Hierarchical Organization of the Coordinative Structure of the Skill of Clay Kneading

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Abstract

An experiment was conducted to study the skill of clay kneading in pottery. This task usually requires a few years to master and is therefore well suited to study the long-term development of a complex motor skill. Participants' kneading movements were measured in 3D using a motion-capture device and phase relations among coordinates and joint angles were analyzed in terms of the mutual phase relative to a reference point using the Hilbert transform. While a certain degree of periodicity was observed in all ten participants, the behavior of the experts was characterized by a significant delay for the right elbow (i.e., the pushing arm) and the fore-aft position of the upper torso and only brief delays for the other parts, which all tended to synchronize with the reference. These findings are consistent with our notion of "differentiation within coordination", according to which skill learning proceeds in a hierarchical manner in that coordination among limb movements is established first, followed by modulations of specific limb movements within the established coordination. Although this feature of expert behavior was also apparent in our previous studies of clay kneading and samba performances, the numbers of participants in those studies were not sufficient to draw firm conclusions. Since the present study involved more participants and a superior method of analysis, the present evidence for the principle of differentiation within coordination is more conclusive.

key words: motor skills, motor control, development, synchronization , differentiation

PsycINFO 2330

1. Introduction

Physical skills, such as crafting a product or playing a musical instrument, involve delicately controlled movements. Highly skilful performances appear to be fluent and natural, but how this motor proficiency achieved is largely unknown. One reason for this may be that it is impossible to describe in a few words how one moves. Hence, to study skill learning incisive, powerful abstract concepts are needed. In the study of the acquisition of perceptual-motor skills and expertise, Bernstein's (1967) notions of "coordinative structures" and the "freezing and freeing" of degrees of freedom are often employed for this purpose (e.g., Balasubramaniam & Turvey, 2004; Higuchi & Imanaka, 2002; Vereijken, van Emmerik, Whiting, & Newell, 1992).

The central tenet of Bernstein's perspective is that skill acquisition is essentially a process of reducing the number of degrees of freedom recruited in the performance. This reduction in recruited degrees of freedom is thought to be a common feature of all skill acquisition and is often achieved in cyclical skills trough synchronization of limb movements and other body parts. In the present experiment, we studied the development of the skill of clay kneading for pottery, focussing on a particular aspect of skill development that we coined "differentiation within coordination" in a previous studies on the development of clay kneading (Abe, Yamamoto & Fujinami, 2003, Yamamoto & Fujinami, 2004). According to this concept, freezing and freeing occur recursively in hierarchical manner.

In previous studies on the development of samba performances (Yamamoto, Ishikawa, & Fujinami, 2006) and clay kneading (Yamamoto & Fujinami, 2004), we observed that some body parts are no longer fine tuned or modulated once a particular coordination has been established, whereas others are. In the study on samba performances, we used the autocorrelation function to reveal the presence of temporal differentiation in the coordination pattern of interest. In particular, we found that accents only appeared after a certain degree of periodicity had been achieved. Accent was represented as the amplitude difference of the up-down movements corresponding to the strong and weak sounds produced by the shaker: in the experts the unit of periodicity was twice that of the novices. We believe that the skilled participants generated two periods of oscillation (strong and weak sounds) from a single control cycle. In the study on clay kneading, we also found evidence for differentiation of the movement pattern but the number of participants (only five) was too limited to make a convincing case and our analysis was not complete. In the present study, we invited more skilled and less skilled persons to participate and applied a new analysis method to clearly demonstrate that expertise in the skill of clay kneading is indeed achieved by differentiation within coordination.

2. Methods and Materials

Two men and eight women, aged 24 to 71 years (mean age 32.7 and SD 14.5) participated in the experiment. The two male participants (42 and 71 years old) were pottery instructors and had more than 10 years of experience in the skill of interest. The other eight (female) participants (mean age 26.8 and SD 2.5) all had more than 1 year of experience. The first two participants were considered “experts” and the latter “experienced”. After a brief explanation of the experiment, all participants signed an informed consent form.

The clay kneading movements of the participants were measured with a MotionStar (Ascension Corporation) electro-magnetic 3D motion capture system at a sampling rate of 86.1 Hz. To this end, 18 wired sensors were attached to the participant. The left panel of Fig. 1 shows the marker positions and the right panel the 13 segments and 8 joints of the body model used. Marker positions were as follows:

- Left/Right Head: lateral sides of the head, above each 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 and 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 iliacae (no. 11 and 12)
- Left/Right Thigh: lateral of each grater trochanter (no. 13 and 16)
- Left/Right Knee: lateral of each humeral condyle (no. 14 and 17)
- Left/Right Ankle: lateral of each malleolus (no. 15 and 18)

Endpoints of the head (e1) and the upper arms (e2 and e3) were represented by the mid points of two markers. The joints were defined as a planar angle between two segments, which were defined by two markers or endpoints. The following joints were defined: neck (J1), lumbar (J2), left elbow (J3), right elbow (J4), left hip (J5), left knee (J6), right hip (J7) and right knee (J8).

Insert Fig. 1 About Here

The clay kneading activities were performed on a wooden stage to avoid metal interference to the sensors. The clay was kneaded on a 71 cm high wooden desk. Slip-free sheets were used to keep the desk stable. The cables were suspended using a 141 cm high wooden shelf so as not to interfere with the participant's movements. All participants performed five trials. Each trial lasted 60 s. Upon completion of the trials, no obvious signs of fatigue were observed, not even in the oldest (71-year old) participant.

