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DESIGNING A COMPUTER MODEL OF DRUMMING: THE BIOMECHANICS OF PERCUSSIVE PERFORMANCE

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Abstract: *Becoming a competent musician requires significant practice, including rehearsal of various musical pieces. Complex sequences of musical notes and the associated bodily movements must be choreographed and memorized so that the human body can reproduce these sequences consistently. Such bodily movement occurs within the instrumental performance space, with some instruments, notably the drum set, requiring more bodily movement than most. Choreographed bodily movement in drumming is fundamental for producing the timbral and timing variations crucial in delineating human vs. computer percussive performance. Current computer models designed to simulate percussive performance focus on the cognitive aspects of performance or the musical structure to determine the simulation, while other systems focus on reproducing the physics of musical instruments. The focus of this paper is on the complexities of human movement in drumming, with a view toward proposing, as part of a larger research project, a background understanding and methodology for extracting empirical data from human performance for interactive computer-based percussive performance modeling applications.*

Keywords: *percussion, performance, modeling, drums, biomechanics, computer music.*

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INTRODUCTION

Considerable literature exists concerning the field of computational modeling of expressive music performance (Gabrielsson, 1999, 2003). This research includes a diverse array of approaches, owing to the complexity of human performance (Widmer & Goebl, 2004). Arguably, one of the more complex instruments to computationally model is the drum set because of the complexity involved in playing the instrument. In percussive performance, the interaction between the player and instrument is perhaps the most significant variable in timbre production. This interaction is manifested in different techniques, skill levels, musical knowledge and experiences, and the physical attributes of the performers themselves (e.g., height, body mass, fitness, etc.). The act of musical performance encompasses a variety of contributory aspects (Gabrielsson, 1999, 2003; Palmer, 1997), specific examples of which include the physiological (Fujii, Kudo, Ohtsuki, & Oda, 2009; Lee, 2010), cognitive (Dahl & Friberg, 2004; Laukka & Gabrielsson, 2000; Repp, 1999), technical (Dahl, Großbach, & Altenmüller, 2011), and musical (Repp, 1997), as well as both theoretical and empirical perspectives (Shove & Repp, 1995).

Several aims of music performance modeling have been identified in the literature, encompassing the design of interactive music performance systems, virtual music environments, and compositional software tools. One aim of performance modeling seeks to generate human-like computer performance; therefore, it is useful to consider how human performance is distinct from computer performance. In this research, the analysis regarding human and computer performance addresses particularly the context of modeling percussive performance on a nine-piece drum set comprising bass drum, snare drum, hi-hat, floor tom, low tom, medium tom, high tom, and ride and crash cymbals. Such a drum set configuration is typically used in rock, jazz, and pop music genres. Firstly, the empirical research into the physics of percussion instruments shows that a number of physical factors are involved in timbral variation, such as strike location, construction, material, and so forth (Fletcher & Rossing, 1998; Rossing, 2000; Taylor, 2015). Secondly, timbral variations in drum sounds are important to listeners' overall perception of music (Rath & Wältermann, 2008). Because playing the drums is a time-sensitive endeavor, the human movement involved in percussive performance can be considered to be "chronemic movement" (Sutil, 2015), in which the qualitative determinations of speed, sustain, attack, or delay (Sutil, 2015, pp. 35–37) in musical and timbral qualities are directly related to instrumental interaction and trajectory control. This article presents part of a wider research investigation into the computational simulation of human percussive performance and presents discussion of relevant literature as a prequel for further empirical work.

Why Is Modeling Human Performance on a Drum Set So Difficult?

Drumming comprises a variety of set drum patterns and techniques that are learned and performed in different rhythmical and musical contexts, often in an improvisatory manner. To perform these drum patterns and techniques, the drummer must choreograph the human movement of the patterns within the biomechanical constraints of his/her abilities in order to execute them within the rhythmic and time constraints of the music. Each drum must be played optimally at all times, with the performer able to add nuances, such as gestural embellishments or timbral variations that could affect either the timbre or the timing, in each strike. Consequently, a drum performance can be regarded as multiple patterns containing choreographed sequences of human movement. A computer model of drumming therefore encapsulates the choreographed movements contained within a performance and the transitional movements between choreographies.

The main aim of this article is to deconstruct and discuss the key aspects of human movement that lead to timing and timbral imperfections in percussive performance on a nine-piece drum set. This analysis enables the identification of a methodology that can be used to analyze human percussive performance with the goal of creating a computer model that represents, musically, the continuum of percussive performance movement in the physical world. More specifically, this analysis identifies ways in which real-world drumming interactions can be captured and how a human might interact with a system that models that interaction. Such a computer model could be used in interactive systems, virtual music environments, and in compositional software tools. This article evaluates methodologies for measuring human movement in order to create a framework that utilizes interactive computer algorithms to simulate percussive performance.

This paper begins with a description of drum rudiments and drummers' development goals that are fundamental to learning optimal movement and form in drumming. The paper then presents an analytical framework, based upon information processing systems and human motor control, with which to understand the underlying causes of performance variation, particularly regarding instrumental interaction and physical control. This will involve a summary review of the literature in the discipline of biomechanics and the subsequent application of these principles in relation to percussive performance of a nine-piece drum set. This article does not address the different options and timbral and acoustical effects of striking implements (see Halmrast, Guettler, Bader, & Godøy, 2010, pp. 204–207), nor is it intended to be an exhaustive discussion. Many specific aspects have been omitted, including the effect of batter head models on timbre (Henzie, 1960; Lewis & Beckford, 2000); the effect of disuniform tension; potential tonal evolution due to the age (and usage) of the head; tempo (Desain & Honing, 1993); feedback conditions (Brandmeyer, Timmers, Sadakata, & Desain, 2011; Dahl & Bresin, 2001; Pfordresher & Palmer, 2002), and temporal independence (Goebl, 2011). In addition, aspects such as style and genre which, with their obvious contextual performance differences, will not be discussed in detail.

Drum Rudiments and Development Goals

Drummers develop their technique by learning drum rudiments established by the international drum rudiment committee, part of the Percussive Arts Society. The rudiments currently consist of 40 techniques (Percussive Arts Society, 2014[1]) that often are choreographed independently and have been derived from various musical styles to form a pedagogical method for learning percussion. This method is designed to provide an "orderly progression for the development of physical control, coordination, and endurance" (Carson & Wanamaker, 1984, p. 3). Although not explicitly defined, these development goals can be interpreted and summarized as follows:

- Physical control, referring to the performers' management of stick and instrument interaction, which comprises wrist and hand movement and arm control;
- Coordination, referring to the strike accuracy and the performer's ability to exert physical control over sequences of strikes in different locations; and,

- Endurance, referring to performer attributes, instrumental configuration, and the complexity of piece being performed.

Although these development goals can be considered independent of each other, there is considerable interdependence among the three. One example of this is where a performer has good stick and instrument management but poor coordination. The result is a drummer who could play rhythmic sequences and timbres correctly but not necessarily hit the drum in time. Choreographically, this could be attributed to a disconnect between the sequence design and poor motion control or form. Another example of independent development goals can be observed in a performer's ability to maintain arm control and coordination during prolonged movements in complex percussive sequences. Control and coordination will deteriorate at varying rates depending on the endurance levels of the performer. Essentially these development goals are individually important to the successful execution of a choreographed movement and contribute towards the overall form of the movement and the sound of the performance. The relationship between the development goals is described in Figure 1.

There is no "magic spot" among these development goals because each drum rudiment requires a unique mix of the three components, depending on the percussionist's current developmental stage and the demands of the choreographical context. Although these goals are fundamental to the development of a percussionist's skill, obtaining an understanding of percussive performance by way of deconstructing principles of human movement from these goals is difficult due to the effect of environmental factors on skilled movements (Dahl, 2005). Such factors could include, among others, the effect of temperature and altitude on endurance, auditory feedback on coordination, and stick thickness on physical control. As a result, it is both difficult and impractical to account for all these independent variables.

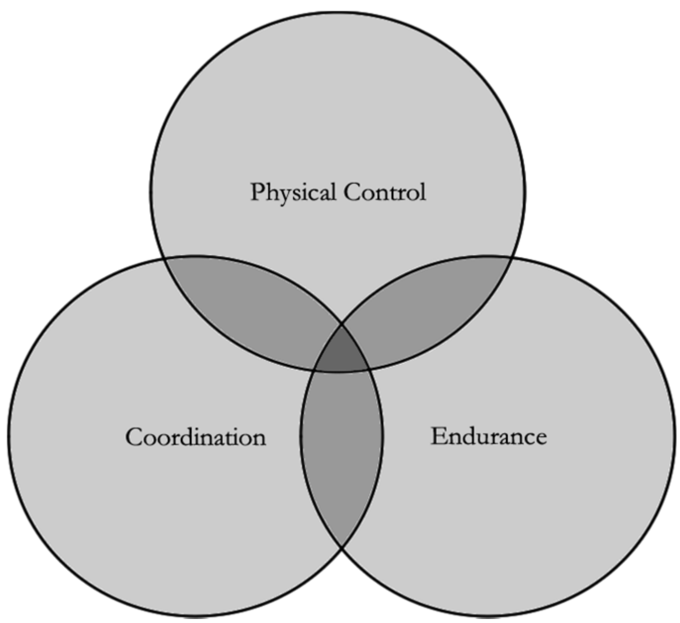

Figure 1. A diagram outlining the interdependency among the three development goals in drumming. Individually and collectively, the developmental goals impact performance. Adapted from Carson & Wanamaker (1984).

The reduction of independent variables in the analysis of human movement, extending to environmental variables, is not new. In fact the dimensionality of variables in understanding human movement has been the subject of investigation since Nikolai Bernstein first proposed the theory of the degrees of freedom (DOF) in 1967. He theorized that because there are an almost infinite number of ways a movement could be executed through the large network of muscles, joints, and cells in the human body, there are an infinite number of ways that muscles can achieve the different movements.

