Robotica (2004) volume 22, pp. 577–586.
DOI: 10.1017/S0263574704000372 Printed in the United Kingdom

Emotion-based biped walking

Hun-ok Lim*†, Akinori Ishii* and Atsuo Takanishi*†

(Received in Final Form: February 21, 2004)

SUMMARY

This paper describes emotion-based walking for a biped humanoid robot. In this paper, three emotions, such as happiness, sadness and anger are considered. These emotions are expressed by the walking styles of the biped humanoid robot that are preset by the parameterization of its whole body motion. To keep its balance during the emotional expressions, the motion of the trunk is employed which is calculated by the compensatory motion control based on the motions of the head, arms and legs. We have constructed a biped humanoid robot, WABIAB-RII (WAseda BIpedal humANoid robot-Revised II), to explore the issue of the emotional walking motion for a smooth and natural communication. WABIAN-RII has forty-three mechanical degrees of freedom and four passive degrees of freedom. Its height is about 1.84 m and its total weight is 127 kg. Using WABIAN-RII, three emotion expressions are experimented by the biped walking, including the body motion, and evaluated.

KEYWORDS: Emotional walking; Compensatory motion; Motion parameters; Parameterization; Biped humanoid robot

I. INTRODUCTION

It has been forecast that many robotic systems will be employed in the non-industrial fields, such as services and social welfare in the 21st century. These robots are expected to have the human-like mechanism and function to coexist with human beings. Especially, a two-legged system will be effective as a locomotion system in human living spaces, for example, homes, offices and so on.

For the last three decades, our research group has studied on human-like biped robots with two main thrusts. One thrust has been toward realizing the dynamic complete walking, not only on an even or uneven terrain, but also on a hard or soft terrain. Takanishi and co-workers realized complete dynamic walking with the walking speed of 1.3 s/step, using the sequence control.[1] Dynamic walking on an uneven terrain, like stairs and inclined planes, was realized using the control algorithm based on a virtual surface.[2] The other thrust has beentowards exploring the robot-environment interaction. Also, we achieved dynamic walking under an unknown external force 100 N acting on the waist of a biped robot.[3,4] A pseudo-human walking control was proposed which has the pattern switching technique based on human-robot physical interaction.[5]

Other research groups have researched on the analysis of biped walking control and hardware.[6,7] Vukobratovic and his co-workers[8] modeled a walking biped that balances by manipulating the projected center of gravity and the support area provided by the feet. Kajita and Tani[9] developed the linear inverted pendulum mode to control a biped walking. In more recent research, Honda's humanoid robot called P2 has been constructed and dynamic walking on the plane and stairs has been realized.[10]

Up to the present, almost of all researches on biped robots have covered the problems of control systems for their stable walking, but not included an issue of emotion expression for a smooth and natural communication. However, a few of researches on a human's walking behavior have been proposed. Wallbott,[11] and Barclay and co-workers[12] studied a person's character, sex and age from the standpoint of a person's gait. Montepare and co-workers[13] have explored human's emotions from a human's walking style. In addition, the study of facial expressions has been researched by many workers.[14−17] The research of emotion expressions using biped humanoid robots has not been proposed until now, excepting that by Lim and Takanishi.[18]

In this paper, we focus on the emotion expression using the whole body motion and the walking of a biped humanoid robot to understand a human's emotion fully. However, the facial expression is not included in this paper. We have constructed an anthropomorphic intelligent robot, WABIAN-RII, that will contribute to the development of "human-like biped robots". The biped humanoid robot has forty-three mechanical degrees of freedom and four passive degrees of freedom (a translational motion and three rotational motions). A picture of WABIAN-RII is shown in Figure 1. Its height is about 1.84 m and its total weight is 127 kg. Three emotions such as happiness, sadness and anger are considered in this paper. Each emotion is parameterized, and a motion pattern of the lower-limbs and upper-limbs is determined. During walking, the combined motion of the trunk and waist controls the balance of the biped humanoid robot, which is calculated using the compensatory motion control algorithm proposed already.[19]

This paper is organized as follows: In Section 2, we describe motion parameters and walking patterns to realize emotion expression. Section 3 describes emotional walking simulations. Section 4 illustrates an experimental system

† Humanoid Robotics Institute, Waseda University (Japan)
* Dept. of Mechanical Engineering, Waseda University, 1-104 Totsuka-muchi, Shinjyuku-ku, Tokyo 169-50 (Japan).

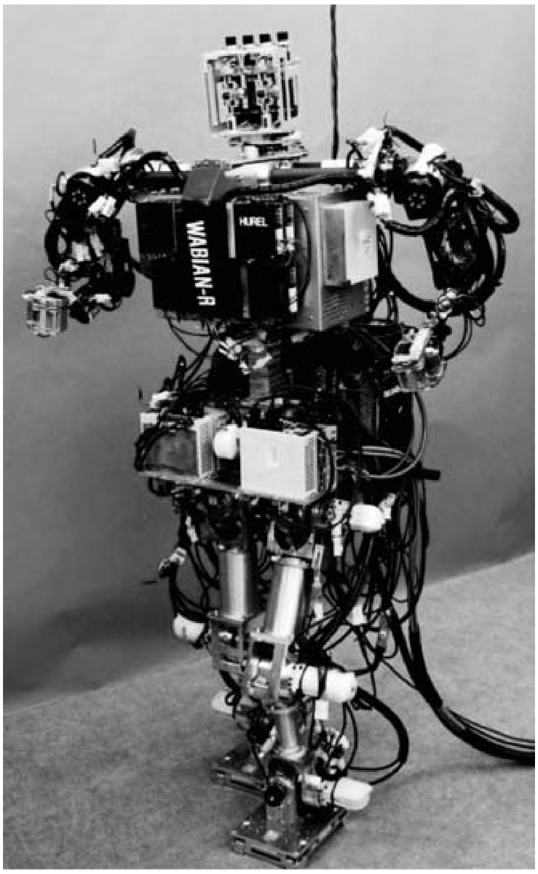


Fig. 1 The Photo of WABIAN-RII.

and shows experimental results. Finally, conclusions are discussed in Section 5.

II. EMOTION EXPRESSION BASED ON MOTION PARAMETERS

To identify human walking in certain emotional states, three walking styles of a biped humanoid robot are considered: happy, sad and angry walking. In this section, the walking pattern for locomotion and stability is described. For stability, the motion of the waist and trunk is calculated by the compensatory motion control method already proposed.[20] Also, the motion parameters that play an important role in emotional walking are discussed.

