Potential Use of Inertial Measurement Sensors for Piano Teaching Systems: Motion Analysis of Piano Playing Patterns

Aristotelis Hadjakos, Erwin Aitenbichler, Max Mühlhäuser
Telecooperation Group, Department of Computer Science, TU Darmstadt, Germany
{telis, erwin, max} @tk.informatik.tu-darmstadt.de

Abstract

Recent piano teaching systems mainly rely on MIDI data. However, MIDI data contains only little information about the student's movement. Therefore, additional data channels can potentially be valuable for future piano teaching systems. In this paper we have examined the question, if inertial measurement sensors attached to the piano student's arm can provide information that could be relevant for a piano teaching system. Therefore, we have attached a prototypical sensor that provides accelerometer and gyroscope data to the arm of a pianist. The pianist performed different piano playing patterns such as rotation of the forearm, tremoli, trills, scales, jumps, vertical forearm motion, repetition, octave repetition and connection of loud and soft notes. We show that these playing patterns can be distinguished based on the data from our sensor. Using this technique, a piano teaching system could also be able to assess the piano student's arm motions.

1. Introduction

Piano performance includes many aspects. The most elementary are rhythm and pitch. These two aspects are usually the main focus of early piano education. Other aspects of piano playing like dynamics, articulation, expression, technique, etc. gain more attention when the elementary aspects have been mastered. In face-to-face piano pedagogy the teacher can demonstrate something and the pupil can imitate. The pupil can learn by hearing and watching when the teacher performs. Imitation is especially important for acquiring technique. By imitating the teacher's playing movements, the pupil can adopt a better technique. The teacher can correct an unfavorable technique and help the student to aquire a better technique. Current piano teaching systems can only assess a very limited part of technique and can therefore not support a student in overcoming technical difficulties.

To acquire good piano playing skills, a student has to practice many hours. The most of the time, the student will have to practice without the teacher. The success of the practicing time depends on what the students does in the practicing hours. A piano teaching system that could assess piano technique could help to improve the student's piano technique.

In this paper we have concentrated on the pianist's arm movement because sensors attached to the arm can be unobtrusive. Arm movement plays a role in different piano playing patterns, e.g., tremoli, jumps, scales, etc.

This paper is structured as follows. In section 2 related work is discussed. In section 3 the reasons to use inertial measurement sensors are given. Then, our sensor prototype (section 4) and characteristics of the data (section 5) are discussed. In section 6, graphs of piano playing patterns are discussed. The graphs can are listed at the end of the paper (section 9). The conclusions are discussed in section 7.

2. Related Work

2.1. Piano Teaching Systems

Most piano teaching systems have depended on MIDI data. Systems based on MIDI can detect errors or inaccuracies in the student's performance. However, the MIDI data gives only a rough representation of the student's motion. The Piano Tutor [7] analyzes the incoming MIDI data and provides feedback in form of video, notation, graphics, and voice. The Piano Tutor has an expert system module that selects new pieces for the student. The pianoFORTE system [15] analyzes the incoming MIDI data and generates visualizations of tempo and dynamics. The MIDIATOR [16] compares the incoming MIDI data to the score or a previous recording and visualizes differences in tempo, dynamics, and articulation. The practice tool for pianists by Goebl and Widmer [19] finds reoccurring patterns from a live MIDI stream and overlays the rhythm of the found patterns graphically so that the student can see possibly unintended timing deviations. Other visualizations display automatically extracted beats, timing deviations between chord notes, and a piano roll overview. The Intelligent Virtual Piano Tutor [12] analyzes incoming MIDI data and determines a fingering that is displayed in form of a 3D animation to the student. Akinaga et al. implemented a MIDI-based piano teaching system that evaluates scale performances of piano students [4].

Montes et al. have used EMG signals to teach thumb touches on the piano [13]. They identified certain muscular patterns that professional pianists use when performing thumb touches and used biofeedback to training the student. A group trained with biofeedback achieved significantly better results than a control group that was trained traditionally. Riley used a system that integrates EMG, MIDI, and video [17]. MIDI and video are automatically synchronized.

