# The kinematic analysis of motion curves through MIDI data analysis

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**This paper postulates that the analysis of MIDI data allows for the statistical analysis of motion in music, in particular, the kinematic analysis of motion curves in music. The paper deals with the analysis of the kinematic motion components within music, specifically music velocity (i.e. tempo) and music acceleration/deceleration (i.e. tempo change), based upon Truslit's definition of the predominant up–down motion types in music (1938). Thus, the variables of music velocity and acceleration are mathematically defined and extracted from MIDI encodings. Analysis of music velocity indicates that the differing motion types have specific and consistent velocity profiles, and that these profiles can be expressed mathematically and analysed statistically. In particular, the paper focuses on the open motion curve fit, relating the open motion velocity curve to the beta distribution. Analysis of acceleration within music suggests that music acceleration is not constant in nature, implying that theories of linear velocity are inaccurate models. Hence, it is suggested that MIDI data analysis allows for the statistical exploration into music kinematics and the motion curves within music.**

## 1. INTRODUCTION

This paper postulates that the analysis of MIDI (Musical Instrument Digital Interface) data allows for the statistical manipulation and analysis of music information. MIDI is the most prevalent communications protocol for the realtime transmission of digitised music information, where the data format comprises a quantitative and serially structured representation of the music note event. The protocol represents the note event in terms of DELTA TIMES (essentially time stamping the data in terms of the predefined entities of *ticks*), MIDI PITCH and MIDI VELOCITY components. Therefore, the protocol forms numerical and objective encodings of the note entity that can be mathematically transformed into higher-order abstracted components and structures. Thus, the lowest atomic unit within the protocol is the note structure. Through mathematics and statistics, MIDI data can be analysed, extending the field of music informatics and allowing for the empirical analysis of music at abstractions above the note event.

In particular, this paper focuses on the analysis of motion variables within music based upon Truslit's definition of the predominant motion types in music (Repp 1993, Shove and Repp 1995). For centuries, motion has been considered to be a fundamental characteristic of music, denoted by shifting tensions that are constrained within the dimensions of music time and space and realised through music structure. Assuming that music captures and/or reflects physical motion, it follows that it inherently consists of the same aspects: kinematic behaviour (i.e. motion characteristics) dictated by dynamic components (i.e. forces and energies). Hence, motion within music can be analysed with respect to these components thus leading to the *kinematic* and *dynamic* analysis of music.

Relatively recently in the history of music, research has focused on the scientific study of motion in music (Kronman and Sundberg 1987, Feldman, Epstein and Whitman 1992, Todd 1992, Repp 1993, Shove and Repp 1995, Todd 1995, Friberg and Sundberg 1999). This paper proposes that through the multivariate MIDI data, a mapping between the music dimensions of time, pitch and dynamics can be constructed with respect to the motion dimensions of space and time, and the low-level MIDI parameters of DELTA TIME, MIDI PITCH and MIDI VELOCITY. Hence, links are forged between music components and structures, mechanical motion and the MIDI representation of music.

Thus, the work outlined in this paper is based upon the underlying assumption that differing motion types exist and are distinguishable within music and that kinematic components can be extracted through the exploitation of statistical techniques on multivariate MIDI data. Hence, this work specifically deals with the investigation of the kinematics of music with respect to the underpinning motion that is expressed.

### 1.1. The predominant motion types in music

The predominant motion types stated in this paper are based on Truslit's definitions (1938) of fundamental motion configurations in music (Repp 1993). Truslit identified four basic up–down motion types in music, essentially representing *imaginary motion* in the dimensions of music space and time (as opposed to real physical motion). Truslit postulated that complex up–down motion trajectories could be derived through the transformation and manipulation of these fundamental

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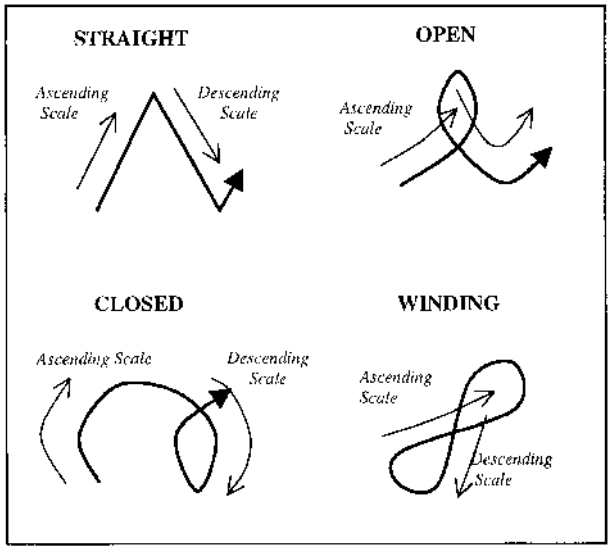



