being stretched. For example, lifting the leg and keeping it high without any external support (other than leg muscles).
- *Static-passive flexibility* - (also called *passive flexibility*) is the ability to assume extended positions and then maintain them using only the body's weight, the support of limbs, or some other apparatus such as a chair. Note that the ability to maintain the position does not come solely from human's muscles, as it does with static-active flexibility. Being able to perform the splits is an example of static-passive flexibility.

V. Description of Flexibility in Humanoid Robot

In humanoid robotic field, we may want robots with human form to act like humans, but it is easy to forget that flexibility of the human body is very subjective, whereby the ability to perform certain motions is most likely influenced by a combination of flexible degrees of freedom at the joints with help from muscles contractions. We do not intent to copy the "human design", which is senseless, but rather to clarify effective elements in humanoids mechanical design to correlate with the human flexibility to attain motion.

A. Description and Correlation

We describe humanoid robots flexibility as the absolute range of joint trajectories in a humanoid's manipulator to satisfy certain degree of human-like motion within the joint rotation range by determination of kinematics and dynamics factors. From the description, we clarify correlation with human's flexibility characteristics as followings:

- *Dynamic flexibility* in a humanoid robot means the ability of humanoids manipulator to perform dynamic movement within its allowable angle of joint rotation range to mimic human motion, such as running, climbing stairs and avoiding obstacles. The humanoid's orientation may not remain at the initial orientation and mobility may be observed. For example, as shown in Fig. 2 where humanoid robot performs a fast-walk in broad steps.
- *Static-active flexibility* in a humanoid robot means the ability to remain stable in extended orientations while a part of humanoids body performs a motion without changing the whole body's initial position. For example, as shown in Fig. 3, humanoid robot stretches its arm to grasp an object while other parts of its body remain static.
- *Static-passive flexibility* in a humanoid robot means the ability to maintain extended orientation while waiting for the next motion command. For example in Fig. 4, where the humanoid robot maintains its orientation in the crawling position. For a humanoid robot to remain static, torque supplied to the joints remain in the active condition to hold body weight in an extended static orientation.

B. Torque Evaluation

To attain human-like motion, it is vital to evaluate one particularly important element that is motor torque, especially in regard to static-passive flexibility, where the load applied to the joint is continuous and remains at an extended value for a certain duration of time. Torque can be calculated using (1). Here, F is the applied load of body weight, r is the distance from the center support point, and τ is the torque resulting from the humanoid's body weight.

$$\tau = \sum_{i=1}^{n} r_i F_i \tag{1}$$

For example, to remain static in the orientation depicted in Fig. 5 (a), it is apparent that the humanoid's upper body weight may mostly concentrate at the arms' joints and be distributed evenly at the right and left arms. Here, as shown in Fig. 5 (b), r can be defined by applying parameters values of a (arm's upper-link length), b (arm's lower-link length), and L. As for each arm's trajectory, L is defined from inverse kinematics calculations. From (1), the torque applied to the each arm due to the humanoid's weight is defined in (2).

$$\tau_{right\_arm} = \frac{rF_r}{2}, \quad \tau_{left\_arm} = \frac{rF_l}{2} \tag{2}$$

Meanwhile, the continuous torque is defines in (3) for a humanoid robot with DC servomotors, harmonic drive-reduction systems, and a transmission system comprising belts and pulleys like *Bonten-Maru II*. In this equation, τ_{motor_max} is the maximum torque supplied by a DC servomotor, h is the harmonic drive reduction ratio, $P_{harmonic}$ is the number of pulley gear attached to the harmonic drive, and P_{motor} is number of pulley gears on the motor side. Finally, in this example the torque can be evaluated using (4) and (5).

$$\tau_{cont.} = \frac{\tau_{motor\_max}}{h} \times \frac{p_{harmonic}}{p_{motor}} \tag{3}$$

$$\tau_{right\_arm} \le \tau_{cont.} \tag{4}$$

$$\tau_{left\_arm} \le \tau_{cont.} \tag{5}$$

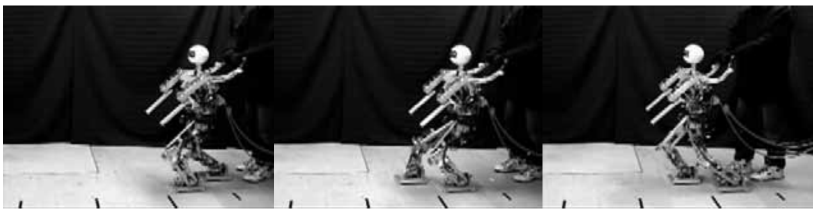

Fig. 2. Example of dynamic flexibility of a humanoid robot: fast-walk while stretching legs widely steps.

