1 Introduction

Walking is one of the basic motor skills which human beings can perform unconsciously. However it is very difficult to explain clearly how we can perform such skills. Walking needs very complicated muscle coordination. The human body contains around 500 muscles and 200 bones. We have to select the appropriate combinations of these to walk. If we develop any disorders in walking, a lengthy rehabilitation process involving considerable effort is necessary to recover normal walking skill.

We can perform high level motor skills unconsciously once we build a motor program. The motor program is the structure supposed to carry out actions which are planned in advance and carried out with little or no perceptual input. Skill can be divided into "open" and "closed" categories [Schmidt, 1991]. Open skill denotes a skill for which the environment is typically unpredictable, so that advance organization of movement is limited. In contrast, closed skills are found in stable, predictable environments which allow a greater degree of prior organization for movements. Playing competitive sport like soccer is an example of an environment requiring open skills. Typing or playing musical instruments are good examples of closed skills. Here we focus only on closed skills. The autonomous stage where players perform without conscious attention to movement is only reached after lengthy repetitive practice. 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 observations show that our repetitive motor behavior can be performed at the level of tacit knowledge.

Musicians, dancers and athletes acquire high-level skills in the process of motor learning. The ordinary strategy for memorizing motor programs is to repeat the same motor pattern. However, it is very hard to construct motor programs unless one performs actions repeatedly in a very similar way. In addition, we are apt to acquire bad habits in controlling instruments if our motions do not take into account the structure of the human body and movement constraints based on physical laws. This suggests that we should understand the characteristics of the body from the perspectives of anatomy and dynamics. If we understand the relevant anatomical and physical constraints then this may be useful in improving skills.

Moreover it can also be helpful in prevention of injuries arising from incorrect muscle usage [Sazer, 1995, Bruser, 1997, Turner-Strokes et al., 1998].

2 Redundant Factors in the Human Body

Let us consider our arms and shoulders. In comparison with robot arms, human arms and shoulders have redundant degrees of freedom. This means that we cannot obtain a unique solution for problems of inverse kinematics, even for simple tasks such as grasping.

For example, the connection between scapula and thorax at the back has redundancy. These bones are connected by back muscles (e.g. the trapezius and serratus anterior muscles). This is a special and virtual joint because there are no joint parts such as the 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. In sum, the human upper extremity has highly redundant connections which other animals do not have.

Such redundancies present difficulties for understanding skilled movement. The motion analyst must know which parts of bodily movement are essential or not for the performance of particular skills. The Russian physiologist Bernstein described such problems in observation of skill in driving nails by experts [Bernstein, 1967]. He found that experts performed well when the hammer was close to the nail, although there was no reproducibility of this skill when it was far from the nail. This observation suggests that it is important to select the essential parts of body movement relevant to the skill that we would like to analyze.

3 Motor Skill as Constraint Satisfaction

3.1 Motion Integrity Constraints

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

Let us define MIC here. MIC will contain anatomical constraints and spatio-temporal constraints. Anatomical constraints include range-of-motions (ROMs), deviation from functional position [Castaing et al., 1984], viscoelasticity of muscles and so on. ROMs play a very important role when we flex or extend limbs. We can easily move limbs in the middle of the ROM of a joint. However, it is very hard to move limbs at the boundary of the ROM. The flexion reflex[1] is one of the mechanisms which automatically prevent the muscle and joint disconnection caused by too strong hyper-extension. The functional position is the easiest position from which to move bones in 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.

Spatio-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 the best performance. Appropriate spatial preparation allows us to realize stable performance. For example, the relative position of the musical instrument to the body constrains the performer's motion space.