**Figure 1.** Truslit's motion types represented synopically: straight, open, closed and winding motion.

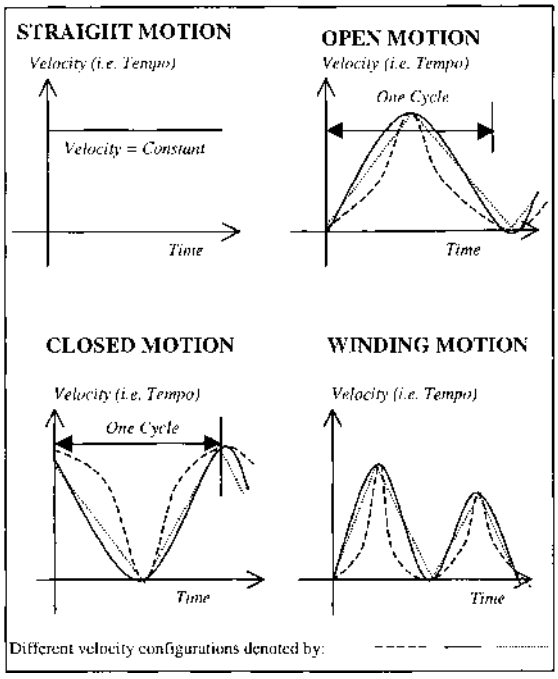



**Figure 2.** Theoretical tempo profiles: the interpretation of Truslit's motion types in terms of music velocity.

motion types (Repp 1993, Shove and Repp 1995). Thus, the motion types outlined in this paper have been labelled according to Truslit's work:

(1) straight motion,
(2) open motion,
(3) closed motion, and
(4) winding motion.

Based upon the ascending and descending melodic scalic pattern, straight motion can be defined as mechanically constant motion and can be interpreted as linear upward and downward motion with sudden changes in pitch direction. Since there is an abrupt change in motion direction, the motion is considered *unnatural* and contrasts the alternative motion-type forms in music that reflect the curvilinear evolutions evident in natural motion (Repp 1993). Thus, open motion begins gently, accelerating upwards in pitch direction and then decelerating downwards. Closed motion begins rapidly, decelerating upwards and then accelerating down. Winding motion ascends and descends with fluctuations in motion accelerations, leading back to its origin (figure 1).

The qualitative descriptions of motion types can be interpreted in terms of music velocity (i.e. music *tempo*). These descriptions are independent of changes within the pitch dimension, and hence, focus on the metrics within the music (i.e. music metre). Thus, metric velocity characteristics encapsulating the motion type can be theoretically hypothesised (although the exact nature of the velocity profile is left undetermined) (figure 2).

Thus, straight motion translates into unchanging and therefore constant, music velocity (irrespective of changes in pitch dimension). Open motion maps onto gradually increasing then decreasing music velocities, and closed motion forms the inverse (being constructed from decreasing then increasing velocities). Winding motion marks alternating music velocities and hence it has been denoted in terms of fluctuating sinusoidal characteristics (figure 2). Where appropriate, the example profiles of figure 2 denote several different possibilities that are represented by the contrasting line styles.

### 1.2. Extracting the kinematic variables from music data

Since motion exists within the fundamental dimensions of space and time (Repp 1993), for music to capture motion the dimensions of space and time need to be translated into the equivalent dimensions that exist in music. It is postulated in this paper that in music the fundamental dimensions of space and time can be mapped into the three spatial dimensions consisting of pitch space, metric space and dynamic space, and time. Thus, due to the multidimensional nature of music, motion in music is suggested to be fundamentally complex in nature, resulting in two planes of analysis that can be denoted as *tonal motion* and *rhythmic motion*. This is consistent with general theories dealing with motion in music where motion is considered to be a combination of tonal and rhythmic components (Todd 1995). Hence, within this paper, a focus is made that essentially deals with the effects of rhythmic motion (i.e. discarding the pitch dimensions) for clarity.

In order to analyse the motion types postulated by Truslit, the synoptic definitions (figure 1) were interpreted in terms of music velocity (i.e. *tempo*) and acceleration (figure 2), which could be mapped and extracted from the MIDI encoding of DELTA TIME. The work is

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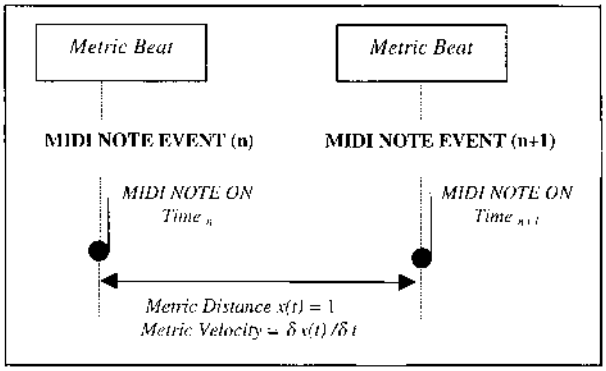



**Figure 3.** Music metric distance and velocity in terms of MIDI data and note event.

therefore based on the fundamental assumption that motion in music can be modelled using Newtonian mechanics (Todd 1995), where high-order derivatives (i.e. music velocity and music acceleration components) can be obtained through the mathematical manipulation of low-level MIDI data.

