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Movement, planning, and music: Motion coordinates of skilled performance

Caroline Palmer, Christine Carter, Erik Koopmans and Janeen D. Loehr

McGill University, Montreal, Canada

ABSTRACT

Skilled musicians are capable of fast, fluent performance of complex musical sequences whose motor demands can shape sequential aspects of performance, similar to principles of coarticulation in speech. We address how performers' motor systems can influence the ways in which melodies are performed, both in motion and sound. In contrast to energy conservation models that favor small movements at fast tempi, musicians often use larger movements when performing at fast tempi on several non-wind instruments. Possible explanations include the fact that faster movements on those instruments tend to produce louder sounds, and increased tempo is often accompanied by increased loudness. We report here on motion characteristics of clarinet performance, a musical instrument for which finger height does not alter the loudness of tones. Skilled clarinetists performed melodies at different tempi, and motion capture techniques recorded their finger movements above the clarinet keys. All clarinetists raised their fingers higher when performing the same melodies at fast rates, despite the absence of a loudness-finger height relationship. Furthermore, finger height was related to direction of finger motion and to the number of simultaneous finger movements. These findings document the importance of biomechanical constraints on body motion that influence music performance in ways that can be nonintuitive and differ from energy conservation perspectives.

1. INTRODUCTION

Music and motion have been linked theoretically for a long time; scientific interest in this link arises from a belief that we can understand better how musicians communicate by studying the physical motion that leads to sound (Sundberg, 2000). Examples of how music and motion are linked include performers' movements that correlate with acoustic aspects in rule-based ways, how listeners respond to music with body motion, and motion-based terminology used to describe musical changes such as tempo. Scientific approaches document similar rules that govern tempo rubato in music performance and other forms of human motion, such as locomotion (Friberg & Sundberg, 1999); other lines of work focus on how predictive a musician's motions are of the ultimate sounded events (Dalla Bella & Palmer, 2006). Perhaps the most direct source of motion-to-sound mapping is the human voice, with which gestures are converted directly to acoustic events; the shape and position of vocal articulators during speech or song contribute to the expressivity of the voice.

Music performance on physical instruments also provides an opportunity for articulating through gestures such as tonguing, breathing, and fingering. One can conceptualize performance as a sequence of articulatory movements resulting in a continuous acoustic wave. This approach attempts to answer questions similar to those in the study of speech articulation: what are the meaningful movement segments, which articulatory gestures give rise to the movement segments, and how do they map on to musical units such as tones and chords? Musicians interact with a variety of physical instruments that require precise and responsive control of motion sequences with finger, wrist, tongue, and other effector movements. The mapping of movement to sound differs across instruments; for example, finger movements in piano performance usually control changes in timing, pitch, and loudness, whereas finger movements in clarinet performance usually control pitch changes, while breathing controls changes in loudness, and both control timing in coordination with the tongue. Only comparisons across musical instruments can elucidate which movement aspects are important for sound control and which are shaped by effector-specific biomechanical aspects of the human body.

We describe a study of clarinet performance that addresses an aspect of finger motion that has been attributed to the control of musical sound in piano performance. Pianists typically use larger finger movements when performing at fast tempi, which often results in louder performance; increased finger height at faster tempi has been documented in the context of piano performance (Palmer & Dalla Bella, 2004; Dalla Bella & Palmer, 2006) and in pianists' tapping on a tabletop (Loehr & Palmer, 2007). This performance style is contrary to many pedagogical approaches that promote keeping the fingers close to the instrument, especially at fast tempi (Hadcock et al, 1999; Russianoff, 1982), in an effort to conserve energy. Kinematic principles of mass-spring motion predict that reducing movement amplitude at faster speeds is necessary to maintain the same energy level; however, the kinematics of finger movements may not follow mass-spring principles, especially when they are coupled to each other and to the hand. Faster movements on non-wind instruments tend to produce louder sounds, and increased tempo is often correlated with increased loudness in music performance (Gabrielsson, 1987; Palmer 1996). It is likely that both musical and nonmusical (biomechanical) principles affect the relationship between musical sound and the movements that produce it; we attempt to disentangle the different principles at work by drawing comparisons across instruments.

