Effect of Body Structure on Skill Formation in a Force Precision Task Mimicking Cello Bowing Movement*

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To elucidate the skill formation mechanism in a complex force precision task mimicking cello bowing movements, three-dimensional joint orientations and changes in bowing force are measured for 2 novice and 2 expert subjects. A rigid link model of the human upper limb is constructed in order to calculate changes in joint moment, potential energy and structural inductivity of motion during bowing, and the motions are compared kinetically. Results show that the novices generate low-in-potential energy bowing motion, but not suitable for skillful control of the bow. In contrast, the experts can fulfill a task requirement by skillfully coordinating the musculo-skeletal system, but the motion is not easy as that of the novices. It is suggested that the transition from a novice to an expert may be difficult due to the ease in the initially generated motion, which obstructs the search for the optimal skillful motion.

Key Words: Biomechanics, Human Engineering, Bio-motion, Cello, Skill Acquisition, Motion Analysis, Morphological Constraints, Inductivity of Joint Motion

1. Introduction

Humans are able to acquire highly sophisticated dexterous movements by skillfully coordinating the musculo-skeletal system of their upper limbs. However, due to the redundancy in the number of degrees of freedom and the complexity of the human musculo-skeletal system, acquisition of skill, finding an optimal coordination of movement out of infinite number of possibilities, is generally very difficult. How are humans able to acquire a skillful movement that fulfill intended functions? Elucidating such skill formation mechanism may suggest scientifically justifiable, more efficient teaching method of skill. Furthermore, new insights may be gained concerning the mechanical implementation of skill, which has applications in the fields of robotics, cognitive science and ergonomics.

Analyses of the skill acquisition process have been conducted for various movements, such as crawling, dart-throwing, writing, slalom-like ski movements, kicking a soccer ball, and standing pulls. Previous research has shown that in the early stage of skill acquisition, people tend to limit the number of the degrees of freedom of joint motion to a manageable number by stiffening joints, but as learning proceeds, they gradually master the skill by extending the ranges of joint motion and allowing the joints to function under a greater number of degrees of freedom. This finding supports Bernstein's theory of human motor learning, which indicates that degrees of freedom are initially frozen and are later released.

Previous research mainly describes changes in motions that occur through practice. In the field of psychology, such gradual formation of skill through practice is considered to be realized by modification of movement based on an internal reference. This idea is mathematically modeled as an optimization problem searching for adequate motor commands that satisfy the reference, for example, desired trajectory. However, the underlies the changes in motion that may occur in the process of skill acquisition is not fully elucidated.

In this study, the inherent human body structure is hypothesized to have a strong influence on process of formation of skillful movement. Human movements generally seem to be generated favorably to the structure or formation of the musculo-skeletal system, such as mass distribution of body linkage, joint structure, and muscle location. Such case (or difficulty) in

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generation of motion originated in the morphological constraints may affect formation of a skill as well.

To uncover this effect of the musculo-skeletal structure on the acquisition of skillful motions, a complex force precision task mimicking cello bowing movements was measured for novice subjects, and compared to those of experts. Bowing motion requires a high degree of skill because both bow position and the force acting on the strings should be precisely controlled simultaneously by the upper limb. Therefore, not only the bowing motion of the upper limb, but also the force on the strings were measured for both novices and experts, and the relationship between the skill formation and the body structure were analyzed.

2. Methods

2.1 Experimental apparatus

The tone of a cello, ignoring the qualities of the musical instrument, is determined by the following three physical quantities: bowing force (the reaction force acting on the bow from the string), bowing speed (speed of bow movement), and sounding point (the contact point of the bow on the string). In the present study, a wooden model of a cello is constructed in order to enable these three quantities to be measured during bowing for evaluation of bowing performance. Actual tone produced by a real cello is too difficult to analyze with respect to the skill of the cellist, but the cello model allows the actual tone to be converted into the simple physical quantities.

Figure 1 provides a general description of the cello model, which is approximately the same size as a real cello. Rather than strings, the model has a revolving cylinder (diameter: 30 mm, length: 200 mm), the position and slant angle of which closely approximate those of the actual cello. Both ends of the cylinder are supported by aluminum bars (5 mm × 5 mm × 40 mm) attached to bearings. Bowing force is measured by strain gages attached to the bars, and bowing speed is calculated by differentiating the linear displacement, which is measured by an electrical potentiometer, with respect to time. The sounding point can also be calculated from difference of vertical components of the forces acting on both ends of the cylinder. A rubber sheet is placed around the cylinder in order to increase the surface friction.

