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Analysis of Flexibility in Humanoid Robot Structure Design to Attain Human-Like Motions

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ABSTRACT

This paper presents analyses of flexibility in humanoid robot structure design focusing on design parameters of degree of freedoms and joint angle range characteristic to identify elements that provide flexibility for humanoid robots 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. This analysis utilized the joint structure design, configuration of degree of freedoms and joint rotation range of a 21-dof

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humanoid robot Bonten-Maru II. Experiments utilizing this robot were conducted, with results indicates effective design parameters to attain flexibility in human-like motion.

Keyword: *Humanoid robot, flexibility, joint structure design, human-like motions, degree of freedoms*

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 yet to be 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. In the past decade, enthusiastic efforts were demonstrated 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 [5]. Certainly, humanoid robots are expected to be more 'humanized' and able to achieve high degrees of flexibility and redundancy so that they could mimic human motion in a smooth, safe, and reliable way.

In this research, a 21-dof humanoid robot *Bonten-Maru II* is analyzed to define effective flexibility elements in the robot structure design. The purpose is to verify performance of *Bonten-Maru II* to attain difficult motion during real-time application in built-for-human environments and emergency sites such yawing motions, avoiding obstacle, crawling, etc. The outcome of this research is expected to provide guidelines for future humanoid robot design so that it can perform human-like tasks and work along humans effectively.

It is apparent that to perform motions in real environment, humanoid robots must be able to recognize and perform human-like motion [6]. Therefore, analysis using our humanoid robot *Bonten-Maru II* is conducted to clarify elements that provide flexibility to attain human-like motions. 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 [7] has proposed joint availability function in robot control algorithm to detect the joint limit, while Nakai [8] proposed shape definition evaluation method of the robustness and manipulability in metamorphic robot.

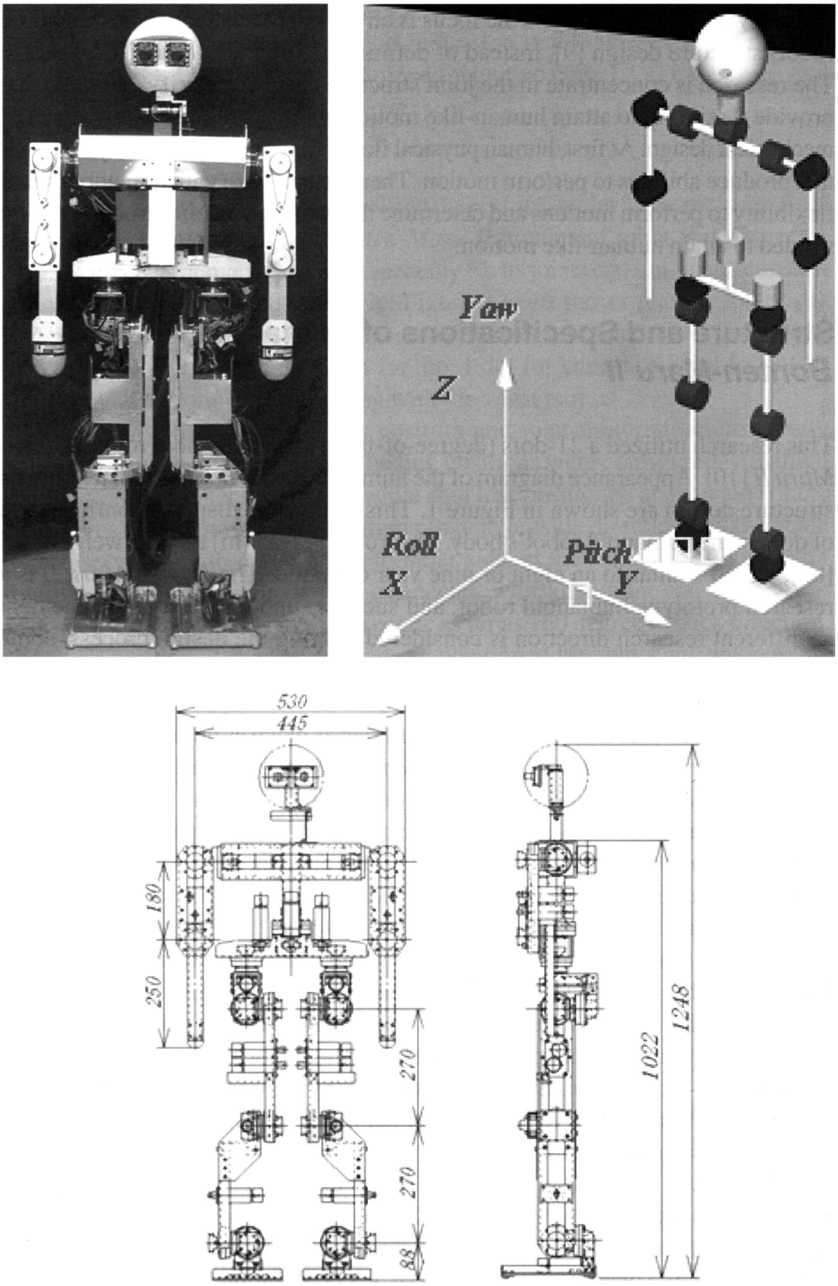


Figure 1: Humanoid Robot *Bonten-Maru II*; Distributions of Dof and Structure Design

However in this analysis the focus is on the approach to analyze humanoid robots structure design [9], instead of defining manipulability index solutions. The research is 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, human physical flexibilities is study 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.

