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PAPER

Striking movements: A survey of motion analysis of percussionists.

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Abstract: Like all music performance, percussion playing requires high control over timing and sound propterties. Specific to percussionists, however, is the need to adjust the movement to different instruments with varying physical properties and tactile feedback to the player. Furthermore, the well defined note onsets and short interaction times between player and instrument do not allow for much adjustment once a stroke is initiated. The paper surveys research that shows a close relationship between movement and sound production, and how playing conditions such as tempo and the rebound after impact affect the movements. Furhtermore, I discuss differences in movement organization, and visual information from striking movements.

Keywords: drumming, percussion, music performance, movement analysis, movement strategy, timing

PACS number: 43.75.Hi, 43.75.St

1. Introduction

Professional percussionists train extensively to acquire the movement skills needed for detailed control of timing and sound production. Most of these movements appear to be primarily aimed at sound production, and the movement amplitude and sound characteristics are closely linked. The visual information from these movements also provide additional information on timing, and may also influence the perception of the sound.

In this paper, I survey research on movements in percussion playing, give examples of movement strategies, and discuss how professionals use movements to control their sound and timing. At present, most of the work done on movements in percussion playing has focused on playing with mallets or drumsticks, something that is reflected in this review. In section 2.1., I give a brief overview of characterstic traits of percussion playing, and present some of the more important aspects of stick control. I then continue to discuss how this control is influenced by the playing context and rhythm (sections 3 and 4), discuss how grip can influence the sound of a stroke (section 5), and how skill level influence performance (section 6). I end with a brief survey of research showing how the visual information from striking movements can influence our perception of a performance.

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2. Playing percussion

Characteristic of percussion playing is that the duration of the excitation is short, typically producing impulse-like sounds with well-defined note onsets. A player's direct contact with the instrument can be very brief. Typical contact durations between drumstick and drumhead are 5–8 ms for a mezzoforte stroke at the center of a tom tom [1] or snare drum [2]. This implies that whatever striking force and dampening effect a player is aiming for needs to be integrated in the entire striking movement. A player's movement defines the velocity and effective mass at impact, and the same striking gesture will also determine the contact duration. As might be expected, these striking gestures differ considerably with each specific instrument and context. For instance, the playing technique used for indian tablas (played by fingers in a sitting position), is very different from what is needed when playing multiple tenor drums in a marching band (played with drumsticks or mallets while walking).

The sound level and timbre of a drum stroke is related to the history of the force pulse from the contact. A brief force pulse with high amplitude generates a rich spectrum with many partials. This can be achieved with the bare hands. However, by using an implement like a mallet, stick, or hammer, the player can excite an instrument more vigorously (through a higher striking velocity) than would be possible using only the hand. By changing the shape, weight, and hardness of a mallet, it is also possible for a percussionist to alter the timbre of the sound when playing (something that otherwise can be difficult for many types of percussion instruments).

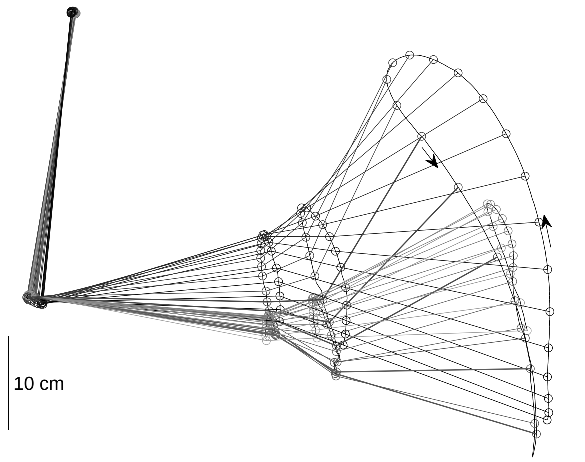

Fig. 1 Arm, hand, and stick trajectories during a stroke. Movement trajectories of markers attached to a player's shoulder (upper left), elbow (bottom left), wrist , hand, and stick (rightmost loop) are seen during one mezzoforte stroke at 50 beats per minute. The "stickfigure" is made by straight lines connecting the markers every 25 ms. The preparation for the stroke starts with the hand moving upward and the stick following (see upward arrow). After reaching the preparatory height, the actual downstroke starts (downward arrow) and the stick quickly gains velocity. After the impact the rebound from the drum moves the stick up for another, smaller loop.

