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研究論文

Motor coordination in santūr players: Implications for santūr education

Masato Tani*　　Tetsushi Nonaka*　　Masahiro Okano*

Abstract： The present study provides a detailed analysis of upper-limb motor coordination in two professional santūr (an Iranian musical instrument) players using a motion capture system and a high-speed camera, whose data have not been previously available in the scientific as well as instructional literature. We focused on the level of organization of muscular-articular components and analyzed the tempo-dependent modulation of motor coordination of the dominant arm and fingers controlling the movement of the mallet involved in playing a musical passage with the santūr. We found that the movements of the wrist and elbow played a major role in playing the santūr, whose contributions exhibited tempo-dependent modulation in a systematic manner. The results further indicated the difference in motor solutions between the two professional players, both at the level of joint coordination of the dominant arm and at the use of fingers, even though they played the same exact passage. The idiosyncrasy of motor solution observed in the two professional players implied that the process of learning involved individual exploration and guided discovery of the dynamic constraints in such a way to meet the demand of the task, which has implications for the process of learning to play musical instruments including santūr.

Key words： Santūr, Percussion Instrument, Teaching and learning, hand-finger-arm joint movements, motor control

1　Introduction

Iranian percussion instrument called the santūr is one of the main instruments used in Iranian traditional music. Playing the santūr requires dexterous control of the movement of the mallet in such a way to strike twenty-seven points on the board of the instrument located at various distances in quick succession (Figure 1), which involves complex motor coordination between the elbow, wrist, and fingers. The tacit knowledge underlying such a complex motor skill typically goes beyond simple instructional language, and learners of the instrument face significant challenges when they try to acquire the skill.

Each of the traditional Iranian instruments has its own set of instructional books for learners.

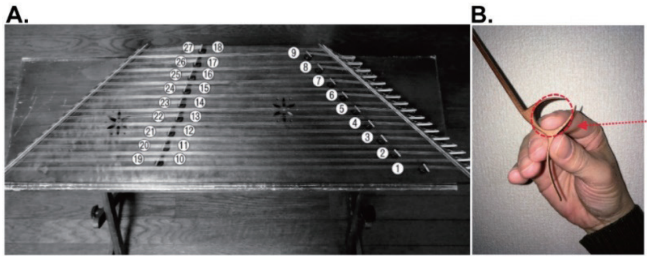

Figure 1. (A) Top-down view of a Santūr musical instrument. (B) Shape of the mallet and position of the fingers (the circle of the mallet).

They have titles that combine the name of the instrument with words, such as Dastūr (instruction, grammar) and Shīve (method), Dastūr-e Santūr (Santūr Instruction) and Shīve-ye Santūrnavāzī

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(Santūr Playing Method), and are widely used for learning to play the instrument. The following are some of the titles of the books and the actual instructions presented in the books:

Book 1: Khod-āmūz-e Santūr (Self-study Santūr), by Sabā, Hosein (1924–1960). 1956

Hold the mallet with all fingers aligned downward in sequence, so that the mallet can be swung down firmly and strongly. (Sabā 1956:16, 18)

Always lower the mallet from the wrist. This is because the sound generated by the wrist is powerful and reliable. (Sabā 1956:16, 18)

With your thumb, index finger, and middle finger, hold the half circle of the mallet in three directions. (Sabā 1956:17)

Book 2: Dastūr-e Santūr (The Santūr Instruction), by Pāyvar, Farāmarz (1933–2009). 1961

Place the circle of the Santūr mallet between one, two, and three fingers (thumb, index, and middle finger). Recall that the fourth and fifth fingers should be in contact with the third finger and lined up together or aligned down. In other words, they should not be bended or positioned in the hand. Simultaneously, the circle of the mallet should not reach the first joint of the second and third fingers. (Pāyvar 1961a:7)

Strike the stand with the right-hand mallet and raise it as if it were a ball bouncing off the ground. After a rest, do the same as on the left. These movements must be performed from the wrist rather than from the fingers or elbow. (Pāyvar 1961a:7)

Book 3: Shīve-ye Santūrnavāzī (How to Play the Santūr). By Kāmkār, Pashang (1951-). 1999

Grip the circle of the mallet tightly with three fingers (thumb, index, and middle) with the circle not extending beyond the first finger joint. The fourth and fifth fingers should be positioned consecutively, with the lower part of the middle finger touching.

When striking, it is better to use wrist movements as if turning a rotating object and refrain from monotonous wrist and elbow movements whenever possible. (*Kāmkār 1999:20*)

As can be seen in the above descriptions, instructional books for beginners typically show a static model of how to hold the mallet, but without showing how the manner changes in the dynamic phase of actual performance—how the way of holding the mallet should be changed depending on musical styles or tempo used dynamically. This tendency is not necessarily due to the limitations of print media in instructional books. Even in face-to-face lessons and in many explanatory videos of santūr performances currently available on the internet, a similar tendency is observed where performance techniques in a dynamic environment are not addressed but are explained only as static objects. The term static here refers to a situation in which, as mentioned above, the instructor limits the description of the 27 hitting points on the board, with only one place being considered as the standard, ignoring the dynamic changes that occur in actual performance. Even though how to hold the mallet and how to use the fingers differ between a simple strike and striking multiple notes in quick succession in actual performance, such difference has not been addressed but only one type of static, specific form of the fingers and hands has been emphasized in instructional materials.