A. General walking pattern

The positions and orientations of the foot, waist and head $\boldsymbol{x}_{foot} \in \Re^6$, $\boldsymbol{x}_{waist} \in \Re^6$ and $\boldsymbol{x}_{head} \in \Re^6$, can be determined by a polynomial. Here, how to determine the smooth motion of the lower-limbs is briefly discussed. The smooth motion of the foot according to the ground is generated by using the sixth order polynomial, considering angle, angular velocity, angular acceleration and angle of the highest position of the foot. Three constraints of the foot position and orientation arise from the selection of initial and final values:

$$\boldsymbol{x}_{foot}(t_0) = \boldsymbol{x}_0,\ \boldsymbol{x}_{foot}(t_f) = \boldsymbol{x}_f,\ \boldsymbol{x}_{foot}(t_m) = \boldsymbol{x}_m, \qquad (1)$$

where t_0, t_m and t_f are the initial, intermediate and final times of a step, respectively.

The position and orientation $\boldsymbol{x}_{foot}$ have an additional four constraints that are the zero initial and final velocity and acceleration:

$$\begin{aligned}\dot{\boldsymbol{x}}_{foot}(t_0) = \boldsymbol{0},\ \dot{\boldsymbol{x}}_{foot}(t_f) = \boldsymbol{0},\\ \ddot{\boldsymbol{x}}_{foot}(t_0) = \boldsymbol{0},\ \ddot{\boldsymbol{x}}_{foot}(t_f) = \boldsymbol{0}.\end{aligned} \qquad (2)$$

These seven constraints are satisfied by a sixth order polynomial. The sixth order polynomial is written as

$$\boldsymbol{x}_{foot}(t) = \boldsymbol{a}_0 + \boldsymbol{a}_1 t + \boldsymbol{a}_2 t^2 + \boldsymbol{a}_3 t^3 + \boldsymbol{a}_4 t^4 + \boldsymbol{a}_5 t^5 + \boldsymbol{a}_6 t^6, \qquad (3)$$

and the velocity and acceleration along the path are clearly

$$\begin{aligned}\dot{\boldsymbol{x}}_{foot}(t) &= \boldsymbol{a}_1 + 2\boldsymbol{a}_2 t + 3\boldsymbol{a}_3 t^2 + 4\boldsymbol{a}_4 t^3 + 5\boldsymbol{a}_5 t^4 + 6\boldsymbol{a}_6 t^5,\\ \ddot{\boldsymbol{x}}_{foot}(t) &= 2\boldsymbol{a}_2 + 6\boldsymbol{a}_3 t + 12\boldsymbol{a}_4 t^2 + 20\boldsymbol{a}_5 t^3 + 30\boldsymbol{a}_6 t^4.\end{aligned} \qquad (4)$$

Combining Equation (3) and Equation (4) with the seven constraints, the seven coefficients ($\boldsymbol{a}_0 \cdots \boldsymbol{a}_6$) can be obtained. Then, substituting these coefficients for Equation (3), the foot pattern will be obtained.

Also, a desired pattern of the waist can be determined by using Equation (3). However, this desired waist motion is changed by the compensatory motion control algorithm to compensate for the moments produced by the motion of the head, lower-limbs and upper-limbs during the walking. A desired knee pattern is geometrically computed on the basis of the foot and the waist pattern. The compensatory motions of the waist and the trunk are obtained by the iteration method, depending on the ratio between the compensation moments of the trunk and the waist and the initial position and orientation of the trunk. A desired head pattern can be obtained by the fifth or sixth order polynomial. Also, an arm desired pattern is defined, using forward kinematics, depending on the shoulder position and orientation. After calculating the compensatory motion, these desired patterns are recomputed based on the foot, waist and trunk motions. The complete walking pattern that consists of the patterns of the head, waist, trunk, lower-limbs and upper-limbs is obtained according to the step direction, as shown in Figure 2. A general walking pattern generation can be found in our previous paper[21].

B. Motion parameters

There are eight parameters and four gait characteristics for the happy expression, and eleven parameters and two gait characteristics for the sad expression. Also, we set eight parameters and three gait characteristics for the angry expression. Combining the parameters and the gait characteristics, thirty-two walking motion patterns each emotion are determined.

In the happy expression, the motion parameters are set as follows:

- A: the normal step has toe's middle x-position of 0.075 m and final x-position of 0.15 m, while the long step has

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

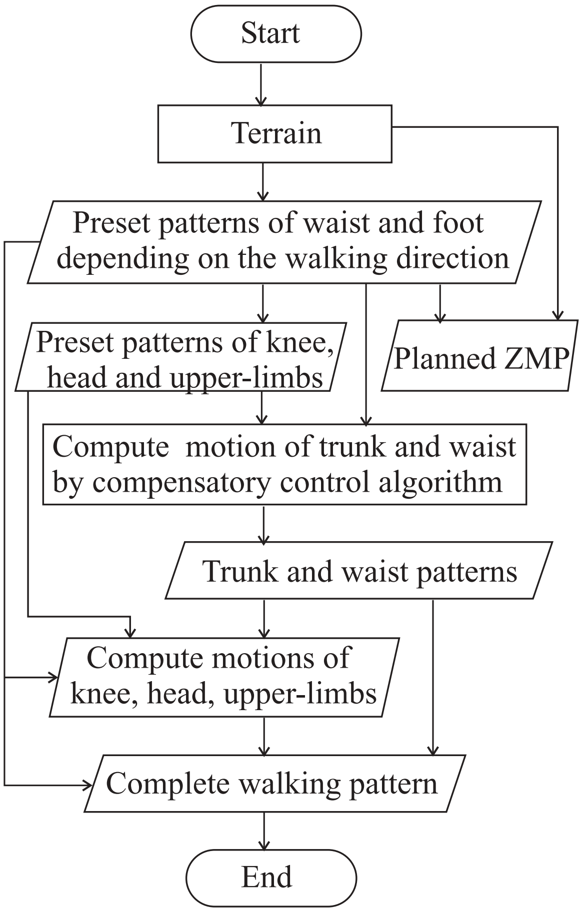


Fig. 2. Pattern generation of complete walking pattern.

toe's middle x-position of 0.10 m and final x-position of 0.20 m.

- B: the normal foot has the acceleration of the toe of 0.002 m/s^2 to the Z direction in the first and the last term of the swing phase. The M shape foot trajectory is determined with the acceleration of 0.05 m/s^2 to the Z direction in the first and the last term of the swing phase. In the center foot, the Y position of the toe is fixed. The side foot has toe's y-position of −0.20 m and roll orientation of −20 deg in the middle term of the swing phase. The high foot has toe's z-position of 0.10 m and z-acceleration of 0.002 m/s^2 in the middle term of the swing phase.
- C: the outward foot has with the yaw orientation of the toe of 30.0 deg.
- D: in the middle of the swing phase, the normal waist has the z-position of −0.1 m with respect to the moving coordinate frame set on the center of the waist. On the other hand, the moving waist moves up and down within 0.1 m.
- E: to make the rotating waist, the roll orientation of the waist is set as −10.0 deg in the middle of the swing phase. Also, the initial and final angular velocities of the waist are −1.0 deg/s and 1.0 deg/s, respectively;
- F: to shake largely front-to-back the trunk, the ratio of the pitch moments is 0.7. The pitch angle of the head is −10.0 deg in the middle of the swing phase.
- G: to shake largely side-to-side the trunk, the ratio of the roll moments is set as 0.7. The roll angle of the head is 10.0 deg in the middle of the swing phase. Also, the initial and final angular velocities of the head are 1.0 deg/s and −1.0 deg/s, respectively.
- H: the amplification constant of the pitch shoulder and elbow with respect to the yaw angle of the trunk is 1.0 in the normal arm and 2.5 in the swing arm.