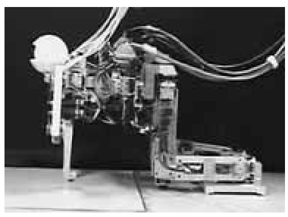

Fig. 4. Example of a humanoid's static-passive flexibility: crawling position.

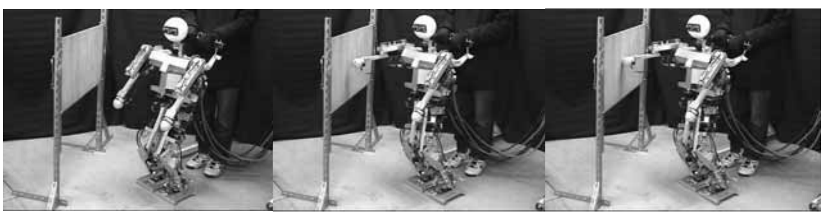

Fig. 3. Example of static-active flexibility of a humanoid robot: grasping.

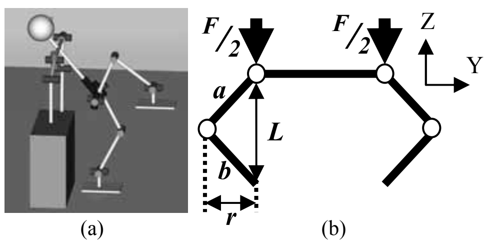

Fig. 5. Torque evaluation diagram at arm joints.

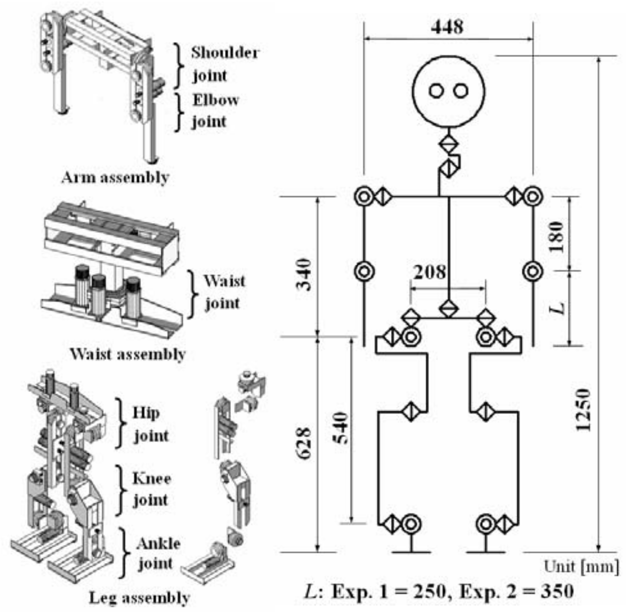

Fig. 6. Physical structure design and configuration of links and joints of the humanoid robot *Bonten-Maru II.*

VI. Joint Structure Design of a 21-DOF Humanoid Robot *Bonten-Maru II*

Human joints are amazing biomechanical structures, whereas humanoid joints are the result of mechanical hardware design. Normally, a humanoid's body structure consists of rigid materials such as aluminum and steel that does not permit the same freedom to move like in human. Furthermore, it is basically impossible to perfectly mimic the functions of human muscles. We are attempting to overcome these handicaps experienced in humanoid robots from the design points of view particularly at the joints structure and configuration of DOF to improve the flexibility of humanoids' bodies to attain human-like motion.

Figure 6 shows body structural design and configuration of links and joints, while Fig. 7 shows joint structure at the leg and arm of the humanoid robot *Bonten-Maru II*. Refering to these figures, to minimize the gap between human and humanoid structure flexibility, the joint structure, rotation range, and configuration of DOF have been designed uniquely to provide a wider rotation range to compensate for the functions performed by muscles in humans. For example, the ankle joint structure was designed to rotate in a wider angular range than humans'. Another example is at the legs where the hip-joint pitch, knee-joint pitch and ankle-joint pitch are designed to sequentially connected each other that permits to move more flexible in relatively wider angular range to forward and backward direction. The same design approach is also performed at the shoulder-joint roll and elbow-joint roll that permits the arms to move more flexible to cover wider trajectory area.