Regardless of the form of knowledge transfer (paper-based or face-to-face), there are cases where ambiguity and inconsistency in the definition of words used by instructors have caused confusion among learners. One example is the discourse on wrist use. As can be seen from the aforementioned examples, the word "wrist" appears in many instructional books, but the movements recommended in them are never the same. The wrist movements recommended by Pāyvar (and Sabā) refer to the abduction/adduction of the wrist joint, as evidenced by the fact that they are described as "lower the mallet from the wrist" (Sabā 1956:17), "raise it as if it were a ball bouncing off the ground" (Pāyvar 1961a:7). One of the authors, MT, who has been studying the mechanism of improvisation in Iranian music and has participated in numerous Santūr lessons, experienced a case where the teacher prohibited the pronation/supination movement of the elbow and instructed only to use the abduction/adduction of the wrist joint by using the words "down" and "up" (from the wrist). By contrast, Kāmkār

Pashang used the word “rotation” to describe the movement of the upper limb which is intended to refer to the pronation/supination movement of the elbow; as he states, “use wrist movements as if turning a rotating object” (Kāmkār 1999:20). What the author (MT) heard in the actual lesson was the expression “like turning a door knob.” Due to the lack of scientific description of motor behavior involved in playing the santūr, such ambiguous definitions have been made invisible in the discourses of different schools and generations.

Previous scientific studies on santūr include the change in the santūr performance style (Piraglu 2010), the differences between the left and right hands in santūr performance (Menā 2010), and how to hold the mallet in the context of santūr education (Pāyvar 1961b). However, none of these studies reported the details of hand and finger motor coordination involved, nor did they measure actual movements. This lack the objective assessment of the facts (e.g., Safvat 1957) is likely to be among the sources of inconsistencies in the terminology that we mentioned above.

To improve santūr education and help learners of the instrument, the first priorities would be to observe, measure, and describe what performers actually do, and to provide the data in a manner that can be shared in the community of instructors and learners of the instrument. The main aim of the present study is to provide detailed data on the movement of two professional santūr players, using a motion capture system and a high-speed camera, which have not been previously available in the scientific as well as instructional literature. Human movement can be described in many different levels, from nerve impulses, and muscle activities, to whole-body movement relative to the environment. To describe the dexterous skill of santūr players, we specifically chose to focus on the level of synergy (Bernstein, 2014)—the level of the structural organization of muscular-articular components (Bernstein, 1967; Turvey, 1977; Fowler & Turvey, 1978; Turvey, Shaw, & Mace, 1978)—instead of focusing on the behavior of each individual component. We then introduced variation in tempo with the aim of capturing the context-conditioned variability of motor coordination inherent in dexterous motor skills (Newell, 1986; Biryukova & Bril, 2008; Nonaka & Bril, 2014). Since this study is the first to investigate the structure of motor coordination in playing the santūr, the principal purpose of the present paper was to describe motor solutions exhibited by the two professional santūr players. In particular, we focused on the tempo-dependent changes in motor coordination in the dominant arm and fingers when players performed a series of strokes at different tempi, based on the performance of a phrase based on the actual musical piece for santūr.

2 Methods

2.1 Participants

Two professional male santūr players who had studied in Iran under the Iranian contemporary virtuoso santūr players Kāmkār, Ardavān (1968-) and Kāmkār, Pashang (hereinafter called the Kāmkār brothers) participated in the present study. Participant P1 has been playing the santūr for 14 years, and practices more than 3 hours a day on average. P1 studied playing the santūr under the Kāmkār brothers for four years. Participant P2 has been playing the santūr for 32 years, and practices more than 3 hours a day on average. P2 studied playing the santūr under Pāyvar, Farāmarz for four years, and later under the Kāmkār brothers. Both participants have considerable skills, which are confirmed by their awards and degrees from national universities in Iran. The experiment was approved by the ethics committee of Graduate School of Human Development and Environment, Kobe University (approved number 553-2), and it was conducted in accordance with informed consent and in accordance with the Helsinki Declaration.

2.2 Apparatus

Movements of the dominant arm holding the mallet were recorded using an electromagnetic tracking system (Polhemus Liberty; Polhemus Corporation, Colchester, VT, USA) with a recording frequency of 240 Hz. The system uses a stationary source that emits a time-varying electromagnetic dipole field. Using a sensor containing a coil, the field strength can be measured, and the orientation and position of the sensor with respect to the source can be calculated. Accordingly, attaching sensors to body segments allows measurement of the position and orientation of the segment using one sensor per segment. An advantage of the system is that a direct line of sight between the source and the sensor is not necessary. Because the same angular motions at wrist and elbow could result in different movements of the end-effector (i.e., the mallet) depending on the angle of the shoulder joint, we measured all the seven joint angles of wrist, elbow, and shoulder following the procedures described by Biryukova et al. (2000). Sensors were attached with double-adhesive tape to the acromion (Sensor 4), the lateral surface of the humerus (Sensor 3), the posterior distal surface of the forearm (Sensor 2), and the dorsal side of the hand (Sensor 1). Sensor 1 tracked the movements of the hand segment, sensor 2 tracked the movements of the forearm, sensor 3 tracked the movements of the upper arm, and sensor 4 tracked the movements of the shoulder. The source was placed next to the players to ensure that no metallic objects distorted the electromagnetic field.

