Full Length Research Paper

Analysis of dexterous finger movement for piano education using motion capture system

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Although finger bones construction of human body is very complex and difficult to measure but it is necessary to measure the dexterous finger movement of a pianist for piano playing. This paper has measured the finger movements with six degrees of freedom of an expert pianist, using a magnetic motion capture system by which it is possible to measure any type of finger movements during their activities. From the current research novice players/beginners can get the information about intertap interval time of a particular finger, finger height in space, finger status and finger tip velocity during playing the piano. Moreover it has shown an easy digital recording process of the hand's movements using a hand MoCap system. These themes are crucial to acquire knowledge of any kind of finger movements and its digitization. The results has presented in this paper are particularly helpful for novice players as well as applications where dexterous finger movements are essentials such as piano education and different games.

Key words: Dexterous finger movement, motion capture, piano education, finger status, finger tip velocity.

INTRODUCTION

It is a great need to acquire the complete information about hand/finger movements for piano education. However, a system is also required to capture the dexterous finger movements for educational purposes. Dexterous is defined as skillful in physical movements, especially of the hands. It is necessary to measure the finger movements of an expert pianist accurately for a better understanding of the beginners/novice players. As there are twenty seven bones and nineteen joints in each hand of the human body, so it is very difficult to measure the finger movements of human hand during piano playing. Professionals are always used to do their jobs skillfully by their hands. Pianists' play the piano with their fingers in various positions and by observing the finger movements, novice players can earn the knowledge for piano playing. And it is possible to measure the finger movements using a motion capture (MoCap) system.

MoCap is the name given to the technique or several techniques, which enables to obtain motion data from human performers/subject (Motion Technology Entertainment). Another popular term is 'performance animation,' taking the emphasis off the capturing of data, which is seen as just one part of the entire performance animation process (MIT Communications Forum). It is used in different sectors such as; virtual reality, motion acquisition for medical researches, biomechanics, ergonomics for humanoid robots, entertainment (James et al., 2000) etc. There are several kinds of MoCap system such as; optical systems, electromagnetic systems, mechanical sytem though the most common technologies for MoCap are optical systems and electro magnetic systems. In the present research, it used magnetic MoCap system instead of optical MoCap system. There are some advantages of magnetic MoCap system for hand measurement over optical MoCap system. The resulting data stream of magnetic MoCap system consists of positions and orientations six degrees of freedom (6 DOF) for each receiver whereas optical MoCap system can measure only position not orientation data from a marker (Motion Technology Entertainment; Rahman et al., 2010). Optical MoCap system requires obtrusive retro-reflective markers or LEDs and many camera setups. It is prone to light interference, so reflective dots can be blocked by the

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performers or other structures (MIT Communications Forum; Disadvantages of Optical Motion; Robert et al., 2008; Park et al., 2006; Tovi et al., 2004, causing loss of data sometimes. Optical markers are placed just on the top of finger joint during finger measurement so it is very difficult to fix them tightly on the joint, whereas magnetic sensors are placed in the middle of two joints of finger bone. So it is very easy to fix them tightly on the bone. For this optical markers may move slightly out of position, whereas magnetic sensors may move very less than optical markers. Thus magnetic MoCap maintains more accuracy than optical MoCap system for hand measurement but for other purposes optical MoCap system performs better than magnetic MoCap system.

It was developed a magnetic MoCap system for hands with an auto calibration system (Rahman et al., 2010; Mitobe et al., 2006; Rahman et al., 2008; Rahman et al., 2009; Mitobe et al., 2007;). Pianist hands were installed using our magnetic MoCap system. During piano playing, finger movements of the pianist were recorded in the computer as digital data for each position and posture of fingers. To earn the knowledge in piano education for the beginners, there were some lacking of works in our former journal (Rahman et al., 2010). So the current research has analyzed that how a beginner can get the useful information using hand MoCap system during piano education. The aim of this research is to investigate the pianist's finger movements and from this result to get some useful knowledges for the beginners during piano playing. During playing the piano beginners should know about the musical notes which are described in this research. Before playing the piano they should know about their finger status whether it is curl or flat finger position. Finger status is important for piano playing and it is also described in this research. In the present research has described about finger tapping rate of particular finger, finger height from the keyboard, finger height in respect of backside of palm and finger tip velocity for the beginners which is important to change the musical tempo and musical tone during piano playing. So it examined and investigated the complex finger movements of a professional pianist for piano education.