In an earlier biomedical data acquisition experiment we found anatomical constraints during cello bowing action through electromyography (EMG), which measures muscle activity [Ueno et al., 1997]. It was found that inexperienced cello players sometimes used antagonist muscles during agonist muscle activation, whereas professional cellists used these muscles differently. Agonist muscles are the main muscles used to achieve movement towards a goal position, whereas antagonist muscles resist motion in the goal direction. When both muscles are used at the same time the joint stiffness level will increase and greater force is required to flex joints. For example, the biceps brachii muscle is the agonist and triceps brachii is the antagonist muscle in flexion of the elbow joint. This means that flexibility of the elbow joint decreases when these muscles are used at the same time. When this occurs the player must rely mainly on using the shoulder joint in order to achieve bowing movement. This movement disrupts the appropriate spatial relation between the bow and the string, which reduces the quality of the sound produced.

Spine posture may affect the performance. This is a factor dependent on both anatomical and spatio-temporal constraints. From the point of view

[1] This is not a voluntary mechanism.

of spatio-temporal constraints 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 keep the spine straight in order to transmit muscular force from the back to the right arm. In a straight spine posture we do not have to use extra force at the upper part of the back muscles. Only slightly more muscular force at the waist is required in the straight posture than in the bent [Ueno et al., 1998]. As we mentioned above, the upper arm connects to the scapula. The scapula connects to such back muscles as the trapezius. The upper arm also connects to the back and chest muscles such as the latissimus dorsi, pectoralis major and so on. These connections explain why back posture affects the skill executed by shoulders and arms.

3.2 Conscious Skill Helps Unconscious Skill

Given a skilled task to perform, we use muscles to control our body in a way suited to the task. Although distal[2] movement such as wrist rotation is important, proximal[3] movement is actually more critical to the execution of sequential closed fine skills. For instance spine posture is very important in obtaining good performance without excessive muscular force. The reason for this is that the proximal parts of the body dominate the distal parts from the point of view of topology and anatomy.

Michie has suggested that there are two agents in our bodies which collaborate with each other to realize physical performance [Michie, 2000]. One is called the "zombie" and is responsible for reproducing what has been memorized. For example the zombie can reproduce fingering skills unconsciously (at the sub-cognitive level) because the necessary motor programs are in some sense compiled in the performer's brain. The companion to the zombie is a conscious agent having the ability to control the spine, the scapula, and the arms. The conscious agent helps the zombie to achieve its best performance by arranging the best environment for the task. This idea is very natural from the aspect of nerve conduction velocity. The required performance speed for the zombie is much faster than that for the conscious agent.

The zombie theory gives us some clues that we have to separate motions into two kinds of skills: a distal motion conducted by the 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 necessary for realizing skilful performance. Nevertheless, in this paper we focus on proximal motion because of the proximal domination characteristics mentioned above. Experts seem to know the natural way to use proximal parts. This probably results from the search for optimal usage of whole body control which is part of the process of acquisition of their expertise. Our conjecture is that movement of the proximal parts can help the zombie perform stable reproduction of motor programs. Note also that the proximal parts make the movement more dynamic because the proximal movement proceeds and induces the distal one. In fact MIC provides us with the clues to obtain optimal proximal movement. Proximal motion can be optimal when MIC is satisfied because MIC is the sign of an optimal relationship between distal motion and proximal motion. In other words

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[2] far from torso

[3] close to torso

MIC provides the coordination between the proximal and the distal part of the bodies.

In the remainder of this paper we describe an approach to extract MIC from performance measurements, focusing on differences between experts and novices.

4 Extracting MIC with Biomedical Sensors

The aim of extracting MIC from an expert's performance is to discover critical factors for high level performances. Once we identify the critical MIC, we propose that it may play a central role in teaching physical skills to students. Novice-level performers probably cannot satisfy some of the critical MICs. Also, if a performer suffers from difficulties in his or her skill improvement (sometimes known as a slump), we may be able to diagnose these faults.

We have many built-in sensors in our bodies to monitor the effects of our own movements. These include real-time sensors to monitor the produced sound (the auditory centers), how far the muscle fibers are extended (muscle spindles), how strongly tendons are 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 kinesthetic data by biomedical sensors. Fortunately we can measure the action potential of muscles by using Electromyography (EMG). This helps us in monitoring the status of muscles instead of the kinesthetic information.