### *1.2.1. The derivation of motion velocity: music tempo*

Although *tempo* is a psychologically derived variable, through simplification and constraints it can be considered a function of time and equivalent to music velocity $v(t)$ (i.e. consisting of metric units per unit time). In particular, music velocity can be regarded as change in music distance with respect to time. Hence, the derivation of velocity is based upon Newtonian Mechanics (Todd 1995), which states:

$$v(t) = \delta x(t)/\delta t, \tag{1}$$

where $v$ = velocity, $x$ = distance, and $t$ = time. In terms of music data, this can be mapped and translated into:

$$v(t) = \delta x(t)/\delta t, \tag{2}$$

where $v$ = music velocity, $x$ = metric distance, and $t$ = time. Hence, the definition of the variable metric distance $x$ is fundamental to the work, allowing for the derivation of the higher-order kinematic variables within music.

Here, the term metric distance denotes the derived distance parameter in terms of music metre and is subject to the notes being metrically equivalent, i.e. of the same note-value (contrasting the alternative distance parameters of pitch distance or dynamic distance). Through the analysis of motor-rhythmic sequences, where by definition the distance moved between notes can be considered independent of velocity and hence constant in nature (Todd 1995), metric distance $x(t)$ can be defined as unity between adjacent notes. Therefore, the distance between notes is formally constrained to be $x(t) = 1$. This signifies the distance between notes in terms of music metre (figure 3).

In terms of MIDI, DELTA TIMES representing MIDI NOTE ON timings can be converted into absolute time, signifying the start time of distinct note entities in seconds. Thus, the music velocity (i.e. metric velocity) between notes comprising metric units per second can be denoted by (figure 3):

$$v(t) = \delta x(t)/\delta t \tag{3}$$

$$= 1 / (\text{NOTE ON TIME}_{n+1} - \text{NOTE ON TIME}_n)$$

for $n = 1,2,3, \ldots$

### *1.2.2. The derivation of motion acceleration: music* rubato, ritardando *and* accelerando

Motion acceleration and deceleration in music (essentially mapping onto music *rubato*, *ritardando* and *accelerando*) can be derived where acceleration is denoted as change in velocity with respect to time (Todd 1995). Therefore:

$$a(t) = \delta v(t)/\delta t, \tag{4}$$

where $a$ = music acceleration, $v$ = music velocity, and $t$ = time. Thus, in terms of MIDI, music acceleration (i.e. metric velocity per second or metric units per second$^2$) can be expressed as a function of NOTE ON TIME:

$$a(t) = \delta v(t)/\delta t, \tag{5}$$

where $\delta t = (\text{NOTE ON TIME}_{n+1} - \text{NOTE ON TIME}_n)$, and $v(t) = 1 / (\text{NOTE ON TIME}_{n+1} - \text{NOTE ON TIME}_n)$ for $n = 1,2,3, \ldots$

Thus, theoretical models and hypotheses have been derived which mathematically describe the basic metric kinematic variables within music, mapping onto the MIDI parameters dealing with time.

## 2. EXPERIMENTAL RESEARCH: EXPERIMENTAL METHODOLOGY

In order to quantify the theory, experimental research was undertaken. Ten competent performers (not all at virtuoso or concert level) took part in producing MIDI data concerning the superimposition of *straight*, *open*, *closed* and *winding* motion types on the constraint task. The performers were all classically trained[1] and hence it was assumed that all the performers had access to the same fundamental knowledge concerning music structure and music expression. The experiment was standardised in that all the performers were exposed to the same preliminary information and instructions and the

[1]Performer I: male (Grade VIII); Performer II: male (Advanced Certificate); Performer III: male (Grade VII/VIII); Performer IV: female (Grade VIII); Performer V: female (Grade VIII); Performer VI: female (LTCL); Performer VII: male (Grade VIII); Performer VIII: female (Grade VII); performer IX: male (Grade VIII); Performer X: male (Diploma).

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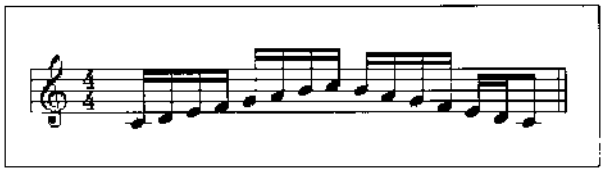


**Figure 4.** The monophonic constraint task (C major scale).

experimental conditions were kept as consistent and constant as possible.

The constraint task (forming the system input), consisted of a single ascending and descending C major scale in the score notation shown in figure 4. The sequence is considered to be *neutral*, allowing for the differing motion types to be superimposed without bias due to pitch and harmonic constructions. Due to the specification of the task, there is an explicit statement of music macrostructure with tonal, harmonic, textual, timbral and metric parameters formally constrained, with timing fluctuation, dynamic levels and durations unconstrained. In order to simplify the performance variables within the music generation process, a focus was made on monophonic, motor-rhythmic sequences where the complex interactions introduced by polyphonic music are avoided (e.g. the effect of harmonic forces and the detection of tempo in complex music). Subjects were given qualitative descriptions of the differing motion types that included the synoptic representations. Hence, the actual execution and specifics of the motion type were open to interpretation.

Pedalling effects were disregarded in an attempt to constrain as many performance parameters as possible. Thus, the information captured through MIDI NOTE ON and NOTE OFF messages depicts the manipulation of music parameters intended by the performer.