We have also designed the configuration of joints and links so that it can provide more space for the manipulators to move, which in addition minimizes possibility of collision between humanoid body parts. Especially at the hip joints which play an important role in humanoid's motion, the roll joint is placed at the rear side and is connected with L-shaped frame to the pitch joint at inner side, as shown in Fig. 6. These design considerations provide more space for the knee joint and the shin links that are connected to the ankle joint structure, which in turn reserves space at the foot in each leg. Note that the collision problem usually occurs at the feet when they step on each other during locomotion. This structure also can improve the strength of the manipulator's structure and reduce flexure problems.

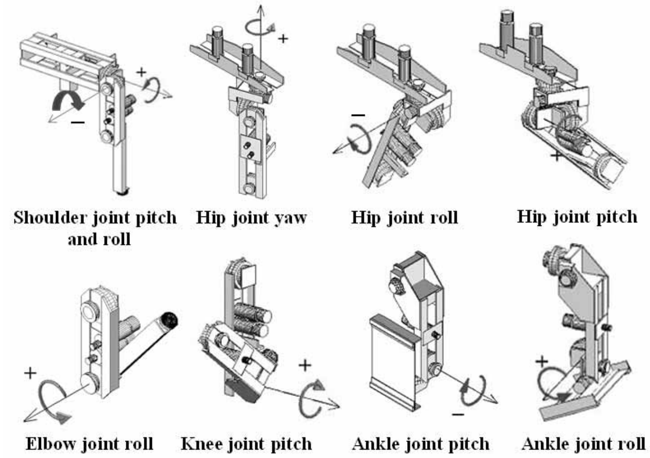

Fig. 7. Arm and leg joint structure of humanoid robot *Bonten-Maru II.*

TABLE II JOINT ROTATION RANGE

Axis	*Bonten-Maru II* (deg)	Human (deg)
Neck (roll and pitch)	-90 ~ 90	-90 ~ 90
Shoulder (pitch) right & left	-180 ~ 120	-180 ~ 120
Shoulder (roll) right/left	-135 ~ 30/-30 ~ 135	-135 ~ 30/-30 ~ 135
Elbow (roll) right/left	0 ~ 135/0 ~ -135	0 ~ 135/0 ~ -135
Waist (yaw)	-90 ~ 90	-45 ~ 45
Hip (yaw) right/left	-90 ~ 60/-60 ~ 90	-90 ~ 60/-60 ~ 90
Hip (roll) right/left	-90 ~ 22/-22 ~ 90	-60 ~ 45/-45 ~ 60
Hip (pitch) right & left	-130 ~ 45	-130 ~ 45
Knee (pitch) right & left	-20 ~150	0 ~150
Ankle (pitch) right & left	-90 ~ 60	-30 ~ 90
Ankle (roll) right/left	-20 ~ 90/-90 ~ 20	-20 ~ 30/-30 ~ 20

VII. Consideration of Joint Rotation Angle

In humanoid robot design, joint rotation angle are decided from consideration of elements such as correlation with human joint rotation angles, position of body parts, and body structure design. These elements lead to mobility and flexibility of humanoids' manipulators to attain trajectory, as well as to avoid collision problems.

The humanoid robot *Bonten-Maru II* presented in this research consists of 21-DOF, and the configuration of the DOF is to repeat human characteristic. Figure 7 in previous section illustrates the structure and direction of rotation for the arms and leg joint. The humanoid robot rotation angle specifications in this research are shown in Table II. We estimate human's joint rotation angle, as indicated in this table, approximately. The human joints angle was measured

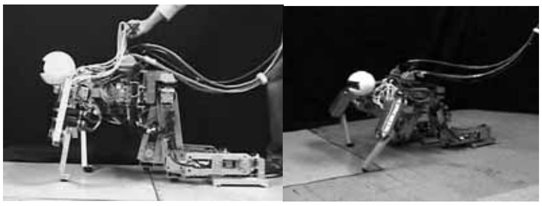

Fig. 8. *Bonten-Maru II* crawling along the floor.