We examined clarinetists' finger movements during performance to address three questions: How do finger movements change with tempo in clarinet performance? How are finger movements related to tone onsets? And how do finger movement combinations change the timing of performance? In the study described below, skilled clarinetists performed simple melodies while finger movements were measured with motion capture techniques and sound was recorded. Clarinetists performed the same melody at a variety of tempi, to test the generalizability of previous findings that pianists raise their fingers higher at faster tempi (Dalla Bella & Palmer, 2004; Palmer & Dalla Bella, 2004). Finger height above the clarinet keys was measured before the finger's arrival on the keys (before an attack) and as fingers released keys (after a release), the two types of movement that produce pitch changes in clarinet performance. If finger movement properties arise directly from sound control, then clarinetists' performances may not show the same relationship between finger height and tempo as in piano performance, due to the fact that air is responsible for clarinet sound production. Alternatively, if changes in finger height arise from biomechanical (non-musical) constraints, then finger heights should increase at faster tempi, similar to effects in piano performance.

2. METHODS

Eight musically trained clarinet performers (mean = 10 years of private instruction) performed on their own A-clarinets. The melodies were isochronous and contained 6-8 eighth-notes each; they were designed to manipulate particular finger sequences of alternating down / up finger attacks and releases. Here we describe performances of a melodic sequence which contained the following cyclical order of finger movements: (Index Finger, Index + Middle, Index + Middle + Ring, Index + Middle). Each set of finger movements produced a single pitch, regardless of the number of fingers involved.

Each clarinetist performed the melodies at three tempi of 68, 120, and 200 beats per minute (corresponding to 441, 250, and 150 ms interonset intervals, IOI, respectively). A metronome continuously indicated the tempo at which the melody should be played; the metronome sounded on every other tone (every quarter-note). Each melody tone required the use of one of the finger combinations listed above in one of two directions of motion relative to the clarinet keys (Up / Down). These variables: tempo, individual finger (Index, Middle or Ring), finger pattern, and direction of motion, were combined in a within-subjects design.

On each trial, clarinetists were presented with the melodies in music notation and were asked to continuously repeat the melody and to slur their performances (using no tonguing), breathing as needed at the end of a cycle of the repeating melody. Cycles immediately before or after each breath were excluded from analysis. Each clarinetist performed the melody for a minimum of 10 cycles within a trial, and two trials were performed at each tempo. The finger positions above the clarinet keys were measured from the motion data, and the interonset intervals were measured from the sound recording.

The finger motions were captured using a 3020 Optotrak active marker system, with 4 infrared markers attached to the clarinetists' fingertips on each hand (excluding thumbs) and 4 markers on the clarinet (placed to measure the plane of the clarinet keys, so that finger height could be measured perpendicular to that plane). Figure 1 depicts an example of the marker placement on the clarinetists' fingers. Motion was recorded at 167 Hz and sound was recorded at 40 kHz and was synchronized with the motion capture measurements.

Figure 1: Example of marker placement on fingertips of clarinetist.

The onset timing of individual tones was determined from the acoustic recording, using autocorrelation techniques (Boersma & Weenick, 1996) that detected large changes in the frequency with highest amplitude. Those tone onset times were marked in the motion data as well. Analyses of the finger motion trajectories were conducted with functional data analysis techniques (Ramsay & Silverman, 2005). Occasional missing values due to occlusion factors were replaced with linear interpolation. B-splines were then fit to the discrete data as it contained nonperiodicities. Order 6 splines were fit to the second derivative (acceleration), and the data were smoothed using a roughness penalty on the fourth derivative (lambda = 10^{-16}), which allowed for control of the smoothness of the second derivative. The smoothed data were interpolated between each tone to contain 80 equally spaced observations.