Table I. Motion parameters for happy walking.

Parameters	Gait Characteristics a	b	c	d
A:step length	long	normal	normal	normal
B:foot	M-shape	M-shape	high	normal
C:toe	outward	straight	straight	straight
D:waist	moving up and down	normal	normal	normal
E:waist	rotating on roll axis	fixed	fixed	fixed
F:trunk and head	shaking front-to-back	trunk only	neck only	fixed
G:trunk and head	shaking side-to-side	trunk only	neck only	fixed
H:arm	swinging largely	normally	normally	normally

Table II. Motion parameters for sad walking.

Parameters	Gait Characteristics a	b
A:speed	slow	normal
B:head	tilting sideward	straight
C:toe	inward	straight
D:foot	dragging	normal
E:trunk	shaking front-to-back	fixed
F:trunk	bending front	straight
G:trunk	bending sideward	straight
H:trunk	rotating on yaw-axis	fixed
I:step length	short	normal
J:head	drooping	straight
K:arm	fixed	swing

Table I describes eight motion parameters and four gait characteristics of the happy expression.

Table II describes eleven motion parameters and two gait characteristics of the sad expression. The sad motion parameters are set as follows:

- A: the normal speed is 1.28 s/step, while the slow speed is 1.92 s/step.
- B: the initial roll angle of the head is set as 20 deg to tilt sideward.
- C: the yaw angle of the toe is set as −10 deg and the foot turns inwards.
- D: to make the dragging foot, the z-position of the toe is 0.02 m in the middle of the swing phase. However, the z-position of the toe is 0.10 m in the normal foot.

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

Table III. Motion parameters for angry walking.

	Gait Characteristics		
Parameters	a	b	c
A:speed	fast	normal	normal
B:fist	clench	open	open
C:armpit	open	close	close
D:trunk	bending front	straight	straight
E:foot	stamping	high	normal
F:step length	long	normal	normal
G:face	sticking forward	normal	normal
H:toe	outward	straight	straight

- E: the ratio of the pitch moments is set as 0.7 for the trunk to shake largely front-to-back.
- F: the roll offset position of the trunk is set as 0.1 m to tilt forward.
- G: the pitch offset position of the trunk is set as 0.1 m to tilt sideward.
- H: the ratio of the yaw moments is set as 0.7.
- I: the normal step has the middle x-position of the toe of 0.075 m and the final x-position of 0.15 m, while the short step has the middle x-position of 0.05 m and the final x-position of 0.10 m.
- J: the initial pitch angle of the head is set as 20.0 deg to droop forward.
- K: the amplification constant of the pitch shoulder and elbow with respect to the yaw angle of the trunk is set as 1.0 to move the arm.

Table III describes eight motion parameters and three gait characteristics of the angry expression. The angry motion parameters are set as follows:

- A: the normal speed is 1.28 s/step, while the fast speed is 0.96 s/step.
- B: the fist is clenched or opened.
- C: to open the armpit, the roll and yaw offset position of the shoulder are set as −30.0 deg and 60.0 deg, respectively. Also, the pitch offset position of the elbow is set as −40.0 deg.
- D: the pitch offset position of the trunk is set as 0.1 m to tilt forward.
- E: the initial and final accelerations of the toe in the first and final term of the swing phase are set as 0.01 m/s^2 and 0.05 m/s^2 to make a march step, while the initial and final accelerations of the toe are set as 0.002 m/s^2 and 0.002 m/s^2 in normal step. The initial z-position of the toe for the high foot is 0.3 m in the middle of the swing phase.
- F: the normal step has the middle x-position of the toe of 0.075 m and the final x-position of 0.15 m, while the long step has the middle x-position of 0.10 m and the final x-position of 0.20 m.
- G: the initial pitch angle of the head is set as 20 deg to make the sticking face.

Table IV. Evaluation points in happy walking.

	Parameters								
Patterns	A	B	C	D	E	F	G	H	Sum
1	a	a	a	a	a	a	a	a	33
2	b	a	b	b	b	a	b	b	6
3	a	a	a	a	b	b	c	b	22
4	b	a	b	b	a	b	d	a	11
5	b	a	a	b	a	c	c	a	10
6	a	a	b	a	b	c	d	b	35
7	b	a	a	b	b	d	a	b	5
8	a	a	b	a	a	d	b	a	37
9	a	b	b	b	a	a	c	b	4
10	b	b	a	a	b	a	d	a	24
11	a	b	b	b	b	b	a	a	16
12	b	b	a	a	a	b	b	b	12
13	b	b	b	a	a	c	a	b	24
14	a	b	a	b	b	c	b	a	12
15	b	b	b	a	b	d	b	a	45
16	a	b	a	b	a	d	d	b	5
17	b	c	b	a	b	a	c	a	37
18	a	c	a	b	a	a	d	b	4
19	b	c	b	a	a	b	a	b	25
20	a	c	a	b	b	b	b	a	13
21	a	c	b	b	b	c	a	a	18
22	b	c	a	a	a	c	b	b	29
23	a	c	b	b	a	d	c	b	13
24	b	c	a	a	b	d	d	a	24
25	b	d	a	b	b	a	a	b	6
26	a	d	b	a	a	a	b	a	30
27	b	d	a	b	a	b	c	a	9
28	a	d	b	a	a	b	c	a	10
29	a	d	a	a	b	c	c	b	36
30	b	d	b	b	a	c	d	a	9
31	a	d	a	a	a	d	a	a	37
32	b	d	b	b	b	d	b	b	2

- H: the initial yaw angle of the toe is set as 30 deg for the foot to face outward.

C. Analysis of variance

To explore three emotions, such as happiness, sadness and anger, 3D walking motion simulations are conducted. Considering the motion parameters, thirty-two walking motion patterns are determined by the pattern generator.[21] Using a Borland Builder C^{++} and an Open GL software for Windows the 3D emotional walking is animated and videotaped. Then, the recorded 3D animations are played for about 15 s for evaluation. In order to show more realistically the biped model begins to walk straight ahead and turns 90 deg to the left around the yaw axis at the final step. In this study, seventeen undergraduates serve as appraisers and evaluate each emotional walking as five levels, from 0 point (lowest point) to 4 point (hightest point). The sum of points each happy pattern is shown in Table IV, while the sum of points each sad pattern is shown in Table V. Also, the sum of points each angry pattern is shown in Table VI.