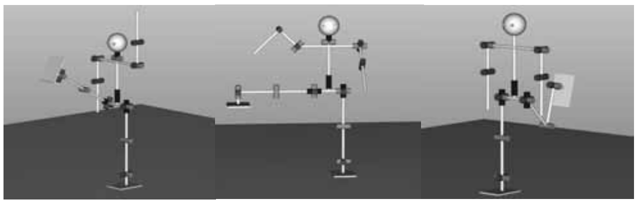

Fig. 9. Animation of motions in the 21-DOF humanoid robot *Bonten-Maru II*.

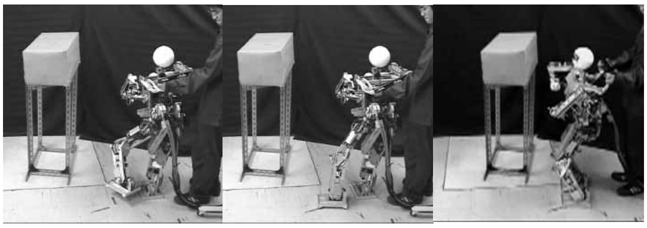

Fig. 10. Sequential photograph of humanoid robot motion in *Experiment 1*.

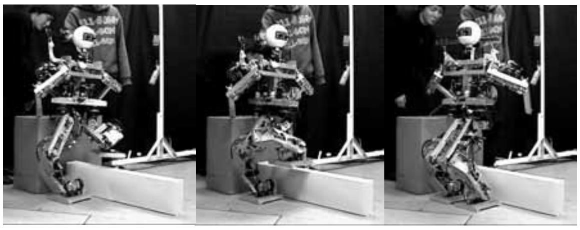

Fig. 11. Sequential photograph of humanoid robot motion in *Experiment 2*.

geometrically on a normal human subject in *static-active flexibility* without any external support or apparatus. The rotation angle of human joints are approximate because the range of human joints is difficult to measure accurately due to range of one joint depends on the angle of the other joints. Note that the direction of rotation follows the right-hand law.

Joint rotation angle in *Bonten-Maru II* was designed to provide manipulability and flexibility to perform human-like motions, in addition to provide safety for the humanoid robot during locomotion. For example, the yaw component of the hip joint of both legs is rotated open wide until 90 degrees in the outer rotation direction and 60 degrees in the inner direction. Also for hip-joint-roll, the angle is 90 degrees in the outer rotation direction and only 22 degrees in the inner rotation. These angles provide an advantage to the humanoid robot in attaining difficult motion, as well protecting body parts from colliding with each other.

For ankle joints (pitch and roll), the joint rotation range is designed to be wider than humans' in the outer rotation direction for the pitch and in the inner direction for roll (refer Table II). The purpose is to compensate for the flexibility of shin muscles and the functions of toe joints in humans that not available in a humanoid's body structure. This is useful for performing difficult motion such as crawling [13], as shown in Fig. 8, which can be applied in hazardous location. Thus, based on the rotation angle and the configuration of DOF, the 21-DOF *Bonten-Maru II* can perform flexible motion like that shown in Fig. 9.

VIII. Experiment with a 21-DOF Humanoid Robot

Experiments were conducted to evaluate the performance of physical structure design in 21-DOF humanoid robot *Bonten-Maru II* to attain human-like motion. In this experiment, we at first create an algorithm within the *Bonten-Maru II's* control system and then design a motion planning to produce satisfactory human like movement. The motion planning covers joint trajectory of almost every joint in the humanoid's body. The trajectories are designed so that the joints can rotate through the maximum possible range. The joint rotation range is initially fixed, as presented in Table II, where each joint features a relatively wide range of rotation angles. From experimental result, we analyze the joints rotation characteristic to determine adaptive elements involved in performing human-like motion.

- *Experiment 1*- The humanoid changes its orientation to the back-left position by rotating its left hip joints, like in marching. The sequential motions are shown in Fig. 10. This experiment deals mostly with joints in the lower part of the humanoid's body, especially the left leg. This basic movement is useful, for example, when avoiding obstacles [14] and during operating in confined spaces.
- *Experiment 2*- The humanoid steps over an object with the help of its arms. This motion occupies almost all joints in the upper and lower sections of the body. Both arms support the robot's body weight to provide balance, while one leg supports the stepping motion. Figure 11 shows a sequence image captured during this experiment. This movement should eventually lead to the ability to hop over an object [15] and also avoid obstacles.