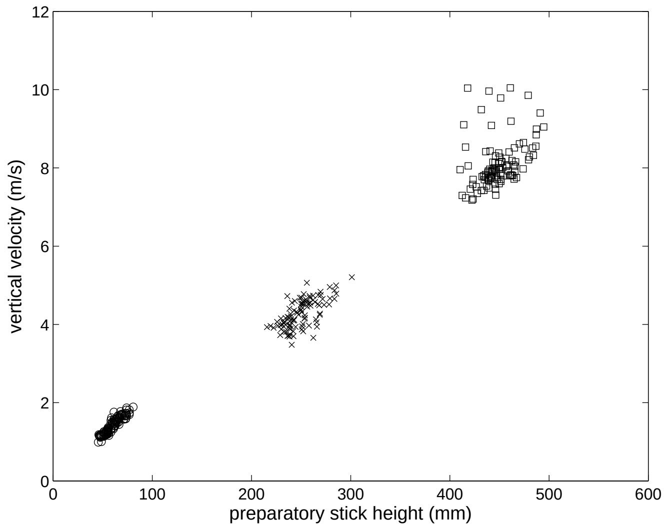

Fig. 2 Preparatory heights and striking velocity used by a professional player. The peak velocities of a marker at the tip of the drumstick just before impact are plotted against the preparatory heights for strokes at 120 beats per minute at three different dynamic levels: *p* (circles), *mf* (crosses) and *f*(squares). The strong relationship between preparatory height and striking velocity is clearly seen. When playing at louder dynamic levels the stokes are initiated from a greater distance compared to strokes at soft dynamic levels.

2.1. Initiating a stroke

A single stroke begins by the lifting of the drumstick to a height at which the actual downstroke is initiated. This *preparatoy movement* can be seen in Figure 1, which shows the positions of markers attached to a player's shoulder, elbow, wrist, knuckle and at the tip of the drumstick during a stroke at mezzoforte at a slow tempo. The movement is initiated from the wrist, but the magnitude of the movement is largest for the drumstick marker (rightmost loops with circles). As indicated by the arrows, the hand lead the upward movement with the stick lagging behind, tip pointing down. As the stick approaches the maximum vertical displacement, its *preparatory height*, the hand initiates the downstroke, flicking the stick down towards the drumhead. By letting the wrist lead the motion, the player can use the time available before the stroke to create a "runway" for the stick to be accelerated at low physiological cost.

The smooth, wavelike characteristics of this kind of "whiplash" movement is described in books on playing technique (e.g. [3–5]); and observed in studies on movements of drummers using motion capture (e.g [6–9]). However, the precise playing strategies used to accelerate the stick can vary considerably between players (c.f. [6, 7, 10, 11]).

The preparatory height to which a player lifts the drumstick and the dynamic level of the stroke to be played are related. Strokes at higher dynamic level are initiated from a greater height compared to softer strokes, when there is enough time between strokes to do so. Although different players may interpret dynamic levels as having different loudness, there is a clear relationship between preparatory height and striking velocity at impact [7]. This relationship is illustrated in Figure 2, where preparatory heights and striking velocitys for strokes at three different dynamic levels are seen.

2.2. The rebound

Playing with an implement makes it possible for a player to excite an instrument with more force than the bare hands. If held in a relaxed grip, the stiffness of a drumstick also allows the player to use the *rebound* from the impact. A normal drumhead is elastic, which allows the drumstick to move "on its own." At slow tempi, and for single strokes the effect of the rebound on the drumstick movement is easily observed. Figure 1 shows how the stick abruptly changes movement direction after the hit and completes a smaller loop.