To obtain an effective emotional walking pattern, we analyze the variance of the motion parameters. The variability of a set of n measurements (the number of

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

Table V. Evaluation points in sad walking.

Patterns	Parameters A	B	C	D	E	F	G	H	I	J	K	Sum
1	a	a	a	a	a	a	a	a	a	a	a	31
2	a	b	b	b	a	a	a	a	b	b	b	18
3	a	a	a	a	a	a	b	b	b	b	a	25
4	a	b	b	b	a	a	b	b	a	a	b	28
5	a	b	b	a	a	b	a	b	a	a	a	20
6	a	a	a	b	a	b	a	b	b	b	b	16
7	a	b	b	a	a	b	b	a	b	b	a	6
8	a	a	a	b	a	b	b	a	a	a	b	35
9	a	a	b	b	b	a	a	b	b	a	a	24
10	a	b	a	a	b	a	a	b	a	b	b	26
11	a	a	b	b	b	a	b	a	a	b	a	31
12	a	b	a	a	b	a	b	a	b	a	b	37
13	a	b	a	b	b	b	a	a	b	a	a	13
14	a	a	b	a	b	b	a	a	a	b	b	16
15	a	b	a	b	b	b	b	b	a	b	a	8
16	a	a	b	a	b	b	b	b	b	a	b	34
17	b	b	a	b	a	a	a	b	b	b	a	22
18	b	a	b	a	a	a	a	b	a	a	b	27
19	b	b	a	b	a	a	b	a	a	a	a	24
20	b	a	b	a	a	a	b	a	b	b	b	24
21	b	a	b	b	a	b	a	a	b	b	a	14
22	b	b	a	a	a	b	a	a	a	a	b	23
23	b	a	b	b	a	b	b	b	a	a	a	18
24	b	b	a	a	a	b	b	b	b	b	b	18
25	b	b	b	a	b	a	a	a	b	b	a	15
26	b	a	a	b	b	a	a	a	a	a	b	28
27	b	b	b	a	b	a	b	b	a	a	a	39
28	b	a	a	b	b	a	b	b	b	b	b	27
29	b	a	a	a	b	b	a	b	b	b	a	28
30	b	b	b	b	b	b	a	b	a	a	b	12
31	b	a	a	a	b	b	b	a	a	a	a	29
32	b	b	b	b	b	b	b	a	b	b	b	7

Table VI. Evaluation points in angry walking.

Patterns	Parameters A	B	C	D	E	F	G	H	Sum
1	a	a	a	a	a	a	a	a	38
2	a	a	a	a	b	b	b	b	10
3	a	a	a	b	c	a	a	b	11
4	a	a	a	b	a	b	b	a	26
5	a	a	b	a	c	a	b	a	21
6	a	a	b	a	a	b	a	b	22
7	a	a	b	b	a	a	b	b	6
8	a	a	b	b	b	b	a	a	19
9	a	b	a	a	c	b	a	a	7
10	a	b	a	a	a	a	b	b	7
11	a	b	a	b	a	b	a	b	12
12	a	b	a	b	b	a	b	a	6
13	a	b	b	a	a	b	b	a	17
14	a	b	b	a	b	a	a	b	9
15	a	b	b	b	c	b	b	b	0
16	a	b	b	b	a	a	a	a	12
17	b	a	a	a	c	b	b	b	2
18	b	a	a	a	a	a	a	a	28
19	b	a	a	b	a	b	b	a	24
20	b	a	a	b	b	a	a	b	16
21	b	a	b	a	a	b	a	b	17
22	b	a	b	a	b	a	b	a	19
23	b	a	b	b	c	b	a	a	15
24	b	a	b	b	a	a	b	b	10
25	b	b	a	a	a	a	b	b	12
26	b	b	a	a	b	b	a	a	13
27	b	b	a	b	c	a	b	a	9
28	b	b	a	b	a	b	a	b	9
29	b	b	b	a	c	a	a	b	13
30	b	b	b	a	a	b	b	a	2
31	b	b	b	b	a	a	a	a	10
32	b	b	b	b	b	b	b	b	1

emotional patterns) is the proportional of SS (sum of squares of deviations).

$$SS = (\textit{sum of squares of all y values}) - CM$$
$$= \sum_{i=1}^{p}\sum_{j=1}^{n_i}(y_{ij} - \bar{y})^2 = \sum_{i=1}^{p}\sum_{j=1}^{n_i} y_{ij}^2 - CM$$
$$= SST + SSE, \tag{5}$$

where y_{ij} and $\bar{y}$ denote the variance of a sample of ij measurements and the mean of a sample, respectively. The terms CM and SST denote the correction for the mean and the sum of squares for treatments, respectively. The term SSE denotes the sum of squares for errors. These quantities are written as.

$$CM = \frac{(\textit{total of all observations})^2}{n}$$
$$= \frac{\left(\sum_{i=1}^{p}\sum_{j=1}^{n_i} y_{ij}\right)^2}{n} = n\bar{y}^2,$$

$$SST = \sum_{i=1}^{p} n_i(\bar{T}_i - \bar{y})^2 = \sum_{i=1}^{p}\frac{T_i^2}{n_i} - CM,$$
$$SSE = SS - SST, \tag{6}$$

where T_i is the treatment totals.

Although the easy way to compute SSE is by subtraction, as just shown, it is interesting to note that SSE is the pooled sum of squares for all p samples and is equal to

$$SSE = \sum_{i=1}^{p}\sum_{j=1}^{n_i}(y_{ij} - \bar{T}_i)^2, \tag{7}$$

where $\bar{T}_i$ is the mean of the treatment totals.

When the null hypothesis is true, MST (the mean square for treatments) and MSE (the mean square for error) both estimate the same quantity. When the null hypothesis is false, MST will probably be larger than MSE. The F probability distribution is given as a test statistic to test the hypothesis against the alternative.

$$F = \frac{MST}{MSE}, \tag{8}$$

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

Table VII. The analysis of variance in happy walking.

Parameter	SST	DOF(ν_t)	MST	F
A	69.031	1	69.031	2.269
B	54.094	3	18.031	0.593
C	52.531	1	52.531	1.726
D	3140.281	1	3140.281	103.203
E	11.281	1	111.281	0.371
F	238.844	3	79.615	2.616
G	216.844	3	72.281	2.375
H	504.031	1	504.031	16.565
Error	517.281	17	30.428	0

Table VIII. The analysis of variance in sad walking.