The bowing force can be calculated using the following equation (1):

\[
F_x = a_xA_x + b_xB_x \\
F_y = a_yA_y + b_yB_y
\]

where \( F_x \) and \( F_y \) are the horizontal and vertical components of the bowing force with respect to the surface of the cello, \( A \) and \( B \) are the outputs of strain gages at end A and B, and \( a \) and \( b \) are coefficients, respectively. For calibration, known forces are applied to five different positions on the cylinder and the coefficients are calculated by using the least squares method. The mean percentage error accompanying each measured value is 3.1%.

The acquired data are passed through an analog-to-digital converter and recorded on a PC. The result is displayed on a monitor to provide feedback information, rather than actual sound, to the subject. Thus, the cello model is silent.

2.2 Subjects

Four male university students participated in this experiment: two novice subjects (A, B) and two expert subjects who have played the cello for 6 years (C, D). The mean age of the participants is 22.5 years old. Averages and standard deviations of the height and weight of the participants are 1.73 m and 0.05 m, and 66.5 kg and 5.2 kg, respectively. The novices have no previous experience playing the cello or any other string instruments.

2.3 Task

The subjects are asked to play the cello model such that the bowing force is maintained constant (2.0 N) for 15 sec, while also maintaining a 4 sec bowing cycle, as illustrated in Fig. 2. In actuality, bowing force is related to sound volume, so this task corresponds to playing a cello at a constant volume. The subjects are asked to perform bowing

![Fig. 1 Cello model. A. General view, B. Measurement system](image-url)
motion while viewing real time visual feedback of the bowing force displayed on a monitor. In addition, subjects are asked to move the bow as much as possible from bow tip to bow nut, and to follow as precisely as possible the bowing cycle provided by a metronome. Before starting, each subject is instructed to hold the bow nut between the thumb and fingers as described in the text book. Twenty trials (30 trials for novices) are conducted, each of 15 seconds in duration and separated by two-minute intervals.

As bowing of actual cello is guided by the tones produced, use of the experimental cello model makes the task even new for the expert subjects. Yet, the task is far more difficult for those who have no experience in playing string instruments.

2.4 Motion measurement

For three-dimensional measurement of human movement, an optoelectronic movement registration system (Hamamatsu Photonics C3570) having two semiconductor diode cameras that register the positions of infrared light-emitting diodes (LEDs) were used (see Fig. 2). This system calculates the three-dimensional coordinates of the LEDs by the direct linear transformation method. The mean error accompanying each of 16 measured positions equally distributed in the calibrated space is 4 mm. In this study, tape and belts are used to fix marker attachment units, having three LED markers each, on the hand, forearm, upper arm, and scapular region of each subject as shown in Fig. 2.

2.5 Calculation of joint angles

In this study, three-axis Eulerian angles are used to describe the relative angular orientation of two segments connected by a joint. Let the positions of the three LEDs of each marker unit in a global coordinate frame be \(\mathbf{t}_o, \mathbf{t}_i\) and \(\mathbf{t}_b\) as shown in Fig. 3. Then, origin \(\mathbf{O}_T\) and unit vectors \(\mathbf{x}_T, \mathbf{y}_T, \mathbf{z}_T\) of a local coordinate frame fixed on the marker unit (LED coordinate frame, \(T\)) are calculated as follows:

\[
\begin{align*}
\mathbf{O}_T &= \mathbf{t}_o, \\
\mathbf{x}_T &= \mathbf{t}_i - \mathbf{O}_T, \\
\mathbf{z}_T &= (\mathbf{x}_T \times (\mathbf{t}_i - \mathbf{O}_T)) / \| \mathbf{x}_T \times (\mathbf{t}_i - \mathbf{O}_T) \|, \\
\mathbf{y}_T &= \mathbf{z}_T \times \mathbf{x}_T \\
M_T &= [\mathbf{x}_T, \mathbf{y}_T, \mathbf{z}_T]
\end{align*}
\]  

(2)

where \(M_T\) is a 3×3 orthonormal matrix consisting of the unit vectors pointing the direction of the LED coordinate frame fixed to the \(i\)th segment.