The music interface used to provide the MIDI data was a Roland Digital HP1800e Piano. Time was given for the performer to adjust to the interface, minimising the effects of interface unfamiliarity or performer adaptability. When performance errors occurred, the task was repeated and rerecorded in order to ensure that the final sample of information was a faithful representation of the performer's intentions. Therefore, it could be assumed that spurious errors and effects were constrained. During the performance, MIDI data was recorded via the PC sequencer package Cakewalk Pro Audio™ for Windows 3.1, and was saved as a standard MIDI file (SMF) in Format 0 (i.e. single track format). This was later converted into text allowing for file transfer and analysis using MATLAB. Therefore, higher-order parameters could be transformed and manipulated, and extracted from the SMF.

## 3. RESULTS

The results documented in this paper specifically focus on music velocity and acceleration and, in particular, the *nature* of music velocity and acceleration with regard to the underpinning motion type.

### 3.1. The statistical analysis of music velocity

The statistical analysis of music velocity indicates that specific tempo profiles embodying the underlying motion type exist (figure 5 and 6). The results represent the transformed data (where the inherent micro-fluctuations within the data have been smoothed using the moving average, specifically a moving average window of three). In order to reduce the effects of in-motion type (i.e. in-group) variation, the velocity profiles were constructed against percentage time (figure 5). From this, the average motion type profiles could be generated where the mean metric velocity is derived from linearly interpolated data using a sample rate of 100 (figure 6). Thus, errors in the construction of the average profiles were minimised and considered negligible.

By inspection, it appears that the straight motion velocity profile is approximately constant in nature, although micro-variations are evident, reflecting motor-control limitations (figure 7). Open and closed motion types reflect curvilinear velocity, with winding motion being pseudo-sinusoidal in nature. In general, the results also provide evidence for the final decrease in tempo denoting the effects of the final *ritardando* (i.e. deceleration), therefore reflecting the end of the phrase boundary that is structurally significant (except for the closed motion type). Hence, the results are consistent with the theoretical hypothesis stated previously (figure 2), and so the predicted velocity characteristics are validated through empirical experimental research with specific information dealing with the nature of velocity profiles exposed (figure 7).

Statistical analysis of the data indicates that the straight motion standard deviation, variance and range are approximately, or close to, zero when compared with the alternative motion types. Thus, the velocity values are not widely dispersed from the mean, contrasting the alternative motion types that have higher variance and deviations (figure 8). Hence, the straight motion type is separated from the open, closed and winding motions.

The kurtosis statistically separates the straight motion characteristic (i.e. unnatural motion) from the others (i.e. natural), with the straight motion velocity profile generating a positive kurtosis (i.e. relatively peaked distribution when compared to the normal distribution), whereas the results concerning the skewness of the distributions (i.e. the degree of asymmetry around the mean) statistically separate straight, open and winding motion types from the closed motion configuration (figures 8 and 9).

#### *3.1.1. The open motion velocity statistical curve fit*

Through statistical curve fitting techniques, the nature of the profiles can be determined and matched against

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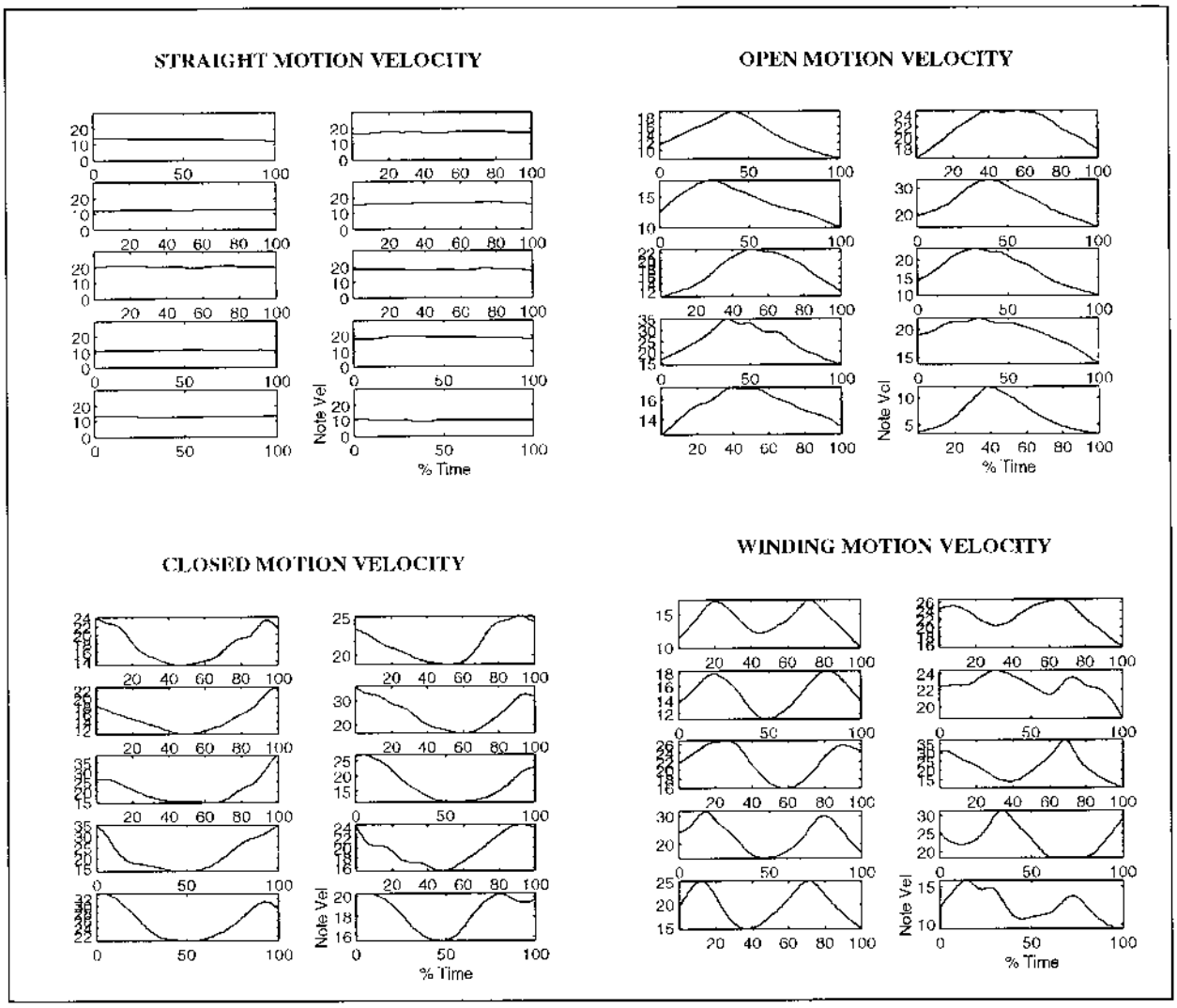