There are some related research works in the world for finger movements. A pianist can use different combinations of movements in different joints to perform a touch (Gat, 1965). Biomechanical factors differentially influenced pianists' production of tapping sequences (Janeen et al., 2007). Timing accuracy is affected by biomechanical and sequential constraints on finger motion in trained pianists' tapping (Janeen et al., 2009). Finger movements in action sequences may also be constrained by biomechanical and neural factors that can contribute to lack of independence among neighboring fingers (Baader et al., 2005). Biomechanical constraints that influence interactions among finger movements include factors such as the soft tissues in the webs between fingers and connections between the tendons of the finger muscles (Schieber et al., 2004). They have great limitations that they can measure only position x, y and z but not both position and angle together from the subject. Finger joint movements recorded during ball throwing using pressure detector (Hore et al., 1999). During the experiment they setup the sensors on the front side of the fingers so it may affect the result for experimental subject whereas our sensor setup backside of the finger so it can not affect the experimental subject. Organization of the upper limb movement for piano key-depression shows Shinichi et al. (2008) using electro-myography (EMG) and 2-D position sensor. There are more some works on finger joint coordination are found but they used different system. Those works were measured using the electromyography (EMG) and finger joint angles during typing of computer keyboard they used individual miniature goniometers (Kuo et al., 2006; Jindrich et al.,2004; John et al., 2008). They have some limitations that they can not find the phalanx position whereas our system is suitable to find the phalanx position and posture together.

Experimental guidelines

Magnetic MoCap system for hands was made with 15 receivers for 5 fingers and 1 receiver on the back side of the palm. Each receiver was installed on each bone of fingers in a way so that it fit with the finger. 3 receivers are used to measure each finger. So finally 16 receivers in one hand and totally 32 receivers are used for both hands. The weight of each receiver is only 2 g and the size is 9.6 x 9.6 x 9.6 mm. Each receiver is called a channel and attached on the finger using Kinesiotex tape and liquid type plastic in order to prevent the receiver movements and it did not any affect pianist performance. Figure 1(a) shows an experimental arrangement of hand MoCap system. In the figure only right hand connection is shown for 16 receivers, left hand is also same configuration. In the figure the position of 16 receivers are shown by the numbers 1, 2, 3 - - - - 16 with square symbols. Receivers 1, 2 and 3 are on the thumb, 4, 5 and 6 are on the index, 7, 8 and 9 are on the middle, 10, 11 and 12 are on the ring and 13, 14 and 15 are on the pinky finger. Receiver 16 is placed on the back side of the palm. Each receiver is placed tightly just on the bone, that is between the joint of the fingers for not to slides on the finger bone. The magnetic tracker that is composed of a transmitter (23×28×16 mm) and 16 receivers can digitize the distance (X, Y and Z) from the transmitter to receiver. The magnetic tracker can also digitize the position and relative angles (Azimuth, Elevation, and Tilt) of a receiver against a transmitter. During the operation of a pianist, his finger moves, as well as each phalanx of fingers also moves to the direction X, Y, Z, azimuth, elevation and tilt. Transmitter coordinates are shown the dimensions in Figure 1(a). LIBERTY[TM] 16 systems (POLHEMUS)
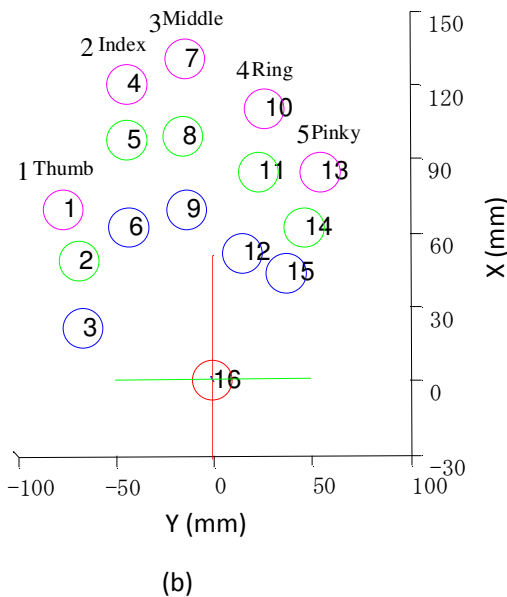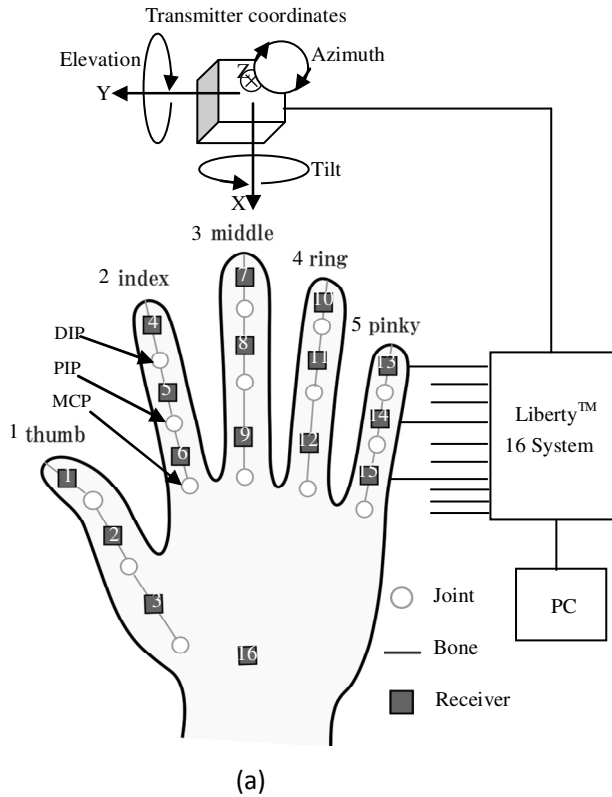
(a)