To support the student to adopt a good posture at the piano, Mora et al. developed a system that overlays a video of the student at the piano with a suggested posture. The suggested posture was recorded with motion capturing from a professional pianist. The Elbow Piano [11] is our first attempt to use physical data for piano teaching. Two custom built angle-measuring devices are attached to the arms of the players and measure the angle between the upper arm and the forearm. Dependent on the motion of the arm the system plays different sounds and hereby increases the awareness for the arm motions.

2.2. Motion Analysis

There exist a plethora of work about motion analysis of piano performance. The earliest motion analysis we are aware of, is the work of Binet and Courtier [6], which was carried out in 1895. A single caoutchouc tube was mounted under the keys of the piano. As the player moves the keys on the piano, the pressure in the tube changes. The current pressure level is drawn on a continuously moving paper strip. Binet and Courtier examined different pianistic patterns, like trills and scales, with the apparatus. Interestingly, the apparatus provides more information about the player‘s movement than a MIDI recording can. That is because the apparatus provides continuous information about the key position.

Recent piano motion analysis studies have often used motion capturing systems to track the pianists motion. For example, Ferrario et al. determined angular velocities and kinetic energy of fingers by using a motion capturing system [8]. Wristen also used a motion tracking system to analyze differences between sight reading and repertoire performance [20]. Goebl and Palmer [10] used a motion tracking system to investigate the role of tactile feedback on timing accuracy.

The interested reader can find a survey of performance analyses in [9].

In this paper we present piano playing patterns, like trills and scales, as they appear on inertial measurement sensors attached to the arm of a pianist. We are not aware of a study where piano playing movements were recorded with inertial measurement sensors.

3. Motivation for Inertial Measurement Sensors

Inertial measurement sensors, i.e., accelerometers and gyroscopes, have been used for tracking movement in musical contexts, e.g., in violin performance [18] or conducting [5]. Therefore, we hypothesized that the use of inertial measurement sensors can potentially provide valuable data about arm movement in piano performance. Inertial measurement sensors are small in size. (The sensors we used for this study, the ADXL330 from Analog Devices [1] and the IDG300 from InevenSense [3], have an outline of only 4x4 mm respectively 6x6 mm.) Therefore, it is possible to manufacture small boards with integrated inertial measurement sensors that can be worn by the pianist and that are unobtrusive.

Compared to computer vision-based approaches, inertial sensors provide us a number of advantages. Using off-the-shelf cameras and computer vision to track the motions would be limited to coarse movements because of the resolution of the devices. Furthermore, latency introduced by video processing could be problematic for interactive techniques like sonification.

Small musical schools, a hobbyist, or the parents of a young student with no professional ambitions (yet) might not be willing to buy expensive acquisition hardware. Visual or magnetic motion tracking system are also, in our opinion, too expensive for the mentioned target groups.

For tracking finger movements, a data glove (e.g., the CyberGlove from Immersion 2) could be used. However, a data glove can encumber the pianist.

Furthermore, data gloves are also too expensive. Therefore, we have chosen to use inertial measurement sensors to assess arm movement.

4. Sensor Prototype

We connected a SparkFun IMU 5 DOF breakout board, which consists of a ADXL330 3-axis accelerometer and an IDG300 2-axis gyroscope, to a Create USB board [14]. The ADXL330 provides acceleration measurements along three axes with a minimum range of +/-3g- [1]. The IDG300 provides rotational velocity in 2 axis with a minimum range of +/-500 degree/s [3]. The accelerometer and gyroscope data is transmitted to the computer via USB at a rate of 100Hz. The setup provides 5 measurements, which will be called x-rate, y-rate, x-accel, y-accel, and z-accel henceforth (see figure 1). The electronics was fixated inside a plastic casing. The sensor was fixated on the pianist‘s wrist or upper arm with Velcro fasteners and rubber bands for additional stability. To attach the sensor to the back of the hand, the pianist had to wear a glove on which the sensor was fixated with Velcro fasteners and rubber band. We built one sensor which was successively attached to the different parts of the pianist‘s right arm.

