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Design Strategy for Robotic Spines of Androids with a Natural Postural Appearance

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***Abstract*— This paper presents a design strategy for simple robotic spines for androids with a natural upper-body postural appearance. The strategy allows us to develop a robotic spine with a minimum number of required movable joints, granting androids the ability to adapt natural upper-body postures while performing various gestures. In this study, by restricting the motion of the spine to sagittal plane for simplicity, the minimum number of required movable joints was determined using measured human spinal motion data. The error between the measured data and the model with a limited number of movable joints was calculated and the required number of joints was determined depending on its value. The efficacy of the proposed design strategy was validated through impression evaluation with five subjects. We also developed a prototype with four movable joints using low-cost mass produced parts.**

I. INTRODUCTION

Humanoid robots working in our society and daily living space have gained increased research attention off late. Studies on robots imitating human forms and movements have mainly focused on three aspects.

- Development of robots that automate or support human activities.
- Understanding human physical mechanisms and achieving dynamic movement using bio-inspired robots.
- Realizing smooth communication with humans using facial expression and whole-body gestures.

Regarding the first point, disaster-recovery or assistive robots are currently under development worldwide [1], [2]. Regarding the second point, the bio-inspired research field aims to develop robots with high physical performance and dynamic movement by implementing structures similar to those of biological muscles and bones [3], [4], [5], [6]. Finally, the human-robot interaction research field aims to understand modes of communication and emotional expression between humans and robots through facial expressions and gestures with a focus on natural appearance [7], [8], [9], [10]. Android research is included in the third field [11], [12], [13], [14].

An android is a robot that can move through actuators, i.e., electric motors and pneumatic cylinders, in contrast to still human figures, such as mannequins or wax figures. Therefore, to realize a natural human likeness, the robot needs not only human-like appearance but also motion, i.e., natural facial and postural expression [15], [16], [17]. In previous research concerning androids, the appearance and mechanisms of the robots were intuitively designed by artists or engineers. As a result of this background, the systematic methodology for designing the mechanisms and structure of an android is limited [18]. Mechanism and structural design based on motion analysis of human facial and postural expression is important for realizing natural and human-like androids.

Regarding postural expression, the human spine comprises 33 bones and many muscles for its smooth and flexible movement [19]. This structure allows humans to assume various upper-body postures, which are (like facial expressions) used to express various emotions [20]. For example, sitting hunched and looking down the floor indicate disappointment. Most previous research regarding robotic spines has focused on the functional capabilities and dynamic characteristics of biological spines in order to realize robots with high-performance motion [21]. However, robotic spines with a natural postural appearance for expressing emotions have not been studied well.

In this research, we focus on the human-likeness and naturalness of postural appearance from the hips to the head. Since robotic spines with a complicated structure, such as that of the Kenta robot [22], have had several joints driven by an actuation mechanism composed of cables and pulleys for realizing high-performance robotic motion, the control is difficult and the durability is low. we present a design strategy for a simple robotic spine with a minimum number of joints required to realize natural postural appearance considering practical utility. Since a robotic spine with a simple structure can be constructed from a few mass produced parts, the complexity of the control is reduced, the durability of the structure is increased, and the robot becomes more cost effective. In the proposed design strategy, the minimum number of required joints for achieving natural postural appearance and the lengths of the links between them are determined based on actual human spinal motion during everyday gestures, such as bowing or back-stretching. The experiment for the measurement of the spinal motion was conducted with two subjects. The test subjects' spine motions were restricted to the sagittal plane for simplicity. The efficacy of this strategy was validated through an impression evaluation by five different subjects using line animations of several human spinal motions generated from analyzed data collected by human motion measurement. We also reported

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the development of a prototype with four movable joints using low-cost mass produced parts.

