ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 90 (2004) 762 – 776

Playing the Accent - Comparing Striking Velocity and Timing in an Ostinato Rhythm Performed by Four Drummers

S. Dahl
KTH Speech, Music and Hearing, Royal Institute of Technology, Stockholm, Sweden

Summary
Four percussion players' strategies for performing an accented stroke were studied by capturing movement trajectories. The players played on a force plate with markers on the drumstick, hand, and lower and upper arm. The rhythmic pattern – an ostinato with interleaved accents every fourth stroke – was performed at different dynamic levels, tempi and on different striking surfaces attached to the force plate. The analysis displayed differences between the movement trajectories for the four players, which were maintained consistently during all playing conditions. The characteristics of the players' individual movement patterns were observed to correspond well with the striking velocities and timing in performance. The most influential parameter on the movement patterns was the dynamic level with increasing preparatory heights and striking velocity for increasing dynamic level. The interval beginning with the accented stroke was prolonged, the amount of lengthening decreasing with increasing dynamic level.

PACS no. 43.75.St, 43.66.Mk, 43.75.Hi

1. Introduction

Mastering rhythm and tempo requires a playing technique, which can be adapted to the feedback from the instrument. Percussion playing in general requires that the player perform the same rhythm on several different instruments with different physical properties (e.g. the stiffness of the drumhead and the mass, hardness, and shape of the mallet). The instruments are also positioned at varying distances from the player who has to plan the movements in order to reach the right spot at the right time. In view of this it could be assumed that even simple elements in percussion playing need some kind of preparation in order to be well performed. The scope of this study was to identify and analyze strategies that skilled players use when performing an accented stroke interleaved in a steady rhythm.

There are many examples of how expert athletes and sportsmen develop movement strategies that distinguish them from less skilled practitioners (see [1] and [2] for examples of skilled movement patterns). An example is the way a stroke with a racket or bat is planned and carried out to achieve the highest velocity at impact. A baseball player initiates the stroke from a turned position with one hip facing the approaching ball and the bat positioned at the opposite side of the body. The stroke then starts with a step towards the ball after which the hip, trunk and arm rotate, swinging the bat forward. Strategies used in tennis (when there is enough time for a full stroke), or for pitching are similar; they all aim at prolonging the elongated arc during which acceleration occurs. When hit or release velocity is emphasized the differences between average and excellent hits can be sought in the final adjustments of the grip [2].

Musicians show a variety of carefully prepared strategies in their performances. The way professional string players organize their bowing offers good examples [3]. Generally, loud dynamics require high bow velocity and bow force, and are played rather close to the bridge.

A *sforzando*, consisting of a sudden, loud attack part and a following soft, sustained part, needs a more intriguing bowing strategy. The loud and short attack part is played close to the frog and with a short distance to the bridge, using a high bow force and bow velocity. The main control parameter here is the bow velocity, which quickly can be increased to form the sudden start of the sforzando, and quickly reduced to terminate the attack part. Once the soft, sustained part of the sforzando has been initiated, the bow-bridge distance is successively increased, allowing for convenient soft playing. A change in bow-bridge distance takes much longer time than a change in bow velocity and is not suitable for ending the attack part.

There are plenty of other examples of how musicians take advantage of the built-in responses of musical instruments in the performance. In this study the rebound of the drumstick after the hit offers such an example.

Received 5 June 2002,
accepted 5 March 2004.

The questions addressed in the present study were:

1. What kind of strategies are used for performing an accented stroke in drumming?
2. Is this strategy dependent on the playing conditions (dynamic level, tempo, striking surface) and the feedback from the instrument?
3. How does an accent affect timing and striking force?

These questions were answered by studying the performance of four percussionists under different playing conditions, including tempo, playing surface and dynamic level.

The study was divided into three parts;

- an analysis of the movement of the drumstick for four subjects (Section 3)
- an analysis of the striking velocity (Section 4)
- a timing analysis of the performed sequences (Section 5)

1.1. Accents, taps and up- and downstrokes

The definitions of accents vary through the literature.

Parncutt [4] divided accents into *performed* accents that are added by the musician, and *immanent* accents that are perceived as accented even in a nominally performed score (see also [5] for citation). The performed accents frequently coincide with the immanent accents. In a number of studies on music performance, accented tones have been found to be played lengthened, legato (tied to the following note) and with increased loudness (see e.g. [6] [7] [8] [9]).

In drumming, techniques are taught to prepare for a stroke at different dynamic levels. A common way to denote the stroke preceding a sudden change in dynamics is to use the terms *upstroke* (or *pull-out*) and *downstroke* (or *control stroke*). These terms describe the desired final position of (the tip of) the stick in preparation for the next stroke. Together with the term for a soft, unaccented stroke, *tap*, they are commonly used to help the performer plan and carry out the right movements (see e.g. [10] [11]).

Generally, soft strokes will be played with the hand in a resting position about 10 centimeter above the drumhead and the drumstick barely rising above it, "tapping". Before a strong blow, the hand will need to lift the drumstick after the preceding tap, (upstroke), and then deliver the stroke. When strong strokes are repeatedly played the stick is usually allowed to bounce up to full height, *full* (or *free*) *stroke*. If the following stroke is to be a soft tap the stick must end up in the suitable lower position, downstroke. These basic strokes enable the player to execute sequential strokes of different heights. This is a prerequisite for playing various combinations of strokes at different dynamics, including accents.

2. Method

2.1. Subjects

Three professional subjects (S1, S2, S3) and one amateur (S4) participated in the experiments. The professional subjects were all acquainted with different types of percussion instrument, but their experiences (ranging between 20 and 40 years) were from different backgrounds: classical percussion playing in symphony orchestra (S1), drumset playing in jazz bands (S2), and military snare-drum playing (S3). All three subjects were established as teachers in percussion. The amateur (S4) had a 12-year experience of drumset rock playing. All four subjects were right-handed. The subjects were paid a small fee for their participation.

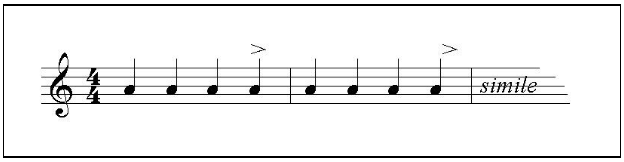

Figure 1. Music notation pattern presented to the subjects including three unaccented strokes (beat 1–3) followed by an accent (beat 4). The sequence was repeatedly played with the right hand during the recording interval (20 seconds).

2.2. Task

The task of the subjects was to perform different versions of a repeated drumming pattern consisting of single strokes with interleaved accents every fourth note (Figure 1). Using the drumming terms described above the pattern could be assumed to be performed as tap, tap, upstroke, downstroke, etc.

The task was presented to the subjects in common music notation. A total of 27 different conditions, consisting of combinations of three tempos, 116, 160, and 200 beats/min (BPM), three dynamic levels *pp*, *mf*, and *ff*, and three striking surfaces: *soft*, *normal*, and *hard*, were recorded for each subject. The nominal beat separation at the three tempi were 517, 375, and 300 ms, respectively. The nominal tempo was indicated by a metronome immediately before each recording sequence. The choice of striking force at the three dynamic levels was left to the subjects.

2.3. Equipment

A schematic picture of the experimental setup is showed in Figure 2. A movement detection system (Selspot) with two cameras was used, recording the motion of four markers. The cameras were both positioned on the players' right side, about two meters above the floor and approximately at about the same distance from the players. Each of the four markers consisted of a cluster of three infrared LEDs positioned in a triangle with an intra-distance of about 5 cm (total weight 6 g). One marker was attached to the drumstick (Vic Firth, American Classic 5B, weight 53 g), and the three other markers on the player's hand, lower and upper arm, respectively. The frontal LED of the drumstick marker (later selected for main analysis) was positioned at distance of 6.5 cm from the tip of the drumstick (total length 40.5 cm). All subjects reported that the attached LEDs and the associated cables did not obstruct their playing. All 12 LEDs were tracked by the system at a rate of 400 Hz (sampling period $T_s = 2.5$ ms).

A custom-designed cylindrical force plate made of dural (diameter 100 mm, height 60 mm, weight 1.1 kg) was used as a substitute for a drum. The plate was divided into two parts, a base and a top, with a force sensing piezoelectric crystal (diameter 15 mm, height 3 mm) mounted in between. The base and top were held together by screws, which also set the preloading of the crystal. During the experiments the force plate was fastened to a 10 kg steel plate.

The force plate had three different striking surfaces; *soft, normal*, and *hard*. The normal surface consisted of an 11 mm thick natural rubber disc with playing characteristics close to a regular practice pad. For the soft condition the force plate was covered by a cushion filled with foam rubber (approx. 80 mm), and in the hard condition only a very thin rubber cover (approx. 0.7 mm) was applied to the force plate.

The signal from the force plate was amplified by a charge amplifier (BK 2635). The amplified force signal was recorded on DAT tape together with a synchronization signal from the movement analysis equipment. The force plate was calibrated by observing the step in the force signal when a weight with known mass was removed abruptly.

The sound at impact as the stick hit the force plate with the normal surface was rather soft, about 50/75 dB(A) for unaccented/accented strokes at mf, compared to about 80/105 dB(A) when playing on a snare drum (snares released).

2.4. Procedure

The subjects were seated on an ordinary drum stool and given sufficient time to acquaint themselves with the settings and equipment before the recording session started. When starting a recording sequence, the subject took up a reference position, holding the stick in resting position in the right hand with the tip in contact with the striking surface. A metronome with click sounds, giving the nominal tempo, was turned on. The metronome was left sounding until the subject indicated, with a nod, to switch it off. After the metronome was switched off the movement analysis recording was initiated, and upon command of the experimenter the subject started drumming. A 20 s sequence was recorded, corresponding to about 35 strokes at 116 BPM and 65 strokes at 200 BPM. The delay between the moments when the metronome was turned off and the drumming started was less than 5 s.