Figure 2 depicts the melody (in music notation) and one performance in terms of finger height above the clarinet keys for the Index (blue), Middle (green), and Ring fingers (red); the pitch information extracted from the acoustic recording is indicated in purple at the bottom. The vertical lines indicate the tone onsets extracted from the pitch information; the 0 height values indicate the fingers positioned on the clarinet keys.

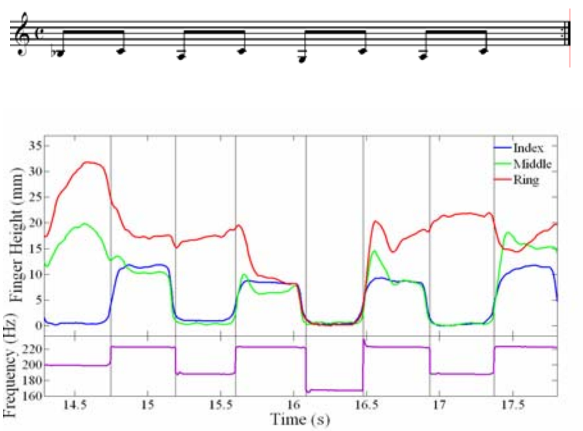

Figure 2: Example of a clarinetist's finger heights above clarinet keys for Index, Middle, and Ring fingers during a slow performance (68 bpm) of the melody indicated in notation; pitch (in Hz) shown below.

3. RESULTS

Clarinetists' timing of successive tones, measured by the interonset intervals (IOIs) between tones, was highly accurate for each tempo condition; the mean IOIs were 442 ms, 249 ms, and 149 ms in the 441ms, 250 ms, and 150 ms tempo conditions, respectively. Although there were no differences in IOIs across the three fingers, the direction of motion did influence timing ($F(1, 7) = 51.1$, $p < .01$); IOIs were longer on average (15 ms) following fingers being raised upwards off the clarinet keys than they were following fingers being moved downward toward the keys. The timing differences due to direction of motion were larger for IOIs that followed multi-finger attacks and releases (Index+Middle+Ring fingers) than for those following single-finger attacks and releases (Index finger alone) ($F(2, 14) = 14.8$, $p < .01$), suggesting two influences of physical motion on temporal accuracy: direction of finger motion and number of fingers.

Finger motion was examined in terms of finger height above the clarinet keys in the plane perpendicular to the clarinet. First we examined finger height in terms of tempo effects on individual fingers right before they pressed clarinet keys, for comparison with the piano performance findings. Analyses of the local maximum finger height (the nearest height greater than adjacent values, in mm) in the IOI prior to each pressed pitch event indicated significant effects of the performance tempo ($F(2, 14) = 10.75$, $p < .01$). As shown in Figure 3, fingers were raised higher at faster tempi, similar to previous findings in piano performance and tapping tasks. Differences across tempo interacted with finger used ($F(4, 28) = 4.3$, $p < .01$); the difference across tempo conditions was larger for the Ring finger than for other fingers (wrist rotation may have contributed to differences across fingers).

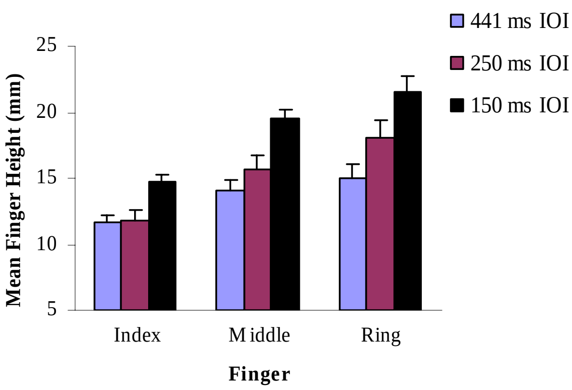

Figure 3: Mean finger height by finger and tempo condition.