(b)

Figure 1. Experimental arrangement during playing the piano. (a) Systematic arrangement of hand MoCap system for right hand connection (16 receivers position on finger bone with liberty connection, Transmitter coordinates). (b) Actual receivers position on right hand in respect of receiver 16 (X-Y plane)

connected to a computer (ThinkPad IBM) through a USB interfacing. It can measure the data from the experimental

setup of Hand MoCap system of 6DOF by 32 receivers at the rate of 240 Hz simultaneously. Each data has six directions, so we get a total of (240 × 6) data per channel per second from each position of a finger on each hand. The spatial resolution of our MoCap system is 0.0038 mm, 0.0012 deg. and accuracy is 0.76 mm, 0.15 deg. which were supplied by POLHEMUS. Figure 1(b) shows the actual measured position (X-Y plane) of the receivers on right hand finger bone. Fingers are numbered from 1 to 5 starting with thumb which is also shown in the Figures 1(a) and 1(b).

METHODOLOGY

Musical information

The music of this research was "Sonata KV 331, Turkish March (Mozart, Wolfgang Amadeus). Out of three movements of Sonata KV331, it was "Alla Turca (Allegretto)". There are 388 quarter musical notes for the right hand and 319 quarter musical notes for the left hand and 56 bars in this music. It was very complex music and required an expert pianist. Expert pianists are skilled at accurately timing long sequences of finger movements (Janeen et al., 2009; Repp, 1995; Palmer, 1989; Werner et al., 2008). We select an expert pianist as an example for the first time as there is no standard analyzing system of finger movement. After analyzing this we can select different types of subjects for other purposes.

Intertap interval time

To calculate the intertap intervals (ITI) time, total taps were calculated for the particular time. For this it was selected 5 receivers near the finger tip (1, 4, 7, 10, 13) out of 16 receivers. The music was examined for 40 s (10 to 50 s) for calculating the total taps. Then ITI was calculated by dividing the total taps for individual finger of each hand.

Finger height between finger tip and receiver 16

To calculate the height between finger tip and receiver 16, it was selected 5 receivers near the finger tip (1, 4, 7, 10, 13) out of 16 receivers. Actually it was receiver's position on finger tip, we usually used to say it finger tip though it was not finger tip. It was examined 40 s (10 to 50 s) for the music, for calculating the height between finger tip and receiver 16. At first the vertical height of receiver 16 was calculated in respect of transmitter then vertical height of individual finger tip was calculated. After that each finger tip height was subtracted from the height of receiver 16. So it is the vertical height between finger tip and receiver 16.

Finger amplitude/height form the keyboard

To calculate the finger height from the keyboard it was selected 5 receivers (1, 4, 7, 10, 13) as like finger height between finger tip and receiver 16. For calculating finger height, it was observed 40 s of the music for individual finger tap. Within this period it was examined total finger taps 708 for right hand fingers and 498 for left hand fingers of the music for calculating finger height from the keyboard. An analysis of variance (ANOVA) was carried out for significant test. A post hoc analysis was performed by using the Tukey test.

Finger tip velocity

For calculating the finger tip velocity we used two coordinates systems one is global (transmitter) coordinate and the other is local (Receiver 16) coordinate. Using the global coordinates, it can get the velocity for both the hands and fingers movements together and using the local coordinates, it can get only finger movements velocity in respect of Receiver 16. To calculate the velocity, first we have calculated finger movement trajectory, that is, finger movement length. Finger movement trajectory was calculated using 3 dimensional distance formula among all positions (x_n, y_n, z_n) of individual receiver data, "n" indicates the number of data of individual receiver. That is if point 1 is (x_1, y_1, z_1) and point 2 is (x_2, y_2, z_2) then distance between two points, $d=sqrt([x_1-x_2]^2+(y_1-y_2)^2+(z_1-z_2)^2])$. Velocity was calculated using the length divided by time. Time $(t=1/240$ s) was calculated from our experimental data transmitting rate, that is, sampling rate $(f=240$ Hz). After that it calculated the average velocity.

RESULTS AND DISCUSSION

Hand MoCap system was developed using magnetic MoCap system. Figures 2(a), (b) and (c) shows the X, Y and Z axis component of Receiver 4 on right hand index finger. Right hand index finger was selected as per as an example, though it can select any finger for the analysis. A sample period (28 to 29 s) is taken for the analysis. According to our experimental conditions X moves front and back, Y moves left and right and Z moves up and down which is also shown in the transmitter coordinates in Figure 1(a). Figure 2(c) shows the 5 taps within a sample period and surface line of the keyboard. Using this data it is useful to calculate for further analysis of finger tip velocity, finger height from the keyboard, height between finger tip and backside of palm and intertap interval time. Figures 2 (d), (e) and (f) shows the related rotational angular position azimuth, elevation and tilt of Receiver 4 on right hand index finger. These angles are useful to calculate any types of finger movements and to find the exact finger position, to calculate finger joint angles; distal interphalangeal (DIP), proximal interpha-langeal (PIP) and metacarpophalangeal (MCP) and to transfer the global coordinates to local coordinates for further analysis. The finger joint angles of the pianist were calculated in our former research; (DIP=1 to 38 deg., PIP=26 to 49 deg. MCP=5 to 43 deg.) for right hand index finger (Rahman et al., 2010). The joint angles are important to know about the finger status whether it is 'flat finger position (FFP)' or 'curled position', that is, angles forms with the fingers during piano playing. Beginners should know first, about their finger status during piano playing. So beginners can get the information about their finger joint angles using this data, which indicates finger status during piano playing. Besides this it is useful to calculate the finger joint angles of pitcher of baseball and cricket player during grip their ball and throwing the ball during bowling. It is also useful for the tennis player to calculate their wrist variation during playing the game.