Finger movements of the right hand controlling the mallet were videotaped using a high-speed camera (480 frames/sec) from the palmer side of the hand where the contact locations between fingers and the mallet were directly visible without occlusion (Figure 2). In the experimental task, the right and left hands holding the mallets were separated by two octaves where the distance between the two hands is approximately 25 cm so that the high-speed camera could be placed in between the hands to record the palmer side of the hand.

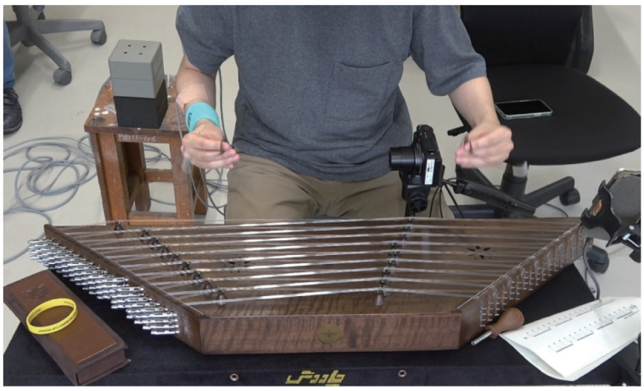

Figure 2. Shooting position of the high-speed camera.

2.3 Task

The participants were instructed to play a four-bar phrase (Figure 3) composed of a series of repetitive right-hand strokes at four different tempi (70, 82, 95, and 105 BPM). Five trials were recorded at each tempo (40 trials for two players). The phrase is based on the actual piece “Bārāneh” (Original tempo is specified as 95) by Kāmkār Pashang, the elder of the Kāmkār brothers—well-known virtuosos of santūr in Iran.

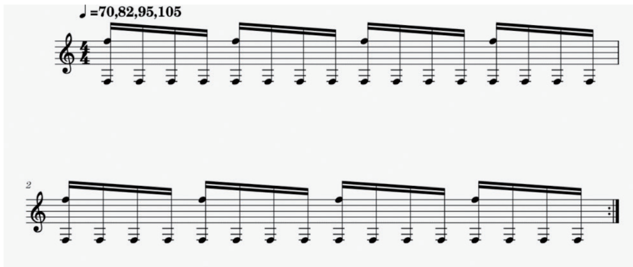

Figure 3. Score of the passage used as an experimental task.

2.4 Data Analysis

Using the method described in Biryukova et al. (2000), the position and attitude data from the magnetic tracking system were used to calculate the time courses of the joint rotation angles that corresponded to the seven degrees of freedom of the arm: abduction-adduction and flexion-extension in the wrist; pronation-supination and flexion-extension in the elbow; and abduction-adduction, flexion-extension, and rotation in the shoulder. To determine the positions and orientations of the axes of rotation in the joints, the rotations around the corresponding axes were recorded in the two players immediately before each experimental session with the sensors in place. The precision of the biomechanical model was assessed through the deviations between the position of the hand marker, as calculated by the forward model, and the actual position of the hand marker, as measured by the motion capture system.

During the performance of the passage, the joint rotations involved in the oscillatory movements of the mallet were characterized by the amplitude of each oscillation. First, the peaks and valleys of the oscillations of the joint rotations were detected using a customized routine in MATLAB (Mathworks, Natick, MA), and the amplitudes (peak-to-valley distance) of each cycle oscillation were computed based on the detected peaks (Figure 4). For shoulder joint angles that did not exhibit obvious oscillation patterns, we computed the difference between the maximum values of the joint angles within each period of the oscillation cycle, as determined by wrist abduction-adduction. In total, 1378 amplitude data were obtained from five trials of the approximately 10 s passage played

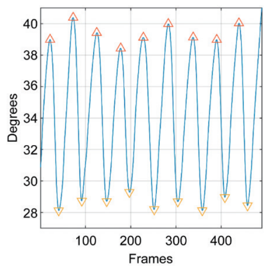

Figure 4. Sample time series data of the oscillatory movement of the wrist joint (abduction-adduction) of P1 playing at 70 BPM. Red and yellow triangles indicate the peaks and valleys of oscillation, based on which the amplitudes of joint angle oscillations were extracted.

in four tempo conditions for the two players.

We examined the covariation in the amplitudes of the seven joint angles for each oscillatory cycle using principal component (PC) analysis. PCs were calculated separately for each trial for each participant. The proportion of explained variance is computed as the sum of the squared correlations with a given PC. A large amount of total variance accounted for by a given PC would indicate that the amplitudes of the seven joints tend to covary together for each oscillatory cycle, and would provide a low-dimensional description of the seven-dimensional joint space. The joint-angle contributions in PC1 and PC2 were used to characterize the multi-joint arm movement during the performance of the passages. Statistical differences among joint covariation patterns across the four tempo (BPM) conditions and between the two players were examined using the permutation tests on the set of joint amplitude values for seven joints using the adonis function in the R package vegan (Oksanen et al. 2016). Permutation tests examined whether the across-tempo variation of joint covariation patterns was larger than within-tempo variation, and whether the across-player variation of joint covariation patterns was larger than within-player variation; if significant, this test would indicate the presence of playing-tempo and/or player influences on joint covariation patterns.

