Linköping Electronic Articles in
Computer and Information Science
Vol. 5(2000): nr 36

Motor Skill As Dynamic Constraint Satisfaction

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Linköping University Electronic Press
Linköping, Sweden

http://www.ep.liu.se/ea/cis/2000/036/

Published on December 21, 2000 by
Linköping University Electronic Press
581 83 Linköping, Sweden

Linköping Electronic Articles in
Computer and Information Science
ISSN 1401-9841
Series editor: Erik Sandewall

Typeset by the author using LaTeX
Formatted using étendu *style*

Recommended citation:
<Author>. <Title>. Linköping Electronic Articles in Computer and Information Science, Vol. 5(2000): nr 36. http://www.ep.liu.se/ea/cis/2000/036/. *December 21, 2000.*

This URL will also contain a link to the author's home page.

Abstract

Motor skill is one of the most basic intelligent activities by human beings. We can acquire various high level physical skills such as throwing, typewriting, playing musical instruments and so on. However, it is difficult to understand the mechanism of the skill by experts. Here, we discuss motor skill in terms of dynamic constraint satisfaction including motion integrity constraint (MIC). Some biomedical experiments show that some constraints for joint angle coordination and combinations of activated muscles are satisfied by experts. If we know the skill achievement mechanism by experts, it can be quite useful to improve amateurs' skills. In addition, it can also be helpful to prevent injuries coming up from bad muscles usages.

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1 Introduction

Walking is one of the basic motor skills which human beings can perform unconsciously. However it is very difficult to explain how we can perform such skills clearly. Walking needs very complicated muscle coordination. Human body contains arround 500 muscles and 200 bones. We have to select the appropriate combinations to walk. If we have any disorders to walk, long time rehabilitation is necessary to recover walking skill with numerous efforts.

We can perform high level motor skill unconsciously once we build a motor program. This is a different kind of skill from walking. It needs concious exercises with repetition. Here we focus on only closed skills [Schmidt, 1991]. Open skill is very difficult to automate motor patterns because we have to decide which motor program has to be used when the situation is dramatically changing in short time. Playing musical instruments is a good closed skill example. Players perform without consciousness only through long time repetitive exercises well. Recall that we cannot explain how to control muscles in order to walk. We cannot explain how to control muscles to play musical instruments well either. These observation show that our repetitive motor behavior can be performed in a tacit level.

Musicians, dancers and athletes acquire high level skills in the process of motor learning. The ordinary strategy for memorizing the motor programs is to repeat the same motor pattern. However, it is very hard to make motor programs unless one performs repeatedly in a very similar way. In addition, we apt to obtain a bad habit to control the instruments if the motion is irrelevant from the human body structure and movement constraints based on physical law. It suggests that we should understand characteristics of our body from the anatomical perspectives with dynamics. If we understand the constraints for anatomy and physics, it can be useful to improve our skills. What is more, it can also be helpful to prevent injuries coming up from bad muscles usages [Sazer, 1995, Bruser, 1997, Turner-Strokes et al., 1998].

2 Redundant Factors in Human Body

Let us consider our arms and shoulders. In comparison with robot arms, human arms and shoulders have redundant degrees of freedom. Therefore it causes inverse kinematic problems that we cannot obtain a unique solution to perform a simple task such as grasping. A connection between scapula and thorax in a shoulder has also redundancy. These bones are connected by back muscles (e.g. trapezius muscle and serratus anteriour muscle). This is the special and virtual joint because there is no joint parts such as articular capsule between bones [Castaing et al., 1984]. The real problem is that the upper arm is connected to the scapula which moves freely on the thorax. We can say that a human upper extremity has highly redundant connections which other animals do not have.

Such redundancy causes the difficulty to understand skilled movement. Motion analyst must know which part of the body movement is essential to perform skills or not. Russian physiologist Bernstein described such problems in observation of driving nail skill by experts [Bernstein, 1967]. He found that experts performed well when the hammer was close to the nail, however there was no reproducibility when it was far from the nail. This observation suggests that it is important to select the essential part of body movements relevant to the skill that we would like to analyze.

3 Motor skill as Constraint Satisfaction

3.1 Motion Integrity Constraint

The redundancy is the most difficult point in analyzing skills. For example, in measuring locus of one performer, we cannot obtain the completely same data due to the redundancy problem. Our fundamental methodology is to extract motion integrity constraints (MIC) which most experts exibit.

