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From experimental music technology to clinical tool

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Human body motion is integral to all parts of musical experience, from performance to perception. But how is it possible to study body motion in a systematic manner? This article presents a set of video-based visualisation techniques developed for the analysis of music-related body motion, including motion images, motion-history images and motiongrams. It includes examples of how these techniques have been used in studies of music and dance performances, and how they, quite unexpectedly, have become useful in laboratory experiments on attention-deficit/hyperactivity disorder (ADHD) and clinical studies of cerebral palsy (CP). Finally, it includes reflections regarding what music researchers can contribute to the study of human motion and behaviour in general.

Introduction

In the early 2000s, I started experimenting with live video in interactive music/dance performances. At that time, laptop computers were barely fast enough to handle the simple manipulation of live video feeds and were nowhere near the advanced realtime analysis that is possible today. Never would I have imagined that the video analysis tools I originally developed for these experimental music performances would be tested in clinical practice at hospitals on three continents a decade later. In this article, I will tell the story about how my software moved from the stage to the hospital, how this has shaped its related methods and tools, and how the experience has helped me as a music researcher and as a research musician.

It was during my PhD research on music-related body motion that the *Musical Gestures Toolbox* came to life (Jensenius, 2007; Jensenius et al., 2005). The main goal of my research at this stage was to understand more about the body motion of both *performers* (such as musicians and dancers) and *perceivers* (people experiencing music), and specifically about the ways in which such motion was related to the sound of the music to which they moved or which they created. The human body has always been integral to all aspects of *musicking*, from performance to perception. The concept of musicking is used here to denote that music is seen as a process rather than a product (Small,1998), and should be studied accordingly. It is only in recent decades, however, that larger groups of music researchers have started to investigate music-related body motion more systematically (Gritten & King, 2011, 2006; Godøy & Leman, 2010).

One core challenge when it comes to studying music-related body motion is the need for methods and tools to record and analyse the motion itself. Here, we must differentiate between two principal methodological directions: a) Qualitatively based observation techniques from visual inspection and/or video recordings, and b) Quantitatively based analyses from various types of motion capture data. More and more researchers are also combining these two directions in order to study larger sets of recordings and data, while at the same time looking more closely into certain specific parts of the data sets. This is the approach I have taken over the years.

Due to rapid technological development, the availability and accessibility of various types of *motion capture* systems have improved enormously. I use ‘motion capture’ in a broad sense to encompass all of the technological systems that in some way track and record the body and its motion in space over time. Several different motion capture techniques exist, falling broadly into two main categories: sensor-based systems and camera-based systems. One example of the former is *inertial sensors*, such as accelerometers, which measure the gravitational pull on the object and output information about its orientation and acceleration. Their flexibility and usability, combined with their decreasing size and cost, have allowed inertial sensors to appear in all sorts of electronic devices, including computers, mobile phones and motion capture systems intended for research. Inertial sensors do have some drawbacks, however. First of all, the data coming from the sensors is not always immediately useful. For example, accelerometers, despite the name, do not output the acceleration of the object but rather the gravitational pull on it. While this information can be used to estimate the true acceleration, and possibly even position, of the object, it requires a considerable amount of analysis and interpretation to do so. Another drawback with sensor-based systems is that the sensors must be placed directly on the body of the subjects being studied. My own experience with studying musicians, dancers and people moving spontaneously to music is that they often feel uncomfortable wearing the sensor system. In some cases, a musician may even experience difficulties playing his or her instrument due to the sensors and cables that are attached to the body.

Working with a camera-based system, on the other hand, allows for a sensorless setup and still allows the researcher to track motion, even if only from a single, two-dimensional recording. Using multiple cameras and reflective markers, in addition, it is even possible to get a fully three-dimensional motion tracking with a high resolution (at the millimetre level, or lower) and very high speeds (at 500 frames per second, or faster). For many situations, however, a single ordinary video camera provides the researcher with a cheap, flexible, and reliable tool for studying body motion. While such a setup may not offer the tracking precision and speed of sensor-based or multicamera-based systems, it is perfectly capable of allowing for both quantitative and qualitative analyses of the same type of source material.

Exactly these qualities of simplicity, accessibility and flexibility are what led to my initial interest in exploring the possibilities of video-based analyses techniques. This article begins with a brief introduction to some of the video-analysis methods I have developed and includes descriptions of *motion images*, *motion-history images* and *motiongrams*. Next, it includes an overview of how these tools have proven useful in analytical studies of music-related motion, in experimental studies of ADHD and in clinical studies of CP. Finally it presents some thoughts on the further development and artistic use of these methods.