**Figure 5.** Metric velocity profiles for all subjects and motion types.

mathematical algebraic expressions, thus formally defining the kinematic characteristic in terms of its fundamental components. In particular, this paper focuses on the open motion profile and acts as an illustration of technique (other motion type profiles can be treated in a likewise manner).

In order to execute the curve fit, the open motion typical velocity profile was transformed: essentially shifting the data to begin with zero velocity and considering the velocity ($y$-axis) as a frequency count yielding percentage velocity (figure 10). The equivalent open motion velocity distribution was generated and modelled against differing statistical distributions (in particular the Normal and Poisson distributions), yielding positive results when modelled against the Beta ($\beta$) distribution (figure 10).

The beta distribution was derived by manipulating percentage time and specifying values for $\alpha$ and $\beta$, denoted mathematically by:

$$\beta \equiv x^{\alpha-1}\,(1-x)^{\beta-1}, \tag{6}$$

where $x$ = percentage time. Hence, through the curve fit, the algebraic expression representing the open motion velocity profile can be stated as being (figure 10):

$$v(t) = t^{2.4}\,(1-t)^{2.8}, \tag{7}$$

where $v$ = metric velocity, and $t$ = time. Therefore, the open motion velocity profile is a function of time. This is consistent with the fact that metric velocity was initially derived as being $v(t) = 1$ / (NOTE ON TIME$_{n+1}$ − NOTE ON TIME$_n$), which is essentially a function of time. However, the exact relationship between velocity and time for the open motion profile can be specifically stated through the curve fit as $v(t) = t^{2.4}\,(1-t)^{2.8}$.

Thus, the statistical curve fitting technique generated a method for mathematically describing velocity profiles and kinematic characteristics.

### 3.2. The statistical analysis of music acceleration

Inspection of the typical acceleration profiles indicates that acceleration within music is not generally constant

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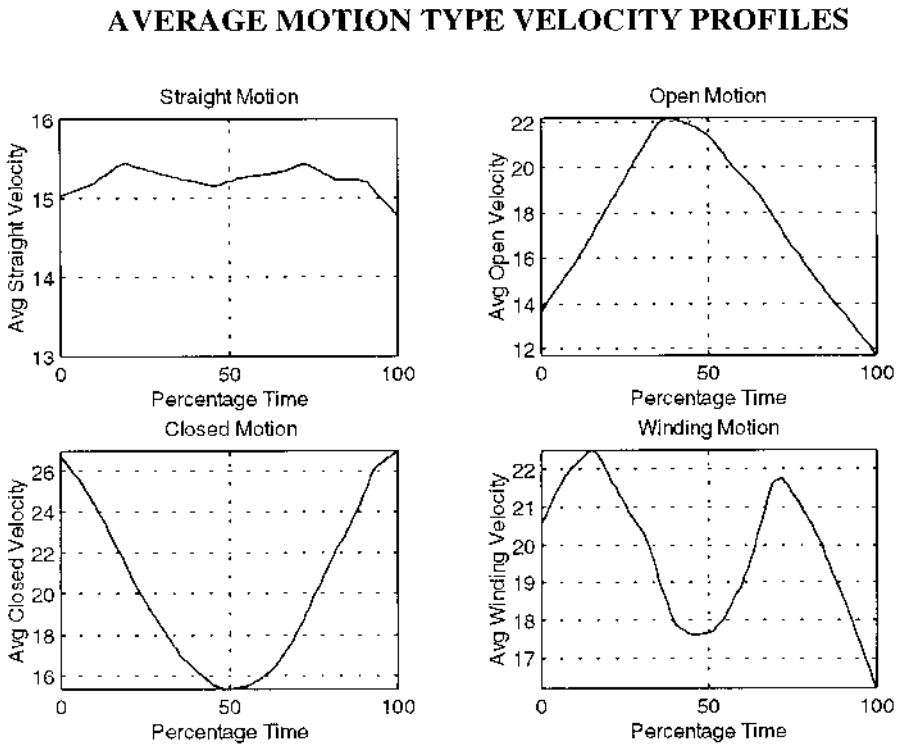