The sensor is attached to the back of the hand with the x-axis pointing forward and the y-axis pointing to the right. The sensor is similarly attached to the wrist. The sensor is attached to the upper arm approximately half way between shoulder joint and elbow joint. The x-axis is pointing to the floor and the y-axis is pointing backwards. For some measurements the sensor was attached with a different orientation to measure rotation around the z-axis.

For visualization we implemented a program that shows the graphs of the data together with synchronized MIDI data from a MIDI keyboard that is attached to the computer.

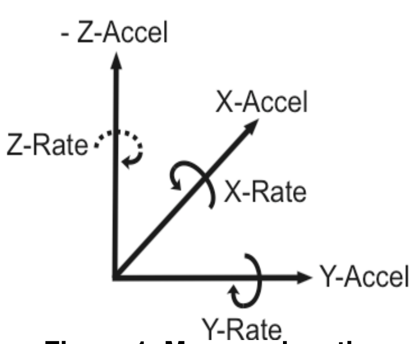

Figure 1. Measured motion

5. Data Characteristics

The data signal consists mainly of the following parts: (1) angular velocities and acceleration because of the deliberate movement of the arm, (2) passive arm motion from finger forces, (3) motion of the sensor because of inertia, and (4) inaccuracies of the measurement hardware. If the finger presses the key with force, the force of the finger will lift the arm slightly when the key reaches the keybed. Additional passive arm motion is generated when the finger strikes the key from above and from the rebound of the piano action. The signal from the back of the hand has the most passive motion components. The signal from the wrist has considerably less passive motion components. The signal from the upper arm has even less passive motion components.

To determine angular velocities and acceleration that appear during typical piano playing, the sensor was successively attached to upper arm, wrist and hand of the right arm while playing the Haydn‘s Variations f-minor Hob. XVII:6. The measured angular velocities are summarized in tables 1-3.

Table 1. Upper arm

	Min	Max
X-Rate (deg/s)	- 239	+ 245
Y-Rate (deg/s)	- 169	+ 79
Z-Rate (deg/s)	- 68	+ 129
X-Accel (mg)	- 620	+ 1637
Y-Accel (mg)	- 1776	+ 1276
Z-Accel (mg)	- 1647	+ 1207

Table 2. Wrist

	Min	Max
X-Rate (deg/s)	- 442	+ 344
Y-Rate (deg/s)	- 108	+ 205
Z-Rate (deg/s)	- 253	+ 223
X-Accel (mg)	- 940	+ 1870
Y-Accel (mg)	- 2977	+ 2028
Z-Accel (mg)	- 679	+ 3397

Table 3. Back of hand

	Min	Max
X-Rate (deg/s)	- 594	+ 577
Y-Rate (deg/s)	- 310	+ 406
Z-Rate (deg/s)	- 426	+ 406
X-Accel (mg)	- 1022	+ 3280
Y-Accel (mg)	- 2918	+ 3553
Z-Accel (mg)	- 1373	+ 3905

6. Piano Playing Patterns

In this section, inertial measurement data visualizations of different piano playing patterns are presented and discussed. Additionally to the graphs of the data, received MIDI note-on events from the attached MIDI keyboard are marked with dots on a separate track. The graphs of the piano playing patterns are located on the last two pages of this paper.

6.1 Rotational Patterns

6.1.1 Pronation and Supination

The rotation with the ulna and the radius bone of the forearm plays an important role in many piano technique patterns. The clockwise rotation of the right arm is called supination; the counterclockwise rotation of the right arm is called pronation. Supination and pronation is most prominently visible on the x-rate signal from the sensor attached to the player‘s wrist. In figure 2 different notes were played using the rotation of the forearm. The timing of the nine notes is shown by the dots representing note-on events. The first four notes were played with supination of the forearm. This is visible by the upward spikes of the graph. The next four notes were played with pronation of the forearm. This is visible by the downward spikes of the graph.

