Generating Natural Posture in an Android by Mapping Human Posture in Three-Dimensional Position Space

Takashi Minato and Hiroshi Ishiguro

***Abstract*— In order to develop a robot working in daily situations, it is necessary to discover the principles relevant to establishing and maintaining social interaction between human and robot. One important issue is discovering how to naturally animate a robot to maintain social interaction. This study tackles the issue through implementing natural motions in the android which closely resembles those of human beings. This paper proposes a method to implement postures that look human by mapping the three-dimensional positions of a human subject body onto the android.**

I. INTRODUCTION

Much effort in recent years has focused on the development of humanoid robots with the aim of communication with people. However, the design methodology of the robot has not focused on human-robot communication. Even if short-term human-robot interaction can be performed by implementing simple behaviors in a robot, it remains difficult to realize long-term social interaction. It is therefore necessary to discover the principles relevant to establishing and supporting social interaction between human and robot. In other words, a fundamental representation of robot behavior in daily situations is required.

In order to understand the essence of human-robot communication, it is crucial to investigate the contribution of the behavior and appearance of humanoid robots. Most research on interactive robots has focused little on the impact of appearance. It is not yet clear whether the most comfortable and effective human-robot communication would come from a robot that looks mechanical or human. Some researchers have evaluated how the behavior of a robot affects human-robot interaction (e.g., [1]), but in these studies the machine-like appearance of the robot may distort the interpretation of its behavior. In other words, it may not be straightforward to clarify how the appearance and behavior of the robot affect each other. This appearance and behavior problem prevents us from understanding the essence of communication that is not specific to the robot. In order to tackle this problem, we adopt an elimination approach, in which we initially build a robot which has the same motion and appearance as humans and evaluate the interaction while removing some aspects of behavior or appearance. In addition, based on the fact that human beings have evolved specialized neural centers for the detection of bodies and faces [2], [3], [4], [5], we can also infer that a humanlike appearance is important. Our study tackles the appearance and behavior problem through development of an android which closely resembles a human being [6].

Takashi Minato is with Asada Project, ERATO, Japan Science and Technology Agency, 2–1 Yamada-oka, Suita, Osaka 565–0871, Japan (phone:+81-6-6876-8884; fax:+81-6-6876-8994; minato@jeap.org)

Hiroshi Ishiguro is with Department of Adaptive Machine Systems, Graduate School of Eigineering, Osaka University, 2–1 Yamada-oka, Suita, Osaka 565–0871, Japan (ishiguro@ams.eng.osaka-u.ac.jp)

The human-likeness of the android must be investigated not only from the standpoint of appearance but also perceptions and motion. The android developed in our study has a humanlike appearance and a motion mechanism with many degrees of freedom, which can imitate various human postures and gestures. Even a subtle motion such as a shoulder movement caused by breathing can be expressed. Studies on biological motion have revealed that people can distinguish gender, emotions and differences in exerted effort from observation of point-light displays of another person's motion [7], [8], [9], [10]. This fact suggests that we obtain much information from slight differences in people's posture and motion. The android can also convey such information in communication with humans by displaying such subtle motions or slight changes in posture and motion. In addition, we can examine how these motions influence human-robot communication using the android.

A straightforward method by which to animate the android is through implementation of the motion of an actual human subject, as measured by a motion capture system. Riley et al. [11] and Nakaoka et al. [12] calculated human joint angles from three-dimensional motion data measured by a motion capture system by solving the inverse kinematics, and implemented them in the joints of a humanoid robot. In these studies, the authors assumed the kinematics of the robot to be similar to that of a human body. However, since the actual kinematics and joint structures are different between human and robot bodies, calculating the joint angles from only the human motion data could in some cases result in visibly different motion. Moreover, evaluating the similarity between a human motion and the mapped motion of the robot is an important issue. Harada et al. [13] investigated a criterion by which a person evaluates the similarity of a pair of poses or motions of computer graphics human figures. The authors revealed that a human's intuitive measure of similarity is enhanced by similarities in the positions of each body region rather than the joint angles. Most previous research transfers the joint angles measured for humans into the joint angles of the robots to allow for the humanoid robot to have different forms and sizes. In contrast, since the shape of an android's body is similar to that of a person, the positions of each body region can be compared without ambiguity. The above-mentioned results suggest that in order to implement humanlike motion in the android we must

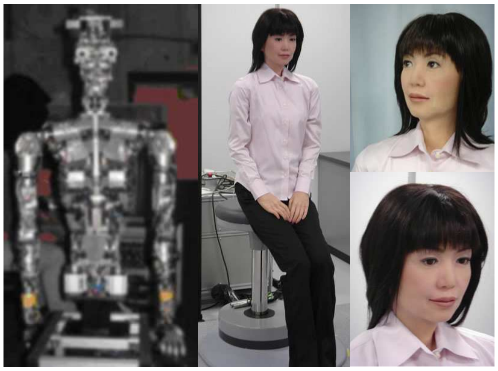

Fig. 1. The developed android "Repliee Q2".

imitate human motion through the similarities of positions of each body region rather than joint angles.