Figure 3(a) shows the average finger height in respect of Receiver 16, that is, vertical height between finger tip and backside of the palm. Finger 1 for thumb, Finger 2 for index, Finger 3 for middle, Finger 4 for ring and Finger 5 for pinky (little), which is also shown in Figure 1(a) and 1(b). Standard error (SE) is under ±0.21 mm for left hand fingers and under ±0.22 mm for right hand fingers which is shown in the figure. SE=SD/sqrt(n), where SD is the standard deviation of the mean and "n" is the number of observation. From the figure it is shown that the middle finger is quite lower height and thumb and little fingers are higher height than all others fingers for both hands of the music. It indicates that peak height of the middle finger from the keyboard was the highest and thumb and little finger was the lowest than all other fingers during playing the piano. Janeen et al. (2007) also shows that middle finger is the highest amplitude during piano playing but they did not show the finger height between finger tip and backside of palm. Their purpose was to find biomechanical influences of finger movements. Figures 3(b) and 3(c) shows an example of peak height between finger tip and Receiver 16 using computer graphics. It shows the different height of finger tip in respect of Receiver 16 which indicates different height of finger tip from the keyboard also. Another findings is that if longer the vertical height (Figure 3b) between Receiver 16 and finger tip then increases the finger joint angle specially MCP of 4 fingers index, middle, ring and pinky and increases the curl between Receiver 16 and fingertip and this is called the 'curled position' in piano practice. If shorter the vertical height (Figure 3c) between Receiver 16 and finger tip then decreases the MCP angles of 4 fingers and curl between Receiver 16 and finger tips, so that gradually when fingers are straight to the hand it is called 'flat finger position (FFP)' in piano practice (Fundamentals of piano practice). Flat finger position (FFP) as the one in which the fingers are basically stretched straight out from the hands, sometimes it is called non-curled position. Experienced pianist can use both curled position and FFP. But the starting finger shape for learning the piano is the partially curled position (Fundamentals of piano practice). However, Funda-mentals of Piano Practice (2006); demonstrated that the flat, or straight, finger position is also very useful. FFP is not only useful but is also an essential part of technique and all accomplished pianists use it (Fundamentals of piano practice). So this data is also useful as like finger joint angles to observe the finger status which is important for the novice player during piano playing.

