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RESEARCH ARTICLE

Pitch and space maps of skilled cellists: accuracy, variability, and error correction

Jessie Chen · Marjorie H. Woollacott · Steven Pologe · George P. Moore

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Abstract Based on a newly developed method that combines finger position tracking and spectral analysis of the concurrent acoustic record, we studied the accuracy and variability of pitch performance in eight skilled cellists and the role of acoustic feedback in their performance. The tasks required shifting movements between pairs of notes and separated by various distances (pitch intervals) on a single string at the rate of 1 note/s. The same tasks were performed either using the bow, providing acoustic feedback, or without the bow. Overall, our subjects exhibited a high degree of accuracy in executing tasks when using the bow. When using the bow, two types of variability were observed: (1) trial-to-trial variability: in most subjects the mean fundamental frequency of a single nominal note was significantly different from trial to trial; and (2) within-trial variability. The within-trial variability includes two subtypes: (a) the pitch of a given note changed between notes within a 50-note trial; and (b) within a single note there were positional changes that we hypothesize are attempts by the performer to adjust the fundamental pitch within the note. When acoustic feedback was absent, note distributions were shifted, multimodal, and had large variability; error-correction movements within a single note also significantly decreased, indicating that the stability and precision of the motor map depends on constant re-calibration and updating by acoustic information. Our results suggest that a performer's intonation should not be viewed as a fixed entity implied by the score but as a sample from a statistical distribution.

Keywords Music · Kinematics · Error correction · Pitch perception · Variability

J. Chen (✉)
Department of Physiology and Neuroscience,
New York University School of Medicine,
550 First Avenue MSB 442, New York, NY 10016, USA
e-mail: chenj16@med.nyu.edu

J. Chen · M. H. Woollacott
Department of Human Physiology and Institute of Neuroscience,
University of Oregon, Eugene, OR, USA

S. Pologe
School of Music, University of Oregon, Eugene, OR, USA

G. P. Moore
School of Engineering, University of Southern California,
Los Angeles, CA, USA

Introduction

One of the important questions in the study of skilled performance in musicians is the problem of pitch accuracy or intonation. Performers are often required to produce a series of notes in rapid succession. Proper intonation—the ability of a musician to produce the correct pitch of a note within a specific musical context—is one of the most daunting tasks in the development of performance skill. This is especially true for string instrument players who have a continuum of note pitches from which to choose along the length of the strings with limited visual and/or kinesthetic cues. For string players, the fundamental frequency of a tone is determined primarily by the length of the freely vibrating string and the pitch to which that string is tuned. To achieve the desired pitch, the performer depresses the string at a specific point creating a length of freely vibrating string from the contact point to the bridge, which corresponds to the new intended pitch. Even more challenging for string players, the spatial distances between successive notes are not equal along the fingerboard, i.e., lower-pitch notes (away from the bridge) are further apart, whereas higher-pitch notes are closer together.

The difficulty is increased when the task requires the hand to move along the fingerboard from one location to another, in a movement called a "shift". Such movements can require a displacement of the hand of many centimeters in addition to the associated movements of the arm and changes in the posture of the hand. Ultimately, the resulting accuracy will depend on the precision of the performer's sense of the desired pitch and upon the development of the skill that enables the performer, after years of training, to move to the required position. Because the distance between notes becomes smaller when moving higher on the string (closer to the bridge), the required degree of spatial accuracy also increases, on the order of millimeters.

At the most formal and abstract level, a note is a symbol in a musical score. The sound of that note depends on how it is played and with what instrument. Though the score indicates the pitch of the note in an abstract way, a performer may choose a slightly different pitch depending on factors other than the dictates of the score; or, because of limitations in technique, may play a tone that is out of tune. In this report the term note will be used both for the printed symbol, which is categorical, and also for portions of the data record corresponding to that note. The sound produced will be referred to as a tone, which is variable. The performer's internal concept of the tone or note will be referred to as an auditory image. The performer's or the listener's perception of the tone or note produced on the instrument will be referred to as pitch. In other words, performers see (or are told the name of) a note, generate an auditory image of the corresponding tone, and try to match the perceived pitch of the tone actually produced on the instrument with that auditory image. We compare here the fundamental frequency of the tone with the theoretical value of the fundamental frequency of the nominal note according to some scaling standard, such as the equal-tempered scale (Pierce 1983).

There are several accounts of accuracy of musical performance on keyboard instruments (Palmer 1997) and the influence of sensory feedback and skill level on its execution (Gates and Bradshaw 1974; Repp 1999; Drake and Palmer 2000; Palmer and Meyer 2000; Finney and Palmer 2003). But there are few studies of pitch precision (Fyk 1995; Ginzburg 1983) or bimanual coordination in string players (Baader et al. 2005; Winold et al. 1994). (See Gabrielsson (2003) and Zatorre et al. (2007) for comprehensive reviews of research in the field of music performance). We are not aware of any studies examining the actual ability of performers to achieve target pitches. Except for research from our own laboratory (Chen et al. 2006), none has examined the problem in relation to the cello, a relatively large instrument ideally suited to such studies. Only one earlier study has addressed this problem, and that was with wind instrument players (Morrison 2000).

In this report we will present findings from a study that employed a recently developed technology that tracks the contact point on the fingerboard between the string and the finger producing the note sounded by the instrument. This technique allows us to calculate the resulting fundamental frequency of that note and, at the same time, to monitor error corrections and other variations in frequency and position, in real time, that may be employed by the performer as a means of expression. Using this method we are able to observe the nuanced details of how string players move from note to note as well as the fine movements of the finger within a single note. This creates the potential for observing in detail some of the most precise and rapid movements of which humans are capable. Observing movements with high resolution in time and space gives us a chance to speculate on the perceptions and responses that allow skilled musicians to achieve levels of intonation so accurate as to be perceived as perfect by average listeners, and to achieve such precision without the aid of frets or keys.

The primary goal of this study was to study the pitch performance in skilled cellists, the variability and corrections of that performance, and the degree to which that depended on whether the subject was allowed to use the bow to obtain acoustic feedback, or had to rely entirely (in the absence of the acoustic feedback when not using the bow) on learned movement patterns in the coordinate space of the body and the cello.