In order to realize human motion in robots, it is necessary to generate a sequence of desired postures and to design a controller to reproduce the sequence, considering the dynamics of the actuators. In this research we divide this problem into two sub-problems; implementing the human postures and constructing the controller. This paper proposes a method to transfer the data gathered on human posture, as measured by a motion capture system, into a three-dimensional position space for the android. By defining the posture similarity between the human and android as the similarity of the surface shape of the bodies, we can avoid the deviations in posture that occur due to differences in the kinematics. The method is essential in transferring a person's posture to an android which closely resembles a human being.

II. The Developed Android

Fig. 1 shows the developed android called *Repliee Q2*. The android is modeled after a Japanese woman. The standing height is about 160 cm. The skin is composed of a kind of silicone that feels like human skin. Forty-two highly sensitive tactile sensors composed of PVDF film are mounted under the android's skin and clothes over the entire body. Since the output value of each sensor corresponds to its deforming rate, the sensors can distinguish different kinds of touch. The soft skin and tactile sensors give the android a human appearance and enable natural haptic interaction.

The android is driven by air actuators (air cylinders and air motors) that give it 42 degrees of freedom (DoFs) from the waist up. The legs and feet are not powered; it can neither stand up nor move from a chair. Many air actuators can be mounted in the human-sized body thanks to a high power-to-weight ratio of the actuator.

The configuration of the DoFs is shown in Table I. Fig. 2 shows the kinematic structure of the body, excluding the face and fingers. Some joints are driven by the air motors and others adopt a slider-crank mechanism. The DoFs of the shoulders enable them to move up and down and backwards and forwards; this shoulder structure is more complicated than that of most existing humanoid robots. Moreover, parallel link mechanisms adopted in some parts complicate the

TABLE I
THE DoF CONFIGURATION OF REPLIEE Q2.

	Degree of freedom
Eyes	pan×2 + tilt×1
Face	eyebrows×1 + eyelids×1 + cheeks×1
Mouth	7 (including the upper and lower lips)
Neck	3
Shoulder	5×2
Elbow	2×2
Wrist	2×2
Fingers	2×2
Torso	4

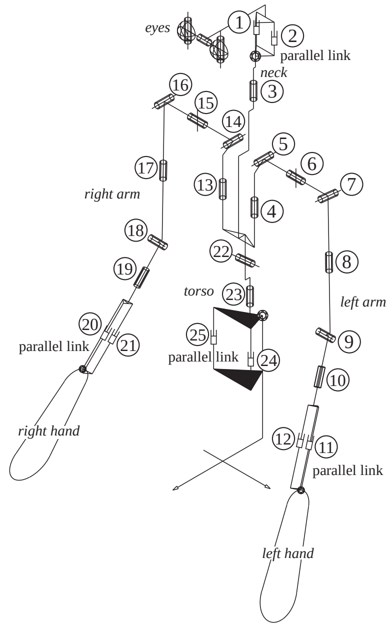

Fig. 2. Kinematic structure of the android.

kinematics of the android, for example in the waist. The android can generate a wide range of motions and gestures as well as various kinds of micro-motions such as the shoulder movements typically caused by human breathing. Furthermore, the android can make some facial expressions and mouth shapes. Because the android has servo controllers, it can be controlled by sending data on the desired joint angles (cylinder positions and rotor angles) from a host computer. The compliance of the air actuator makes for safer interaction with movements that are generally smoother than other systems typically used. Because of the complicated dynamics of the air actuator, executing the trajectory tracking control is difficult.

III. The Basic Idea

In order for the android to imitate human motion, we first measure the motion of a human subject using a motion capture system and obtain a posture sequence by extracting postures at every keyframe. The android then must reproduce the given posture sequence. The kinematics and dynamics of the developed android are complicated as mentioned above. Basically, there are two main difficulties:

1) Calculating the android's joint angles (cylinder positions and rotor angles) to reproduce a target posture from the three-dimensional position data by solving the inverse kinematics of the android in consideration of the difference of kinematics and the deformation of the silicone skin.
2) Designing a controller to track the desired trajectories of the joint angles in consideration of the dynamics of the actuators.