Let us define MIC here. MIC contains anatomical constraints and spacio-temporal constraints. Anatomical constraints are range-of-motions (ROMs), deviation from functional position [Castaing et al., 1984] and so on. ROMs play a very importantrole when we flex or extend limbs. We can easily move limbs in the middle of ROM of a joint. However, it is very hard to move limbs at the boundary of ROM. Flexion reflex[1] is one of the mechanisms which automatically prevent the muscle and joint distraction caused by hyper-extension. Functional position is the most easiest position to move bones towards any direction. It is often defined in the middle of the ROM. We can move our arms with least force if the motion starts at this point.

Spacio-temporal constraints contain the relative position among joints and instruments, and velocity (acceleration) of their movements based on Newton's law. It is crucial to satisfy these constraints in order to achieve best performances . Appropriate spatial preparation makes us realize stable performance. For example, relative position between the musical instrument and the body restricts the performer's motion space.

In our past biomedical data acquisition experiment we found anatomical constraints during cello bowing action through electromyography (EMG) which measure muscle activity [Ueno et al., 1997]. Non-experienced cello players sometimes use antagonist muscles during agonist muscles activation, whereas professional cellists use these muscles in the different phase. Agonist muscles are the main muscles to achieve goal movement and antagonist muscles are the muscles which resist the motion towards the goal direction. When we use both muscle at the same time, joint stiffness level will increase and we can not flex joints without much force. For example, biceps brachii muscle is the agonist and triceps brachii is the antagonist muscle when we achieve the flexion of the elbow joint. It means that flexibility of the elbow joint decreases when we use these muscles at the same time. Then the player can not do without mainly using shoulder joint in order to achieve bowing movement. This movement distracts an appropriate spatial relation between the bow and the string. Such a bad spatial relative position results in producing bad sound.

A spine posture may affect the performance. The spine posture is a factor coming from both anatomical constraints and spacio-temporal constraints. From the spacio-temporal constraints point of view a bent spine posture restricts the bowing motion. In a bent spine posture the bowing range can be narrower than that in a straight spine posture. In addition, the back is the root segment of the whole bowing motion. Therefore it is very important to make the spine straight in order to transmit the back muscular force to the right arm. In a straight posture we do not have to use extra force at the upper part of back muscles. Only slightly more muscular force at the waist is required in the straight posture than in the bent. As we mentioned above, upper arm connects to the scapula. The scapula connects to such back muscles as trapezius muscle. The upper arm also connects to

[1] This is not a voluntary mechanism.

the back and chest muscle such as latissimus dorsi muscle, pectoralis major and so on. These connections explains why back posture affects the skill executed by shoulders and arms.

3.2 Conscious Skill Helps Unconscious Skill

When the skill task is given, we use muscles to control our body suitable for the task. Although the distal[2] movement such as wrist rotation is important, the proximal[3] movement is more critical to the sequential closed fine skills. Spine posture is very important to realize good performance without extra muscular force. The reason is that the proximal part of the body dominates the distal one from the topological and anatomical points of views.

Michie suggests that there are two agents in our bodies who collaborate each other to realize physical performance [Michie, 2000]. One is called "zombie", and is responsible to reproduce what we memorized. The zombie can reproduce fingering skills unconsciously (in subcognitive level) because they are complied in a brain as a motor program. Another is a conscions agent having the ability to control the spine, the scapula, and the arms. The conscious agents helps "zombie" to achieve his best performance by arranging best environment for the task. This idea is very natural in the aspect of nerve conduction velocity. The required performance speed for zombie is much faster than that for the other one.

The zombie theory gives us some clues that we have to separate motions into two kinds of skills: a distal motion conducted by zombie and a proximal one conducted by the conscious agent. There are quite a few studies analyzing motion by the zombie because it is more directly related to the fine movement for realizing skillful performance. Nevetheless, in this paper, we focus on the proximal motion because of the proximal domination characteristics mentioned above. Experts seem to know the natural way to use proximal parts through the searching process for optimal usage of the whole body control. Our conjecture is that proximal parts can help zombie perform stable reproduction of motor programs. Note also that proximal parts makes the movement more dynamic because the proximal movement proceeds and induces the distal one. In fact MIC provides us the clues to obtain optimal proximal movement. Proximal motion can be optimal when MIC is satisfied because MIC is the sign of the optimal relationship between distal motion and proximal motion. In other words MIC provides the coordination between the proximal and the distal part of the bodies.