This feature of producing several impacts per stroke movement is something that players spend much time learning to control. If the time between strokes is too long the player has to initiate each stroke from the very beginning, lifting the stick anew. At faster playing, however, the rebound is incorporated in the preparatory motion for the following stroke (c.f. panels in Figure 3).

Because of the rebound, a single striking gesture can result in several hits, as has been reported for swing patterns [12]. In fact, detailed control of the interaction between implement and instrument is a prerequisite for playing rolls and other complicated two-hand patterns. Without utilizing the stiffness of the drumstick and the elasticity of the drumhead it is not possible to play fast patterns like closed rolls (with clusters of up to six hits per stroke reported [13]). However, there may also be cases when a player needs to actively control the effect of the rebound. For instance when players have to play strokes at different dynamic levels, as in the case of accents (see [7]).

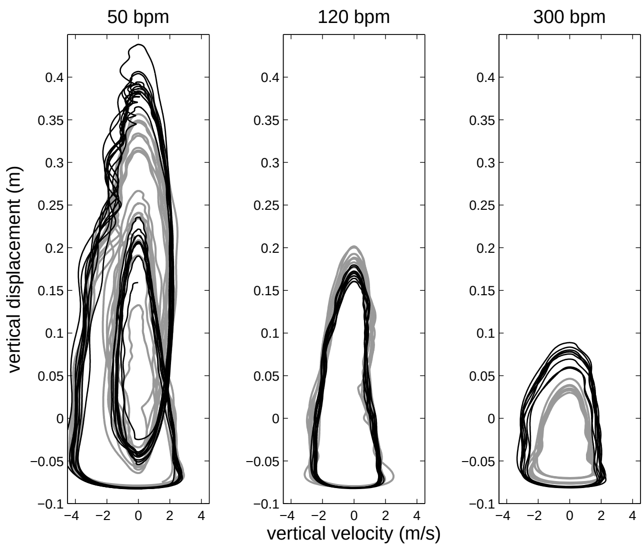

Fig. 3 Vertical displacement vs. vertical velocity for the same player as in Figure 1 playing mezzoforte strokes at three tempi. The panels show phase plots of the drumstick marker played with the left (grey) and right (black) arm at slow, medium, and fast tempi (left, middle, and right panel, respectively). The ample time (1200 ms) between strokes at 50 beats per minute allows for the rebounding stick to complete an extra loop. At higher tempi, the rebound becomes incorporated in the preparation for the nextcoming stroke. Similarly, the reduced time for preparation between strokes at higher tempi can be traced in the reduced magnitude of the vertical displacement of the stick marker compared the slowest tempo.

3. Influence of playing context

Despite the observed large inter-variability of playing strategies between players, a player's own strategy tends to be used consistently. Each movement strategy is, however, adjusted slightly to fit the playing conditions at hand. A player is often expected to perform the same rhythmic pattern using mallets having different properties, and playing on surfaces that respond very differently. Thus it makes sense for a percussionist to use a playing strategy that can be adjusted to the differences in feedback from the instruments and the mallets.

Players adjust the striking velocity according to the surface they play on. Dahl [7] compared striking velocities for strokes on different surfaces attached to a force plate (soft, normal, and hard). In general, players reduced striking velocity when playing on the hard surface as compared to normal. By comparison, the soft surface resulted in an increase in striking velocity.

For strokes at the same dynamic level, there is an influence of tempo on movement characteristics, and preparatory heights. Figure 3 shows an illustrative example, where phase plots of vertical displacement and vertical velocity are seen for mezzoforte strokes at three extremely different tempi. Comparing the magnitude of the vertical displacement between the three panels, we clearly see how preparatory height decreases with increasing tempo. At faster tempi a player has less time for preparation between strokes, and must sometimes reduce movement magnitude to deliver each stroke on time. An analogy can be made with the bouncing of a ball. Bouncing a ball at a high rate with large amplitude is quite demanding, but becomes much easier if one moves closer to the ground and reduce the amplitude.