We divide the problem of motion mapping from the subject to the android into these two sub-problems. This paper deals with the former problem.

In order to transfer the subject's posture to the android, it is necessary to calculate suitable joint angles to ensure the android's posture resembles that of the subject. Here we must consider the following aspects:

- The appearance of the android closely resembles that of humans.
- The joint structure and arrangement of an android are different from those of a human body. Unlike the joint of an android, the rotation center of the human joint moves in addition to the rotation.

Since the shape of the android's body is similar to that of a person, each body region (e.g. head, elbow, wrist, and shoulder) can be made to correspond without ambiguity. As a past study has suggested [13], the positions of each body region should be matched. Most previous research has assumed the kinematics of a robot to be similar to that of a human body, and the joint angles of a human have been implemented as the joint angles of the robot to normalize their different body shapes. However, using joint angles calculated only from a human's posture data could lead to the body regions being in different positions since the kinematics of an android actually differs from those of a person. Hence, the positional errors of the body regions should be fed back into calculation of the joint angles. Our method imitates a human posture based on the similarities of positions of each body region. In other words, it can be said that the method transfers the person's surface shape to the android because the positions of body regions are obtained by measuring positions of markers attached to the body surface.

In order to calculate the joint angles based on the desired positions of body regions (three-dimensional position data), it is necessary to solve the inverse kinematics of the android. However, this leads to the following difficulties:

- The kinematics relating the joint and surface positions are complicated since the android's body is covered by an elastic silicone skin and cloth which are not fixed to the links.
- The inverse kinematics of regions where a parallel link mechanism is adopted cannot be solved analytically.

We then adopt an optimization method to find the desired joint angles by minimizing an evaluation function that considers the positional error of all body regions. We can then avoid dealing with skin deformation in modeling the android's kinematics.

In designing a suitable evaluation function, the following issues arise:

- The range of joint motion of the android is more limited than that of an average person.
- The search space is large since the android has many degrees of freedom.

With regard to motion mapping based on joint angles, Pollard et al. [14] proposed a method to adaptively scale the human joint angles to the robot's range of motion. Their method considers only differences for individual joints. In contrast, our method attempts to minimize the positional error without scaling, because the joint angles of the human subject are not calculated. Additionally, there is the problem of selecting which joints are used to compensate the positional error, owing to limitations in the range of joint motion. Unlike the method in [14], all joints are used in our method. In respect of the optimization cost, the optimization process needs to be divided into sub-processes, one for each body part, such as the head, torso, and left and right arms as shown in [11]. However, it is possible that a difference in hand position could be compensated by a movement of the waist as well as the elbow and shoulder. In order to map the posture of the entire body, it is necessary to compensate for differences in body shapes by adapting all joint angles. We thus adopt an evaluation function that considers the positional errors of all body regions and search the desired joint angles without splitting the search space.

IV. POSTURE TRANSFER METHOD

This section describes the method of transferring the posture of a human subject to the android. The human subject is assumed to have a similar body shape to the android and is asked to sit on a chair in the same manner as the android is capable of. We use a motion capture system to measure the posture of the human subject and the android. This system can measure the three-dimensional positions of markers attached to the surface of the body in a global coordinate space. First, some markers are attached to the android so that all joint motions can be discriminated. Then the same number of markers is attached to corresponding positions on the subject's body. Data for both subject and android are transformed into a local coordinate system fixed at the center of their bodies. There is no scaling between the two coordinate systems.

The marker positions of the subject and android $\boldsymbol{x}_{hi}, \boldsymbol{x}_{ai} \in \mathcal{R}^3$ $(i = 1, \ldots, n)$ are represented in local coordinates, where n is the number of markers. Let $\boldsymbol{u} \in \mathcal{R}^m$ be the android's joint angles, where m is the number of actuators that should be controlled. First, the subject's posture is measured and $\boldsymbol{x}_{h1}, \ldots, \boldsymbol{x}_{hn}$ are obtained. Then, the method finds $\boldsymbol{u}$, which minimizes the following evaluation function by a hill-climbing search algorithm.

$$E_p = \sum_{i=1}^{n} w_i \delta_i, \tag{1}$$

$$\delta_i = ||\boldsymbol{x}_{ai} - \boldsymbol{x}_{hi}||, \tag{2}$$

where δ_i is the distance between corresponding pairs of markers (hereinafter: position error) when both coordinates are superimposed and $\boldsymbol{w} = (w_1, \ldots, w_n)^T$ is a weight vector for evaluation of position errors.