II. DETERMINATION OF NUMBER OF JOINTS REQUIRED FOR A SIMPLE ROBOTIC SPINE

Figure 1 shows side views of the android named *Geminoid F* and a human. Geminoid F is a female-type android with one degree of freedom at the hip and three degrees of freedom at the neck. Since there are no degrees of freedom on its spine, it makes an inverted-pendulum-like motion around its hip joint. On the other hand, humans can generate various upper-body postures owing to their spine with many joints. In Fig. 1, each red line represents a link model generated from the motion-capture data of the spine at certain times and the black dots represent the trajectory of each marker. This trajectory takes an almost-circular arc shape, but differs from the motion trajectory of the android's spine. The stick-like spine of the android gives in the hard impression of always looking nervous.

The purpose of this research is to find the *minimum number* of joints required for a robotic spine to realize natural postural appearance with a simple structure. In the section below, a design strategy for determining this number through analysis of motion-capture data of a subject's spine is given. For simplicity, we address on the motion in the sagittal plane.

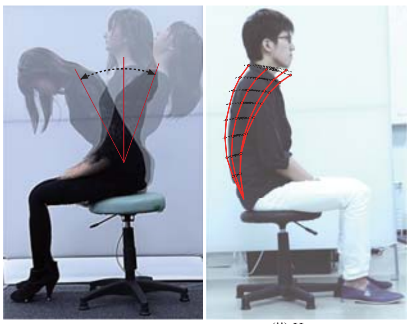


Fig. 1. Comparison of the postural appearance between an android and human.

To this aim, the proposed robotic spine consists of multiple links connected in series. Several statistical methods suggest that the human posture has relatively low dimensionality while its body has many degrees of freedom [23]. Even if the movement is in a low dimensional space by moving multiple joints simultaneously, the robot has to have same number of joints to the human to reproduce the motion. In this research we propose a design strategy for the robotic spine consisting of mass produced parts.

A. Measurement of Human Spine Motion

The spinal motion was recorded during a scenario in which a human participant performed several motions. Figure 2 shows the experimental setup. The participant sat in front of a computer screen and performed various activities by following instructions on the screen. The participant's motion was measured by a motion-capture system, OptiTrack V120:TRIO, at a 120Hz sampling rate.

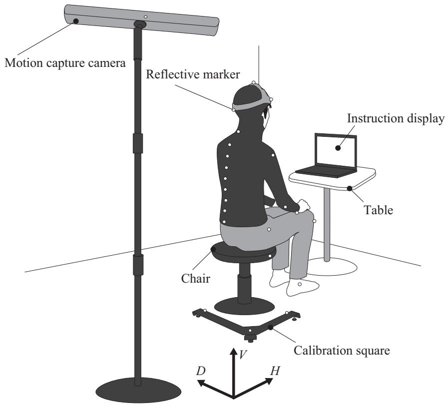


Fig. 2. Experimental environment.

To measure the spinal motion, nine reflective markers were attached to the spine and one marker was attached to the chair as a reference point. Markers on the head, arm, and leg were used to evaluate the subjective impression of the spinal motion, since this impression might have been affected by movements of those organs. As a result, the positions of 19 markers were recorded by the motion-capture system. Nine markers are attached on the spine. The top marker is in the proximity of the vertebra prominens and the bottom one is on the hip. The positions of other markers on the spine is determined to avoid inaccurate measurements such as occlusions.

The experimental procedure is outlined as follows. The motion-capture system was calibrated using a reference frame (calibration square) put by the chair, which was removed from the field of view. The participant sat on the chair and performed four motions (bowing, stretching their back, raising their arm, and typing a key) by following instructions on the monitor. The top picture of Fig. 3 shows the rest posture that the participant was directed to assume after each motion was completed. The four bottom figures show the target postures of the motions.

In this research, we focused on the spinal motion in the sagittal plane, and so the participant was directed to neither bend laterally nor rotate their body during the experiment.

B. Example of Measured Spine Motion

Figure 4 shows the movement of the markers during bowing motion. The trajectories of the spine markers on the sagittal plane are shown in (a). The frontal direction of the body is to the left. The temporal change in the heights of markers are shown in (b); the horizontal axis denotes time (s) and the vertical axis denotes height (m) (along V axis in Fig. 2).