Video-based visualisation

A main challenge when one works with video recordings as source material for various types of analyses is to create proper representations of the motion being studied. One such representation is *visualisation* – that is, a visual display that in various ways illuminates certain aspects of the motion. From a musical point of view, one must further create visualisation techniques that can capture different types of temporal levels. In cognition in general, and in music cognition in particular, it may be useful to distinguish between three different temporal levels, each related to the three main memory levels: the *sensory memory*, the *short-term memory*, and the *long-term memory* (Snyder, 2000). Based on such a tripartite division, Godøy (2008) has suggested three levels of grouping, or what is often referred to as *chunking* in psychology:

- Sub-chunk level: perceiving continuous sound and motion features, up to 0.5 seconds (sensory memory)
- Chunk level: fragments of sound and motion perceived holistically – that is, sound objects and goal-directed actions that are typically between 0.5 to 5 seconds (short-term memory)
- Supra-chunk level: several chunks concatenated into larger structures (long-term memory)

Human beings have the ability to handle these levels effortlessly and in parallel. For example, we may observe the instantaneous unfolding of sound and motion while at the same time preserving an internal memory of the trajectories of a sequence as well as an overall image of its longer patterns. A video recording, however, is only a series of individual frames at the sub-chunk level, typically recorded at a rate of 25 to 60 frames per second. An interesting question, then, is how to create visualisations of the other two levels (chunk and supra-chunk) which can then be used for further analysis, or as illustrations in, say, a research paper. The following sections will present some of the techniques I have developed for representing body motion at these three levels.[1]

Motion images

When one works with motion analysis from video files one of the most common techniques is to start by creating a *motion image*. The motion image is found by calculating the absolute pixel difference between subsequent frames in a video file, as illustrated in figure 1. The end result is an image in which only the pixels that have changed between the frames are displayed.

Figure 1: *A motion image from a performance of a piano piece, recorded from the front: The motion image is created by subtracting subsequent frames in a video file (that is, looking at the difference between each individual pixel in two adjacent frames) looking at the difference between each individual pixel in two adjacent frames*

The quality of the raw motion image depends on the quality of the original video stream. Small changes in lighting, camera motion, compression artefacts, and so on can influence the final image. Such visual interference can be eliminated using a simple low-pass filter to remove pixels below a certain threshold, or a more

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[1] All of the examples presented in the following sections are created with software that is freely available from http://www.fourms.uio.no/software. Readers interested in the technical implementation can find details in Jensenius 2007 and in the source code that accompanies the software.

advanced 'noise reduction' filter, as illustrated in figure 2. Either tool cleans up the image, leaving only the most salient parts of the activity in the motion.

Figure 2: *The motion image is improved by applying either a simple low-pass filter or a more advanced noise reduction filter.*

The video of the filtered motion image is usually the starting point for further processing and analysis of the video material.

Motion-history images

A motion image represents the motion that takes place between two frames but does not represent a motion sequence that takes place over more frames (the chunk level). To visualise the motion itself over time, then, it is necessary to create a *motion-history image* – a display that keeps track of the history of what has happened over the course of some number of recent frames. There have been numerous implementations of this idea over the years (summarised in Ahad et al., 2012), most of which have been based on averaging the results of a certain number of frames of motion images. One of my approaches, in fact, is to simply average over the frames of an entire recording. This produces what could be called an *average image* or a *motion-average image*, such as that shown in figure 3. These images may or may not be interesting to look at, depending on the duration of the recording and the content of the motion. The examples in figure 3 are made from a short recording that includes only one short passage and a raising of the right hand. The lift is very clearly represented in the motion-average image, whereas the average image mainly indicates that the main part of the body itself stayed more or less in the same place throughout the recording. For longer recordings, in which there is more activity in larger parts of the image, the average images tend to be more 'blurred' – in itself an indication of how the motion is distributed in space.

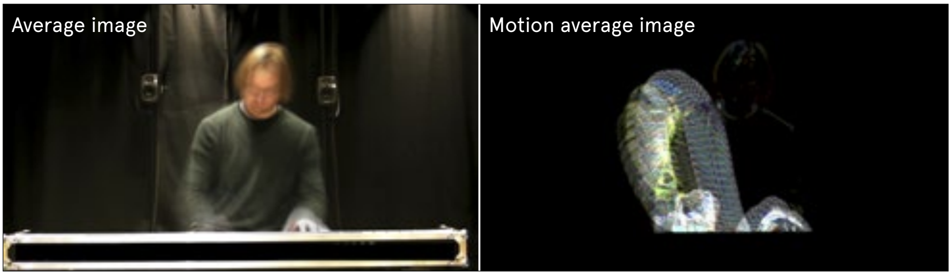

Figure 3: *The average image (left) shows a 'blurred' version of the performer as it transpires over the entire recording. The motion-average image (right) more clearly shows the trajectories of the motion in the recording.*