Since a hill-climbing search always explores a solution in the direction in which a given evaluation function is improved, it is more likely to get stuck in a local optimum (a sub-optimal point or plateau that has no superior neighboring points) than simulated annealing. Regarding this problem, it is known that multi-objectivization reduces local optima in single-objective problems [15]. We add another evaluation function to (1) to reduce the number of local optima in this method. In this paper, we use the standard deviation σ_s determined from the weighted position errors $\{w_1\delta_1, \ldots, w_n\delta_n\}$, and obtain the following evaluation function.

$$E = E_p + \alpha\sigma_s, \tag{3}$$

where α is a weight for evaluation of standard deviation. The search procedure is summarized as follows:

1) Initialize $\boldsymbol{u}$ and calculate E.
2) Generate the next candidate solutions $\boldsymbol{u}'_1, \ldots, \boldsymbol{u}'_m$ as follows:

$$\boldsymbol{u}'_i = \boldsymbol{u} + g_i z \boldsymbol{e}_i, \tag{4}$$

where $\boldsymbol{e}_i$ is a vector whose i-th element is 1 and whose other elements are all 0. z is a random variable that follows a normal distribution $N(0, \sigma)$. g_i is the gain for the i-th joint's variation.
3) Evaluate every candidate solution according to (3) and find the candidate $\boldsymbol{u}'_{min}$ which has a minimum evaluation value E_{min}.
4) $\boldsymbol{u} \leftarrow \boldsymbol{u}'_{min}$ and $E \leftarrow E_{min}$, if $E_{min} < E$.
5) If E does not change for n_c steps, the search terminates. Otherwise, go to 2.

V. POSTURE TRANSFER EXPERIMENT

A. Experimental Setup

To verify the proposed method, we conducted an experiment testing how effectively human posture was transferred to the android Repliee Q2. We used only 21 of the android's 42 DoFs by excluding the 13 DoFs of the face, the 4 of the wrists, and the 4 of the fingers $(m = 21)$. Eighteen markers (4 markers for the head, 2 for the chest, 2×2 for the shoulders, 2×2 for the elbows, and 2×2 for the wrists) were attached to the android as shown in Fig. 3. Another eighteen markers were attached to corresponding positions on the subject's body. The markers attached to the neck and the belly were not used in this experiment. Because the android's waist is fixed, the middle point of the positions of the markers on the waist set the origin of the android-centered coordinate system (Fig. 3). The origin of the subject's coordinate system was similarly defined. We used a Hawk Digital System[1] for motion capture. The system is highly accurate with a measurement error of less than 1 mm.

[1]Motion Analysis Corporation, Santa Rosa, California. http://www.motionanalysis.com/

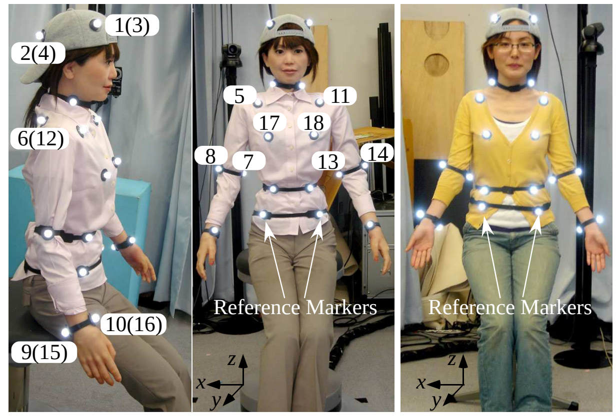

Fig. 3. The marker positions. The number in parenthesis indicates the marker on the opposite side.

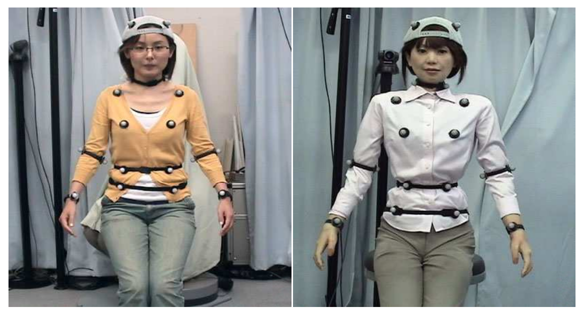

Fig. 4. The subject's postures mapped onto the android (sitting (reference), $\delta_e = 28.6$mm, $\sigma_s = 6.5$mm).