Methods

Experimental apparatus

The fundamental frequency of a given string is controlled by the performer primarily by varying the length of the freely vibrating string. In the case of instruments in the violin family, the length is measured between the contact point of the string with the bridge and the point of the string where it contacts the fingerboard in response to the force exerted on it by the finger of the performer. In our studies we took advantage of the fact that most strings today have a precision wire-wound exterior. As a result, the string can be used as a resistor whose resistance is linearly dependent on string length. A properly designed circuit can measure the resistance of the string between the bridge and the contact point with the fingerboard. In practice we used a current source applied across the string, completing the circuit through a thin, low-resistance copper strip pasted on the fingerboard (Moore et al. 1988; Chen et al. 2006). One terminal for the circuit was at the bridge. A second terminal was the end of the copper strip. When there was no contact between the finger and the fingerboard, the voltage drop between the bridge and the end of the open string was measured. The voltage drop across the circuit was amplified and digitized at 360 samples/s. Given a suitable choice of commercially available strings with a total resistance of several 100 Ω, we were able to map the entire string length to a voltage range of about 10 V.

A Sony MP3 digital recorder (Sony Corp., MZ-N707) was used to record the acoustic signal. The recorder had a frequency response that was flat from 10 to 20 kHz. The acoustic signals were re-sampled at 8,000/s using the freeware Audacity (http://audacity.sourceforge.net/) and later subjected to spectral analysis using the MatLab (The MathWorks, Inc., MA, USA) FFT function to establish the fundamental frequency of selected notes. The acoustic signal was sampled concurrently with the circuit output at 360 samples/s for the purposes of synchronization.

Participants

A group of eight skilled cellists, four males and four females, were studied in an effort to determine their sense of pitch in the presence of acoustic feedback provided by bowing, and their ability to locate notes on the fingerboard when not using the bow. Six were recruited from the University of Oregon School of Music and two were professional cellists. None of the participants had absolute pitch. The informed consents approved by University of Oregon IRB were obtained before experimental sessions.

Protocols

Subjects were asked to shift alternately between two notes in a pair (without using vibrato) on the A string, at the rate of one note per second, for 1–2 min. Each note was played using the index finger, which required a shifting movement of the hand and arm along the string. Though not instructed about bowing style, all subjects employed legato and all played one bow per note. The note pairs were B (246.9 Hz) and D (293.7 Hz), B and E (329.6 Hz), and B and A (440 Hz). These pairs were separated approximately by 10, 16 and 26 cm, respectively. All subjects used the laboratory cello equipped with the string circuit. The string was tuned by each subject at the beginning of each trial, using a conventional musician's frequency meter, independently calibrated. All trials were paced for a few seconds with a metronome set to one beat per second.

In an equal number of trials subjects were instructed to shift between the same note pairs but without the use of the bow. The strings were muffled to eliminate any acoustic feedback. Participants were free to look at the fingerboard during no-bow trials but did not consistently do so. Note pairs and auditory feedback conditions were randomized.

Calibration

For calibration, we asked performers to play—and hold—two notes of different pitch, for example B (246.9 Hz) and E (329.6 Hz), separated on the cello A string (tuned to 220 Hz) by 15.3 cm. The mean voltage drop along the string was determined for each note. We then determined the mean fundamental frequency of the tones from spectral analysis of the concurrently recorded acoustic signal. This allowed us to determine the relation between the monitored voltage, the string length, the calculated frequency (given the length) and the actual frequency determined by spectral analysis. An example is shown in Fig. 1a and b. Once calibrated, the output of the circuit allowed us to calculate frequency over a range of finger placements. In Fig. 1c is shown the circuit output, converted to frequency, and the spectrum of the various notes played within a musical passage that extends beyond the range of the two calibration points (arrows at the base of the figure indicate the frequencies of B and E used in the calibration). Unlike experimental protocols used in the main part of the study, vibrato is used in the performance of this music passage. The correspondence is evident, demonstrating that when the string is properly calibrated, the resulting accuracy at any output is within a millimeter or less, and that the resistance of the A string used here is length-linear.

Data analyses

Figure 2 shows the histograms of a subject shifting between notes B and A (top), B and E (middle), B and D (bottom). We use this example to show our data extraction method. As can be seen, values for all the points sampled from the circuit in a trial fall into two main masses, one for each note in the pair. There are also points intermediate between the masses, representing points of contact sampled as the subject shifted between notes.

To extract representative data from each note played (which includes hundreds of raw data points) for statistical analyses, the following procedures were employed. First, the magnitude of the inter-note baseline was estimated. To do this, a point midway between the peaks of the two masses was selected, and a range equal to one-third the distance to the mode of each mass was chosen. Within that range, the mean and standard deviation of the baseline (counts, which are dependent on bin width) was calculated. Second, a threshold (3 standard deviations above the mean of the baseline) was chosen as the value above which we treated histogram points as belonging to one of the notes.