3. Players' movements

Using the experimental set-up described above, a large quantity of data was collected. The complete data set would allow an extensive movement analysis of the subjects, including angles and rotations of segments. The following analysis is essentially limited to the actual sound-producing part of the movement; the vertical movement of the drumstick.

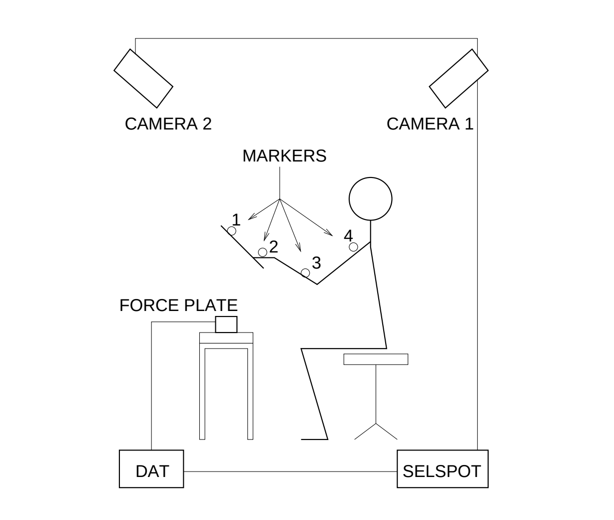

Figure 2. Experimental set-up used in the experiment. The two cameras connected to the Selspot movement capture system detect the positions of the infrared LEDs on the markers. The system recorded the markers three-dimensional positions. The signal from the force plate was recorded by a digital audio tape recorder, which also received a trigger signal from the Selspot system each time a 20-s recording was initiated.

The hypothesis in Section 3 was that the vertical displacement of the drumstick at the initiation of each stroke, the *preparatory height*, would in general be higher for the accented stroke than for the unaccented, across all subjects and conditions. A further objective was to study whether a consistent preparatory movement was maintained regardless of changes in playing conditions, such as dynamic level, tempo and striking surface.

3.1. Method of analysis

In an initial analysis, the registered coordinates from the Selspot system were checked for missing values and outliers, after which the files were exported to Matlab. Missing data were retrieved by interpolation. Outliers were judged individually, and corrected in the critical regions at the hit (see Section 3.3).

Figure 3 shows an example of the trajectories of the four markers on the four players. The excerpt includes approximately four measures at mf, 200 BPM, played on the normal surface. As seen, the movement patterns are dominated by the trajectories of the drumstick. For this reason, the data from the marker on the drumstick was selected for further analysis. Only one LED, the frontal in the marker cluster, was used.

Figure 4 shows a detailed view of the raw data from the marker on the drumstick, giving the vertical displacement z and vertical velocity v (calculated as the first-order derivative). The upper panel displays the path of the drumstick in the air as smooth and wave-like. The abrupt changes of direction defining the hits are seen as sharp

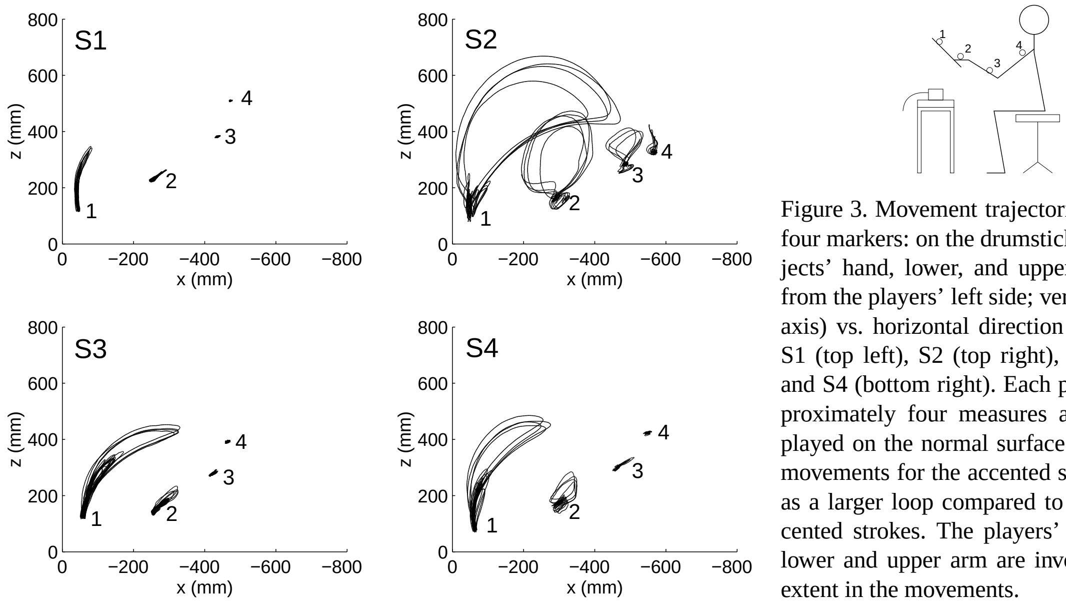

Figure 3. Movement trajectories captured from four markers: on the drumstick, and on the subjects' hand, lower, and upper arm. Side view from the players' left side; vertical direction (z-axis) vs. horizontal direction (x-axis). Subject S1 (top left), S2 (top right), S3 (bottom left), and S4 (bottom right). Each panel includes approximately four measures at mf, 200 BPM, played on the normal surface. The preparatory movements for the accented stroke can be seen as a larger loop compared to that of the unaccented strokes. The players' drumstick, hand, lower and upper arm are involved to different extent in the movements.

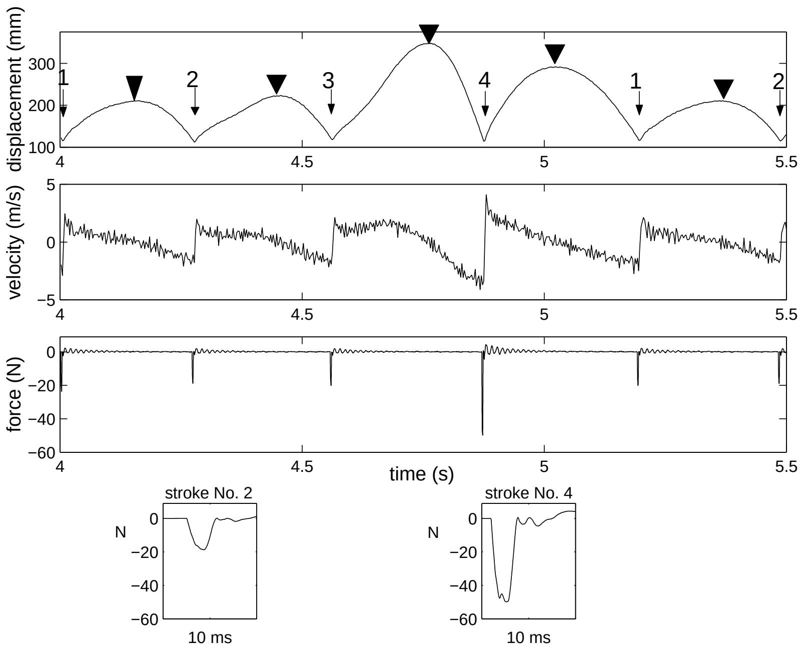

Figure 4. An excerpt of the raw data as recorded for one of the subjects (S1). Vertical displacement of the drumstick marker versus time (upper panel); vertical velocity (second panel); and signal registered by the force plate (third panel). The hits (arrows) and preparatory heights (triangles) are indicated in the displacement plot. The numbers refer to the beats in the rhythm where beats 1-3 are unaccented and beat 4 is the accented stroke. The time scale indicates the time from the start of the recording. Inserted at the bottom are two blow-ups of stroke No. 2 and stroke No. 4, exemplifying the differences in the shape of the force impulse between an unaccented and accented stroke.

dips. The preparatory heights are seen to differ markedly between strokes.

The second panel shows the velocity of the marker, resembling a saw-tooth wave. When comparing the vertical displacement with the velocity it can be seen that initiating the accented stroke from a greater height helps the player to achieve increased striking velocity and force. The effect on the force can be seen in the bottom panels, which shows the shape of the force peaks as recorded by the force plate.

To enable comparisons between recorded sequences, only the first 32 strokes (eight measures) were selected for analysis. Eight was the maximum number of measures available from some of the sequences recorded at the slowest tempo. In three cases, all at pp level, a missing hit in force data made other than the initial eight measures more suitable for analysis.

3.2. Detection of hits

The hits were automatically detected from the displacement and velocity data. First the vertical component of the displacement of the selected marker was sparsely smoothed in order to reduce noise. In order to preserve the definition of the sharp hits, crucial for their identification, the filtering was restrictive. A Savitzky-Golay filter, which performs a least squares linear regression fit of a polynomial over a specified frame size f, was used. In most cases the polynomial order and the frame size were chosen to 1 and 3, respectively, reducing the filter polynomial to a straight-line interpolation over three points.

Subsequently, the velocity was calculated as the first-order derivative. This signal was then filtered using the same algorithm as for the displacement.

The hit-detection algorithm used two criteria for tracking the real hits among minima in the vertical displacement.

1. The height above the striking surface. A fixed threshold was set, below which the local minima must fall in order to qualify as a hit.
2. The change in the vertical velocity v, reflecting the "peakedness" of the displacement curve.

$$v(i) = [z(i+1) - z(i)]/T_s,$$

where $T_s = 2.5$ ms is the sampling period.

$$\Delta vel_1 = [v(i) + v(i-2)]/2,$$
$$\Delta vel_2 = [v(i+1) + v(i+3)]/2,$$

if $|\Delta vel_1 - \Delta vel_2| >$ threshold a hit was detected.

Once a hit had been identified, the highest negative velocity within a time window of 25 ms (equal to 10 samples) before the sample identified as the hit was found. This value was taken as the striking velocity, indicating the excitation strength (see Section 4).