Structure and Specifications of Humanoid Robot *Bonten-Maru II*

This research utilized a 21-dofs (degree-of-freedoms) humanoid robot *Bonten-Maru II* [10]. Appearance diagram of the humanoid robot *Bonten-Maru II* and its structure design are shown in Figure 1. This figure also displays configuration of dofs in the humanoid robot's body. This robot is 1.25 [m] tall and weight 31.5 [kg], which similar to an eight or nine year old child. The *Bonten-Maru II* is a research prototype humanoid robot, and such has undergone some refinement as different research direction is considered. During the design process, some predefined degree of stiffness, accuracy, repeatability, and other design factor have been taken into consideration.

The *Bonten-Maru II* was designed to mimic as much as human characteristic, especially for contribution of its joints. *Bonten-Maru II* is consists of total of 21-dofs: six for each leg, three for each arm, one for the waist, and two for the head. Each joint feature a relatively wide range of rotation angles, particularly for the hip yaw of both legs, which permits the legs to rotate through wide angles when correcting the robot's orientation and avoiding obstacles. The specification of each joint rotation range is considered factors such as correlation with human's joint rotation range, manipulability of humanoid's manipulator and safety of the humanoid robot motion [10]. The high numbers of dofs provide the ability to realize 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. Every joint is driven by DC servomotor with a rotary encoder and harmonic drive reduction system, and PC with Linux is utilized for control. The sampling frequency is 200 Hz.

The power is supplied to each joint by timing belt and harmonic drive reduction system. Gear number at the DC servomotor side is 60; while at the harmonic drive side is 16. Therefore, it makes reduction ratio at the harmonic side to be 1:100, while overall reduction ratio is 1:333. Rotation angles of joints were recorded by the rotary encoder that installed at rear side of DC servomotor. The motor driver, the PC and the power supply are placed outside of 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.

Leg Structure

The basic idea of legged robot is the ability to perform wider and variety range of human-like gait motions. The *Bonten-Maru II* humanoid robot is designed to mimic as much as human structure, especially for its joints and links configuration to have wide range of rotation angle. Figure 2 (*top*) shows photograph of the *Bonten-Maru II* lower side body consists of two legs, hip and waist joint parts. Each leg is consists of 6-dofs: 3 dof for hip, 1 dof for knee, and 2 dof for ankle. Hip-joint yaw is connecting each leg with the waist part.

Eventually, the design of link position and joint-motor structure greatly influence the joint rotation range. The link positions were configured with thigh link positioned at inner side of leg, while shin link positioned at outer side of the leg. It gives the hip joints wide rotation range to outside direction and the ankle joints also possible to rotate wider to inner side, at the same time gives better stability. Both of these links were connected with knee joint and were given specific space so that knee joint can rotate as far as 160 degree to back direction.

Configuration of the harmonic drive position at hip joints and ankle joints were installed at the rear side of roll direction so that the leg's link can swing to front direction in wide rotation angle. Moreover, both thigh links were given specific space so that when hip joint rotates to yawing direction, both links do not collide to each other. Consequently, rotation of hip joint at yaw direction can reach until 90 degree. In this research, a wide rotation angle range of yaw direction is required so that the robot can easily change its direction in wider angle, particularly during avoiding obstacles and operation in confined spaces. Configuration of links, joints and harmonic drive at the *Bonten-Maru II* lower side body were shown at Figure 2 (*top*).

Arm Structure

The arm consists of three joints; two joints for pitch and roll direction at shoulder and one joint for roll direction at elbow. The arms were designed to accomplish such motion at *xyz*-axes direction with a wide rotation angle. Reference coordinates for arms is fixed at center point of shoulder joints pitch and roll. Axis direction is following right hand method, where *x*-axis direction is heading to front, *y*-axis direction to left, and *z*-axis is to upper directions of the robot's body. Figure 2 (*bottom*) shows *Bonten-Maru II* upper side body and configuration of arm links and joints.

In order to allow for better maneuvering of a humanoid robot arm toward application in a real environment, rotations of shoulder and elbow joints at roll