The recorded raw data were analyzed as follows:

• calculation of joint angles

Joint angles were calculated from the marker positions, using the body model depicted in Fig. 1. Joint angles were approximated as the planar angle between two segments.

• filtering

The joint angle time series were first smoothed with a fourth-order-lag-free Butterworth filter with a cutoff frequency of 10 Hz. Subsequently, low-frequency trends were subtracted to evaluate coordination within a single period of motion. Low-frequency trends were eliminated by means of a long-term moving average (101 was used; the results did not strongly depend on the lag length). The latter procedure was required because the Hilbert transform (see below) presupposes that low-band frequencies are negligible. No other arbitrary parameter was used in the analysis.

• Hilbert transform

Instantaneous phase and amplitude were obtained by applying the Hilbert transform (Panter, 1965; Pikovsky, Rosenblum, & Kurths, 2001). This transform was applied to all time series.

• calculation of mutual phase

The calculation of mutual phase was based on the method described in Pikovsky, Rosenblum, and Kurths (2001). After the mutual phase was calculated, the phase distribution was evaluated by plotting the phases in histograms. A reference point was defined for each analysis (i.e., time series).

3. Results

Kneading is an essentially oscillatory activity, consisting of forward and afterward movements. Fig. 2 depicts the Y-Z (Y is fore-aft and Z is up-down) projection plot of a typical kneading trajectory. As can be seen, the hands move in a circle to mold the clay into a flower-like shape. Torso and hand movements are coordinated to form a global single-periodic motion. This may be regarded as a process of freezing degrees of freedom. However, in the movements of the experts a phase difference was present that was absent in the less skilled participants.

Insert Fig. 2 About Here

3.1 Time series

Fig. 3 shows representative time series of the horizontal positions of the hip center (thick line), the right wrist (dotted line), and the top of the torso (gray line). Only 5 s of data are shown to highlight the main features. First we consider the waveforms of the experienced participants. While the shapes of those waveforms are different for the two participants in question (see Figs. 3B and 3C), they are approximately synchronized. The highly periodic and synchronized waveform depicted in Fig. 3B is typical of experienced clay kneading, albeit that the degree of periodicity may differ across individuals. For example, in the time series shown in Fig. 3C, periodicity is hardly visible for the wrist (dotted line), indicating that this participant did not succeed in handling the clay very well. Since the top of the torso and the hip center move periodically, the global movement pattern is periodic. While periodicity is not strictly required for the purpose of kneading, it is an ubiquitous feature of repetitive skills. We therefore regard periodicity as an index of the stage of skill development. This also applies to other cyclical activities like bimanual finger wiggling (e.g., Haken, Kelso, & Bunz, 1985) and hula hooping (Balasubramaniam & Turvey, 2004), although a much longer learning time (i.e., at least a few years) is typically required to master the skill of clay kneading.

Insert Fig. 3 About Here

Periodicity is achieved through coordination of the limbs and other body parts by means of several grouping processes. In the time series of an experienced kneader shown in Fig. 3B, a single cycle is visible but there are still independent degrees of freedom. Of those independent degrees of freedom, the wrist is the most important. The hand rotates the clay, resulting in unpredictable changes in its shape that require real time adjustments, especially in less skillful kneaders. To investigate the movement of the hands and fingers, a more detailed 3D analysis is required than provided here. In contrast, in the time series of the expert kneader shown in Fig. 3A, a certain degree of periodicity is present but in this case the waveforms are not entirely synchronized due to phase delays among the waveforms. This was found to be a feature of the kneading trajectories of both experts. In particular, there appeared to be a delay between the wrist and the top of the torso. Nevertheless, the kneading movements of the experts and the experienced participants were rather similar and without detailed time series analyses, the delay was hardly recognizable through visual inspection. This suggested that there were several body parts that broke out of the global coordination without destroying it (i.e., the overall fore-aft oscillatory movement of torso and arms was preserved). As a result of this differentiation within the coordinative structure of kneading, the mean kneading frequency of the experts (1.34 Hz) was significantly higher ($p < .01$, unpaired *t*-test, $t(26.7) = -9.15$) than that of and the experienced group (0.96 Hz). (Kneading frequency was calculated from the first peak of the autocorrelation function of the horizontal position of the hip center.)

3.2 Mutual phase

We examined the hypothesis of “differentiation within coordination” by analyzing mutual phases. We selected the Y (fore-aft) position of the center of the lumbar as reference point for this analysis, because this point approximated the center of gravity (CoG) of the body most closely. All mutual phases were calculated with respect to the reference point (see Section 2). In Fig. 4 the distributions of the mutual phases of the torso top (J1, the joint center in Fig. 1), the right wrist (e3), and the angle of the right elbow (J4) are plotted. For each participant, data of all five trials were collapsed together. The box in each plot denotes the expert group (Participants 1 and 2). Visual inspection of the plots suggested that delays were longer in the expert group, especially for the top of the torso. We tested if the mutual phase distributions differed between group, which was indeed the case (all *p*’s < .01, t-test, $t(3.63 \times 10^4)=-197.9$, $t(3.65 \times 10^4)=-66.1$, $t(4.39 \times 10^4)=-140.5$). While high variability was observed in the mutual phases of the right wrist of Participant 1 (Fig. 4B), some trials were clearly more variable than others (see Fig. 4D). However, since the average mutual phase was about the same, we did not eliminate these trials. Why the mutual phases of the right wrist was so variable was not apparent, but the reason may be related to the condition of the clay. The mutual phase delay for the top of the torso resulted from torso bending. While the average mutual phase delay was only small (i.e., -0.25 rad) in the experienced group, it was markedly larger in the expert group (i.e., -1.07 rad). By comparing video recordings, we inferred that the torso bends at the hip in the experts but not in the experienced participants. The mutual phase of the elbow and the wrist corresponded to the phase relation between the rocking motion of the torso and the circular arm movements. All participants showed some delay because a certain delay is necessary for folding the clay (i.e., backward movements). Nonetheless, the delays were markedly larger in the experts. This suggests that the arms were pushed forward later in the experts than in the experienced participants.

