A Dynamical Analysis of Kneading Using a Motion Capture Device

Mamiko Abe* **Tomoyuki Yamamoto**** **Tsutomu Fujinami****
*Knowledge Media Laboratory,
Corporate Research and Development Center, Toshiba Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki-shi, 212-8582 JAPAN
mamiko.abe@toshiba.co.jp

**School of Knowledge Science,
Jpan Advanced Institute of Science and Technology
Tatsunokuchi Ishikawa, 923-1292 JAPAN
{t-yama,fuji}@jaist.ac.jp

Abstract

Physical skills such as playing the musical instrument are hard to learn and take long time to master. To investigate what makes physical skills so difficult to learn and how we can evaluate the level of skills, we examined the kneading in ceramic art, an action to prepare the clay for shaping and studied the physical movements of both the learners and experts.

Kneading is an appropriate sample of physical skill for studying the body movement because all the parts of body need to be coordinated to accomplish the task. The task is not hopelessly difficult for the complete novices to follow the instruction although the end result is not satisfactory. It normally takes about three years to master the kneading skill. It is also relatively easy to judge how well the subjects accomplished the task by observing the shape of the clay.

After careful examination of the movement using video tapes, we employed a motion capture device to collect the data of movement from an expert, an experienced person, and three novices. We discovered that the expert elegantly splits his body into two parts, torso and arms, and effectively coordinates these two parts while kneading the clay.

1. Introduction

Physical skills such as playing the musical instruments are only acquired through long period of practice. One cannot even mimic the act if he or she is given an instruction or manual. He needs an experience to develop his skill. What makes physical skills so difficult to learn? What is the essence of skills? To investigate the difference between skilled and unskilled persons in terms of physical movements, we employ a motion capture device for detailed biomechanical analysis.

We examined as a skill the kneading in ceramic art called "Kikuneri", which is an action to prepare the clay for shaping. The clay becomes dense through kneading as its air is removed. Figure 1 shows the steps of kneading, in which the Kikuneri kneading is indicated with the dashed box. Kneading is an ideal skill for our investigation because the motion is almost periodic and the center of mass does not drift. The whole body needs to work together to accomplish the task and it is relatively easy to judge how well the subject accomplished the task by checking the shape of the clay. The skill is modestly difficult to learn as it takes about three to five years to master, which makes it possible to observe developmental stages.

The goal of our research is to develop a teaching method that shortens the period of skill acquisition. The first step towards the goal is to clarify the essence of physical skills, which is the theme of this paper. We believe that our results make it possible to implement into robots a function for performing physical skills. Developing a teaching method leads to an easier programming of robots. We believe that skill acquitision and instruction are closely related with each other. We will discuss the issue in §4.2.

As for the investigation into human movements, there is a pioneering work by Haken, Kelso, and Bunz (Haken et al., 1985), where they found an order in human hand movements. Our findings conform with their results, but we found more detailed structures in experts' movements as we will see in what follows. The reseach of physical skills is relatively new. Ueno and his colleagues among few studied the bowing of cello (Ueno et al., 1998, Ueno et al., 2000). They investigated the difference between the expert and learner by collecting the data of arm movements. It is however still open question how a skill is acquired and why it is hard to learn. We employ a dynamical analysis for investigating the kneading because the method allows us to look into the details of human movements (Yamamoto and Kuniyoshi, 2002a, Yamamoto and Kuniyoshi, 2002b).

The paper is organized as follows. We explain the kneading and the data collection in Section 2. We report the results in Section 3 and discuss the distinctive points in the expert's movements in Section 4. We conclude the paper in Section 5 by briefly mentioning our ongoing projects.

2. Keading and data collection

As none of us were familiar with the kneading in the ceramic art, we started our research by examining an expert's movements on video tapes. We identified through our examination four steps in the kneading. As shown in Figure 2, the clay is transformed into the flower, shell, bell, and egg like form at each step. The origin of the name, "Kikuneri", comes from the flower like shape at the first step as depicted in the leftmost of the figure. ("Kiku" is chrysanthemums in Japanese).