Figure 4 shows the 3 dimensional (D) trajectory of pianist finger tapping for 5 fingers during playing the piano. In the figure, finger movement waveshapes are drawn using the numerical number which indicates the particular finger. A sample period is choosen (28.6 to 29 s) for observing the 3D view of pianist finger tapping during playing the piano. Figure shows the actual finger tapping position of the pianist. It is observed in Figure 4 that three fingers thumb, index and pinky are touching the
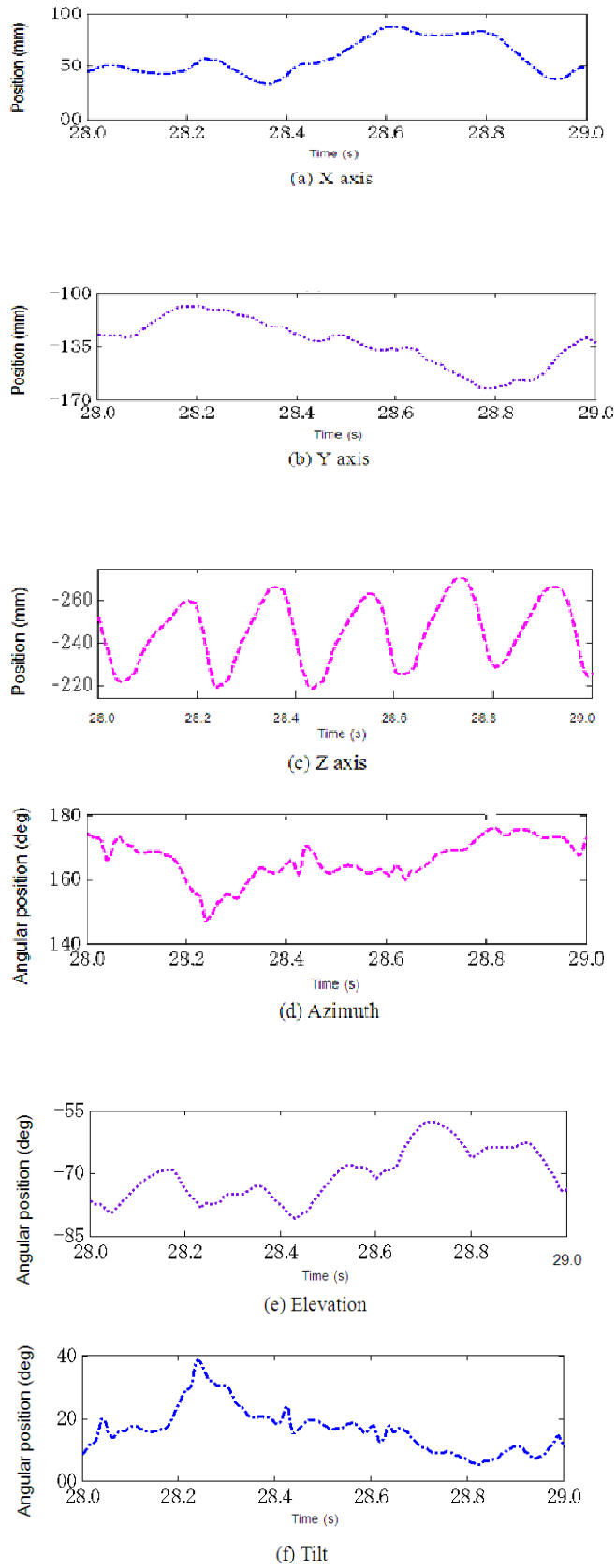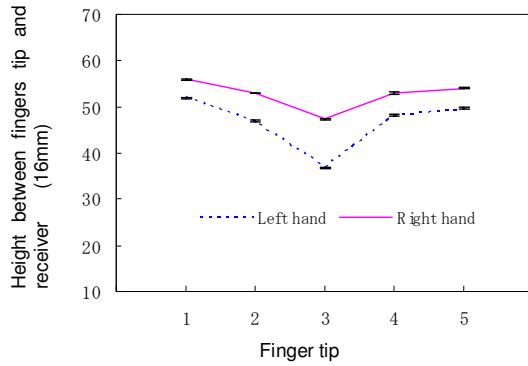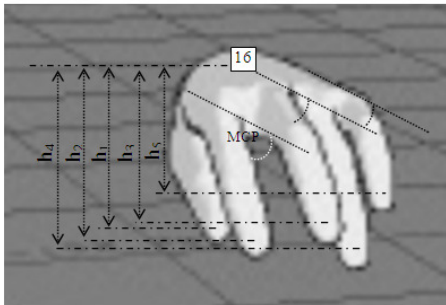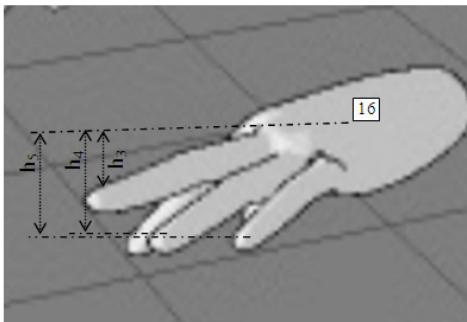
Figure 2. Right hand index finger movement of pianist in 6 dimensions (position and rotational angles, Receiver 4).

(a)

(b)

(c)

Figure 3. Mean finger height between finger tip and backside of palm i.e. receiver 16 (10 to 50 s). (a) Vertical height between finger tip and receiver 16. (b) Longer vertical height between finger tip and receiver 16 (increases MCP angles). (c) Shorter vertical height between finger tip and receiver 16 (decreases MCP angles)

surface line of keyboard during this short period. Surface line is shown in Figure 4. Finger movement direction of three axis components X, Y and Z are also given in Figure 4. So using this data novice player can observe their finger movements in 3D and tapping sequence in various ways by changing finger movements direction and the axis of 3 components X, Y and Z.

Figure 5 shows the intertap intervals of all fingers of both hands. Intertap intervals (ITI) are defined as the time interval from one finger tap to the next. The variability of the intertap intervals indicated that both hands are not operated at same timing rate due to the different musical notes and musical bars of the music. From the figure it is observed that pianist plays faster with the right hand than his left hand as per the musical notes of the music. Note is a sign, used in musical notation to represent the relative duration and pitch of a sound. It is the musical pitch with specific frequency (Music theory). It is observed in Figure 5 that ITI of each finger of individual hand is almost similar timing rate though thumb finger of left hand is quite faster than other fingers. Pianist can use his all fingers in equal rate during piano playing which can evaluate in our research using hand MoCap system. Tapping speed is important factor for musical tone during piano playing. Each pianist can control the tone by numerous means, such as by playing loudly or softly, or by varying the speed. That is by playing louder and at a higher speed, each can produce music consisting mainly of the prompt sound (Fundamentals of piano practice). Thus the system can be helpful to know about the finger tapping speed and to maintain the speed for his both hands as per the musical notes during piano playing. So by observing the experienced pianist data, novice player can also change the musical tone by changing the finger tapping speed during piano playing. Similarly using this MoCap system it is also possible to calculate the timing rate of any types of finger movements during their activities.