4. Rhythmic patterns

Most musical rhythms include notes of different time intervals and played with differing emphasis, e.g., accents. One way to emphasize a note is to play it louder. To play one stroke louder than its neighbouring strokes, however, a player needs to prepare for it.

Studying preparatory movements for accented strokes, Dahl [7] found interactions between overall dynamic level and emphasis on the accented stroke. In the study, four players performed an ostinato pattern, with an accent every fourth stroke, at varying combinations of dynamic level, tempi and striking surface. All players initiated the accented stroke by lifting the stick to a greater height compared to unaccented strokes. However, they clearly displayed different movement strategies in their preparatory movements and different emphasis of the accented stroke relative to the unaccented strokes. In some cases, the preparation

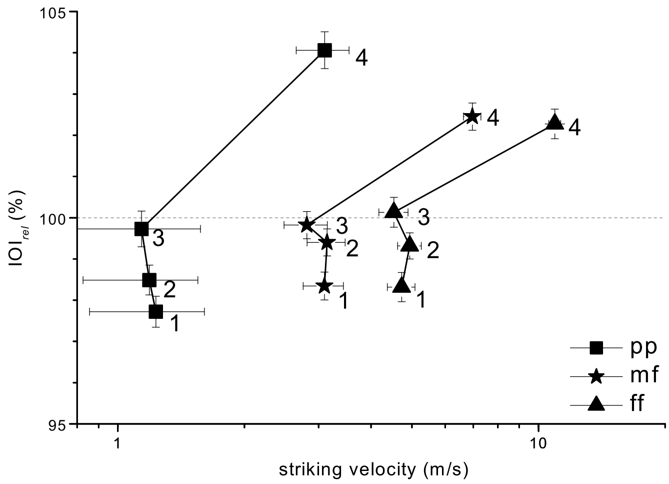

Fig. 4 Change in striking velocity and relative timing IOI_{rel} for an ostinato with an accent every fourth stroke. Each data point in the figure represents 288 analyzed strokes at each of four different metric locations (numbered 1, 2, 3, and 4) and three dynamic levels: *pp* (squares), *mf* (stars) and *ff* (triangles). The values are grand averages across four players and three tempi, the 95% confidence intervals are indicated by error bars. The actual velocity at the tip of the drumstick is estimated to be about 30%higher. As seen in the figure, the increase in striking velocity for the accented stroke is by about a factor of 2 for all the dynamic levels. The lengthening in IOI_{rel}, however decreases with increasing dynamic level [7].

started as early as during the previous (unaccented) stroke. The rebound ensures that the drumstick does not stay in contact with the drumhead and the player can take advantage of this and start the preparation earlier. Thus, the hand moves upward with the stick pointing down already during the third, unaccented stroke, reducing the striking velocity at this impact.

Dahl [7] found that players emphasized the accented stroke by increasing the striking velocity, but also by delaying the nextcoming strokes. Figure 4 shows the change in striking velocity and relative inter-onset-interval for accented strokes. In the figure, ensamble averages of striking velocity and relative time between strokes at the four different metrical locations in the pattern: 1, 2, 3, and 4, with the 4th interval beginning with an accented stroke. The 4th interval was prolonged more by the players at soft dynamic level compared to louder playing. The increase in striking velocity for the accented stroke was about a factor of two at all dynamic levels. We clearly see the reduced striking velocity for the stroke preceding the accented stroke (metric location 3).

Another example of different emphasis of strokes is found in the common rhythmic swing pattern used in jazz music. The swing pattern is normally played on a cymbal, with the emphasis on the second beat. Waadeland [9] investigated the movement patterns used when the emphasized stroke was altered in the pattern. He found changing preparatory heights depending on which beat in the swing pattern the player was asked to emphasize. The second beat, however, retained some emphasis, also when other beats were to be stronger.