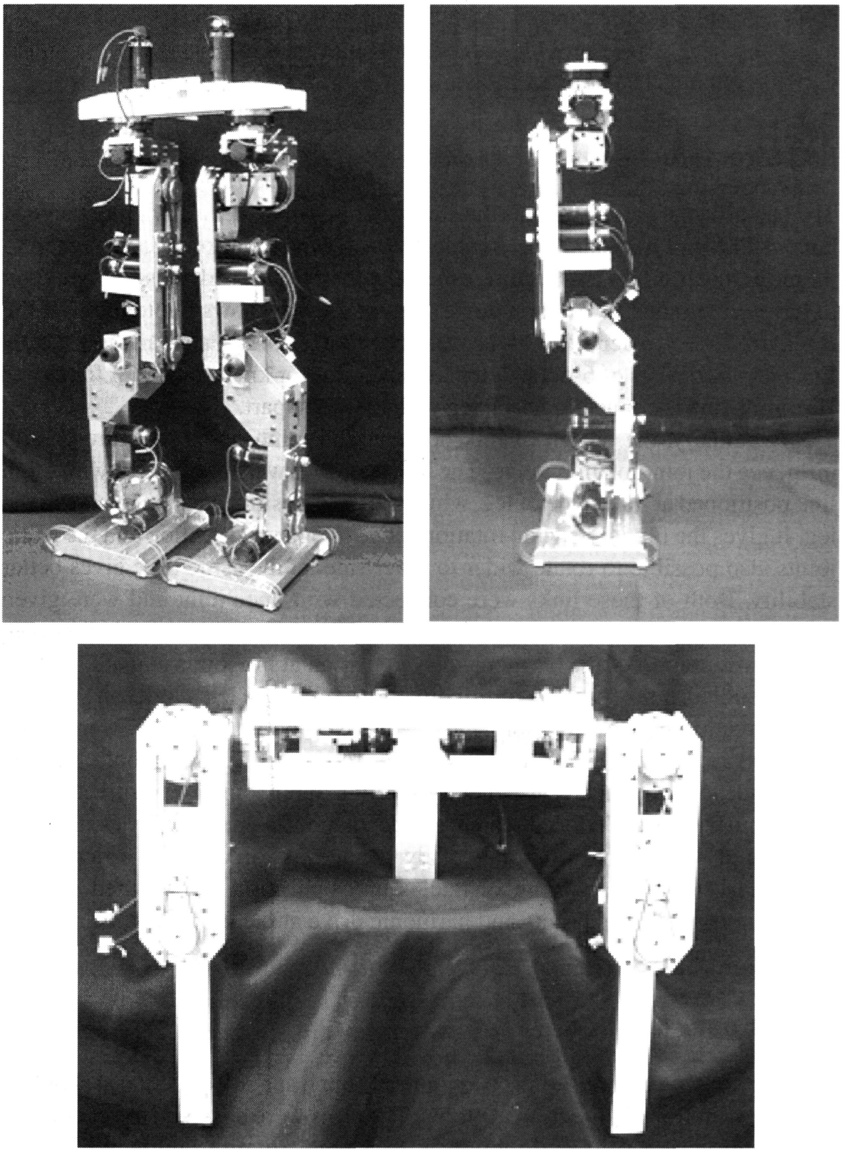


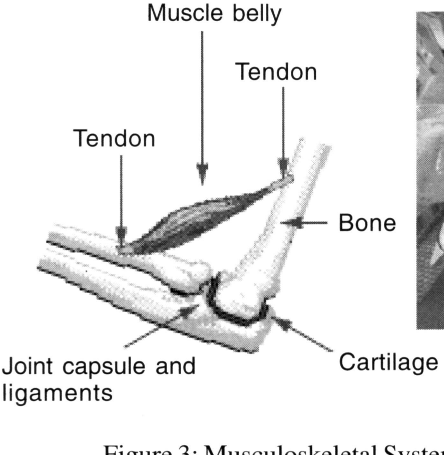
Figure 2: Humanoid Robot *Bonten-Maru II* Lower Side Body (*top*) and Upper Side Body (*bottom*)

angle direction are important. The shoulder joint pitch angle was rotated and remained at minus 90 degree. The link lengths of upper arm and lower arm are used as parameters for kinematical calculation and trajectory control. A six-axis force sensor is installed at each arm as end-effector for force control. In the robot controller, motion of arms can be classified in two patterns. First is the motion where rotation is centered at elbow joint. Second is the motion where rotation is centered at shoulder joint.

Comparison of Human and Humanoid Robot Physical Structure

In humanoid robotic research to perform human-like motion, it is necessary to understand the physical structures of human and the 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, as shown in Figure 3 (*left*). The bones give posture 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, as shown in Figure 3 (*right*). Joints form a connection between a neighboring pair of links. To describe the translation and rotational relationship between adjacent joint links, the Denavit-Hartenberg method [11] for



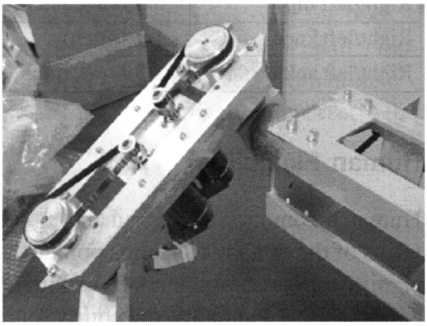


Figure 3: Musculoskeletal System in Human (*left*). Joint-link Structure in Humanoid Robot (*right*)

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 [12], 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 servomotor 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 1, 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.

Table 1: Comparison of Joint Distribution in Human and Humanoid Robot *Bonten-Maru II*

Joint	Quantity of dof right/left (rotation axis)	
	Human (Estimation of main dof only)	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)

Human Flexibility

Human locomotion stands out among other forms of biped locomotion chiefly in terms of the dynamic systems point of view. This is due to the fact that during a significant part of the human walking motion, the moving body is not in static equilibrium. Eventually, the ability for humans to perform dynamic and flexible motions is greatly influenced by their learning ability [3]. Apparently humans cannot walk when they are born but they can walk without thinking that they are walking as the years pass by. However, robots are not good at learning. They are what they are programmed to do. In order to perform reliable biped locomotion in robots, we must at first identify the desired human-like motion, and then develop locomotion strategy of the desired motion base on motion planning and control with correct joint trajectories synthesis on the articulated manipulators.

Human flexibility is defined by Gummerson [13] 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 [14], flexibility in a joint is also "*specific to the action performed at the joint.*" Meanwhile, according to Kurz [15], 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.

Description of Flexibility in Humanoid Robot

In humanoid robotic field, robots with human form are required 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.