The control of the nervous system on the musculoskeletal system is highly complex: For any given movement, there are a high number of DOF. This complexity is illustrated during the activation of a single muscular element either in isolation or in any particular sequence (Bernstein, 1967). Thus, if the nervous system controls movement by controlling synergistic groups rather than individual muscles and joints, the number of DOF (and therefore the dimensionality of variables) is reduced (Turvey, 1990). Bernstein (1967) also suggested that sensory feedback from the environment interacts with the nervous system to reduce the number of DOF. Turvey (1990) substantiated the omission of environmental factors within the context of Carson and Wanamaker's (1984) development goals for this framework by arguing that, "If the environment to which the movement system relates is interpreted as just another large set of variables, then the juxtaposition of an animal and its environment would amplify the problem of degrees of freedom" (Turvey, 1990, p. 940).

Juxtaposing environmental factors onto percussive performance would not only concern human movement and the number of DOF but would necessitate extending environmental variables to the vibrational behavior of each of the nine drums under investigation as well. Because the speed of sound increases with air temperature (Fletcher & Rossing, 1998, p. 70), a bigger picture emerges regarding the inherent difficulty in adequately applying several environmental factors as variables across the different themes noted in this article. In light of this, Turvey's (1990) position will be considered to be the most appropriate view and, consequently, environmental factors will be considered outside the scope of this discussion.

THE ANALYSIS OF HUMAN MOVEMENT: A THEORETICAL FRAMEWORK

In 1982, neuroscientist David Marr presented a tri-level hypothesis by which information processing systems could be analyzed. These levels of analysis can be summarized as follows (Marr, 1982, p. 25):

- Computational level: What does the system do?
- Algorithmic/Representational level: How does the system do what it does?
- Physical level: How is the system physically realized?

Marr (1982) described how these three levels of analysis are not intrinsically dependent upon one another and that, in some circumstances, analysis can be achieved by using only one or two levels. The choice of analytical level is critical in correctly understanding certain systems. More importantly, Marr described how the computational level of analysis is essential in understanding certain phenomena, particularly where there are significant levels of abstraction between the understanding of a system and the computational representation. Examples of this include a priori understanding of the nature of biological or perceptual processes prior to computational representation, rather than by analyzing the computational representation of such process in a given computational environment (Marr, 1982, p. 27).

David Rosenbaum (2010), in his book on motor control, described how Marr's three analytical levels of information processing systems also represent "the study of human motor control" (p. 4). At the computational level of analysis, Rosenbaum described how, during physical activity, animals and humans plan their movements using what he described as "implicit equations" (p. 5). These implicit equations are derived from Marr's (1982) computational level, where a system must achieve a function whose representation is often described mathematically. However, for humans and animals, this refers to the mental representation of task to be performed. One example of this is the mental representation a rock climber has of a "dyno" (a jump or leap) to the next position. In the context of percussive performance, this can be a mental representation of an impending drum fill and the drum striking sequence following from the "current position." Critically, the current position is spatiotemporally unique, thus requiring transitional or linkage movements between sequences. Rosenbaum (2010) noted that the computational level of analysis does not include the execution of the action, which is unsurprising considering the number of DOF.

In applying Marr's (1982) second level, the algorithmic/representational level, Rosenbaum (2010) noted that a computer's algorithms are designed to enable a system to undertake their functions with guaranteed success. In the natural world, movements operate in real time (analogous to runtime algorithms) without guaranteed success. As examples, a rock climber might not jump high enough to grab the next hold (and thus fall to the safety net below) and the drummer can hit the wrong instrument or strike the shell of the drum by accident. As Rosenbaum pointed out, each of these real time movements relies upon a procedure, and the person executing the action will draw upon behavior and cognition in order to execute and verify the movement, hence Rosenbaum's extension of this term as the "procedural level" (Rosenbaum, 2010, p. 5).

Rosenbaum (2010) described the final level of Marr's (1982) analysis, the implementation level, as the physical aspects of the movement. These biological elements are described by Rosenbaum (2010) as muscle operation and brain activity (e.g., a rock climber will use leg muscles to jump, stretched arms to grab the hold, and fingers and forearms to grip and maintain the hold). For the drummer playing a snare drum followed by a ride cymbal, muscle operation can include the fingers and hand for gripping the stick, adduction of the lower arm for the strike, followed by a lateral rotation and abduction of the arm to reach cymbal height. Such movement can be considered either a choreographed pattern or a transitional or linkage movement. These examples are highly simplified, as it is in this analytical level that the DOF problem is encountered.

Rosenbaum's (2010) biological adaptation of Marr's (1982) tri-level analysis provides a solid approach to understanding the movement process. If this three-stage analysis is undertaken in the context of Carson and Wanamaker's (1984) development goals, it is possible to objectively evaluate existing research and literature on human movement, specifically for percussion. Furthermore, the bottom-up nature of the three analytical levels in relation to performing a drumming action allows for a more comprehensive and structured discussion. This recontextualization is described in Table 1.

Understanding the nature of percussive performance variation requires only the computational level of analysis to gain an understanding of the relevance of human performance on timbre and timing and to uncover critical aspects of human movement in physical performance. Although other additional aspects in the other levels contribute to performance variation, this article presents

Table 1. Three Analytical Levels Applied to a Drummer's Development Goals. Adapted from Carson and Wanamaker (1984) and Rosenbaum (2010).

Level/Goal	Physical	Coordination	Endurance
Computational	Planning the control of ▪ The physical movement ▪ Instrumental interaction	Planning coordinated movements ▪ Coordinating simultaneous multiple physical events ▪ Multiple instrumental interactions	Planning movement for improving endurance ▪ Economy of movement
Procedural	The behavioral and cognitive aspects of carrying out a physical movement, relating to ▪ Timbre ▪ Timing	The behavioral and cognitive mechanisms for ▪ Measuring current position ▪ Verifying next movement ▪ Anticipating next timbre/timing	The behavioral and cognitive aspects of improving endurance ▪ Performance psychology
Implementation	The physical aspects of carrying out a movement • Muscle activity • Brain function	The physical aspects of coordinating multiple instruments ▪ Interlimb coordination ▪ Muscle activity ▪ Brain function	Physical ways of improving endurance ▪ Training ▪ Warm up protocols ▪ Performer impairments

rationales regarding why the majority of these are outside of the scope of this investigation due to their highly individual and highly subjective natures, as well as the challenges in adequately proving these.

The first aspect of the framework outside of the scope of this investigation is the behavioral and cognitive aspects of carrying out a physical movement (physical/procedural). This is because behavior and cognition are highly individual, as well as highly dependent on the context of the performance (e.g., genre). An important cognitive element of this analytical level and context includes sensorimotor synchronization (SMS), which is the rhythmic coordination of an action with a regular external event (Repp, 2005). As a result, the computational representation of SMS would be difficult to realize, and the empirical testing required for such a model is outside the scope of this investigation. For further reading on this subject, consider Fujii et al. (2010), Hove, Keller, and Krumhansl (2007), Repp (2005, 2006), Wing, Church, and Gentner (1989), and Wing and Kristofferson (1973a, 1973b).

Another area of the framework outside of investigative scope is the physical aspect of carrying out a movement (physical/implementation), particularly regarding muscle and brain activity. This particular area presents two separate problems. In terms of muscle activity, the most significant modeling challenge lies with the DOF problem and determining which classifiers and representative organizational systems of muscle activation to model. One such solution would be to use a single DOF as a representative for all similar movements in the model. In the case of a drummer, more than one DOF would need to be modeled to cover all limbs. In addition, determining the most appropriate DOF for the movement, and even the process of making such assumptions, will produce theoretical shortcomings (particularly for neurophysiologists). Modeling muscle activations also presents problems regarding the relationship between abstracted models of muscle movement and timbre production—a problem that also is found in modeling brain activity. Further reading on muscle activation and brain activity during performance is available in Fujii et al. (2009), Fujii and Moritani (2012a, 2012b), Gabrielsson (2003), and Todorov and Jordan (2002).

The behavioral and cognitive mechanisms associated with performance feedback (coordination/procedural) encompass a range of methods of feedback acquisition. These include auditory, visual, tactile, haptic, and kinesthetic, and combinations of one or more. Each of these individual types of feedback has different effects on cognitive and behavioral mechanisms and varies depending on the performance conditions. With so many combinations of feedback conditions and environmental variables, finding an appropriate representative model is difficult. Additionally, modeling specific effects of certain feedback conditions would have limited practical application. Therefore, aspects of performance are outside the scope of this research and the reader is directed to Brandmeyer et al. (2011), Dahl and Bresin (2001), Fujii et al. (2010), Gabrielsson (2003), Petrini et al. (2009), Pfordresher and Palmer (2002), and Pfordresher and Benitez (2007).

It was noted above that modeling muscle activity was challenging given the DOF problem, the high level of abstraction from timbre production, the timing of both muscle activity and brain function, and the selection of suitable organizational systems for modeling control and muscle activation. This problem is compounded when considering interlimb coordination as a physical aspect of coordinating the strikes of multiple drums (coordination/implementation), particularly in complex tasks such as rhythm production. In creating complex rhythms bimanually, task complexity between the hands (which include cooperative and disjointed tasks) together with the dexterity levels and handedness of the individual will affect the brain's organizational control of the two hands. In the case of drumming, it is more likely to include leg control for operating the bass drum and hi-hat. This would result in a highly complex study with too many variables to allow for meaningful conclusions relevant to performance modeling. Further reading on this subject, however, is available from Bernstein (1967), Calvin, Huys, and Jirsa (2010), Iannarilli, Vannozzi, Iosa, Pesce, and Capranica (2013), and Kelso, Southard, and Goodman (1979).

Endurance is unique to individuals and can be increased with correct training. However, during performance, endurance can be affected by an individual's level of physical exertion, which can be mitigated by designing sequences of movement that require less movement or that increase their economy of movement. Other behavioral and cognitive aspects of improving levels of endurance fit firmly within the realms of performance psychology, which are difficult to represent in a computational performance model. Similarly, the modeling of training and warm up protocols also is outside of the scope of this investigation in that they do not bring any direct benefit to the modeled system. No benefit would be gained by modeling a performer with an impairment, such as modeling a drummer with low levels of endurance, because the system would be designed with a level of performer obsolescence, resulting in poor playing after a period of time. Therefore computational, procedural, and implementation levels of analysis relating to endurance are outside the scope of this investigation. However, further reading is available from Abernethy, Hanrahan, Kippers, Mackinnon, and Pandy (2005), Gabrielsson (1999, 2003), and Shaffer (1989).