Of these four steps, we focused on the first step because we observed that the body motion is almost periodic and the center of mass does not drift, which is ideal for data collection using our motion capture device. We also found a regularity in the body movements, namely, a coordination between the torso and hands, which we thought is worth investigating.

To collect the data, we used the MotionStar, an electro-magnetic motion capture system developed by Ascension Technology Corp. With the knowledge obtained through our video-tape examination, we constructed a body model that consists of 9 segments with 11 marker points as shown in Figure 3. Figure 3 (a1), (a2), and (a3) show our model in detail and Figure 3 (b1), (b2), and (b3) are the pictures of a subject with the sensors put on him according to the model.

The marker positions are as follows:

- Left/Right Head: each lateral of the head, above the respective ear.
- Bottom Neck: behind of seventh cervicale.
- Left/Right Shoulder: top of each acromion.
- Left/Right Elbow: lateral of each olecranon.
- Left/Right Hand: about middle of each carpus.
- Left/Right Hip: lateral of each crista illacae.

We did not set markers in the lower limbs because we observed that the expert did not move legs while kneading the clay. We can thus safely disregard the movements in the lower limbs.

We employed five subjects for our experiment. One person is a professional ceramic artist with more than ten years of experience. Another person has some experience at a hobby school, where he practised the ceramic art for a year. The other three are complete novice. Four of them are male and one is female. Their ages vary from 25 to 40 years old. The three novices were shown the expert's movements on video-tape and were instructed in the experiment by an experienced person so that they can understand what they have to achieve in the task. We captured their movements while they were kneading the clay with his or her intention to produce the folower-like form as shown in Figure 2.

3. Results

3.1 The coordination of movements

We found that the expert's movements are well organized as the result of our experiments. Figure 4(a), (b), and (c) show the trajectories of three subjects seen from the left side as indicated in Figure 4(d). Figure 4(a) depicts the trajectory of the expert, Figure 4(b) that of the experienced, and Figure 4(c) that of a novice.

It is clear from the figure that the movements of the expert is more stable than those of the others while the torso rocks forward and backward for kneading. The area of trajectory around the waist is very narrow for the expert as seen in Figure 4(a) compared with those found in Figure 4(b) and (c) for the experienced and novice, respectively.

We can also observe in the figure that the expert pivots his rocking motion at his hip while the experienced and novice pivot their motions around their legs. The observation is supported by the fact that the amplitudes of their heads do not vary so much between the expert and the experienced. Since the rocking motion of the expert originates from the foot, i.e., by kicking the ground, the energy is effectively transferred to the upper torso by pivoting at the hip and causes the body to swing. The trajectory of the experienced is less localized compared with that of the expert. His joint movements are somehow coordinated, but unstable. The trajectory of the novice is rather chaotic and no coordination among his joints is established.

We now turn our attention to the trajectories around their hands. It is easily noticeable that their hands move circularly in the Figure 4. The area of hand movements becomes more localized as the person acquires the skill better. We have observed the same phenomena for the movement of the torso, too. These two findings are strong enough for us to believe that the torso and hands