Since the coordinate axes of the LED coordinate frame do not coincide with the rotation axes of human joint orientation, another local coordinate frame (link coordinate frame, \(L\)) is defined by the anatomical landmarks listed in Table 1. If four landmarks on a segment represented in the global coordinate frame are \(\mathbf{p}_s, \mathbf{p}_i, \mathbf{p}_o\) and \(\mathbf{p}_b\), then the orthonormal matrix of link coordinate frame of the \(i\)th segment \(M_L\) is defined as

\[
\begin{align*}
\mathbf{O}_L &= (\mathbf{p}_i + \mathbf{p}_0)/2, \\
\mathbf{z}_L &= ((\mathbf{p}_i + \mathbf{p}_0)/2 - \mathbf{O}_L) / ((\mathbf{p}_i + \mathbf{p}_0)/2 - \mathbf{O}_L) \\
\mathbf{x}_L &= (\mathbf{z}_L \times (\mathbf{p}_o - \mathbf{O}_L)) / \| \mathbf{z}_L \times (\mathbf{p}_o - \mathbf{O}_L) \| \\
\mathbf{y}_L &= \mathbf{z}_L \times \mathbf{x}_L \\
M_L &= [\mathbf{x}_L, \mathbf{y}_L, \mathbf{z}_L]
\end{align*}
\]  

(3)

As described in Fig. 3 and Eq. (3), joint center is defined approximately as the midpoint of two landmarks at the joint and is the origin of the link coordinate frame. The \(\mathbf{z}_L\) axis is the major axis connecting joint centers. The \(\mathbf{y}_L\) is defined to be the flexion-extension axis except for the shoulder joint (for the shoulder, \(\mathbf{y}_L\) is the abduction-adduction axis).

If the positions of the anatomical landmarks, \(\mathbf{p}_s, \mathbf{p}_i, \mathbf{p}_o\) and \(\mathbf{p}_b\) are assumed to be fixed points on the nearest LED coordinate frame, as shown in Table 1, these landmarks are calculated from the measured coordinates of the LEDs \(\mathbf{t}_o, \mathbf{t}_i\) and \(\mathbf{t}_b\). For instance, epicondylus lateralis is located close to the upper arm marker unit, so that relative position is approximately constant regardless of joint motion. Consequently, if
the positions of anatomical landmarks in terms of the corresponding LED coordinate system are obtained prior to motion measurement, then the in-motion positions of those landmarks can be calculated.

Eulerian angles between the two link coordinates are calculated using the following method, described by Chao. Let the orthonormal matrix of the link coordinate frame fixed to the \((i+1)\)th segment be \(M_{i+1}\), and that of the distal \(i\)th segment be \(M_i\). If \(M_{i+1}\) is rotated with respect to the three link coordinate axes to become \(M_i\), the transformation matrix \(R_{i+1}^{i}\) is written as

\[
R_{i+1}^{i} = [M_{i+1}]^{-1} \cdot M_i \tag{4}
\]

If the three rotations occur following the sequence of \(u_1, x_1, z_1\), elements of the transformation matrix are expressed as

\[
R_{i+1}^{i} = R_z \cdot R_y \cdot R_x
\]

\[
= \begin{bmatrix}
    c_y c_z & -c_y s_z & s_y \\
    c_x c_z s_y + s_z c_x c_y & c_z c_x c_y - s_x s_z & -c_x s_z - c_z c_x s_y \\
    -c_x s_z s_y + c_z c_x c_y & c_x c_z c_y + s_x s_z & c_x s_z - c_z c_x s_y
\end{bmatrix}
\]

\[
= \begin{bmatrix}
    c_y & -s_y & 0 \\
    s_x s_y & c_x c_y & -s_x s_z \\
    c_x s_y & c_x c_y & c_x s_z
\end{bmatrix}
\]

where \(\theta, \phi, \psi\) are the angles around \(x, y, z\) axes, and \(c\) and \(s\) stand for \(\cos\) and \(\sin\), respectively. Using this equation, the \(i\)th joint angles, \(\theta_i, \phi_i\), and \(\psi_i\) can be calculated. Figure 4 illustrates the link coordinates and the definitions of the joint motions. The joint angles are all zero if the positions of the link coordinate systems correspond to one another, as shown in Fig. 4(a). The angles are positive if the joints are extended, abducted or medially rotated (adducted for wrist). This definition of joint angle is not strictly equivalent to the clinical definition of joint motion; however, the coordinate systems defined above are very similar to those of the clinical definition.