Thus in the following sections, discussion will focus on physical movement, instrumental interaction, and bodily movement in the context of human movement in the physical world. The aim of this research is to identify a method for analyzing the critical elements of music performance movement for electronic representation in either an interactive music or a virtual system. It is worth noting that, although some aspects of the framework are specifically identified as being outside the scope of investigation, there are overlaps between some of the variables mentioned and aspects of performance that will be discussed in the following sections. Their inclusion within the discussion serves to highlight the complexity of percussive performance and demonstrates the wide reaching implications and importance of the discussion.

CONTROLLING INSTRUMENTAL INTERACTION

Why is physical control so important? Striking an object with another object has two repercussions. Firstly, when the struck object produces sound, vibration in the stick travels through the fingers to the hand. In some instances, and depending on the force of the strike and the materials involved, this can extend into the arm. In severe cases, this can cause discomfort (e.g., using a metal bar to strike a large mass of solid metal with extreme force). Secondly, striking an object can cause the striking tool to be deflected away from the surface and, depending on the elasticity of struck materials, the level of deflection will be either minimal (e.g., a hard metal surface) or more significant (e.g., a membrane under tension). Because playing the drums requires striking many objects consisting of different materials, and striking them at different strengths, the amount of vibration experienced in the player's body varies among the instruments and which, during drum set performance, is exacerbated by deflections of the striking implement caused by different elasticities in the struck surfaces, the angles of the initial strikes, and the strike forces across the individual components of the drum set. Strike location plays a significant role in modal frequency excitation, subsequently affecting the timbre of the drum. Moreover, because playing the drums often requires multiple strikes, it is important for timbral consistency that the drummer maintains physical control of the striking implement across a diversity of potential strike interactions.

Understanding how a performer maintains physical control of a striking implement is important in contextualizing how timing and timbral variations occur in a drumming performance. This information also is useful for developing a performance ontology in which the system either simulates the elements or the results of physical control or transitions into new states as a result of identifying embodiments of physical control as input parameters. This section provides a bottom-up approach to discussing and reviewing the literature concerning instrumental interaction, starting with stick contact and grip, stick rebounds, and preparatory strike movements, to coordinating bodily movement and drum strike trajectories across multiple drums. This approach facilitates a detailed discussion of the complex nature of percussive performance and helps in identifying emergent themes in human percussive performance movement and biomechanics.

Stick Contact

The first point of interaction between a drummer and the drum lies with the stick contact on the surface of the drum, particularly stick contact time. Billon, Semjen, and Stelmach (1996) found, during finger tapping exercises of accented beats, that finger contact time was greater than nonaccented beats. An investigation into stick contact times on a tom-tom by Dahl (1997a) found contact times to decrease with strike force. These stick contact times were measured electrically by using adhesive copper foil on both the surface of the drum and the stick, with data collected for different strength strokes (*pp*, *mp*, *mf*, and *ff*)[2] at the center of the membrane (Dahl, 1997a, pp. 64–65). The results showed that contact time decreased in a nonlinear manner with increased strike strength, ranging from 8 ms to 5.5 ms for the four dynamic levels of strikes in the experiment. Dahl ruled out the surface material and vibrational reflections from the rim of the drum as contributing to this behavior by performing similar strikes on a softer surface (a carpet) and obtaining similar results; he also measured the reflected waves of the drum head on the stick with an accelerometer. Dahl found that the reflected waves were not strong enough to influence the stick motion, but did affect the stick's bending mode at around 475 Hz.

These findings present an interesting paradox in accented playing and contact times. In some kinematic analyses of percussionists, Dahl found that drumming accents that alternated between hands (i.e., interleaved) were played with increased stroke height (Dahl, 2004). With a correlation between higher preparatory strike heights and striking velocity, including higher dynamic levels (Dahl, 2004, p. 768), Dahl reported that accented strikes tended to have lower stick contact times. In a direct comparison between tapping with a finger and a drumstick on a force transducer, Fujii and Oda (2009) found that there was little difference between tap speed and peak force variability between the finger and stick in 10 s tapping bursts among 17 drummers. However the authors noted that tapping with a stick produced shorter contact times, with a larger peak force and greater stability in the intertap interval, than finger tapping. The authors concluded that the stick "allows drummers to play drums powerfully and stably" (Fujii & Oda, 2009, p. 969). The authors also noted a difference in tap rate and stability between the left and right hand, with the nondominant hand being generally the weaker of the two.

Beyond the practical aspect of force and stability, the player can dampen the vibration of instrument by forcing extended contact with the drum head, thereby adjusting the timbre of the strike. However, due to the generally small contact times with the drum head, such actions must be preparatory and integrated into the strike (Dahl, 2005). The challenge faced by the player, particularly with higher striking velocities, is the deceleration of the drumstick when it makes contact with the membrane and the rejection of the drumstick when the membrane contributes towards the stick's acceleration in the opposite direction (Wagner, 2006), referred to in drumming as rebound. In the case of a damping effect, the player must exert an opposing force greater than the accelerating force of the membrane and, in the case of a nondamping strike, the player must cease the downward force on the membrane to ensure no further stick contact once the initial opposing acceleration has subsided (e.g., a stroke that can rebound freely). In either case, the stroke is largely determined by the player's grip on the stick.

The effect of stick grip on the sound characteristics of a drum was investigated by Dahl & Altenmüller (2008a, 2008b), who measured contact force, duration, and pre- and poststick velocity for two different types of grip: a normal grip, where the stick was allowed to rebound freely, and a controlled grip, where the player was asked to stop the stick as close as possible to the membrane after the strike. The authors adopted an approach similar to Wing et al. (1989) in measuring the movement of the stick, index finger knuckle (Metacarpophalangeal or MPC joint), and wrist for both grip types. The authors found that more energy was transmitted to the drumhead in the controlled stroke, with higher peak force and lower contact durations. In addition, the constraining actions of the wrist and MPC joint in the controlled stroke produced a lower poststrike velocity. In order to identify the effect of these grips on the sound of the drum, listening tests were carried out and the normal stroke was considered to have a more full timbre as compared to the timbre of the controlled stroke. The authors noted that this was due to the longer contact durations dampening some modes of the drum but, more interestingly, they "appeared to have affected both the effective mass and possibly also the stick modes" (Dahl & Altenmüller, 2008a, p. 1494).

Different timpani stick grips were analyzed by Bouënard, Wanderley, and Gibet (2008) using motion capture techniques to simulate virtual timpani performance in character animation. This study included analysis of shoulder and elbow motion, which was subsequently simulated using a hybrid approach (Bouënard, Gibet, & Wanderley, 2009) combining inverse kinematics or IK (using equations to determine the joint positions and the position of the stick tip) and inverse dynamics or ID (using position velocity and acceleration to calculate forces and moments). The model was then extended further to include 11 joints with 33 DOF together with the calculation of stick contact information for modal synthesis (Bouënard, Gibet, & Wanderley, 2011), which produced accurate character animations of timpani performance. However this approach was limited to a single drum with the performer using only arms in playing a limited number of drum techniques. Extending this approach to a nine-piece drum set may be computationally impractical, owing to the number of IK, ID, and modal synthesis calculations.

Exclusive of the timbral variations created by the instrumental mechanics, producing an accent or a desired timbre requires preparation on the part of the performer. The performer must be able to adjust (loosen or tighten) his/her grip or adjust the looseness of his/her lower arm (the wrist and MPC joint) to change the interaction between the stick and the drumhead, thus producing variations in timbre. One of the key drivers for grip modification in drumming is to control the amount of rebound. However, as Dahl and Altenmüller (2008b) noted, a grip adjustment for controlling rebound should theoretically be done poststrike because the implicit equation in the preparation for physical movement affects the sound production of the stroke.

Stick Rebounds

Stick rebounds can have both a positive and negative effect on drumming, depending on the required loudness of the subsequent stroke (Dahl, 2003, p. 11). Furthermore, stick rebound is determined largely by the player's grip, with looser grips allowing more rebound. In a pilot study on drumming sequences with interleaved accents, Dahl (1997b) found that the stick tip position immediately following an accented strike was heavily influenced by the rebound. Dahl noted that the tip height of the rebound following an accent is "above the optimal starting position for the following soft blow" (1997b, p. 5). In the study, the players' dampened rebound was manifested in fluctuations in tip position following the accented strikes. This fluctuation resulted from the player exerting force on the stick in opposition to the upward acceleration and then reacting to a small overcompensation before returning to the typical stick motion (albeit with a higher starting position for an unaccented strike). Despite the increased (suboptimal) stick height, the time between the onsets of the unaccented strikes (also referred to as the inter–onset–interval, or IOI) appear unaffected, owing to an increase in strike velocity to counteract the height (despite the drummers in the study playing some preaccented strikes early as part of the planning process).

A later study by Dahl presented data addressing this issue, in which larger IOIs occurred in sequences played at softer dynamic levels and at slower tempi (Dahl, 2000, p. 229). In this study, Dahl concluded that the 68% drop in IOI range from *ff* actions at 200 bpm (beats per minute) to *pp* actions at 160 bpm was the result of weak rebounds from the softer strikes that, in turn, made "the playing more difficult to control" (Dahl, 2000, p. 232). Generally, notes in drumming can be accented using either a higher dynamic level or prolonged note durations. The former method for accentuation requires a higher preparatory movement. Despite this, Dahl observed that movement increase did not necessarily equate to a delay in the accented note. Instead some of the unaccented strokes following an accent were delayed, although this delay was not consistent. This lack of consistency suggests that rebound control stemming from the greater accented stroke preparatory movement that, when combined with the difficulty in controlling weak rebounds, could account for the "short term variations between adjacent IOIs" or "flutter" (Dahl, 2000, p. 228). This flutter ranged between 2% and 8% of the relative tempo of the subjects and was more noticeable at slower tempi.