In most cases the algorithm for automatized selection worked satisfactorily. In a few cases where the algorithm overlooked hits, they were easily discovered in a following (visual) inspection of data, and identified manually. In all, 3456 hits (4 subjects $\times$ 3 tempi $\times$ 3 dynamic levels $\times$ 3 striking surfaces $\times$ 32 strokes) were analyzed.

3.3. Data repair and error estimation

As mentioned, one or more LEDs were occasionally obscured from the view of one or both of the cameras, causing gaps and/or outliers in data. These problems usually occurred in connection with the accented stroke (beat No. 4) and most pronounced for subject S2. The primary reason was a rotational movement of the arm or drumstick, usually during the initial part of the preparatory movements. In all, 83 out of a total of 3456 detected hits (less than 2.5%) had outliers or gaps in the data around the hit region that needed repairs. Maximum data gaps at hits were 3 sample points. The gaps in data were interpolated. Outliers were identified manually and corrected to an estimated value.

In order to estimate the error introduced by flaws in data (noise, gaps and outliers), comparisons between different filtering and repairs of data files were made. An estimation of the measurement error in vertical displacement before filtering would typically be ± 0.6 mm in amplitude, reducing to ± 0.3 mm after filtering.

For the calculated striking velocity the estimated error was typically ± 0.3 m/s before filtering, and ± 0.1 m/s after. This corresponds to about 6% of the average velocity at the softest strokes (pp, unaccented strokes). The striking

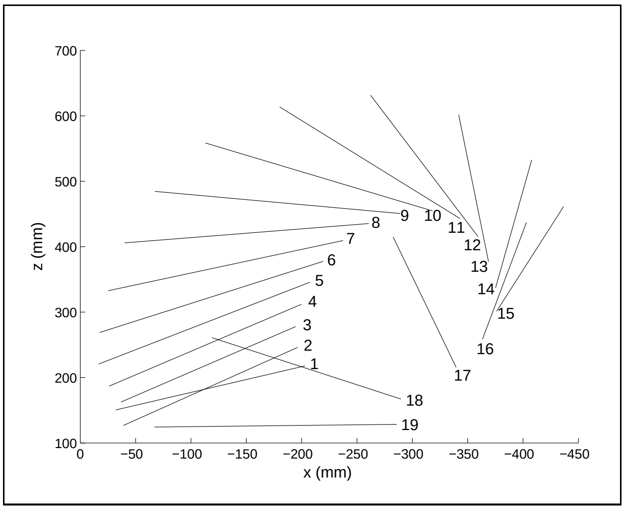

Figure 5. Schematic representation of the movement of the drumstick, obtained from the markers on the drumstick and on the hand. The sequence shows subject S2 during the preparation for an accented blow at mf, 200 BPM on the normal surface. The lines show the relative position of the two markers with a separation of 20 ms between frames. The hand leads the upward movement before the drumstick (frames 1-8), until just before reaching maximum height (9). Then the outer part of the drumstick overtakes and passes the position of the hand, while the hand moves towards the player's shoulder (10-14). From this position the actual downstroke (15-19) is initiated. Note that the upward movement of the hand starts before the hit of the preceding unaccented stroke (beat No. 3), which occurs at frame 2. For a more detailed description of preparatory movements, see [12].

velocities presented in the following analysis were averaged over at least 24 strokes.

The error in time for hit detection was estimated to ± 1 sample (± 2.5 ms). For a worst-case scenario, involving much noise, severe gaps, and an outlier at the moment of hit, the error could reach ± 5 samples (± 13 ms). In these cases also the error in displacement could occasionally be large, reaching ± 5 mm. (It should be noted that the data on timing from the hit detection in the velocity curve was not used in the timing analysis in Section 5. Instead the force signal was used.)

In 19 of the 3456 analyzed strokes (0.5%), the top part of the LED trajectory was obscured so that the maximum in displacement and thus the true preparatory height was missing. The worst case was found for subject S2 playing at ff, 116 BPM on the normal surface where a truncated trajectory generated a preparatory height that was 40 cm lower than the undamaged trajectories in the same recorded sequence. The normal preparatory height for this subject was 60 - 80 cm for the accented stroke.

3.4. Results

3.4.1. General observations

From the movement trajectories some general observations can be made (see Figure 3).

1. All subjects raised the stick to a greater height in preparation for the accented stroke.

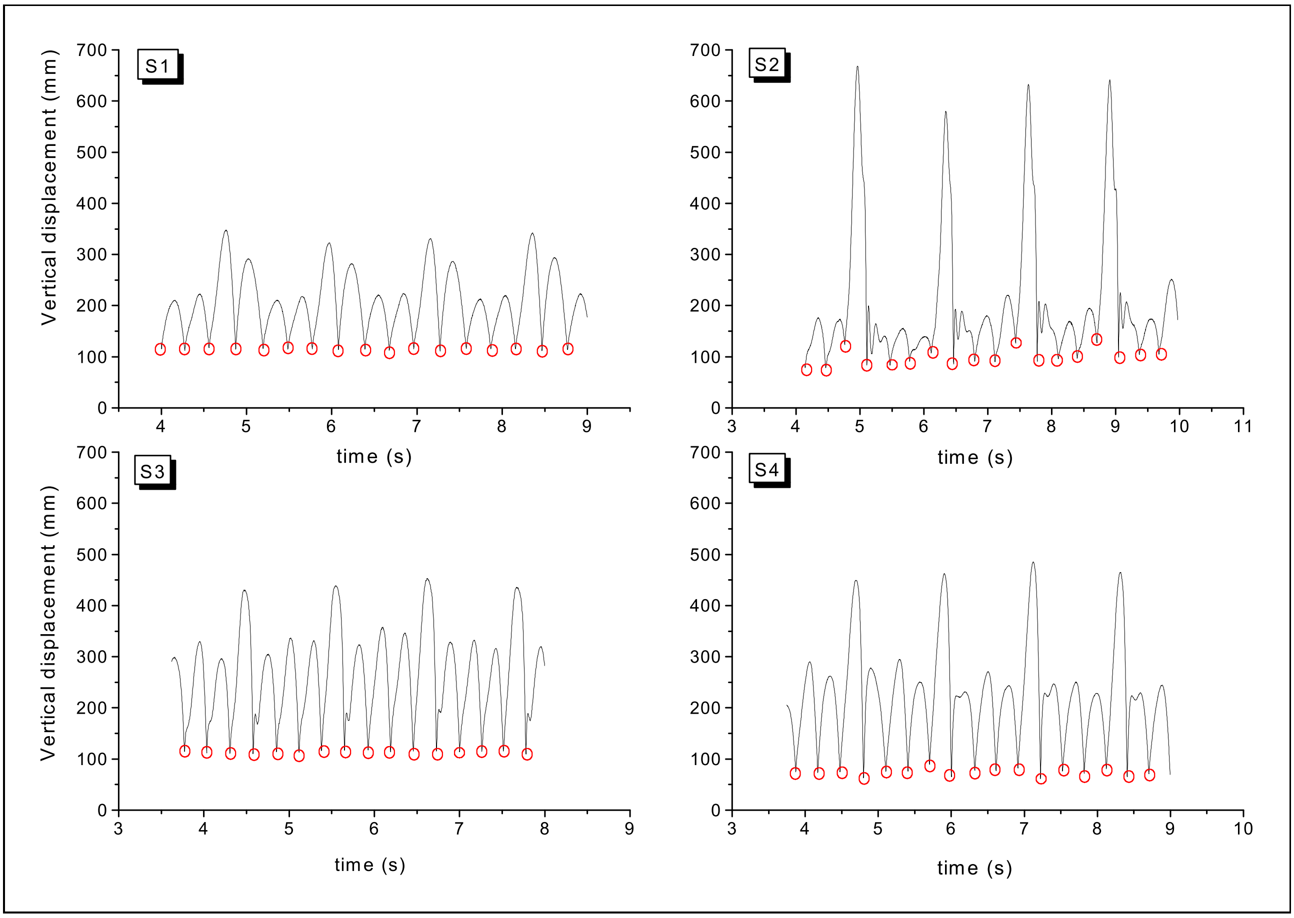

Figure 6. Vertical displacement versus time for the four subjects playing at mf, 200 BPM on the normal surface (the same excerpt as in Figure 5). The hits are marked with circles. The time scale indicates the location of the excerpt within the 20-s recording. The increased preparatory heights before the accented stroke are clearly seen. After the accented stroke the stick is allowed to rebound up to different heights, different between players.

2. For each condition (tempo, dynamic level and striking surface) each subject executed the task fairly consistently. Also between conditions the movement patterns for each subject showed clear resemblances.
3. The major condition influencing the movement patterns was the dynamic level.

During the preparation for the accented stroke, the trajectory of the drumstick (the leftmost orbit in each panel) describes a large loop, with a contour that differs between subjects. The players involved the drumstick, hand, and lower and upper arm to different extent. Although the vertical displacement along the z-axis generally is the largest, movement along the x-axis (in the direction of the arm of the player) is present to a varying degree. Subject S1 (top, left) displays very small movements along the x-axis, while subject S2 (top, right) lets the drumstick cover about the same distance horizontally as vertically. As seen from his other three trajectories, subject S2 involves the whole arm in the preparatory movement for the accented stroke.

A schematic reconstruction of how the hand and the drumstick move during an accented stroke can be seen in Figure 5. The figure shows the displacement of the markers at the drumstick and the player's hand during one of the accented strokes of subject S2 in Figure 3. The stroke develops as follows: The hand starts to move upwards already before the preceding hit at beat No. 3 (frame 1). During the first half of the movement the hand leads and the drumstick follows in an upward movement to gain height (frames 2-8). The outer part of the drumstick catches up with the hand just before the maximum position (frame 9), and continues its loop above the hand, approaching the player's shoulder (frames 10-13). After reaching the turning point (frame 14) the actual stroke is initiated in a "whiplash" manner that allows the drumstick to gain considerable speed.