C. Kinematic Model for Robotic Spines

Figure 5 shows a kinematic model of the robotic spine, which has two movable joints. In this case, the robot consists

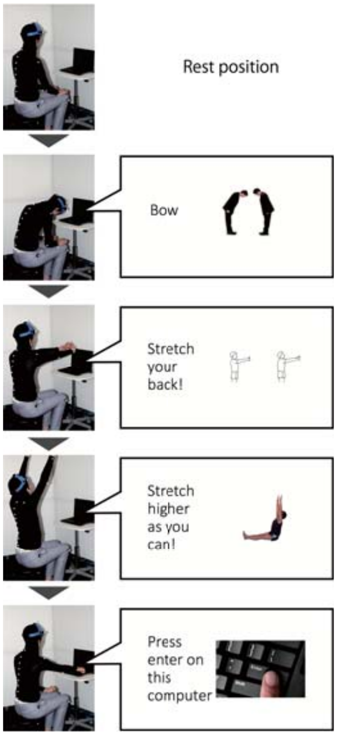
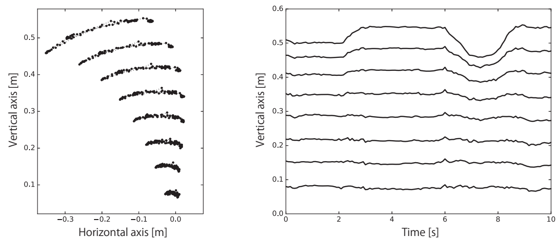


Fig. 3. Motions and instructions for the subject.



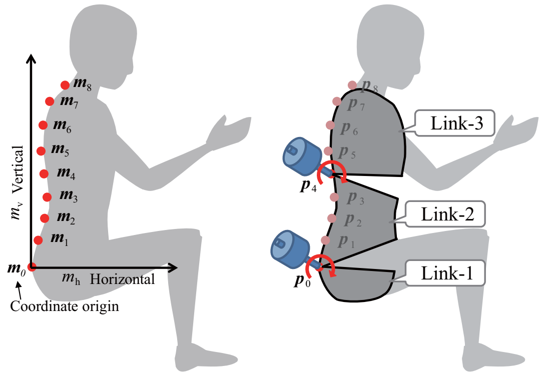
(a) (b)

Fig. 4. Measurement of human spinal markers; (a) trajectories of each marker; (b) movements of each marker (vertical axis).

of three rigid links, to which virtual markers are attached. The initial positions of the markers were determined as below. First, the reference posture of the robot was defined according to the average positions of the markers on the human subject.

Next, movable joints were added at the positions of some selected virtual markers. In the case of Fig. 5(b), the 0-th and 4-th markers were selected. As a result, groups of virtual markers, $\{p_1, p_2, p_3\}$ and $\{p_5, \cdots, p_8\}$, were fixed to links 2 and 3, respectively (the bottom link was link 1). The markers p_0 and p_4 were placed at the first and second joints, respectively.

The similarity between two postures is defined by the sum of the squared distances between the markers. p_i and m_i, which denote the positions of the virtual and measured markers, respectively; in Fig. 6(a), d_i denotes the distance between the i-th markers. The positions of the i-th virtual



(a) Markers on the human spine. (b) Robotic spine.

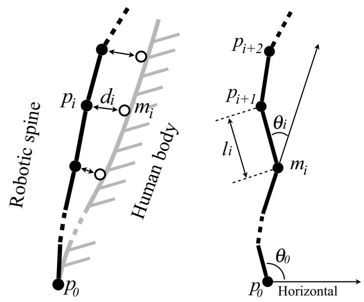
Fig. 5. Design of a simple robotic spinal model.

marker is calculated as

$$p_i = \left(\sum_{j=0}^{i} l_j \cos \left\{ \sum_{k=0}^{j} \theta_k \right\}, \sum_{j=0}^{i} l_j \sin \left\{ \sum_{k=0}^{j} \theta_k \right\} \right), \quad (1)$$

where l_i and θ_i are the length and angle of the i-th link, respectively (Fig. 6(b)). Thus, the similarity of the posture is defined as

$$E(m, \theta) = \frac{1}{2} \sum_{i=0}^{8} d_i = \frac{1}{2} \sum_{i=0}^{8} \|p_i - m_i\|^2. \quad (2)$$



(a) (b)

Fig. 6. Relationship between the robotic spine and the markers on the subject. (a) Kinematic model of the robotic spine and the subject's body. (B) kinematic model of the robotic spine with movable and fixed joints.

