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Synchronisation and Differentiation: Two Stages of Coordinative Structure

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Abstract

While motor skill acquisition process is regarded as development of coordination, typically regarded as synchronisation among joint movements, we found another phenomenon which we call *differentiation* as a consequence of synchronisation. The synchronised movement established is decomposed into several sections or modulated to be executed on different timings without breaking the coordination among them, resulting in the gain of efficiency or flexibility. In the acquisition of skills, the coordinative structure thus goes through two stages: synchronisation and differentiation. We verify in this paper our observation through our experiments and dynamical analysis of the kneading of ceramic art and playing the shaker in samba.

1 Introduction

The ability of the bodily movements such as walking or throwing has been thought to be acquired by decreasing the degrees of freedom inherent in the structure of our body. Our body consists of many parts and the number of possibilities in combining them is enormous. In his pioneering work, Bernstein found that the combination among the body parts has to be restricted to make our body controllable (Bernstein, 1967). Then coordinating joints show freezing, coupling, synergy or synchronisation. In this paper, we denote this phenomenon simply as synchronisation since we focus on the temporal relationship among joint movements.

Is the same principle governing the basic bodily movements applicable to skills, too? In this paper, we regard the skill as a highly sophisticated movement that fulfills the task such as seen in craftwork. To obtain a skill, it usually takes years of training. What makes skills so distinctive from novice's (or even experienced person's) movements? We have studied several skills such as kneading in the ceramic art to identify the characteristics of skills.

We have so far examined two skills, kneading clay in the ceramic art and playing the shaker on the samba rhythm, both of which are repeated, cyclic movements. Through our examination of kneading, we found that the expert organizes his body into two sections, namely, the torso and arm sections, and correlates them by moving them at different timings, while unskilled persons tend to move their bodies on a single timing (Abe et al., 2003).

Our finding reported in (Abe et al., 2003) was to extend the conception of motion. Previous studies of motion presuppose the coordination among the body parts to be fallen into smaller number of degrees of freedom (i.e., synchronisation). Haken, Kelso, and Bunz, for example, found such a decrease in the degree of freedom (Haken et al., 1985), where they studied human hand movements. We found, however, it is a half of the story and there comes the next stage of development, where the degree of freedom increases to obtain flexibility and adaptability.

The first stage of development is characterised with the notion of *synchronisation*, which indicates that the movements of each body part are synchronised on a single timing due to the loss of degrees of freedom (DOF). The second stage is characterised with the notion of *differentiation*, which indicates that the synchronised movement established is decomposed into several sections to be executed on different phases, maintaining coordination of the whole body. The motion capture device is necessary to investigate these features. By direct measuring of coordinates in three dimension, the joint angle is obtained and by high temporal resolution (86.1 Hz), temporal relationship is accurately observed. Without the motion capture device, we could not have found the characteristics of the expert's motion when we studied the kneading.

We explain in this paper the data we measured through our experiments and present an analysis to distinguish experts from novices with the notions of synchronisation and differentiation. As for measurement, we carried out two sets of experiments. In the first set of experiment, we examined the motions for kneading clay as a follow-up to our previous experiment (Abe et al., 2003). In the second set, we examined the motions for playing the shaker on the samba rhythm. As

for analysis, we employ Hilbert transformation to calculate the magnitude of coordinations found in the bodily movements.

2 Motions Studied

2.1 kneading

The potter kneads the clay in early stage of ceramic making to prepare it for shaping. Kneading removes the air contained in the clay and makes the clay evenly dense. If the potter fails to knead the clay properly, the ceramic is broken when it is burned in the oven due to the expanded air. The motion of kneading is similar to that of working dough in baking.

Kneading requires three to seven years to master. The difficult point in kneading is that the potter has to knead the clay very quickly, often in a few minutes, because the clay gets dry due to the heat from his hands and the dried clay is difficult to shape. He had better thus touch the clay as shorter time as possible while kneading. It is fairly difficult to push and form the clay on the desk very quickly without touching it too much. That is why it takes so long time to master kneading.

