Baby steps: A design proposal for more believable motion in an infant-sized android

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Abstract. In studying human interaction, an android can serve as a precisely controlled apparatus to elicit human response. However, if an android is to substitute for a human being in social, cognitive, and neuroscientific experiments, it is essential to control for the effects of appearance by designing it to look and move as much like a human being as possible. The goal of this project is to create an infant-sized android to use in experiments. We propose design concepts for android joints and joint control to imitate human muscle control and appearance. The synchronized motion of servomotors and anatomically correct muscle-joint relations combine with the passive motion of elastic muscles to control the android's movements. The implementation of an android leg exhibits these concepts.

1 INTRODUCTION

People can perceive and respond to very humanlike robots (androids) as if they were human [18]. This cannot be said of less humanlike robots, because they fail to control for such extraneous variables as the effects of their nonhuman appearance. Thus, androids open the way for a new methodology to explore human cognition and interaction. They can be used in place of human stimuli as an experimental apparatus in social, cognitive, and neuroscientific experiments. This has the advantage of increasing experimental control, because androids—unlike human actors—can be programmed to respond with consistency and precision. In addition, an android's physical embodiment affords a sense of physical presence that human interaction with other technological alternatives lacks, such as interaction with computer-generated characters or recorded videos. An android's heightened ecological validity as compared with other media is of particular value during interactions with infants, because a baby cannot be told what to do during an experiment.

While it has long been supposed that infants develop cognitively by imitating adults [20], researchers in infant development have found evidence that infants first begin learning by being imitated by adults [13]. Contingency is a key factor in the infant's learning process. Contingency denotes the property of one event depending on another. For example, if one robot beeps when an infant vocalizes and another beeps randomly, an infant will make vocalizations (probes) to determine rapidly which robot is responding contingently. Movellan [23] has argued that infants are nearly optimal contingency detectors endowed with a rapid learning mechanism to maximize the amount of information they acquire about those in their surroundings. Adult imitation of the infant provides contingent feedback about what the infant's body is doing. The infant starts by reproducing the effects of the adult's actions and then learns to reproduce the actions themselves [13]. Associative learning enables observed contingencies to shape future interactions and transform agency [5]. Contingent feedback also enables the development of mirror neurons in the infant's brain. Mirror neurons fire both when someone performs an action and when that person sees someone else perform the same action. Thus, they enable us to understand the intention behind another person's action by putting ourselves in that person's place.

Our goal is to develop a baby android to study how contingency and timing shape infant interactions and their role in learning nonverbal behavior. The investigators will use the baby android for the fine-grained study and analysis of contingency in both infant-android interaction and adult-android interaction. It has been established that even three-month-old infants are highly sensitive to contingent feedback, reacting negatively when a live interaction with their mothers through a video link was replaced with a noncontingent, recorded interaction [24]. We plan to explore contingency by interacting with infant participants through an android that is controlled by telepresence. This method, commonly referred to as *Wizard-of-Oz,* entails a person responding to information from the robot's sensors and controlling its actuators through haptic devices like a joystick or a Wii remote. The influence of timing on contingency will be studied by inserting delays of varying duration into these technology-mediated interactions. Machine learning and data mining techniques will be used to analyze the statistical relation between the responses of interaction partners by using motion capture equipment.

In using a robot to investigate the micro-dynamics of infant interaction, it is important to control for the effects of the robot's appearance. If an infant responded differently to a mechanical-looking robot than to another infant, it would be difficult to determine whether the

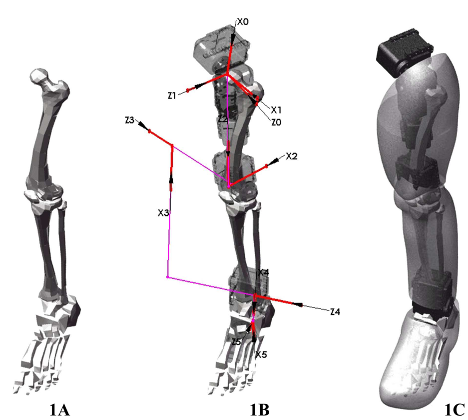

Figure 1. Design Concept for Infant Leg

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Table 1. Human synovial joint types [10]