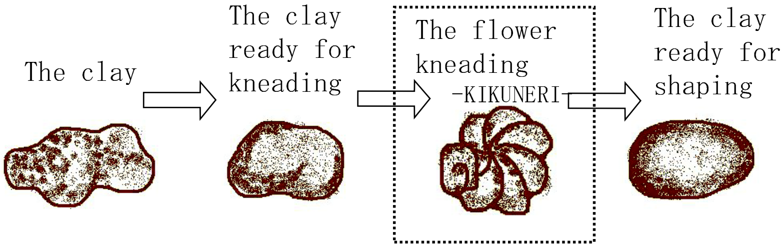

Figure 1: Schematic process of kneading

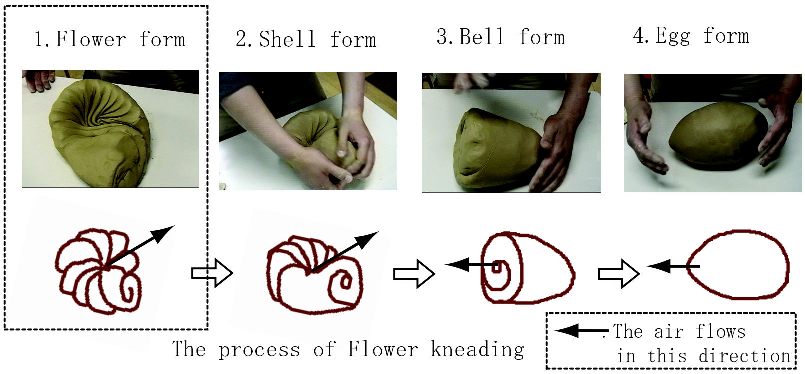

Figure 2: The four steps observed in the kneading

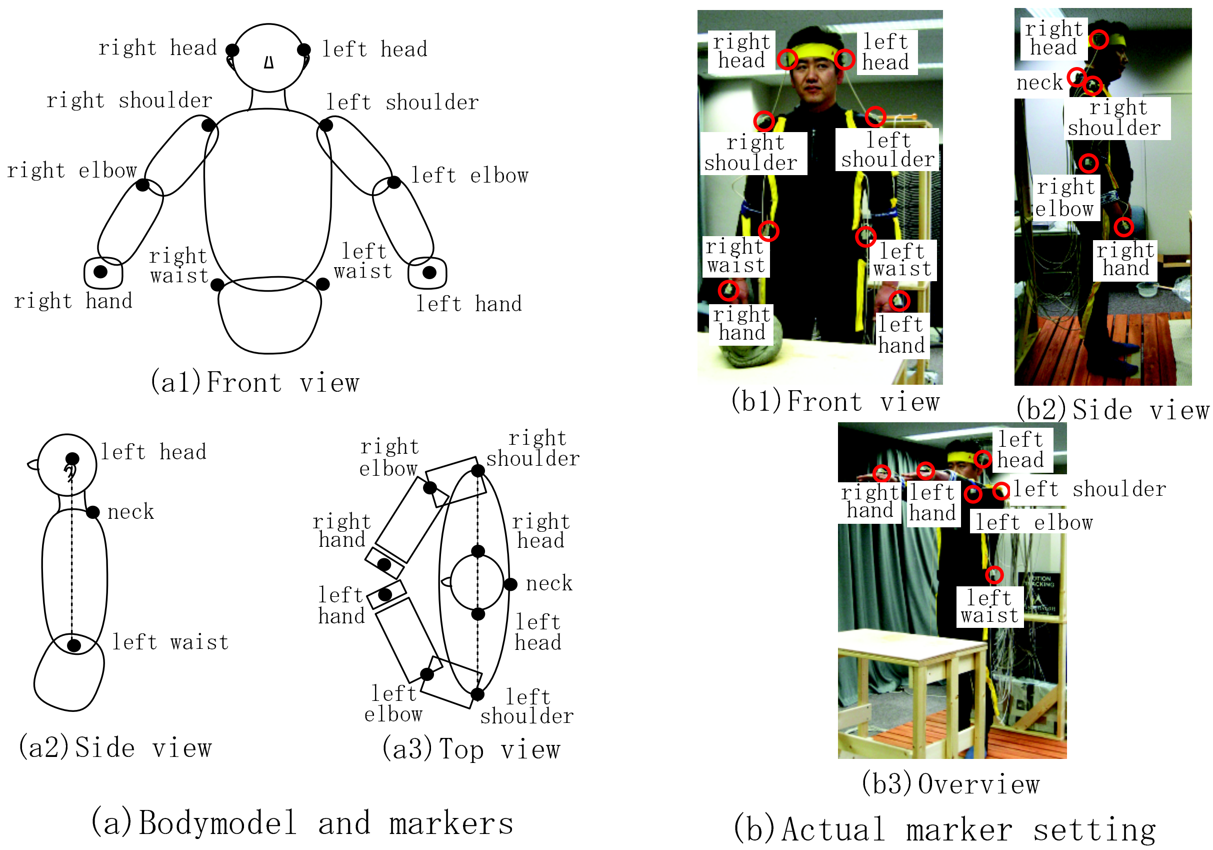

Figure 3: The bodymodel

are coordinated for producing the effective act of kneading.