In order to imitate human spinal posture with this robotic spine, the optimal joint angles, $\theta^*_{i \in I_{\mathrm{Selected}}}$, are determined so as to minimize equation (2). The optimal value is obtained by repeatedly updating the angle according to the gradient as

$$\theta_i := \begin{cases} \theta_i - \eta \frac{\partial E(m,\theta)}{\partial \theta}, & i \in I_{\mathrm{Selected}} \\ \theta_i := \theta_i, & i \in \neg I_{\mathrm{Selected}} \end{cases}$$

until the angle converges. Here, η is a small positive constant. Note that joint angles $\theta_{i \in I_{\mathrm{Selected}}}$ are variable, whereas $\theta_{i \in \neg I_{\mathrm{Selected}}}$ are fixed. In the case of Fig. 6, $I_{\mathrm{Selected}} = \{0, 4\}$.

Figure 7 shows the best-fitted postures of several robotic spinal models. Black stars represent the measured marker positions on the sagittal plane, whereas the blue points represent the virtual marker positions on the robotic spine. The red circles represent the positions of movable joints. The left-most figure shows the posture of the robotic spine with only one movable joint (at 0), and the right-most figure shows the posture of the robotic spine with 8 movable joints. When the number of movable joints is insufficient, the difference between the target human posture and the best-fitted robotic posture becomes large. The performance of each robotic spine model is evaluated by the average difference between the measured posture and reproduced posture by the robotic spine, i.e., the average squared error, in this research.

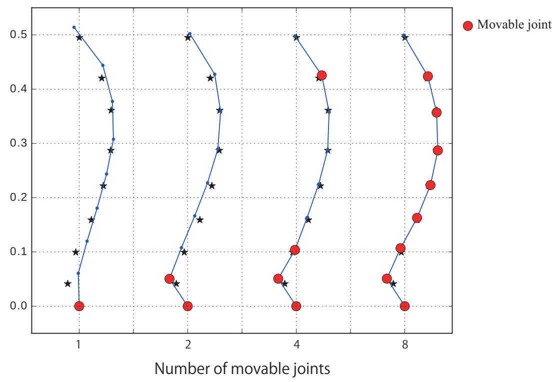


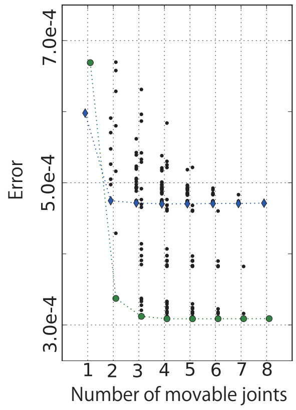
Fig. 7. Imitated postures by different robotic spinal models.

Figure 8 shows the average error between the target posture and the best-fitted posture of the robotic spine. The vertical axis denotes the average error and the horizontal axis denotes the number of movable joints. Each point denotes the average error of a robotic spinal model. The number of n movable-joints robotic spinal models is ${}_8C_n$, and the errors of the best models are connected by lines. Green squares and blue circles represent the errors of the best-fit models of two subjects' motions. The graph shows that the error does not decrease significantly even when the number of movable joints is larger than three. This result suggests that a simple robotic spine with a few movable joints can be designed by setting joint positions appropriately.

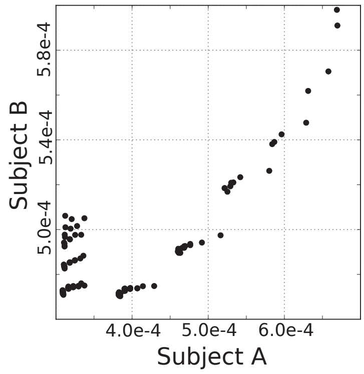
Figure 8(b) shows the correlation between the errors of robotic spinal models with the same structure (same number of movable joints) evaluated based on the motions of different subjects. This result suggests that the evaluation of the simple robotic spine determined by one subject is consistent with that determined by another subject.