3.4.2. Preparatory height and rebound

All four subjects initiated the accented stroke from a greater height, but the preparatory heights for the unaccented and the accented strokes differed considerably between subjects.

Figure 6 shows the vertical displacement of the marker on the drumstick versus time for the four subjects playing the same excerpt as in Figure 3 (mf, 200 BPM on the normal surface). The hits (encircled) can be identified as sharp dips in the vertical displacement. The vertical position of the marker at the moment of the hit, the *hit height*, varies somewhat between strokes, depending on the an-

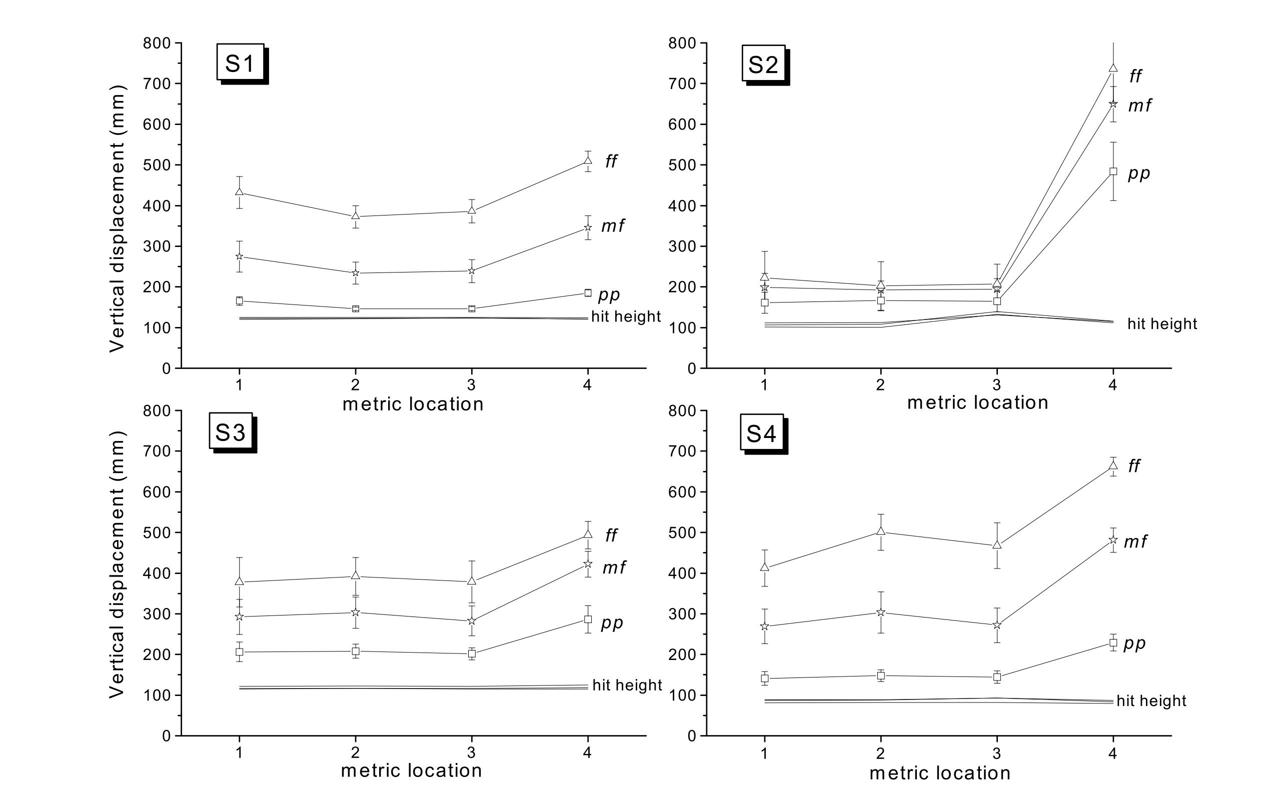

Figure 7. Average preparatory heights and hit heights for the four subjects playing on the normal surface. Each panel shows the preparatory height and hit height at the four metric locations for the three dynamic levels (pp - mf - ff), averaged across tempi. The error bars indicate standard deviations. The subjects increased the preparatory height with increasing dynamic level. The panels reflect the individual strategies of the subjects, shown in the movement trajectories (Figure 3) and the vertical displacement vs. time plots (Figure 6). The variations in hit height is due to the inclination of the drumstick at the moment of the hit (see text).

gle of the drumstick. Most markedly, the hit height at beat No. 3 for subject S2 is consistently raised. The reason is that the hand leads before the stick in the initial phase of the preparatory upward movement for the accented stroke at beat No. 4. This inclination of the stick is clearly illustrated in Figure 5.

Figure 7 displays the average preparatory heights and hit heights for three dynamic levels for each subject playing on the normal surface. Each value is averaged according to the position of the strokes in the measure, their *metric location*. A data value referring to metric location No. 1 is thus averaged across all first strokes in the measures for the specified dynamic level, and so forth. The vertical error bars indicate the standard deviation.

To reveal the importance of any differences between the different playing conditions, the preparatory height was subjected to a four-way repeated measures Analysis of variance (ANOVA; 3 surfaces $\times$ 3 tempi $\times$ 3 dynamic levels $\times$ 4 metric locations). The dependent variable was the preparatory heights at each metric location and for each condition. The analysis showed main effects for surface $[F(2,72) = 44.55, p < 0.0003]$, dynamic level $[F(2,72) = 28.52, p < 0.001]$, and metric location $[F(3,72) = 6.58, p < 0.02]$, and significant results for the two-way interaction metric location $\times$ dynamic level $[F(6,72) = 8.38, p < 0.0002]$.

The main effect of surface is simply explained by different level of the three striking surfaces, influencing hit height. The pillow (uncompressed height 8 cm) raised the hit height and the preparatory heights for the soft surface, compared to the normal and hard surfaces. When playing on the soft surface the strokes were generally initiated from a greater preparatory height (mean 368 mm) than for the normal surface (mean 310 mm), which in turn received higher preparatory heights than did the hard surface (mean 283 mm).

All subjects increased the preparatory height with increasing dynamic level, but the amount of increase differed considerably between subjects. For each step in dynamic level subject S3 raised the over-all preparatory height about 10 cm. Subject S1 increased the preparatory height by 10 cm between pp and mf, and by 15 cm between mf and ff. In contrast, the differences in preparatory height between dynamic levels for subject S2 occurred mainly at the accented stroke.

Averaged across all dynamic levels, the ratio in preparatory height between accented and unaccented strokes was just above 1.6 for subjects S1, S3 and S4. For subject S2, on the other hand, the average ratio reached 7. Subject S2 also raised the average hit height during stroke No. 3, an effect of the angling of the stick during the initial phase of the preparatory movement (see Figure 5 and 7).

The rebound after the accented stroke strives to bring the drumstick up to a greater height than for the unaccented strokes. The general effect of the rebounding stick can be seen in Figure 7. The resulting preparatory height for the first stroke in the measure (beat No. 1) is related to the striking force, the rebound of the stick, and the firmness of the player's grip. Subject S1 generally lets the stick bounce up to a greater height right after the accent, which raises the preparatory height for beat No. 1 (see Figure 6 and 7). For the other subjects some short-lived, rapid oscillations can be seen immediately after the accented hit, indicating that the players try to control the rebound actively by their grip. In particular, subject S2 first let the stick bounce up before damping its oscillating movements and then initiating stroke No. 1 from about the same preparatory height as strokes No. 2 and 3.

In summary, each of the four players maintained their movement patterns very consistently. Tempo and striking surface had little effect on the movement trajectories, although the raised level of the striking surface for the soft surface shifted the preparatory heights up compared to the other surfaces. Higher dynamic levels required all strokes to be played from a greater height. Regardless of the dynamic level, the accented stroke was always initiated from a greater preparatory height, compared to the unaccented. In preparation for the accented strokes the trajectory of the drumstick described a larger loop compared to that of the unaccented strokes. The major difference between the movement patterns of the four players was the choice of preparatory height at each dynamic level.

4. Striking velocity

The hypothesis to be tested in this section was that the striking velocity would be closely related to the preparatory height. Consequently, the striking velocity should be higher for the accented stroke compared to the three unaccented strokes in each measure.

4.1. Method of analysis

The *striking velocity*, i.e. the vertical velocity of the frontal LED of the drumstick marker right before the impact, was used as an estimate of the excitation strength (dynamic level). The approximation was made because the vertical component of the movement was clearly dominant close to the striking point. Also, the prominent modes of vibration in a drum are excited mainly through the vertical component of the striking force. The striking velocity was calculated from the filtered vertical displacement component z as described above in Section 3.2.

The use of the striking velocity as a measure of excitation strength was justified by a comparison with the impulse delivered to the force plate. A comparison between the integrated force signal and the striking velocity for a sequence shown in Figure 8. As expected, there was a close relationship (correlation coefficient 0.99) between the two indicators of excitation strength (dynamic level).

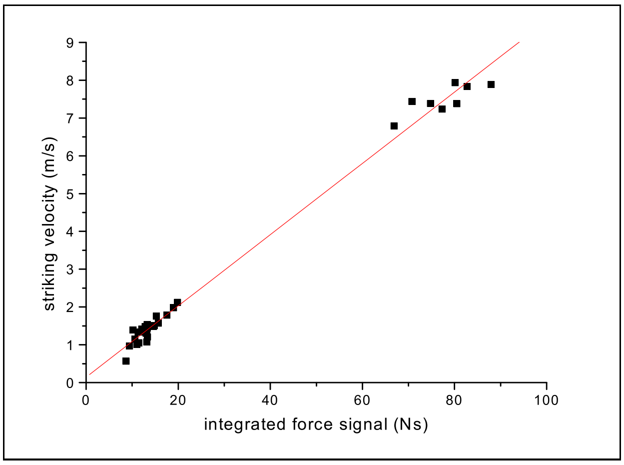

Figure 8. Comparison between the integrated force signal and the striking velocity for subject S2 playing at mf on the normal surface. The figure shows the close relationship between the two indicators of excitation strength (dynamic level).