Joint Type	Motion	Locations	Motors
Hinge	Uniaxial	Ankle, elbow, interphalangeal	1
Pivot	Uniaxial	Vertebral column	1
Saddle	Biaxial	Hand, foot	2
Condyloid	Biaxial	Wrist	2
Ball and socket	Multiaxial	Hip, shoulder	3
Plane	Gliding	Scapula	N/A

robot's appearance, motion quality, or contingency were the cause. Of particular concern with robots that are intended to look human is the uncanny valley [18]. The negative evaluations associated with the uncanny valley can result from a mismatch among robot elements, such as a robot that has human-looking eyes but metallic "skin" [12]. However, even in a consistently human-looking robot, negative evaluations can result when the robot's kinematics and dynamics are unable to match its morphological realism. For example, covering a mechanical-looking robot (e.g., Honda's Asimo) with a human-looking "skin" might seem eerie to observers, especially when it starts to move because of the placement of its joints, their movement beyond allowable human ranges, uneven stretching of the skin, absence of apparent muscle movement, lack of inertial dampening, fixed compliance, and so on.

This paper proposes design concepts for android joints and applies these concepts to building an infant-sized android to be used in the aforementioned experiments. Section 2 compares human and robot joint systems. Section 3 explains the proposed android design concepts. Section 4 presents the results of the concept simulation. Section 5 explains our directions for future work.

2 HUMAN VS. ROBOT JOINT CONFIGURATION

The muscles and skeletal system of the human body work together under the control of the nervous system to maintain posture and produce movement [9]. The muscles are arranged into antagonistic sets which control motion around a joint. A given joint may have from one to three axes of rotation and sets of antagonistic muscles (Table 1). Contracting a set of muscles applies a torque at the joint. The net movement of the joint results from the net torque of opposing sets of muscles around the axis. The nervous system allows one set of muscles to relax while contracting the opposing set. When a muscle contracts, the cross-sectional area of the muscle increases, causing the skin around the muscle to bulge. When the muscle relaxes, the skin flattens. For example, flexion (bending) and extension (straightening) of the knee involve movements in opposite directions: The biceps femoris, gastrocnemius, soleus control flexion, and the quadriceps femoris controls extension. The nervous system is continuously sending signals to antagonistic sets of muscles to slightly adjust their contraction for the body to maintain its posture. The nervous system continually adjusts the body's posture by processing input from proprioception (position sensors in the body), comparing the present state to the desired posture, and moving opposing muscle sets to maintain the desired posture.

Unlike human limbs, robot links are moved by actuators-at the actuator axis for revolute actuators or at the pivot point for prismatic actuators. Although the properties of revolute actuators differ from the human muscle system, they are widely used because of their compact size, high precision, and low maintenance. Servomotors have been mainly used in humanoid robots including Asimo [11], Hubo [26], HRP [15], HRP-2 [14], iCub [31], Qrio, SDR-4X, Kenta [21], and Kenji [22]. Many robotics researchers conceive of robots as tools helping people performing household tasks [15, 14, 21, 22, 29, 30]. Thus, motors and joints in humanoid robots are typically placed to yield high motor performance. In addition, they are typically aligned perpendicularly or in parallel to simplify the kinematic chain calculation. Human beings in natural postures do not have any two joints that are perpendicular or parallel. The characteristics of the actuators and the kinematic chain design of humanoid robots results in very robot-like movement. However, observers do not feel perturbed by the unnatural movement, because the humanoid robot does not look human [4].

Much research has attempted to create biologically inspired robots using prismatic actuators, which have contraction and extension properties similar to human muscle. Pneumatic actuators were used to move such human replicas as Repliee Q1 and Q2 [19] and Geminoid [25]. The androids were covered by clothes, so the skin movement was not noticeable. Joint configuration using pneumatic or hydraulic actuators can be similar to the joint configuration of humans. However, without an antagonistic arrangement of actuators, the limbs of the robots yielded too much compliance and could overshoot the intended target at higher speeds. Their pneumatic actuators also need more maintenance than servomotors and require a large, external air compressor. Many attempts have been made to create biomimetic robot joints [21, 22, 30, 3, 16]. One of them used electroactive polymer (EAP) actuators in an antagonist setup around the pivot point of the robot's eyeballs [3]. Even though the system can emulate human movement, EAP actuators have been capable of only a small displacement [16, 2], which is insufficient to move robot limbs, although EAP actuators capable of larger displacements are under development [1]. However, these systems are good at making facial expressions [26]. Festo AG has created Airic's_arm using a proprietary pneumatic system, which employs contraction membranes without piston rods [8]. The arm features a human skeletal structure, including shoulder blade movement. However, the system also requires an external air compressor, and the cost is still too high for mass production.