6.1.2 Tremoli and Trills

A tremolo is a rapid and repeated succession of two notes. A trill is a tremolo of two adjacent notes. Therefore, from the view of piano technique tremoli and trills are similar. Tremoli (or trills) can be executed in a variety of ways. It is possible to press the keys with activity of the fingers alone and without active participation of the arm. This is called finger-tremolo. It is also possible to execute a tremolo with pronation and supination of the forearm. This is called a forearm-tremolo. In figure 3 the data of a sensor at wrist, while first playing a finger-tremolo and then changing to a forearm-tremolo, is shown. The two variants can be distinguished on the displayed x-rate graph. When the pianist plays the finger-tremolo, the signal on the x-rate graph has only a small amplitude. Small imbalances in the x-rate graph are because of finger forces moving the arm when pressing the keys. The forearm-tremolo is visible by the oscillation of the x-rate signal with relatively high amplitude.

There is a third variant of tremoli and trills: the upper arm tremolo. It is executed by rotating the upper arm in the shoulder joint while rotating the forearm at same time. In figure 4, the data of the sensor attached to the upper arm is shown. The pianist first executes forearm-tremoli and then switches to upper arm tremoli. In the beginning, the x-rate signal oscillates lightly. This is because of forearm rotation forces moving the upper arm when pressing the keys. Later, the x-rate has a higher amplitude. The upper arm is intentionally rotated by the player. The volume of the played notes did not increase as can be seen from the MIDI volume numbers shown over the dots.

Usually finger-tremoli are used for soft parts. Forearm-tremoli are most commonly used with occasional help of the upper arm, especially for loud parts. The use of upper arm tremoli generates accents on the lower of the two notes, which has to be taken into musical consideration when selecting what type of tremolo to choose for a specific part.

6.1.3 Scales

Rotation of the forearm also plays a role for the execution of scales. Scales consist of a sequence of a group of three (i.e., thumb, index finger, middle finger) and group of four (i.e., thumb, index finger, middle finger, ring finger). To connect the two groups the thumb has to pass under the middle respectively the ring finger. The touch of the thumb can be accompanied by pronation of the forearm. In figure 5, the data of the sensor attached to the forearm is shown. The pianist executes a C-major scale along four octaves. Upward spikes show the pronation of the forearm. One can see the groups of three and four by considering the space between the spikes. The downward spike at the end of the graph shows a supination of the forearm. The player played out the last note of the scale with the little finger and supinated toward it.

A piano teaching system could recognize supination and pronation and determine their timing in playing patterns like scales. The piano teaching system could than suggest the student to adopt a better movement if necessary. A piano teaching system could teach different types of tremoli.

6.2. Jumps

Jumps can best be seen on the x-rate signal of the upper arm or the z-rate signal of the wrist. In figure 6, the sensor was attached to the upper arm of the pianist. The pianist notes of the jump were two octaves apart. The pianist used thumb and little finger to play the two notes. An upward jump is visible as downward spike in the graph. A downward jump is visible as an upward spike in the graph.

A piano teaching system could use the x-rate signal to determine the exact timing of the jump. If a student frequently misses the target note of the jump, a piano teaching system could suggest to position the arm ahead of time (if this is possible in context of the previous notes).

6.3. Vertical Forearm Motion

Vertical forearm motion is an aggregated motion consisting of motion from the shoulder and the elbow. Vertical forearm motion is often used when a loud note is connected to a soft note, for example when a dissonance is dissolved. The first note is played with a downward movement of the forearm, which adds to the finger velocity and therefore generates a louder tone. The second note is played with an upward movement of the forearm, which results in a softer tone since the movement of the forearm and the movement of the finger are complementary. In figure 7, the sensor was attached to the player‘s wrist. The first six notes were played without motion of the forearm; the next six notes were played with vertical movement in groups of two (loud - soft).