We addressed further how clarinetists' finger heights differ in terms of the direction of motion. Differences in the timing of interonset intervals following upward and downward finger movements, reported above, suggest that upward and downward finger motions might differ in the extent of their motion. We therefore investigated whether finger heights differed before key depresses (in downward movements) or after key releases (in upward finger movements) (this analysis was conducted on finger movements for melodic events preceded by a downward motion or followed by upward motion, but not both). As shown in Figure 4, finger height increased slightly from downward to upward finger motions across tempi ($F(1, 7) = 4.44$, $p = .07$), but this difference only reached significance in slower tempo performances ($F(2, 14) = 4.56$, $p < .05$). Larger-amplitude finger movements following release of fingers from keys coincides with the significantly longer timing of tones following releases reported above, and suggests that it takes longer to control and execute finger releases in clarinet performance than to control their arrival on clarinet keys. Thus, the direction of finger motion affected both finger height and the timing of tones in clarinet performance.

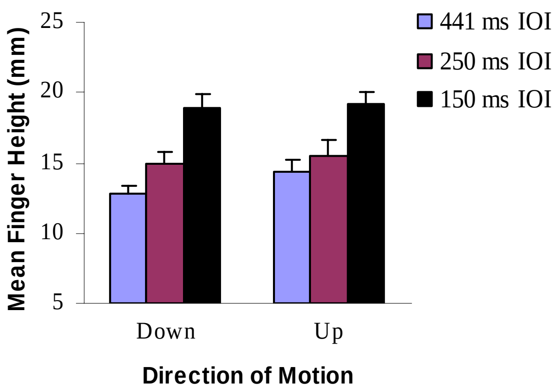

Figure 4: Mean finger height by direction of motion and tempo condition.

Another biomechanical principle that affects rapid finger motions in piano performance and tapping is finger coupling, or non-independence among physically adjacent fingers (Hager-Ross & Schieber, 2000; Slobounov, Johnston, Chiang & Ray, 2002). Coupling can cause interdependencies among finger motions; for example, consider the effects in Figure 2 of the Middle finger (green line) on the Ring finger (red line) during the first two melodic tones (when neither finger is pressing or releasing a key); they show similar movements while another finger (Index) is pressing a key. These fingers are typically coupled or less independent in motion in many tasks (Hager-Ross et al, 2000; Loehr & Palmer, 2007). When the Index finger (blue line) and Middle finger (green line) press the keys simultaneously to produce the third melodic tone, the Ring finger (red line) shows some downward movement coincident with the downward movement of its physically neighboring fingers. The combinations of finger movements used by clarinetists thus offer an opportunity to test coupling effects on finger heights.

Figure 5 depicts the mean height of the Index finger across tempo conditions when its motion alone produced the pitch change, compared with when it combined with other finger movements to produce a pitch change. Analyses of finger height indicated a significant influence of single / combination movements ($F(2, 14) = 13.74$, $p < .01$) and a significant interaction with tempo condition ($F(2, 14) = 5.31$, $p < .05$). The more fingers that moved together to produce the pitch change, the closer to the clarinet keys the Index finger stayed; this is consistent with previous findings that finger movements are non-independent and can constrain the possible movements of surrounding fingers. Figure 5 also indicates that the influences of tempo on finger height were most evident when multiple fingers were involved (I+M+R movements). Thus, biomechanical influences of the fingers on individual finger motions change in nonlinear ways with performance tempo.

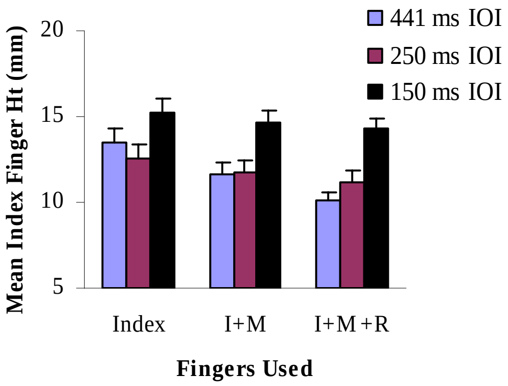

Figure 5: Mean height of Index finger, by finger combinations used and tempo condition.