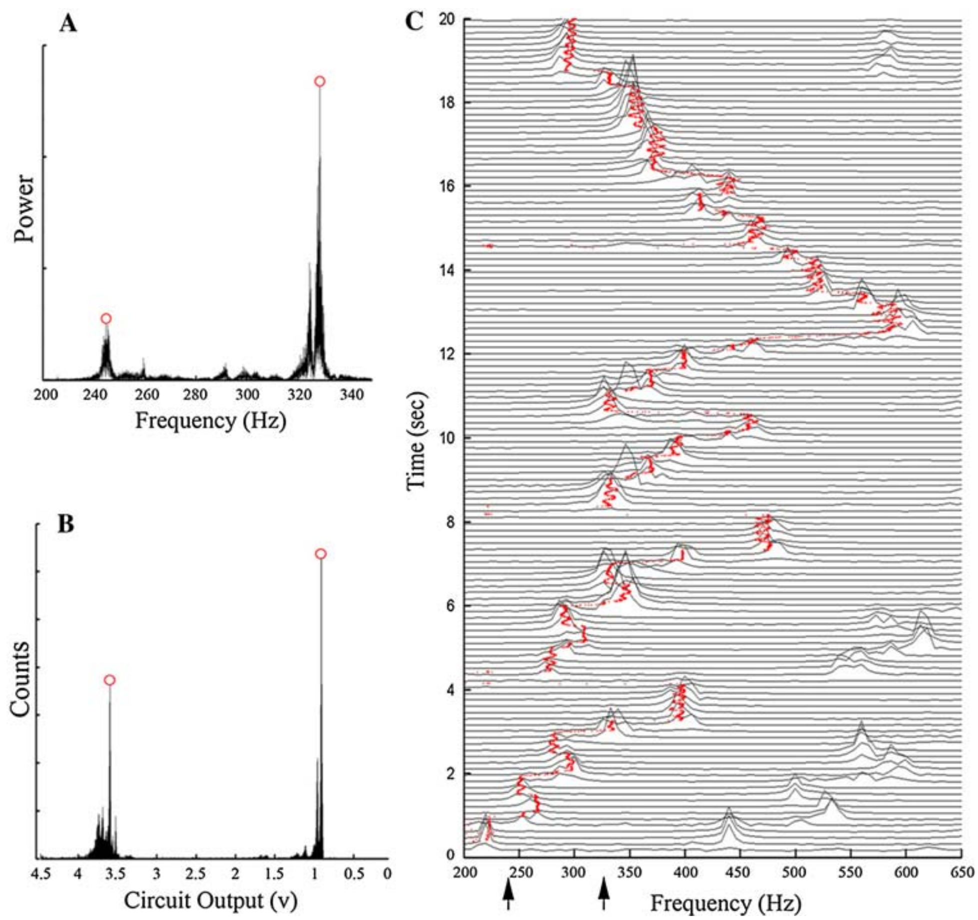

Fig. 1 **a** A spectrum calculated from 60 s of acoustic recording consisting of alternating shifts between B and E. The two peaks were near B and E, at 244.7 and 328.5 Hz. Power in arbitrary units. **b** Histogram of the circuit data for the same time period used in the frequency analysis shown in **a**. The *horizontal axis* is in volts; the *vertical axis* is in counts per bin. Bin width: 0.001 V. The *small peak* in the histogram (**b**) just to the *left* of the peak corresponding to E is the voltage counterpart to the smaller peak in the spectrum near E (**a**). **c** Twenty-seconds of acoustic data from the performance of a musical passage are used to generate a sequence of spectra based on sequential time segments each lasting 0.15 s. Superimposed are the calculated frequencies derived from the circuit data plotted every 1/360 of a second

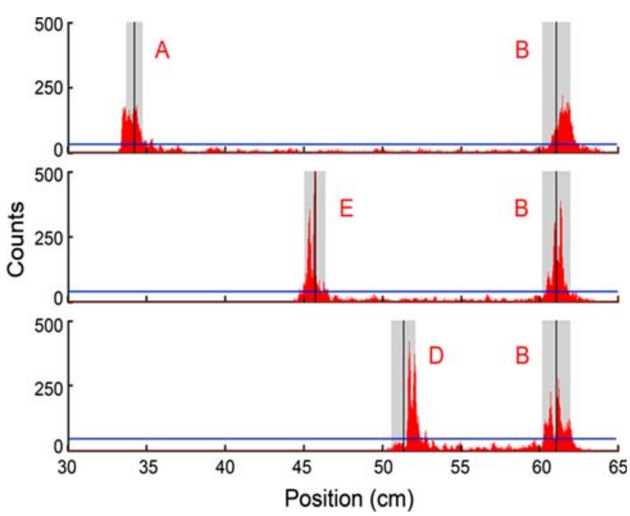

Fig. 2 Histograms from three 60-s trials from one subject shifting between *B* and *A* (*top*), *B* and E (*middle*), and *B* and *D* (*bottom*). The bow was used in these trials. The contact positions for true *B*, *A*, *E*, and *D* are indicated by *vertical lines*. *Gray* areas represent the "pitch window" for each note (see text). *Horizontal lines* in each trial represent the threshold calculated as 3 SDs above the mean of the baseline. Notice that the threshold is higher in the *B*-to-*D* trial due to a higher baseline level (caused by a slower shifting speed). Data above the threshold are treated as belonging to each of the notes

From this procedure, two separate histograms were created, one for each note. In step three, a histogram for the points above the threshold was created for each individual note. The modal value (peak) of each one-note histogram was then selected as a representation of the finger position for that single note. This yielded about 22 modal values for each note in each trial. The mean and standard deviation of these modal values were calculated and later used in statistical analyses. All histograms in this report have a bin-width of 1 mm. (Our histogram displays do not include points corresponding to the open-string A; these points arise when, during a shift, the subject moved in such a way that the string and fingerboard lost contact.)

Trials were grouped by shifting pairs and bowing conditions to compute mean modal finger positions for each note in each subject. A *t*-test analyzed whether there was a significant difference between the finger position and the theoretical note position for each note. An analysis of variance model analyzed whether there was a significant difference in finger position between bowing conditions. Since note B is the common note among the three shifting pairs tested, a one-way ANOVA was also performed, for both bowing conditions, to test whether the note B position was significantly different when paired with different notes. The significance criterion was $P < 0.05$.

Results

The goal of this study was to study pitch performance in skilled cellists. Specifically, we examined the accuracy and variability of pitch performance.

Trial-to-trial variability

Note B-natural was a common note in the three shifting pairs we tested in each subject. The verbal instruction given to the subjects was to play the two assigned notes in tune, or as accurately as possible, at the set tempo. Our group exhibited some surprising variability in the production of the same note when played at different times and when it was paired with different notes.

Figure 2 shows the histograms for 60 s of data from one subject (cellist 5 in Table 1) shifting between B and A (top), B and E (middle) and B and D (bottom). Vertical lines correspond to the true note position (if the pitches were tempered). Surrounding each true-note-position line is a shaded area showing the width of the zone we term the "pitch window", a 1/8th-step zone around the fundamental frequency within which any tone would be difficult to distinguish from the true-pitch tone. The bow was used in all three trials. It can be seen that B, the note common to all three trials, was not constant in mean position or dispersion. Several other features are also of interest. In general, note D was slightly, but consistently, flat, though it was not as dispersed as any of the B peaks or the A peak. Although histograms of B and A in the B-to-A pair were unimodal, they were more dispersed compared to the note positions in the other two pairs. In the shifts to E and D, the B histogram was multimodal, showing that the subject returned to different B positions (and frequencies) within those trials. The histogram for D was multimodal, too.