Vertical motion of the forearm can be used when playing repetitions of octaves over a long time interval. By moving the forearm up and down over the timespan of several touches, the pianist changes the starting position of the wrist joint and the fingers. This can reduce fatigue, which can occur when executing fast octave repetitions over a long time interval. In figure 8, the sensor was attached to the wrist. At the beginning, octave repetitions were executed without the forearm movement. Later, octave repetitions were executed with forearm movement, which can be seen as oscillation of the y-rate signal over several touches. The y-rate signal is uneven. This is because of forces from the wrist joint and the fingers that lift the arm.

Fast repetitions over short time intervals (for example two or three notes in rapid succession) that are performed by moving the hand in the wrist joint, can benefit from upward forearm motion. By lifting the arm between the touches, the hand attains a position so that the pianist can execute the next touch by moving the hand downwards. The wrist does not need to lift the hand in preparation of the touch, as this is already done by the upward motion of the forearm. Therefore, the player can execute faster repetitions with this movement pattern than he could by pushing down and lifting up the hand from the wrist joint.

In figure 9, the sensor was attached to the player‘s wrist. The pianist first played repetitions of two notes in rapid succession without movement of the forearm. This was repeated four times. Then, the pianist performed repetitions of two notes in rapid succession with upward movement of the forearm. This was repeated four times. The upward spike of the y-rate signal, which has its peak approximately when the second of the repetition is played, indicates the upward movement of the forearm.

Fast and moderate movements of the forearm are visible on the y-rate signal when the sensor is attached to the wrist. However, slow movements on the are difficult to see on the y-rate signal as the angular rate is too small. Fortunately, these slow movements are visible on the x-accel signal of the sensor attached to the back of the hand (see figure 10). The pianist plays four notes. Between the third and fourth note the pianist slowly lifts his forearm. Because the hand must stay in contact with the keys the pitch of the back of the hand changes. Because of the change of the hands pitch, earth gravitation component of the x-accel component increases, which is visible.

A piano teaching system could evaluate the vertical motion data to teach the typical vertical motions when connecting a loud to a soft note, for example when a dissonance is dissolved. This is an elementary skill. For the advanced player, a piano teaching system could monitor the vertical forearm motion to provide technical hints when the student has a problem executing repetitions.

6.4. Flexible or Rigid Arm

In figure 11 and 12, the data of the sensor attached to the player‘s wrist is shown. All five data signals from the sensor are displayed. In figure 11 the pianist plays with normal arm movement. In figure 12 the pianist plays the same piece but tries to avoid arm movement. The amplitude of the sensor signals when the player avoids arm movement are reduced in comparison to the sensor signals when moving normally. In figure 12, the arm moves mainly because of the finger forces which lift the arm when a key is pressed and because the hand has to be repositioned on the keyboard.

The experiment was repeated with the sensor attached to the upper arm of the player. In figure 13, the player uses normal arm movement; in figure 14, the player tries to avoid arm movement. The two conditions have distinct appearances on the graphs.

A piano teaching system could monitor the amplitudes of the signals and determine when the student uses too little arm movement, which could be an indication of too little supporting movements of the arm.

7. Conclusions

Recent piano teaching systems have mainly relied on MIDI data. However, MIDI data contains only very limited information about the player‘s movement. We therefore think that piano teaching systems could be improved by using additional sensor data.

Inertial measurement sensors are of relative low cost compared to other options like motion capturing. Therefore, a piano teaching system based on inertial measurement sensors could be affordable for hobbyist players or musical schools. In this paper we have examined if the data of inertial measurement sensors attached to the student‘s arms can be used as a valuable additional input source to a piano teaching system. To this end different piano playing patterns were recorded with a prototypical sensor. The playing patterns that were discussed in this paper were: rotation of the forearm, tremoli, trills, scales, jumps, vertical forearm motion, repetition, octave repetition and connecting loud and soft notes. These patterns were visible in the graphs of the recorded data so that a piano teaching system could use this information to retrieve information about the occurring motion by evaluating the inertial measurement sensor data of a student‘s play.