IX. Experiment Result and Discussion

The joint rotation angles of *Bonten-Maru II*'s arms and legs in *Experiments 1* and *2* are compiled and presented in Figs. 12 and 13, respectively. Joint angle data of the neck joint and waist joint are not presented because these joints' rotation angles are predictable and fixed at extended values. From the graphs presented, we can explain the joint rotation characteristic as follows:

- Hip-joint yaw always starts and ends at its origin. This explains why the hip joint yaw controls leg's rotation around the *Z*-axis to determine the leg orientation and guide body orientation.
- Hip-joint roll and pitch, and knee-joint pitch show variations that explain the control pattern of the leg's trajectory to define the legs' positions.
- Ankle-joint roll and pitch rotation are related to legs position to decide the leg's end-point orientation.
- Arm joints at the shoulder and elbow show smooth and controlled trajectories which describe the ability of the 3-DOF arm to attain the desired motion in the *X*-*Y*-*Z* axes.

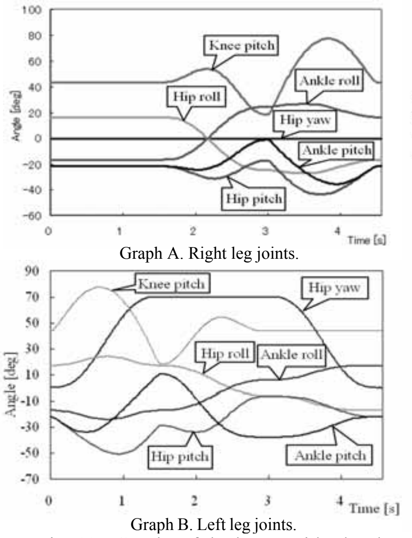

Fig. 12. Graphs of the humanoid robot legs joint rotation angle in *Experiment 1*.

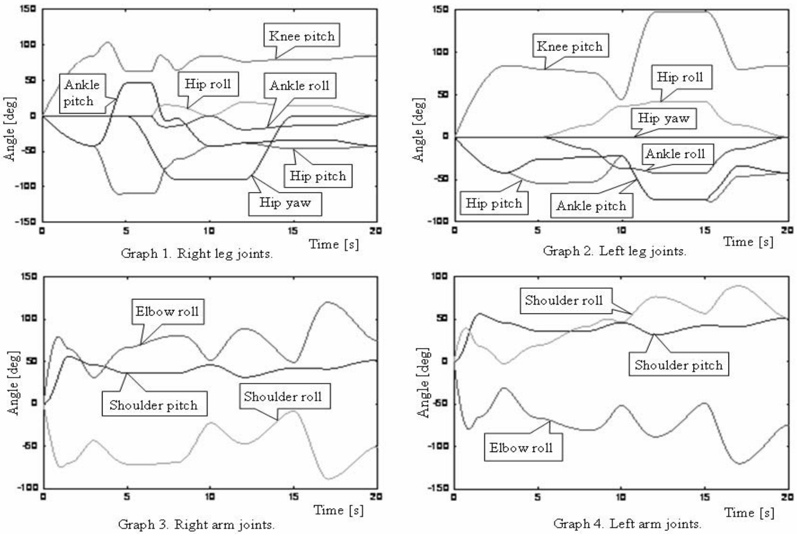

Fig. 13. Graphs of the humanoid robot legs and arms joint rotation angle in *Experiment 2*.

These characteristics guided us to perception that a humanoid robot leg should have at least six DOFs so that it can attain a trajectory similar to that of a human. Meanwhile, for the arms, a 3-DOF humanoid robot arm is the minimum requirement to attain the desired human-like motion at *X-Y-Z* axes space. Note that we can have a humanoid robot with more DOFs, but this will certainly increase body weight and lead to difficulties in system control and stability.

The result of joint rotation angles shows controlled trajectories at each joint which relatively rotates within the limit of joint rotation range, as indicate in Table II, to satisfy the experiment purpose of attaining human-like motion. The results also indicate some joints like the hip yaw, knee pitch and ankle pitch rotate closely to the maximum limit of the rotation range (refer to Fig. 13 on leg joints). The observation result in these experiments shows a smooth and controlled trajectory of the robot's manipulator to attain desired motion.