The data from the high-speed video recording of the fingers holding the mallet was analyzed using the MAXqda2020 (VERBI Software, Berlin, Germany). In the analysis, the timings of the following events were coded as follows: (1) The code "swinging down" (SD) refers to the time between the start of the downward motion of the mallet and the moment of strike. (2) The code "ring-finger contact" (RC) refers to the timing when the ring finger was in contact with the mallet. Since P2's ring finger was never in contact with the mallet, this code was only used for P1. (3) The code "index finger contact" (IC) refers to the timing when the index finger was in contact with the mallet. Since P1's index finger always remained in contact with the mallet, this code was only used for P2.

3 Results

3.1 Joint coordination patterns

Figure 5 presents the movement amplitudes of the seven joints during the performance of each tempo condition in the two players. Visual inspection of Figure 5 suggests that there are similarities and differences in the joint coordination patterns between the two players. For both players, the movement mainly consisted of wrist and elbow movements, with little contribution from shoulder movements. The difference lies in the pattern of contributions of the wrist and elbow joints between the two players. P1 used the relatively greater movement of elbow pronation-supination as well as that of elbow flexion (Figure 5A), whereas P2 relied heavily on wrist abduction-adduction movement (Figure 5B). Interestingly, both players decreased the amplitudes of the wrist abduction-adduction movement as the tempo increased from 70 to 105 BPM. In contrast, the relative contribution of the elbow pronation-supination movement increased as a function of tempo up to 95 BPM but again dropped slightly at 105 BPM.

The amounts of total variance explained by PC1 for the two players, which are related to the degree of covariation of the amplitudes of the seven joint angles, indicated that the degree of covariation of joint amplitudes of P1 were slightly lower (PC1=55%) than those of P2 (PC1=65%). As shown in Figure 6, the joint covariation patterns varied across different tempi, where the effect of tempo was more pronounced in P2 compared to P1. The relative joint contributions in both PC1 and PC2 for the two players (Figure 7) provided details of the kinematic structure of the movement across different tempi. For both players, PC1 was strongly correlated with wrist abduction-adduction, whereas PC2 was strongly correlated with elbow pronation-supination. This means that, as shown in Figure

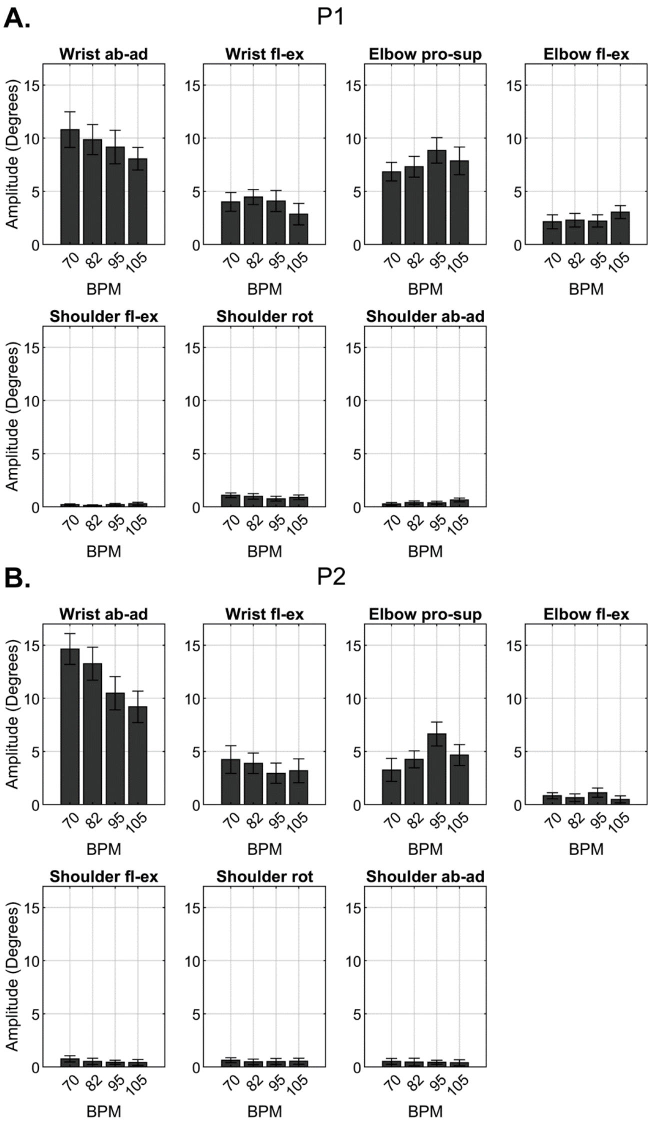

Figure 5. (A) Means of the joint movement amplitude of the seven joints during the performance of each tempo condition in P1. (B) Means of the joint movement amplitude of the seven joints during the performance of each tempo conditions in P2. Error bars represent standard deviations.