It should be noted that the velocity at the tip of the drumstick is higher than the values here defined as striking velocity. The motion of the drumstick is composed of a vertical translational component and a dominating rotational component, describing a semi-circular arc (se Figure 5, frames 16 - 19). Assuming a pure angular movement of the drumstick around an estimated fulcrum at the player's grip at about 2/3 from the tip, the difference would be about 30%.

4.2. Results

As expected, the striking velocity was closely correlated to the preparatory height (see Figure 9). The correlation coefficients were 0.95, 0.92, 0.96, and 0.95 for subjects S1, S2, S3, and S4, respectively. The overall range of striking velocities spanned from 0.2 to 20 m/s. As noted above, the actual velocity at the tip of the drumstick would be about 30% higher.

The influence of the different playing conditions on the striking velocity was investigated in a four-way repeated measures ANOVA (3 surfaces × 3 tempi × 3 dynamic levels × 4 metric locations). The dependent variable was v, with 8 values at each metric location and condition. The analysis showed main effects for dynamic level $[F(2,72) = 51.7, p < 0.0002]$, metric location $[F(3,72) = 11.26, p < 0.003]$, and surface $[F(2,72) = 9.80, p < 0.02]$, and significant results for the two-way interactions metric location × dynamic level $[F(6,72) = 6.46, p < 0.001]$, and metric location × surface $[F(6,72) = 3.28, p < 0.03]$.

An increase in dynamic level was implemented as an increase in striking velocity, a hardly surprising result. The striking velocity was higher for the accented stroke compared to the three unaccented strokes in each measure, also this was expected. Comparing different striking surfaces, the players tended to increase striking velocity when playing on the soft (pillow) surface (mean 4.6 m/s), but decrease striking velocity for the hard surface (mean

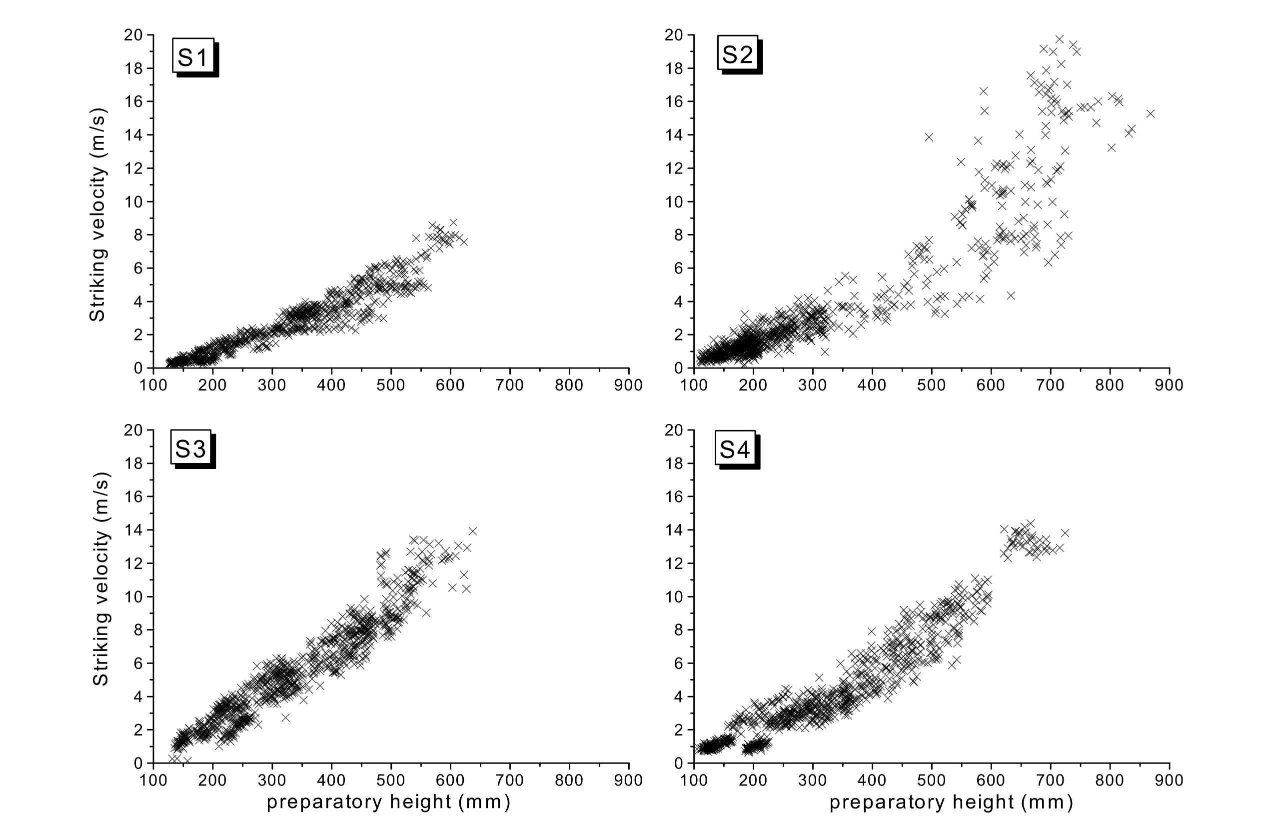

Figure 9. Striking velocity vs. preparatory height for all strokes by each subject. Each panel includes 864 strokes (32 strokes × 3 tempi × 3 dynamic levels × 3 striking surfaces). The preparatory height does not take values below the hit height, about 100 mm (cf. Figure 6 and 7).

3.3 m/s). The decrease in striking velocity for the hard surface also interacted with the increased striking velocity for the accented stroke. The accent was played with less striking velocity on the hard surface compared to the normal and soft. Similarly the interaction between metric location and dynamic level reflected that the striking velocity for the accented stroke was generally increased more for ff than for mf, and pp. For some players there was also a tendency for increasing striking velocity with increasing tempo. There was, however, no significant effect of tempo ($F(2, 72) = 5.12, p = 0.05$). An overview of the striking velocity at different dynamic levels and tempi for one subject is shown in Figure 16.

Figure 10 shows the average striking velocity vs. metric location for the four subjects playing on normal surface. As in Figure 7, the data points at metric location No. 1 represents all first strokes in each measure, averaged across all tempi and dynamic levels. The figure clearly shows that the subjects increased the striking velocity for the accented stroke (beat No. 4). The average striking velocity for the accented stroke varied from 3.5 m/s for subject S1, to almost 10 m/s for subject S2. The unaccented strokes (beat No. 1-3) are played with approximately the same striking velocity. Subjects S1 and S2 use about 2 m/s, while subjects S3 and S4 end up on each side of 4 m/s. Two of the players, S2 and S4, show a slight decrease in striking velocity for the stroke preceding the accent (beat No. 3).

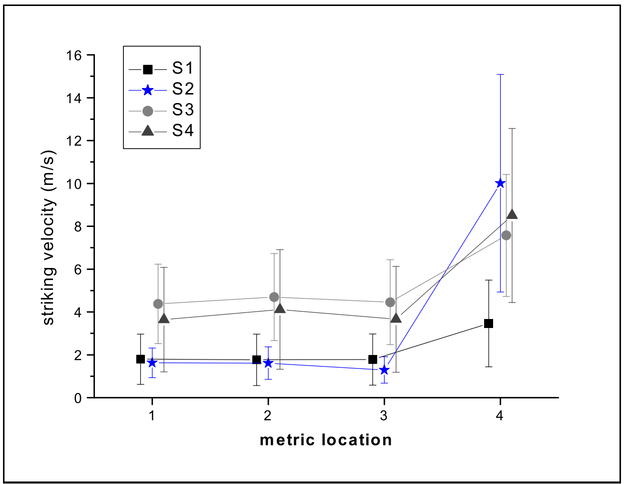

Figure 10. Average striking velocity at the four metric locations for all four subjects playing on the normal surface. Each value is averaged across tempo and dynamic level. The standard deviations are indicated by vertical error bars.

The ratio between the striking velocity for unaccented and accented strokes, respectively, differed between subjects, as seen in Figure 11. Here, the striking velocity at each metric location is normalized to the mean value for metric location No. 1, emphasizing the contrast between the accented and the unaccented strokes. Modest changes

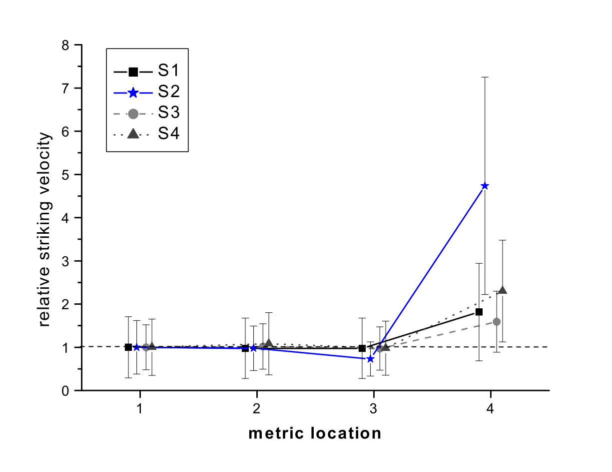

Figure 11. Relative striking velocity for the four subjects vs. metric location (averages across all dynamic levels, tempi and striking surfaces). The values are normalized to the average striking velocity of the first stroke in the measure (metric location 1). The standard deviations are indicated by vertical error bars. The figure illustrates the large differences between subjects in their interpretations of the accented stroke in terms of relative striking velocity. Note that subject S2 reduces the striking velocity for the stroke preceding the accented stroke, before delivering the accent. Beat No. 4 is played with more than 6 times higher striking velocity than beat No. 3.

are observed for subjects S1, S3 and S4 who increased the striking velocity for the accented stroke by a factor 1.7, 1.5 and 2.3 respectively. In contrast subject S2 increased the striking velocity between beat No. 3 and beat No. 4 six times.