We believe a carefully constructed actuation model underneath the skin can greatly enhance the human motion realism of an android robot. We wish to find a simple way to achieve natural movement while maintaining low costs and a compact design in an android replica of a 13-month-old baby. The size of the actuators and the placement in the android body were the determining factors for the selection of the age of the android. We found that 13 months was the minimum age at which the body size could accommodate all the actuators.

3 PROPOSED CONCEPTS

A robot's kinematics constrains the appearance of its movement. Therefore, the mechanics of its underlying structure should be as close to that of a human being as existing technology allows. Three main concepts are described in this section: the robot's internal construction, its controlling schema, and its external construction.

3.1 The Selection of Actuators

A mechanical actuator that has the physical properties of human muscles does not exist. Prismatic actuators are the closest. However, they do not satisfy the requirements of this project because of their large size and high maintenance costs. The actuators should be small enough to fit within the proportions of an infant, and their operation should not interfere with apparent muscular movement, as described in section 3.3. For these reasons, we use revolute actuators. Various combinations of revolute actuators can mimic human joint motions, as shown in the last column of Table 1, except for gliding joints, as indicated in last entry of that column. Because the goal of the design is human-looking movement, the placement of each actuator axis has to align closely with the corresponding human joint axis.

3.2 Joint Control

Robot movements often look awkward because joints are moving independently of each other; furthermore, the motion of the joints can include abrupt changes in acceleration. The perceived visual salience of independent joint movement are highlighted when human dancers perform moves in the "robot" dance style. Under normal conditions, human muscles work differently. Most influence more than one skeletal joint [10]. Moreover, kinematic calculations have focused on the input angles of joints to accomplish the position and orientation of the end effectors, for example, the hands and feet [11, 26, 15, 14]. Without paying close attention to the angle outcomes of intermediate joints, the inverse kinematics calculation might result in limb positions that are abnormal or impossible for human beings—a disturbing sight to watch. In computer graphics (CG), animators face difficulty in moving a character's limbs naturally by giving an angle input to each joint. Part of the problem in mimicking human motion is that some human muscles simultaneously apply torque to two or more joints or axes of a single joint.

To overcome this problem, the controlling schema should involve muscle-like control of the joints rather than joint angle control. As with the biological model, muscle movements should determine limb angles. Movement of a given joint may result in movement of the adjacent joints. Moving one joint but failing to mimic the effects of the controlling muscles on other joints can cause the movement to look eerie.

3.3 Mimicking Muscle Shape

In most cultures and climates, some degree of skin exposure is typical and, indeed, beneficial to communication; clothing can obscure gestures, facial expressions, and other nonverbal behavior. Because the surface of the android is visible where clothing is absent, care must be taken to make it look human. However, simply covering moving mechanic parts with synthetic skin might create a strange twisting and stretching effect. In addition, the selected actuators lack the shape changing properties of human muscles. To create a believable muscle effect, a layer of muscle-shape rubber material should be inserted between the actuator housing and the synthetic skin. This has the following advantages: First, when rubber muscles are stretched or contracted, they help distribute the stretching of the android skin more evenly. Second, the cross-sectional area of rubber muscle decreases when stretched and increases when contracted, which is the same as human muscle.

4 IMPLEMENTATION

Although a different part of the body could have been chosen for the initial work, the leg was chosen because of its relative simplicity compared to other parts of the body. For example, it is reasonable to ignore the motion of the toes for this model because of their limited size and range of motion; however, ignoring the motion of the fingers would not be an option when designing the arm.