Figure 6 shows the the two sequences of computer graphics of pianist finger movement, picked up using MoCap data. It is the sample period of pianist finger movement during piano playing. The figure shows that both hands are operating at different position during playing the piano. The figure shows that middle finger is quite higher, thumb is quite lower and index and ring are about same level during piano playing. It is observed in the computer graphics for two sequences that during piano playing pianist operates his fingers in different position at different angles.Thus our system can identify every sequence of finger movements during playing the piano. So from this research novice player can observe every moment of finger movements, as well as every sequence of finger status which they can apply in piano education. Besides this cricket bowlers and base ball pitcher can also observe every sequence of finger move-ments during throwing the ball which is useful during playing the respective games.

Figure 7 shows the average finger tip height/amplitude from the keyboard of all fingers for both hands. Standard error (SE) is under ±1.50 mm for left hand fingers and under ±1.25 mm for right hand fingers which is shown in the figure. An analysis of variance (ANOVA) was carried out for significant test. The tapping finger had a significant effect on peak height, $F_{(4,493)}=4.39$, $P<0.01$ for left hand and $F_{(4, 703)} = 11.81$, $P<0.01$ for right hand. (Tukey's
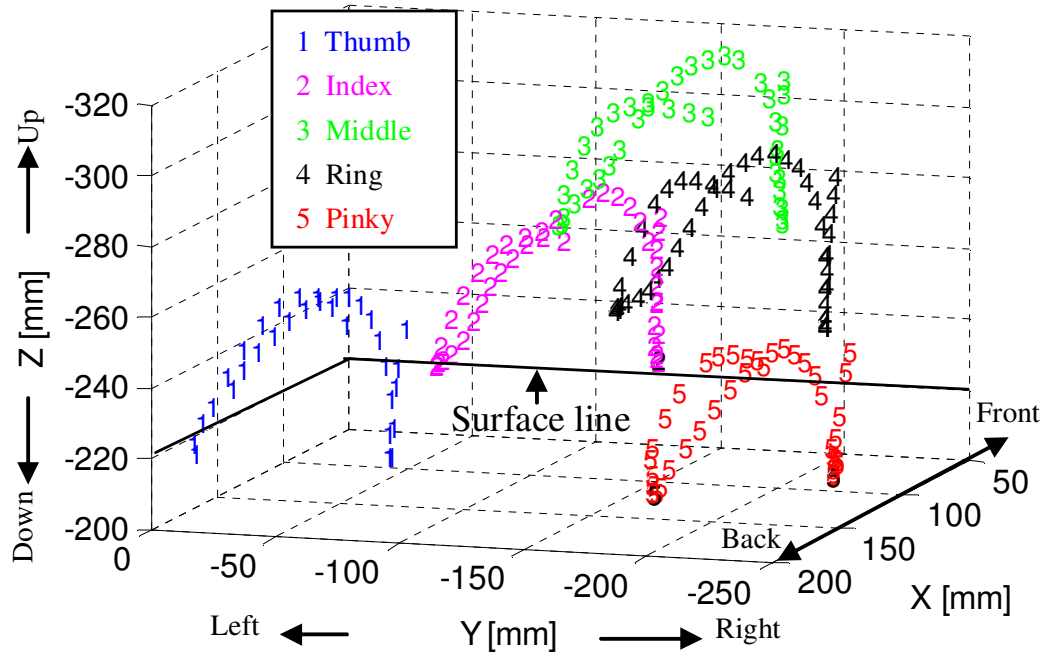
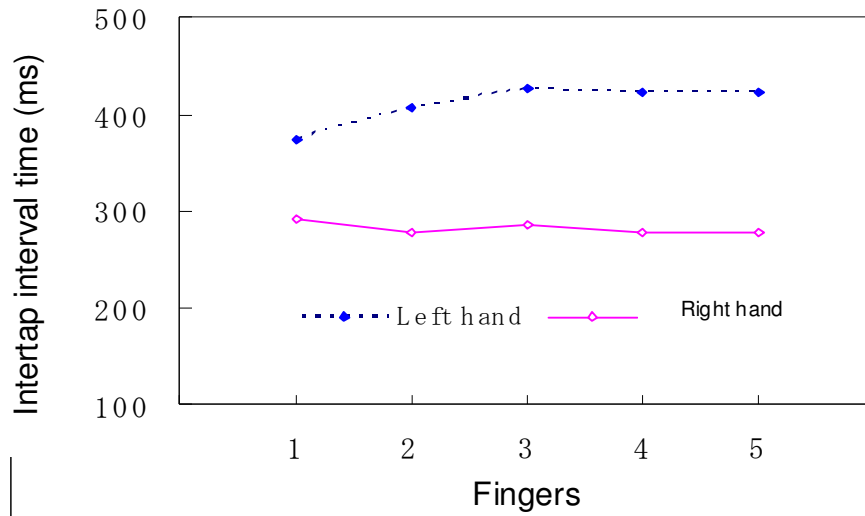**Figure 4**. A sample period of 3 dimensional trajectory of pianist finger tapping (28.6 to 29 s).