Now we try to extract MIC focusing on differences between experts and novices.

4 Method to Extract MIC by Biomedical Measurements

Aims of extracting MIC during experts performance is to discover critical factors for high level performances. Once we identify the critical MIC, it is supposed to play a central role for teaching physical skills to students. Novice level performers can not probably satisfy some of the critical MICs. If anyone suffers from the difficulties about his or her skill improvement (sometimes known as a slump), we can diagnose these faults.

[2] far from torso

[3] close to torso

We have many built-in sensors in our bodies to feel the status. They are the real time sensors to monitor the produced sound (the auditory centers), how long muscle fibers are extended (muscle spindles), how strong tendon is strained in ROM (Golgi tendon organ) and so on.

Of course visual perception plays an important role in skill acquisition. However, we can not watch our bodies continuously during performance. In closed skill acquisition, kinesthesis (proprioception), which monitors internal body motion, is one of the most important inner sensors as well as hearing.

The problem here is that we can not directly acquire the kinesthesis data by biomedical sensors. Fortunately we can measure the action potential of muscles by using Electromyography (EMG). This helps us monitoring the status of muscles instead of the kinesthesis information.

EMG data provides us the information how the monitored muscle is contracted. However, we can not decide whether relevant bones have moved or not. There are 3 types of muscle contractions: concentric contraction, eccentric contraction and isometric contraction. The muscle is shortened during the concentric contraction, lengthened during the eccentric, has no change during the isometric even if all contractions show amplitudes in EMG.

Therefore we have to measure three dimensional coordinates motion data with motion capturing system together with EMG. With this system we can trace the joint positions in time sequences. It is possible to know how muscles move limbs with the muscular force which we can monitor with EMG.

5 Preliminary Experiment as a Case Study

5.1 Outline of the Measuring System

We had one preliminary experiment to discover MIC. The aim of this experiment is to look over how MIC is discovered by the simple traditional analysis. Note that our final goal is the automatic discovery of MICs.

We constructed the data acquisition system as shown below. Three dimensional infra-red motion capturing system and EMG sensor are used simultaneously in this experiment. We measured EMG by wireless transmission in order not to interfere performers' motion. An electric metronome pulses are also measured in order to synchronize performers' motion, motion capturing data, and EMG data.

5.2 Tasks for Subjects

The task for cellists is to play a simple D Major scale containing 16 sounds in 16 seconds in accordance with metronome sounds. This task consists of up scale (*D*, *E*, *Fis*, *G*, *A*, *B*, *Cis* , *D*) and down scale (*D*, *Cis*, *B*, *A*, *G*, *Fis*, *E*, *D*). We focused on the right arm bowing skill during down scale in this analysis. During the down scale subjects, firstly perform down bowing motion, secondly bow returning motion, and the finally up bowing motion.

Subjects are the musical college students as experts and an amateur student as an amateur player. The experts have more than 10 year cello playing experience, while the amateur has only 3 year experiences.

5.3 Data Processing

5.3.1 Motion Capturing Data

We define a 4-segment 3-link model to represent performance data from motion capturing system. Five markers were put on various parts of the subject's body and the bow: articulatio sternoclavicularis (1), acromion (2), epicondylus lateralis (3), bow root (4), and bow top (5) as shown in Figure 1. Four infra-red cameras was used. The frame rate of each camera is 60 Hz. The 2D data obtained by all cameras are integrated and calculated to 3D coordinates by using DLT method [Marzan et al., 1975, Shapiro, 1978] which is a standard algorithm for 3D transformation. The 3D data contain noise due to skin shift. We apply 3.0 Hz Butterworth IIR low pass filter to the data to remove this kind of noise.

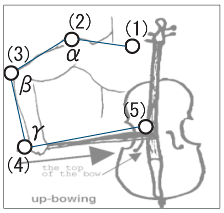

Figure 1: markers for motion capturing

Some related studies measures wrist rotation and finger motion during playing the violin [Kihara et al., 1995, Sakai et al., 1996]. However these method can not capture proximal motion. Here we adopted articulatio sternoclavicularis (joint between breast bone and clavicula) as a root of link model. Clavicula motion shows the relationship between torso and arm motion as it connects to the torso and scapula on each end.