Insert Fig. 4 About Here

4 Discussion

4.1 Advantages of experts' movement pattern

How should the phase difference observed in the experts be interpreted? Based on the features identified in the preceding, we offer in Fig. 5 a schematic drawing of the difference in clay kneading between expert and experienced performers. We believe an important advantage of the kneading strategy adopted by the experts resides in its quickness. There is a trade-off in kneading: while the purpose of kneading is to carefully remove air bubbles by pressing the clay, it has to be kept wet implying that hand contact should be minimal. Clay is usually dried due to the heat from the hands and quick kneading is thus favored. As a consequence, the kneading frequency of experts is generally higher than that of experienced persons (see Section 3.1). This is thought to be due to the fact that the experts bend their torsos at the hip. Since the oscillation period of a pendulum depends on its radius, the advantage of this strategy is clear. Also, the delayed extension of the elbow suggests that the arm extension helps the torso to return. In contrast, experienced clay kneaders tend to push down the clay by oscillating the torso as a single body, as this is suitable for effective pressing.

Insert Fig. 5 About Here

It should be noted that the establishment of coordination is far from trivial. The participants in the experienced group had at least one year of experience. The kneading movements of novices that we measured in the course of our studies were hardly ordered. We therefore conclude that the movement pattern observed in the experts is more advantageous than that seen in experienced performers. Since the overall coordination of clay kneading is preserved and the hand trajectories are similar (i.e., the end product has the same shape), we believe that the reason for the observed difference between expert movement patterns and those of experienced performers has to be sought in the timing of their execution. Also, in the experts, rocking of the torso is kept but bending (i.e., flection of the hip) is added, causing a delay in the top of the torso. These two differences do not interfere with the overall synchronization of the movements as seen in the experienced performers. Therefore, we assume there are two levels of development, that is, coordination is established first, followed by a differentiation within this established coordination.

4.2 Dependences on age and gender

In the present experiment, the two expert clay kneaders were both old males, whereas the experienced participants were all young females. This introduces the possibility that the observed differences in performance were confounded by gender and/or age. Let us discuss both possibilities in turn. With respect to gender, it is important to note that in our previous study (Yamamoto & Fujinami, 2004), all experienced participants were male rather than female. Nevertheless, the results of this study were the same as here, i.e., strong synchronization in the experienced group and differentiation in the expert group – even though, admittedly, the analysis method used was less conclusive than in the present study. Although we have no recordings of the kneading performance of a female expert, we see no reason why expert clay kneading performance would be gender dependent. Since expert movements are always more efficient (see above) once mastered than non-expert movements, we deem it rather unlikely that gender differences exist in expert clay kneading. As regards the issue of age, it should be noted that the oldest participant, who was 71 years old, showed the same movement pattern as the other expert, who was 42 years old. Thus, no age difference was present in the experts. A possible reason could be that the oldest subject is still active as an instructor and physically fit. Also, at the younger end, we found no young experts as a consequence of the extensive training period that is required to become an expert. Nevertheless, clay kneading within the experienced group may depend on age and this remains an issue for future study. In the present study, we focused on the difference between experts and experienced persons. To be able to identify subtle differences within a group, more sensitive methods of analysis are required that are not yet available.

4.3 Hierarchical differentiation

We described two stages of development in clay kneading. The first stage is the establishment of coordination, achieved by synchronization and resulting in a certain degree of periodicity. The second stage is characterized by differentiation within the established coordination, where some body parts are delayed or advanced in phase relative to the overall pattern so as to become independent of other parts without breaking the overall periodicity. By interviewing several experts, we learned that it takes about three years to master the skill of clay kneading. We suppose the degree of periodicity increases during this stage. Although we did not evaluate the precise skill level of the individual participants, and although individual progress rate are likely to differ, the participants in the experienced group were all at this stage of skill development. Further development takes more than a few years of dedicated practice. The delay of the arms and double-pendulum like oscillation of the torso are achieved by adding modulations of the original (i.e., synchronized) overall movement pattern. In caly kneading these modulations are thought to be achieved through a process of differentiation in the timing of movement execution. It should be noted that although the movement trajectories are similar, their dynamic properties are different. In the arm, the differentiation resides in the timing of the arm extension with the arm contributing to a quick return of the body. In the torso, differentiation is achieved by changing the actuation pattern of the hips resulting in bending of the torso. We assume that differentiation is essentially a sequential process. Without synchronization, modulated trajectories do not make sense. This process may be related to Bernstein's theory of dexterity, where real-time adaptation is based on knowing the timing or the pose that are suitable for changing movements.

4.4 Developmental process of skill

Fig. 6 shows a schematic representation of our concept of “differentiation within coordination” for skill development. The left panels show angular time series and the right panels show phase diagrams. In novices (Fig. 6A), periodicity and coordination are hardly seen. After a certain period of practice, coordination is established through synchronization, resulting in a high degree of periodicity (Fig. 6B). This stage corresponds to the skill level of experienced persons. Finally, in experts, modulations are added to the movement pattern resulting in differentiation within the established coordination without breaking it (Fig. 6C).