2.2 shaking

Ganza, or shaker, is a simple instrument widely used for playing samba to produce rhythmic sounds. The instrument we used for our experiment is a cylindrical shaker, 23 cm long and 6.5 cm diameter, and contains a handful of small plastic balls within. The instrument produces a characteristic dry noise when shaken quickly and a dim, low-pitched noise when shaken slowly.

The difficulty in playing the shaker on samba rhythms lies in producing the correct accents. Let H be high-pitched, dry, short noise and L low-pitched, dim noise. The shaker typically produces four patterns of H-L-L-H for a measure, resulting in a 16 beat rhythm, i.e., H-L-L-H H-L-L-H H-L-L-H H-L-L-H. The first H of H-L-L-H is hit when the shaker is moved out and the following L is hit when it is moved in towards the player's head. The next L is hit when the shaker is moved out again and the following H is hit when it is moved in. To produce the accents marked with H tone, the player has to move the shaker quickly, for the first H when he moves it out and for the second H when he moves it in. The same asymmetry applies to the two L tones, too. Most learners are confused by this asymmetric pattern, that is, moving the arm out-in-out-in to produce the H-L-L-H pattern. Producing the correct accents gets more difficult as the tempo becomes faster.

3 Methods and Materials

3.1 motion capture

For both experiments, we used same experimental settings with a few exceptions. For measurement, we used MotionStar electro-magnetic motion capture system by Ascention Corp. Its temporal resolution is 86.1 Hz. To avoid magnetic interference, performance was done on a wooden stage. 18 wired sensors were used. Their locations were as follows (see Figure 1):

- Left/Right Head: each lateral of the head, above the respective ear. (no. 1 and 2)
- Left/Right Shoulder: top of each acromion. (no. 3 and 7)
- Left/Right Elbow: lateral of each olecranon. (no. 4/8).
- Left/Right Radius (lateral anterior wrist): lateral of each distal of radius. (no. 5 and 9)
- Left/Right Ulnar (lateral posterior wrist): lateral of each distal of ulnar. (no 6 and 10)
- Left/Right Hip: lateral of each crista illacae. (no. 11 and 12)
- Left/Right Thigh: lateral of each grater trochter. (no. 13 and 16)
- Left/Right Knee: lateral of each humer condyle. (no. 14 and 17)
- Left/Right Ankle: lateral of each mallelous. (no. 15 and 18)

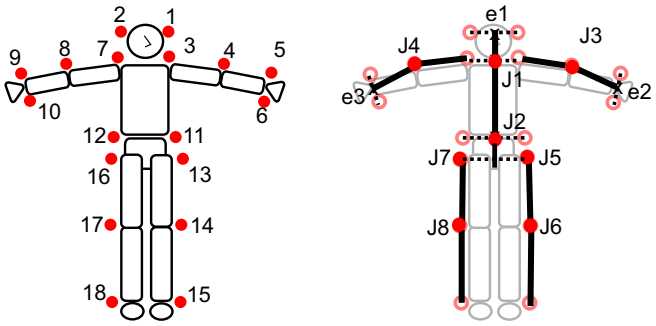

Figure 1: The bodymodel. Left: marker settings. Right: Segments and joints. J denotes a joint and e denotes an endpoint.

For samba shaking, the radius and ulnar sensors of the other side were moved to each side of the shaker to measure the wrist angle.

For each subject, we ensured the marker cables did not interfere his motion. No subject reported a difficulty for his performance.

Based on the marker setting, the body model was constructed. Our body model consists of 8 joints and 13 segments. The joints were defined as a planar angle between two segments, which were defined by two sensor points or virtual points (i.e., derived points from two sensors). The joints are: neck (J1), lumbar (J2), left elbow (J3), right elbow (J4), left hip (J5), left knee (J6), right hip (J7) and right knee (J8). For samba shaking, the sensors on the left wrist were moved to the shaker and the joint was moved from right elbow to left wrist. While the joint angles were evaluated by calculating the plane angle between two segments, we regarded this angle as an approximated hinge angle since both motions could be regarded as a planar movement on the sagittal plane.

Experimental methods and protocols were as follows. For kneading motion, five subjects participated in the experiments: one professional (subject A, the expert), three experienced (subject B, C, and D) and one novice person (subject E). They were ordered by the years of experience.