To summarize, the striking velocity was raised for the accented stroke, for some subjects considerably. Striking velocity was higher for soft and normal surfaces compared to the hard surface. When comparing with the movement trajectories, the striking velocities closely reflected the preparatory heights. Also, the level of contrast in striking velocity between accented and unaccented strokes reflected the differences in preparatory heights for the four subjects.

5. Timing analysis

Timing is a major component in percussion playing. In many ensembles, the function of the drummer is to be *the* timekeeper. Keeping a steady rhythm and tempo are fundamental elements in any percussion training. In view of this it could be hypothesized that percussion players have a highly developed ability to control the timing.

The main hypothesis in this section was that the accent would cause a prolongation of the accented beat. As mentioned in the introduction, duration is one of the major means of marking an accent. In view of the large differences in preparatory movements, the timing analysis was also used to determine whether the movement patterns were reflected in the timing, and not only in striking velocity.

5.1. Method of analysis

The focus of the timing analysis was on the separation of the strokes in time, the *inter-onset intervals* (IOI). The recorded force signal showed a train of pulses with steep slopes, giving a clear definition of the onset of each stroke. The force signal, originally recorded at 48 kHz, was downsampled to 4.8 kHz, corresponding to a sampling period of 0.2 ms, and semi-automatically analysed for the pulse separation. The analysis used a waveform-matching technique implemented in a correlation algorithm [13].

A basic check of the correlation algorithm with manipulated files showed that the correlation algorithm traced timing manipulations down to the sampling period. Comparisons with manual measurements of the IOIs were also made. Discrepancies between the manual measurements and the algorithm did not exceed 3 ms, corresponding to a maximum relative measurement error in IOI of 1% (200 BPM). Due to the differences in waveform for the accented and unaccented strokes (see Figure 4), the maximum deviations normally occurred at intervals beginning with the accented stroke.

From the comparisons with the manual measurements and the check on the manipulated file it was concluded that the correlation algorithm gave a reliable and accurate measurement of the inter-onset intervals. All results with one exception were obtained with this method. One of the recorded sequences (subject S3, ff, 200 BPM, soft surface), had such poor signal quality that it could not be automatically extracted. An estimation of the inter-onset intervals was made manually on the force signal, using the identification of the onset of the pulses, as described above.

In the following, inter-onset interval number n is defined as the interval between stroke number n and $n+1$. The average IOI across a whole sequence (32 intervals) is denoted by IOI_{avs}, and normalised IOIs as $\mathrm{IOI}_{rel} = \mathrm{IOI}/\mathrm{IOI}_{avs}$.

5.2. Results

5.2.1. General observations

Figure 12 shows examples of the timing analysis of three recorded sequences performed by subjects S2 and S3. The timing data display different features such as recurrent cyclic patterns, and long time drift in tempo. In general, the cyclic patterns show a lengthening of every fourth interval, the one beginning with the accented beat.

The most pronounced cyclic patterns usually occurred only for a few measures at a time. As an example, subject S2 displays two kinds of cyclic patterns: prolongation of every fourth interval (intervals No. 1-16), or every other interval (No. 24 - 32). Subject S3 maintains a pattern of lengthening every fourth interval during the whole recorded sequence. The magnitude of the lengthening differs between the two conditions for S3. In the sequence

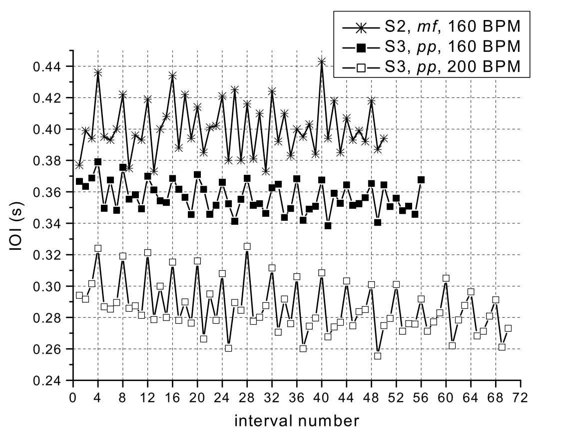

Figure 12. Three examples of timing in the performances of two subjects playing on the normal surface. The figure shows the IOIs for subject S2 playing at mf, 160 BPM (top), subject S3 playing at pp, 160 BPM (middle), and at 200 BPM (bottom). Intervals 4, 8, etc start with the accented stroke. The three sequences give examples of cyclic patterns with lengthening of every fourth interval (recurring in all three panels), and drift in tempo (bottom).

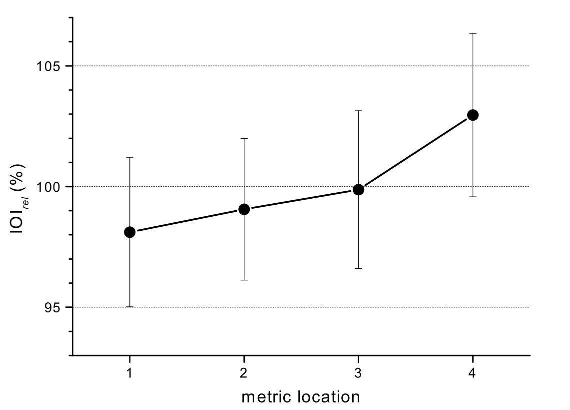

Figure 13. Grand average of IOI_{rel} across all subjects and conditions (dynamic level, tempi, striking surface) vs. metric location. An IOI_{rel} of 100% corresponds to the mean value over the recorded sequence (IOI_{avs}). The average prolonging of the accented interval was 3%. The standard deviations are indicated by vertical error bars.

at 160 BPM (middle) the lengthening is relatively small, about 25 ms or 7% in IOI_{rel}, compared to 40 ms (14% IOI_{rel}) in the sequence at 200 BPM (bottom). The only difference in the instructions to the player for the two cases was the indicated nominal tempo.

Also, it can be noted that subject S3 consistently increased the tempo throughout the whole sequences. Drift in tempo was observed for all subjects, increasing in some cases and decreasing in other. The drift over all subjects and conditions was typically 0.05% per interval (median), corresponding to a change in tempo of 2 -3 BPM after 8 measures.

5.2.2. Accent and prolongation

The influence of the different playing conditions on IOI_{rel} was investigated in a four-way repeated measures ANOVA (3 surfaces × 3 tempi × 3 dynamic levels × 2 metric locations). The dependent variable was IOI_{rel}. As each IOI_{rel} depend on two strokes, every other IOI_{rel}, that is values for two metric locations, No. 2 and No. 4, were analyzed. Averaged across all four metric locations the IOI_{rel} should be 100% for all conditions. The expected result of the analysis was therefore to only have effects of metric location or interactions with metric location.

The analysis showed a main effect for metric location $[F(1, 24) = 36.2, p < 0.01]$, and significant results for the two-way interactions metric location × dynamic level $[F(2, 24) = 35.7, p < 0.0005]$, and also for the interaction tempo × dynamic level × surface $[F(8, 24) = 2.42, p < 0.05]$.

There was a clear tendency of prolonging the interval beginning with the accented stroke for all subjects. The cyclic patterns were usually more prominent for a couple of measures at a time, but nevertheless the basic phenomenon of prolongation could easily be identified throughout the sequences. The lengthening of the accented interval decreased with increasing dynamic level.

The three-way interaction between tempo, surface, and dynamic level is due to the fact that only two of the four metric locations entered the ANOVA analysis. Nevertheless some interactions between dynamic level, tempo and surface could be discerned in IOI_{avs}. Several subjects displayed slower mean tempo when playing at pp, 116 BPM on the normal surface, but faster when playing at ff, 116 BPM on the soft surface.

Figure 13 shows mean IOI_{rel} for the four metric locations, averaged across all measures, subjects, and conditions (tempo, dynamic level, surface), in all 8 × (4×3 ×3×3) = 864 values for each metric location. An IOI_{rel} of 100% corresponds to the mean value over the recorded sequence (IOI_{avs}). The characteristic feature of prolonging the interval beginning with the accented stroke (interval No. 4) is evident. The average prolongation reaches 3%.

Figure 14 shows IOI_{rel} for each metric location and player, averaged across all dynamic levels, tempi, and surfaces. The figure shows that all subjects prolonged the fourth interval (the interval beginning with the accented stroke) at the expense of the first two intervals in the following measure.

It is to be noted that the accented stroke is delivered on time, in spite of the larger preparatory movements for this stroke. Even the elaborate preparatory motion of subject S2, involving the whole arm, does not delay this stroke.

The subjects perform the lengthening and shortening of the intervals to different extent. Subject S1 shortens the first two intervals and prolongs the two last. Subject S2 prolongs interval No. 4 (104%) mainly by delaying the following stroke and shortening interval No. 1 (96%). Subject S1 shortens interval No. 2 even more than interval No. 1. Subjects S3 and S4, on the other hand, shorten all first

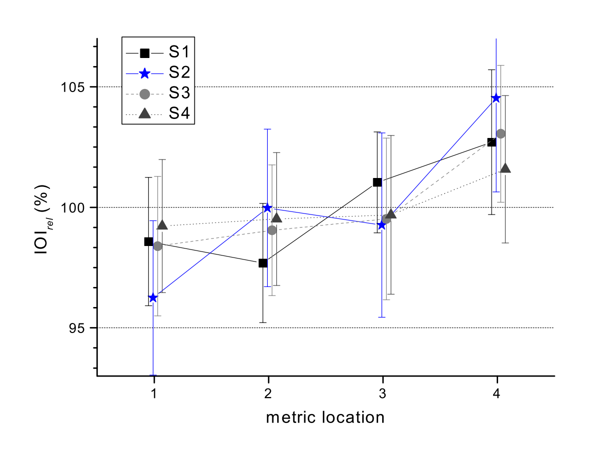

Figure 14. Averaged IOI_{rel} vs. metric location for all subjects. The values are averaged across all dynamic levels, tempi, and playing surfaces. The standard deviations are indicated by vertical error bars. All subjects prolonged the interval beginning with the accented stroke, (interval No. 4), by delaying beat No. 1 in the following measure.