One approach that would not work for this project is to have a simulation movie of the leg by itself (or any other part of the body) to get feedback from individuals as to whether the motion appears natural. The reason for this is that the leg is not an independent system; motion at the hip partially depends on the hip's connections to the torso. One of the fundamental approaches of this work is to take into account the lack of independence of motion of the joints. In this section the concept of the infant android leg is implemented on a CAD program for engineering.

4.1 Actuators and Their Placement

Robotis Dynamixel AX-12 servomotors [28] were selected as the android's actuators for the following reasons. First, the servomotors are small enough to fit in infant limbs. Second, small servomotors require no maintenance once installed. Third, each of these particular servomotors can be controlled in velocity mode, imputing the desired angular velocity and clockwise or counter-clockwise direction. Changes in angular velocity can be translated into torque. Fourth, the actuators have enough torque to lift up each limb. In the planned experiments the robot is not required to walk but is seated on a chair, table, or floor. Thus, one actuator does not need to hold the entire weight of the robot.

Table 2. Joint Movement of the Lower Limb

Joint Type	Actuator	Movement	Maximum Values Displ. $(deg.)$	Accel. $(\frac{deg.}{s^2})$
Hip	A	Flexion	120	660
Ball and		Extension	-45	
socket	B	Adduction	20	280
		Abduction	-50	
	C	Lateral rotation	80	400
		Medial rotation	-20	
Knee	D	Flexion	160	648
Hinge		Extension	-2	
Ankle	E	Dorsiflexion	45	300
Hinge		Plantarflexion	-30	
Foot	F	Inversion	35	200
Pivot		Eversion	-15	

A computer graphics model of the infant skeleton was created to verify the accuracy of the actuator placements (Figure 1A). Actuators, then, were placed to ensure the alignment of each actuator axis with the skeletal joint axis. Figure 1B shows the result of the placements. The types of lower limb joints, listed in Table 1, are ball-and-socket joint at the hip, hinge joint at the knee, hinge joint at the ankle, and many small saddle joints at the ankle. However, the saddle joints were simulated by a single pivot joint. There are a total of 12 major movements of a human leg with 2 antagonistic movements per axis. Thus, the robot requires a total of six actuators for each leg. Table 2 describes the skeletal joints of the leg, joint movement, and actuators involved in each movement. Movements are illustrated in Figure 1B. Some actuator placements were shifted owing to a lack of space inside the robot's limbs. Nevertheless, they still maintain the projected axis of the skeletal joint axis.

Table 3. Link Parameters

i (actuator)	a_{i-1}	α_{i-1}	d_i
0 (A)	0	0	0
1 (B)	−90.00	0	0
2 (C)	−87.06	0	−143.44
3 (D)	−86.33	5.00	−179.19
4 (E)	149.60	144.36	92.90
5 (F)	80.83	27.95	0

The resulting placement of the actuators clearly contrasts with that of humanoid robots. For example, at the anatomically normal human standing position, the knee axis is not parallel to the ankle axis, but tilted inwards about ten degrees. Table 3 shows link parameters in the Denavit-Hartenberg notation derived from actuator placement in Figure 1B.

All the actuators are covered by an inner shell: fabricated plastic cases holding the servomotors in place and smoothing out their sharp edges. The shape of the inner shell is similar to the shape of a limb, as shown in Figure 1C. The outside of the shell was designed to be smooth with no sharp edges to impede the movement of the muscle layer.

4.2 Elastic Muscles Mimicking the Changing Shape of Moving Muscles

A rubber sheet was designed to be cut in a narrow leaf shape in a variety of lengths and widths depending on the structure of each muscle. Each end of a rubber muscle will be attached to the inner shell of the leg.

For example, the *tibialis anterior* contributes to inversion, tilting the foot towards the center of the body, and dorsiflexion, rotating foot at the ankle upward. Thus, servo F will be turned 35 degrees inward, the maximum displacement of inversion, and servo E will be turned 45 degrees upward, the maximum displacement of dorsiflexion. This position ensures the minimum stretched displacement of the elastic material corresponding to the *tibialis anterior* as allowed by ankle motion. This results in the maximum allowed cross-sectional area of the elastic material for that muscle. Then, one end of the muscle will be glued to the under surface toward the inside of the foot and the other end will be glued to the front of the calf below the knee. Toward the completion of the android, all limbs will be covered with rubber skin material.