To clarify the motion-history image, I often prefer to combine the average image and the motion-average image, or possibly incorporate one frame (for example, the last frame) into the motion-average image. The latter alternative makes it possible to combine a clear image of the person in the frame with traces of the motion-history, as illustrated in figure 4:

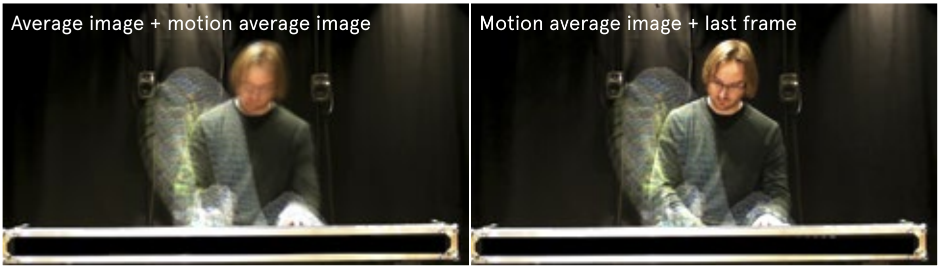

Figure 4: *A motion-history image becomes more informative when it incorporates either the average image (left) or a single frame from the recording (right)*

Motiongrams

The motion-history images above reveal information about the spatial aspects of a motion sequence, but there is no information about the *temporal* unfolding of the motion. Inspired by the chronophotographies of Etienne-Jules Marey from the late nineteenth century (Marey, 1884), as well as slit-scan photography (Levin, 2005), I have developed a technique for displaying motion over time that I have called a *motiongram*. Averaging over a motion image, as illustrated in figure 5, creates a motiongram. The tandem of horizontal and vertical motiongrams makes it possible to see both the location and the quantity of motion in a video sequence over time:

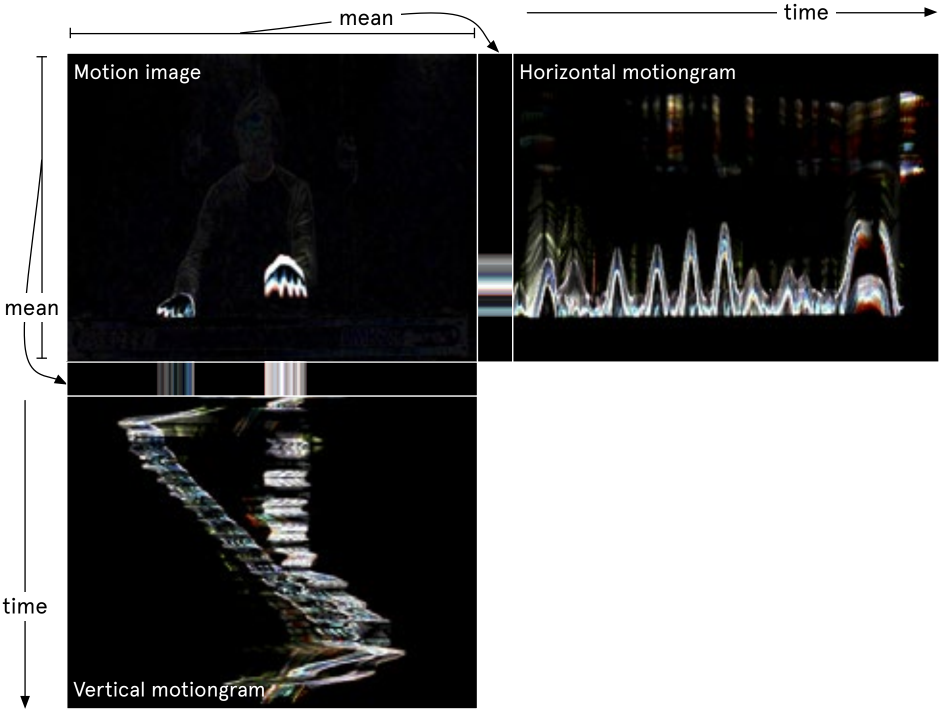

Figure 5: A schematic overview of the creation of motiongrams, based on a short recording of a piano performance. The horizontal motiongram clearly reveals the lifting of the hands, as well as some swaying in the upper part of the body. The vertical motiongram reveals the motion of the hands along the keyboard, here seen from the front, as in the previous figures

One of the fascinating aspects of a motiongram is that there is no analysis involved in its creation – the process is based solely on a simple reduction algorithm. This also makes the technique very flexible, because no a priori knowledge about the content of the video recording is necessary for creating a motiongram. The most important choice that is made during the creation process is the level of filtering that is applied to the motion image used to create the motiongram. It does not change the overall shape of the motiongram, but it is important with regard to determining the level of detail (or noise) to be included in the final visualisation.