**Figure 6.** Average metric velocity profiles against percentage time.

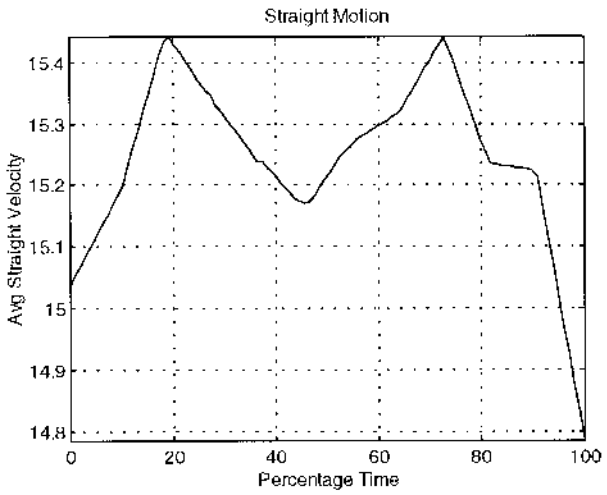



**Figure 7.** The straight motion type profile in detail.

| | *Straight* | *Open* | *Closed* | *Winding* |
|---|---|---|---|---|
| Mean | 15.25 | 17.73 | 20.33 | 19.85 |
| Std Error | 0.013 | 0.312 | 0.392 | 0.17 |
| Median | 15.25 | 17.93 | 19.78 | 20.16 |
| Std Dev | 0.13 | 3.12 | 3.92 | 1.72 |
| Variance | 0.02 | 9.76 | 15.40 | 2.97 |
| Kurtosis | 1.98 | -1.23 | -1.38 | -1.24 |
| Skewness | -1.14 | -0.17 | 0.262 | -0.21 |
| Range | 0.66 | 10.44 | 11.63 | 6.28 |
| Minimum | 14.78 | 11.73 | 15.34 | 16.21 |
| Maximum | 15.44 | 22.17 | 26.97 | 22.48 |
| Sum | 1524.69 | 1773.09 | 2032.8 | 1985.12 |

**Figure 8.** Music velocity statistics for average profiles.

in nature (figure 11). This result is consistent with mechanical motion where constant acceleration (and hence linear velocity) is considered to be a special case of motion. Thus, despite linear tempo (LT) theories in music (Todd 1992), our data imply that linear tempo theories are inaccurate models of motion in music. Hence, the basic assumption used to model motion components within music with elementary mechanics (specifically dealing with linear motion in one dimension) needs further validation.

For the average straight motion profile, the acceleration tends to centre around zero, although there are inherent fluctuations between increasing and decreasing acceleration (i.e. music *accelerandi* and *ritardandi*). This is perhaps indicative of motor control limitations and effects and implies that for unnatural motions in music the acceleration tends to be pseudo-constant rather than exactly constant. However, for the alternative forms (i.e. natural motion patterns) where the characteristic of the velocity change is postulated to be dependent upon the motion type, the accelerations and decelerations are less predictable in nature. Hence, it is concluded that the nature of the acceleration in music is context-dependent and dictated by the underlying motion type.

The results concerning straight, open and winding motion suggest that music tends to end with decelerating tempo, which can be specified as increases in deceleration (i.e. the tempo getting markedly slower and slower