5. Control of contact force and sound characteristics

As noted in section 2.1., the duration and shape of the contact force between drumstick and drumhead is the major factor affecting the sound. Because the contact time between drumstick and drumhead is in the range of milliseconds, a player has no time to consciously change anything during the actual time of contact. Thus, the sound is determined from the stick's movement during the downstroke. Like in golf, a player's grip becomes a crucial part of the control.

Typically, a percussionist or drummer will grip the drumstick or mallet so that it is free to rotate around a fulcrum point, most commonly between the thumb and index finger. In this way, the stick is free to rotate in the vertical plane, but the player can use the other fingers to stabilize or lock it if needed. In some cases there is a need to tighten the grip to stabilize the stick, for instance to restrain a rebound when the next stroke is to be played at a softer dynamic level than the current one.

If a player tightens the grip of the stick during a stroke it should affect the sound. In recent work, Dahl and Altenmüller [17] investigated the effect of restraining the rebound after a stroke. Stick movements, force, and sound characteristics were measured for 'normal' strokes, where the player let the drumstick rebound freely from the surface, and 'controlled' strokes, where the player was instructed to stop the stick as close as possible to the drumhead after each stroke. The controlled stroke instruction was to simulate a playing technique used to prepare for a stroke at softer dynamic level (see e.g. [5]).

Motion capture analysis confirmed that the player differentiated between the two types of strokes. As expected, the change in grip needed to restrain the rebounding stick also affected the interaction stick – drumhead, resulting in different sound characteristics between the two types of strokes. In a listening test, the controlled strokes were rated as having less full sound compared to the normal strokes. Perhaps somewhat counter intuitively, the controlled strokes overall displayed shorter contact duration and higher peak force compared to the normal strokes [17].

6. Influence of handedness, skill, and movement related disorders.

Several studies report clear differences in movement control between players of different skill. Trappe et. al. [8] found the movement patterns of professional players to be flexible and whiplash-like. Similar patterns were found for students, but calculated angles between segments revealed less control of the drumstick compared to the professionals.

Differences in movement strategies have also been reported in studies of muscle activity during playing. Fujii *et al.* [15] used electromyogram (EMG) to compare muscle activity for drummers and nondrummers during 12 s fast playing on a force plate. The drummers displayed less timing variability compared to nondrummers. Furthermore, drummers also had lower level of co-contraction compared to nondrummers. That is, less overlap between antagonist muscle groups indicating a more efficient recruitment of muscles. Measurements of the world's fastest drummer (producing average inter-onset intervals of 100 ms) displayed a high level of control with wrist flexors and extensors quickly alternating their activity with little overlap [14].

All participants in the study by Fujii *et al.* were right-handed and, on average, the tapping rates were slower for the left (non-preferred) hand. Tthe drummers displayed less difference between the hands than did the non-drummers [14].

Professional percussionists are required to perform the same type of rhythmic patterns with both hands, something that can be demanding with increasing tempi and level of difficulty. In Figure 3 the motion for the left (grey line) and the preferred right hand (black line) can be seen to differ more at fast compared to slow and medium tempi.

Fujisawa and Miura [16] investigated EMG for amateur drummers and nondrummers playing single strokes on a drum for three minutes at different tempi. By comparing the average EMG for the first and the last minute, they concluded that nondrummers had significantly higher mean EMG during the last minute of playing more often (72% of trials) than did the trained drummers (42% of trials). According to Fujisawa and Miura, these results indicate that trained drummers can maintain relaxed playing and play with less strain compared to non-drummers.

6.1. Musician's focal dystonia

In unfortunate cases professional players can display considerable co-contraction between wrist flexors and extensors. Musician's cramp, or focal dystonia can be defined as a painless, involuntary loss of motor control. Dystonic players display symptoms such as muscle cramp and tremor, typically at more demanding playing conditions such as loud and fast playing.