The EMG data provides us with the information on how a 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 concentric contraction, lengthened during the eccentric, and has no change during the isometric even if all contractions show amplitudes in EMG.

Therefore we have to measure motion data in three dimensional coordinates with a motion capturing system together with EMG. With this system we can trace the joint positions in time sequences. It is possible to discover how muscles move limbs with the muscular forces detected by EMG.

5 Preliminary Experiment as a Case Study

5.1 Outline of the Measuring System

A preliminary experiment to discover MIC was carried out and is described in this section. The aim of this experiment was to investigate how elements of MIC could be discovered by simple methods of traditional analysis. Note that our final goal is the automatic discovery of MICs.

We constructed the data acquisition system as follows. A three dimensional infra-red motion capturing system and EMG sensor were used simultaneously in this experiment. We measured EMG by wireless transmission in order not to interfere with performers' motion. An electronic metronome pulse was also measured in order to synchronize the performers' motion, the motion-capture data and the EMG data.

5.2 Tasks for Subjects

The task for cellists was to play a simple D Major scale containing 16 sounds in 16 seconds in accordance with the metronome pulse. This task consisted of an up scale (D, E, $F\sharp$, G, A, B, $C\sharp$, D) and a down scale (D, $C\sharp$, B, A, G, $F\sharp$, E, D). We focused on right arm bowing skill during the down scale in this analysis. During the down scale subjects firstly perform a down-bow motion, secondly a bow-returning motion, and finally an up-bow motion.

We had 3 subjects in this experiment. Subjects were music-college students (the experts) and a non-music student who is an amateur player (the novice). The experts have more than 10 years cello-playing experience, while the novice has only 3 years experience.

5.3 Data Processing

5.3.1 Motion Capture Data

We defined a 4-segment 3-link model to represent performance data from the motion capture 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 were used. The frame rate of each camera is 60 Hz. The 2D data obtained by all cameras were integrated and calculated to give 3D coordinates using the DLT method [Marzan et al., 1975, Shapiro, 1978] which is a standard algorithm for 3D transformation. The 3D data contained noise due to skin shift. We applied a 3.0 Hz Butterworth IIR low pass filter to the data to remove this noise.

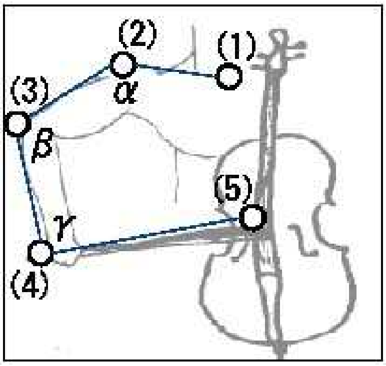

Figure 1: markers for motion capture

In some related studies wrist rotation and finger motion during violin playing were measured [Kihara et al., 1995, Sakai et al., 1996]. However the methods used in their work cannot capture proximal motion. Here we adopted the articulatio sternoclavicularis (the joint between the breast bone and the clavicula) as the root of the link model. The clavicula motion shows the relationship between the torso and arm motion as it is connected to the torso and scapula at each end.

We calculated three joint angle changes: right shoulder angle (α), elbow angle (β), and forearm-bow angle (γ) from the 3D motion capture sequential data. An increase of the shoulder angle implies that the upper arm is being raised in a rightward direction. An elbow angle increase shows that the forearm straightens with respect to the upper arm. A forearm-bow angle change contains many other angle changes including wrist rotation and finger joint angles.

5.4 Experimental Results

5.4.1 Joint Angle Changes

In the α graphs there are few angle range difference between the novice and the experts. The novice tends to use shoulder joint angle in a wide range (Figure 2).