The group results listed in Table 1 confirm the pattern shown in Fig. 2 at the level of the individual performer. In six of the eight subjects, the mean modal finger positions of note B were significantly different among the three shifting pairs in the with-bow condition. All players had significantly different Bs in the no-bow condition.

Table 1 The mean modal finger positions (standard deviation) in cm of each note in three shifting pairs (B-to-D, B-to-E and B-to-A) and 2 bowing conditions (with-bow and no-bow) of 8 skilled cellists

Cellist	Condition	B-to-D		B-to-E		B-to-A	
		B	D	B	E	B	A
1	With-bow	60.8 (0.2)[a,b]	51.4 (0.1)[a]	60.8 (0.4)[a,b]	45.3 (0.2)[a]	60.8 (0.4)[a,b]	34.4 (0.2)[a,b]
	No-bow[c]	**59.6** (0.7)[a]	51.2 (0.7)	61.7 (1.4)[a]	45.3 (0.4)[a]	60.2 (1.0)[a]	**36.7** (0.6)[a]
2	With-bow[c]	**62.4** (0.3)[a,b]	**52.2** (0.2)[a,b]	**62.2** (0.3)[a,b]	45.9 (0.2)[a,b]	**62.0** (0.5)[a,b]	**31.0** (0.2)[a,b]
	No-bow[c]	**64.6** (0.9)[a]	**53.3** (2.0)[a]	**65.3** (0.5)[a]	45.4 (0.3)[a]	**63.7** (0.5)[a]	**33.6** (0.3)[a]
3	With-bow[c]	60.9 (0.2)[a,b]	51.2 (0.3)[b]	61.1 (0.4)[b]	45.7 (0.2)[b]	60.9 (0.4)[b]	34.6 (0.3)[a]
	No-bow[c]	**62.8** (0.8)[a]	51.9 (0.8)[a]	60.6 (0.5)[a]	45.5 (0.3)[a]	61.3 (0.7)	**34.9** (0.7)[a]
4	With-bow[c]	61.4 (0.2)[a,b]	51.7 (0.1)[a]	61.7 (0.4)[a,b]	45.9 (0.1)[a,b]	60.5 (0.2)[a,b]	34.3 (0.5)
	No-bow[c]	**60.0** (0.5)[a]	51.7 (0.5)[a]	**59.2** (0.5)[a]	45.3 (0.3)[a]	**60.1** (0.5)[a]	34.1 (0.6)
5	With-bow[c]	61.0 (0.4)[b]	51.9 (0.2)[a,b]	61.2 (0.2)[a,b]	45.5 (0.3)[a]	61.5 (0.4)[a,b]	34.0 (0.4)[a,b]
	No-bow[c]	**62.7** (0.6)[a]	**47.4** (0.3)[a]	**62.1** (0.7)[a]	45.6 (0.3)	60.4 (0.9)[a]	**34.8** (0.7)[a]
6	With-bow[c]	61.3 (0.3)[a,b]	51.4 (0.1)[a,b]	61.1 (0.3)[b]	46.2 (0.1)[a,b]	60.9 (0.2)[a,b]	**34.8** (0.2)[a,b]
	No-bow[c]	**63.1** (0.4)[a]	**53.3** (1.0)[a]	**62.6** (0.7)[a]	**46.5** (0.2)[a]	**62.0** (0.8)[a]	**35.9** (0.8)[a]
7	With-bow[c]	61.2 (0.2)[a]	51.5 (0.2)[a,b]	61.2 (0.2)[a,b]	46.1 (0.2)[a,b]	61.4 (0.2)[a,b]	34.6 (0.2)[a]
	No-bow[c]	61.1 (0.3)	**53.0** (0.6)[a]	60.9 (0.5)	45.5 (0.2)[a]	60.7 (0.4)[a]	**34.7** (0.7)[a]
8	With-bow	61.4 (0.4)[a,b]	51.4 (0.1)[a,b]	61.3 (0.3)[a,b]	45.9 (0.3)[a,b]	61.2 (0.4)[b]	34.3 (0.6)
	No-bow[c]	**63.1** (0.6)[a]	**49.9** (0.4)[a]	**62.4** (0.4)[a]	45.2 (0.3)[a]	**63.0** (0.5)[a]	34.6 (0.8)[a]
TP (PW)		61 (60.1–61.9)	51.3 (50.6–52.1)	61 (60.1–61.9)	45.7 (45.1–46.4)	61 (60.1–61.9)	34.3 (33.8–34.7)

Those notes that had a mean modal position outside the pitch window are bolded

TP Theoretical position based on tempered pitch scale, *PW* range of the pitch window

[a] The mean modal finger position is significantly different from the theoretical position at the 0.05 level

[b] The mean modal finger positions are significantly different in the 2 bowing conditions at the 0.05 level

[c] The mean modal finger positions of note B are significantly different among the three shifting pairs at the 0.05 level

Within-trial variability: drift

In addition to the trial-to-trial variability, we also observed variability of a note within a single trial. An example is shown in Fig. 3. The pitch/position of a single note was not always constant, and there was also pitch/position variability in successive realizations of the same note within a trial. In principle, we can make a separate histogram of contact positions for each note in a trial. This is a measure of the time spent at each position during that note. The peak value of that one-note histogram, i.e., the most probable contact position for that single note, might be taken as representing the subject's preference for the target pitch at that moment. We can then construct a histogram of those peaks for all notes in a trial. This is shown in Fig. 3, where we have stacked the one-note histograms for a trial consisting of shifts between B and D. Also shown in the bottom panel are the distributions for the modal values of B and D from those one-note histograms. They estimate the distribution of the two note positions for this performer during this trial. Thus, we can usefully conceive of each nominal note and its associated tone not as the fixed entity implied by a score but as a sample from a statistical distribution. The distribution reflects the variability or uncertainty in the performer's auditory image of the required pitch and the performer's ability to achieve that pitch.