Is this concept applicable to skill development in general? We have shown that in the development of samba shaking, tempo (periodic beating pattern) is established first, after which accents (strong/weak within a beat) are introduced (Matsumura, Yamamoto, & Fujinami, 2007; Yamamoto et al., 2006). Also, in studying samba shaking, Yamamoto et al. (2006) showed that differentiation of the wrist is only present in experts. Those features are compatible with our concept of “differentiation within coordination” and we are going to investigate other kinds of physical skills. The pottery experts that we interviewed were also instructors. However, they could not explain how the movement of their torso. Their instructions concentrated on hand movements. We believed their optimised movements are all too natural for them, so that they were unaware of their importance. This may be one of the reasons why motor skills are so difficult to teach.

4.5 Future directions

So far, we have shown that differentiation within coordination occurs in the movement of the body as a whole. In the future, detailed investigation should include movements of the hands and fingers, which creates a challenge in terms of measurement and instrumentation. Three dimensional analysis is required and motion capture is difficult without interfering the kneading movements, especially for the fingers. This problem is common for all conventional motion capture systems including optical ones. Small wireless motion sensors are currently being developed and this problem will be solved in the future. Another method to obtain detailed measurements would be to use pressure sensors under the clay and the finger tips. Combined with a motion capture system, it may then be able to analyse when participants press the clay. Direct information about this aspect is thought to be helpful for further analysis since touching the clay should be minimized to keep it wet.

On a more practical note, our results may well be applied in the training of physical skills. Our main finding, i.e., the differentiation of movement patterns in the torso and the arms, is directly important for individuals aspiring to become experts in clay kneading. Usually learners concentrate on controlling the fingers (i.e., contact point with the object where force is applied) and tend to be less aware of the movements of the torso, which approximates the position of the CoG. We therefore suggest the training of hip-only movement as a first course of teaching, possibly even before handling the clay. After having mastered the hip movement, we expect that learning will be more effective. If there is a dance that resembles the hip movement of the skill to learn, this may be helpful. Actually, this is the reason why we started study on skill acquisition process of samba dancing (Yamamoto & Fujinami, 2004, Yamamoto et al., 2006).

5. Conclusion

In the present study we provided evidence for the concept of “differentiation within coordination” in the clay kneading performance of pottery experts. This concept was confirmed through an in-depth analysis of phase relations among angular time-series derived from marker coordinates. In the expert group, marked delays were observed in the top of the torso, the right elbow angle, and the right hand position, whereas overall synchronization predominated in the experienced group. We believe that the observed phasic differentiation may shed a new light on the development of motor expertise and dexterity. While the establishment of coordination is a necessary step to reduce the number of degrees of freedom of a particular behavior, differentiation is a necessary next step for further skill improvement. In future research, whole-body analyses are required to examine all relevant degrees of freedom. So far, we have not yet investigated the movements of the fingers, which are thought to be crucial in mastering the skill of clay kneading. Furthermore, the analysis method itself should be investigated. Approximate CoG is used in this work but other coordinate systems should be tested as well. Besides samba music-making and clay kneading, we are going to study other motor skills, especially musical and crafting skills.

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Figure Captions

Fig. 1. The bodymodel. Left: positions of the 18 markers used. Right: Segments and joints. There are 13 segments and 8 joints. e1, e2, e3, J1 and J2 are mid points of marker 1 and 2, 5 and 6, 9 and 10, 3 and 7, and 11 and 12, respectively.

Fig. 2. Marker trajectories on the Y-Z plane.

Fig. 3. Time series of the hip center, the right wrist and the torso top. Y-axis (fore-aft). A: expert and B,C: experienced persons.

Fig. 4. Box plots of distributions of mutual phases with respect to the position of the hip center. A: position of the top of the torso; B: position of the right wrist; C: angle of the right elbow. Shaded boxes denote expert group (participants 1 and 2). Numbers on the right side of the plot show the averages of each group. D: comparison of participant 1's distributions of mutual phases of the right wrist.

Fig. 5. Schematic representations of patterns of clay kneading produced by expert and experienced performers. Top: pattern produced by experienced persons. Synchronized coordination is evident. Bottom: pattern produced by experts. Total coordination is preserved but a particular phase relation is achieve within this coordination.

Fig. 6. Schematic representations of our concept of "differentiation within coordination". A: Novice. No structure is evident. B: Experienced person. Movements become synchronized and a single-periodic coordination is established. C: Expert. A phase delay is implemented and "differentiation within coordination" is observed.