In contrast to weaker rebounds, stronger rebounds are more conducive to player control. Furthermore, players can exploit the upward acceleration of stronger rebounds to achieve greater preparatory height with less effort (Dahl, 2000, p. 232). For the moment, ignoring the issue of stroke height apex control, the exploitation of rebounds requires significant planning and has some far-reaching implications on a player's drum performance. A drum set consists of several drums often on multiple dimensional planes. For example, tom-toms (particularly those mounted on a bass drum) can be adjusted to different angles from the horizontal, depending on preference, their mounting mechanism, and size. Additionally, cymbals tend to be angled to avoid weakening the edge of the instrument from repeated strikes or chewing up the drumstick and to allow the player to strike the bell. From a practical viewpoint, these also can be positioned at any angle on the vertical plane relative to another instrument, depending on personal preference. Thus, the angles of deflection of the rebound can be more or less complementary to a subsequent stroke on another drum, depending on their relative positioning. Furthermore, the angle of deflection on the first drum relies upon the initial stroke angle. This is determined largely by the positioning and deflection angle of precedent strokes (if any), planar positioning of the drum relative to the player, and player posture. It is in this context that instrumental interaction has a significant impact on the execution of transitional movements. This is depicted in Figure 2. For clarity, the strike locations have been placed off center, although the principle applies to a centrally struck drum.

The horizontal drum on the left in Figure 2 is a simplified example of a typical rebound of a drum in a low horizontal plane, similar to the position of a snare drum; the downward stroke tends to be more vertical due to the player's superior position. The stroke angle is assumed to be closer to the player and the rebound angle away from the player. The angled drum on the right provides an example of a drum closer to the vertical plane and positioned to the right of the player. This example shows the effect of a single strike in a drum fill, where the previously struck instrument was positioned to the left of the player (causing the strike trajectory as illustrated) and

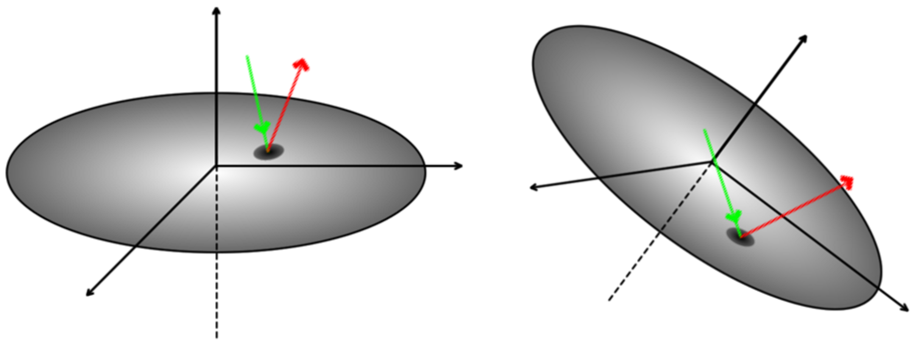

Figure 2. An illustration showing a potential deflection angle on a horizontal drum (left) and an angled drum (right). Arrows indicate strokes (downward) and the rebounds (upward). The black arrows represent the three dimensional Cartesian coordinate system to illustrate the rotational change of the drum head (not to scale).

the rebound points towards the next drum target. In this example, the deflection angle is complementary to the following stroke. However, a deflection relies on a number of variables. Figure 3a shows a theoretical ideal of the angle of deflection relative to the strike trajectory. In practice however, the contact between the drum and stick can be forcefully increased during a narrow strike angle coupled with momentum (Figure 3b). In this example, the angle of deflection becomes wider, potentially reducing the complementarity to the subsequent stroke. The prolonged interaction of the stick and drumhead also can affect the timbre of the drum.

Many variables can affect the rebound angle and velocity, several of which already have been discussed. However, it was noted by Wagner (2006) that the rebound speed also depends on the tension of the membrane. Wagner's experiments on the force, contact time, and acceleration of a drumstick at different membrane tensions demonstrated that an increase in stiffness affects the speed of the transversal wave propagation and internal reflection from the rim. At the same time, this also decreases the contact time in that fewer vibrational modes are excited due to a reduced force pulse (Wagner, 2006).

Drums come in different sizes and with different tensions, so a drum set contains variations in rebound behavior. Although Dahl's (2000) experiments used two-headed drums, the investigations focused on player movement. Wagner's (2006) experiments concentrated on the interaction between the stick and drum but used single-headed drums. There currently is no detailed literature investigating stick and cymbal interaction although, given the pivotal movement of a ride or crash cymbal on a stand, it can be assumed that there would be limited interaction with the stick as the cymbal moves away from the stick as a consequence of the downward force of the cymbal movement. In the case of a rebound that is in opposing trajectory to the subsequent strike, Dahl's (2000) controlled striking experiment demonstrated that the player preemptively compensated for the rebound by using finger, wrist, and arm muscles to counteract the acceleration.

Rebounds also occur in the foot pedals associated with the bass drum and the hi-hat. In the case of a bass drum, the static strike location of the beater on the membrane ensures that rebounds manifest themselves consistently between strikes. The bass drum pedal mechanism also amplifies the rebound because the weight of the beater on the swing arm, combined with the torque from the movement of the foot pedal, tends to push the beater to its default "open" position. As a result, pedal control is important and muscle use is more constant. In the case of the hi-hat, the opposing force to the foot is in the counterweight of the upper hi-hat cymbal, thus

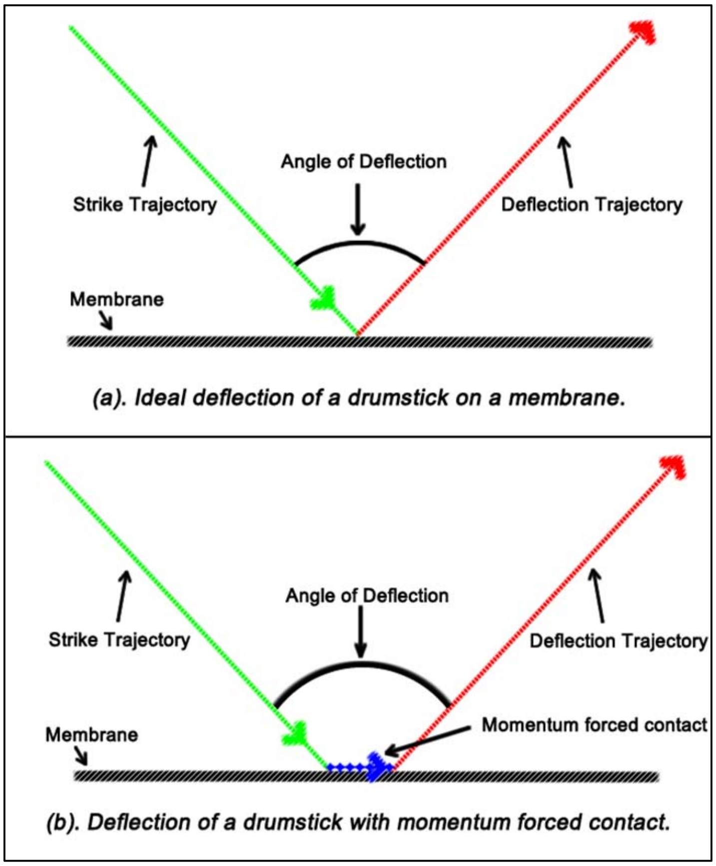

Figure 3. An ideal deflection of a drumstick on a membrane (a) and the deflection of a drumstick with an acute strike trajectory and momentum forced contact (b).

releasing the pedal opens the hi-hat. Opening the hi-hat generally occurs less often than striking the bass drum in many genres of music so constant pressure is usually applied to the pedal with pressure release opening the hi-hat. The ratio of pedal to hi-hat movement can be adjusted but, in general, controlling this is much easier than controlling a bass drum. Rebounds do not always have an inherently positive effect on playing. Weak rebounds are difficult to control, and opposing rebound trajectories can require either more effort to control or quick reflexes for immediate control. For immediate control, the player must anticipate the rebound and/or modify the preparatory movement of the stroke.

Preparatory Strike Movement

In Dahl (2000), the comparison between the motion of a drumstick tip and the hand during an accented stroke showed that the hand moved upwards before the tip of the drumstick and that this leading hand movement occurred while the stick was still in contact with the surface of the membrane (Dahl, 2000). The maximum upward velocity of the hand was 2 m/s with a height of 50 cm above the membrane compared with 4 m/s for the tip and a height of 70 cm (Dahl, 2000). Dahl explained that the differential in upward velocity and height means that it is

> not until the stick has passed its upper turning point [that] an actual force delivery may be applied by the wrist (or fingers) to increase the speed. The result is a “whiplash” of the tip of the drumstick but the motion of the hand is smooth, resembling a fishtail-gesture. This characteristic fishtail motion of the hand in the preparation and delivery of the accented blow is certainly used in other ways in drumming, like reaching a position on another drum far away in ample time. By starting the movement before the last note is finished the player gains time and thereby effort. While the hand and fingers still control the last stages of the present tone the lower and upper arm have already started to move in position for the next. (Dahl, 2000, p. 227)

The fishtail movement described by Dahl is characteristic of several of the findings by Kelso, Buchanan, and Wallace (1991) in which the sequence of strikes resembles prone in-phase (where similar muscles simultaneously contract) movements of the forearm to a metronome. These prone in-phase movements were found to produce a more curvilinear trajectory than antiphase movements (where similar muscles do not simultaneously contract), thus having implications for drumming performance. Firstly, Kelso et al. found that, at a certain metronome frequency, around 1.5 Hz, or 90 bpm, a participant starting in an antiphase manner spontaneously switched to an in-phase movement to keep in time with an increase in metronomic frequency. Kelso et al. noted that, prior to the automatic switch to an in-phase movement, the velocity (which was generally more stable with in-phase movements as compared to antiphase movements) became unstable with a sharp decrease of instability observed shortly after the phase switch. They also observed that, conversely, a participant starting in an in-phase position does not switch to an antiphase position with an increase in frequency. This one-way automatic phase transition suggests that the heterologous nature of the muscle activity in the antiphase movement is less economical, resulting in a decrease in consistency of velocity and, ultimately, comfort. Additionally, the prone in-phase hand positions coupled with the velocity stability allows drummers greater control of the stick-to-hand interaction.