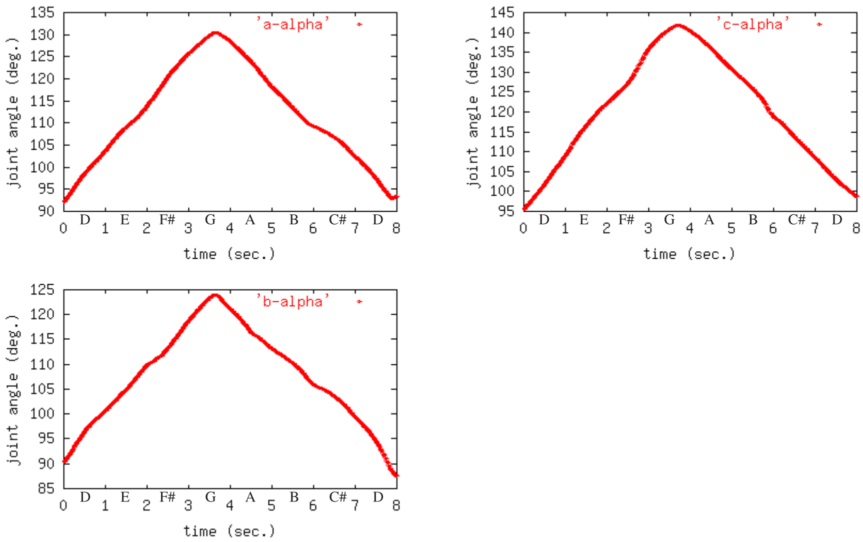

Figure 2: α for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

The β pattern of the novice is very different from that of the experts. It seems that the novice used the elbow joint based on a different principle from that of the experts (Figure 3).

There are some differences among subjects in γ. The novice's γ chart has a 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 plotted the $\alpha - \gamma$ points to investigate the factor of joint angle coordination between shoulder angle and bow-forearm angle (Figure 5).

In the $\alpha - \gamma$ plots we can see the difference between the novice and the expert data. In 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.

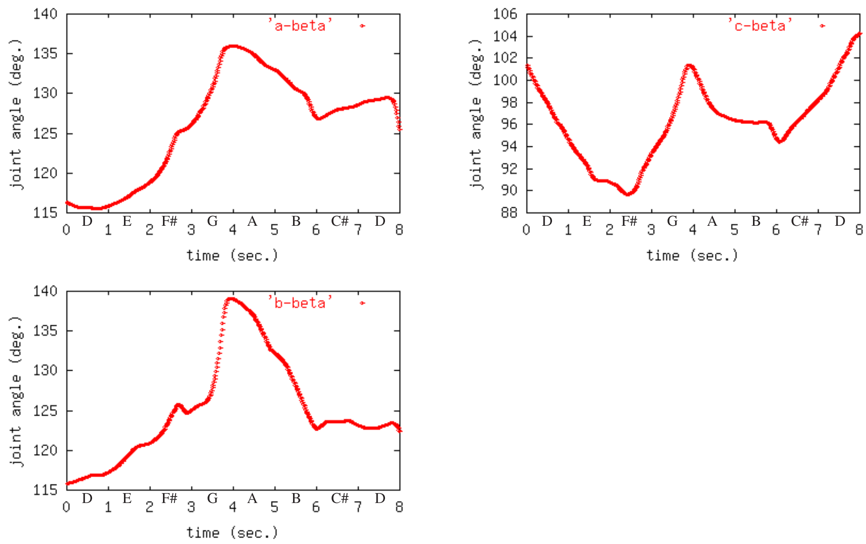

Figure 3: β for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

6 Discussion

Experts can play musical instruments without violating MIC as described above. In addition, players have to satisfy dynamic constraints as well as MIC in order to perform well. In this section we discuss this in more detail using experimental results and observations from our past experiments.

6.1 Muscle Usage and Physical Constraints

Muscle usage is the main activity in realizing motor skill. Therefore it is reasonable to conjecture that better usage of muscles should produce better motor skill. In this paper, we consider the converse: worse usage of muscles should produce worse motor skill. Then we will consider how to avoid it. First, let us show some examples of incorrect muscle usage.