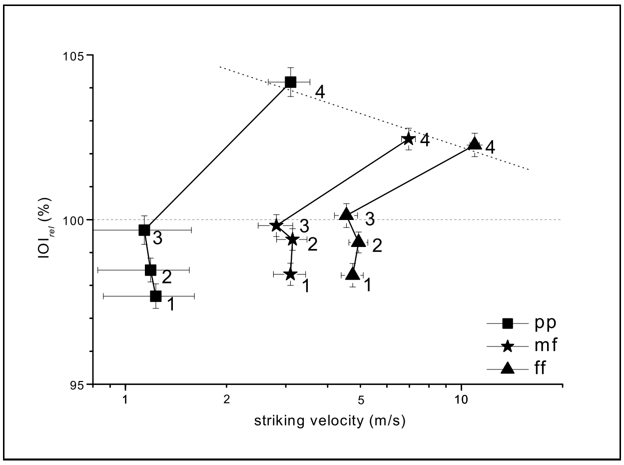

Figure 15. The relation between striking velocity and IOI_{rel} for the different metric locations and dynamic levels. The figure shows the grand average for the metric locations (numbered 1, 2, 3, and 4), at pp (squares), mf (stars) and ff (triangles), across all subjects, tempi and striking surfaces. Each data point represents 288 analyzed strokes. The 95% confidence intervals are indicated by error bars. The striking velocity, here used as an indicator of excitation strength (dynamic level), is defined by the motion of the drumstick marker. The actual velocity at the tip of the drumstick would be be about 30% higher (see text). As seen in the figure, the striking velocity for the accented stroke is about doubled at all dynamic levels (note the log scale on the abscissa). The lengthening in IOI_{rel} after the accented stroke, however, decreases with increasing dynamic level (dotted line).

three intervals and prolong only the last interval (103% for S3 and reaching 101% for S4).

5.2.3. Dynamic level and spread in IOI

As the players increased striking velocity with rising dynamic level the lengthening of the fourth interval decreased. Figure 15 shows the average IOI_{rel} versus striking velocity for the four metric locations at each dynamic level. Each data point is averaged across all measures, subjects, tempi and surfaces. The average prolongation is 4% at pp level, but decreases to 2% at ff.

Figure 16 summarizes the performance of subject S1, and his strategy for marking the accent. The figure shows IOI_{rel} versus striking velocity for all analysed strokes played by S1 on the normal surface. Also included are the averages for each of the four metric locations at the three dynamic levels (large symbols).

The averages display different relationships between the striking velocity and IOI_{rel} at the three dynamic levels, reflecting rather different strategies for marking the accent. At pp level the player is mainly prolonging the accented interval without much increase in striking velocity. At mf and ff levels the accented stroke is played with much higher striking velocity but the prolongation of interval No. 4 is less pronounced.

Dynamic level and tempo influenced the spread in IOI, dynamical level being the most important. Generally, the spread increased at pp level compared to mf and ff. This is clearly illustrated in Figure 16, where the scatter in data tapers off towards higher striking velocities (dynamic level). Also, for some subjects tempo had an effect. For subject S1 playing at pp level, the standard deviation in IOI_{rel} exceeded 7% at 200 BPM (normal surface), compared to just above 4% at the two slower tempi. At mf and ff, the spread was substantially lower, between 2 and 3.5%, still with the higher values at 200 BPM.

In summary, the subjects marked the accent by prolonging the interval between beat No. 4 and No. 1. The lengthening was dependent on the dynamic level but did not differ much between subjects. The average lengthening of the accented interval across all playing conditions was 3%. In spite of the sometimes very large preparatory movements before the accented stroke, this stroke was not delayed.

6. Discussion

Accents are simple components in the performance of music, but they need to be prepared in order to be performed satisfactorily. The accented stroke is a musical element that is much practised in percussion training in order to be carried out "automatically".

Our experiments support the assumption that skilled performers have acquired a strategy for playing an accented stroke. The strategy may differ between performers, but the players seem to stick to their own movement patterns consistently.

For unaccented strokes at soft dynamic level the movement of the stick is mainly restricted to a rotation around a fulcrum at the grip point, involving very little movement of the hand and arm. With increasing dynamic level, or in preparation for the accent, the wrist joint becomes involved to a greater extent, and for some subjects, also the arm.

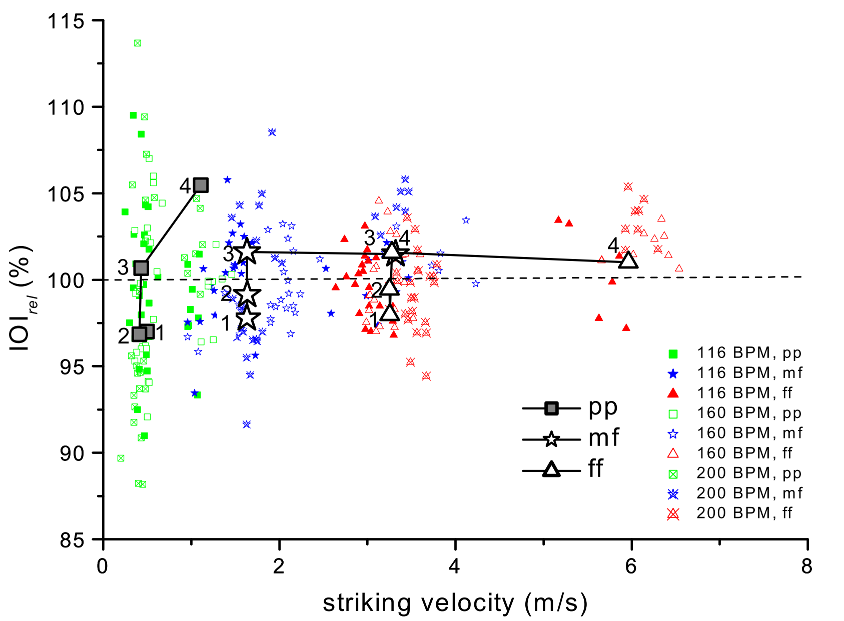

Figure 16. Overview of the performance of subject S1, showing IOI_{rel} vs. striking velocity for each individual stroke played on the normal surface. Dynamic levels: pp (squares), mf (stars), and ff (triangles). Tempi: 116 BPM (filled), 160 BPM (unfilled); and 200 BPM (crossed). The averages across each metric location are indicated by superimposed large symbols and lines. Note the decrease in spread in IOI_{rel} and in the prolongation of interval No. 4.

6.1. Before the accent (upstroke)

A common element in the strategies of all four subjects is the raising of the stick to a greater height in preparation for the accented stroke. In doing so the drummers prolong the path of acceleration before the hit, similar to golfers or players of baseball or tennis. Subjects S2 and S4 initiated the accented stroke by letting the hand and lower arm drag the drumstick in a wide loop, and, for S2, including even the upper arm. To be able to reach a greater height in ample time to deliver the downstroke, the hand and arm sometimes start their upward movements already during the preceding stroke (see Figure 5, frame 1). This causes an angling of the stick at the time of hit, seen as a raised hit height (cf. Figures 6 and 7. The angling also results in a decrease in striking velocity at stroke No. 3 for subject S2 and S4 (see Figure 10).

6.2. The accent (downstroke)

The greater preparatory height before the accented stroke gives the player a longer distance to accelerate the stick before the hit. The player's individual interpretations of dynamic level, and amount of emphasis on the accent, were reflected in the movement patterns. The preparatory height for unaccented and accented strokes correlates well with the corresponding striking velocity (see Figure 9).

The ratio between the striking velocity for unaccented and accented strokes, respectively, differed between subjects (see Figure 11). Subject S2 displayed the largest differences in the movement trajectories and striking velocities between the unaccented and accented strokes. The average ratio between the striking velocities for the accented stroke No. 4 and unaccented strokes No. 1-3 almost reached 5 (just below 7 at ff level). In view of this great difference in striking velocities it is hardly surprising that this subject actually reduces the striking velocity for the stroke preceding the accented note. The preparatory movement of this player may seem elaborate (se Figure 5), but it clearly serves a purpose in producing a high dynamic contrast between the unaccented and accented strokes. The technique is sometimes referred to as the "Moeller stroke"(see [10] or [11]).

6.3. The rebound

The drummer takes advantage of the rebound in preparation for the following stroke. It is the rebound from the striking surface that allow subjects to start moving the hand upwards immediately after, or even before, the following stroke, while the tip still is moving downwards. This feature is clearly illustrated for subject S2, in particular after stroke No. 3 (see Figure 5).

The rebound needs, however, to be controlled by the player at some points. Positioning the tip of the stick at the desired height at the end of a downstroke (i.e. after the hit) can be difficult. The rebound may well strive to lift the stick higher than the intended preparatory height for the following strokes. The greater the striking force, the stronger the rebound. If the player seeks a great difference in striking force between the unaccented/accented strokes, the stick needs to be brought down to a suitable height before initiating the unaccented stroke (tap). Also in the control of the rebound the four players chose different strategies.

Subject S1 incorporates the rebound after the accent in the preparation for the following stroke, and the trajectory appear as smooth as for the other strokes (see Figure 6). For the other three players, a complete integration of the rebound in the following stroke is not possible, as they all used higher striking velocities in general. Also, they applied larger differences in striking velocity between the unaccented/accented strokes, with a slight exception for S3.