2.6 Data analysis

Acquired kinematic and kinetic data are filtered using a second-order Butterworth low-pass digital filter. The cut-off frequency is determined by residual analysis to be 1.0 Hz. One bowing cycle is defined as the period beginning from the point at which the bow tip begins to move away from the cylinder and ending at the next such point, thus i.e., the hand holding the bow approaches the cylinder, turns when the bow nut reaches the cylinder, and then moves away from the cylinder to complete one cycle. In one 15-second trial, approximately three bowing cycles can be measured. Of these, the cycle showing the highest task proficiency is selected as being representative of the trial and is compared with other trials. Here the task is to maintain constant bowing force, so the task proficiency is determined as the difference between mean bowing force and the target force (2.0 N) of each cycle.

3. Biomechanical Motion Analysis

3.1 Calculation of joint moment

Differences in human movement are primarily originated in differences in moment generated around each joint due to activation of muscles attached across the joint. Therefore, a rigid link model of the human upper limb was constructed and joint moments during bowing were calculated.

The upper limb, including the bow, can be considered as a linear chain of rigid bodies connected by pin joints, as shown in Fig. 5. Using the Newton-Euler method, we can derive equations of motion for this rigid link model as

\[

M_i \ddot{r} = \sum_i f_i + \sum_i m_i g
\]

\[
M_i \ddot{L} = \sum_i \omega_i \times f_i + \sum_i m_i \omega_i \times (I_i \omega_i)
\]

\[
= \sum_i (r_i - r_i') \times f_i - (r_i' - r_i') \times f_i' + \sum_i \omega_i \times (I_i \omega_i)
\]

\[
+ \sum_i (r_i - r_i') \times f_i + M_i \dot{a}_i + M_i a_i - \dot{a}_i I_i a_i - \dot{a}_l a_l
\]

where \(i\) is the segment number, \(m_i\) is the segment mass, \(r_i, r_i'\) and \(r_l\) are the position vectors of the joint center, the center of gravity, and the application of
external force, respectively, \( f_i \) is the joint reaction force, \( f_i^e \) is the external force, \( n_i \) is the joint moment, \( 'I \) is the inertia tensor, \( \omega_i \) is the angular velocity vector, \( M_i \) is the orthonormal matrix of the link coordinate frame fixed to the \( i \)th segment, and \( 'a_i \) is the passive elastic moment around the \( i \)th joint. The left superscripts, \( i \) and \( i-1 \), indicate vectors and matrices represented in the local link coordinate frame fixed on each segment. Parameters that have no left superscripts are represented in the global coordinate frame. Because the task motion instructed here is very slow, viscous moment around joints are not considered. Using Eq. (6), the joint reaction force and the joint moment can be calculated repeatedly from the end segment (in this case the bow stick), towards the center of the body.

In order to make the joint moment correspond to the joint angle, the joint moment \( n_i' \) is transformed to a locally represented notation, and further transformed to scalar joint moments by solving the following equation:

\[
M_i^{-1} \cdot n_i' = [n_{x_2} \, 0 \, 0] + [c_{\phi_i}, -s_{\phi_i}, 0] \cdot \begin{bmatrix} c_{\theta_i} s_{\phi_i} \\ c_{\theta_i} c_{\phi_i} \\ -s_{\theta_i} \end{bmatrix}
\]

where \( 'n_{x_2}, 'n_x, 'n_z \) are the joint moments around each of three rotational axes as in Eq. (5).

The mass, position of center of gravity, and inertial moment are determined according to Winter\(^{15} \) and Chandler at al.\(^{17} \) and are listed in Table 2. Since there are no significant differences in the physical constitution of the subjects, these inertial parameters are assumed to be identical for all subjects. Inertial moments of the bow and fingers, and the mass of the fingers are assumed to be significantly smaller than other masses and inertial moments, and are therefore ignored.

The passive elastic moments exerted by resistive elements around joints are expressed by the following equations:

\[
\text{Table 2 Inertial parameters of the rigid link model}
\]

<table>
<thead>
<tr>
<th>Link</th>
<th>Mass (kg)</th>
<th>C of G (lxz (kgm))</th>
<th>1xx (kgm)</th>
<th>1yy (kgm)</th>
<th>1zz (kgm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bow</td>
<td>0.13</td>
<td>0.36</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>finger</td>
<td>0.00</td>
<td>----</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>hand</td>
<td>0.36</td>
<td>0.51</td>
<td>0.0008</td>
<td>0.0006</td>
<td>0.0002</td>
</tr>
<tr>
<td>forearm</td>
<td>0.96</td>
<td>0.43</td>
<td>0.0065</td>
<td>0.0067</td>
<td>0.0099</td>
</tr>
<tr>
<td>up. arm</td>
<td>1.68</td>
<td>0.44</td>
<td>0.0133</td>
<td>0.0133</td>
<td>0.0022</td>
</tr>
</tbody>
</table>