Towards clinical applications

Music research

The above-mentioned motion-visualisation techniques have been used in the analysis of various types of music-related motion, including the performance motion of pianists (Godøy et al., 2010), clarinettists (Jensenius, 2007) and violinists (Schoonderwaldt & Jensenius, 2011). They have also been used in studies of people moving spontaneously to (musical) sound – for example, when dancing freely (Casciato et al., 2005), playing 'air instruments' (Godøy et al., 2006b) or carrying out so-called sound tracing (Godøy et al. 2006a; Nymoen et al., 2013).

Figure 6 presents one example of the usefulness of motion-history images in the study of performance technique. Here, each image represents an individual stroke on the drum pad, and the image series serves as a compact and efficient visualisation of a total of fourteen different strokes by the percussionist:

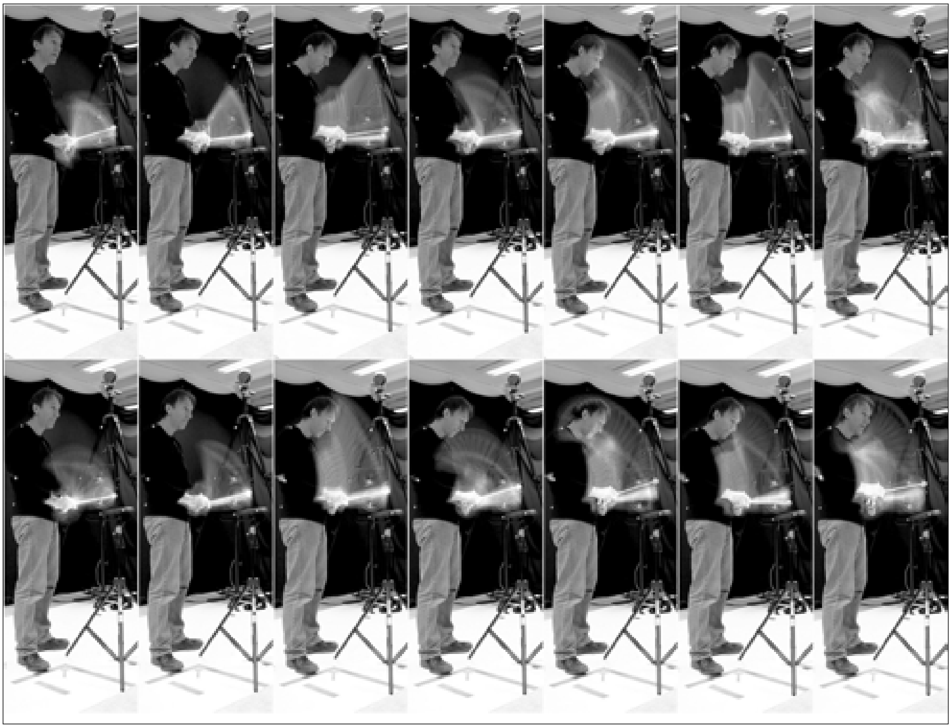

***Figure 6:** Motion-average images overlaid upon the last frame of fourteen video recordings of a percussionist performing the same drumming pattern in different ways. Each display represents around fifteen seconds of video material*

One example of the ways in which motiongrams can be used to study dance performance can be seen in figure 7. This display shows motion-average images and motiongrams of forty seconds of dance improvisation by three different dancers who are moving to the same musical material. The motiongrams reveal spatiotemporal information that is not possible to convey using keyframe images, and they facilitate the researcher's ability to follow the trajectories of the hands and heads of the dancers throughout the sequences. For example, the first dancer used quite similar motions for the three repeated excerpts in the sequence: a large, slow upward motion in the arms, followed by a bounce. The third dancer, on the other hand, had more varied motions and covered the whole vertical plane with the arms. Such structural differences and similarities can be identified in the motiongrams, and then studied in more detail in the original video files. As shown in figure 7, motiongrams can also be used together with spectrograms of the sound to reveal and explain relationships between motion and sound.