Figure 5. Intertap interval time of the pianist (10 to 50 s)

HSD=64, P<0.01 for left hand and 8.89, P<0.01 is for right hand). Post hoc tests revealed that the peak height of thumb and little fingers are quite smaller than other fingers and peak height of middle finger is significantly higher than that all other fingers of both hands. Figure 7 shows that right hand fingers amplitude are quite higher than left hand fingers and middle finger is the highest and thumb is the lowest amplitude than all other fingers for both hands. Naturally middle finger is the longest and thumb is the shortest length than all other fingers. The length of 5 fingers of current subject was; thumb 6.75 cm, index 9.75 cm, middle 10.5 cm, ring 9.5 cm and little 7.75 cm. Moreover IP joint of thumb finger and MCP joints of other fingers are not the same line of human hand. IP joint of the thumb finger is situated behind of MCP joints of other fingers and all MCP joints are situated at different position in hand, that is, not in same line in hand. So finger tip position varies at different lines in human hand.
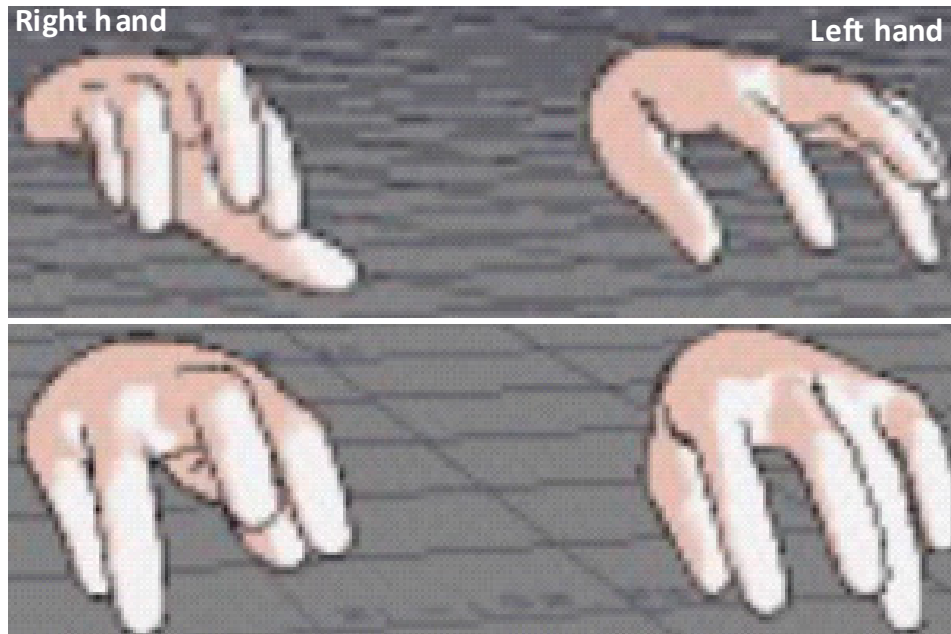
Figure 6. Computer graphics of pianist finger movement and its status during playing the piano.
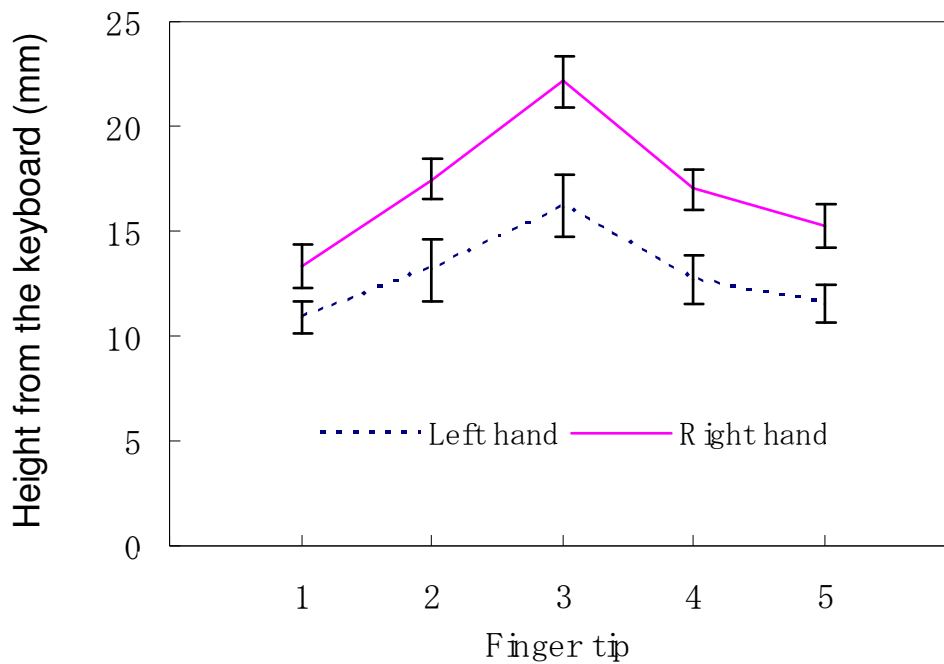

Figure 7. Mean finger height from the keyboard (10 to 50 s)

Thus fingers length varies and finger tip shows like a pyramid shape in the hand. For this, if 5 fingers move up and down together at same angle from a horizontal plain then finger tip height will be the difference from the plain. So for the highest length and suitable position of the hand, middle finger can maintain the highest amplitude than other fingers. This result is similar to the result of Janeen et al. (2007), but they showed only one hand and their purpose was to analyze biomechanical influences in pianists' finger tapping, whereas we examined and described both hands for piano education.