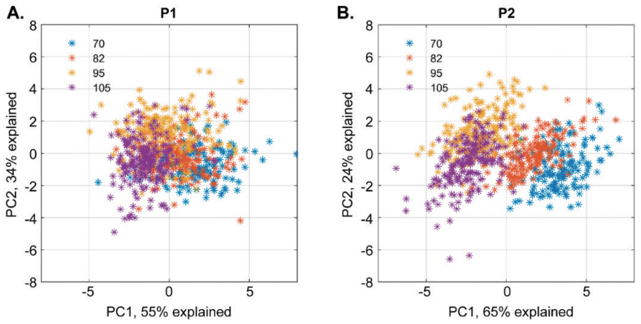

Figure 6. Distribution of the seven joint rotation amplitudes during the performance of each tempo condition in the principal component space for (A) P1 and (B) P2.

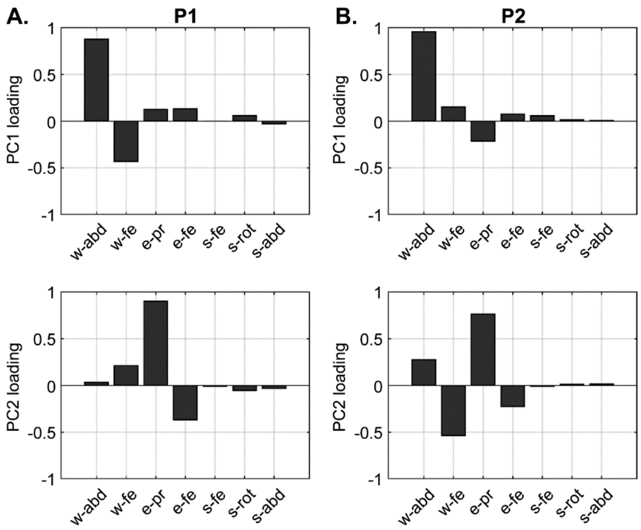

Figure 7. Loadings for the first (PC1) and the second (PC2) principal component for wrist abduction-adduction (w-abd), wrist flexion-extension (w-fe), elbow pronation-supination (e-pr), elbow flexion-extension (e-fe), shoulder flexion-extension (s-fe), shoulder rotation (s-rot), and shoulder abduction-adduction (s-abd) for (A) P1 and (B) P2.

6, the positive direction in the x-axis indicates an increase in wrist abduction-adduction, while that in the y-axis indicates an increase in elbow pronation-supination. In both figures, the joint amplitudes at 70 BPM tended to cluster around the lower right, while those at 95 BPM tended to cluster around the upper left. Permutation tests confirmed that among-tempo variations in joint covariations were significantly larger than within-tempo variations (df=3, R2=0.18, $p<0.0001$), and that among-player variation in joint covariations was significantly larger than within-player variation (df =1, R2=0.47, $p<0.0001$), corroborating the idea that joint covariation patterns differed across different tempi, and that each player exhibited a distinct motor solution even though they played the same exact passage.

3.2 High-speed video analysis of finger movement

High-speed video analysis of finger movements interacting with the mallet found the tempo-dependent modulation of the uses of the index and ring fingers as well as their inter-individual differences. Regarding the use of the ring finger, the percentage of the duration of the contact between the ring finger and the mallet tended to increase as the tempo increased in P1 (Figures 8A and 8B), while for P2 the ring finger was never in contact with the mallet irrespective of tempo change. On the other hand, with regards to the index finger, the percentage of the duration of the contact between the index finger and the mallet tended to increase as the tempo increased in P2 (Figures 8C and 8D), while for P1 the index finger always remained in contact with the mallet irrespective of tempo change. We further analyzed the details of the movements of those fingers that changed with the tempo in the two players. In P1, at a slow tempo (BPM 70), the thumb, middle finger, and index finger were always in contact with the mallet, while P1's ring finger contacted the mallet only momentarily (RC in Figure 8A), implying that the ring finger did not play a significant role at a slow tempo. At a fast tempo (BPM 105), in conjunction with the downward swinging motion (SD in Figure 8B), flexion of the ring finger occurred in P1. This flexion movement of the ring finger mechanically pushed up the tail of the mallet, which was converted into a swinging down movement of the mallet beyond the fulcrum point (the area surrounded by the thumb, middle finger, and index finger). In other words, P1 recruited the movement of the ring finger so as to control the downward stroke at fast tempo.

For P2, at a slow tempo, even during the swinging down movement of the mallet, the index finger was occasionally not in contact with the mallet (IC in Figure 8C). By contrast, at the fast tempo (BPM 105), the contact between the index finger and the mallet (IC in Figure 8D) was linked to and was slightly ahead of the descending movement of the mallet, which implies that the index finger led the swinging down movement of the mallet. The duration of P2's index finger contact relative to the duration of the downward swing of the mallet was longer for 105-BPM trials compared to 70-BPM trials (Figures 8C and 8D). Non-contact between the index finger and the mallet occurred almost exclusively after a downward stroke. Taken together, high-speed video analyses suggested that the index finger of P2 and the ring finger of P1 contributed to the downward stroke as the tempo increased, but in a different manner across the two players. P1 pulled up the tail of the mallet by flexing the ring finger to swing down the tip of the mallet, while P2 pushed down the mallet from the circle by extending the index finger. A summary of the high-speed video analysis on how the mallet was held by the two professional santūr players is presented in Table 1.