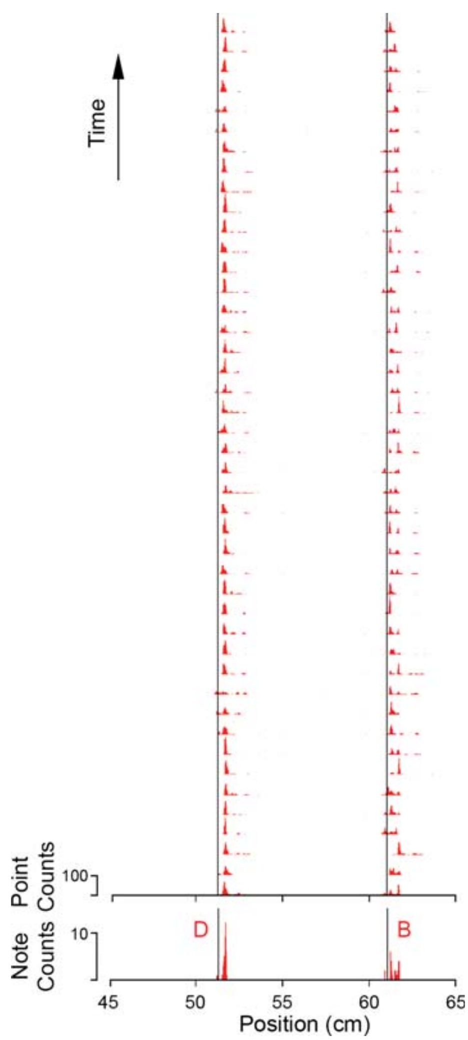

Fig. 3 Two minutes of circuit data from a *B*-to-*D* trial from a single subject have been partitioned into one-note histograms. Time runs from *bottom* to *top*. The contact position at the peak of each single-note histogram was taken as a token for the pitch of that note in the sequence. This trial had 44 notes at each pitch. A composite histogram of peak values for these notes is shown at the *bottom*. The true *B* and *D* positions are shown as *vertical lines*

Within-trial variability: adjustments

In Fig. 4 (left) are shown 10 s of data taken from a longer record. The subject was shifting alternately between B and A without the use of bow. The top display shows the finger contact position as a function of time. Below this is shown a histogram of the circuit output, transformed to a distance scale. Vertical lines correspond to the positions of true A and B. On either side of these lines are two other lines giving the positions of notes one half step above and below the central note. In this example the half step notes surrounding A would be, in musical terminology, $G^{\#}$ and $A^{\#}$, and $A^{\#}$ and C for B.

In this example, all As (at the left in the display) were outside the pitch window but all Bs were within the window and almost exactly at the true B position. The As were too far from the bridge and hence too low in frequency. In musical terminology they were "flat".

The scarcity of data points during the shift between B and A (points are separated by 1/360th of a second) indicates the shifts were executed at a fairly rapid speed. The histogram of A had four distinct peaks reflecting the fact that the steady-state holding position was different for all four A notes played in this excerpt (as seen in the upper portion of the figure). The B histogram was tightly distributed and centered exactly at the expected theoretical location for B. This indicates that the subject repeatedly returned to the correct location for B but had some uncertainty about the exact position of A. Moreover, all (unsounded) notes in this example were held without obvious correction. The spread of each histogram reflects variability in the contact position of each note.

In Fig. 4 (middle), from the same subject shifting between B and A—but using the bow—we see a different pattern. What distinguishes this record from the one on the left is the presence of variations in the holding position during each note. We hypothesize that this behavior, reflecting the intent of the performer to adjust the tone, may have become so "automatic" over years of practice as to require little or no conscious attention. In contrast to the panel on

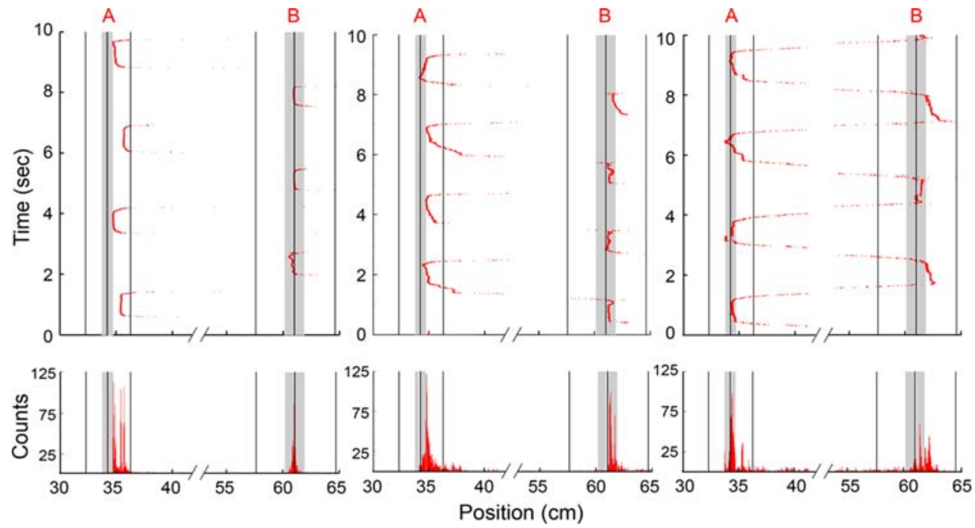

Fig. 4 Three 10-s excerpts from subjects shifting between *B* and *A*. Contact position expressed as distance from the bridge (in cm) (*top*). Histograms of all data in the excerpts *Bottom*). Sampling rate: 360/s. Bin width: 1 mm. The positions for true *A* and *B* are indicated by *vertical lines*. The *vertical lines* on either side of the *A* and *B* lines are a half-step away. *Shaded areas*: pitch window. The subject in the *left panel* was not using the bow. *Middle panel* is the same subject using the bow. The *right panel* is from another subject, also using the bow

the left, the final holding positions were all near or within the pitch window. The peak of the histogram near A was just at the border of the window; at B all major peaks were within the window. There were more data points in the record between B and A, reflecting the fact that the subject was moving more slowly during these shifts.

In Fig. 4 (right) another subject using the bow shifted between B and A. The shifting movements were slower here, and hence there were more points in the histogram between the B peak and the A peak. The first and third Bs were initially flat, but the contact position changed in an exponential-like trajectory toward the final holding position, very close to the true B position. The A contact position moved from an initially flat location toward the final value after a succession of small "jumps" in the contact position, ending almost exactly at true A location. We note that when the contact position/pitch was flat the finger moved in the sharp direction; the converse is true when the contact position/pitch was sharp. An important observation is that the dispersion in the histogram of A note in the left panel was determined by the different holding positions for different As: there was little variability within a given note. The multiple peaks reflect the between-note variability. In the middle and right panels the dispersion reflects the movement within each note: there was little difference in the final position. The histogram dispersion primarily reflects the within-note variability.