The weight of the standard deviation α in (3) was set to 18.0 so that the positional errors and standard deviation were of the same order of magnitude. The gains of joint variation $g_1, \ldots, g_m$ and σ in (4) were obtained empirically so that the marker movements involved in the joint movements were of the same order of magnitude. All weights for position error were set to $w_i = 1$. The parameter defining the convergence criterion n_c was set to 20 steps.

The android closely resembles a human being in appearance to the point that it is possible to convey information about a situation or emotion by displaying a slight difference

Fig. 5. The subject's postures mapped onto the android (discouraged, $\delta_e = 24.9$mm, $\sigma_s = 6.3$mm).

Fig. 6. The subject's postures mapped onto the android (taking a deep breath, $\delta_e = 21.6$mm, $\sigma_s = 5.5$mm).

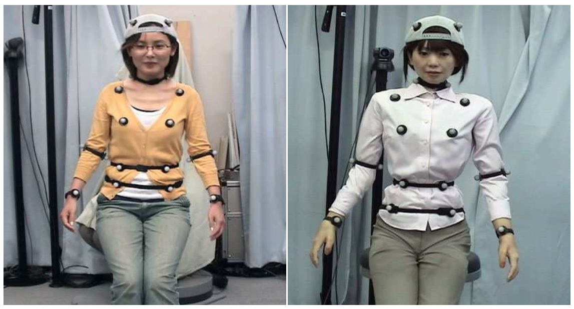

Fig. 7. The subject's postures mapped onto the android (avoiding a close object, $\delta_e = 29.7$mm, $\sigma_s = 5.0$mm).

in posture. It is meaningful to investigate how a slight difference in an android posture affects the human-likeness. We transferred the following five postures to the android (experiment 1).

1) The subject is sitting (reference posture).
2) The subject appears discouraged and has sagging shoulders.
3) The subject is taking a deep breath.
4) The subject is avoiding an obstacle that appears close to the face.
5) The subject is holding heavy baggage with one hand.

The four postures (2 to 5) are similar but are slightly different to the reference posture. We asked the subject to adopt a natural posture while roughly taking into account the limited range of motion of the android. The initial posture (initial $\boldsymbol{u}$) was set by transferring the reference posture using manual control of the android. For the other postures, the mapped reference posture was given as the initial posture.

In addition to the above, toward the goal of motion mapping, we extracted sequential postures from the subject's motion and transferred them to the android (experiment 2). Fourteen postures were extracted from a guiding behavior recorded every 166 msec. The postures were transferred sequentially; the mapped posture was given as the initial $\boldsymbol{u}$ when transferring the posture of the next time step, with the exception of the first time step.

B. Experimental Results and Analysis

1) Experiment 1: Figs. 4-8 shows the postures of the subject and the corresponding postures of the android. In

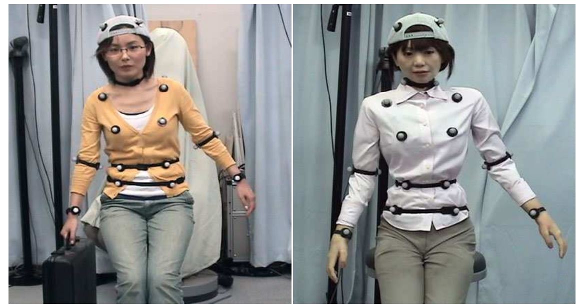

Fig. 8. The subject's postures mapped onto the android (holding heavy baggage, $\delta_e = 36.1$mm, $\sigma_s = 12.8$mm).

each figure, the right image shows the android. δ_e and σ_s are the average of the position errors and the standard deviation, respectively. Because the body shapes of the subject and android are not identical, the average of the residual position error is about 30 mm for each marker. In addition, the limitation of the range of joint motion in the android causes a residual error. Although α in (3) was determined such that δ_e and σ_s have the same order of magnitude, the position error was eventually much more weighted.

In Fig. 5, the subject's shoulders sagged and dropped. In the mapped posture, the angles of joints 5 and 14 (see Fig. 2) had changed so that the android's shoulders dropped compared to the reference posture. As a result, a posture indicating discouragement was expressed. However, the angles of joints 4 and 13 also changed, so that the android drew back its shoulders even though the subject's shoulders were sagged. It seems that this is because the subject bent the upper body backward.

In Fig. 6, the subject has squared shoulders. In the mapped posture, the angles of joints 5 and 14 changed so that the android also had squared shoulders and the angles of joints 4 and 13 changed, drawing the shoulders back. Furthermore, the angle of joint 22 changed so that the upper body of the android was bent backward. As a result, a posture showing a deep breath was expressed. However, the posture of the head was not appropriately transferred.