4.3 Control System

Out of more than 50 muscles in the human lower limb [10], we selected only 12 muscles that related to major movements of the leg. Our selection criterion was the muscle's contribution to a noticeable movement. An infant's subcutaneous layer of fat is relatively wide compared to healthy adults. This is partly caused by the underdeveloped state of an infant's muscles. It is also caused by the infant's higher surface area-to-volume ratio. This results in heat loss from a skin surface area that is large relative to the volume of the body generating heat through metabolism. Therefore, infants have a relatively large fat layer as a form of insulation [17]. So the movement of infant muscles is not as visible as in most adults.

For the purposes of our design, *gluteus maximus* contributes 80% of the total torque for extension at the hip joint with the remaining 20% provided by *biceps femoris* and muscle group B. The *gluteus maximus* also provides 70% of the torque for lateral rotation at the hip joint with the remaining 30% provided by *quadriceps femoris, biceps femoris,* and muscle group B. Minor contributions of muscles to movement around a joint axis were ignored. For example, *gluteus maximus* is also involved in flexion at the hip joint, but the contribution is negligible and therefore excluded.

Lacking data regarding the contribution of various muscles to torque, we assumed that the maximum torques of the antagonistic muscles or muscle groups are equal at each axis. Thus, a joint stops moving or moves at constant speed when the antagonistic muscles simultaneously contract by an equal amount.

Let A be a 6×12 rectangular matrix containing the percentage of torque each muscle contributes to each movement. Let $\hat{x}$ be a 12×1 input vector containing for each muscle the percentage of its maximum torque to be applied for the duration of the movement frame (system interval). And, let $\hat{b}$ be a 6×1 vector.

$$\frac{A}{100} \cdot \hat{x} = \hat{b} \quad (1)$$

From the result of (1), $\hat{b}$ constitutes the directions and net torques at the axes. In angular motion,

$$\tau = I \cdot \alpha \quad (2)$$

where τ is torque, I is the moment of inertia, and α is the angular acceleration. To simplify the control system calculation, we let I be a constant denoted by k because of its small mass and small distance from the axis of rotation to the center of gravity of the limb.

Another simplification in this system is the assumption of linearity. The muscle itself is not a linear system; however, typical length-tension curves for skeletal muscle comprise the sum of active and passive tension components. Although the sum of the tension components is not linear, its deviation from linear for most of the range of motion is limited enough that we feel that the assumption is justified [27]. Thus,

$$\tau_{max} = k \cdot \alpha_{max} \quad (3)$$

From (3), angular acceleration is scaled by the net torque applied to a joint. To find an order of magnitude estimate of α_{max} for each axis, we assumed that the full range of movement can be completed in approximately one second with constant angular acceleration for the first half of the movement and constant angular deceleration for the second half of the movement. The extreme case occurs when a joint is moved in a full range of motion. Under such a circumstance, each muscle related to the movement direction contracts with maximum torque to reach the maximum angular acceleration. We can obtain an order-of-magnitude estimate for maximum acceleration as shown in the last column of Table 2.

Two variables that the servomotor controller requires for each motor are the goal position and the desired angular velocity. The desired torque can be computed by these two variables. First, a comparison of the current position and the goal position indicates the turning direction—maximum displacement of each movement, from Table 2, was used for the goal position. Second, the desired torque is calculated from the angular acceleration—the angular acceleration is the change of the angular velocity with respect to time. Thus, in each time period of the trajectory calculation, the angular acceleration can be calculated by the following equation:

$$\alpha = \frac{d\omega}{dt} \quad (4)$$

where ω is the angular velocity.