In this research, humanoid robots flexibility is describe 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, correlation with human's flexibility characteristics is clarified 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 Figure 4 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 Figure 5, 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

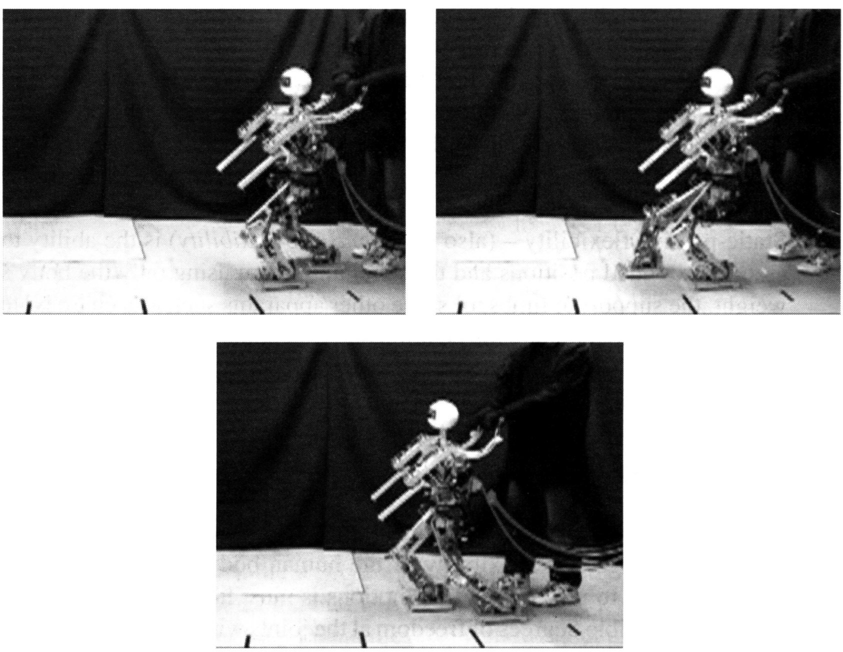


Figure 4: Example of Dynamic Flexibility of a Humanoid Robot: Fast-walk with Broad Steps

in Figure 6, 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 active condition to hold body weight in an extended static orientation.

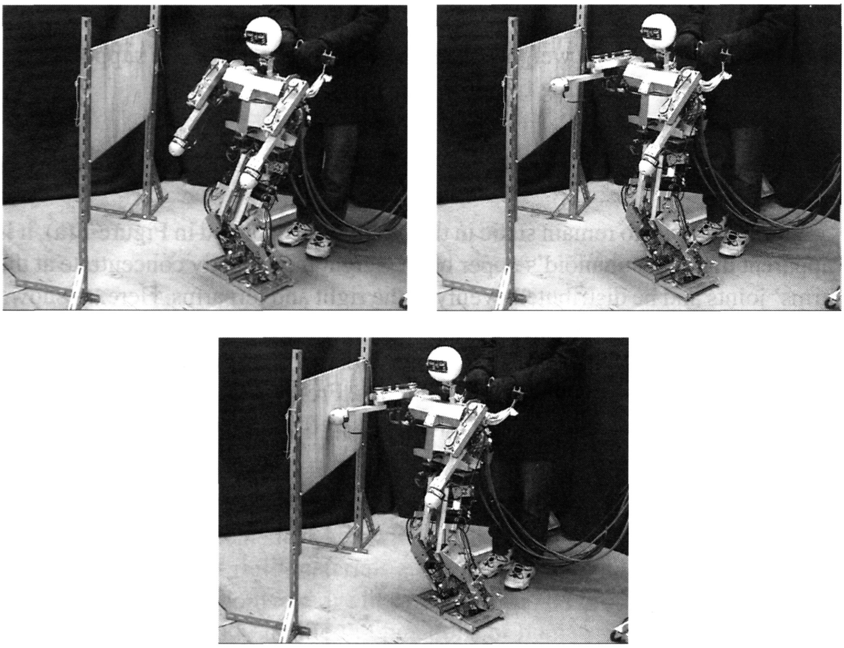


Figure 5: Example of Static-active Flexibility of a Humanoid Robot: Grasping

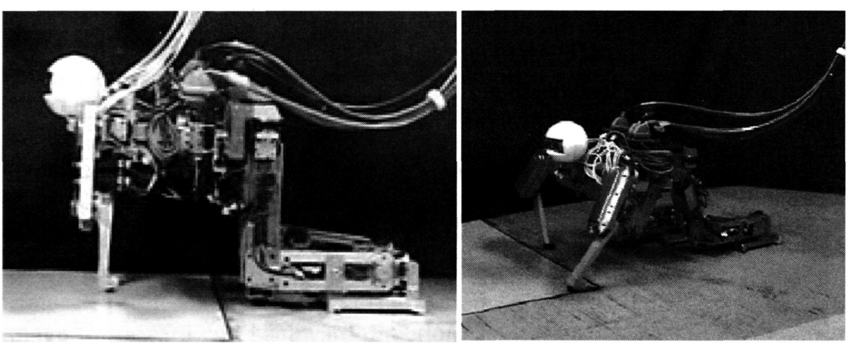


Figure 6: Example of a Humanoid's Static-passive Flexibility: Crawl Position

Torque Evaluation

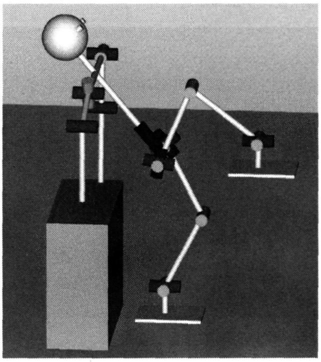
To attain human-like motion, it is vital to evaluate one particularly important element that is motor torque [16], especially in regard to static-passive flexibility, where the load applied to the joint is continuous and remains at an extended value for a certain duration of time. Torque can be calculated 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.