3.2 The phase relationships among movements of limbs

We focus on the phase relationships between the torso and the hands and examine their movements in terms of time series. We analyze the phase relationships among the movements at 11 markers along the X-axis, i.e., in the forward and backward direction. The analysis in this direction only is sufficient for our purpose because the movements of kneading is mostly restricted in the sagittal plane.

Figure 5 shows the time serieses of each marker points. The time scales are different between the three graphs because the speed of kneading varies among the subjects. The expert obviously moves more quickly than the others. The frequency is 1.4Hz as for the expert's movement (Figure 5(a)), 0.85Hz as for the experienced (Figure 5(b)), and 0.55Hz as for the novice (Figure 5(c)). The difference in frequency is not relevant here for our analysis because we are primarily interested in the phase relationships.

We can identify in Figure 5(a) and (b) two sets of waves, to either of which each wave belongs. One set is the trajectory of the "arm group" consisting both sides of the hands and arms, i.e., elbows. The other is the trajectory of the "torso group", which consists of the head, the torso including the shoulder, and the hip. It is recognizable in Figure 5(a) and (b) that the arm group and the torso group are coordinated, while we cannot find such a coordination for the movements of the novice in Figure 5(c). It is particularly interesting that there is a phase difference between the two groups in the expert's movements.

Figure 5(a) depicts two groups observed in the body movement by the expert, each of which is governed by a unique cycle. In the figure, the black line depicts the movement at the left head and the gray line the movement at the left hand. The peaks of each phase are indicated with the lines such as α_1 or α_2. The line α indicates that the head, shoulder, neck, and waist form the torso group. The other line β indicates that the right and left hand, the right elbow, and the left elbow form the arm group. The phase differentiation is evident in the expert's motion.

The two groups are observable in the movement of the experienced, too, as shown in Figure 5(b), but the pattern is slightly different from that found for the expert. His arm group is not completely distinctive from his torso group as seen in the wave form around the line, α_1 or α_2 in Figure 5(b). We conclude that his movement of the right elbow is not as regular as is found for the expert.

We found no distinctive groups for the novice's movement in Figure 5(c). We can only observe that his body parts are synchronized on the lines, α_1 and α_2. The wave forms are also irregular compared with those found in the expert or the experienced.

We discovered as the result of our experiment that the body parts of the expert are organized into two groups, one of which is the torso group indicated by the line, α, and the other of which is the arm group indicated by the line, β. We also found that the phase difference between the two groups is constant for the expert. That is, the expert not only organizes his various parts of body into two groups but also correlates them through his movement.

3.3 The cluster analysis of the phase difference

The phase relationhips provide us with valuable items of information for analyzing the organization of human movements. We thus further apply to our data the cluster analysis so as to see the difference between the subjects in terms of phases in finer detail.

We truncated 10 cycles from the data of each subject to pick up 10 peak values. We analyzed the data based on the Euclid distance using Ward's method. We employed SPSS application program for our analysis. Figure 6 shows for each subject the dendrogram of the phase relationship and the body model on which the clusters are marked.

As for the expert, the dendrogram in Figure 6(a1) shows the distinctive groups of torso and hands. Figure 6(a2) and (a3) depict the two groups. The magnitude of clustering is significantly bigger than others. We thus conclude that the phase differentiation is established in his movement.

As for the experienced, the dendrogram in Figure 6(b1) indicates that the body parts are organized to some extent, but the torso is divided in the upper and lower parts. The data shows that the waist is not stable. We also observe that his right elbow is grouped into the waist and the left elbow is not grouped into any other parts. Figure 6(b2) and (b3) depict his bodymodel with the grouped parts depicted with dashed circles. We conclude from the data that his body movements are not well organized compared with those found for the expert.