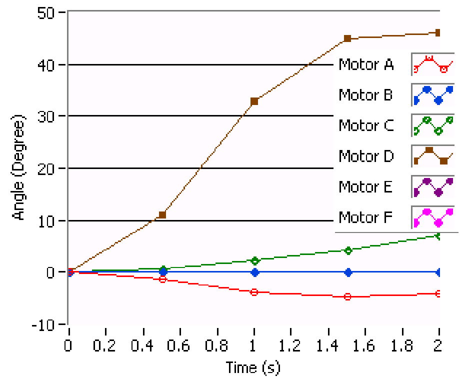

Figure 2. The angular motion of motor A to F in two seconds

$$\alpha = \frac{\omega_2 - \omega_1}{\Delta t} \tag{5}$$

where ω_1 is the initial angular velocity of the time step and ω_2 is the final angular velocity; Δt is the system frame interval. Thus,

$$\omega_2 = \omega_1 + a \cdot \Delta t \tag{6}$$

This equation can be rewritten in term of percentage of maximum angular acceleration as

$$\omega_2 = \omega_1 + \%\alpha_{max} \cdot \Delta t \tag{7}$$

And, θ can be found by $\theta = \int_{t_1}^{t_2} \omega \, dt$.

Table 4. Net Torque Input to Muscle at Four Time Frames

Muscle	$\hat{x}_{t1}$	$\hat{x}_{t2}$	$\hat{x}_{t3}$	$\hat{x}_{t4}$
Tibialis anterior	0	0	0	0
Fibularis	0	0	0	0
Tibialis posterior	0	0	0	0
Gastrocnemius & Soleus	0	0	0	0
Quadriceps femoris	0	0	12%	1.50%
Biceps femoris	15%	0	0	0
Iliopsoas	0	0	0	0
Gluteus maximus	0	0	0	0
Group A	0	0	0	0
Group B	0	0	0	0
Group C	0	0	0	0
Gracilis	0	0	0	0

For example, Table 4 shows the vector $\hat{x}$, input of the system, in four time frames, from t_1 to t_4, to flex the knee joint at about 45 degrees in two seconds. The system interval, Δt, is half a second. *Biceps femoris* contracts 15 percent in the first interval.

Quadriceps femoris then contracts at 12 and 1.5 percent to counteract the motion of the flexing knee in the third and fourth interval. Figure 2 shows the trajectory simulation results of the input from Table 4. All servomotors start at 0 degree when $t = 0$. The servomotor at the knee joint, motor D, decelerates when *quadriceps femoris* contracts at $t = 1$. The results clearly show the effect of contracting biceps femoris on the hip joint, motor A, and motor C (Fig. 3).

5 FUTURE WORK

5.1 Telepresence Data Mining for Contextualized Interaction

A major limitation of social robots that support human interaction is that the interaction is designed in advance by robot engineers. However, it is difficult to plan for the social context, because it is not a static property of situations. Instead, it is created dynamically during the course of the interaction [6]. Interactional microdynamics are not under conscious control. As a result, they are often overlooked by engineers who do not build them into the design specification. For this reason, the robots fail to elicit our sense of human presence, which is the most highly therapeutic aspect of the interaction.

We propose an entirely new methodology for developing an android that can support social interaction. Instead of "designing the interaction," the engineer builds a system in which a human interacts with another human by controlling the android. Furthermore, the human can be limited to observing the same processed information from the android's sensors that an android control system would. After collecting a large amount of data from these robot-mediated interactions, data mining and machine learning techniques are applied to extract patterns of interaction that are then implemented in the robot so that it can function autonomously.

5.2 Potential Applications for Eldercare

Socially-assistive robots have been successfully employed for companionship, social mediation, monitoring care, and encouragement in performing rehabilitation exercises [7]. Just as robots have served as rehabilitation coaches for patients recovering from heart surgery or stroke, they have the potential to motivate older adults to exercise more to reduce obesity and improve cardiovascular health to prevent these ailments. Three major threats to quality of life in older adults are delirium, dementia, and depression, which is often associated with loneliness owing to social isolation. Robot pets, such as Paro, have been used successfully in nursing homes in Japan, the United States, and Europe, for companionship and as a vehicle to stimulate social interaction among patients [32]. Although the cognitive capacities of these robots are extremely limited compared to those of people, animal pets, and other robots, nonverbal cues such as head tracking and touch response can create a sense of presence that alleviates loneliness and stimulates sharing.