III. SUBJECTIVE EVALUATION OF ROBOTIC SPINAL MODELS

There is no guarantee that a robotic spine that replicates human posture with a small error will appear convincing to human viewers. Therefore, we investigated the relationship between average error and subjective assessment by conducting an evaluation experiment using computer graphics.



(a) Error



(b) Correlation

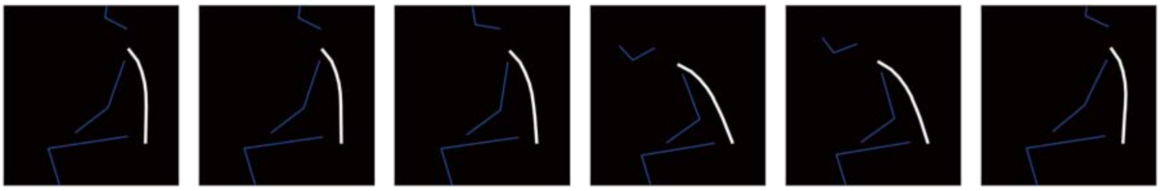
Fig. 8. Average deviation of imitated postures.

We employed the semantic differential (SD) method [24] to evaluate the impressions.

The subjects watched synthesized line animations of each robotic spine, as shown in Fig. 9, and assessed the movements on a 1-to-7 scale score in terms of 1) Pleasant/Unpleasant, 2) Smooth/Jerky, 3) Fast/Slow, 4) Careful/Thoughtless, 5) Interesting/Boring, 6) Experienced/Inexperienced, and 7) Human-like/Machine-like, referring to [25].

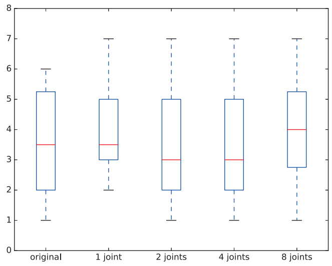
Figure 10 shows a box plot of the scores of robotic spinal models with different numbers of movable joints. Since five participants evaluated four motions, we obtained 20 scores for each model; "original" shows the score for line animations created by the measured marker positions. The best-fit model was used to create an animation for each number of joints. Each animation had a frame rate of 30 fps. The result shows that two- or four-joints robotic spinal models performed better than the others. One possible reason why the eight-joints model performed worse than the four-joints model is that it sometimes assumed a zigzag posture to decrease the error (over-fitting).

Although statistical tests between assessment of the robotic spinal models have not yet been conducted, the result suggests that there is a *magic number* that indicates the minimum number of joints required for making natural



(a) 4.0 s (b) 5.0 s (c) 6.0 s (d) 7.0 s (e) 8.0 s (f) 9.0 s

Fig. 9. A sample of the line animation movie (bowing motion).



(a) Scores

(b) Zigzag posture

Fig. 10. Subjective impression: human-like or machine-like.

gestures. To confirm this, it is necessary to increase the number of subjects participating in the impression assessment. Furthermore, it is necessary to consider the individual variability and the method of displaying animations, since there are large variations in each score and the impressions of the "original" model are not necessarily good.

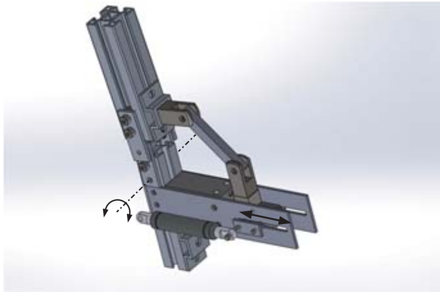
IV. PROTOTYPE

Based on the data acquired for the ideal robotic spine, some requirements for the mechanical design, as well as simplifying factors, were determined:

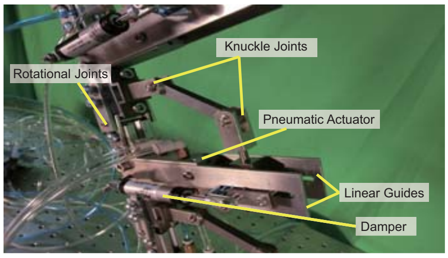
1) A minimum joint-to-joint distance, defined as the distance between adjacent points of rotation, of 100 mm must be possible for all joint pairs.
2) Each joint must be capable of reaching a minimum angle of -3° and a maximum angle of 17°, measured with respect to the immediately lower link. The face-forward direction was taken to be positive for all angular measurements.
3) The system must be driven exclusively by linear pneumatic actuators.
4) Each joint must be capable of providing passive damping to the system motion.