Note. Center of Gravity (C of G) is represented as a fraction of a segment length from the proximal end. 1xx, 1yy, 1zz = Moment of inertia about x, y, and z axes, respectively.

\[
\text{Table 3 Coefficients in the passive joint structures}
\]

<table>
<thead>
<tr>
<th>Joint</th>
<th>( k_x )</th>
<th>( k_y )</th>
<th>( k_z )</th>
<th>( k_{x-y} )</th>
<th>( k_{x-z} )</th>
<th>( k_{y-z} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>sh</td>
<td>0.010</td>
<td>-1.47</td>
<td>-2.37</td>
<td>-4.61e-5</td>
<td>-1.73</td>
<td>6.54</td>
</tr>
<tr>
<td>elk</td>
<td>0.43</td>
<td>1.02</td>
<td>0.42</td>
<td>0.19</td>
<td>0.96</td>
<td>-1.24</td>
</tr>
</tbody>
</table>

\[
'a_i = [a_x, a_y, a_z]^T, a_x = 0, a_y = 0,

a_w(\phi_i) = -k_x \exp(-h_x(\phi_i - \psi_i))
\]

(8)

where \( \phi_i \) is the joint angle around the \( z_i \) axis (rotational angle), \( z_i \) is the offset, and \( h_x, k_x \) are coefficients, the values of which are listed in Table 3. The double exponential equation was originally proposed by Davy and Audu\(^{18} \) in order to model the passive moments of joints in the lower extremities. Here the same equation is used to represent the passive elastic moment of joints in the upper limb since they have the same tendencies. The coefficients are determined by fitting the equation to the corresponding experimental data obtained by Engin\(^{19} \), using a quasi-Newton method. A shoulder rotational angle of \(-90\) deg and an elbow rotational angle of \(90\) deg are equivalent to zero in general notation of the rotational angles (see Fig. 4), thus these are the offset values in this equation. In this study, only the rotational passive moments of shoulder and elbow are considered because the passive moments around other axes are very small in the range of joint motion in bowing movement, according to the experimental data\(^{20,21} \).

3.2 Calculation of energy

In order to evaluate energy storage and release in the upper limb during bowing, potential energy, \( U_P(q) \), and kinetic energy, \( U_K \), are calculated as

\[
U_P(q) = \sum_{i=0}^{n} m_i g_i \cdot (r_i^e - r_i^m) + \int_{q_{min}}^{q_{max}} m_i \cdot \dot{g}_i \cdot \dot{q}_i \cdot (q_{min} - q_{max}) \cdot ds
\]

\[
U_K = \sum_{i=0}^{n} \left( \frac{1}{2} m_i \ddot{r}_i \cdot \ddot{r}_i^e + \frac{1}{2} \dot{\phi}_i \cdot \dot{\phi}_i \cdot (\Phi_i) \cdot (\Phi_i) \right)
\]

where \( q \) is the a 9 x 1 vector of Euler joint angles, \( \Phi_{ea} \) and \( \Phi_{fa} \) are the rotational angles of the forearm and upper arm, and \( \phi_{ea} \) and \( \phi_{fa} \) are the offset angles when \( 'a_i = 0 \).
3.3 Structural inductivity of joint motion

Human movement is restricted by biomechanical constraints such as mass distribution, body linkage, and passive joint properties, but such morphological constraints are often utilized rationally in formation of movement, like in human locomotion\(^{22}\). In order to evaluate how such constraints in the body structure induce (or restrict) the bowing motion, an evaluative index, structural inductivity of human motion, is defined.

If human motion is naturally generated only due to the gravity and the elasticity due to the passive joint structures, such generated motion can be considered as the most structure-utilizing motion at a specific posture \(q\). In that case, inertial moments generated around \(i\)th joint can be calculated as

\[
\begin{align*}
\tau_{x,i} &= -\frac{dU(q)}{dq_i} \\
\tau_{y,i} &= -\frac{dU(q)}{dq_i} \\
\tau_{z,i} &= -\frac{dU(q)}{dq_i}
\end{align*}
\]

where \(\tau_{x,i}, \tau_{y,i}, \tau_{z,i}\) are the inertial moments around \(x, y, z\) axes. Since the motion having inertial moments \(\tau_{x,i}, \tau_{y,i}, \tau_{z,i}\) is the most structurally induced motion of the joint, the structural inductivity of motion of the \(i\)th joint around each of \(x, y, z\) axes, \(\tau_{E_x}, \tau_{E_y}, \tau_{E_z}\), can be defined by comparing \(\tau_{x,i}, \tau_{y,i}, \tau_{z,i}\) with the actually measured inertial moments around the same axes at a specific posture \(q\) as