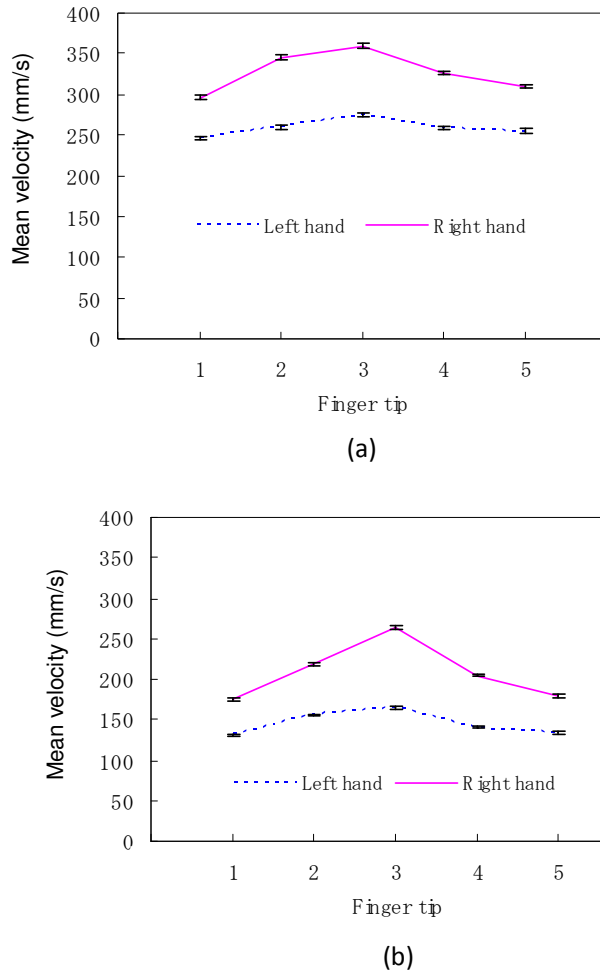Figure 8(a) shows the mean velocity using the global

Figure 8. Mean finger tip velocity (10 to 50 s). (a) Mean velocity using global coordinate. (b) Mean velocity using local coordinate.

coordinate system. SE of mean velocity is under ±2.7 mm/s for left hand and under ±2.9 mm/s for right hand in global coordinate system which is also shown in the figure. Figure 8(b) shows the mean velocity from the local coordinate (Receiver 16 as the reference) system. SE of mean velocity is under ±1.5 mm/s for left hand and under ±2.2 mm/s for right hand in local coordinate system which is also shown in the figure. From Figures 8(a) and 8(b), it is observed that mean finger tip velocity for global coordinate is greater than mean finger tip velocity for local coordinate for both hands. During piano playing usually, hands and fingers move together, which was observed from the global coordinate system but from the local coordinate, it was observed only finger movement in respect of Receiver 16. And thus measured from the local coordinate data will be quite difference than measured from global coordinate data. So using the local coordinate system it is useful to get the finger movement information in the particular place. Similarly it is possible to estimate any receiver as the local (reference) coordinate and

possible to get the relative information from other receiver. Another findings from our research was that the mean finger tip velocity of right hand is greater than left hand finger tip velocity and middle finger is greater and thumb and little fingers are quite smaller than other fingers mean velocity, both for global and local coordinate system. It is similar to finger tip height (Figure 7) that right hand is higher than left hand and middle finger is higher and thumb and little finger is lower than other fingers during piano playing. The finger tip velocity curves and finger height curves show like a pyramid shape which is similar to the finger tip point of human hand. That is when finger height is increasing finger tip velocity is also increasing during piano playing. Finger tip velocity is important to change the musical tone during piano playing. Tone is mainly a property of a group of notes and depends on the musical sensitivity of the pianist (Fundamentals of piano practice). Thus novice player can also change the musical tone by varying the finger tip velocity during piano playing. So it is possible to evaluate the finger tip velocity of all fingers individually during piano playing using our hand MoCap system.

Conclusions

In this paper the soft and dexterous finger movement of a pianist with 6DOF using motion capture system has been investigated. The finger height from the keyboard, finger height in respect of backside of palm, finger tapping rate and finger tip velocity were then calculated that are important to change the musical tempo and musical tone during piano playing. The finger status, that is, whether it was in a curled position or a flat finger position which is important information for the beginners during piano playing has also been presented. It has been shown that the magnetic MoCap for hands can measure its movement which is vital not only for the beginners but also for the pitcher, cricket bowler, tennis player etc. The only limitation of our system is that the magnetic MoCap system can not measure in presence of metal objects, so to overcome this metallic objects should be replaced with plastic or wooden materials during the measurement.

The finger movement of an expert pianist has been examined in this work and therefore, future works can be carried out for the case of beginners and making a comparison between the two cases. It can also be extended to other such types of players as, base ball, cricket and tennis using motion capture system.

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