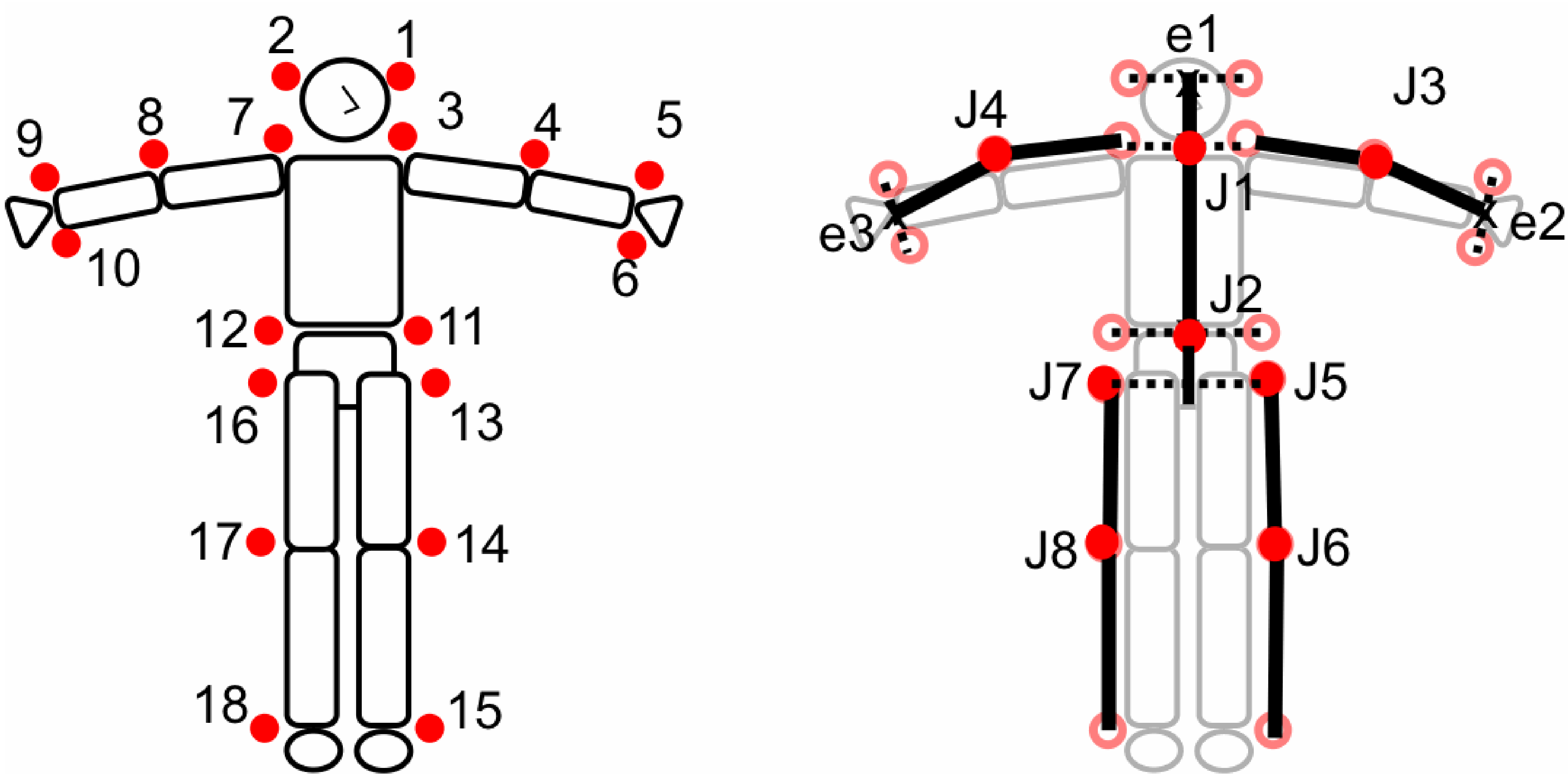

Figure1

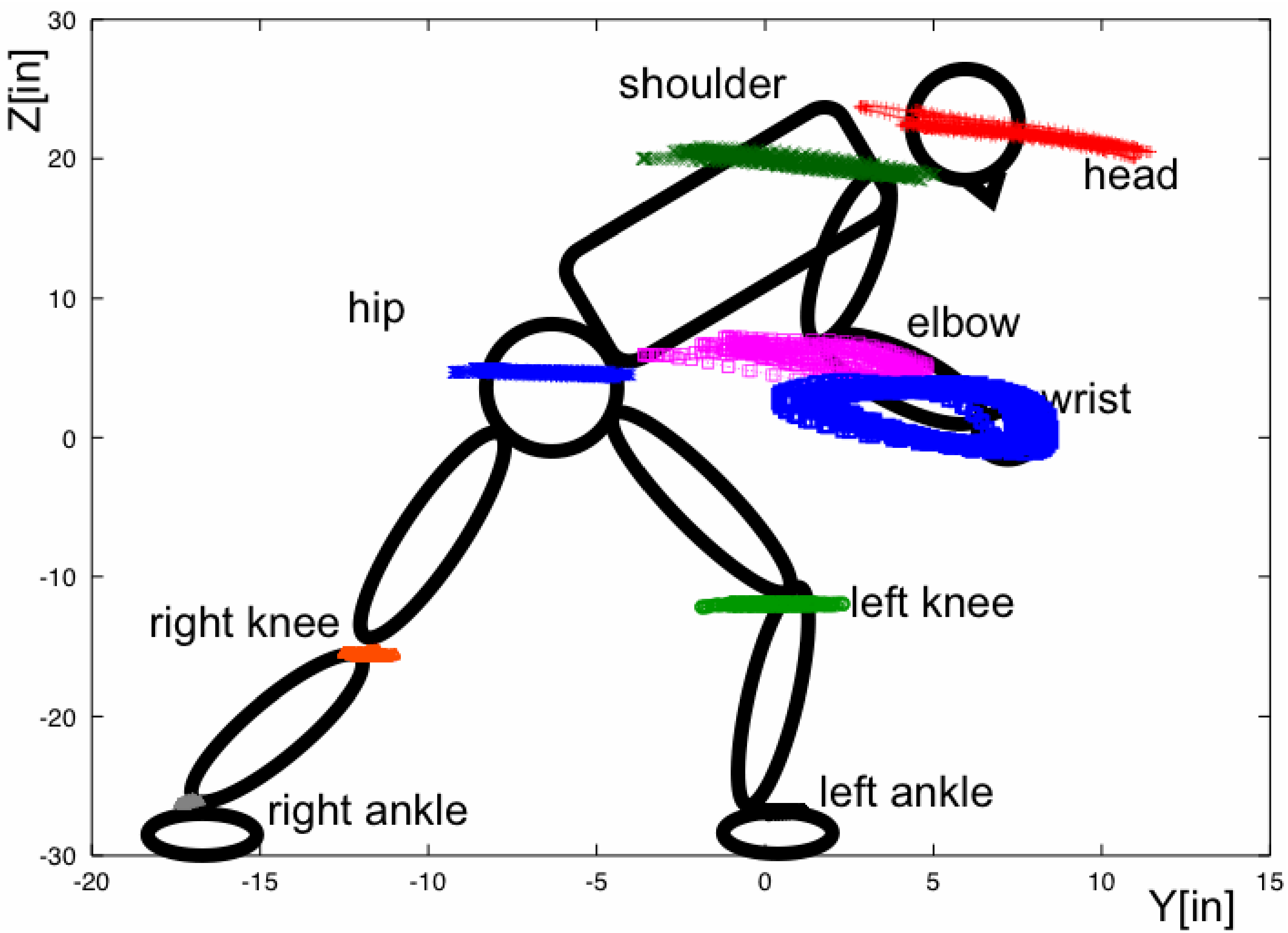