4 Discussion

The present study provided a description of the structure of upper-limb motor coordination involved in playing the santūr, which had not been previously available in the literature of performance science or instructional books. In particular, we analyzed the context-dependent change in motor coordination of two professional santūr players according to the change in tempo, focusing on the following aspects: (1) covariation among the seven joint angles of the dominant arm, and (2) the finger movements of the dominant hand that controlled the movement of the mallet. The main findings of this study were that both arm joint and finger covariation patterns of the dominant hand changed depending on the tempo, and that the patterns of change in motor coordination exhibited individual signatures as well as commonalities.

The structure of upper-limb motor coordination of the dominant hand-arm system that the two professional santūr players had in common include the following: (1) The movements of the wrist and elbow, including wrist abduction-adduction and elbow pronation-supination, played a major role in the repetitive stroke using the mallet when playing the santūr, whereas the movement of the shoulder in each stroke was very small along each axis. (2) The amplitude of wrist abduction-adduction decreased with increasing tempo. (3) In contrast, the amplitude of elbow pronation-supination increased with the tempo up to 95 BPM, but decreased slightly at 105 BPM. These constraints may have reflected the intrinsic dynamics of the body and the constraints of the task (c.f., Newell & Jordan, 2007). For example, to increase the frequency of a stroke, one can increase the frequency of the joint movement by decreasing its amplitude. The decrease in elbow pronation/supination amplitude at 105 bpm is likely to be related to the change in movement strategy. As can be seen in Figure 5, there was a tendency for pronation and supination to become more noticeable as the tempo increased. A possible explanation is that elbow pronation/supination was an involuntary byproduct of wrist movement in the slower tempo band to a certain faster tempo band, whereas it changed to the target to be controlled at higher tempi. At a slow tempo, there was no problem if the elbow pronation followed the abduction of the wrist during the swing up. On the other hand, at a fast tempo, if the elbow pronation follows the abduction of the wrist during the swing up, the amplitude of the mallet can increase, which in turn may deteriorate the accuracy of the stroke (Fitts, 1954; Schmidt & Wrisberg, 2008). Following this line of reasoning, it seems not improbable that pronation and supination of the elbow may need to be suppressed at faster tempi to balance between speed and accuracy.

We also found the patterns of motor coordination of the dominant arm that differed across the two professional players during the repetitive stroke of santūr using the mallet. First, the movements of P1 had a relatively large contribution from elbow pronation-supination movement, whereas P2 depended strongly on the wrist abduction-adduction. Second, P1 exhibited a tempo-dependent change in the motor coordination pattern of the arm that required a relatively high-dimensional description compared to P2 whose change occurred mostly along a single dimension (c.f., Newell, & Vaillancourt, 2001; Verrel et al., 2013). Third, as the tempo got faster, P1 recruited the movement of his ring finger to lift the tail of the mallet in such a way to contribute to swinging down the tip of the mallet, whereas P2 recruited his index finger to push the mallet down from the circle of the mallet.

The idiosyncrasy observed in motor solutions is worth attention. The presence of such idiosyncratic motor solution in professional santūr players seems to provide support for the idea that the underlying mechanism of acquiring the skill was not that of faithful reproduction of movement patterns per se, but was that of individual exploration and guided discovery of the dynamic constraints in such a way to meet the demand of the task (Newell, 1986; Newell et al., 1989; Ko, Challis, & Newell, 2003). These results have further implications for santūr education. The results seem to imply that the acquisition of skill in the process of learning to play the santūr may be a result not of transmission of static knowledge but of guided rediscovery, where learners are instructed to attend to the important aspects of dynamic situations, so as to get the feel of it for learners themselves (Ingold, 1998; King, Ranganathan, & Newell, 2012). Such process of learning has been referred to as "education of attention" (Gibson, 1966, p.51; Gibson, 2014/1979, p.243), which may be a useful concept to characterize the process of learning to play musical instruments including santūr.

5 Conclusion

With the aim of improving santūr education, the present study measured the movement of two professional players of santūr—an Iranian percussion instrument—using a motion capture system and a high-speed camera, whose description has not been previously available in the scientific as well as instructional literature. We focused on the level of organization of muscular-articular components and analyzed the tempo-dependent modulation of motor coordination of the dominant arm and fingers controlling the movement of the mallet involved in playing a musical passage with the santūr. The movements of the wrist and elbow played a major role in playing the santūr, whose contributions exhibited tempo-dependent modulation in a systematic manner. The results further highlighted the distinct motor solutions exhibited by the two professional players, both at the level of joint coordination of the dominant arm and the use of fingers, even though they played the same exact passage. The idiosyncrasy of motor solution observed in the two professional players implied that the process of learning involved individual exploration and guided discovery of the dynamic constraints in such a way to meet the demand of the task, which has implications for the process of learning to play musical instruments including santūr.

In this study, the sample size had to be small due to visa issues between Iran and Japan. Therefore, this study focused on individual differences by analyzing a small sample of movements in detail. A study with a larger sample size would reveal, for example, whether individual differences in motor solution are exhibited as several different typologies, such as those described in the instructional books, or as a continuum of differences.