The subjects were requested to knead the clay for 60 seconds on a wooden table. Five trials were performed on the same day, with short intervals between each trial. Novice subjects were instructed the method by an experienced person (one of the experienced subjects).

For samba shaking, two subjects (subjects X and Y) participated, both of who were advanced beginners. For this experiment, we removed the table from the stage and the subjects performed dance without obstacles. No music was provided but a metronome signal was given to them. Five trials were performed on different tempos, 90, 100, and 110 bpm (Beat Per Minute). Each performance continued for 180 seconds. Subjects were asked later which tempo had been most natural to them. Both subjects reported that 100 bpm was favored. One beat consists of four shaker sounds and one period of wrist oscillation makes two sounds. Then, 200 periods of wrist oscillation (usually 100 period of the rest of the body) per minute were recorded.

3.2 data processing

After measurement was done, time series data were processed as described below. Relative phase was evaluated by calculating instantaneous phase using Hilbert transformation (Panter, 1965) (Pikovsky et al., 2001). With this method, the instantaneous phase and amplitude are obtained for arbitrary signals. After calculating the relative (instantaneous) phase between joint angles, the magnitude of coordinations was evaluated.

After joint angles were calculated, time series data was processed as follows.

- filtering
  First, smoothing by fourth-order Butterworth filter (cutoff frequency is 10 Hz) was applied. Second, to evaluate coordination within a single period of motion, low-frequency trends were subtracted. Low frequency trend was obtained by long-term moving average (101 in our case, the result did not strongly depend on the length of lag). The latter filtering was required to obtain unambiguous origin on the phase plane (i.e., for the instantaneous phase). We did not use other parameters in the rest of process.

- Hilbert transformation
  Instantaneous phase and amplitude were obtained by applying Hilbert transformation (Panter, 1965) (Pikovsky et al., 2001). By this transformation, phase portrait was reconstructed for each joint angle. The phase was obtained by defining the origin within the phase plane.

- calculation of relative phase
  Reference angle (i.e., time series of) was defined for each subject. For kneading, the reference angle was the hip of anterior stance side (left hip in Figure 2). For samba shaking, left knee was chosen. Both angles had sinusoidal-like time series and were regarded as regularly moving parts. In kneading, the hip joint defines the attitude of the torso and can be used as a pivoting point for pushing down the clay. In samba shaking, the knee and the wrist showed the most regular movement. Because the wrist's period was twice shorter than other joints, the knee was chosen. Calculation of relative phase is based on the method described in (Pikovsky et al., 2001).

  After the relative phase was calculated, distribution was evaluated by making histograms. The results are shown in the next section.

4 Results

4.1 overview of kneading

The movement of kneading was decomposed into two motions. One is the rocking motion of the torso and the other is the circular motion of the hands and arms. See Figure 2 for schematic representation. The two motions were combined to efficiently stretch and fold the clay. One may think that it is more efficient to push down the clay at the swing down (i.e., forward) phase, but we found pushing the clay in the swing backward phase to be more efficient: the arms also help to move the torso backward. However, it turned out to be nontrivial feature. Only subject A (expert) showed this motion.

One reason for the phenomenon may be sought in the complexity of motion. If one pushes the clay in the forward phase, the motion is essentially simple cycle without phase difference. On the other hand, when he pushes

the clay in the backward phase, there is a delay between the torso and arms. The motion consists of two parts with phase relationship, forming a single cycle with two modes. We think that this phase relationship is acquired at the final stage of skill acquisition, following the establishment of coordination. We discuss below this issue based on our experimental results.