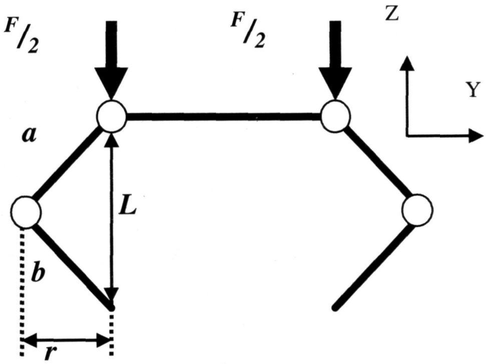
$$\tau = \sum_{i=1}^{n} r_i F_i \tag{7.1}$$

For example, to remain static in the orientation depicted in Figure 7 (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 Figure 7 (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 (7.1), the torque applied to the each arm due to the humanoid's weight is defined in equations (2) for right arm, and (3) for left arm.

$$\tau_{right\_arm} = \frac{rF_r}{2} \tag{7.2}$$

$$\tau_{left\_arm} = \frac{rF_l}{2} \tag{7.3}$$


(a)



(b)

Figure 7: Torque Evaluation Diagram at Arm

Meanwhile, the continuous torque is defines in (4) 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 the number of pulley gears on the motor side. Finally, in this example the torque can be evaluated using equations (5) for right arm, and (6) for left arm.

$$\tau_{cont.} = \frac{\tau_{motor\_max}}{h} \times \frac{p_{harmonic}}{p_{motor}} . \tag{7.4}$$

$$\tau_{right\_arm} \leq \tau_{cont.} \tag{7.5}$$

$$\tau_{left\_arm} \leq \tau_{cont.} \tag{7.6}$$

Joint Structure Design

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 [17]. Furthermore, it is basically impossible to perfectly mimic the functions of human muscles. This research 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 8 shows body structural design and configuration of links and joints, while Figure 9 shows joint structure at the leg and arm of the humanoid robot *Bonten-Maru II.* Referring 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.

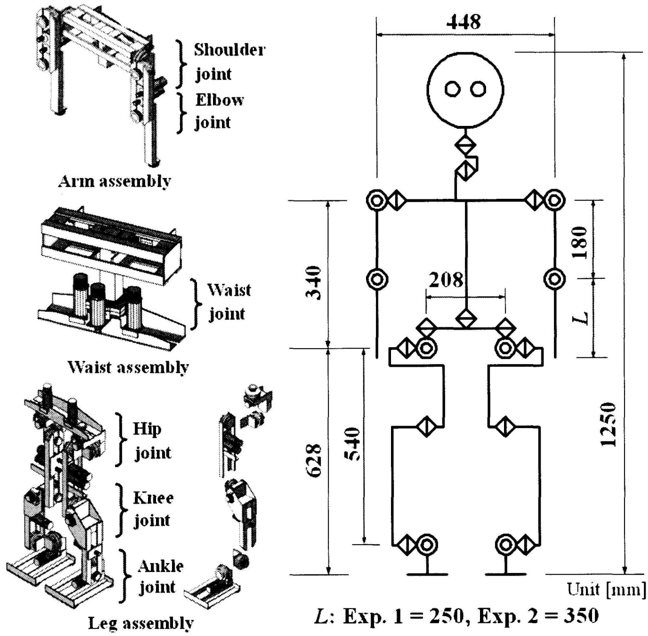


Figure 8: Physical Structure Design and Configuration of Links and Joints of the Humanoid Robot *Bonten-Maru II*

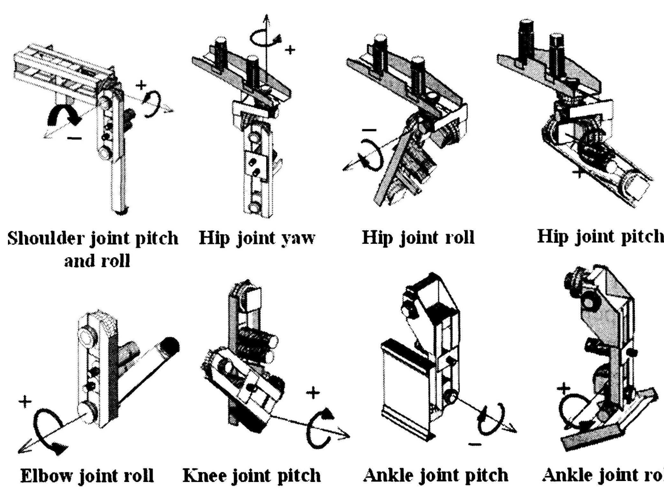


Figure 9: Arm and Leg Joint Structure of Humanoid Robot *Bonten-Maru II*

In humanoid robot *Bonten-Maru II*, the configuration of joints and links was designed 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 Figure 8. 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.

Consideration of Joint Rotation Angle

In humanoid robot design, joint rotation angle is 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. According to Kurz [15], the normal ranges of joint motion for various parts of human robot body are shown in Table 2.

The humanoid robot *Bonten-Maru II* presented in this research consists of 21-dofs, and the configuration of the dof is to repeat human characteristic. Figure 9 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 3. We estimate human's joint rotation angle according to description by Kurz as indicated in Table 2, and we approximately estimate it in conjunction with joint rotation axis is the robot body.

In Table 3, the human joints angle was measured geometrically on a normal human subject in *static-active flexibility* without any external support or apparatus. The rotation angles of human joints are approximate because the range of human joints is difficult to measure accurately due to range of one joint is depends on the angle of the other joints. 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.