In addition to the different styles in finger position adjustments after initial landing on a note, these two cellists also showed different styles of shifting movements. For the subject shown on the right, the finger never lost contact with the fingerboard: all data points lie between A and B. The other subject always lifted the finger from the fingerboard during shifts and hence the circuit detected a distance of 68.5 cm, corresponding to the length of the open A string, a distance beyond the scale of the figure.

What accounts for the different holding patterns in the left panel compared to the middle and right panels is that the subject, though instructed to shift between B and A, was not using the bow and hence did not have acoustic feedback by which adjustments in contact position might be triggered. In the two other trials shown here the subjects used the bow. As a result the movement patterns and holding patterns were different. Interestingly, in the left panel the subject, even without acoustic feedback, returned to the correct location for B (an unusual result; see also Fig. 5) but had some uncertainty about the correct position for A. But all positions were held without obvious correction. Because the within-a-single-note variability largely disappeared when the bow was not used, we are led to conclude that this type of positional adjustment within a single note is a result of acoustic feedback; it is an attempt by the performer to adjust the finger position toward the desired point in response to perceived pitch inaccuracies.

Influence of acoustic feedback

In the absence of acoustic feedback (and possibly of some proprioceptive cues from the bowing—right—arm), not only did we find diminished within-note adjustments, we also found that the performer's ability to direct his finger to the correct note position on the fingerboard was both inaccurate and unstable: contact positions wandered relatively widely, and were generally not near the correct position compared to those in the with-bow trials.

Figure 5 shows the results from 60 s of data from four subjects shifting between B and D under two conditions: with and without the bow. The results using the bow are shown as positive histograms (above the baseline); the trials without the bow are plotted as inverted histograms (below the baseline). At the top is a subject (subject 6 in Table 1) who, using the bow, played D at exactly the right

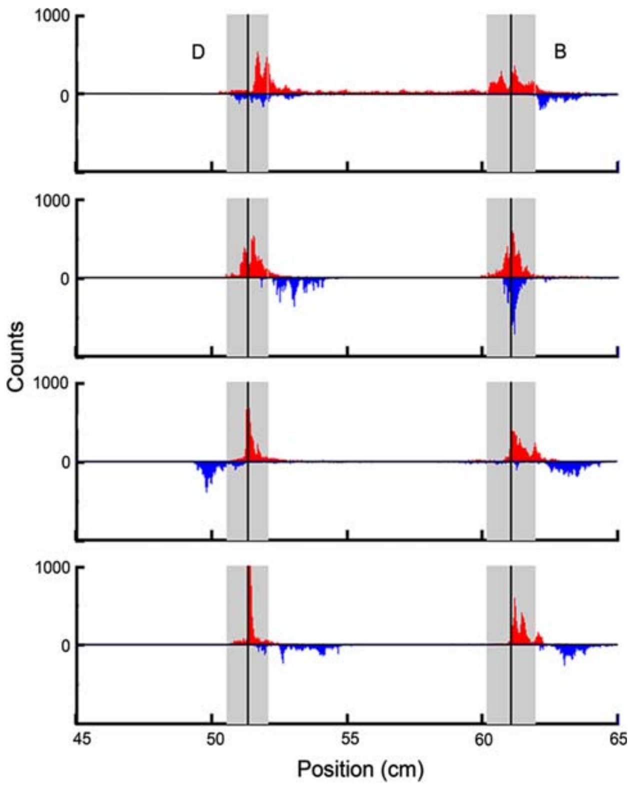

Fig. 5 Histograms of eight 60-s trials from four subjects, shifting between *B* and *D* with the bow (*positive* histogram) and without the bow (*inverted* histogram). The locations of true *B* and *D* are shown. In two of the four pairs the trial with the bow preceded the trial without the bow

location. The highest B peak was very near the true value, but there were other peaks that were flat in pitch. Without the bow, the subject was unable to find the correct location for either note. All points in the histogram were considerably to the right (flat) of the true note positions. The histogram pair below this shows another subject (subject 8 in Table 1) who was almost exactly on pitch for D using the bow (the B peak was near the true value but had some spread in the flat direction). Without the bow the subject moved in the sharp direction on D and the flat direction for B. The resulting shifting distance, without the bow, was increased by nearly 6 cm! The subject in the second-to-bottom panel (subject 7 in Table 1, the same subject shown in the left and middle panels in Fig. 4) kept the same position for B under both conditions, but without the bow had a more widely dispersed position for D and at locations where the pitch would be quite flat. The shifting distance was decreased by several cm. At the bottom is a subject (subject 5 in Table 1) whose performance, even with the bow, was somewhat variable. Without the bow this subject also appeared to have only a vague idea of where the true notes were located. Overall, this figure calls into question the idea that our subjects had a precise idea of the location of any given note on the fingerboard when the bow was not used.

Results in Table 1 further support what is evident in Fig. 5. Our subject group had a high degree of accuracy in executing the tasks when using the bow. The contact positions closely corresponded to the assigned note positions; and the variability was low. In trials where the performers were not allowed to use the bow but otherwise instructed to shift between the same note pairs, in a majority of the notes, performers were only able to find the approximate position on the fingerboard. Two aspects of their inferior performance in the no-bow condition are evident. (1) The performer's sense of note position was less accurate in the no-bow condition. Although about the same number of notes in both conditions showed significant deviation from true note position (39 of 48 in the with-bow condition and 42 of 48 in the no-bow condition), a higher percentage (67%) of these deviated notes in the no-bow condition landed so far from the true position that they were actually outside the pitch window, whereas only 15% went outside the pitch window in the with-bow condition. (2) The performer's sense of note position was more unstable in the no-bow condition. All notes showed increased variability in the no-bow condition compared to those when the bow was used.