Parameter	SST	DOF(ν_t)	MST	F
A	5.281	1	5.281	0.176
B	258.781	1	258.781	8.635
C	101.531	1	101.531	3.388
D	166.531	1	166.531	5.557
E	19.531	1	19.531	0.652
F	520.031	1	520.031	17.352
G	101.531	1	101.531	3.388
H	13.781	1	13.781	0.460
I	47.531	1	47.531	1.586
J	457.531	1	457.531	15.267
K	26.281	1	26.281	0.877
Error	599.375	20	29.969	0

where MST is obtained by the relationship between the SST and the degrees of freedom of treatments (DOF) ν_t and MSE can be obtained by the relationship between the SSE and the degrees of freedom for error ν_e.

$$MST = \frac{SST}{\nu_t}, \quad MSE = \frac{SSE}{\nu_e}. \tag{9}$$

The critical value of the F_α statistic ($\alpha = 0.05$ or 0.01) for ν_t and ν_e is determined from the Tables of Percentage Points of the F Distribution.[22]

The effectiveness of the motion parameters for each emotion is evaluated using the analysis of variance. Tables VII, VIII and IX show the evaluation result of the happy, the sad and the angry walking. In happy walking, the critical values of the F_α statistic ($\alpha 5 = 0.05$ or $\alpha 1 = 0.01$) for $\nu_t = 1$ and $\nu_e = 17$, and $\nu_t = 3$ and $\nu_e = 17$ are as follows:

$$F^{\alpha 5,1}_{\alpha 1,17} = \begin{cases} 4.45 \\ 8.40 \end{cases}, \quad F^{\alpha 5,3}_{\alpha 1,17} = \begin{cases} 3.20 \\ 5.18 \end{cases}$$

where α is the probability that the test statistic will fall in the rejection region.

In sad walking, the critical values of the F_α statistic for $\nu_t = 1$ and $\nu_e = 20$ are as follows:

$$F^{\alpha 5,1}_{\alpha 1,20} = \begin{cases} 4.34 \\ 8.10 \end{cases}$$

Table IX. The analysis of variance in angry walking.

Parameter	SST	DOF(ν_t)	MST	F
A	16.531	1	16.531	0.584
B	657.031	1	657.031	23.213
C	42.781	1	42.781	1.511
D	81.281	1	81.281	2.872
E	219.094	3	73.031	2.580
F	30.031	1	30.031	1.061
G	195.031	1	195.031	6.890
H	371.281	1	371.281	13.117
Error	594.406	21	28.305	0

Table X. Evaluation of emotional walking simulations.

Walking style	Agreement [%]
Happy walking	94
Sad walking	76
Angry walking	88

In angry walking, the critical values of the F_α statistic for $\nu_t = 1$ and $\nu_e = 21$ and $\nu_t = 3$ and $\nu_e = 21$ are as follows:

$$F^{\alpha 5,1}_{\alpha 1,21} = \begin{cases} 4.32 \\ 8.02 \end{cases}, \quad F^{\alpha 5,3}_{\alpha 1,21} = \begin{cases} 3.03 \\ 4.87 \end{cases}$$

If the computed value of F exceeds the critical value F_α, there is sufficient evidence to reject the null hypothesis and conclude that a real difference does exist in the expected response in the group of subjects. In the happy emotion, the parameters D (the waist moving up and down) and H (the arm swing largely) have effects on the happy walking greatly when $\alpha = 0.01$ or $\alpha = 0.05$. In the sad emotion the parameters B (the head tilting sideward), F (the trunk bending forward) and J (the drooping head) have effects on the sad walking greatly when $\alpha = 0.01$, $\nu_t = 1$, $\nu_e = 20$. Also, the parameters B, D (the dragging foot), F and J affect on the sad walking, when $\alpha = 0.05$, $\nu_t = 1$, $\nu_e = 20$. In the angry emotion the parameters B (the hand clenching fist), G (the face sticking forward) and H (the outward toe) have effects on the angry walking largely when $\alpha = 0.01$, $\nu_t = 3$, $\nu_e = 21$, while the parameters B and H have effects on the angry walking greatly when $\alpha = 0.01$, $\nu_t = 1$, $\nu_e = 21$.

D. Simulation results

Three complete emotional walking patterns such as happy, sad and angry walking pattern are generated on the basis of the effective motion parameters obtained by the variance analysis. The complete walking patterns include the balance motion patterns determined by the compensatory motion control that is based on the motion of the head, shoulders, lower-limbs and upper-limbs. Using the complete emotional walking patterns, computer simulations are conducted and videotaped. The simulation results are evaluated by seventeen people.

The emotional walking is evaluated as shown in Table X. The agreement rate in the happy walking was 94 percent. The reason is that the motion parameters of the arm, head and

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

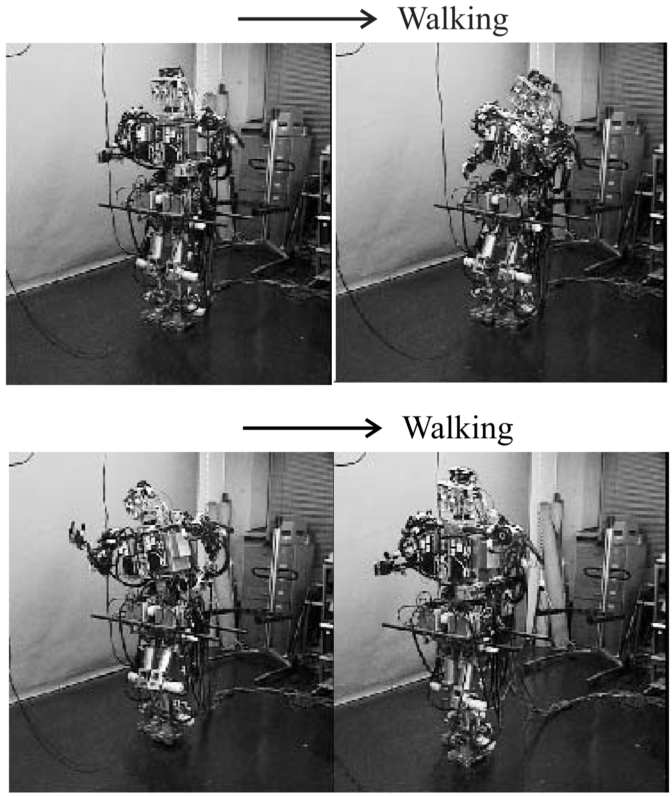


Fig. 3. Scenes of happy walking experiment.