On the subject of movement analysis, two distinguishing features exist between the findings of Kelso et al. (1991) and Dahl (1997b) related to hand movement at the lowest part of the movement (i.e., the stick and drum interaction) and the highest part of the movement (i.e., the fishtail motion at the top of the stroke height). Regarding the stick–drum interaction, when a player starts a movement early (i.e., from the moment of impact), it causes the player to be ahead of time, therefore reducing the need to reactively make inefficient movements. It also allows the player to take advantage of the existing lower and upper arm movement, which is important in instances where the subsequent stroke requires bodily rotation to achieve optimal positioning for the next preparatory movement. For example, this is particularly relevant in sequences involving drums positioned at distance from one another. The greater the distance between the drums, the further the body must move. At higher tempi, it becomes increasingly more challenging to make the movement in the required time.

The second component of the hand movement is the fishtail motion at the upper turning point of the tip. This upper turning point is subject to the least amount of force, and so it is easier to influence. In contrast to the bottom of the strike, there is no rebounding force so the player employs a fishtail motion of the hand to cause the tip to change direction quickly and to move with greater acceleration. Because playing the drums is an ongoing time-sensitive system, both of these two components are necessary for a player’s improved economy of movement.

The overriding goals of these components draw parallels to Shaffer's (1989) description of the motor geometry in piano performance:

> Getting the fingers to the right locations on an instrument is important but only part of the motor task in playing. The performer can learn to shape the trajectories of movement so as to achieve timing of rhythm and variation of dynamic and tone quality with an economy of motor effort. (Shaffer, 1989, p. 383)

It is evident from both Dahl (1997b) and Shaffer's (1989) description of musical performance that drumstick management comprises technical elements of playing the drums, particularly the control of rebounds and the control of stick at the height of the strike motions. Technical elements in drumming contribute toward accuracy in timbre production and timing control. Although Dahl (1997b) described variations in the overall motion among the participants (especially at varying skill levels), the curvilinear trajectory followed the findings by Kelso et al. (1991).

Bodily Coordination

One important concept of choreography that contributes toward motion and form is that of balance arrangement, particularly whether the body is symmetrical or asymmetrical, which is indicative of stability and equilibrium or irregularity and imbalance. Playing the drums requires both bilateral movement (both limbs moving in unison) and unilateral movement (one limb moving at a time). Although drumming can be considered symmetrical (mirrored) or asymmetrical, depending on the combination of individual drums being played (i.e., the context), the process is inherently asymmetrical owing to the configuration of the components of the drum set. This article discusses the effects of the inherently asymmetric environment and how a drummer responds to and uses asymmetry in designing drumming sequences.

Aruin and Latash (1995) investigated the effect of opposing bilateral fast movements on the shoulders (with and without load) of subjects standing on a force platform. They found that anticipatory postural muscle adjustments (APAs) in the trunk and leg muscles were made by the subjects to maintain balance, with adjustments increasing to a maximum when arms were moved in a forward or backward motion and decreasing to no APAs when moving the arm along the sides (i.e., the coronal plane). Furthermore, the authors found no significant difference in muscle adjustment as a result of additional load on the arms. These APAs were evident by changes in the subjects' anterior, posterior, and vertical centers of pressure and gravity on the force plate prior to the movement.

In the case of drumming, it is quite common for the drummer to be in a seated position with much of the player's weight supported by the seat. Consequently, the leg muscles play a lesser role in redistributing centers of force and gravity for an APA. The redistribution of weight using the legs is further complicated by their use in applying independent pressure to the hi-hat and bass drum pedals. Consequently, upper body stabilization is carried out by the trunk, specifically the erector spinae (ES) and rectus abdominis (RA), irrespective of the types levels of support in the legs (Aruin & Shiratori, 2003). These findings were supported by Santos and Aruin (2008), who also found that the lateral muscles contributed to upright posture control in feed-forward movements (i.e., movements relying on anticipatory correction), akin to feed-forward movements in drumming and where the level of muscle activation being is directionally specific. With both legs in a fixed position for operating the hi-hat and bass drum, a drummer's directional posture control is of great importance, particularly in controlling movements requiring axial rotation of the upper body.

Thus APAs in compound multijoint movements—especially those involving changes in direction (Holmes, 1939, pp. 17–19) such as bilateral fast movements of shoulders coupled with point-to-point axial rotation—are critical in maintaining postural stability. However, in addition to bilateral movements, a drummer's arm movements often are unilateral, are not directly opposing, and are executed at different strengths and speeds relative to the location and distance between subsequent drums to be struck. Where a drummer has different maximum arm heights relative to the horizontal plane, as well as different maximum distances in arm reach required from the center of the torso between strikes, then postural control and stability also affects movement on the vertical (i.e., sagittal) plane. Thus, consequently, a hunched-over position is not conducive to playing strikes at greater heights. With this in mind, it is easy to imagine the variations in the centers of pressure and gravity on a player during the course of a percussive performance. In fact, Alén (1995) suggested similar links between movement and performance variations. In his analysis of the Cuban music genre tumba francesa, particularly a type of performance called a toque macota, Alén described how the large size of a Cuban bulá drum may have affected the performer's stabilization, requiring torso movements that could contribute towards timing deviations.

Although there are vast differences between the drum set and the bulá, it is conceivable that Alén's (1995) links also apply to playing the drum set. One theoretical view is that a performer mitigates these effects by maintaining a postural equilibrium, with extreme changes in postural stability countered by APAs stemming from performance planning and musical read-ahead, both of which can be linked to performance skill and having repercussions on musical gesture as a learned deviation.[3] In summary, one general rule of drumming performance variation is that the greater the distance and angle of movement (relative to the torso) prior to the strike, the greater the inequality between the opposing reach angle and distance of the other hand, the greater the synchrony/asynchrony of the arm movements, the more complex the biomechanical and neurophysiological process and the increased likelihood of performance variation.

Drum Strike Trajectory

The trajectory of a drum strike is important in drumming to such an extent that drum strike trajectory was used as an important component in the compositional specification of Karlheinz Stockhausen's composition *Zyklus* (1959). As described previously, rebound control can be used to affect the trajectory of the subsequent strike in a sequence of percussive hits. Between rebounds, the player must move the stick from one strike location to another at a speed sufficient for maintaining correct timing. The success of this aim is largely dependent upon trajectory, defined by Abend, Bizzi, and Morasso (1982, p. 331) as "the path taken by the hand as it moves to a new position and the speed of the hand as it moves along the path."

In their study of hand trajectory to target, Abend et al. (1982) found that the majority of subjects who were asked, with no instruction, to move their hand deliberately to a target, opted for a straight line. With the shortest distance between two points being a straight line, one would expect movements with straight trajectories to have a shorter duration than curved trajectories to the same target. Although this was found to be true, movement duration also is dependent on speed, which Abend et al. found to be more irregular during curved trajectories.

However, in cases where the average speed was low, even straight trajectories showed irregular speed patterns, suggesting greater difficulty in controlling the movement. In a performance context, a lower movement speed and, therefore, a lower strike velocity, will produce weaker rebounds. Thus, the interaction with the instrument in terms of rebound control and the movement between the strikes is harder for the player to control.

Regarding the irregular speed profiles of the curved trajectories in Abend et al. (1982), it was noted previously that the movement of a drumstick during a strike has curvilinear resemblances due to the phasing of muscle movements (Kelso et al., 1991). However, a connection between the two cannot be drawn because there were differences in planar movement in these studies. The participants in Abend et al. (1982) operated on a horizontal plane, compared to sagittal movements in Kelso et al., (1991) and compared to both sagittal and horizontal movements in Dahl (2000). Despite this, there was a correlation in the increased irregularity in hand speed relative to the antiphase nature of the angular velocity of the shoulder and elbow—in other words, a joint-focused dichotomy with parallels to Kelso et al.'s (1991) muscle synergies.

Drumming invariably uses multiple joints, each with different torques applied from the muscles that, in a multijoint movement, extend to the interaction of other joints and torques in the movement. In the case of multijoint movement, each joint will be subject to different velocity interactions at various points in the movement. Where a trajectory is changed midair and not using a rebound (e.g., at a higher preparatory stick height, as in Dahl et al., 2011), the joint torques will change depending on the new trajectory. Such a movement is subject to interactional forces during the planning and control of the movement—such as the Coriolis, centripetal, and reaction torques (Abend et al., 1982, p. 331)—although the effects of these forces change dynamically over the movement. Hollerbach and Flash (1982) observed such behavior in relation to a curved trajectory where "the velocity interaction torques in fact completely dominate the dynamics at the movement midpoint because the inertial torques go through zero as the movement switches from acceleration to deceleration and the arm is moving the fastest at this point" (Hollerbach & Flash, 1982, p. 76).

In the case of a single stroke, as measured in Dahl et al. (2011), the midpoint would be the arc at the peak of the preparatory movement. In some instances, a change in trajectory at this point would have three benefits. Firstly, this enables a greater preparatory stroke height for the next strike. Secondly, the greater height enables higher maximum acceleration and downward velocity. Thirdly, as a point with the least amount of inertial torque, the player can prepare for the joint torque of the next movement. Such torque control can mitigate timing variation.

In terms of accuracy, it has been found that the trajectory of aimed movement can be learned. These learned trajectory movements were demonstrated by Georgopoulos, Kalaska, and Massey (1981) during a study of aimed movements in Rhesus monkeys. They found that practice over a period of time reduced the mean variability of the trajectory towards a target, together with improved accuracy, irrespective of target location. The implication here is that a human drummer is likely to do the same using the drums as targets. However, as previously noted, drumming requires bilateral and unilateral arm movement, and humans can be either left handed or right handed. Each of these have been demonstrated to be contributing factors towards target accuracy (Garry & Franks, 2000), with increases in reaction time for bilateral strikes with targeting aimed by the weaker hand compared to unilaterally mirrored targeting.

The effects of this can be minimized through drum set configuration, with little impact on multijoint bilateral movement.