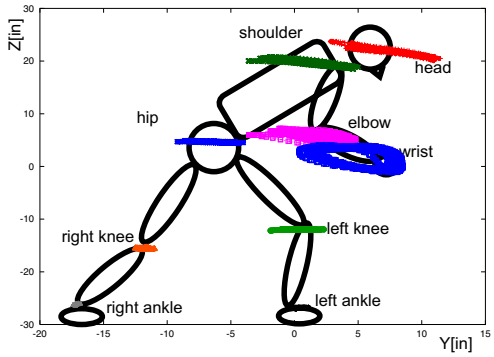

Figure 2: trajectories of kneading (subject A) on the sagittal plane

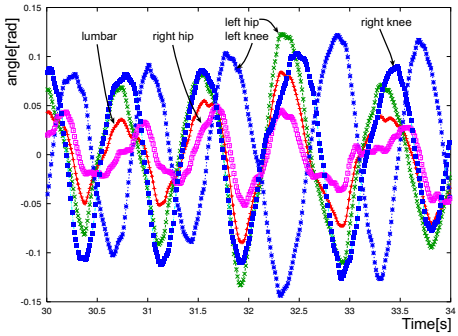

Figure 3: time series of subject A (expert)

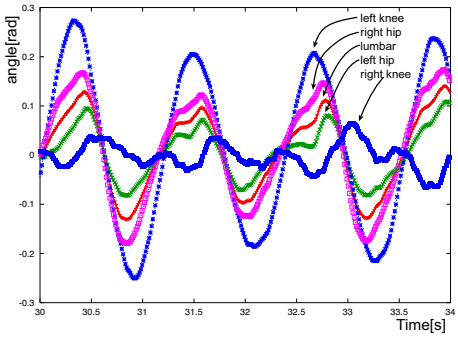

Figure 4: time series of subject B (experienced)

4.2 differentiation within coordination in kneading

As previously reported (Abe et al., 2003), we found the trajectories to be well coordinated as a person gets more experienced in the task. While only a qualitative analysis was presented in our previous work, we present in this paper a quantitative analysis of the coordination.

Let us begin with a description of coordination. In our experiment, the localisation of trajectories are found for both the experienced persons and experts (i.e., subjects A, B, C and D). Although we previously found an expert's trajectory to be highly localised, the experts who took part in the current experiment did not show such strong localisation. Contrarily, the experienced persons (subject B and C) showed better localisation as long as trajectories in the real space is concerned.

Figures 3 and 4 depict the time series of subject A and B, respectively. The latter may give better impression of strong synchronisation. Applying FFT (Fast Fourier Transformation), we found that subject B's motion has sharper peaks for all angles while subject A's has a single broader peak. Then if we only consider the strength of synchronisation, subject A is regarded to be inferior to B.

Subject A is, however, more skillful than the others as long as we judge their skills based on their end products. It is important to note that the establishment of coordination is merely halfway to skill acquisition as described below.

Next, we turn to analysis of differentiation. In the present work, we evaluated the relative phases among joints and confirmed our previous findings.

In Figures 5 to 7, the histograms of relative phase are shown for subjects A, B and C, respectively. The reference angle was chosen to be the hip of anterior stance side, i.e., left hip. Data are extracted from a single trial, but qualitative features are preserved.

For all the subjects except E (i.e., novice), a synchronisation is observed between the reference angle and the lumbar. The other hip is almost synchronising although a small delay was found in subject A.

In the torso, we do not find any synchronisation of the neck. This may be due to that reduction of our body model (i.e., the chest and top of the neck). Especially, the movement of viewpoint affects the attitude of the head (i.e., top of the neck) and we expect a coordination to be observed if we have adopted a more detailed body model.

The movement of arm is most important part of the motion because only the hands touch the clay physically. As noted, one possibility for the efficient way of kneading is to use the gravitational force to help to press the clay down. This pattern is found among the experienced persons. In Figures 6 and 7, the arm is synchronising (subject C) or proceeding (subject B) to the hip. They tended to push the clay with the help of momentum of the whole body. By stretching the elbow prior to swing down of the body, the arms become stiff and easily press the clay to stretch it out. A disadvantage of this movement is that the rest of a cycle is only to swing back the

torso.

The expert (subject A) moves in a different way. While his torso is synchronised, a delay is found in his elbows. This delay suggests that this subject pressed the clay in swinging back phase of the torso. The arms also helped his torso to swing back and thus the motion became quick. To avoid to dry up the clay, this quick method has an advantage.