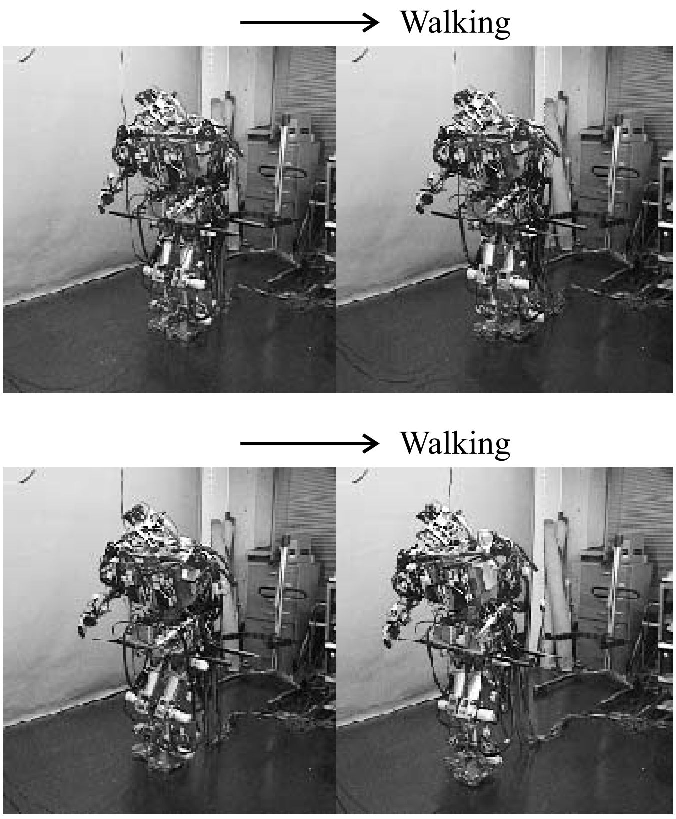


Fig. 4. Scenes of sad walking experiment.

waist were chosen effectively. Also the sad walking was 76 percent, while the angry walking was 88 percent. In these results, the trunk and head parameters have a great effect on the sad walking while the faceand arm parameters a great

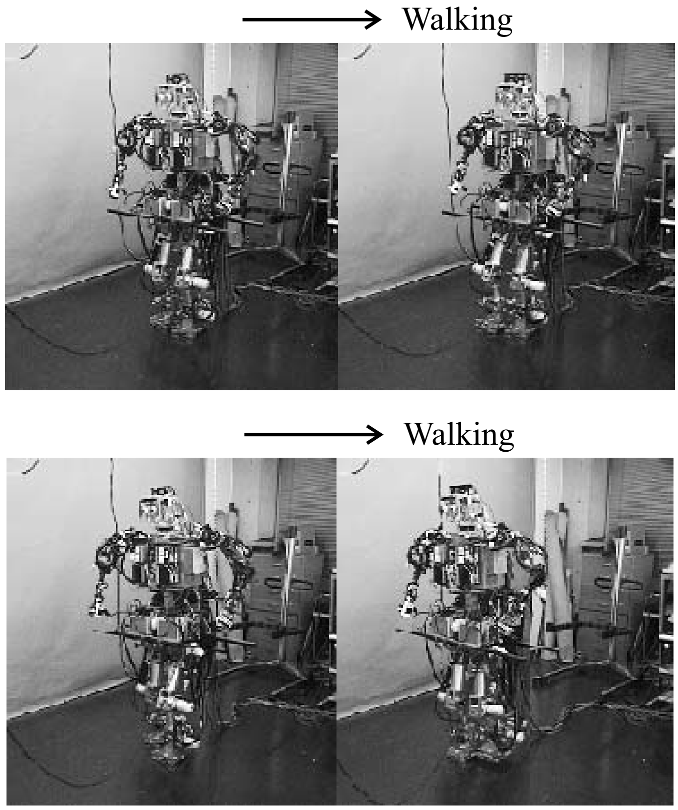


Fig. 5. Scenes of angry walking experiment.

effect on the angry walking. We can observe that the emotions can be easily realized by the parameterization of the motion.

III. EMOTIONAL WALKING EXPERIMENT

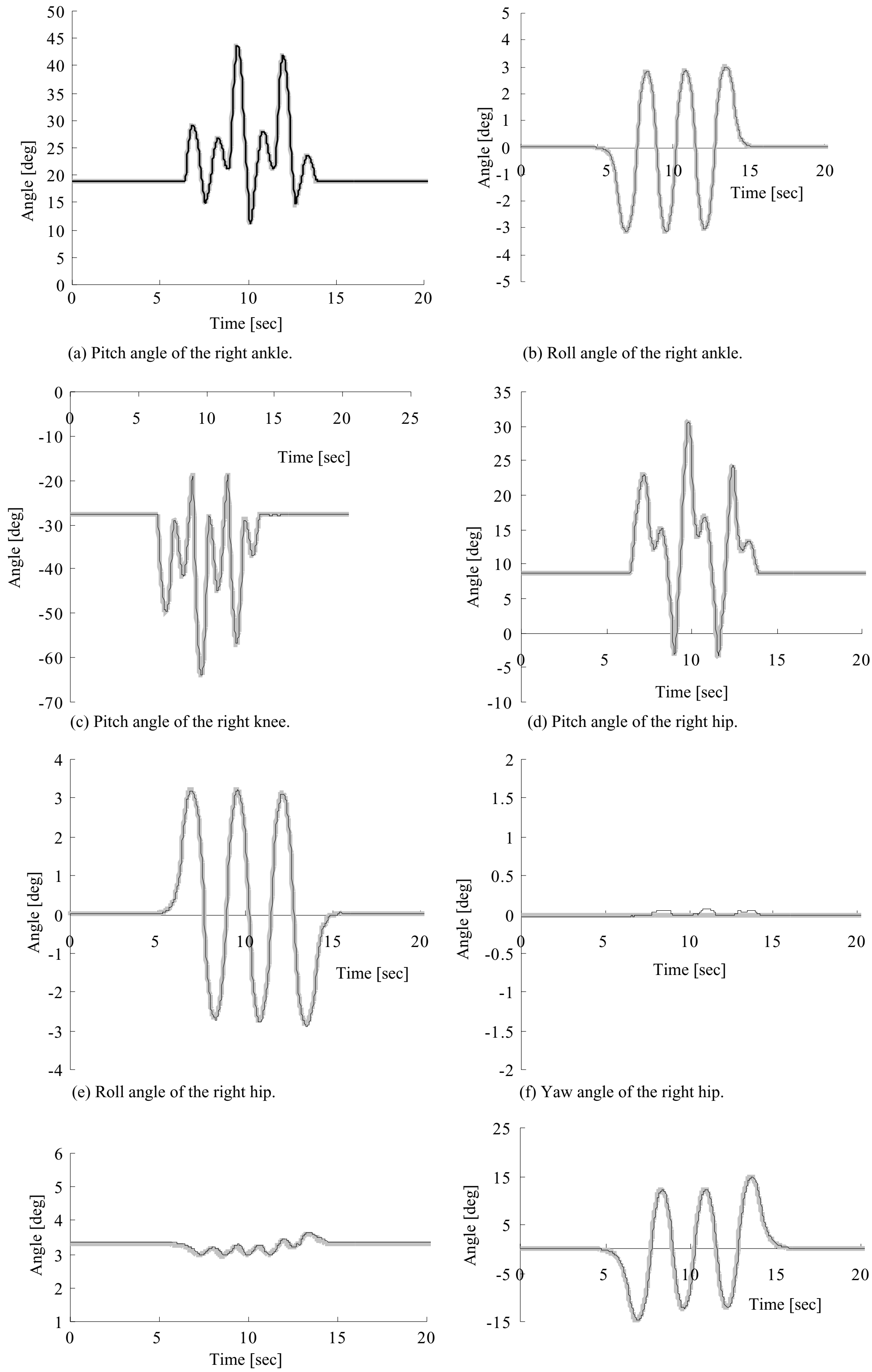
Emotional walking experiments have been conducted to confirm the validity of the motion parameters each emotion.