Table 2: Joint Rotation Range in Human According to Kurz

Body part	Joint motion	Rotation range (deg)	Motion condition
Neck	Flexion	70-90	Touch sternum with chin
	Extension	55	Try to point up with chin
	Lateral bending	35	Bring ear close to shoulder
Lumbar spine	Flexion	75	Bend forward at the waist
	Extension	30	Bend backward
	Lateral bending	35	Bend to side
Shoulder	Abduction	180	Bring arm up sideways
	Abduction	45	Bring arm toward the midline of the body
	Horizontal extension	45	Swing arm horizontally backward
	Horizontal flexion	130	Swing arm horizontally forward
	Vertical extension	60	Raise arm straight backward
	Vertical flexion	180	Raise arm straight forward
	Flexion	150	Bring lower arm to the biceps
	Extension	180	Straighten out lower arm
	Supination	90	Turn lower arm so palm of hand faces up
	Pronation	90	Turn lower arm so palm faces down
Wrist	Flexion	80-90	Bend wrist so palm nears lower arm
	Extension	70	Bend wrist in opposite direction
	Radial deviation	20	Bend wrist so thumb nears radius
	Ulnar deviation	30-50	Bend wrist so pinky finger nears ulna
Hip	Flexion	110-130	Flex knee and bring thigh close to abdomen
	Extension	30	Move thigh backward without moving the pelvis
	Abduction	45-50	Swing thigh away from midline
	Abduction	20-30	Bring thigh toward and across midline

(*continued*)

Table 2 (*continued*)

Body part	Joint motion	Rotation range (deg)	Motion condition
	Internal rotation	40	Flex knee and swing lower leg away from midline
	External rotation	45	Flex knee and swing lower leg toward midline
Knee	Flexion	130	Touch calf to hamstring
	Extension	15	Straighten out knee as much as possible
	Internal rotation	10	Twist lower leg toward midline

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 3). The purpose is to compensate for the flexibility of shin muscles and the functions of toe joints in humans that are not available in a humanoid's body structure. This is useful for performing difficult motion such as crawling [18], as shown in Figure 6, which can be applied in hazardous location. Thus, based on the rotation angle and the configuration of dof, the 21-dofs *Bonten-Maru II* can perform flexible motion like that shown in Figure 10.

Table 3: Joint Rotation Range in *Bonten-Maru II* and Estimated Joint Rotation Range in Human

Axis	*Bonten-Maru II* (deg)	Human (deg) **estimated*
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

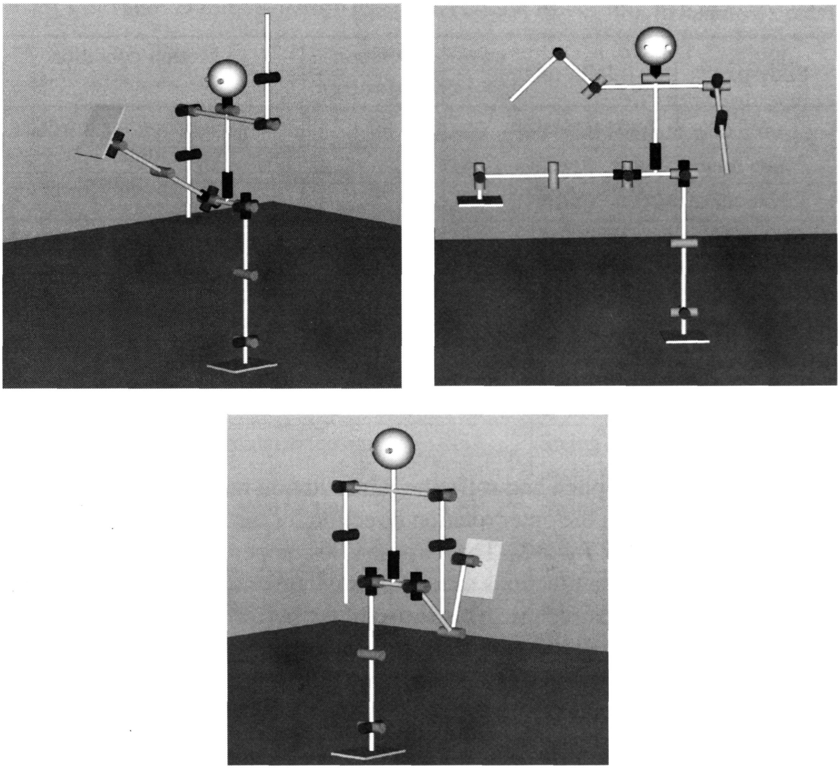


Figure 10: Animation of Flexible Motions in the 21-dof Humanoid Robot *Bonten-Maru II*

Experiments of Human-Like Motion

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, an algorithm and motion planning were created within the *Bonten-Maru II's* control system to produce satisfactory human like movements. 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 3, where each joint features a relatively wide range of rotation angles. From experimental result, we analyze the joints rotation characteristic to determine elements involved in performing human-like motion.

Experiment 1: The humanoid robot changes its orientation to the back-left position by rotating its left hip joints, like in marching. The sequential motions are shown in Figure 11. This experiment is mostly deals with joints at the lower part of the humanoid's body, especially at the left leg. This basic movement is very useful for humanoid motion, for example when avoiding obstacles [19][20] and also during operating in confined spaces [21].

Experiment 2: The humanoid robot 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 12 shows a sequence image captured during this experiment. This movement should eventually lead to the ability for a biped humanoid robot to hop over an object [22] and also avoid obstacles.