The subject in Fig. 7 was avoiding an obstacle that appeared close to the face. The right shoulder was drawn back and the left shoulder dropped. By moving mainly joints 22 and 23 and cylinder 24, the android was able to turn to the right a little and bend its upper body back and to the left. As a result, a posture indicating avoidance of a close object was expressed.

The subject in Fig. 8 had her upper body bent towards the right-front direction. Although the android does not have an actuator to enable its backbone to bend in the lateral direction, the android was able to imitate the subject's upper body posture by moving mainly joint 22 and cylinder 25. Since the android cannot straighten its elbow due to the limited range of joint motion, the right arm pose cannot be imitated. Therefore, the variance in position error was comparatively large.

Thus slight differences in posture can be implemented in

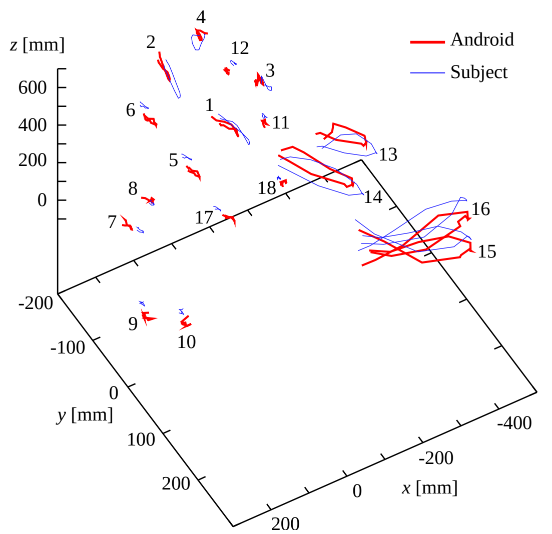

Fig. 9. The marker trajectories in the subject's posture sequence and android's posture sequence in the experiment 2. The number indicates the marker ID.

the android by transferring human postures, although there are positional errors since the body shapes of the subject and the android are not identical. In the experiments, the head pose tended not to be appropriately imitated. One of the causes of this is that the android has no DoF to push its head forwards. It is necessary to reconsider the marker places and the evaluation function.

2) Experiment 2: Fig. 10 shows a sequence of postures where the subject was asked to indicate a direction for the purpose of guiding someone. The number denotes the sequence. We show the results every two steps due to limited space. Since the posture of the subject stretching out the left hand is out of the motion range of the android, the errors in step 5 to 9 were comparatively large. However, the postures did have the effect of drawing attention to the left. Fig.9 shows the marker trajectories in the desired posture sequence (subject) and mapped posture sequence (android). It can be seen that there are biases in the positional errors. The head direction of the android was different from that of the subject as well as the results in the experiment 1. It seems that the optimization process got stuck at a suboptimal solution. The marker places and the evaluation function must be reconsidered.

In this experiment, we extracted a motion sequence of postures from the subject and transferred these to the android toward the goal of motion mapping. From the sequence of mapped postures, we can obtain the desired trajectories for the joint angles. However, it is difficult to achieve accurate trajectory tracking control of the air actuators by feedback control since the air compressibility acts to increase the response lag (i.e., dead time is large). Therefore, it is necessary to design a feedforward controller, which is equivalent to the inverse model of the android. Moreover, we must consider how to define the keyframes from which the subject's postures are extracted. Further research on this matter is required.

C. Comparative Experiments

In order to verify the advantages of the proposed method of surface shape mapping, we conducted an experiment to compare it with the existing method proposed by Riley et al. [11]. Their method models a subject's kinematics using the same kinematics structure as a target humanoid robot with the exception of the link size. The joint angles of the subject are calculated from the three-dimensional positions of markers attached to the surface of the body and are input to the joints of the robot. Since the physical body size and joint structure of the subject are different from those of the robot, the locations of the joint axes in the subject are unknown (the directions of the axes are assumed to be the same as those of the robot). Then, the locations and angles of the joints are estimated based on kinematics constraints.

Most previous research, including that of Riley et al. [11], requires that the markers are placed as close to the bone as possible in order to prevent the markers' movement differing from the bone movement. However, calculating human joint angles with fixed axis locations could produce a different pose since the rotation center of the human joint moves with its rotation. Our method does not have a constraint on the marker places and does not need to consider the moving rotation center of the joint explicitly. In this experiment, the mapping results of our method and the method proposed in [11] were compared using the marker set shown in Fig. 3. In order to simplify, only the right arm postures were implemented. The joints of the right arm and waist (joints 13 to 19, and 22) and the markers attached to the right arm (markers 5 to 10, and 17) were used. Eleven postures were extracted from a handshake motion at every 333 msec. The method in [11] estimated the subject's joint locations from the eleven postures and calculated the joint angles in each posture, which were fed to the joints of the android.