\[
\begin{align*}
\tau_{E_x} &= \tau_{N_x}/\tau_{x,i} \\
\tau_{E_y} &= \tau_{N_y}/\tau_{y,i} \\
\tau_{E_z} &= \tau_{N_z}/\tau_{z,i}
\end{align*}
\]

where \(\tau_{N_x}, \tau_{N_y}, \tau_{N_z}\) are the actually measured inertial moments while bowing around \(x, y, z\) axes. They can be calculated by solving the following equation:

\[
\begin{bmatrix}
\tau_{E_x} \\
\tau_{E_y} \\
\tau_{E_z}
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} + \begin{bmatrix}
\phi_{x,i} \\
\phi_{y,i} \\
\phi_{z,i}
\end{bmatrix} + \begin{bmatrix}
c_{\phi_{x,i}}c_{\phi_{y,i}} & c_{\phi_{x,i}}s_{\phi_{y,i}} & s_{\phi_{x,i}} \\
-c_{\phi_{y,i}} & s_{\phi_{y,i}} & 0 \\
-s_{\phi_{x,i}} & 0 & -c_{\phi_{x,i}}s_{\phi_{y,i}}
\end{bmatrix} \begin{bmatrix}
\tau_{N_x} \\
\tau_{N_y} \\
\tau_{N_z}
\end{bmatrix}
\]

where \(\tau_{E_i}\) is the inertia tensor about the \(i\)th joint. As the inductivity approaches 1, the bowing motion can be interpreted as being induced more by the body structure itself. A negative inductivity means that the motion is induced not toward the direction of \(\tau\) by releasing the energy, but rather toward the direction opposing to the structure, thus the inductivity is low.

4. Results

Figure 6 shows the (a) bowing force and (b) joint angles over time, for Trial Nos. 1, 5, 10, and 20, for all subjects. Time is expressed as percentage of bowing period. Hereafter, bowing movement towards the cylinder is called upward bowing, and movement away from the cylinder is called downward bowing.

4.1 Task proficiency

Figure 6(a) shows that task proficiency is clearly greater for the expert subjects than the novices. As the graph indicates, the bowing force of the novices tends to increase at the bow nut and decrease at the bow tip, whereas the experts are able to sustain a constant bowing force. In bowing, force is more easily applied at the nut than at the tip, where the hand is far away from the string. Therefore, one of the fundamental difficulties in the bowing movement appears to be controlling bowing force as the bow continuously moves up and down.

Figure 7 shows the mean and standard deviation of the bowing force for each trial. This diagram reveals that the novices actually improve in their ability to control bowing force as the trial period progresses. Whereas, the experts are able to maintain mean bowing force at almost 2.0 N from the first trial. In addition, the standard deviations are always smaller for experts than for novices, indicating that their force profiles fluctuate less. Although the novices become more proficient during their 30 trials, the experts exhibit higher proficiency from the start, the level of which the novices are unable to attain.

4.2 Changes in bowing motion

As Fig. 6(b) indicates, the changes in joint angles that occur through practice is larger for the novices, especially for distal joint degrees of freedom. Whereas, the experts are able to maintain almost the same

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The text continues with further details and figures related to the described experiments and analyses.
bowing motion. In order to compare qualitatively the changes in joint angles over trial, the similarity between two joint angle patterns is calculated using correlation coefficient.

For each subject, similarities are calculated over all trial combinations for each joint angle, and the mean of the similarities are compared among the subjects, as shown in Fig. 8. High mean similarity indicates that few changes occurred while the proficiency improved during the 20 (30 for novices) trials. This chart indicates that the novices have lower mean similarities, especially with regard to the extension angle of the hand joint, and the rotational angle of the shoulder joint, implying that these degrees of freedom are modified to improve proficiency. In contrast, the movements of the experts changed little, with the exception of the rotational angle of the elbow. Thus, the experts are able to exhibit their empirically acquired skill with very high reproducibility.