Discussion

Music performance has long been of interest to both music pedagogy fields and motor control communities, because each action during a performance produces sound, which potentially influences each subsequent action, leading to remarkable sensory–motor interplay. Although much research has been carried out into sensory–motor interactions in processes such as reaching/grasping and speech, these actions do not fully capture the requirements of musical execution. The few studies concerning motor control of pitch have been conducted on musicians who play keyboard instruments, which have discrete keys; thus in this case movement accuracy is a far less critical issue. String instruments are far more challenging for pitch performance due to the lack of visual/tactile cues on the fingerboard and the non-linear relationship between position and fundamental frequency on the strings. The only study we are aware of that addresses the issue of intonation in string players was conducted by Fyk (1995) on violinists. However, since the data analysis methods were not well documented in her published study, it is hard to compare her findings with ours. In addition, since the only variable in that study was sound, the effect of conditions when sound was absent could not be examined. The study reported here is based on a method that combines tracking finger contact position and spectral analysis of the concurrent acoustic record.

Overall, our performers exhibited a high degree of accuracy in executing the tasks, but there was also variability in their performance. We observed several types of pitch variability: (1) trial-to-trial variability: significant differences in the mean fundamental frequency of a single nominal note from trial to trial; and (2) within-trial variability: changes in the fundamental frequency of a single note repeated within a trial. Within the second type of variability, two sub-types were found: (a) the modal frequency value of a given note changed between notes within a single trial, a phenomenon we termed "drift"; and (b) positional changes within a single note which we called "adjustments".

Our results show that when using the bow, the finger contact positions were at points that closely corresponded to the assigned (true) note pitches. Although most of the notes tested in the with-bow condition had mean modal positions significantly displaced from the true note positions, the majority were inside the pitch window. There are two possible explanations for the high percentage of significant deviations. (1) The statistically significant deviation might not be perceived. As mentioned earlier, frequencies that were within the 1/8th-step pitch window—were unlikely to be detected. (2) A slightly deviant pitch might be the preferred pitch of the note in that particular trial. We have demonstrated in our results that some performers had a consistent preference for a pitch/position in a trial that was not at the expected values, and this preference seemed to change from trial to trial.

We were also interested in whether, and to what extent, the ability to locate a note depended on acoustic feedback and to what extent it could be supported by modalities other than auditory feedback, such as proprioception and vision. In trials where the performers were not allowed to use the bow but otherwise instructed to shift between the same note pairs, it became clear that in the majority of the notes played performers without acoustic feedback were able only to find the approximate position on the fingerboard. Over a single trial the typical contact position was not only widely dispersed but also significantly displaced from its true value—a value easily achieved when acoustic feedback was present. Although about the same number of notes in the no-bow condition showed significant deviation from the true note position compared to that of the with-bow condition, a higher percentage of these deviant notes landed so far from the true position that they were actually outside the pitch window. As a result, the shifting distance between the notes was significantly increased or decreased. A commonly held concept in music pedagogy, "muscle memory", expresses the idea that much of highly practiced musical performance is so deeply ingrained that it does not require conscious control: the neuromuscular machinery can subserve a performance as if it were already imbedded in the muscles themselves. We find little support for this concept from the present studies.

In thinking about how a performer finds a note we appeal to several concepts. First, we imagine that each subject has some mental "pitch map"; i.e., the subject "hears" the note to be played (the auditory image), whether it be two alternating notes, notes in a scale, or notes in a musical passage. Against this auditory image a played note can then be judged for pitch accuracy. To realize the note faithfully requires another "map", a physical map of the instrument, and "where" in instrument space the target pitch (tone) is located. Accurate pitch performance depends upon the proper "alignment" of these two (and possibly other intermediate mapping transformations). Without acoustic feedback the spatial map and the pitch map are generally dissociated. In several subjects the physical map was not stable. Whether these results are idiosyncratic for these performers is not the point. It is the conceptual dissociation between the two "maps" that we want to emphasize here.

The dissociation implies that movements from one note to another, which are highly skilled and result from years of training, are not invariably independent of some acoustic guidance. The movements are normally practiced in the presence of acoustic feedback, and likely depend in some complex, as yet unexplored way, on the correctional and possibly calibrational effect of sound. A tentative model for this interaction should be taken from studies of speech that have demonstrated both the open- and closed-loop aspects of motor control of speech and the complex ways that interventions and manipulations of acoustic feedback can disrupt normal speech (Larson and Hain 2007). This is a sizable literature, but its methods and implications need to be adapted to the study of musicians.

It should not be inferred that when use of the bow is denied, the only loss to the performer is acoustic, because this ignores the fact that the bowing arm, and the contact between the bow and the instrument, may provide important proprioceptive information that is vital to the subject's three-dimensional model of the instrument, information on which skilled navigation depends. In addition to a potential change in kinematics of the shifting movement, the no-bow protocol used in this study might also have disrupted a vital learned spatial coordination pattern and is a potential methodological shortcoming of the present study.

Though our results reveal that note distributions were statistically different when the same note was played using the bow in different trials, we have no evidence to show that they would be perceived as different in pitch. On the other hand, when the bow was denied, the note distribution was grossly shifted in position and the variability increased. Most of the note distributions in the no-bow trials were displaced outside the pitch window. If these were sounded they would certainly have been perceived as different from those in the with-bow trials.

In some cases there was a systematic drift in note position for one or both notes, especially prominent when the bow was not used. The phenomenon is similar to the behavior of subjects moving between two spatial locations on a plane when visual feedback is removed (Brown et al. 2003). The question of serial dependence between successive realizations of a note, with and without acoustic feedback, will be the subject of a subsequent paper.

Showing that our group had a high degree of accuracy in pitch performance when the bow was used does not mean that errors did not occur during movement execution. Of course not every note was exactly on pitch: some were sharp, others flat. These variations from note to note could also be tracked with our system. Often, the contact position between the finger and fingerboard was adjusted by the performer within a single note in what was most likely a response to some perceived pitch inaccuracies. These results indicate a generally reliable sense of pitch and position in our study group, no doubt achieved over years of practice. In trials where acoustic feedback was prevented by denying the use of bow, note distributions were shifted in position, generally multi-modal and had large variability. In addition, error-correction movements significantly decreased. This suggests that the stability and precision of the motor map depends on constant re-calibration by the pitch map based on acoustic feedback.