The results are shown in Fig. 11. The middle column shows the captured sequence of the subject's posture (six of eleven postures). The left column shows the results of the proposed method and the right column shows those of the method in [11]. The subject raised her right hand/wrist above the elbow level (making an acute angle at the elbow joint) and offered her hand for a handshake. The subject also raised her hand above the elbow level when she retracted her hand. This motion was realized by the android using our method but not using the method of Riley et al. [11]. It seems that the approximation of the shoulder joint by a simple joint caused a displacement of the hand position. The proposed method is able to avoid this kind of displacement by transferring the surface shape of the subject.

D. Future Work

In order to realize a humanlike appearance for a human sized body, the mechanical structure of the android Repliee Q2 is restricted. From our experiments, we realized that the spine needs to have a DoF to imitate human postures, e.g., stooping and extending its head forwards. It is important to develop a mechanism equivalent to the human spine in development of the android.

Since the body shapes of the subject and Repliee Q2 are not identical, there must be positional errors. In this experiment, we defined the evaluation function so as to reduce the variability of the errors: all of the weights $w_1, \ldots, w_n$ were set to 1. Harada et al. [13], however, have shown that when comparing upper body shapes, humans pay more attention to regions more distant from the body center, such as the hands or head. This result suggests that it is necessary for our method to appropriately define the weights to maximize a person's intuitive measure of similarity. Furthermore, the body regions to be measured should be selected according to the intuitive measure of similarity even though we attached the markers so that all joint motions of the android could be discriminated. Through experiments that evaluate a person's intuitive measure of similarity, it will be possible to determine the appropriate weights and marker places. These studies will bring essential knowledge towards realization of natural postures in the android.

VI. SUMMARY

This paper proposed a method for transferring human posture to the android for the purpose of implementing natural motion in the android. The method makes use of the fact that a human's intuitive measure of similarity is best achieved by similarities in the positions of each body region of the android [13]. Most previous methods that assume the kinematics of a robot is similar to that of a person body produce visibly different postures since the kinematics of the robot is actually different. Moreover, the markers need to be placed as close to the bone as possible to measure accurate joint angles of a person. The proposed method is able to avoid the displacement caused by different kinematics structures, the complicated inverse kinematics problem, and the constraint of marker placement by transferring the surface shape of a human using a heuristic search method. The method is also able to inhibit the effect of the accumulated joint angle error increasing with displacement towards the end of the limbs by assessing the position error of all body regions. These features are significant for the android, which has a very humanlike appearance, complicated kinematics, and soft skin. The experiments showed that slight differences in posture can be implemented in the android. Furthermore, it was shown that in some cases the proposed method can reproduce a posture that is more similar to a human's than the existing method.

Although the experiments in this paper did not deal with facial expression, the proposed method can be applied to this also. In particular, if the shape of a flexible body region such as the lips is controlled by multiple actuators the kinematics including the skin deformation becomes further complicated. Our method will also be useful in this case. Whether facial expressions can be transferred accurately to the android needs to be clarified. As described above, potential improvements in the search efficiency and evaluation function must be further investigated along with more appropriate marker placement. Furthermore, this method must be integrated with a trajectory-tracking controller for the air actuators to realize natural motion in the android.

This method is able to not only implement humanlike posture in the android but serves as a test bed for further study of human-robot communication. That is to say, the method enables us to study the essence of human-robot communication through implementing humanlike postures and motions in the android.