We now investigate the movement of the knees. In the expert (Figure 5), each knee has a peak on the other sides of the Y axis. The forward motion of torso is generated by the right knee (i.e., the aft leg) and swing back by the left (fwd) knee. The body motion is thus not like a single pendulum, but a double pendulum which is pivoted around the hip. In other subjects, a peak is found only at the left (fwd) knee while the right (aft) knee does not have a peak. In such cases the body swings like a single pendulum although it is not stiff because of the relatively weak synchronisation than the expert.

We found a hierarchical organisation in the expert's motion. That is, within strong synchronisation, a phase differentiation is established. If we represent a motion as a rhythm, the experienced persons' are fluctuated single beat while the expert's is four beat whose intervals are not equal. To master this rhythm and correct pressing strength at once seems to be difficult for short period of time.

4.3 samba shaking

For shaking, we employed two subjects X and Y, both of whom we think were intermediate level players. We asked them to play the shaker on the samba rhythm on different tempos: 90 bpm, 100 bpm, 110 bpm, and 120 bpm. Each session continued for three minutes. The tempo was given by a metronome and no rhythmic hint was given to the subjects.

Figures 8 and 9 show the frequency distributions of relative phases, which we calculated from the data taken from the two subjects, X and Y. Due to limited space, we only present the distributions for two cases for each subject. For each figure, the upper plots show the distributions of the lumbar and the right knee and the lower plots those of either side of the hip, i.e., the left hip for X and the right hip for Y.

Both subjects reported that they felt most comfortable when they played the shaker on 100 bpm. Contrary to our intuition, the trajectories on the tempo are worst coordinated compared with those on other tempos as long as we judge the degree of coordination in terms of synchronisation. Take the subject X (see Figure 8). His degree of synchronisation got better when he played on 90 bpm (right). The peaks are sharper than those found for 100 bpm (left). On faster tempo of 100 bpm, the left hip is desynchronised and even exhibits two peaks while we observe only one peak for 90 bpm. For tempos

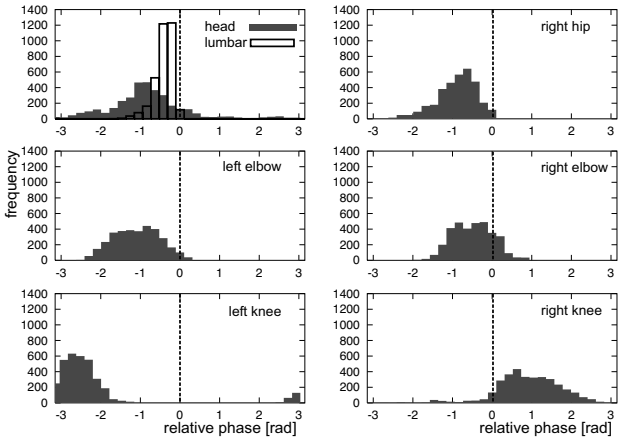

Figure 5: distributions of relative phase of subject A (expert)

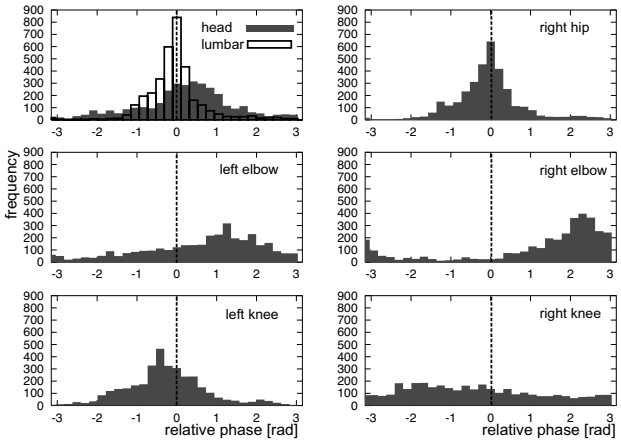

Figure 6: distributions of relative phase of subject B (experienced)