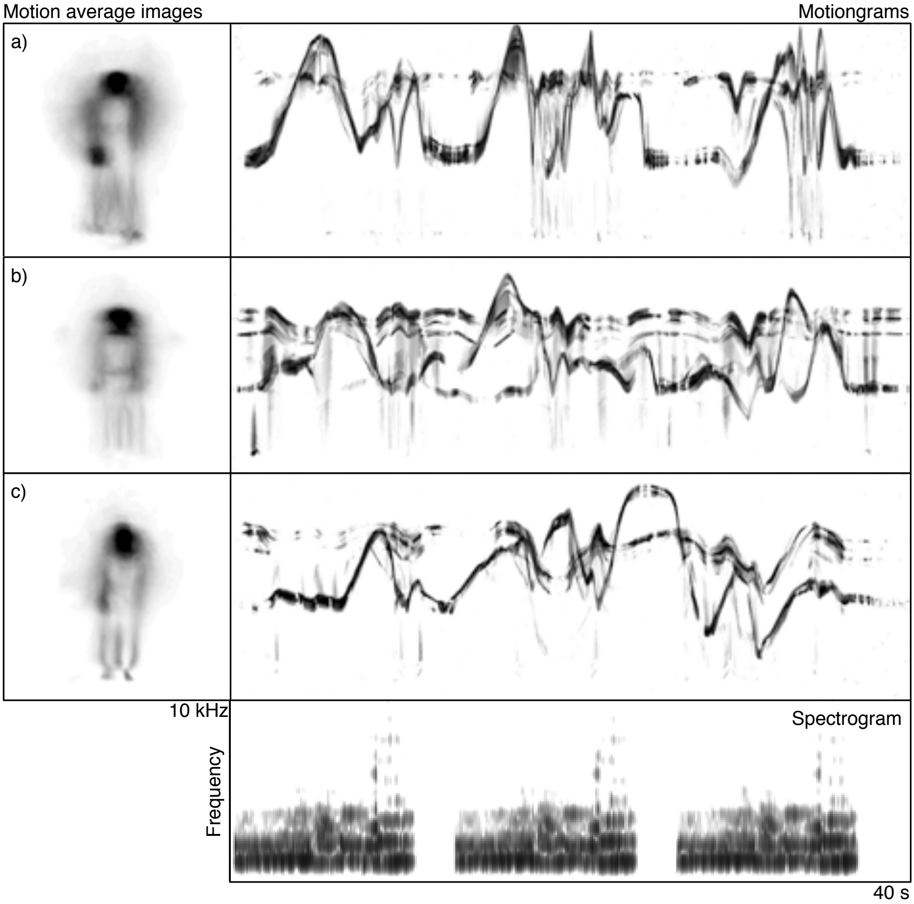

***Figure 7:** Motion-average images and motiongrams of recordings of three dancers improvising to the same musical material (approx. forty seconds). A spectrogram of the musical sound is displayed below the motiongrams*

Animal experiments on ADHD

A very different type of motion patterns can be observed in figure 8. These motiongrams are created from videos of rats with different symptoms of attention deficit hyperactivity disorder (ADHD), recorded in the lab of Professor Terje Sagvolden at Department of Physiology at the University of Oslo. What is popularly known as ADHD, is actually an apparently heterogeneous group of behavioural disorders affecting between 2 and 12 percent of young children (Swanson et al., 1998; Taylor et al., 1998). There are, in fact, three subtypes of ADHD diagnosis and two behavioural dimensions (American Psychiatric Association, 1994):

- *ADHD* (*attention deficit hyperactivity disorder*) is a predominantly hyperactive and impulsive subtype that is typically more common among boys
- *ADD* (*attention deficit disorder*) is a predominantly inattentive subtype that is typically more common among girls
- A combination of ADHD and ADD

ADHD usually manifests itself before the child is seven years old and is characterised by inattentiveness, hyperactivity and impulsiveness (Applegate et al., 1997). Around 50 to 70 percent of the children diagnosed with ADHD will have problems relating to social adjustment and functioning, and they are also more likely to have psychiatric problems as adolescents and young adults (Cantwell, 1985). It is therefore important to identify children with ADHD at an early age so that they can receive the necessary treatment and support (Sagvolden et al., 2005).