Although several factors can affect trajectory and control during percussive performance, the most significant factor occurs during multijoint movement, where joint torques impact not only the choice of trajectory but also the control and speed of the movement. In the case of drumming, sequences involving multijoint movements can often include multiple simultaneous planes of motion and axes of rotation. Such an action is illustrated in Figure 4, where a drummer's movement is described between changes of strike location, from a strike on a snare drum to a strike on a crash cymbal.

In the example in Figure 4, during the movement of the right hand from the starting position (snare drum) to the crash cymbal, there is abduction and extension of the right shoulder on the frontal plane with a posterior axis of external rotation. There is also an elbow and wrist extension on the sagittal plane with a lateral axis of rotation. Assuming no movement to the left arm, then there is also a vertical axis of rotation of the trunk on the horizontal plane to allow the drummer to position the body for reaching the new target. Kinetically, each of these axes of rotation and movement in this multijoint sequence contain torque forces that affect the movement.

If the drummer in the figure had not included a strike at the crash cymbal but a repeat strike to the snare drum, there would have been minimal changes to the existing patterns of joint torque and muscle activation. Additionally, another drum located at the same height as the snare drum, but closer to the crash cymbal, would cause the drummer to make a trunk and shoulder rotation. However, because the drums are at a similar height, there would be less movement over the three planes. Therefore, movements spanning multiple planes of motion and axes of rotation are most likely to affect the movement of a drummer and, subsequently, the timbre and timing variations. Multijoint movements, such as those in Figure 4, are considerably

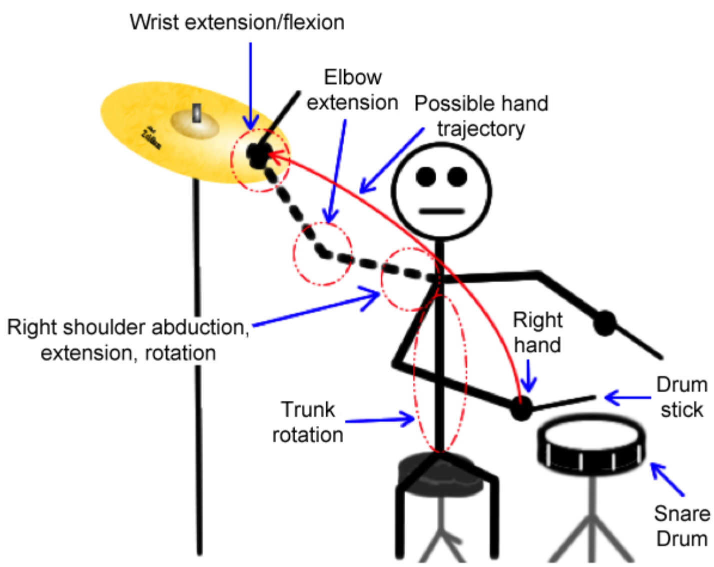

Figure 4. An illustration showing the typical movements associated with a change of strike location by a drummer moving from a snare drum strike to a crash cymbal strike.

problematic to model because there are 17 DOFs in movements of the shoulder, elbow, and wrist: 9 kinematic net moments and 8 dynamic with optimized muscle forces (Chadwick & van der Helm, 2003, p. 15).

This discussion presents some clear difficulties in modeling percussive performance from body, movement, and spatial perspectives. Firstly, stick management plays an important role in the interaction between the stick and the drum in the way that stick contact times can be influenced to alter the vibration of the drum (and the subsequent timbre). Similarly, stick grip influences the rebound of the stick from the drum, which has two effects on drumming: force contact dampening of a drum after a strike and positive and negative rebound use for subsequent strikes, particularly in sequences of drums operating at different angles and locations relative to the torso. Although in most cases stick control can be executed during the strike, due to time constraints much of the rebound and strike control is managed during preparatory movements.

During the downward motion of a strike, a curvilinear trajectory was observed in Dahl's study (1997b); this can be explained by the phasing of muscle activity in the homologous muscle groups of the arm (Kelso et al., 1991). In-phase muscle activity produced greater arm stability and economy of movement, which is a contributory factor in stick control. At the apex of a strike, a fishtail motion was described (Dahl, 1997b), which further exploits the existing synergy between muscle activities by taking advantage of the upstroke to minimize additional muscle activity in the upper arm. In bimanual and unilateral arm movements, which are common occurrences during drumming, APAs were observed as a means to maintain postural stability. These involved small muscle movements that compensated for changes in force (e.g., changes in the center of gravity) resulting from arm extension. The effect of this, when in a seated position, is that the trunk is responsible for postural stability in the upper body. With more complex arm movements in drumming sequences, compared to the simple arm movements as studied in previous research, the potential need for constant postural anticipation and control was highlighted, particularly in arrhythmic unilateral strikes at nonopposing angles and at various distances from the torso.

TOWARDS A TEMPORAL MOVEMENT CONTEXT

This study aimed to assess the current literature relating to human percussive performance on a nine-piece drum set. This was done in order to understand human movement and rehearsal as choreographed motion. The notion of choreography in the real-world context of drumming, as rehearsed sequences of movements, stems from the internationally recognized drum rudiments intended to develop percussionists' physical control, coordination, and endurance.

In the virtual world context of interactive computer systems, a clear understanding of how these development goals relate to instrumental interaction, biomechanics, and human movement provides an opportunity to explore the interaction possibilities between human and machine. The tri-level Marr/Rosenbaum framework (Table 1) for analyzing information systems and motor control, applied through the lens of the development goals, facilitated a bottom-up analysis of real-world human interaction with drums. The significance of this approach from a human-to-machine interaction perspective is that real-world, bottom-level interactions (i.e., end effector interactions) can have a significant impact on any generated simulation (e.g., force contact affecting the timbre of a drum by altering the drum's vibrational characteristics). Such conditions may be either too difficult to mathematically represent or computationally too expensive, particularly across the nine individual components of a drum set. Understanding the nuances of real-world interaction provides for more informed decision making when designing interactive virtual systems and human interaction. Design options include substituting mathematical representations (algorithms or subsystems) of some interactions with similar level representations (algorithms or subsystems) of other interactions. The measurement of such interactions may allow design choices that defer interaction from a dynamic mathematical representation to a sensor-based human interface (e.g., measuring force contact duration on a computer-enabled surface), thus reducing computational overhead while simultaneously maintaining real-world interactive authenticity.

The hierarchical nature of a bottom-up analysis allows each real-world interaction to be contextualized within a larger set of movements. In the virtual world, this is equivalent to merging two subsystems to form a larger complex system representative of a more abstract function. From an interaction perspective, this may mean deriving a force contact duration from a series of assumptions about the current state or the context of the system. Such an abstraction could include the representation that stick control is more difficult with weaker rebounds, thus weaker striking leads to longer durations of force contact. However, as each interaction is abstracted to a larger set of movements, human interaction with the system becomes more abstract. Consequently, in designing an interactive system that simulates human percussive performance, there are trade-offs in deferring simulation functions to either horizontally integrated subsystems or abstract layers with regards to the level of similar real-world human interaction with the system. This analytical framework provides a unique way of investigating human percussive performance while concurrently analyzing computational aspects relevant to the system design. The convergence of these two paradigms manifest themselves in system interactivity and how the system represents real-world movements that are inherently both compromised and unique, depending on the vision of the system.

Representing Human Movement

It is clear that significant issues exist in using the biomechanical considerations of the human body during percussive performance as a method of generating both performance context and in algorithmic control of representative computational musical output. Fundamentally, the main problem in modeling drum set performance is that it is predominantly asymmetrical: The performer's arm movements (e.g., reach distance, height, and angle) are often unequal, and the rhythmic striking of these can be irregular. The inequality of arm location and irregularity in drumming constantly changes the joint torques and the force interactions that affect trajectory control, movement stability, and postural stability, which subsequently affect strike control, strike accuracy, rebound control, and stick management, ultimately causing variations in timbre and timing. This problem is compounded by an almost infinite number of combinations of movements between Cartesian strike coordinates during drumming and, if one takes into account the DOF problem, there is an extreme abundance of potential system representations. Such an abundance of potential representations would be hard to implement computationally; yet, the selection of a smaller number of representatives is difficult to justify theoretically. As Abend et al. (1982) noted, there would need to be an inverse kinematic transformation of the Cartesian-to-joint coordinates and then, using inverse dynamics, the joint torques would need to be calculated. This has significant implications for both the selection of particular variables that would form the basis of any computational model and on the way in which these variables are represented.

One way of representing human body movement in percussive performance would be to examine a specific movement and identify the most likely used DOF in the joints activated during that movement, such as the methods used by Bouënard, Gibet et al., (2011). This would require investigating the effect that each individual joint can have on the overall movement, including the selection of multiple DOFs and subsequent joint angles on the outcome of the movement. Such an approach would allow for an assessment of whether a variation in DOF at a joint closer to the instrument has a greater impact in producing biomechanical errors than variations in DOF at joints closer to the torso. In addition, preferences and/or trends in planar movement for each joint for a given movement could be identified, together with the impact of these planar preferences on biomechanical error. One way of computationally representing this approach is to design an algorithm that uses weighted probability to calculate the likelihood of a selected DOF or angular movement in a given joint. An example of a method of representing this computationally would be a Gaussian distribution of values to represent a joint angle (e.g., shoulder) and a Markov chain to determine the next selected joint angle (e.g., elbow), and so on until a joint angle value is determined for the wrist. At this point, a movement assigned a unique identification number could be used to trigger a predetermined timbral or temporal variation to represent the level of biomechanical error in the movement (as compared to a theoretical ideal).

Determining the probabilities of joint variation within movements would require significant analysis of multijoint, multiplane movement and would require also measuring a quantifiable error from the various movements. Furthermore, deciding which movements to investigate can be problematic in that their relative importance is highly subjective. In addition, identifying preferences or trends in movement at joint level may require significant sample sizes and may generate large quantities of data, particularly should the three axis planar movement be measured at high frequencies. Finally, a link between joint variation and performance variation would need to be quantified and would require multiple methods of analysis, for example, correlating data from joint movement with audio to identify the trends in performance variations associated with combinations joint values. Exactly how the many combinations of joint values represent performance variation also is critical in reproducing human percussive performance in a computer environment, as it relates to a method of controlling one or more aspect of musical parameters, such as timbre or timing.