Our results suggest that performers do have a refined intonation insofar as they can, in a sequence of alternating notes, fairly accurately reproduce a pitch used previously within that trial. They have an internal model of the desired pitch, an auditory image, which is relatively consistent within a trial, but sometimes at variance with the nominal pitch required by the task. Of course we do not know what the internal model for pitch is or how it is related to tempered pitch for these musicians. There is no reason to believe that musicians choose a pitch interval identical to that of a piano; and there are claims that skilled performers intentionally deviate from perfect intervals in performance (Fyk 1995; Ginzburg 1983). Others (Bamberger 1991) insist that there is no meaning for the concept of pitch or interval outside a particular musical context. Neither do we know what the performer "hears" on any given note, or even within a single note. We have hints, though, when the subject appears to adjust the pitch within a note, but it is only a hypothesis that the hunting within a note is in any way related to pitch correction—a correction toward a "preferred" pitch.

It is reasonable to ask whether the results of this study are relevant to the performance of real musical passages. In Fig. 6 we return to the example already illustrated in Fig. 1c. This is a 4-s excerpt from the opening ten measures from the second movement of the Sonata for Violin and Piano by Cesar Franck, arranged for cello and piano. The cello here was unaccompanied. The performer is Subject 4 in Table 1. The same musical phrase occurs twice in this excerpt (see the musical score at the top of the figure). The trace below the music score is the low-resolution acoustic record, sampled at 360/s. It is intended primarily to indicate when the sound from the cello was diminished during rests. The output from the string circuit, already shown in Fig. 1c, is expanded here in detail. It shows the contact location of the string on the fingerboard, at the outer edge of the finger closest to the bridge when it depressed the string. Shifts that required whole arm movements and changes of hand posture (in addition to finger extension) along the fingerboard are indicated by arrowheads. Note that several shifts in this

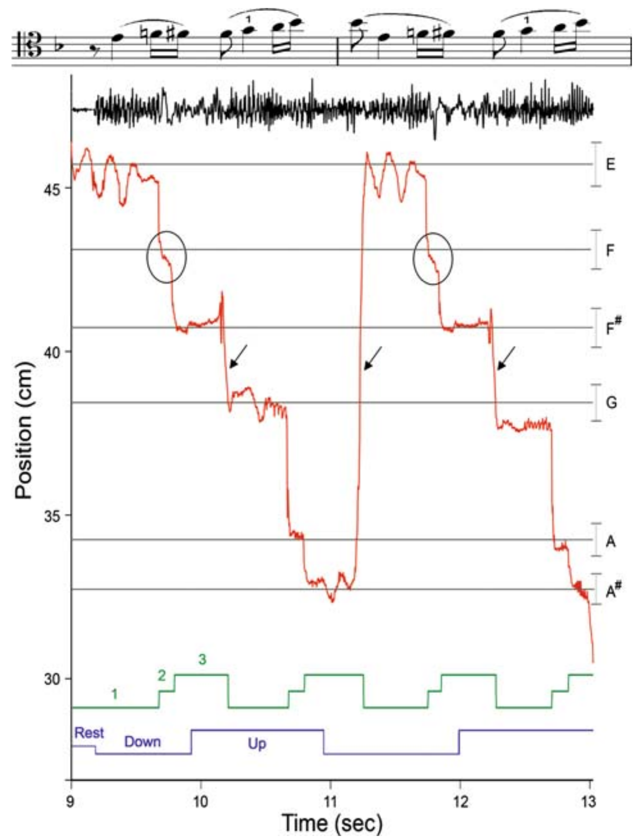

Fig. 6 Four seconds of data from measures 5 and 6 of the opening passage from the second movement of the cello arrangement of Cesar Franck's Sonata for Violin and Piano. The cello was unaccompanied. The musical score for the excerpt is shown at the *top*. Below that is the acoustic record, which begins with a rest. The main trace shows the contact position between the performer's finger and the fingerboard (expressed as distance from the bridge, in cm). The expected contact positions for notes are shown as *horizontal lines*. Their respective pitch windows are indicated at the end of these lines as *brackets*. At the *bottom* is shown the finger used for each note (1–3, 1 being the index finger) and the direction of bow movement (*up* and *down*; *down* referring to movements of the bow when the bow hand is moving away from the main axis of the cello). It can be seen that the bow changed direction during both $F^{\#}$ notes and during the first B^{b}, each time creating the impression of two distinct notes

passage are executed using only the first finger, i.e., were comparable to those used in our study. Horizontal lines intersecting the circuit trace give the theoretical locations of those notes. At the bottom of the figure we show the finger employed for each note (1–3; 1 being the index finger), and the direction of the bow motion. The designations "up" and "down" refer to motions of the arm that move the bow hand away from (down) or toward (up) the string. The times of direction change can be inferred from this.

Several features of interest may be mentioned. Notes that were held sufficiently long were played using vibrato, reflected in the oscillating baselines of those notes. The initial note (E) is an example. Here it can also be seen that finger contact (and even vibrato) is established during the rest (indicated by the absence of significant activity in the acoustic record) that occurred at the very beginning of the section. We note the total amplitude of the vibrato, expressed in cm of movement in the contact point, was approximately equal to the pitch window for E shown at the right side of the figure. That is, the total variation in pitch during this vibrato was about a quarter-step.

Conversely, some notes were held for only a brief time. An example would be the first F (a 16th note, circled) just after the beginning E. Note that the contact point moved throughout the note as it did in the repetition of the same note sequence 2-s later. This note was therefore an acoustic "blur" though it might not be perceived as such by listeners. Overall, we note the close approximation of each note location to its theoretically expected position according to the score; but some variation as well (for example, the two Gs), consistent with the results in Table 1 and Figs. 3, 4 and 5. The examples noted here further expand our concept of a note. The notes held using vibrato did not, in general, have the pitch implied by their representation in the score; their pitch was, in a strict sense, indeterminate. The two F (natural) notes also had no determinate pitch. How these notes are perceived by a listener—or by the performer—is a separate issue and an extremely difficult question to answer. But qualitatively the histograms of these "notes" would be very different from those resulting from the simpler shifting procedures shown in this report.

It is not surprising how little research attention has been given to the subject of pitch performance in string-instrument musicians. Primarily this has been because it is difficult to acquire objective measures of errors or attempts to correct them at a sufficiently high temporal and spatial (spectral) resolution, though every performer and teacher (and many listeners) are acutely aware of the phenomenon. In light of the technical possibilities demonstrated in this report, the ability to study pitch performance and error correction opens up new possibilities for monitoring activity in musical performance at the highest levels, studying learning and the effects of practice, and providing a systematic framework for understanding and interpreting the most complex movements of which humans are capable.

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