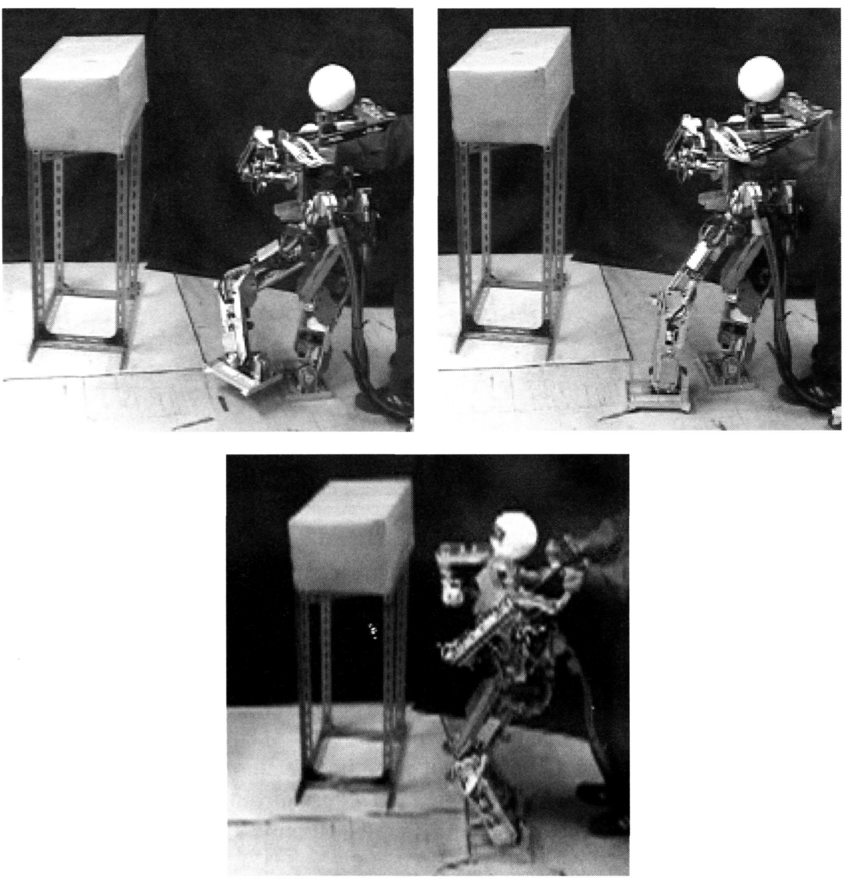


Figure 11: Sequential Photograph of Humanoid Robot Motion in Experiment

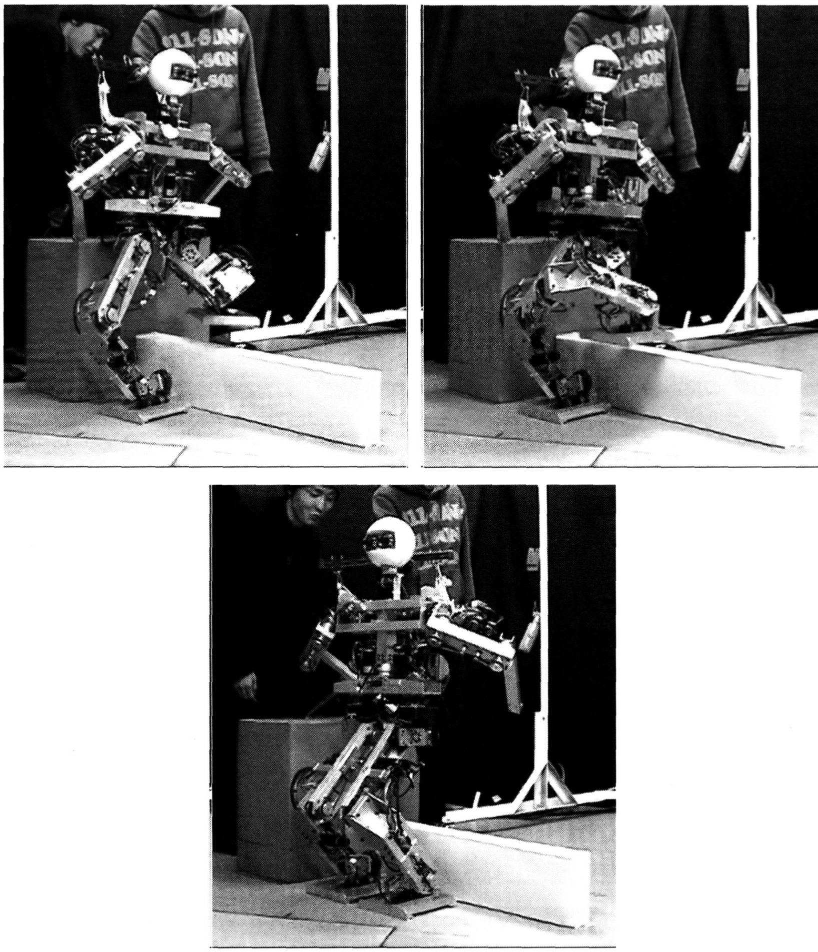
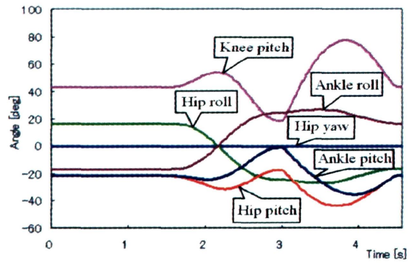


Figure 12: Sequential Photograph of Humanoid Robot Motion in Experiment

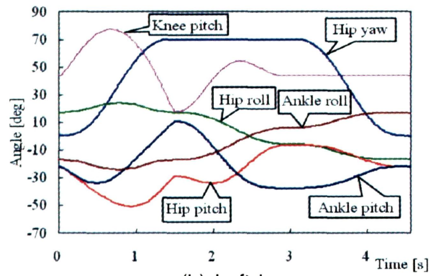
Experiment Results and Discussion

The joint rotation angles of *Bonten-Maru II*'s arms and legs in experiments 1 and 2 are compiled and presented in Figures 13 and 14, 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.

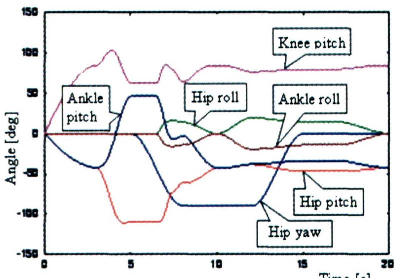


(a) Right leg.