4. SUMMARY

Skilled clarinet performance is characterized by rapid, fluent sequences of finger movements which have direct consequences for the temporal control of performance. Even movements that do not directly control sound properties of performance, such as clarinetists' maximum finger heights, have acoustic consequences. Some aspects of musical motion are counter-intuitive, such as the fact that musicians use larger movements at fast tempi despite pedagogical considerations that performers should conserve energy during difficult fast passages. Musical motion is influenced by body properties that follow physical principles, such as finger coupling that may reflect kinematic relationships of mass-spring models (that do not conserve energy the same way when amplitude of motion is increased at faster tempi), as well as musical considerations. Thus, comparisons across musical instruments may be crucial for indicating which movement aspects are important for sound control and which are shaped by other biomechanical aspects of the human body and the musical instrument.

Performance on a variety of musical instruments demonstrates aspects of articulation that affect both the motion and timing of performance. Similar to coarticulation in speech, this approach provides some answers to the question of which gestures give rise to movement segments that map on to acoustic aspects of the tones produced. Biomechanical factors, such as coupling between fingers, can influence both the motion characteristics and the resulting sound. We were able to attribute the relationship between finger heights and tempo changes to biomechanical features of fingers because the relationship is similar across changes in the musicians studied (pianists and clarinetists), the physical instrument, and finger height's consequences for acoustic properties of sounded tones. Also of interest is whether vocal articulations reflect similar biomechanical constraints that influence song and speech; study of movement combined with acoustic analyses makes it possible to investigate whether the human body shapes music in the same way as speech.

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6. REFERENCES

1. Boersma, P., & Weenick, D. (1996). PRAAT, a system for doing phonetics by computer, version 3.4. *Institute of Phonetic Sciences of the University of Amsterdam, Report 132*. 182.
2. Dalla Bella, S., & Palmer, C. (2004). Tempo and dynamics in piano performance: the role of movement amplitude. In SD Lipscomb, R Ashley, R.O. Gjerdingen, & P.Webster (Eds), *Proceedings of the International Conference on Music Perception and Cognition* (pp.256-257). Adelaide, Australia: Causal Productions.
3. Dalla Bella, S. & Palmer, C. (2006). Personal identifiers in musicians' finger movement dynamics. *J Cog Neurosci, 18*, G84.
4. Friberg, A. & Sundberg, J. (1999). Does music performance allude to locomotion? A model of final ritardandi derived from measurements of stopping runners. *J Acoust Soc Amer, 105*, 1469-1484.
5. Gabrielsson, A. (1987). *Action and Perception in Rhythm and Music;* Stockholm: Royal Swedish Academy of Music.
6. Hadcock, P., Ronkin, B., Benoit, A., & Burlingame, M. (1999). *The working clarinetist.* Cherry Hill, NJ: Roncorp.
7. Hager-Ross, C. & Schieber, MH (2000). Quantifying the independence of human finger movements: Comparisons of digits, hands, and movement frequencies. *J Neurosci* 20:8542–8550
8. Loehr, J., & Palmer, C. (2007). Cognitive and biomechanical influences in pianists' tapping. *Exp Brain Res, 178,* 518-528.
9. Palmer, C. (1996) Anatomy of a performance: Sources of musical expression. *Music Perc, 13,* 433-454.
10. Palmer, C., & Dalla Bella, S. (2004). Movement amplitude and tempo change in piano performance. *J Acoust Soc Amer, 115*, 2590.
11. Ramsay, JO, & Silverman, BW. (2005). *Functional data analysis* (2nd ed). Springer: Berlin.
12. Russianoff, L. (1982). *Clarinet method book II.* London: Collier Macmillan.
13. Slobounov, S., Johnston, J., Chiang, H., & Ray, W. (2002). The role of sub-maximal force production in the enslaving phenomenon. *Brain Res*, 954, 212–219.
14. Sundberg, J. (2000). Four years of research on music and motion. *J New Music Res, 29*, 183-185.