The mechanism was designed in a musculoskeletal fashion, where the components driving the actuation of motion are kept separate from those providing structural support to the system (Fig. 11(a)).

This design enables a high degree of modularity by which all components can be easily replaced with minimum effect on other portions of the design. The prototype consisted of four joint assemblies, four actuators, and five spinal links connecting them one to another. Each joint assembly was



(a) CAD model



(b) Assembled joint module

Fig. 11. Joint module of the robotic spine.

fastened to opposite ends of two spinal links with mounting brackets, allowing the links to rotate around a central axle in the assembly. An actuator acting in parallel to these links drove the system's rotation, with one actuator being used per joint. Advancing and retracting force of each actuator at 0.5 MPa are 101 N an 86.0 N, respectively. The pneumatic actuators were put in perpendicular positions toward the structure and were supported by linear guides. Parallel to the linear actuators, linear damping was added for the smoothest possible movements.

For mimicking the bone structure of the spine, T-slot aluminum extrusions were chosen due to their light weight and simple fastening methods, which also allow for fast adjustments. The linear guide and other linking components were made of stainless steel, due to their higher resistance.

Given the size restriction, a minimum compact actuator was desired to comply with the musculoskeletal and air-powered design requirements. Two rotational joints were used to transfer the linear motion into rotational motion by the links. Stability. For reducing vibration and maintaining smooth motion, a spring-damper system was added; this system maintained the setting of the initial position as well as smoothed the movement. The damper system helped to

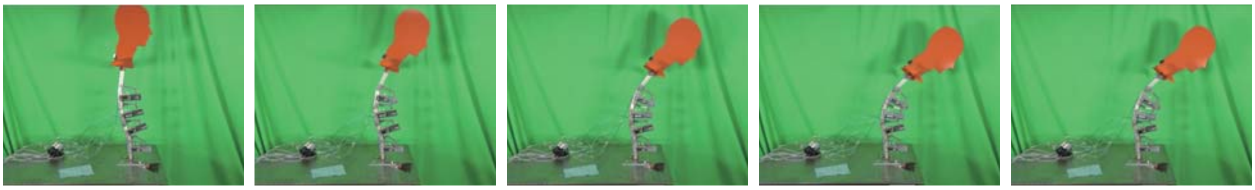


Fig. 12. Stroboscopic motion of the assembled prototype.

control the desired angular speed. Bearing were also put in the rotational joints for smooth angular movement. Figure 11(b) shows the assembled modular joint, and Fig. 12 shows the stroboscopic motion of the fully assembled model.

Each module is designed so that the length of the rigid link can be changed. The length of each link becomes the distance between the two successive movable joints. The shape of each module can be determined by the marker positions of the reference posture.

V. CONCLUSIONS

This paper presented a strategy for designing the robotic spine for an Android, a robot with a human-like appearance. To determine the minimum number of joints required for creating natural motions, we measured the motions of actual human spines and evaluated the models derived using the obtained data. We also built a prototype robotic spine based on our proposed design strategy. Although the results did not have strong support, it was suggested that a simple robotic spine allows the natural gestures required for daily human-robot interactions.

In this research, a few kinds of simple motions are addressed. Furthermore, the motions are restricted on the saggital plane. To evaluate the spine models in more natural scene remains in our future work. It also seems important to consider the change of the length of the body surface on human back. The position of each moving virtual marker becomes the joint position, while measured markers and human spine joints are separated. To take into account the distance between the joint positions and marker positions is also an issue in the future.

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