We calculated three joint angle changes, right shoulder angle (α), elbow angle (β), and forearm-bow angle (γ) from 3D motion capturing sequential data. The increase of the shoulder angle implies that the raise of the upper arm in the right direction. The elbow angle increase shows that the forearm departs from the upper arm. The forearm-bow angle change contain many other angle changes including wrist rotation and finger joint angles.

5.4 Experimental Results

5.4.1 Angle Changes

In the α graphs there is few angle range difference between the novice and the experts. This novice tends to use shoulder angle in a wide range (Figure 2). The pattern β of novice is very different from that of experts. It seems that the novice use the elbow joint based on different priciple from that of experts (Figure 3).

There are some difference among subjects in γ. The novice's γ chart has curved line, while the experts' charts are almost straight lines (Figure 4).

5.4.2 Joint Angle Coordination

In addition to see the angle changes we also plot the $\alpha - \gamma$ points to investigate the factor of joint angle coordination between shoulder angle and

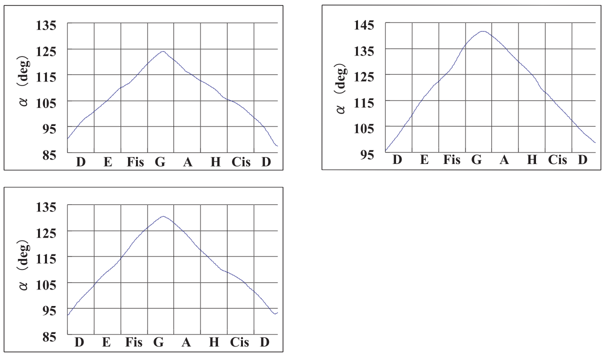

Figure 2: α for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

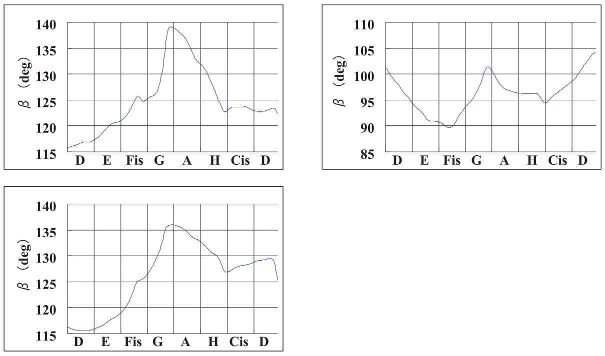

Figure 3: β for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

bow-forearm angle (Figure 5).

In the $\alpha - \gamma$ plots we can see the difference between the novice and the expert data. At the first stage the novice tends mainly to use α dominantly. However, the experts use α and γ simultaneously. This difference shows that their principles for coordination at their shoulder joints and bow-forearm joints are not the same. This suggests that experts satisfy the MIC for the coordination between shoulder joint and bow-forearm joint.

6 Discussion

Experts can play musical instruments without violating MIC as mentioned above. In addition players have to satisfy dynamic constraints as well as MIC in order to perfrom well. In this chapter we will discuss this aspect with experimental results and observation in our past experiments.

6.1 Muscle Usage and Physical Constraints

Muscle usage is the main activity in realizing motor skill. It is reasonable to conjecture that better usage of muscles should bring better motor skill. In this paper, we consider its converse; worse usage of muscles should bring worse motor skill. Then we will consider how to avoid it. First, let us show some examples of bad usage of muscles.