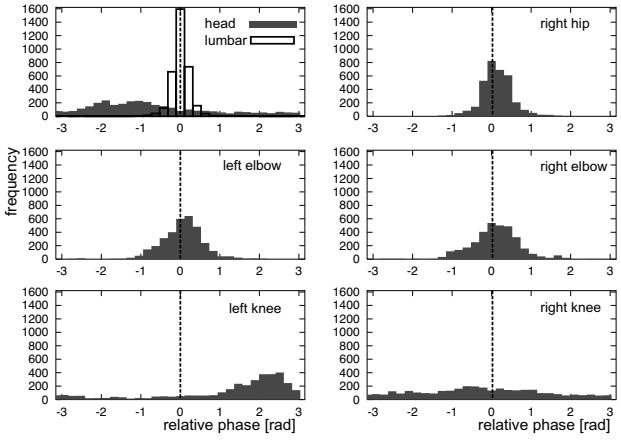

Figure 7: distributions of relative phase of subject C (experienced)

faster than 100 bpm, the tendency is same and a stronger coordination is observed. On 120 bpm the right hip is weakly desynchronised, but the phenomenon may be due to the fact that the body could not be kept up with the fast tempo. 120bpm tempo, for example, requires 3 Hz oscillation.

We face a contradiction here. The performances were musically best for both subjects when they played on 100 bpm, but strengths of synchronisation among joints were worst synchronised on the tempo. On the faster or slower tempo, stronger synchronisation phenomena were seen, but their performances were not musically better. We did not feel a groove or swing in their performances played on tempos other than 100 bpm though they produced correct rhythms with proper accents. Both subjects reported that 120 bpm was too fast for them to play the rhythm. How can we solve this puzzle?

We need to extend our conception of coordination and differentiation to accommodate the case for samba. The desynchronised movement around his hip is thought to be the source of the swinging rhythm and acquired for better musical expressions through practices. The frequency distribution of the left hip exhibits two peaks. This feature indicates that the phase difference is fixed in this subject. The direction of desynchronisation is not regular and the fluctuation of rhythm may be generated.

It should be noted that the desynchronisation is found within coordinated movement where other parts are synchronised. Also, desynchronised part did not break coordination of the whole body. We thus conclude that a hierarchical order is found, too, as is the case with kneading.

The same goes for the other subject, Y (Figure 9). We found additionally a hysteresis phenomenon for his case. We asked him to play for five trials on different tempos: 90, 100, 110, 120 and 100 bpm in this order. We found his hip desynchronised only on 100 bpm (left column in the figure) as is the case with the subject, X. His hip is synchronised to other parts of his body on faster tempos, 110 and 120 bpm.

Especially, for this subject, Y, only at 100 bpm, the result of spectrum analysis by FFT shows a broad hump for his right hip and all other joints exhibit sharp peaks. (The graph is not shown for space limit.) We therefore conclude that his hip is not synchronised to his knee and torso.

Also interestingly, his hip remained to be synchronised when he played the shaker again on 100 bpm (right column in the figure) in the last trial. The phenomenon can be explained as the result of his fatigue as he reported to us. A physical interpretation is that he lost the energy after performing four trials and it might become difficult to maintain the body balance only by his right leg. It is important to note that to make differentiation at the one side of the hip requires a redundant DOF.

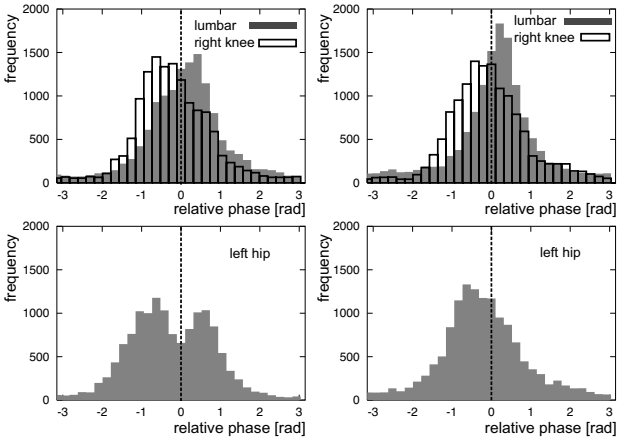

Figure 8: distributions of relative phase of subject X. Left: 100 bpm. Right: 90 bpm.