A. System description

We have constructed a forty-three mechanical degrees of freedom WABIAN-RII with a human configuration to realize human-like motion (see Figure 1). The biped robot is controlled by a PC/AT compatible computer PEAK-530 (an Intel MMX Pentium 200 MHz CPU processor) which are govern by a OS, MS-DOS 6.2/V (16-bit). The servo rate is 1 kHz. The computer system is mounted on the back of the waist, and the servo driver modules are mounted on the upper part of the trunk. The external connection is only an electric power source. A detailed hardware and software description could be found in our previous paper.[23]

The schemes of three emotional walking experiments are as follows: (1) The preset walking patterns of the lower-limbs, waist and head are planned on the basis of the motion parameters determined by various analysis; (2) the compensatory motion of the waist and trunk is calculated using the compensatory motion control algorithm to cancel the moments generated by the motion of the head, shoulders, upper-limbs and lower-limbs; (3) the motion of the head, shoulders, upper-limbs and lower-limbs are recalculated according to the compensatory motion; (4) combining the compensatory and locomotive motions, a complete emotional

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press



(a) Pitch angle of the right ankle.

(b) Roll angle of the right ankle.

(c) Pitch angle of the right knee.

(d) Pitch angle of the right hip.

(e) Roll angle of the right hip.

(f) Yaw angle of the right hip.

(g) Pitch angle of the trunk.

(h) Roll angle of the trunk.

Fig. 6. For caption see facing page.

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

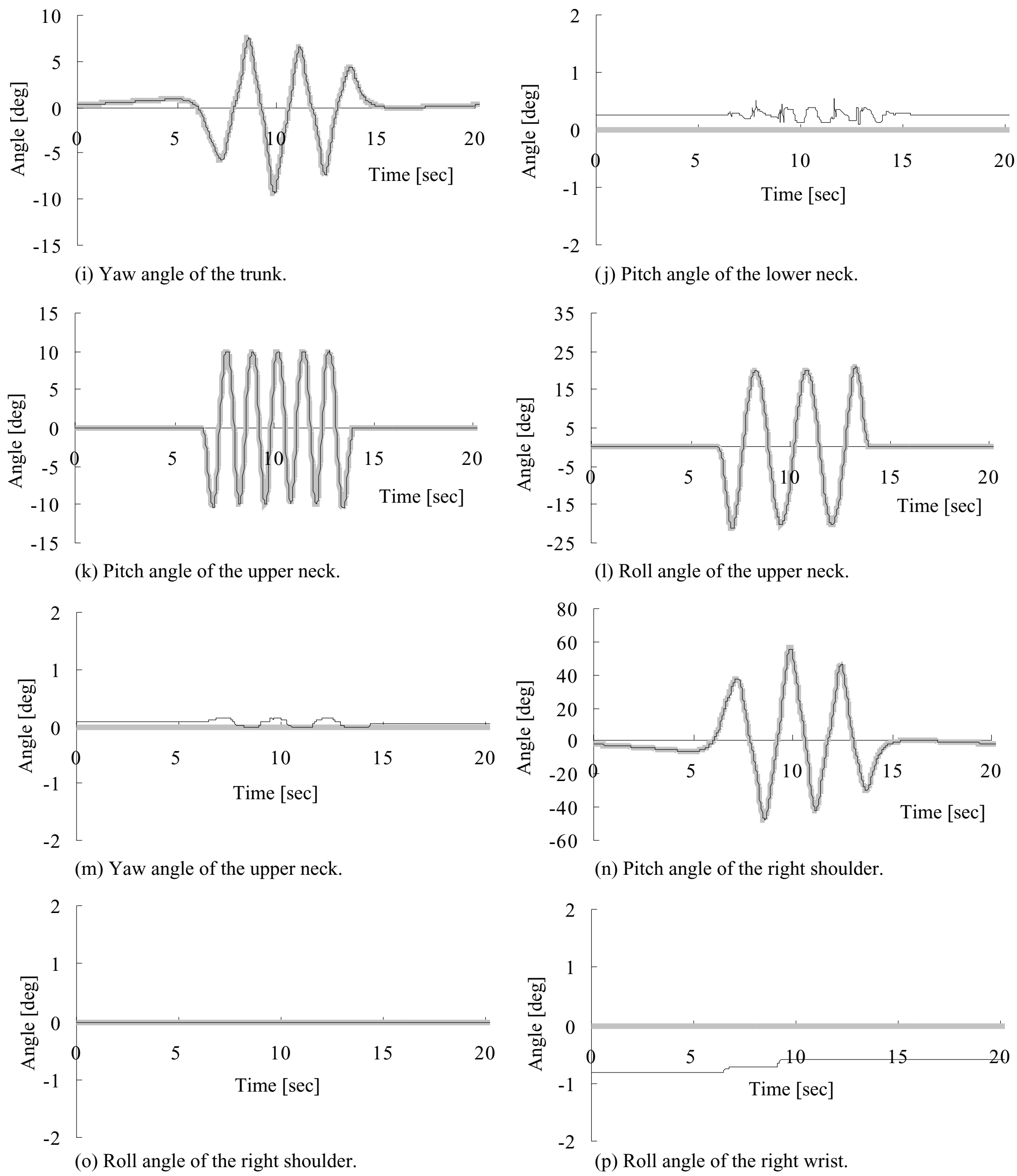


Fig. 6. Joint angle responses of happy walking. The light thick lines denote desired angle and the solid lines denote response angle.

Table XI. Evaluation of emotional walking experiments.

Walking style	Agreement [%]
Happy walking	88
Sad walking	71
Angry walking	53

walking pattern is generated and commanded to WABIAN-RII using the program control.

B. Experimental results

Figure 3, 4 and 5 show the scenes of the happy, sad and angry walking experiments, respectively. In these experiments, the dynamic complete emotional walking is realized with the step time of 1.28 s/step and the step width of 0.15 m/step. Each emotional walking is evaluated by seventeen people as two steps (not agree (0 point) or agree (1 point)). Table XI shows the evaluation of emotional walking. The agreement rates in the happy and the sad walking are 88 percent and 71 percent, respectively. On the other hand, the agreement rate in the angry walking is 53 percent. In the angry walking, the agreement rate of experiment is much worse than that of simulation because the complete walking pattern was not performed properly due to the limited joint angles of the WABIAN-RII. However, in the happy and sad walking, we can see that there is a satisfactory match between experimental and simulation results. These results clarify that the motion parameters are effective for the emotions.