In order to observe the motion modification process of the novices, the time average angles and the standard deviations of (a) wrist flexion, (b) wrist adduction, (c) elbow rotation, and (d) shoulder rotation joint angles, that are low in similarities and appear to be modified while improving the task proficiency, are calculated and plotted over trial as shown in Fig. 9. The time average angle represents basic bowing posture of a specific trial, while the standard deviation stands for range of joint motion. The graphs indicate the means and standard deviations of the joint angles are not monotonously changed, and the changes in joint motion that are directly linked to the improvement of the task proficiency are not observed. Thus the skill acquisition appears to proceed in a trial and error manner.

Although trial-and-error modification in motion due to practice are observed, these changes are actually not so large that the bowing motion is completely reconstructed. The small standard deviations in Fig. 9 shows that the changes in motion are actually not so large, indicating no major changes are exhibited during the 30 trials, despite the improvement in task proficiency.

4.3 Kinematic comparisons of novice and expert subjects

Although large individual differences exist in the construction of bowing motion among the subjects, some bowing characteristics are extracted distinguishing novices and experts as shown in Fig. 6(b).

The abduction angle of shoulder joint in the experts is relatively larger than that of the novices, and also the shoulder of the experts is more flexed than that of the novices. This indicates that the experts basically hold their elbows up, performing bowing in front of their bodies, whereas the novices allow their elbows down and bow toward their sides. Also, the experts extend their elbow while bowing downward, while the novices flex their elbows, reflecting completely opposite bowing motions. Moreover, the ranges of joint motions are clearly smaller for the novices, especially in the elbow and hand joints, implying that the joints of the novice are more rigidly fixed than those of the experts.

4.4 Kinetic comparisons of novice and expert subjects

Figure 10 shows the joint moments of each subject. Only the joint moments of Trial 20 are calculated and compared, since their bowing patterns do not change as the trial period progresses, as explained.
previously.

The graphs in Fig. 10 indicate that the experts generate relatively larger wrist abduction moment that is more greatly changed as the bow moves, but the novices can not utilize wrist abduction moment like the experts, suggesting that the experts are able to utilize this distal joint more effectively for control of the bow. It is also noted that elbow flexion moment is smaller and shoulder abduction moment is larger for the experts, indicating their upper limb is maintained away from their torso. Moreover, although the novice shoulder rotational moments are either generated towards medial direction or maintained relatively constant, the moment patterns of the experts are greatly changed toward lateral direction, increased while bowing upward and decreased while bowing downward. Since the application of force on the string becomes easier as the bow moves toward the string, the experts appear to try to suppress the bowing force by applying lateral moments around the rotational axis of the upper arm.

Figure 11 shows the time course in the potential and kinetic energy of the upper limb over time. The reference point of the potential energy is at the shoulder joint, thus in the bowing motion, the potential energy becomes negative. The kinetic energy is much smaller than the potential energy in this specific bowing task as presented in Fig. 11. As the graph shows, the potential energy is always smaller in the novice subjects. The novices naturally select easy bowing movement in terms of the potential energy, whereas the experts abduct the shoulder to construct bowing motion that requires more energy.

Figure 12 compares the time course in the structural inductivity of joint motion over time. The graphs show the inductivity of wrist, elbow, and shoulder joint motions over time. If the task bowing motion were a faster, more inertia utilizing motion, the inductivity would be higher; however, the bowing task here is a very slow movement so the inertial moment applied to the bowing upper limb is small, and therefore the inductivity becomes a relatively low value. As the graphs in Fig. 12 show, the inductivity of the motions of each of the expert subjects is much smaller than those of the novices for shoulder abduction-adduction and elbow extension flexion movements, especially when making a turn at bow tip. Since the application of force on the string becomes difficult as the bow moves away from the string, the experts seem to control their motions confronting the motion inductivity of the human body. Whereas, the motion of the novice subjects can be considered as relatively more natural, morphologically induced motion.

5. Discussions

Human movement, in general, is altered by practice so as to allow joint degrees of freedom that are relatively fixed during the early stages of practice. However, this study shows that the bowing motion is
not considerably changed within the 30 trials, and the initially fixed degrees of freedom of motion are not freed. More repetitive practice may be necessary, but this result implies that the novices actually feel difficulties searching for more proficient motion.

The comparisons between the bowing motions of the novice and expert subjects show that the novices tend to form bowing motion by relatively lowering their upper extremities, and the time course of the potential energy of the novices is maintained low. This result indicates that the bowing motions of the novices are kinetically easier than those of the experts. The comparisons of the structural inductivity of joint motion also indicate that the bowing motions of the novices are more naturally generated.