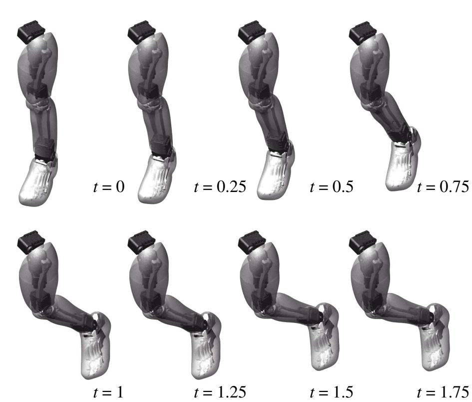

Figure 3. Two seconds of the simulated motion

Simple toys like Tamagochi and Amazing Amanda demonstrate that a device requiring human nurturance can be a "killer application" with vast market potential. A more complex android that combines humanlike nonverbal response with an infant-like form has the potential to have a far greater therapeutic impact in alleviating loneliness than these simple devices. The android baby will succeed to the extent that it is able to "press our Darwinian buttons" by mimicking subconscious behavior that elicits human response [32]. This information tells us, "Somebody's there," which can provide comfort. We propose to extend this by developing simple verbal communication and shared engagement in activities, such as exercise and games. This method has been successfully used by robots like Robovie in primary schools in Japan.

6 CONCLUSION

We have proposed a design for realistic joint movements and illustrated the underlying concepts by applying them to a planned implementation: the leg of a baby-sized android. There is more room for improvement regarding the complexity of the input script to yield a desired posture, for example, by implementing a neural network control scheme. We intend to apply these concepts throughout the body design before fabricating android parts. This project is still in development. The completed android hardware will be controlled mainly by scripted movements or by an experimenter using the Wizard-of-Oz method.

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REFERENCES

[1] Y. Bar-Cohen, K. J. Kim, H. R. Choi, and J. D. W. Madden, 'Electroactive polymer materials', *Smart Materials and Structures*, **16**(2), (2007).

[2] Y. Bar-Cohen, S. Leary, A. Yavrouian, K. Oguro, S. T. Tadokoro, J. Harrison, J. Smith, and J. Su, 'Challenges to the transition of IPMC artificial muscle actuators to practical applications', in *Material Research Society Symposium Proceedings Volume 600: Electroactive Polymers (EAP)*, eds., Q. M. Zhang, T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim, Warrendale, PA, (1999). Materials Research Society.

[3] F. Carpi and D. De Rossi, 'Bioinspired actuation of the eyeballs of an android robotic face: Concept and preliminary investigations', *Bioinspiration and Biomimetics*, **2**(2), S50–S63, (2007).

[4] T. Chaminade, J. Hodgins, and M. Kawato, 'Anthropomorphism influences perception of computer-animated characters' actions', *Social Cognitive and Affective Neuroscience*, **2**(3), 206–216, (2007).

[5] S. J. Cowley, 'How human infants deal with symbol grounding', *Interaction Studies*, **8**(1), 83–104, (2007).

[6] P. Dourish, 'What we talk about when we talk about context', *Personal and Ubiquitous Computing*, **8**(1), 19–30, (2004).

[7] Feil-Seifer, K. Skinner, and M. J. Mataric, 'Benchmarks for evaluating socially assistive robotics', *Interaction Studies*, **8**(3), 423–439, (2007).

[8] Festo AG and Co. KG. Airic's_arm. World Wide Web. http://www.festo.com/INetDomino/coorp_sites/en/ffeed49f2394ea43c12572b9006f7032.htm.

[9] J. T. Hansen and B. M. Koeppen, *Netter's Atlas of Human Physiology*, Icon Learning Systems, Teterboro, NJ, 1st edn., 2002.

[10] J. T. Hansen and D. R. Lambert, *Netter's Clinical Anatomy*, Icon Learning Systems, Teterboro, NJ, 1st edn., 2005.

[11] M. Hirose, Y. Haikawa, T. Takenaka, and K. Hirai, 'Development of humanoid robot ASIMO', in *IROS 2001: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop 2*, (2001).

[12] C.-C. Ho, K. F. MacDorman, and Z. A. D. Pramono, 'Human emotion and the uncanny valley: A GLM, MDS, and ISOMAP analysis of robot video ratings', in *HRI '08: Proceedings of the Third ACM/IEEE International Conference on Human-Robot Interaction*, pp. 169–176, New York, (2008). ACM Press.