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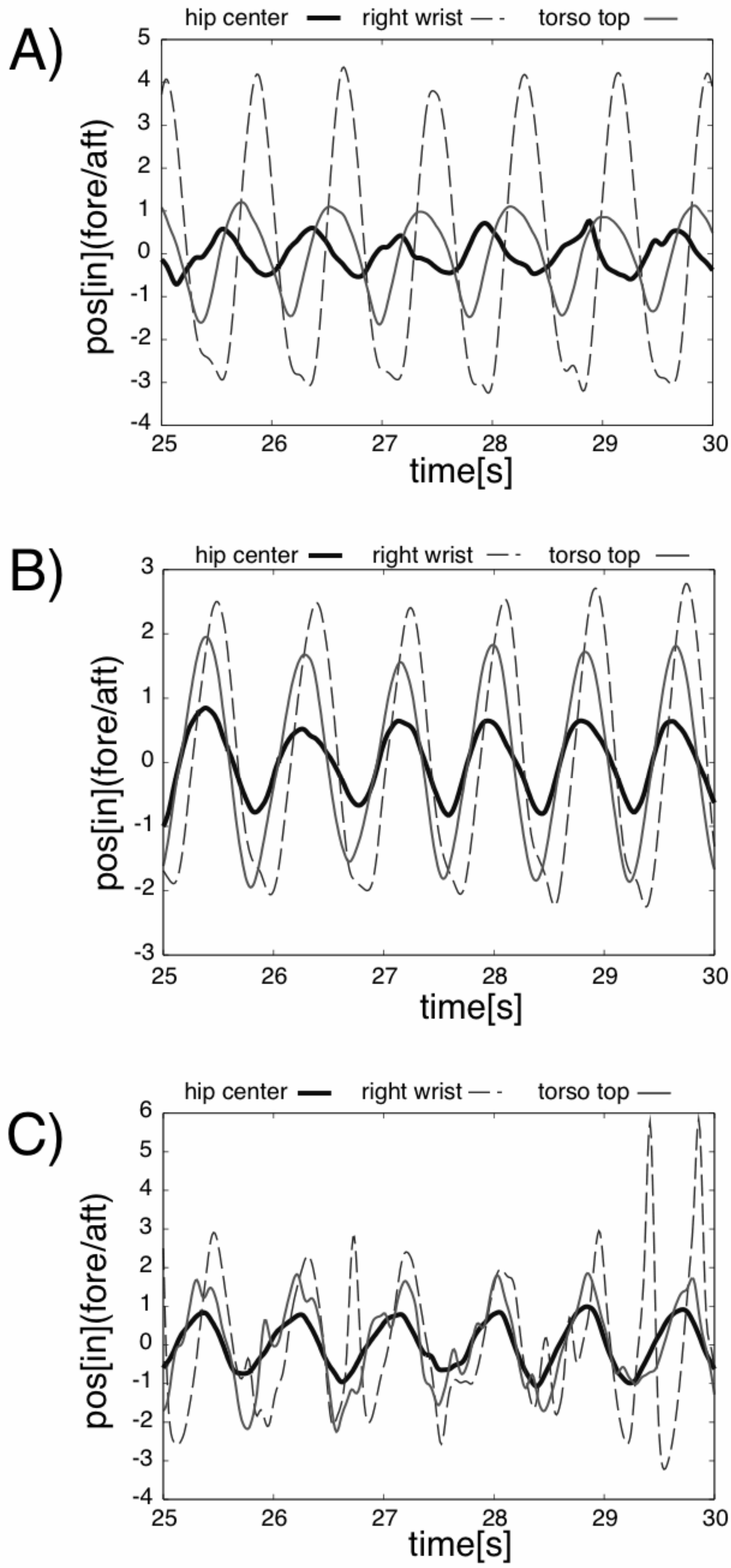
Figure2