In addition, the position of the high-speed camera between the hands restricted the movement of the participants' arms to that shown in Figure 3. This may have limited the movement of the shoulders. Although shoulder action is rarely mentioned in teaching Santūr, it can affect the success or failure of an accurate strike. In the future, camera placement may need to be modified to measure the movement of the shoulder and other parts of the body that are not often mentioned. This will make it possible to study motions for a wider variety of phrases.

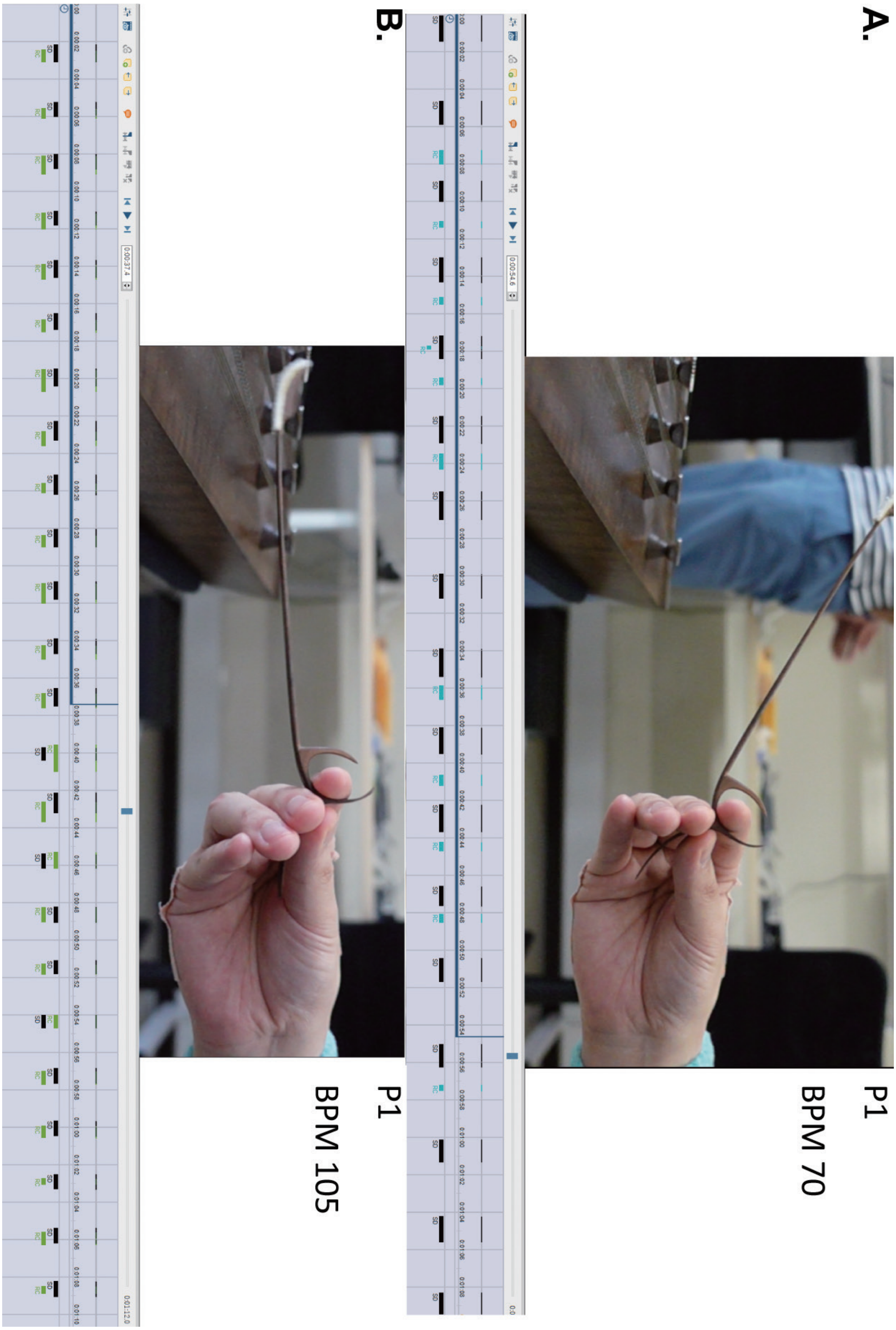

Figure 8. (A) P1 playing at 70 BPM, (B) P1 playing at 105 BPM. The code "SD" refers to the time when the mallet was swung down. The code "RC" refers to the time when the ring finger contacted the mallet.