The interpretation of the movements for subjects S2, S3, and S4 suggests that the rebounding stick is moving upwards faster than the hand can follow after the stronger hit of the accent. Damped oscillations can be discerned in the movement trajectories, most pronounced for subject S2. In practice, the player has to make a compromise between; (1) dampening the rebound completely (and thereby also altering the sound by dampening the drumhead), or (2) let the stick rebound freely away from the drumhead, reaching too high a position for the following, softer stroke.

The grip during impact is of great importance also for sportsmen. In golf, "uncocking" the wrist too early before impact causes loss of speed. A player who is able to maintain the grip as late as possible and still release in time is able to drive the ball further [2]. Of course, very few golfers have to worry about being on time for the next stroke.

6.4. Timing

The timing analysis of the strokes showed a clear tendency of lengthening the interval beginning with the accented stroke. The lengthening amounted to 3% on the average. There is plenty of evidence of lengthening an accented note in studies of timing in music performance. In addition to raised dynamic level, a lengthening of a note is the common mean of expressing an accent [14]. Also, in speech, an accented segment is marked by lengthening [15].

In Drake and Palmer's study of expressive timing of pianists focusing on accented structures inherent in the music [8], a significant lengthening of notes preceding important metric locations was reported. In 4/4 meter, where the first beat is such a "metric accent", the last interval in the (preceding) measure (interval No. 4) was prolonged. The reported lengthening was in the range 2 - 4%. (Note the difference compared to this study where the accents were explicitly marked in the score.)

In Billon, Semjen, and Stelmach's studies of short tapping sequences with interleaved accents at different positions (marked in the score) [16], systematic shortenings before, and lengthenings after, the accented taps were observed. The average lengthening of the interval beginning with an accented tap was 5%.

In the present study, the prolonging of interval No. 4 goes hand in hand with the pronounced rebound after the accented stroke. The preparatory movement of subject S2 might seem elaborate enough to hazard the delivery of the accented stroke No. 4 on time. However, it is not the accent but the following (stroke No. 1) which is delayed. The prolonged accented interval follows timely to allow the oscillations at rebound to decay.

It seems not necessary to maintain the marking of the accent consistently. The lengthenings appeared as clear cyclic patterns (see Figure 12), but usually only for a couple of measures at a time. Even so, they were identified in listening tests, where the subjects were asked to classify synthesized sequences based only on the timing information of the performed sequences, the amplitude information being removed [12]. The task was to sort the sequences according to perceived grouping of strokes. Stimuli based on the timing in the top sequence in Figure 12 were classified as groups of 2, 4 strokes, or no grouping. The bottom sequence in Figure 12 on the other hand was perceived as groups of 4 strokes in 85% of the trials (93% for percussion players). The grouping of the strokes introduced by the accent seems to be efficiently communicated by the lengthening of the accented interval.

Keeping a steady rhythm and tempo are fundamental elements in percussion playing. Nevertheless, a small drift was commonly observed in the recorded sequences, typically 0.05% per interval (median), corresponding to a change in tempo of 2 -3 BPM after 8 measures. This amount of drift is about the same as reported in tapping experiments with non-musicians including synchronization and continuation. The reported drift was between 0.05 and 0.1% per interval for the corresponding tempi [17] [18]. In two cases the observed drift in this study was considerably higher (0.2%), both exceptions occurring at pp and at the slowest tempo (116 BPM). The explanation to the observed drift in the present study may be related to the fact that the subjects were not explicitly instructed to strictly reproduce a given, steady tempo.

6.5. Players' backgrounds

At this point the different backgrounds of the four players should be brought forward. Subjects S2 and S4 are mainly drumset players. When playing the drumset big differences between accented and unaccented strokes are generally used. The accented strokes usually mark the beat, or a syncopation, and should be strongly emphasized. Unaccented strokes, on the other hand, may be played much softer at a completely different dynamic level. The descriptive term "ghost notes" is frequently used to denote the strokes between the accented strokes that are played much softer than the accented. Yet another aspect of drumset playing is that drumset players in general learn a technique that allows them to span large distances across the drumset in short time. Such a technique is particularly useful when improvising.

Subjects S1 and S3 most frequently perform in symphony orchestras and military bands, respectively. In these genres, the music is composed and given in a score, and accents are emphasized in relation to the current dynamic level. Here, detailed control over the production of each single beat would be more useful. Especially in symphonic orchestras there is seldom need for the strongest dynamic range a drum can produce. Military snare drum playing generally requires higher dynamic levels; marches are typically played in the range between mf and ff.

These observations are general characteristics of the different genres. It is not perfectly evident that any of the "ideals" of the subjects' usual playing style would be reflected in their performances of such a simple task as the one in this study. Still, there is no reason to assume that the players would deviate significantly from their normal playing habits during the experiments. Characteristic differences were observed as discussed above, supporting the assumption that the players' performances reflected characteristics of different genres.

7. Conclusions

The four percussionists that participated in this study all had their own strategy for playing an accented stroke, a strategy that was maintained consistently. The movement trajectories showed that the players involved the wrist and arm to different extent, especially in the preparation for the accented stroke. For each player, the contour of the movement trajectories remained essentially the same regardless of playing condition. Strokes at higher dynamic levels were initiated from a greater height than strokes at lower dynamic levels.

A common feature of the strategies of all players was that the accented stroke always was initiated from a greater height than the unaccented. The greater preparatory height facilitated an increase of the striking velocity, and hence excitation strength. The preparatory height and the striking velocities were closely correlated. Some effects of the rebound after the accented stroke could also be seen in the preparation for the following unaccented stroke.

The amount of emphasis given to the accented beat by each player was a recurrent characteristic feature throughout the study. The movement patterns and the preparatory heights for each of the four players were reflected in the striking velocity, and to some extent also in the timing.

The main parameter influencing the preparatory movement and the striking velocity was the dynamic level and, to a lesser extent, the striking surface. Tempo only resulted in minor differences. Also in timing the dynamic level was the most influential parameter. All subjects prolonged the interval beginning with the accented stroke.

Acknowledgements

The author is indebted to the following persons for their help: Markku Haapakorpi for help with setting up the experiment, Virgil Stokes for help with setting up the experiment and help with a first analysis of movement data, Anders Askenfelt for helping with the experiment and valuable comments on data analysis and the manuscript, Anders Friberg for comments on the manuscript and the statistical analysis, Erwin Schoonderwaldt, Giampiero Salvi and Vittorio Sanguineti for help with Matlab. Special thanks are due to the subjects participating in this study.

This work was supported by the European Union (MEGA - Multisensory Expressive Gesture Applications -no. IST-1999-20410; http://www.megaproject.org/, MOSART IHP Network -Music Orchestration Systems in Algorithmic Research and Technology - no. HPRN-CT-2000-00115; http://www.diku.dk/research-groups/musinf/mosart/, and SOb - The Sounding Object - IST-2000-25287; http://www.soundobject.org/)

Part of the study has also been conducted within the project Music and Motion, supported by the Bank of Sweden Tercentenary Foundation.

References

[1] R. L. Wickstrom: Fundamental motor patterns. 3rd ed. Lea & Febiger, Philadelphia, 1983.

[2] B. Abernethy, V. Kippers, L. T. MacKinnon, R. J. Neal, S. Hanrahan: The biophysical foundations of human movement. Human Kinetics, Champaign, Ill., 1997.

[3] A. Askenfelt: Measurement of the bowing parameters in violin playing II: Bow bridge distance, dynamic range, and limits of bow force. J. Acoust. Soc. Amer. **86** (1989) 503–516.

[4] R. Parncutt: Accents and expression in piano performance. – In: Systemische Musikwissenschaft. Festschrift Jobst P. Fricke zum 65. Geburtstag. Peter Lang, Frankfurt, In press.

[5] A. Friberg, U. Battel: Structural communication. – In: The science and psychology of music performance. Creative strategies for teaching and learning. R. Parncutt, G. E. McPherson (eds.). Oxford University Press, 2002, 199–218.

[6] A. Gabrielsson: The performance of music. – In: The Psychology of music. D. Deutsch (ed.). Academic Press, 1999, 501–602.

[7] A. Gabrielsson: Performance of rhythm patterns. Scandinavian Journal of Psychology **15** (1974) 63–72.

[8] C. Drake, C. Palmer: Accent structures in music performance. Music Perception **10** (1993) 343–378.

[9] E. F. Clarke: Generative principles in music performance. – In: Generative processes in music. J. A. Sloboda (ed.). Clardendon Press, Oxford, 1988, 1–26.

[10] S. A. Moeller: The Moeller book. Ludwig Music Publishing Co., 1956.

[11] D. Famularo: It's your move. Motions and emotions. Warner Bros. Publications, 1999.

[12] S. Dahl: The playing of an accent - preliminary observations from temporal and kinematic analysis of percussionists. Journal of New Music Research **29** (Sep 2000) 225–233.

[13] S. Granqvist, B. Hammarberg: The correlogram: A visual display of periodicity. J. Acoust. Soc. Amer. **114** (2003) 2934–2945.

[14] A. Friberg: A quantitative rule system for musical performance. Dissertation. Royal Institute of Technology (KTH), Stockholm, Sweden, 1995.

[15] R. Carlson, A. Friberg, L. Frydén, B. Granström, J. Sundberg: Speech and music performance: Parallels and contrasts. Contemporary Music Review **4** (1989) 389–402.

[16] M. Billon, A. Semjen, G. E. Stelmach: The timing effects of accent production in finger-tapping sequences. Journal of Motor Behaviour **28** (1996) 198–210.

[17] J. A. Michon: Timing in temporal tracking. Van Gorcum, Assen, The Netherlands, 1967.

[18] G. Madison: Variability in isochronous tapping: Higher order dependencies as a function of intertap interval. Journal of Experimental Psychology: Human Perception and Performance **27** (2001) 411–422.