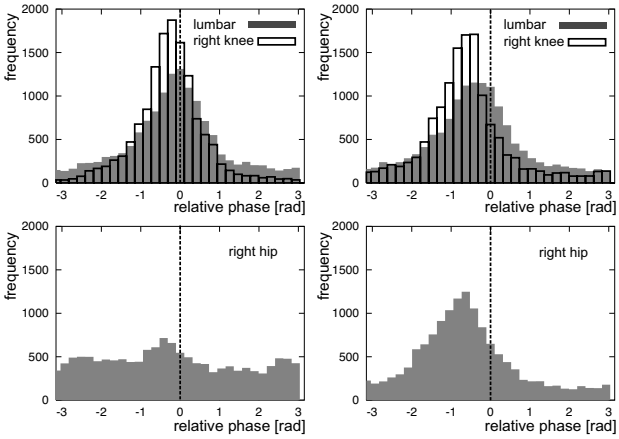

Figure 9: distributions of relative phase of subject Y. Left: first 100 bpm. Right: second 100 bpm (after 120 bpm trial).

Only after this coordination of one leg and the torso is established and balance is maintained, the other leg can make a differentiation.

All the results above point to the hierarchal structure, "differentiation within coordination". The hierarchical organisation of coordinative structure is different from Bernstein's "freezing and freeing" (Bernstein, 1967), where only flat structures are considered.

5 Concluding remarks

We have suggested through our experiments and analysis of kneading and shaking that there are two stages in the development of coordinative structure. In the first stage, the novice learns to synchronise his various joint movements to form a rough trajectory necessary for the task. The synchronisation is achieved by decreasing the degree of freedom innate with our body. In the second stage, the person learns to differentiate the synchronised movement into several sections, executing each section

on different timings. The differentiation is achieved by increasing the degree of freedom without loss of control and leads to flexibility and adaptability.

Our findings are consistent with the theory of dexterity as proposed by Bernstein (Bernstein, 1996). Dexterity means manual or manipulative skill and addresses neat-handedness in the use of the limbs and in movements in general. Bernstein proposed to classify developmental stage of the skill into four levels: A, B, C, and D, each of which is related to some part of the brain functionally. The lowest level A controls the balance. The second level B controls the basic movements. The third level C controls movements performed in the space with a target. The control in the level B only concerns with the body, not with the space surrounding the body. The level D includes other fascinating skills requiring higher brain functions such as reasoning or planning.

The synchronisation we observed in some subjects' trajectories indicates that their movements are controlled in the level of B. The trajectories in the level of B are simple, cyclic and repetitive movements and are performed without a target. The various parts of the body are thus synchronised to produce a force most effectively. The differentiation we observed in the experts' trajectories indicates that their movements are controlled in the level of C. According to Bernstein, the lower level B becomes the background and is adjusted by the higher level C. What we observed in the experts' trajectories as different timings at which some section moves jointly, are the points in which the level C intervenes in the movements controlled in the level of B.

Our interpretation is supported by our inner observation, too. As Bernstein pointed out, we are only aware of the foreground level of control, that is, we do not pay much attention to the background level, letting it to work automatically. For the case of shaking, each subject was aware of beating the samba rhythm in a particular part of his body, i.e., hip or knee, both of which were observed to move at different timings from other parts synchronised.

How is the hierarchical development achieved? Our hypothesis is that in higher levels (level C or above), controlling point is discretised in the phase space of body dynamics. While the lower levels maintain the balance and coordination in shorter time scales, the higher levels activate control input instantly in longer time scales (i.e., intermittently). This hypothesis is based on the concept, "Global Dynamics" (Yamamoto and Kuniyoshi, 2002). One of the authors proposed that higher control input only works on the branching point of stable sets of trajectories within the phase space. The results obtained in this work agree with the concept above and temporal differentiation of controlling point can be investigated as an expansion.

We have seen differentiation of phase in skillful persons' trajectories. Since this feature requires multiple control input per cycle, one might think the brain becomes busy. However, if control signal is preprogrammed as a sequence, a single signal input can describe complex movement with temporal differentiation. It may be helpful to note that due to the delay in neural signal transmission, feedback control is impossible for quick movements.