Another potential method lies in the representation of the drumming techniques by creating an algorithm that represents the DOFs associated with a particular drum rudiment. A skilled drummer will have a standard repertoire of drumming techniques at his/her disposal; so it may be possible to assign various combinations of movement to a given technique that then generates a musical output that closely resembles that technique. However, the execution and application of these techniques will differ across performers and performances, notwithstanding the stylistic differences of the performed music. As a result, the process may produce disjointed sounding performances because the selected techniques are inappropriate, unusual, or humanly impossible for the given musical or performance context. Of course, it may be possible to concatenate algorithmic representations of techniques to form a coherent performance, but that depends upon whether the techniques have unique muscle and joint activations that are reproducible and relevant. The most significant challenge in this approach is identifying and empirically measuring these multiple techniques within a performance and determining a unique movement value. The difficulties associated with collecting joint information as described above are suddenly increased when more variables are introduced into the performance context. It is clear that, in designing a system that simulates human percussive performance, the sheer number of biomechanical and performance considerations pose significant challenges in computationally representing any meaningful or situationally specific interaction. Therefore, it is useful to consider the biomechanical considerations and performance context at a lower level of detail and in the context of playing the drums. So what do we know at this point?

One broader view that can be taken for the purposes of modeling percussive performance is that large multijoint movements operating on multiple planes of motion are more likely to generate performance variations for two reasons. Firstly, a percussive performer playing the drum set is inherently constrained by his/her number of limbs regarding how many instruments can be struck simultaneously. For example, a nine-piece drum set has 64 potential combinations of simultaneous instrument strikes using only the two hands. With the feet fixed in position, the main areas of movement lie in the upper body and torso, which relates to the complexity and equality of bimanual drumming. Secondly, because the number of drums limits the combinations of arm movements, the complexity of the movement is largely affected by prior arm location.

Collecting Data from Human Movement

The literature discussed in this article present various methods for obtaining observational and empirical data from human percussive performance. Despite varying research aims, these studies reveal important insights into real-world human interaction with drums. In order to virtualize this human–drum interaction, various methods can be exploited for system design and control. The task then is to determine whether the system should be event-driven (i.e., software that changes behavior in line with an event), data-driven (i.e., software whose embedded data controls the flow of the program), or a combination of the two.

An event-driven system would respond to human interaction, such as playing a typical commercially available electronic drum machine in which electronic drum pads measure the strike force and play a sampled drum sound in response. One key consideration of this approach is to ensure that the interaction between human and machine accurately simulates real-world, stick-to-drum interaction. However, most modern electronic drum pads account for this need. In fact, most modern electronic drum sets have begun to incorporate different zones into the drum pads in order to trigger different timbres, thus mirroring the action of physical drums. Obtaining a measurement of contact duration ubiquitously from the drum pad may be useful for filtering a triggered sound to simulate membrane dampening. Pressure sensors mounted in or below the drum stool (similar to the force platform used by Aruin & Latash, 1995) could be used to control additional timbral parameters, although how the center of mass relates to meaningful system output would depend on system representation. Consequently, such functions would produce limited meaningful additional interaction. A completely event-driven system such as an electronic drum kit has two drawbacks. Firstly, it relies on the human user to interact with the system and will only produce sounds relative to the skill level of the user. Secondly, with music being a time-sensitive task, system responses from human interaction would need to be extremely low latency. This may not be possible, depending on the speed of the performance and the number of events that need to be handled.

A data-driven system could use data captured from actual human performance in order to create an embedded database or for use in real-time interaction. One method of capturing human performance uses infrared cameras and sensors, as demonstrated by Dahl (2004), Dahl et al. (2011), and Kelso et al. (1991). This approach also was used by Bouënard, Gibet et al. (2008, 2011) to capture timpani performances to create a motion database. Although this approach addressed some limitations in physics-based modeling of performers, Bouënard, Gibet et al. noted that the instrument could obstruct the infrared markers. In relation to a nine-piece drum set, this is a significant limitation in that a typical drum set has components at various points around the performer. In addition, Bouënard, Wanderley, Gibet, and Marandola (2011) described limitations in capturing nuances in performance, such as stick grip. With this in mind, real-time control of a percussive system using infrared cameras and sensors would need to take place in an environment devoid of obstructions because, from a human–machine interaction perspective, a significant portion of the stick-to-drum interaction is lost, such as the rebound and force contact.

The descriptions above provide the polar exemplars of event-driven versus data-driven systems, with each having completely distinct aims and outcomes. The event-driven system with the electronic drum kit is typical of a performance system, while the data-driven system with the motion capture is reminiscent of virtual character animation (Bouënard, Gibet et al., 2011). Interactive systems that employ a combination of event-driven and data-driven methods include interactive computer-generated performance tools and electronic composition tools that render a performance based on human interaction. Such systems require a larger amount of abstraction on the data side complemented by human interaction to trigger events and computer state changes. In the case of abstracting data, several methods are available for creating a representation of an aspect of performance. One method of empirical data collection that could help to identify the levels of movement in a drumming performance is the video capture of multiple performances by different performers with the comparative analysis of the movement level in the video across the performers. It also is possible to attach accelerometers to the performer's hands to measure the amount and direction of their acceleration.

In addition, audio data could help to identify the extent of performance variation by enabling a temporal analysis of performance events and comparing these with elements of the video and sensor data. This could yield information regarding the temporal stability of performance. Although this methodology would facilitate a more generic representation of percussive performance, much information can be obtained from this multimethod approach. Firstly, any empirical performance data obtained could be used in a data-driven model. Secondly, it is possible to infer more generic rules surrounding the use of multiple combinations of instruments and avoid the need for generating multiple variables to cater to the DOF problem. Finally, this approach is more practical because broader observations can be made from a relatively fewer number of participants than would be required to calculate the median joint angle averages for multiple percussive techniques. Therefore, by identifying complex bodily movement in an instrumental performance space, algorithmic logic can be created that can simulate the performance context that forms the fundamental logic of a system that controls the levels of variations simulated in a computer model of drumming. This approach supports rethinking the choreography of performance and its role in designing computer-simulated human interaction, as well as rethinking empirical movement data to contribute towards new concepts of computer generated rhythm systems.

Sound generation and instrumental representation are important components of any performance modeling system. With a variety of techniques available for system-modeling consideration, the main considerations are computational overhead, expressivity of the synthesis, and accuracy of the representation (Kahrs & Brandenburg, 1998). The complexity of accurately synthesizing a nine-piece drum kit comprising membranophones and idiophones places some physical modeling synthesis techniques firmly out of scope, particularly when considering the computational overhead and time sensitivity of the system. Consequently, sound generation is more efficient when the computational overhead is transferred to decision making, database matching, and sound playback, as opposed to calculating complex equations and resythesizing the sound at run time. Therefore, using a comprehensive sample database to sonically represent the instruments would augment the realism of the simulation by allowing timbral variations to be linked to inferred representations of performance.

Towards a Theoretical Model

Adopting a physical-based approach presents two levels of conceptual representation of the system. The first relates to David Marr's (1982) representational level, whereby the relationships between the samples in a database conceptually represent an instrument. The second level further abstracts performance and presents a more contextual understanding of the variables affecting the relationship between the samples by inferring a relationship between the instrumental representations themselves. This is described in Figure 5, a simplified diagram showing the context of two instrumental representations.

Holistically, the instrumental representations should be part of a larger conceptual construct related to performance context. With this in mind, a theoretical model is presented in Figure 6 that shows a performance model derived from information in the sample data, augmented by representations of performance context.

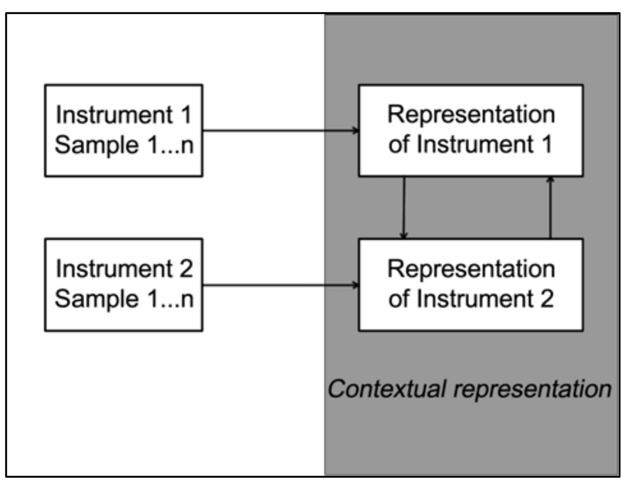

Figure 5. Intrainstrumental performance context. Pulse-code modulation samples of strikes on a single instrument represent only one occurrence of the performance. Therefore, it is necessary to use the sonic content of each sample to provide a contextual representation of the instrument, by inferring a relationship between the spectral features of each sample.

The link between the instruments and the performance context is characterized by the interaction between the performer and the instrument, which is general to all instruments and comprises both intra- and interinstrumental interactions but is unique to the drum set owing to the sheer variety and number of components. The link between instruments and the sample database is an inherent feature of a chosen pulse-code modulation sampling technique and is driven by the diversity of acoustical behaviors of the instrument's components. However, it is important that the feature extraction and classification methodologies in the sample database are informed by the performance context. Such focus ensures that the parameterization and control of the sample database is consistent with human performance, particularly because the sample database is critical to ensuring an accurate representation of instrumental performance in the model. In addition, performance context is not implied by the presence of a sample database alone. Therefore, the control of the sample database in the performance model must be informed explicitly by the performance context, at both intra- and interinstrumental levels, in order to conform a human performance on the control paradigm.