As for the novice, we hardly found any meaningful groups in his movement as shown in Figure 6(c1). Figures 6(c2) and (c3) show his body model.

We realized through our analysis that the two groups of torso and hands become more distinctive as the person gets more skilled. We think that we can gauge the degree of skillfulness based on the degree of distinctiveness of these two groups.

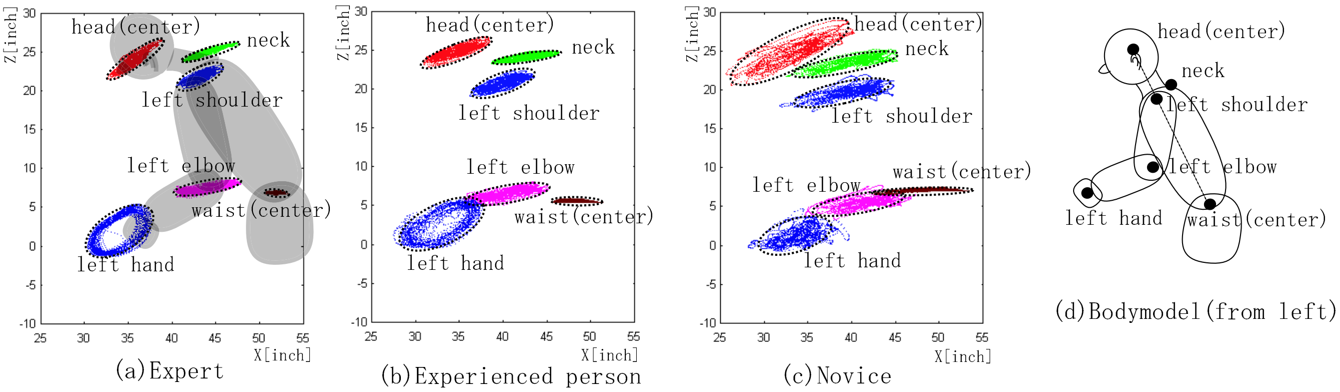

Figure 4: The trajectories of the movements by three subjects

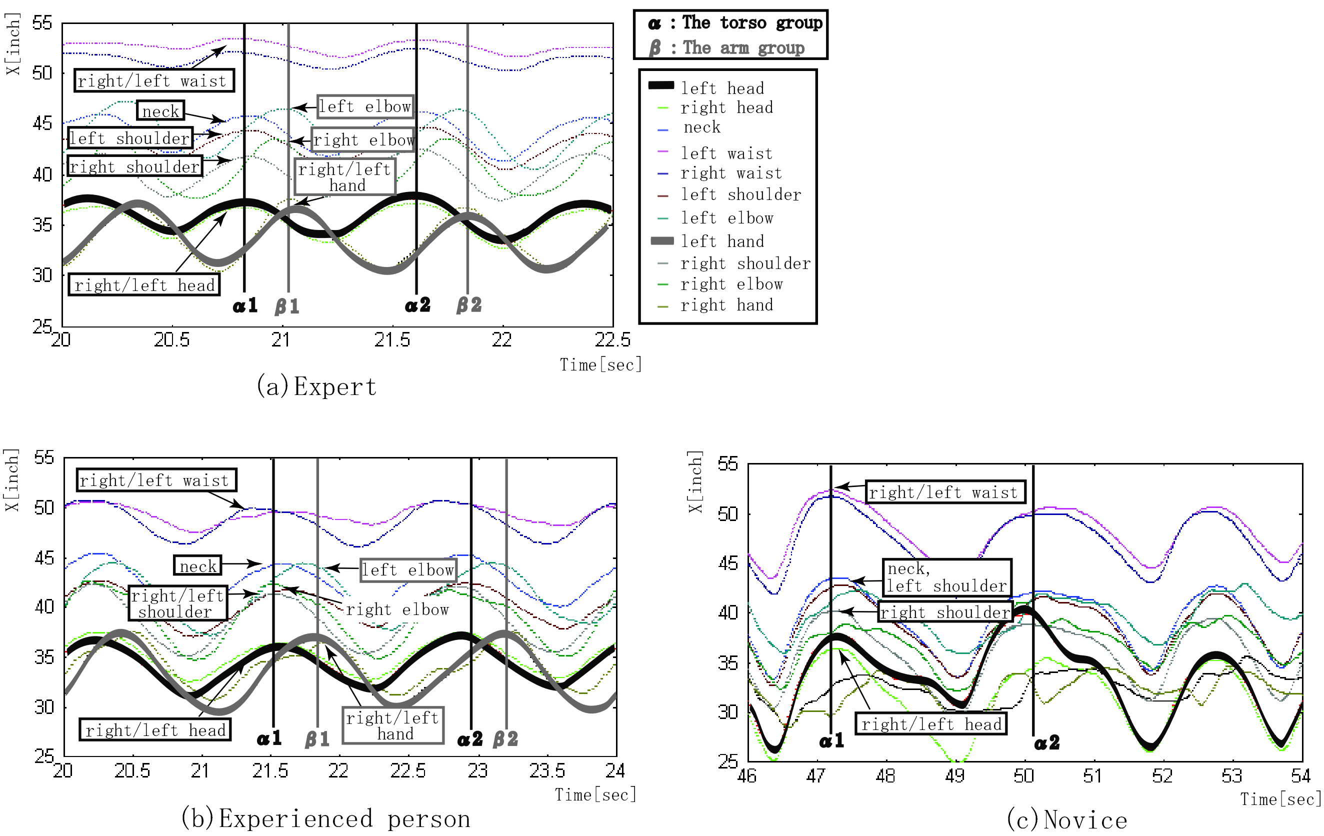

Figure 5: The time serieses of the kneading by three subjects

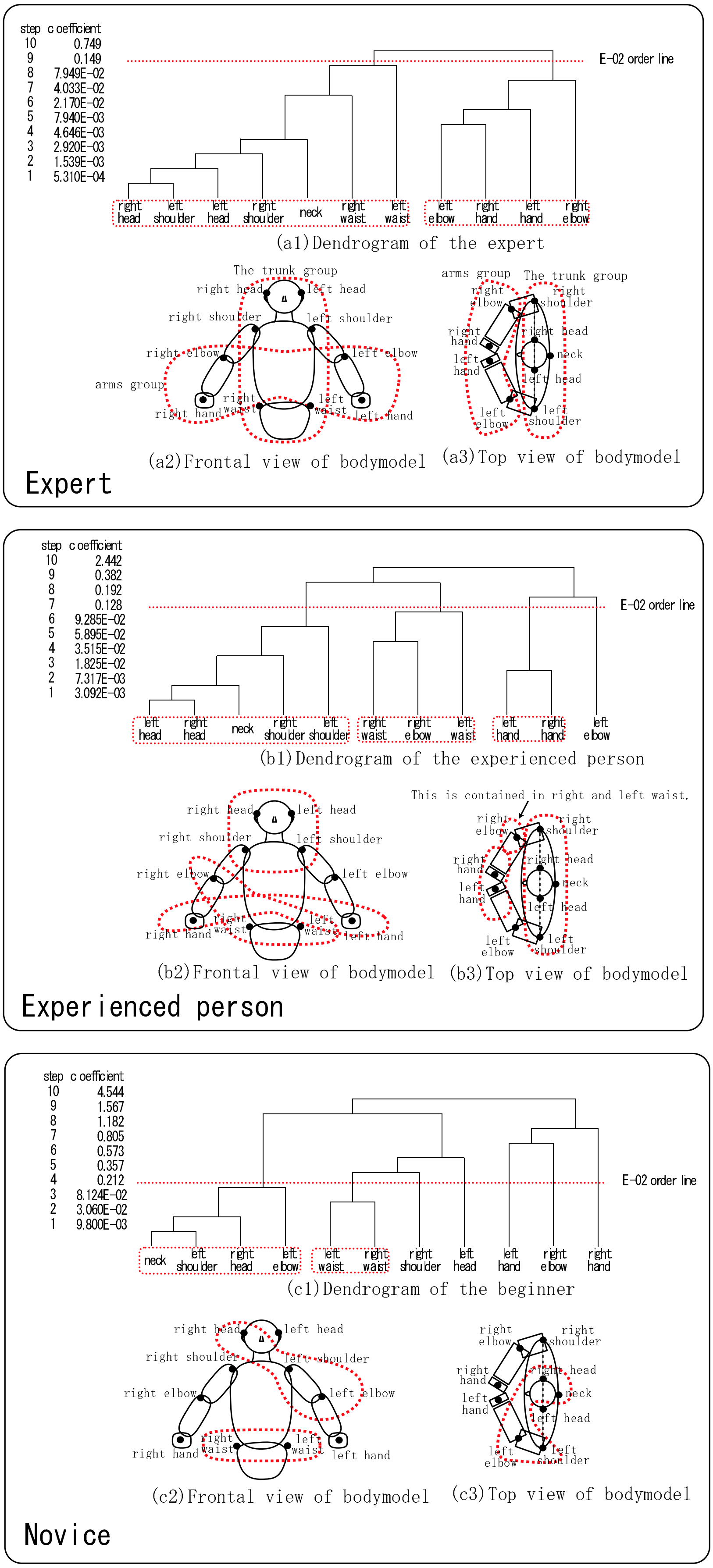

Figure 6: Dendrograms of phase relationships

4. Discussion

4.1 Coordination and phase difference

We found in the expert's motion that the coordination among joints is well established in a hierarchical manner: the phase relationship between the arm group and the torso group is observed and the arm group is governed by the torso group in the sense that the motion is pivoted at the waist belonging to the torso group.

We first discuss the coordination. In the expert's motion, the rocking motion of torso is not merely an inverted pendulum, but has a pivoting feature at his hip, which explains why the upper body of the expert can move so quickly. The rocking