- Complete beginners are apt to apply 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 the higher strings, which actually require less force from the right hand thumb.
- They commonly have difficulty in jumping a large distance to a high position with 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 incorrect usage of muscles. In the trivial case, this comes from the simultaneous activation of

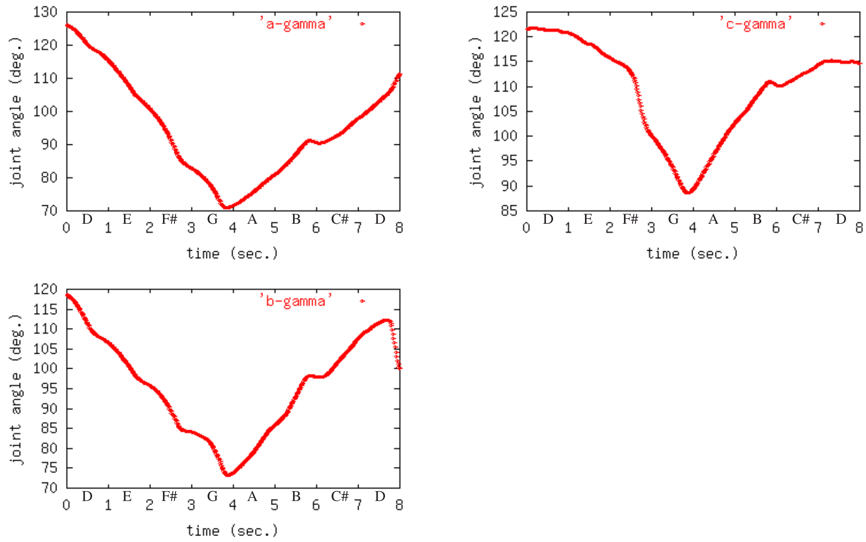

Figure 4: γ for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

antagonist muscles. It happens even during such a simple task as continuous bowing on the same string for complete beginners. Also, quite experienced amateur players commit the error when the task becomes complex, such as jumping a large distance to a high position while playing a legato phrase, moving the left hand fingers independently in a fast passage, rapidly changing bowing direction, and so on. Let us explain the case of jumping a large distance to a high position while playing a legato phrase. It occurred to one of the authors (K.F.) while playing Elgar's small piece called "Salute d'Amour". This requires a jump from D to B on the A string. Since this legato phrase requires vibrato, one has to keep generating sound as long as possible before the jump and this is best realized by fixing the left hand position. Then a sudden position change is required. The rapid state transition causes the above difficulty since the antagonist muscles tend to work simultaneously during the transition phase. Very recently, he has also found a problem with the right hand; the conflict of muscle usage between playing on a single string and changing strings. The former requires control of 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 oscillation, a natural oscillation 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 the arm pendulum's natural oscillation frequency.

Both of the difficulties can be described as constraint satisfaction problems. In the former case, the constraint to be satisfied is to avoid the simultaneous use of both antagonist muscles and those which prevent the natural counter-movement against the main movement due to the action-reaction