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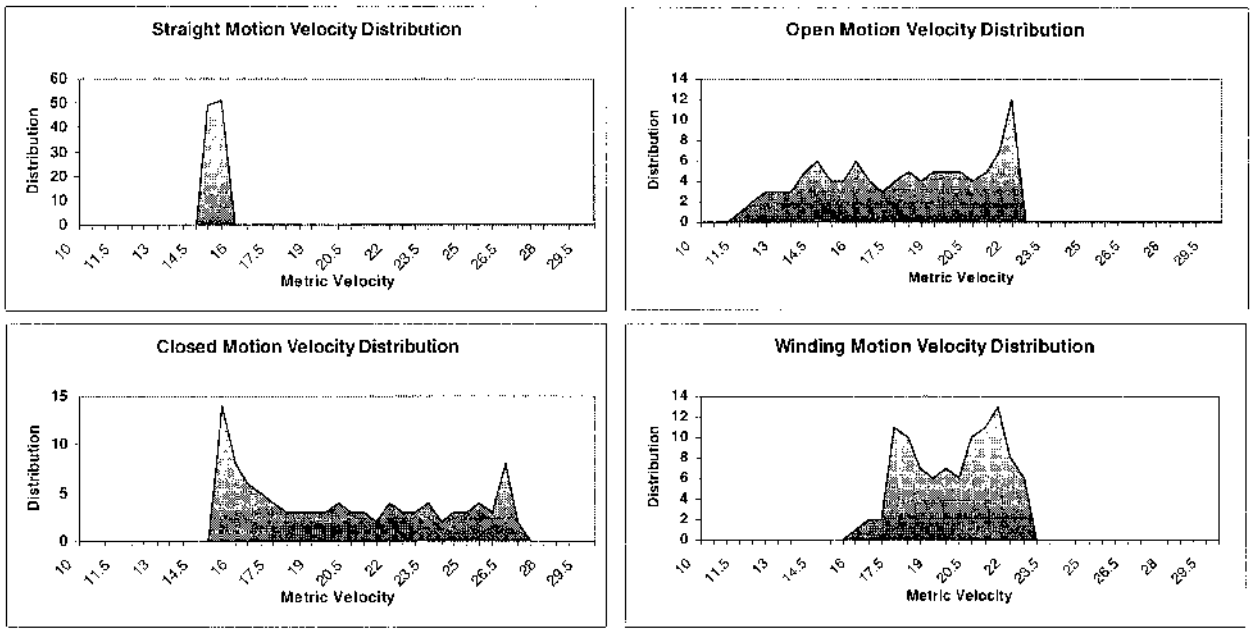



**Figure 9.** Music velocity distributions.

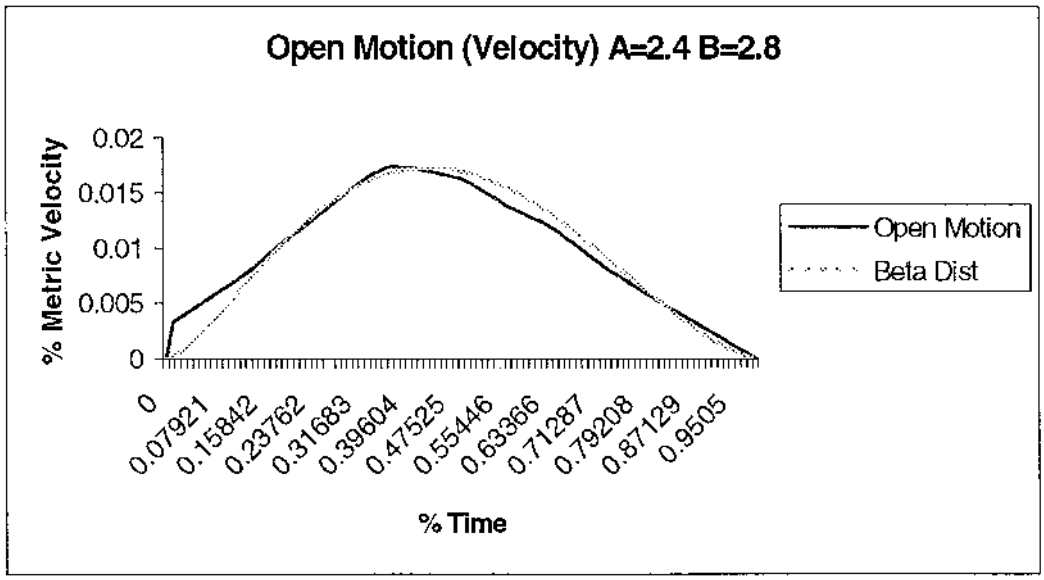



**Figure 10.** Open motion velocity curve fit.

as opposed to a decrease in deceleration rate). This result signifies the end phrase boundary, marking the end of the motion sequence and thus reflects the nature of the final *ritardando*, whose existence is thought to be independent of motion type and set by the structural context of the music. However, for the closed motion profile (figure 11), although there is evidence of a decrease in acceleration rate the final *ritardando* is not evident (due to the definition of the motion type ending with increasing acceleration and perhaps with most subjects considering it structurally incomplete in itself).

The statistical analysis of acceleration data (figure 11) indicates that there is an inherent symmetry in the execution of music velocity change. For the straight, open and closed motion types, the mean acceleration value tends to be close to zero, hence perhaps equalising the overall acceleration to some degree. Thus, in holistic terms the individual motion patterns are perhaps inherently balanced, despite micro-variations and characteristics that dictate the overall form and quality of the motion. Separation between motion types is evident concerning acceleration statistics, with the variance, skewness and kurtosis indicting distinctions between the straight motion type (i.e. unnatural motion) and the open, closed and winding motion (i.e. natural) formations.