8. References

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9. Figures

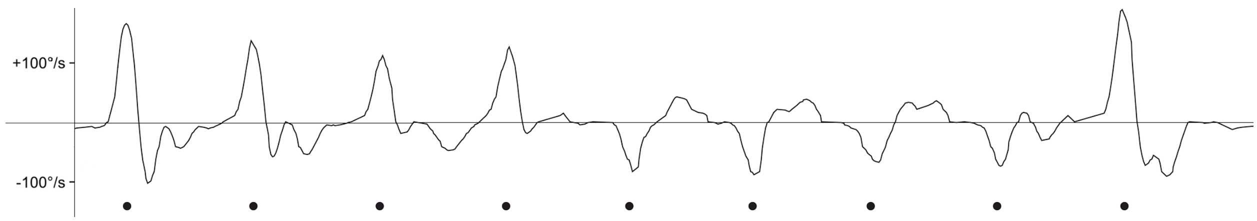

Figure 2. Wrist, x-rate, pronation and supination

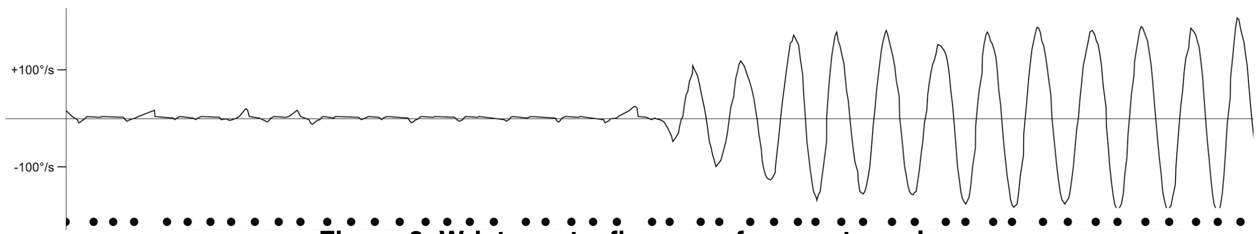

Figure 3. Wrist, x-rate, finger vs. forearm tremolo

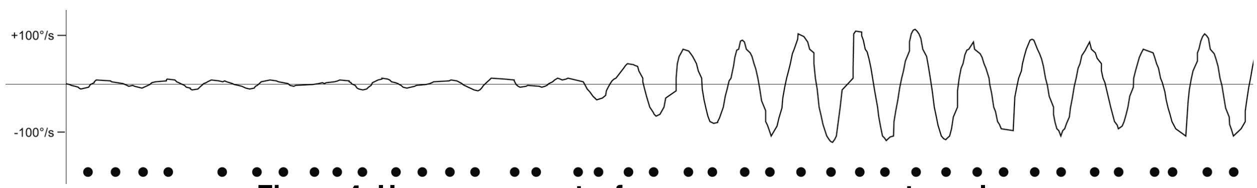

Figure 4. Upper arm, x-rate, forearm vs. upper arm tremolo

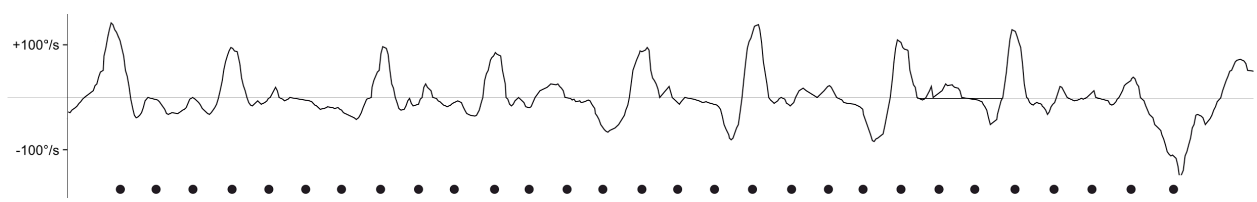

Figure 5. Wrist, x-rate, scale