Sagvolden's group carried out experiments using genetically engineered rats with symptoms equal to those of clinical cases of ADHD and ADD. The experiments were based on tasking the rats with pressing one of two levers inside a cage (Sagvolden, 2006). If the assignment was carried out correctly, the rat received a drop of water as a reward. The experiments were run daily for several hours, and the aim was to study patterns of overactivity, impulsiveness and inattentiveness over sustained periods of time, and to see whether various types of medical treatment would change the behaviour of the rats. The challenge, however, was that only lever presses were recorded in the original design of the experiment, which resulted in very discrete and time-gapped measurements and no information about how the rats behaved when they were not pressing levers. My part in the project was to provide a tool to analyse the motion of the rats *throughout* the experiments. Figure 8 shows motiongrams of recordings of three different rats: one with ADHD symptoms, one with ADD symptoms, and one with no symptoms.

The motiongrams reveal that the ADD rat moved the least of the three rats, showing typical signs of inattentiveness. Both the ADHD rat and the normal rat moved more than the ADD rat, although only the ADHD rat moved continuously throughout the sequence. The normal rat showed generally superior focus on the task, moving up and down and following the light, while the ADHD rat showed signs of whimsical behaviour as well.

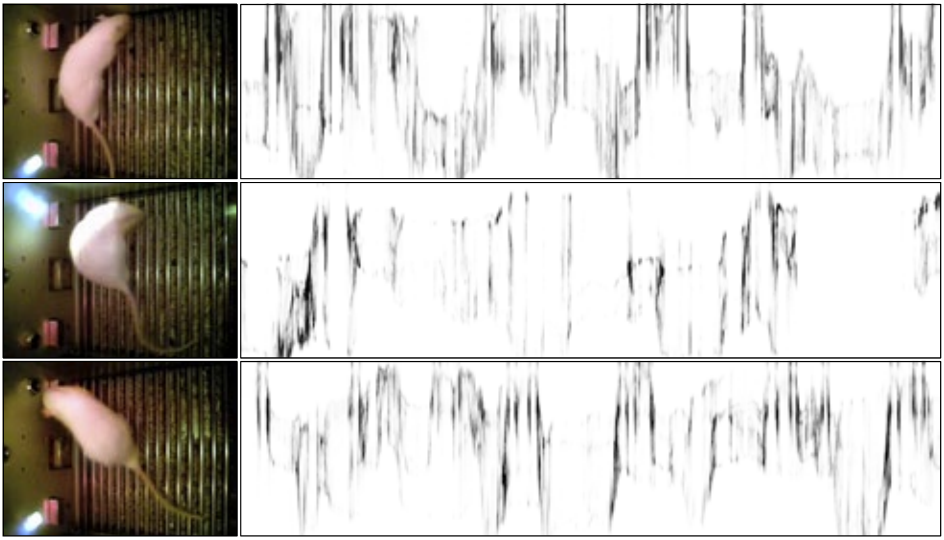

Figure 8: *Motiongrams of rats in the experiment cages: ADHD rat (top), ADD rat (middle) and normal rat (bottom). The motiongrams show a little more than one minute of activity*

Based on the positive findings from the pilot study, we set up video cameras in all of the rat cages and recorded a full season of experiments. We also piloted a similar system in a clinical experiment at Ullevål University Hospital in Oslo that was aimed at screening a large number of school children. Due to sheer extent of the recorded material, we promptly developed a method of extracting statistics from it, including the *quantity* and *centroid* of motion in the image. Based on these data, we started analysis using auto-correlation techniques and produced some very promising results in terms of understanding more about the behaviour of the different groups of rats (Johansen et al., 2010). Unfortunately, the collaboration abruptly ceased due to the passing away of the project leader in early 2011.

Studying infants with cerebral palsy

In 2008 I started collaborating with physiotherapist Lars Adde from NTNU in Trondheim in 2008. His group carries out longitudinal studies of infants and children with CP. Cerebral Palsy is a permanent disorder in the development of motion and posture in the developing fetal or infant brain and is one of the major disabilities that result from extremely premature birth (Adde et al., 2010). As the most serious chronic motor disability that can occur in infants, early identification of CP might be beneficial for early treatment, while the plasticity of the brain is at its peak. Identifying children in the risk group that do not have CP is also important, as it can prevent unnecessary worry in the families of the children.

Diagnosing CP, however, is difficult, and it is most commonly conducted by an expert clinician, who visually assesses what are known as the *general movements* (GMs) of the child. This can be done using a regular video recording, from which the expert seeks signs of spontaneous motor activity. Absence of so-called *fidgety movements* in infants at nine to twenty weeks of post-term age has been shown to be a strong indicator of later CP (Prechtl et al., 1997), so researchers are mainly focused on trying to improve the identification method regarding these types of movements. The General Movement Assessment (GMA) method, which is based on the systematic observation of infants' spontaneous movements in video recordings, has been shown to predict CP with a high degree of accuracy (Einspieler et al., 1997). More particularly, the absence of fidgety movements in the general movements of infants at two to four months of corrected age (that is, expected date of birth) may identify infants who will develop CP with more than 90 percent sensitivity.