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hip center
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C)
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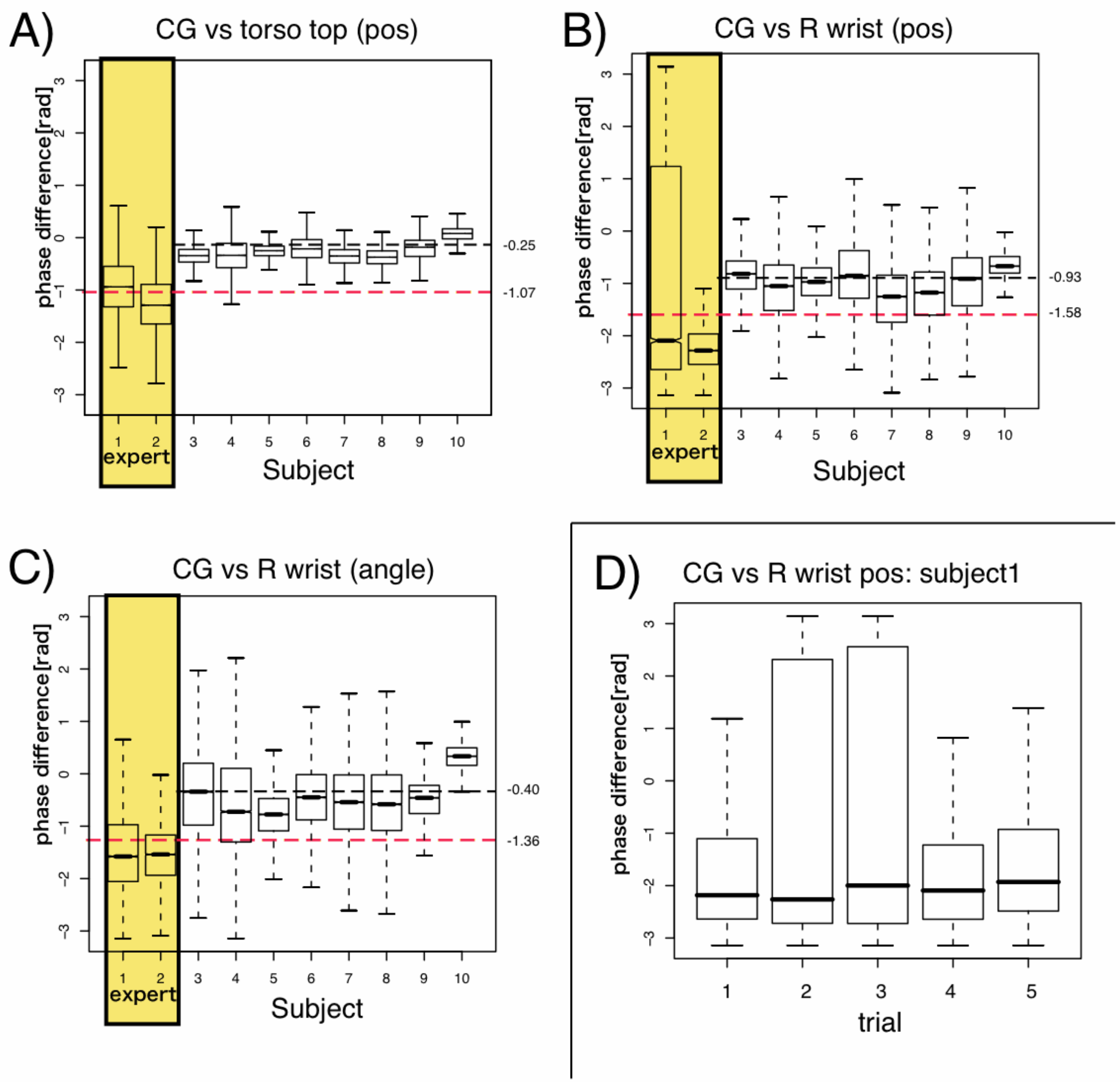
time[s]

Figure3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Subject
C)
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Subject
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Figure4