[13] S. S. Jones, 'Imitation in infancy: The development of mimicry', *Psychological Science*, **18**(7), 593–599, (2007).

[14] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumi, 'Humanoid robot HRP-2', in *ICRA 2004: Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, volume 2, pp. 1083–1090, (2004).

[15] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S. Ota, and T. Isozumi, 'Design of prototype humanoid robotics platform for HRP', in *IROS 2002: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2431–2436, (2002).

[16] R. Kornbluh, R. Pelrine, J. Eckerle, and J. Joseph, 'Electrostrictive polymer artificial muscle actuators', in *Proceedings of the 1998 IEEE/RSJ International Conference on Robotics and Automation*, volume 3, pp. 2147–2154, (1998).

[17] G. Lowrey, *Growth and Development of Children*, Year Book Medical Publishers, Chicago, 8th edn., 1986.

[18] K. F. MacDorman and H. Ishiguro, 'The uncanny advantage of using androids in social and cognitive science research', *Interaction Studies*, **7**(3), 297–337, (2006).

[19] D. Matsui, T. Minato, K. F. MacDorman, and H. Ishiguro, 'Generating natural motion in an android by mapping human motion', in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, (2005).

[20] A. Meltzoff, 'The human infant as imitative generalist: A 20-year progress report on infant imitation with implications for comparative psychology', in *Social Learning in Animals: The Roots of Culture*, eds., B. Galef and C. Heyes, 347–370, Academic Press, New York, (1996).

[21] I. Mizuuchi, R. Tajima, T. Yoshikai, D. Sato, K. Nagashima, M. Inaba, Y. Kuniyoshi, and H. Inoue, 'The design and control of the flexible spine of a fully tendon-driven humanoid "Kenta"', in *IROS 2002: Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, volume 3, pp. 2527–2532, (2002).

[22] I. Mizuuchi, T. Yoshikai, Y. Nakanishi, and M. Inaba, 'A reinforceable-muscle flexible-spine humanoid "Kenji"', in *IROS 2005: Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4143–4148, (2005).

[23] J. R. Movellan, 'An Infomax controller for real-time detection of contingency', in *Proceedings of the International Conference on Development and Learning*, (2005).

[24] L. Murray and C. Trevarthen, 'Emotional regulation of interactions between two-month-olds and their mothers', in *Social Perception in Infants*, eds., Tiffany M. Field and Nathan A. Fox, Ablex Publishing, Norwood, NJ, (1985).

[25] Shuichi Nishio, Hiroshi Ishiguro, and Norihiro Hagita, 'Can a teleoperated android represent personal presence? A case study with children', *Psychologia*, **50**(4), 330–342, (2007).

[26] J.-H. Oh, D. Hanson, W.-S. Kim, I. Y. Han, J.-Y. Kim, and I.-W. Park, 'Design of android type humanoid robot albert HUBO', in *IROS 2006: Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1428–1433, (2006).

[27] R. A. Rhoades and D. R. Bell, *Medical physiology: Principles for clinical medicine*, Lippincott Williams and Wilkins, Philadelphia, 3rd edn., 2009.

[28] Robotis. Robot exclusive actuator dynamixel. World Wide Web. http://www.robotis.com/zbxe/dynamixel_en.

[29] S. Roccella, M. C. Carrozza, G. Cappiello, P. Dario, J. J. Cabibihan, M. Zecca, H. Miwa, K. Itoh, and M. Marsumoto, 'Design, fabrication and preliminary results of a novel anthropomorphic hand for humanoid robotics: RCH-1', in *IROS 2004: Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, volume 1, pp. 266–271, (2004).

[30] Y. Sodeyama, I. Mizuuchi, T. Yoshikai, Y. Nakanishi, and M. Inaba, 'A shoulder structure of muscle-driven humanoid with shoulder blades', in *IROS 2005: Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4028–4033, (2005).

[31] N. G. Tsagarakis, F. Becchi, L. Righetti, A. J. Ijspeert, and D. G. Caldwell, 'Lower body realization of the baby humanoid - "iCub"', in *IROS 2007: Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3616–3622, (2007).

[32] S. Turkle, 'Authenticity in the age of digital companions', *Interaction Studies*, **8**(3), 501–517, (2007).