motion has also to be coordinated with the circular motion by the hands. Although we tend to focus on the movement of the hands, one cannot generate the force for kneading solely by hands. The coordination with the rest of the body is essential.

We can observe in Figure 5 that the novices tend to push down the clay by using their own gravitational forces while the expert uses his own rocking motion for kneading. We think that the delay of the hand group observed in the expert's movement indicates that he uses his hand to push his body back. The act utilizes his body's inertia to transform the clay efficiently and uses the reaction to prepare for the next rocking cycle. The act is highly organized and optimized. The muscular coordination is still difficult problem of biomechanics (Zajac, 2002), but we believe that the coordination in the whole body is an important feature for studying physical skills.

We now turn to the phase relationship and differentiation. We regarded initially the expert's movement to be a single simple movement. We could not find the coordination pattern and the phase difference until we started analyzing the data collected using the motion capture device. We thus think that the coordination pattern may not be acquired only from visual information and producing the phase relationship must be more difficult to learn. In fact, the coordination is somehow established in the movment of the experienced, but the phase difference is not clearly observed as shown in Figure 6.

The experienced person may greatly develop his skill if he is aware of the phase relationship between the two groups, his torso and arms. The skill for coordination may be taught hand-in-hand because the coordination can be represented as a single pose, i.e., as static information, but the phase relationship is essentially dynamic. Producing an appropriate phase relationship is difficult to learn and there is no established method for learning it.

Our findings conform with Bernstein's theory of motor coordination (Bernstein, 1967) and Haken's synergetics (Haken, 1996). They theorize movements in terms of degree of freedoms in coordination. We found the same phenomenon as the localization of trajectories. Our contribution is to have discovered the differentiation of phases that occurs within the envelope, i.e., in the subspace of the localised trajectories. Hermann, Kelso and Bunz found similar phenomena when they studied swinging fingers (Haken et al., 1985). Our setting is however different from theirs in that our control parameter is a skill while theirs is an external constraint.