Because there are so few expert clinicians who are trained to identify CP in infants, researchers are eager to develop a computer-based video-analysis system that can assist in the selection of infants that are in the risk group. So the aim of the CIMA project (computer-assisted infant movement assessment) is to develop a video-based analysis tool that can match the prediction rate of an expert clinician, and that is so easy to handle that it can be used in clinical practice in hospitals. If successful, such a system could allow for the screening of a much larger group of infants in the risk group than is currently possible.

Fortunately, CP researchers had already been filming infants for several years before I met them, so it was possible to start testing a large data set with my software right away. It immediately became apparent that the motiongrams could reveal differences in the motion patterns of infants with and without fidgety movements, as can be seen in figure 9.

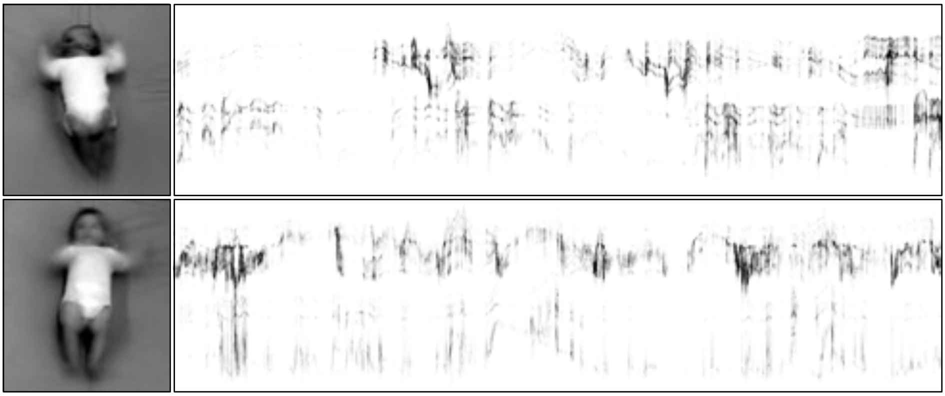

***Figure 9:** These examples show average images and motiongrams of motion sequences of infants without fidgety movement (top) and with fidgety movement (bottom).*

Based on these initial studies, we have continued to develop the technique with a focus on extracting some relevant quantitative features based on the centroid of motion (Adde et al., 2009, 2010, 2013). The project is currently piloting a hardware solution at several hospitals in Norway, USA, India, China and Italy. Here, preterm infants are video recorded while lying on a mattress, and the video analysis tool is used to study some general movement features. The priority now is to validate the system and the analysis methods, and to work towards a clinical tool for more widespread use.

Discussion

One question I have asked myself over this whole period of collaboration is why my approach to studying music-related body motion is attractive to psychologists, physiotherapists and people working in medical science. After all, there has been an abundance of research on various types of motion tracking over the years, most of which is much more technically sophisticated than what I have been working on. But perhaps that is part of the answer – a lot of the motion-capture solutions that exist are either too advanced or targeted at specific applications. Coming from a background in music technology, I am used to working with technology in creative ways, trying to push the borders of what is possible with the technology in question. This has also helped in giving advice and helping researchers in widely different fields than my own.

Choosing the right technology

During my years as a doctoral and post-doctoral researcher, I have been fortunate to have access to many different types of motion-capture systems, ranging from accessible and affordable to absolutely state-of-the-art. Therefore I have had the opportunity to work with different systems, depending upon the needs of the project with which I was involved. Once, we used a video-based markerless tracking solution in an experimental violin performance (Jensenius & Johnson, 2012). Another time, we used a full-body motion-capture suit for a piece of electronic dance music (de Quay et al., 2011). This experimentation with different types of recording and tracking solutions has given me a broad understanding of the possibilities and limitations of these different systems – knowledge that is valuable when approaching entirely new fields of study.

The ADHD and CP researchers with whom I have worked are experts in (human) behaviour and motion but not in motion capture or analysis. The ADHD researchers had mainly been working with quantitative data that was based on discrete measurements of when the rats pushed the levers in the cages. Thus the data sets were very limited and did not contain any information about the actual motion of the rats otherwise. The CP researchers had mainly been working with qualitative observation but had also experimented a little with electromagnetic trackers attached to the limbs of the infants. This required expensive equipment and a cumbersome process of attaching the sensors to the infant, neither of which is ideal when one is working towards clinical application.