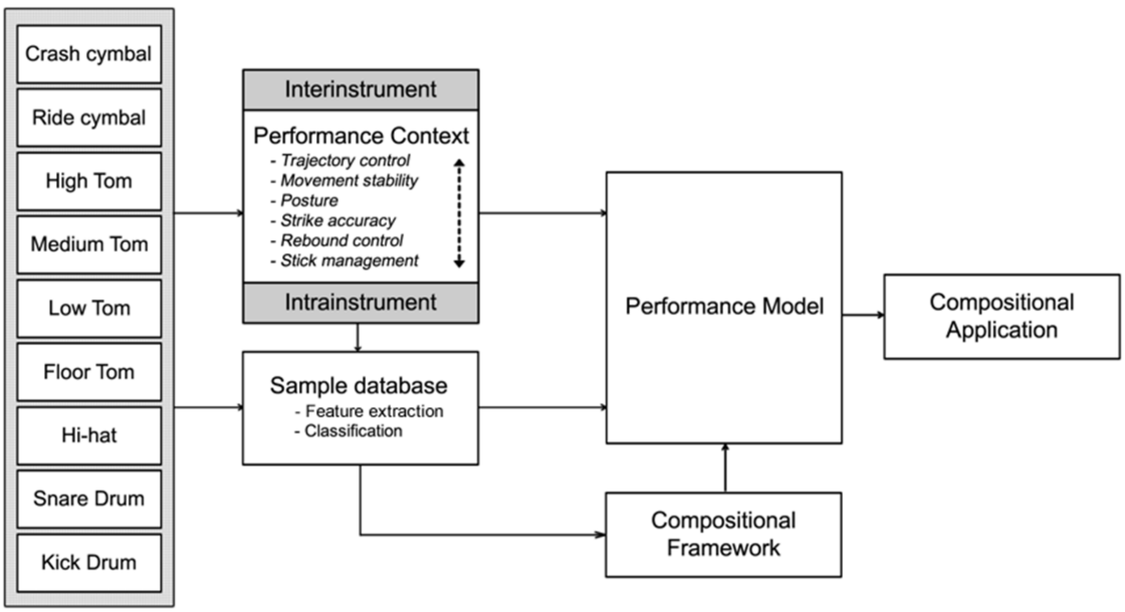

Figure 6. When using multiple instruments, the intrainstrumental context (described in Figure 5) must be considered in relation to other instruments (Interinstrument performance context) through the lens of trajectory control, movement stability, etc. Both the intra- and interinstrument context contributes towards the performance model and towards any novel compositional frameworks.

CONCLUSIONS AND FURTHER WORK

This work forms part of a larger research project into the computer simulation of human percussive performance. This article, as a prequel for further empirical work, has presented a theoretical framework for evaluating the key aspects of choreographed percussive movements that are employed by drummers during performance. The discussion and analysis presented in this article forms the basis for an experimental methodology that will inform the analysis of empirical data to be collected.

Therefore, this study set out to investigate and elucidate the fundamental aspects of human movement in real-world drumming on a nine-piece drum set that lead to variations in timing and timbre during a percussive performance. The goal of this study was to explore the ways in which real-world interaction with drums could facilitate the design of an interactive system that modeled human percussive performance and to understand how a human might interact with such a system. The aims of this study were achieved by examining the literature relating to human movement and percussion in the context of a drummer's developmental goals and in the context of analyzing motor control and information processing systems.

The most obvious finding of this study is that a nine-piece drum set is a physically demanding instrument that involves complex instrumental and biomechanical interactions that must be continuously controlled and, in some cases, preemptively controlled. Given the almost infinite variety of combinations of movements across all limbs, and musical outcomes of human drumming movements, it is not feasible to exhaustively model every performance variable. Consequently, the first task of this article was to address ways of reducing the number of variables. This was achieved by exposing the links between the fundamental attributes of choreographed movements in drumming and how they are understood in the context of information processing systems. This led to the proposal of a theoretical framework based upon Carson and Wanamaker (1984) and Rosenbaum (2010) that drew together two key conceptual levels of human movement: direct physical control and coordinated movements, both of which are highly choreographed. By focusing on literature directly relevant to these two concepts, the scope of this empirical research lies in the disciplines of human movement and percussive performance. By discussing this research through the lens of information processing systems, computer modeling, and biomechanics, the literature reviewed has contributed to an in-depth understanding of human movement in drumming. In addition, the many empirical approaches used in the literature, particularly research that has sought to empirically measure direct physical control and coordinated movement in drumming, were viewed in the context of computer modeling. Consequently, a theoretical model was presented that combines an inferred physical context with a physics-based musical context.

The physical context is present in many of the studies described in this article, with movement being classified into two types: microlevel movements, such as stick contact, grip, and control, and larger localized movements involving multiple joints for rebound control and trajectory modification. These two movement types are inextricably linked because microlevel movements, such as grip modification, can impact larger localized movements, such as rebound control, and larger localized movements, such as trajectory modification, can affect stick contact. Both types of movement directly influence instrumental interaction in the physics-based musical context because they are contributory factors in the control of the timbre and timing variations and the embellishments associated with human percussive performance. Understanding the relationship and effect of microlevel movements and larger localized movements on the musical context provides a preliminary model for guiding experimental setup in reconciling the computational constraints of representing an almost infinite number of variables in human movement while maintaining accurate modeling of percussive performance.

The studies discussed in this article employed a range of empirical approaches to capture microlevel and localized elements of human percussive performance, including audio, video, and sensor data. Although some of the biomechanical research investigated multilimb movement, much of the music performance research concerned performance on a single drum rather than across several drums. When microlevel and localized movements are played across multiple drum set components, simultaneous and sequential contexts add an extra, significant layer of complexity. Simultaneous micro- and local-level movements activate complex biomechanical interactions that, depending on the task complexity and direction, may include agonist and antagonist groupings. This may force implementation of separate stick-management techniques and distinct trajectory plans that require anticipatory postural muscle adjustments in the trunk for bodily coordination. Sequential microlevel and local-level movements also activate complex biomechanical interactions during transitional or linkage movements as the stick is moved from one drum to another. Although the biomechanical interactions occurring in sequential movement are similar to simultaneous movement, the interactions relating to trajectory, speed, and rotation are the most important. These factors are less important when a performer is moving between two adjacent drums as compared to two opposing drums. However, further studies could empirically measure such instrumental interaction in the sequential movement of opposing drums. The implication of this is the possibility that a complex system of representation could emerge from relatively simple interactions, although, owing to computational constraints, these may not be satisfactorily simulated.

One of the more significant barriers in adequately capturing drumming performance are the inherent difficulties in capturing a completely seamless stream of drum performance data with infrared sensors, owing to how the drum set is configured around the performer. Yet it is possible to employ combinations of different performance data—such as audio, video, and other sensors (e.g., accelerometers)—and such an approach may allow for variations in real-world applications, while simultaneously presenting opportunities for exploring various system interactions.

Real-world applications using mixed data collection methods could provide more usable data to advance understanding of percussive performances for future computer-based system design or assessment algorithms For example, a real-time interactive teaching system, based upon an electronic drum set, could calculate the timing stability of a drummer (e.g., is the performer consistently playing in time) and offer suggestions for alternative sequences in order to maintain control. In such a system, the human interaction would be similar to that of real-world drumming. Another application could be a real-time interactive improvisational system that intelligently generates timbral variation based upon embedded performance data controlled by strike location on a multizone interface. Such a system also would mimic real human interaction.

However, a system that infers both timbral and temporal variation would need to abandon a real-world-based human interaction to avoid applying concatenating real-world and virtual temporal variations. To simulate timbre and timing variations, such a system would need to be data driven in order to contain a representation of both simultaneous and sequential movement, as well as be event driven in order to dynamically modify the levels of timbral and temporal variation depending on user input. Using a mixed methods approach to data collection, and by focusing on global-level contextual parameters, the computational overhead could be reduced by deferring system control to fewer decision making algorithms with larger databases of micro-level and local-level variables. This approach would free up system resources to concentrate on providing an accurate synthesis by making use of a large database of high-quality samples to improve the representation of the instrument. The goal then would be to ensure contextual consistency in these timbral features and stability in the model's performance with the additional control of relevant musical parameters.

IMPLICATIONS FOR THEORY OR APPLICATION

This article has analyzed human percussive performance in the context of computer–based system design in order understand the key variables that make human percussive performance distinct from computer-based percussive performance. Investigating these variables has uncovered a number of studies into biomechanics that have significant bearing on the human percussive performance. Bringing these studies to light in a systematic bottom-up way affords practitioners of the art of drumming to perhaps develop a greater understanding of how human drummers interact with their drums, how the interaction is manifested, and the musical consequences of the interaction. Furthermore, by understanding how humans are biomechanically and psychologically predisposed to certain behavior, for example, when automatically swapping to in-phase tapping or a human's propensity for curvilinear over straight trajectories, the practitioner may also direct personal development toward improving choreographed sequences as learned skills. In fact, the innovative or avant-garde practitioner may wish to oppose such existential human behavioral and biological traits by developing a new system for percussive performance that runs contrary to the literature discussed herein. The discussion of the literature may also be of relevance to teachers, either developing their pedagogical approaches or considering widening their professional competencies by providing a comprehensive review of key literature as a starting point for further reading.

From a computational perspective, this article has discussed literature that utilized various methods for obtaining empirical evidence from human movement, with a view to understanding specific behavior or creating computer simulations and models. In this article, the evaluation of empirical evidence in the context of human drumming provides greater clarity on those aspects of human performance that should be considered irrelevant for computational modeling, given the constraints in computing, the complexity of the human activity/function/behavior, and the impact of end result. Therefore, the model presented in this article is of particular interest to researchers or system designers who are developing novel compositional tools that aim to simulate drumming on computers and who are considering adopting one or more of the variables inherent in percussive performance.

ENDNOTES

1. Drum rudiments were initially created by the National Association of Rudimental Drummers in 1933 and subsequently expanded from the original 26 rudiments by the PAS. In addition, the 40 rudiments are considered to be a work in progress, thus enabling future development (Carson & Wanamaker, 1984).
2. The musical abbreviations are as follows: *pp* or *pianissimo* meaning very soft; *mp* or *mezzo-piano* meaning moderately soft; *mf* or *mezzo-forte* meaning moderately loud; and *ff* or *fortissimo* meaning very loud.
3. Musical gesture is closely associated with the behavioral and cognitive aspects of carrying out a physical movement (physical/procedural analytical level). Consequently, gesture is outside of the scope of this study. However, the reader is directed to Godøy and Leman (2010) for further information.

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