X. Conclusion

It is clear that it is practically impossible to mimic the mechanical complexity of the human skeleton. In this report, we clarified effective elements in a 21-DOF humanoid robot from the perspective of DOFs and joint structure design to correlate with the human flexibility to attain motion. The analysis result of joint structure design and joint rotation range demonstrates that to achieve flexible movement in the 6-DOF humanoid legs, it is not necessary to always replicate a human's joint structure and rotation range. This is because suitable design of joint structure and joints rotation range can compensate for the functions of human leg muscles and joints, as proven with *Bonten-Maru II*'s ankle-joint design structure. The experimental results of humanoid robot *Bonten-Maru II* indicate that the joints structure design and configurations of DOF in the *Bonten-Maru II* do provide the effective elements to generate the ability to attain human-like motion.

This report proposed some foundations for further research and development of humanoid robots towards the goal of human-like motion. In addition, the proposed idea should contribute to better understanding of the correlation between humans and humanoid robots. In future, we are going to consider human's motion trajectories in our investigation.

References

[1] H. Lim, Y.Yamamoto and A. Takanishi, "Control to realize human-like walking of a biped humanoid robot," in *Proc. IEEE Int. Conf. System, Man and Cybernetics*, vol. 5, 2000, pp. 3271-3276.

[2] R. Dillmann, "Teaching and learning of robot tasks via observation of human performance," *Robotics and Autonomous Systems J.*, vol. 47, issues 2-3, 2004, pp. 109-116.

[3] T. Salter, K. Dautenhahn and R. de Boekhorst, "Learning about natural human-robot interaction styles," *Robotics and Autonomous Systems J.*, vol.52, issue 2, pp.127-134.

[4] M. Fujita and K. Kageyama, "An open architecture for robot entertainment," in *Proc. 1st Int. Conf. Autonomous Agents (ACM Press.)*, 1997, pp. 435-442.

[5] J. T. Ming and H. C. Yee, "Manipulability of manipulators," *Mech. Mach. Theory J.*, vol. 25, no. 5, 1990, pp. 575-585.

[6] H. Nakai, M. Inaba and H. Inoue, "Shape definition of metamorphic robot by evaluation of the robustness and the manipulability," in *seminar of the 20th anniversary of the RSJ establishment*, 3H22, 2002. Available at: http://www.jsk.t.u-tokyo.ac.jp/bib/bibj02.html

[7] M. Vukobratovic, B. Borovac and K. Babkovic, "Contribution to the study of Anthropomorphism of Humanoid Robots," *Humanoids Robotics J.*, Vol. 2, No.3, 2005, pp. 361-387.

[8] J. Denavit and S. Hartenberg, "A kinematic notation for lower-pair mechanisms based upon matrices," *Applied Mechanics J.*, Vol. 77, 1955, pp. 215-221.

[9] Y. Hanafiah, M. Yamano, Y. Nasu and M. Ohka, "Trajectory generation in groping locomotion of a 21-DOF humanoid robot," in *CDR Proc. 9th Int. Conf. on Mechatronics Tech.*, 2005, ICMT-54.

[10] T. Gummerson, *Mobility Training for the Martial Arts*. A&C Black, 1990, pp. 96.

[11] Health for Life. *SynerStretch for total body flexibility*. Available at: http://www.healthforlife.com/

[12] T. Kurz, *Stretching Scientifically: A Guide to Flexibility Training*, Stadion Publishing Inc., 4th ed., 2003.

[13] M. Yamano, Y. Nasu , S. Kaneko, R. Sato and K. Mitobe, "Creeping motion of a humanoid robot on its hands and knees," in *CD-R Proc. FIRA Robot World Congress 2003*, 2003.

[14] Y. Hanafiah, M. Yamano, Y. Nasu, K. Mitobe and M. Ohka, "Obstacle avoidance in groping locomotion of a humanoid robot," *Advanced Robotic Systems J.*, vol.2 no. 3, 2005, pp. 251-258.

[15] M. Yamano, Y. Nasu, R. Sato and K. Mitobe, "Motion planning of a biped humanoid robot that steps over an obstacle using its hands," in *CD-R Proc. 9th Int. Conf. on Mechatronics Tech.*, 2005, ICMT-151.