An advice to both groups was to use affordable video cameras, mounted above the infant's mattress, respectively. Recording from above gives a clean and accurate overview with little visual interruption or noise. In addition, regular, off-the-shelf video cameras provide technology that is sturdy, replaceable and easily operable by lab technicians or clinicians who are not motion-capture experts. If there is anything I have learned after more than ten years of working with musical performances, dance pieces and interactive installations, it is that the researcher's technology must be easy to use for anyone involved. This is not as trivial as it sounds – much research technology is costly, highly specialised and difficult to operate. Such equipment certainly has some advantages, but they reveal themselves mainly in a controlled laboratory setting in which there are people that know the system. In a hectic hospital setting, all the tools must be as easy to use as possible, and a simple, video-based system may be preferable, if only because no sensors or cables are needed.

A broad perspective

Both the ADHD and the CP groups called for a broad perspective to motion analysis. As mentioned in the introduction, most motion-capture solutions are based on trying to identify and track a certain part of the body – say, a hand or the head. This leads to very detailed analyses of the motion of these specific body points. While such an approach can produce interesting and relevant findings, it can be limiting for those researchers who are, in fact, mainly interested in global motion characteristics. The approach to motion analysis that is presented in this article, is intended to accommodate the study of the *entire* body as one moving object. A broad perspective is useful when one is studying general motion features in large datasets, and it turns out that its methods and tools work as well with video recordings of musicians and dancers as with those of infants and rats.

Temporality

The temporal unfolding of events is one of the core elements of music, and is an important part of any type of music analysis. Thus knowledge of time is one thing that music researchers can contribute to other fields of study. This is not to say that researchers in other fields do not accommodate time as such, but rather that the music researchers' focus on time and temporal development is utterly ingrained in how we think about both the performance and the perception of music. This awareness is also the reason why I began creating visual displays that represent motion at different temporal levels: motion images represent the sub-chunk level, motion-history images represent the chunk level and motiongrams represent the supra-chunk level. Such displays can be used very efficiently to say something about spatiotemporal motion features, which has proven to be particularly important when one is studying the behavioural patterns of ADHD or CP, both of which deviate from regular motion patterns.

Detecting differences in temporal patterns and ordering is only the first part of the problem, however. In my continued collaboration with the CP researchers, we are now working towards extracting more advanced temporal motion features. Here, it will be particularly interesting to see whether and how different types of methods developed within the field of *music information retrieval* (MIR) can also be used to study motion features. The MIR community employs statistical and machine-learning methods to extract information about music from scores and sound files (Downie, 2003). This makes it possible to study music from large collections, and to extract information that is not possible with only close studies of individual songs and pieces. Many of these tools are also based on advanced models of time and temporality, which, again, could be very relevant to use on recordings of human body motion. The challenge, again, remains the development of an easy-to-use and stable solution that it is possible to apply in a clinical setting.

Limitations of the computer

We must always remember that a computer-based system is never better than its theoretical and methodological foundations. For example, in my collaboration with the CP researchers, we are trying to build a computer system that replicates the years of knowledge and experience possessed by expert physiotherapists.

The main problem with my approach to motion analysis, however, is that there is no a priori knowledge in the system – it is mainly based on simple image-manipulation and reduction techniques. How, then, do we build more specific knowledge into the process of analysis? One way to approach this issue is to leverage the expert knowledge of the clinicians at the right points in the process.

Feeding back to music research

Even though I have spent quite a lot of time on non-music-related topics over the last few years, these collaborative activities have had a very constructive impact on my music-related research projects as well. Working towards the realisation of an effective and accessible clinical tool has greatly improved my underlying analytical methods and made the software much more stable and reliable. As a music researcher, I have aimed to maintain an open and exploratory approach to my research questions, and I have often applied a range of methods in order to look at the questions from different angles. It has been exciting to be part of larger teams that are working with a high level of detail and rigour when it comes to planning experiments and analyses. This is, of course, necessary when the subjects in question are children with health problems. The ethical dilemmas that arise are far from those to which we are typically exposed in music research.

Working in an interdisciplinary group, I have also benefited from the lively discussions about terminology, theoretical foundations and methodological directions. While such discussions can take time and energy away from other activities, they are also important when it comes to sharpening one's argument and posing new research questions. Since I have no formal training in human-movement science, biomechanics or physiotherapy, it has been rewarding to learn more about these fields. It has been particularly interesting to see how the body and its motion is treated from a much more biomechanical perspective than that of the music researcher. Exactly this interplay between the different disciplines is the most stimulating part of working interdisciplinary.

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