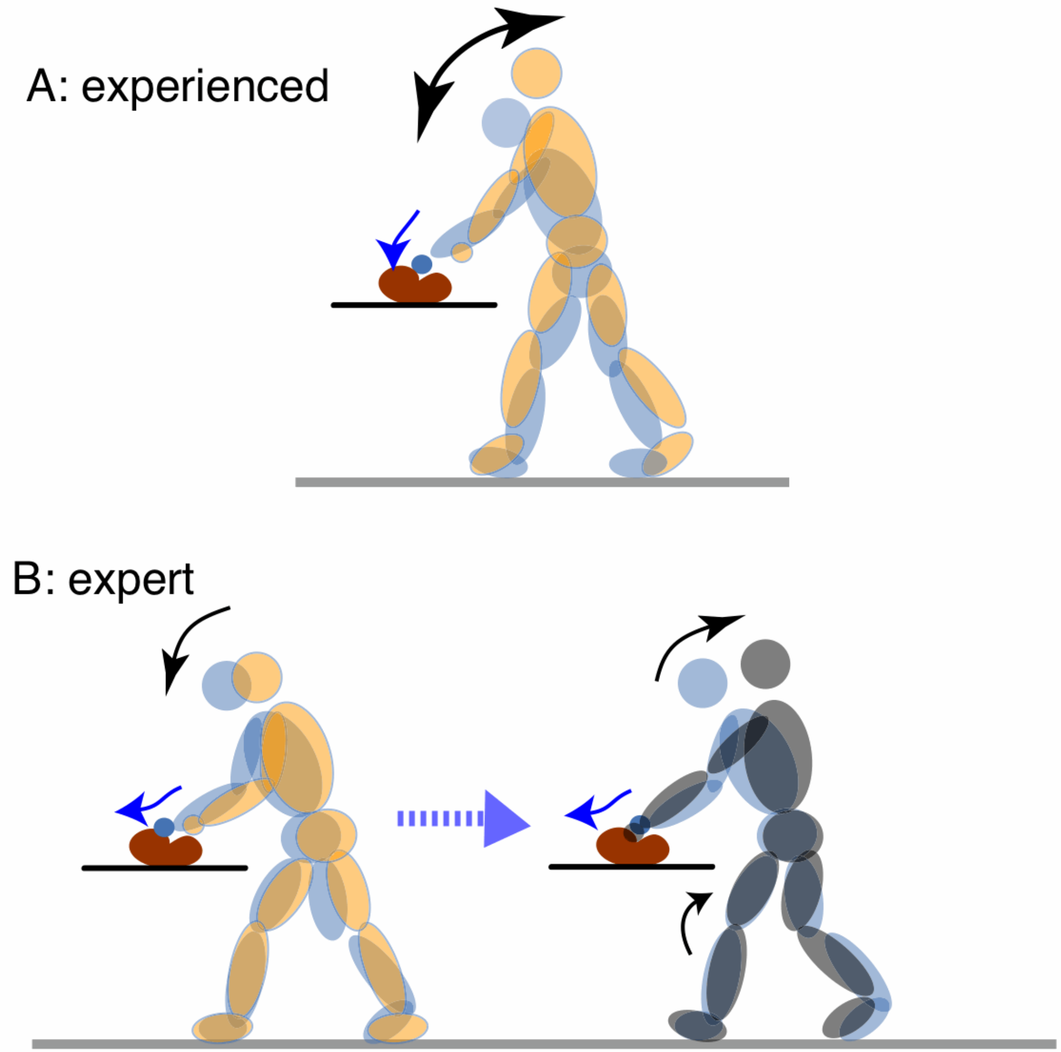

Figure5

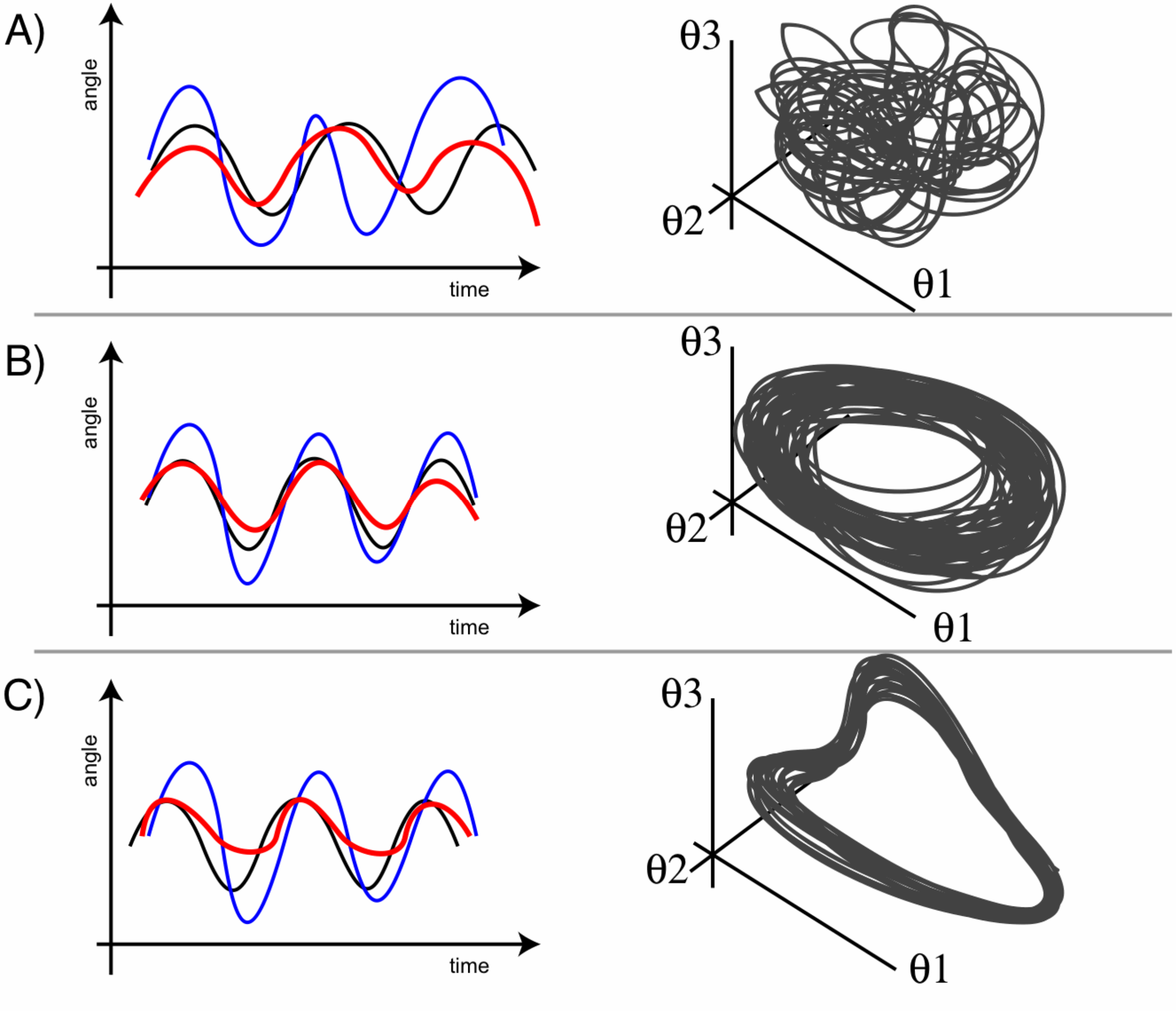

Figure6