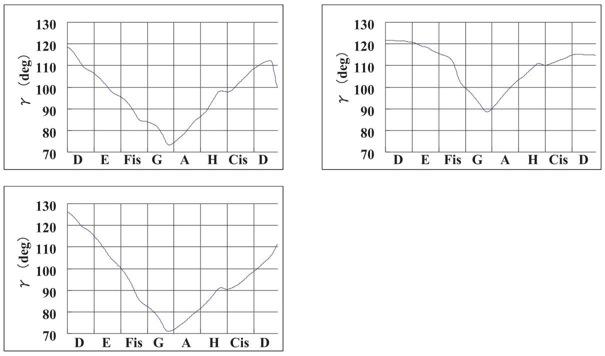

Figure 4: γ for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

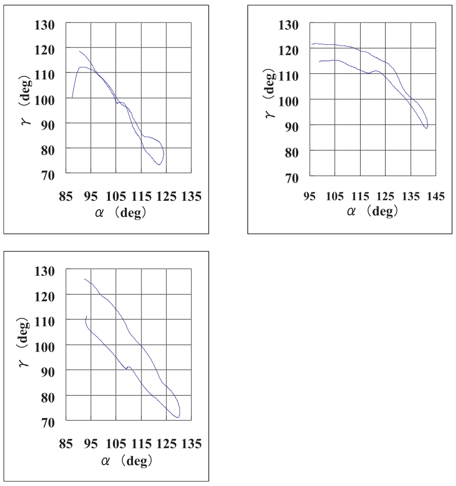

Figure 5: $\alpha - \gamma$ plots for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

- Very beginners apt to give too much force to move the bow even in simple continuous bowing on the same string.
- Even quite experienced amateur players often use more force on higher strings which actually require less force in the right hand thumb.
- They commonly have difficulty in jumping to a far apart high position in their left hand while playing a legato phrase with vibrato.
- They sometimes have difficulty in moving left hand fingers independently in a fast passage.
- Most of them cannot play fast passages with both right hand and left hand freely.

Most of the above phenomena can be explained by bad usage of muscles. In the trivial case, the bad usage of muscles comes from simultaneous activation of antagonist muscles. It happens even during such a simple task as continuous bowing on the same string for very beginners. Also quite experienced amateur players commit the error when the task become complex; jumping to a far apart high position while playing a legato phrase, moving left hand fingers independently in a fast passage, rapidly changing bowing direction, and so on. Let us explain the case of jumping a far apart high position while playing a legato phrase. It occured to one of the authors when he was playing Elgar's small piece called "Salute d'Amour". It requires to jump from D to B on A string. Since the phrase requires vibrato and legato, one has to keep generating sound as long as possible before the jump and it is best realized by fixing the left hand position. Then sudden position change is required. The rapid state transition causes the above difficulty since antagonist muscles tend to work simultaneously during the transition phase. Very recently, he also found the right hand problem; the conflict of muscles usage between playing on a single string and change of strings. The former requires to control the right arm to keep on the same horizontal plane associated with each string whereas the latter requires a rapid vertical movement from one plane to another.

Another kind of difficulty is the last one in the above list: playing a very fast passage. Let us consider the right hand movement when playing a fast passage requiring rapid repetitive changes in bowing direction. Since the arm movement can be modeled by a pendulum osscilation, a natural osscilation frequency associated with the arm pendulum determines its frequency. Sometimes the frequency is too low to achieve a rapid repeated up and down movement. This causes the problem. In this case, we need to change arm pendulum's natural osscilation frequency.

Both of the difficulties can be described as constraint satisfaction problems. In the former case, the constraint to be satisfied is to avoid simultaneous use of antagonist muscles and use of muscles to prevent natural counter movement against the main movement due to action-reaction law. The latter constraint is to satisfy natural physics of osscilation of the physical system consisting of our body and arm.

6.2 How to Satisfy Constraints

Each task has its associated constraints to be satisfied. For the change of the string, one has to be careful not violating simultaneous usage of antagonist muscles. One easy way is to loosen the arm force. However, this causes another problem for the bowing itself: discontinuity of tone arises as a side effect of the loosened force. Another solution is to use the wrist to change the string. This seems quite reasonable and effective. However, it is not ideal because it becomes difficult to maintain the bow direction to be orthogonal to the string due to the unnecessary wrist rotation.

The real solution is to loosen only those muscles which are antagonistic to the muscles being used for changing the string, and move the entire arm. Up / down bowing and string changing can be regarded as horizontal and vertical movements, respectively. Therefore, if one uses a different set of muscles for horizontal movement from that for vertical movement, one can loosen only some of those muscles for vertical movement. This avoids the problem of too much loosening of force which causes the tone discontinuity.

Another example of easy (but incorrect) solution for a simple task is jumping to a far high position by intercepting vibrato and continuous sound generation. This problem can also be solved by differentiating those muscles necessary for jumping to a high position to those for making vibrato and fingering.

Both of the above problems can be solved by applying a straight spine posture [Ueno et al., 1998], as described later.