4.2 Instruction and control methods

We pointed out that the coordination between joints and the phase relationship are established for the skilled person. We believe that these two points are keys for developing a skill and useful for controlling humanoid or animal-like robots. Developing a teaching method leads to an effective programming of robots. We believe that skill acquitision and instruction are closely related with each other.

We first discuss the instruction for the human. We think that the coordination of the limbs can be taught hand-in-hand, but learning the phase relationship requires some other method. We believe that an audio stimulus helps the learner to master the phase differentiation after he or she learnt to coordinate the joints. We have already generated an audio pattern based on the motion data of experts, but the pattern did not sound right to our ears. We realized that the audio stimulus should provide the learner with a trigger, not a feedback of his or her movement. We need a feed-forward mechanism to control the movement.

We assume many "controlling points" to be embedded within the phase space of body dynamics (Yamamoto and Kuniyoshi, 2002b). By controlling points, we mean the points where the body dynamics is in an unstable region and small control input leads to the transition of movements. The audio stimulus should correspond to such controlling points and affect on the act. It should be noted that we need a "cue" to indicate the controlling points if we consider the delay for the signal from neural system to be received by musculo-skeletial system.

One may ask whether or not a human learner can utilize the phase relationship. A study of walking by McMahon, called "Ballistic Walking" (Mochon and McMachon, 1980), suggests that muscles are only active in beginning and end of each phase while walking. Their theory is shown to be applicable for walking machines by Wisse (Wisse and van Frankenhuyzen, 2003), in which active control is applied only few times to a walking cycle. Because the muscle can generate power even when it is inactive, like a spring, the motion is maintained by itself, exploiting passive stability. We think that the feature can be found commonly in oscillatory motions, including the kneading. We would like to point out that kneading is in fact similar to an inverted walking, thus the phase relationship must play an important role for learning the skill.

Learning with phase relationships seems to work effective as long as the actuator reacts quickly, i.e., in phasic manner, and has passive mode, i.e., compliant like a spring. The latter requirement is hard to satisfy by conventional motor-geared systems because it requires mechanical perfection and higher control frequency. Conventional motor-geared systems are prone to making oscillation and destroy passive stability. We thus currently developing a robot arm actuated by the air muscle.

Backing to the topic of audio stimulus, we may develop a controlling method for robots based on impulsive control input when we become to know enough about the robot's body dynamics. In such a case, the delay may be shorter than that of the human. While a similar method is adopted for controlling a powered passive walker in simulation by van der Linde (Linde, 1999) and for controlling a real robot by Wisse (Wisse and van Frankenhuyzen, 2003), we are interested in developing a method applicable to general movements.

We are still far away from implementing our ideas into robots. There are a lot of things to do to see whether a robot can predict how stable its own body movement would be and whether it can construct a map of phase space by itself. It is an open question whether a robot can acquire a physical skill as the humans do. We believe that control signals are similar to rhythmic sequences and we can verify our theory using a sensory-motor system. One possible advantage to conventional control theories is that a higher level controller is not always preoccupied by performing every single bit of action until it reaches the next unstable region. The mechanism allows the robot to concentrate on planning in stable regions if the map is constructed.

5. Conclusion

We discoverd through our experiment of kneading that the coordination among joints are hierarchically organized as the person develops the skill. We also found that the phase relationship between the hand group and torso group is clearly established in the expert's movement. We proposed based on our findings to instruct the learner with audio stimuli after he or she learnt to coordinate the joints so that the leaner can find an appropriate "cue for control" by themselves.

We are currently running two follow-up projects. For the first project we are developing an instruction method for the human such that the learner can acquire the skill in shorter period. For the second project we are developing a control method for human/animal-like robots based on our analysis of human movements. The two projects will conjointly help us to understand the dynamics of human and robot behaviours.

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