In recent work, Dahl and colleagues [18] investigated movements and timing control for professional percussionists without symptoms, and players with the left arm affected by focal dystonia. Movement and timing during single stroke playing at different dynamic levels and tempi were analyzed. For both healthy and dystonic players, variability in timing and peak acceleration was higher at the more extreme tempi. The maximum timing variability occured for piano strokes at 300 beats per minute, performed with the non-preferred (affected) hand. At this fast tempo, the dystonic players displayed considerable stiffening in the forearm, resulting in frequent errors and unintended extra bounces. However, when the more extreme errors were removed, the variability in main inter-onset intervals were comparable to that of the healthy players. This despite the considerable distrorted movement patterns at the highest tempo for the dystonic players.

7. Visual communication

The strong relationship preparatory height–striking force (c.f. Figure 2) and the influence of movement on sound characteristics discussed in section 6, imply that the striking movements are closely linked to sound production. However, the striking movements also play a role in the visual communication between performer and listener. Many studies have confirmed that observers are able to recognize the expressive intent based on the visual information. A few of these studies have used video filmed marimba performances [19, 20].

Broughton and Stevens reported that observers rated a 'projected' (public performance expression) solo performance as more interesting and expressive when presented in audio-visual mode, compared to audio only [20]. Performances made in a 'deadpan' manner, with minimized expressive features, received lower ratings of interest and expressivity in the audio-visual compared to the audio only mode.

Dahl and Friberg showed that also specific emotional expressions can be communicated through movements only [19]. In their study, the actual sound producing movements of hands and mallets was found to be of minor importance for the communication of expressive intention between performer and audience. Instead, movements of the head and in the upper part of the body played a more prominent role in the expressive communication [19]. Again, this is hardly surprising considering that the hand movements of musicians typically are constrained to the production of notes.

There are, however, examples of mallet movements affecting the perception of a performance. Schutz and Lipscomb [21] found that the perceived duration of marimba strokes was longer when observers saw the strokes played with long gestures, compared to short gestures. That is, although the note duration was equal, strokes where the vertical distance 'up - down' covered by the mallet was large were rated as having longer duration compared to strokes played with a 'short' gesture. One would perhaps expect the preparatory height to have an influence on the multisensory information. Interestingly enough, a later study showed the gesture *after* the actual impact to be more important for how long the notes were rated to be [22]. Thus, although a percussionist cannot prolong the played note as such, the long gesture after impact can still make it sound longer.

8. Concluding remarks

With this paper I have given an overview of research on percussionists' movements. Drum strokes can be considered discrete events, separated in time, but they are typically linked together by continuous motion. In order to deliver a stroke on time, its preparation may be initiated as early as during the previous stroke. The feedback and rebound from the instrument also affects the preparation for nextcoming stroke, something that skilled players can take advantage of. Furthermore, the striking movements can also convey visual information on expression and timing to observers.

Compared to the playing movements of other instrumentalists, percussion movements are typically both larger and faster. The fast movement of a drumstick or mallet during playing makes it difficult to study the motion, for both performer and observer alike. Displays of stick movement can therefore be very helpful for students of percussion to understand the mechanics of a stroke. An early example of motion display for didactic purposes can be found in [4], where still images from filmed playing are used to describe techniques for different types of strokes.

With the recent advance in motion capture technology, it is now possible to study the interaction between percussionist and instrument in more detail. Because of the high velocities of a drumstick at impact, sampling rates of 400 Hz or more may be necessary for fast strokes (for most human movements, 100 Hz would be sufficient). However, additional research is needed to fully understand the link between movement control and sound production. Currently, most studies using motion capture have focused on isochronous intervals or fairly simple rhythm patterns played with one or two hands on a single surface. By comparison, a drumset player typically use all four limbs to playing complex rhythmic patterns, sometimes reaching large distances to play on a multitude of instruments. Clearly, a playing technique is required that enables the player to deliver strokes on time at low physiological cost in order to keep playing during a full concert [23].

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