For the problem of playing a very fast passage, we need to change body-arm pendulum's natural osscilation frequency, as stated above. How can it be achieved? Imagine we stretch both our right arm and our backbone, and keep our backbone straight. Then the length of the pedulum becomes longer. On the other hand, if we take a round posture, then the length becomes shorter and the natural frequency increases. If one keeps to have the same straight posture in playing a fast movement, one fails to satisfy the physical constraint of natural frequency.

Common pattern for those dificulties mentioned above comes from the necessity to satisfy constraints associated with complicated tasks. Also in some case, it happens in sequence; from one task to another which require different set of constraints.

Our conjecture is to adopt adequate postures to solve each set of constraints for complex tasks: straight spine posture is very helpful for the right hand string change and for the left hand jumping to a far high position; on the other hand, round posture is very adequate for increasing natural osscilation frequency and therefor for playing a fast phrase.

It should be noticed that pre-motion is very important particularly when complex tasks appear as sequences of different simple tasks. Even in a very simple continuous down/up bowing, pre-motion is essential. Since discontinuous movement often causes problems in realizing a smooth performance, pre-motion should be done smoothly. For example, it is very difficult to control the tip of our hand precisely. The general idea is to use the global movement of our body to start our hand motion. The slight change of center of gravity in the body may help for trigerring the pre-motion.

In satisfying dynamic constraints which change according to music note, planning and practice is very important.

6.3 Learning, Practice and Skill Acquisition

Generally, to improve our skill for music performance, we need to take extensive lessons. We can learn from lessons how to satisfy constraints, but usually teachers do not provide any convincing explanations why their methods are good. They know from their experience that one should keep straight spine posture during playing in general, but the knowledge may contradict when we need to play a fast passage requiring round posture to increase the natural frequency of our body-arm pendulum. One of the aims of our research is to analyze professional players' skill and to provide scientific explanations of how to play.

Practice is a conscious activity paying attention to satisfy constraints. For a sequence of constraints needed to perform a music note, a careful planning is neccesary for preparing best posture for each component task. During the practice, you may find some places which are difficult to play. In most cases, the difficulties come from the fact that there are complex tasks with many constraints to be satisfied simultaneously or in sequence to follow the music note. Then, careful considerations and plannings are required to achieve the target of the performance while satisfying associated constraints.

Skill acquisition is the result of repeated practices to perform while keeping to satisfy constraints unconsciously or subconsciously. Professional players have acquired such skill for dynamically satisfying constraints. The unconscious process of achieving dynamic constraints satisfaction suggests that it is stored in the brain as a set of basic motor skill programs. Note that unbelievable skill comes from only repeated training while satisfying associated constraints. Amateur players often imagine to be able to acquire such skill by simple repeated training but in most cases it results in nothing. This implies the importance of constraints satisfaction.

7 Conclusion and Future Research Directions

In this paper, we tried to provide a unified view of skill for playing string instruments as constraints satisfaction. Also we pointed out the role of lessons and practices as fundamental ways to learn how to satisfy constraints, and skill acquisition as a result. We found that results of EMG measurements strongly support our approach.

For the future research, we are planning to collect data from extensive experimentation and to extract professional skill by applying data mining algorithms. We regard the extraction of professional skill as discovering constraints from performance data. We also aim to verbalize tacit knowledge of skill by machine learning [Furukawa, 1999]. For this purpose, Inducitve Logic Programming (ILP) seems very promising because constraints can be expressed as a set of (negative) logical formula.

Using ILP to learn constraints leads us to consider an extension of behavioural cloning [Bratko et al., 1996]. We envisage using this framework to detect differences in skill between performers, for example comparing a teacher with a student. The teacher acts as a provider of performance data from which a constraint theory is induced. Data for the same piece is then obtained from a student. Where the student's performance data violates the constraints we detect a departure from the model of skill exemplified by the teacher.

Although musicality is beyond our research target, it is very related [Widmer, 1997]. For the musicality of performance, aesthetic feature is more important than simple skill. However, aethetic feature is strongly supported by better skill. In that sense, finger movements are very important both in right hand and in left hand. What we are investigating in our current research are more about arms, shoulders, and torso movements, but less about fingers. The reason why we concentrate more on these parts is that it is essenial to achieve a better control of fingers. Breathing is another important basic activity during the performance. Breathing is also controlled by muslces. It is related both to the skill and to musicality. For further research direction, brain science will become very important in future.

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