## 4. DISCUSSION AND CONCLUSION

Based upon Truslit's postulation of four predominant up–down motion types within music (Repp 1993, Shove

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| | Straight | Open | Closed | Winding |
|---|---|---|---|---|
| Mean | -0.15 | -3.46 | 1.24 | -8.49 |
| Std Error | 0.25 | 3.47 | 4.87 | 2.81 |
| Median | -0.35 | -19.60 | -2.67 | -16.89 |
| Std Dev | 2.53 | 34.70 | 48.67 | 28.13 |
| Variance | 6.42 | 1203.86 | 2368.46 | 791.50 |
| Kurtosis | 0.31 | -1.60 | -1.626 | -1.14 |
| Skewness | -0.27 | 0.42 | 0.10 | 0.37 |
| Range | 12.45 | 90.02 | 134.16 | 93.91 |
| Minimum | -7.63 | -43.98 | -64.32 | -50.20 |
| Maximum | 4.81 | 46.04 | 69.84 | 43.71 |
| Sum | -14.67 | -345.54 | 124.08 | -848.78 |

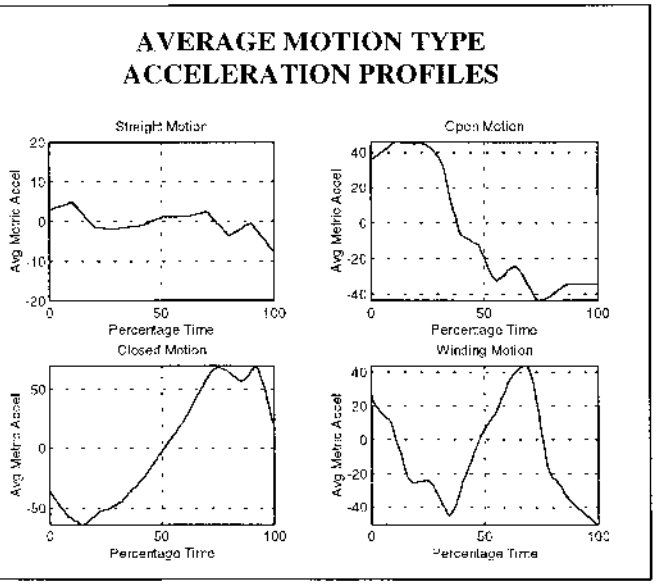



**Figure 11.** Metric acceleration statistics and average profiles against percentage time.

and Repp 1995), this paper documents the extraction of the kinematic variables of music velocity and acceleration from low-level MIDI data streams with reference to the underpinning motion type. From the MIDI encoding of DELTA TIME (signifying MIDI NOTE ON timings) and the formal constraint of the metric distance parameter $x(t)$, the higher-order derivatives of velocity and acceleration were obtained using fundamental Newtonian mechanics. Hence, the work is based upon the assumption that Newtonian mechanics is an adequate model for analysing motion components in music and that the MIDI protocol explicitly or implicitly encodes the necessary data allowing for the extraction of higher-order kinematic components.

The results indicate that different motion types exist within music and have specific and consistent kinematic profiles. In particular, the extraction of music velocity allows for the analysis of music *tempo* and the extraction of music acceleration allows for the empirical investigation of *tempo change* (i.e. music *rubato, accelerando* and *ritardando*). Thus, the nature of the kinematic components can be statistically analysed and formally described through algebraic mathematics.

In terms of music velocity, the straight motion profile is typically constant in nature, although motor-rhythmic variability and the final *ritardandi* are evident. The alternative motion types depict curvilinear velocities that are distinct in form and validate theoretical postulations on velocity behaviour as being motion-type dependent. In particular, the typical open motion velocity profile can be statistically represented by the beta curve distribution and formally denoted by $v(t) = t^{2.4}\ (1 - t)^{2.8}$, where $v$ = open motion metric velocity, and $t$ = time. Thus, constant velocity marks mechanically constant motion and is distinct from curvilinear velocity formations that signify realistic motion patterns.

Our analysis of music acceleration has indicated that change in velocity is not constant in nature and is consistent with theories on mechanical motion where constant acceleration is considered a special case of motion. This finding opposes suggestions that tempo (i.e. music velocity) is linear (Todd 1992) and is consistent with evidence indicating that linear changes have been perceived as being poor (Kronman and Sundberg 1987). In research modelling the final *ritardando* (i.e. the final deceleration in music), the square root function of velocity as a function of metrical distance (i.e. $v(x) = (u^2 + 2ax)^{1/2}$) was suggested as a model (Kronman and Sundberg 1987), based on the assumption that tempo is linear in nature. However, recent work has indicated errors concerned with the underpinning assumptions in the research and this suggestion has since been rejected (Friberg and Sundberg 1999). According to linear tempo (LT) theories, the variation in tempo is governed in a manner analogous to the velocity equations of elementary mechanics that assume acceleration is constant in nature (Todd 1992). Since our data suggests that music acceleration is not constant in nature (except in the case of mechanical motion, where it is approximately zero and maps onto constant velocity), it is implied that linear tempo theories are inaccurate models of motion in music. Hence, the basic assumption modelling motion components within music with elementary mechanics needs further validation. Alternative approaches relating the dynamic components of motion (in particular the *force* components) to kinematic characteristics have been proposed (Feldman *et al*. 1992), indicating music tempo $v(t)$ to be quadratic or cubic in nature. However, errors in data representation have since questioned the validity of the results (Friberg and Sundberg 1999).

This paper has empirical evidence that specific motion types exist within music – generating distinct velocity

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and acceleration characteristics that are obtainable from low-level multivariate MIDI data through mathematical manipulation. Therefore, the MIDI protocol allows for objective, analytical research into the kinematic components of music and in particular the kinematic analysis of motion types in music.

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