Using discretising feature described above, we think that the representation of higher level of motor control can be written as a "score". Temporal discretisation of controlling points may be easily understood through analogy to music score. Spatial discretisation is not one-dimensional. We think minimal information consists of the pattern of coordinating joints, the coupling strength within them, and the initial acceleration or momentum for the joints at the boundaries between groups.

Although the background level must be trained in advance, once mastered, differentiation within coordination of DOFs can be written as modulation of control input sequences. Still we do not have proof of this hypothesis, but our results are consistent with it.

One might think cyclic movement is realised by adopting Central Pattern Generator(CPG) (Taga, 1995). Our hypothesis, however, focuses on the fine tuning of movement after the motion is mastered. Let us describe a hypothesis about the acquisition process of the differentiation phenomenon for CPG based theory. In CPG based studies, the coordinated movement is regarded to be acquired by exploiting entrainment. The phenomenon may be regarded as a synchronising process to a single oscillator. Differentiation within coordination, however, requires a temporal differentiation of oscillators. As long as we are concerned with exploiting entrainment to a limit cycle, differentiation of it means a partial braking of cycles within the limit cycle. It is, however, a non-trivial process since stability (i.e. attraction to a limit cycle) is not expected within the limit cycle.

We think that the differentiation is obtained through trials, in which modulation signals are added to CPG, e.g., (Taga, 1998). Modulation signals can be generated by taking a hint from the sensory input. After skill is acquired, the modulation signals are integrated to CPG by changing parameters of neural network.

It is important to note that the search for controlling point is nontrivial. Like double support phase in walking, trajectories of skillful movements may go across unstable regions in the phase space to switch stable dynamical modes. For such cases, the control input must be adopted in correct timing and state. Also, even for the stable dynamical modes, the possible trajectories occupy only a small volume in the phase space. Small errors then may pull the state out of it and the skill might be not acquired. Only after synchronisation is highly organised, modulation plays a significant role in improving

skills.

Now recall our results. In the kneading, differentiation is highly ordered. We saw temporally hierarchy of phase difference in the experts' movements. There was a major phase delay between arm and torso and torso was divided into two groups pivoted around the hip. While experienced person's trajectories were similar to the expert's and coordination was established, differentiation was lacking. Adding modulation without breaking cycle may require long term self learning.

In samba shaking, modulation was also observed. One of the hip joints desynchronised to the torso although it was synchronised to the whole body to maintain the balance. This is why the samba dancer's upper body looks stable. We may thus conclude that differentiation observed in skill is also hierarchically ordered although differentiated movement of hip was not regular. We need yet to analyse time series of joint angles carefully, but we expect a qualitative difference of desynchronisation to be found between experienced persons and experts (or novices).

Our study may be applied to training or teaching method of skills. We think that controlling points can be found by investigating dynamics, the control points at which modulation is effective.

A promising candidates for controlling points are the zeros of angular momentum or joint torque. The former corresponds to the turning point of joints (i.e., starting point of a stroke) and it has dynamical significance since the direction of momentum changes. The latter has significance for muscular control because some of muscles generate strong torque instantaneously (i.e., pulse-like). This point is also suitable for adding force in any direction since there is no force is added or balancing to the external force. It is important to note that above zeros exist discretely in time. This feature agrees with our hypothesis described above.

Finally, let us discuss the significance of our result in the context of epigenetic robotics. Basic level can be achieved easily, either by machine learning or exploitation of limit cycles. We then discuss further step, differentiation by adding control input.

The learning process should be essentially the same as that for human. However, one possible merit for the robot is that its sensory system is faster and more accurate than that of human. To find controlling points, global stability analysis of body dynamics is helpful, but if we had hints discussed above (i.e., zero of some variables), on-line learning might be possible.

We do not expect real time learning to be easily realised because once stability is broken, there is no way to recover (e.g., falling down in walking). However, by "review" process, learning can be possible. Review process is a data mining process in which causal chain between sensory input and resulting movement (or, simply fitness) to find correct control inputs and there points to apply. What we expect to be most important factor is timing, not strength of control input. Although human muscle is not precision device, highly skillful movement is realised. Timing is also not based on physical time but depends on the phase within each cycle. If we find an appropriate rhythm and feed it to the robot, its body should follow the rhythm.

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