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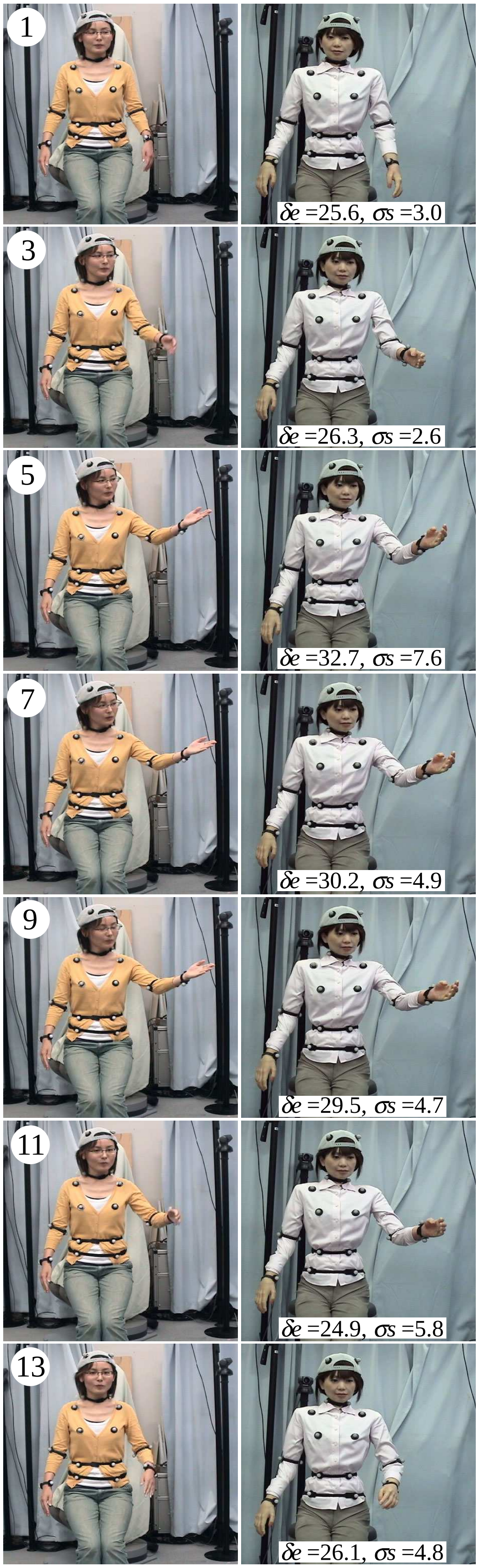

Fig. 10. The subject's postures mapped onto the android (guiding).

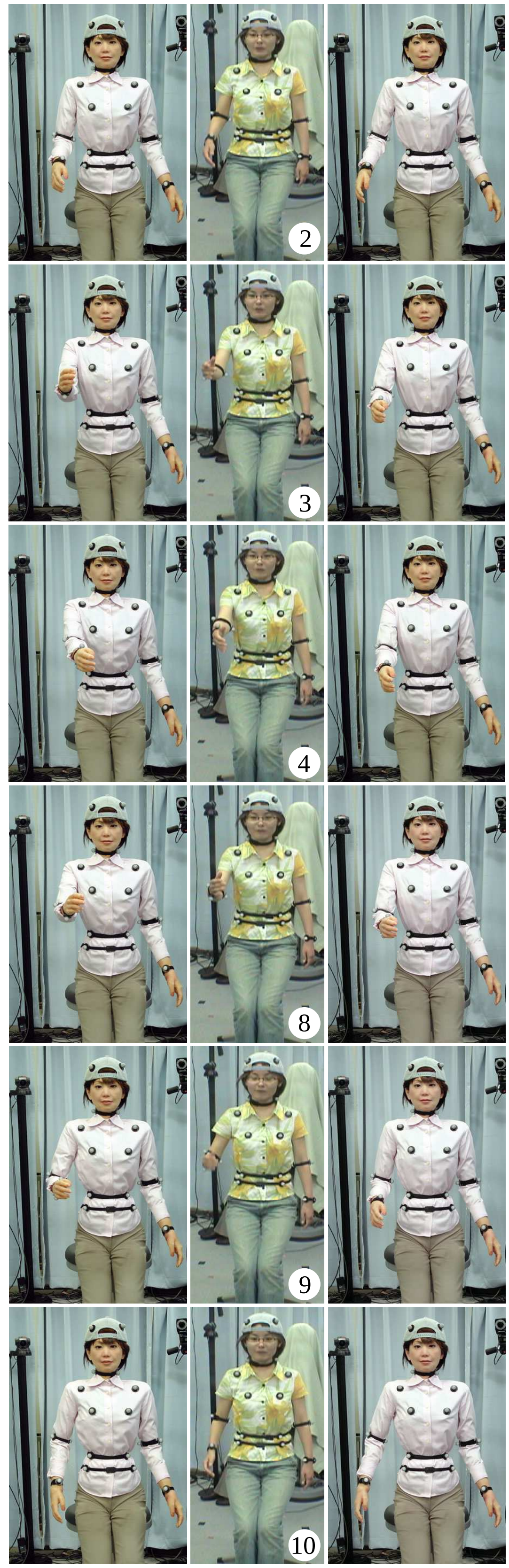

Fig. 11. The android postures generated by the proposed method (left) and the existing method [11] (right).