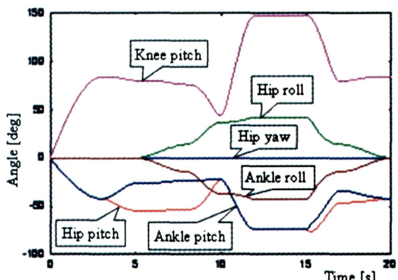


(b) Left leg.

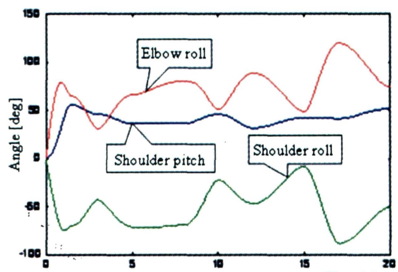
Figure 13: Graphs of the Humanoid Robot Legs Joint Rotation Angle in Experiment 1



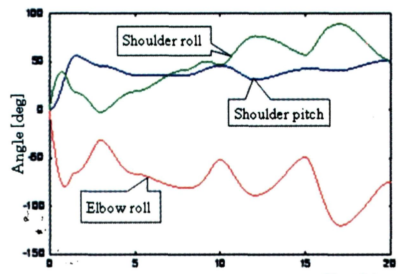
Graph 1. Right leg joints.



Graph 2. Left leg joints.



Graph 3. Right arm joints.



Graph 4. Left arm joints.

Figure 14: Graphs of the Humanoid Robot Legs and Arms Joint Rotation Angle in Experiment 2

- 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-dofs arm to attain the desired motion in the xyz-axes.

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-dofs humanoid robot arm is the minimum requirement to attain the desired human-like motion at xyz-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 3, 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. The observation result in these experiments shows a smooth and controlled trajectory of the robot's manipulator to attain desired motion.

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-dofs 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-dofs 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* revealed that the joints structure design and configurations of dof are significantly provided effective elements to generate the ability to attain human-like motion. This investigation also 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.

Acknowledgement

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References

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

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

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

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

[5] Pollick, F. E., Hale, J.G. and Tzoneva-Hadjigeorgieva, M. (2005). "Perception of humanoid robot movement, *Int. Journal of Humanoid Robotics*," Vol. 2, No. 3, 277-300.

[6] Zinn, M., Khatib, O., Roth, B. and Salisbury, J.K. (2004). "A new actuation approach for human friendly robot design," *Int. Journal of Robotic Research*, Vol. 23, Issue 4/5, 379-398.

[7] Ming, J. T. and Yee, H. C. (1990). "Manipulability of manipulators," *Mech. Mach. Theory J.*, Vol. 25, No. 5, 575-585.

[8] Nakai, H., Inaba, M. and Inoue, H. (2002). "Shape definition of metamorphic robot by evaluation of the robustness and the manipulability," in *seminar of the 20th anniversary of the RSJ establishment*, 3H22.

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

[10] Nasu, Y., Capi, G., Kaneko, S. and Yamano, M. (2004). "Development of "Bonten-Maru" humanoid robot," *Bulletin Yamagata University*, Vol. 28, No.1.

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

[12] Hanafiah, Y., Yamano, M., Nasu, Y. and Ohka, M. (2006). "Trajectory generation in groping locomotion of a 21-DOF humanoid robot," *International Journal of Simulation: Systems, Science & Technology (IJSSST)*, Vol. 7, No. 8, 55-63.

[13] Gummerson, T. (1990). *Mobility Training for the Martial Arts*. A&C Black, 96.

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

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

[16] Sato, R., Nasu, Y., Yamano, M., Kaneko, S. and Mitobe, K. (2003). "An obstacle over striding motion of a humanoid robot with its hands," *The Society of Instrument and Control Engineers Tohoku Chapter 221st meeting*, No. 211-9.

[17] Shinohara, T., Ban, S., Gotoh, T., Inamura, T., Okada, M. and Nakamura, Y. (2002). "Development of humanoid robot with "double spherical hip joint"," *The 20th Conference of the Robotics Society of Japan*, 1C16.

[18] Yamano, M., Nasu, Y., Sato, R. and Mitobe, K. (2005). "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.*, ICMT-151.

[19] Hanafiah, Y., Yamano, M., Nasu, Y. and Ohka, M. (2005). "Obstacle avoidance in groping locomotion of a humanoid robot," *Journal of Advanced Robotic Systems*, Vol. 2, No. 3, 251-258, ISSN 1729-5506.

[20] Hanafiah, Y., Yamano, M., Ohka, M. and Nasu, Y. (2007). "Development of a contact interaction-based navigation strategy for a biped humanoid robot," *Proceedings of 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'07)*, 4241-4246, San Diego, California, USA.

[21] Hanafiah, Y., Ohka, M., Yamano, M. and Nasu, Y. (2007). "Biped locomotion strategy in humanoid robot navigation system towards confined space operation," *Proceedings of 2007 IEEE/RAS 13th International Conference on Advanced Robotics (ICAR2007)*, 850-855, Jeju, Korea.

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

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[1] M. K. Ghosh and A. Nagraj, "Turbulence flow in bearings," Proceedings of the Institution of Mechanical Engineers 218 (1), 61 - 64 (2004).

[2] H. Coelho and L. M. Pereira, "Automated reasoning in geometry theorem proving with Prolog," J. Automated Reasoning 2 (3), 329-390 (1986).

[3] P. N. Rao, Manufacturing Technology Foundry, Forming and Welding, 2nd ed. (McGraw Hill, Singapore, 2000), pp. 53 – 68.

[4] Hutchinson, F. David and M. Ahmed, U.S. Patent No. 6,912,127 (28 June 2005).

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