It was deduced that this ease in motion of the novices, related to the musculo-skeletal formation of the human body, may disturb a search process for more proficient motion. Due to the ease inherently existed in spontaneously formed bowing motion of the novices, searching for a different, more task oriented motion will probably yield a motion that is unfavorable for them in terms of energy consumption and utilization. Therefore, the novices may have extreme difficulty in moving beyond the initial motion, and thus long term, trial-and-error practice is probably necessary to acquire skills.

Moreover, the novice's motion is also favorable in terms of the musculo-skeletal structure. Table 4 lists the cross sectional areas and moment arms of the principle muscles acting to generate the lateral rotational moment according to Wood, Meek & Jacobson. Using these anatomical data, the maximum muscle force is calculated by multiplying the cross sectional area by the specific tension, 23 N/cm², and the maximum moment generating capacity of each muscle is calculated by multiplying the maximum muscle force by the moment arm of each muscle. Table 4 shows that relatively few muscles are present to effectively generate the lateral rotation moment in the human body. The skill required to actively control the lateral shoulder moment in the experts appears not to be well adapted to the musculo-skeletal structure.

Therefore, the motions of the novices are constructed or induced to be easy in terms of the morphological constraints of the upper limb, more specifically, constraints such as the segment inertia, range of joint motion and muscle locations and attachments. Thus, the acquisition of skillful motions, such as those required in sports or the playing of a musical instrument, is extremely difficult, and an advisor capable of observing the movement and providing adequate guidance or feedback is essential to moving beyond easy motion.

Although the skillful bowing motion of the experts is not an easily constructed motion, the motion is actually reasonable for fulfilling the task requirement. If the motion of the experts showed little shoulder abduction, the direction of the bowing motion would not be perpendicular to the front panel of the cello, and effective utilization of the mass of the upper limb to apply a force to the string would be impossible. Moreover, control of the bowing force by the shoulder lateral moment would also be impossible if the motion were so constructed. Therefore, the experts construct the movement so as to maintain their upper arms in a relatively flexed and laterally rotated position, and extend the elbows in bowing downward while flexing in upward motion so that the bowing motion becomes almost perpendicular to the cello. Considering the structure of the human upper limb, this motion is likely to be the best and only way to skillfully control bowing motion and force. The experts can fulfill the task by skillfully organize their motion within the morphological constraints of the body structure.

### Table 4  Moment generating capacities of shoulder rotation muscles

<table>
<thead>
<tr>
<th>Muscle</th>
<th>MA (mm)</th>
<th>PCSA (mm²)</th>
<th>Max Force (N)</th>
<th>Max Mom (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>subscapularis</td>
<td>25.4</td>
<td>1355</td>
<td>312</td>
<td>7.91</td>
</tr>
<tr>
<td>latissimus dorsi</td>
<td>17.8</td>
<td>258</td>
<td>119</td>
<td>2.11</td>
</tr>
<tr>
<td>PM(claviculairis)</td>
<td>20.3</td>
<td>516</td>
<td>193</td>
<td>4.41</td>
</tr>
<tr>
<td>PM(sternocostalis)</td>
<td>17.8</td>
<td>516</td>
<td>119</td>
<td>2.11</td>
</tr>
<tr>
<td>teres major</td>
<td>10.2</td>
<td>358</td>
<td>59</td>
<td>-1.21</td>
</tr>
<tr>
<td>teres minor</td>
<td>-20.3</td>
<td>258</td>
<td>59</td>
<td>-1.21</td>
</tr>
<tr>
<td>triceps (long head)</td>
<td>-20.3</td>
<td>255</td>
<td>59</td>
<td>-1.21</td>
</tr>
<tr>
<td>infraspinatus</td>
<td>-22.9</td>
<td>839</td>
<td>193</td>
<td>-4.41</td>
</tr>
</tbody>
</table>

Note. Moment arm (MA) is positive for medial rotation. PCSA = Physiological cross-sectional area of muscle. PM = pectoralis major

6. Conclusion

In performing an inexperienced task, humans can construct low-in-energy, morphologically easy motion as a makeshift. Expert motion, however, is not easily constructed motion. Rather experts skillfully organize their motion within the morphological constraints of the musculo-skeletal system so as to fulfill a task requirement. It is suggested that the transition from novice to expert is extremely difficult due to the existence of ease in the initially generated motion for an inexperienced task.

This study also suggests that humans may possess an intrinsic mechanism to naturally form an morphologically favorable motion. The authors intend to re-examine the human motor learning process from more structure-oriented perspective, and construct a...
mathematical model based on this hypothesis.

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References