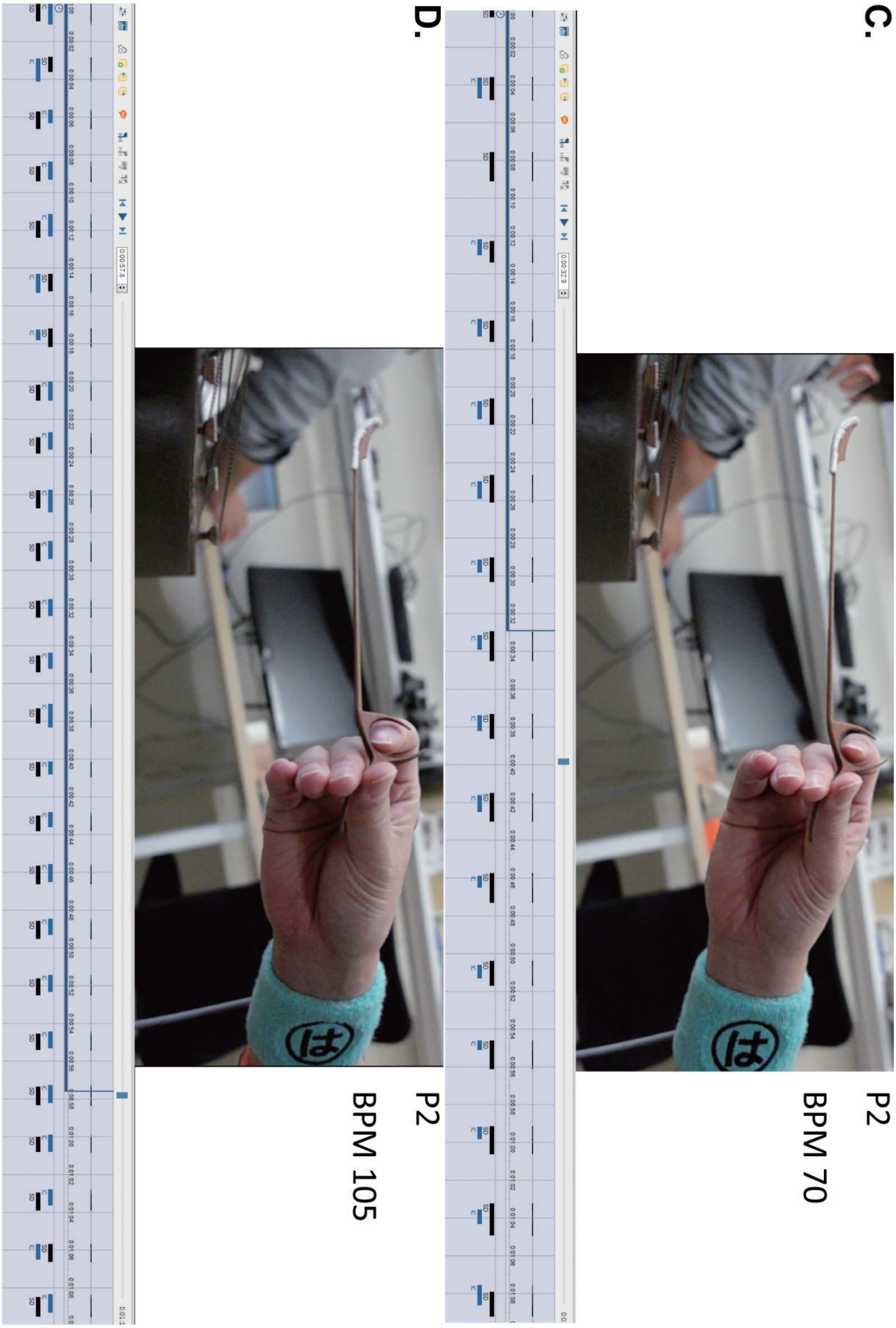

Figure 8. (C) P2 playing at 70 BPM, and (D) P2 playing at 105 BPM. The code "SD" refers to the time when the mallet was swung down. The code "IC" refers to the time when the index finger contacted the mallet.

Table 1. Summary of the high-speed video analysis on how the mallet was held by the two professional santūr players.

<table>
<tr><th></th><th></th><th>70bpm</th><th>82bpm</th><th>95bpm</th><th>105bpm</th></tr>
<tr><td rowspan="6">P1</td><td>Thumb/ Middle finger</td><td colspan="4">Almost in front of each other (with a slight back-and-forth rubbing motion)</td></tr>
<tr><td>The height of the tip of the mallet</td><td colspan="4">High (The tip pointed upward)</td></tr>
<tr><td>Index finger</td><td colspan="4">Always remained in contact with the mallet</td></tr>
<tr><td>Ring finger</td><td colspan="3">Occasional contact with the mallet</td><td>Positioned close to the mallet. Flexion movement appeared after the 3rd trial</td></tr>
<tr><td>Wrist position</td><td colspan="4">Low</td></tr>
<tr><td>Other</td><td colspan="2"></td><td>The mallet was often held quite loosely</td><td></td></tr>
<tr><td rowspan="6">P2</td><td>Thumb/ Middle finger</td><td colspan="4">The sides of the fingers were facing each other</td></tr>
<tr><td>The height of the tip of the mallet</td><td colspan="4">← Middle (The tip pointed horizontally) / Low (The tip pointed downward) →</td></tr>
<tr><td>Index finger</td><td colspan="2">Not in contact with the mallet or contacted only as a mallet stopper</td><td colspan="2">Strong tendency to contact the mallet with the fingertip or underside of the index finger</td></tr>
<tr><td>Ring finger</td><td colspan="4">Not in contact with the mallet</td></tr>
<tr><td>Wrist position</td><td colspan="4">High</td></tr>
<tr><td>Other</td><td>The mallet was pulled up after the mallet had finished bouncing</td><td colspan="3"></td></tr>
</table>

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