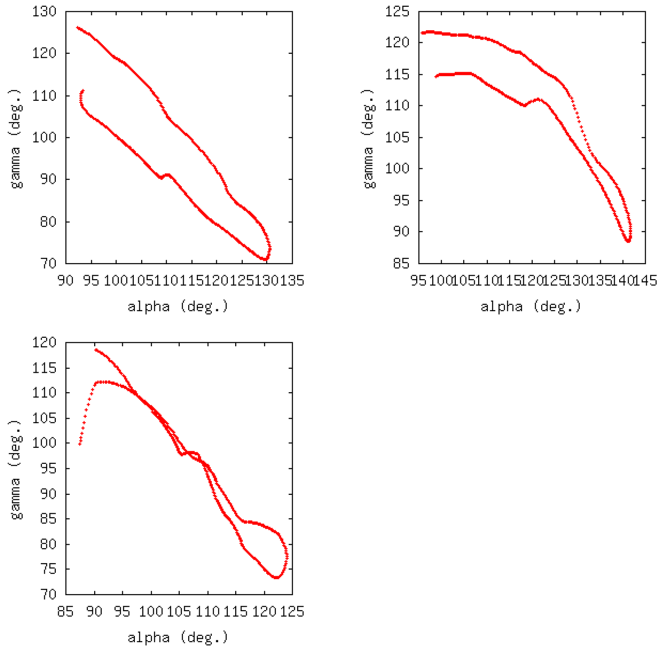

Figure 5: $\alpha - \gamma$ plots for Expert A (Upper Left), Expert B (Lower Left) and Novice C (Right)

law. The latter constraint is to satisfy the natural physics of oscillation 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 string, one has to be careful not to violate simultaneous usage of antagonist muscles. One easy way is to loosen the arm force. However, this causes another problem for the bowing itself: a 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 an easy (but incorrect) solution for a simple task is jumping to a distant 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 from 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 below.

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

A common pattern for those difficulties mentioned above comes from the necessity to satisfy constraints associated with complicated tasks. Also in some cases this happens sequentially; moving from one task to another, each of which require a different set of constraints.

Our conjecture is that adopting adequate postures to solve each set of constraints for complex tasks will provide a solution to these problems: a straight spine posture is very helpful for the right hand string change and for the left hand jump to a high position; on the other hand, a round posture helps to increase the natural oscillation frequency and therefore in playing a fast phrase.

It should be noted that pre-motion is very important particularly when complex tasks appear as sequences of different simple tasks. Even in 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 one's hand precisely. The general idea is to use the global movement of the body to start our hand motion. A slight change of center of gravity in the body may help in triggering the pre-motion.

In satisfying dynamic constraints which change according to the requirements of the musical performance, planning and practice is very important.

6.3 Learning, Practice and Skill Acquisition

Generally, to improve our skill for musical 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 a straight spine posture during playing in general, but this knowledge may not apply in the situation where we need to play a fast passage, which requires a 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 requiring paying attention in order to satisfy constraints. For a sequence of constraints needed to perform a musical note, careful planning is necessary to prepare the best posture for each component task. During practice, one may find some phrases 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 play the music. Careful consideration and planning is then required to achieve the target of the performance while satisfying the associated constraints.

Skill acquisition is the result of repeated performance practice while ensuring satisfaction of constraints unconsciously or subconsciously. Professional players have acquired such skills for dynamically satisfying constraints. The unconscious process of achieving dynamic constraint 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 that they will be able to acquire such skill by simple repeated training but in most cases this does not happen. This emphasizes the importance of identifying and satisfying the required set of constraints.

7 Conclusion and Future Work

In this paper, we proposed a unified view of skill for playing string instruments in terms of constraint satisfaction. We pointed out the role of lessons and practice as fundamental ways to learn how to satisfy constraints, and acquire skill as a result. We found empirically that the results of EMG measurements strongly support our approach.

For the future, 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 the tacit knowledge of skill by machine learning [Furukawa, 1999]. For this purpose, Inductive Logic Programming (ILP) seems very promising because constraints can be expressed as a set of (negative) logical formula using background knowledge.

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]. To assess the musicality of performance, aesthetic features are more important than simple skill. However, aesthetic features are strongly supported by better skill. In that sense, finger movements are very important both in right and left hands. We are more concerned in our current research with movements of arms, shoulders and the torso and less with fingers. The reason why we concentrate more on these parts is that they are essential to achieving better control of the fingers. However there are many more aspects to physical control upon which good performances depend. For example breathing is another important basic activity during performance. Breathing is also controlled by muscles. It is related both to skill and to musicality. In the future brain science will also become very important.

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