Figure 6 shows the joint response histories of WABIAN-RII in happy walking. In Figure 6, the light thick lines denote the desired joint angles and the solid lines indicate the response values. We can see that each joint tracks well

https://doi.org/10.1017/S0263574704000372 Published online by Cambridge University Press

the desired motion pattern, as shown in Figure 6. Although the joint tracking of the sad and angry walking is not shown in this paper due to the limited space, we have obtained good joint responses, like the result of the happy walking.

IV. DISCUSSION AND CONCLUSION

In this paper, motion parameters were proposed to express three emotions such as happiness, sadness and anger, which were determined by the analysis of variances. Using these motion parameters, the initial walking patterns of the head, waist, upper-limbs and lower-limbs are planned by a polynomial and kinematics. To balance the whole robot body during the emotional walking, the compensatory motion of the trunk and waist is calculated based on the motion of the initial walking patterns and the ZMP trajectory. Then, the motion of the head, upper-limbs and lower-limbs is determined again according to the compensatory motion, and combining them a complete emotional walking pattern is generated. Through computer simulations and hardware experiments, the effectiveness of the motion parameters and three complete emotional walking patterns was confirmed.

We simply proposed the emotion expression of a forty-three degrees of freedom biped humanoid robot using a parameterization technique. In the simulation and experimental tests, we can see that there is a satisfactory match between the experimental and simulation results in the happy and the sad walking. However, the experimental evaluation of the angry walking is different from the simulation result. The reason is that the joint angles of the biped robot are limited. To solve this problem, we have been developing a new humanoid robot that has redundant degrees of freedom and movable joint angles like a human. In near future, emotion expression including facial expression will be studied for useful communication.

Acknowledgment

This study has been conducted as a part of the humanoid project at Humanoid Robotics Institute, Waseda University. This study was funded in part by JSPS under Japanese grant-in-aid for Scientific Research and Joint Research Project under the Japan-Korea Basic Scientific Cooperation Program and NEDO (New Energy and Industrial Technology Development Organization). The authors would like to thank Okino Industries Ltd., Harmonic Drive Systems Inc. and YKK Corporation for supporting us in developing the hardware.

References

1. A. Takanishi, M. Ishida, Y. Yamazaki and I. Kato, "The realization of dynamic walking by the biped walking robot," *Proc. IEEE Int. Conf. Robotics and Automation*, St. Louis, MO (March, 1985) pp. 459–466.
2. A. Takanishi, H. O. Lim, M. Tsuda and I. Kato, "Realization of dynamic biped walking stabilized by trunk motion on a sagitally uneven surface," *Proc. IEEE/RSJ Int. Workshop Intelligent Robots and Systems*, Tsuchiura, Japan (July, 1990) pp. 323–329.
3. A. Takanishi, M. Kumeta, K. Matsukuma, J. Yamaguchi and I. Kato, "Development of control method for biped walking under unknown external force acting in lateral plane," *RSJ Annual Conf. Robotics Society of Japan*, Tsukuba, Japan (Nov., 1991) pp. 321–3224 (in Japanese).
4. A. Takanishi, S. Sundo, N. Kinoshita and I. Kato, "Compensation for three-axes moments by trunk motion: Realization of biped walking under unknown external force," *RSJ Annual Conf. Robotics Society of Japan*, Kanezawa, Japan, (Oct.-Nov., 1992) pp. 593–596 (in Japanese).
5. S. Setiawan, S. Hyon, J. Yamaguchi and A. Takanishi, "Physical interaction between human and a bipedal humanold robot-realization of human-follow walking," *Proc. IEEE Int. Conf. Robotics and Automation*, Detroit, Mich. (May, 1999) pp. 361–367.
6. T. McGeer, "Passive bipedal walking," *Int. J. Robotics Research* **9**, No. 2, 62–82 (1990).
7. H. Miura and I. Shimpoyama, "Dynamic walk of a biped," *Int. J. Robotics Research* **3**, 2, 60–74 (Summer, 1984).
8. M. Vukobratovic, A. A. Frank and D. Juricic, "On the stability of biped locomotion," *IEEE Trans. of Biomedical Engineering* **17**, 1, 25–36 (1970).
9. S. Kajita and K. Tani, "Study of dynamic biped locomotionon rugged terrain: Theory and basic experiment," *Proc. Int. Conf. Advanced Robotics* (1991) pp. 741–746.
10. K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka, "The development of honda humanoid robot," *Proc. IEEE Int. Conf. Robotics and Automation*, Leuven, Belgium (May, 1998) pp. 1321–1326.
11. H. C. Wallbott, "Gait, gestures, and body movement," *J. of Nonverbal Behavior* **7**, 20–32 (1982).
12. C. D. Barclay, J. E. Cutting and L. T. Kozlowski, "Temporal and spatial factors in gait perceptions that influence gender recognition," *Perception and Psychophysics* **23**, 145–152 (1978).
13. J. M. Montepare, S. B. Goldstein and A. Clausen, "The identification of emotions from gait information," *J. Nonverbal Behavior* **11**, 1, 33–42 (Spring, 1987).
14. P. Ekman and W. V. Friesen, *Facial Action Coding System* (Consulting Psychologists Press Inc., 1978).
15. K. Mitobe et al., "Consideration of associated movements of head and eyes to optic and acoustic stimulation," *The Institute of Electronics, Information and Communication Engineers*, **91**, 81–87 (1992).
16. H. Kobayashi and H. Hara, "Real time dynamic control of 6 basic facial expressions on face robot," *J. Robotics Society of Japan* **14**, 5, 677–685 (1996) (in Japanese).
17. H. Miwa, A. Takanishi and H. Takanobu, "Experimental study on robot personality for humanoid head robot," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Maui, Hawaii (Oct., 2001) pp. 1183–1188.
18. H. O. Lim, A. Ishii and A. Takanishi, "Motion pattern generation for emotion expression," *Proc. Int. Symp. Humanoid Robots*, Tokyo, Japan (Oct., 1999) pp. 36–41.
19. J. Yamaguchi, A. Takanishi and I. Kato, "Development of a biped walking robot compensating for three-axis moment by trunk motion," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Yokohama, Japan (July, 1993) pp. 561–566.
20. H. O. Lim, Y. Yamamoto and A. Takanishi, "Stabilization control for biped follow walking," *Advanced Robotics* **16**, 4, 361–380 (2002).
21. H. O. Lim and A. Takanishi, "Walking pattern generation for biped locomotion," *Int. Symp. Robotics*, Seoul, Korea (Apr., 2001) pp. 1551–1556.
22. M. Merrington and C. M. Thompson, "Tables of percentage points of the inverted beta (f)-distribution," *Biometrika* **33**, 73–88 (1943).
23. H. O. Lim, A. Ishii and A. Takanishi, "Basic emotional walking using a biped humanoid robot," *Proc. IEEE Int. Conf. Systems, Man, and Cybernetics*, Tokyo, Japan (Oct., 1999) pp. IV954–IV959.