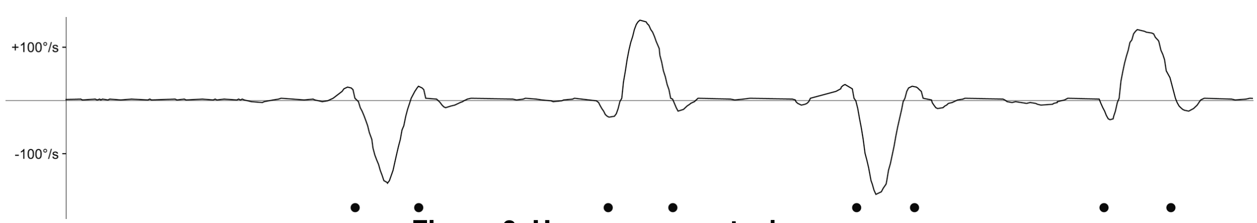

Figure 6. Upper arm, x-rate, jumps

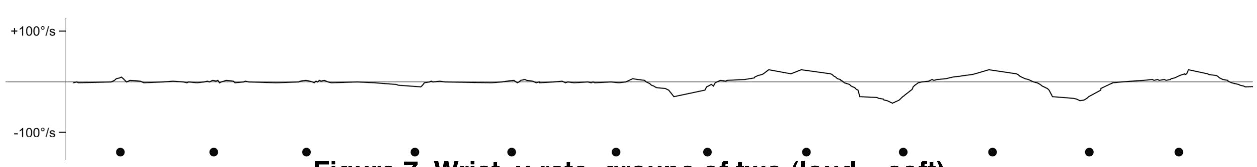

Figure 7. Wrist, y-rate, groups of two (loud – soft)

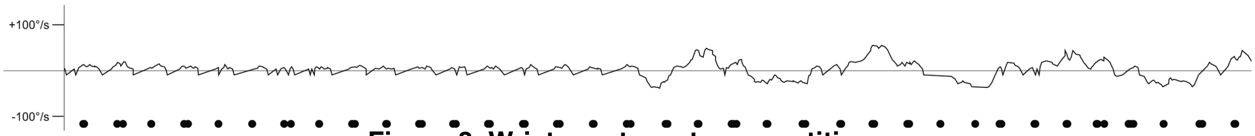

Figure 8. Wrist, y-rate, octave repetitions

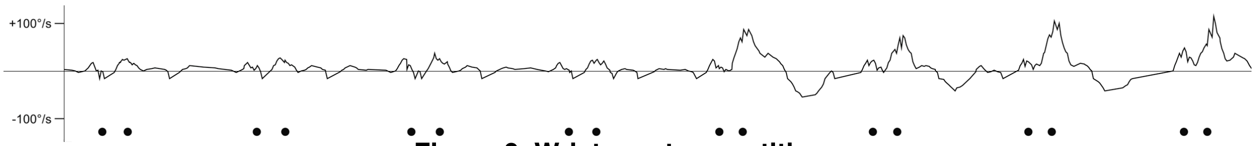

Figure 9. Wrist, y-rate, repetitions

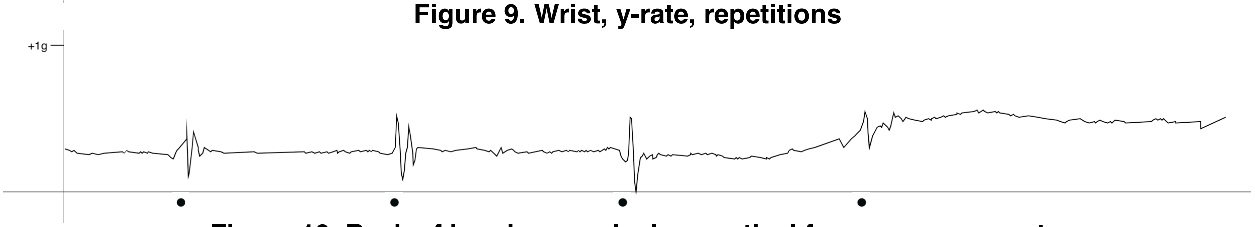

Figure 10. Back of hand, x-accel, slow vertical forearm movement

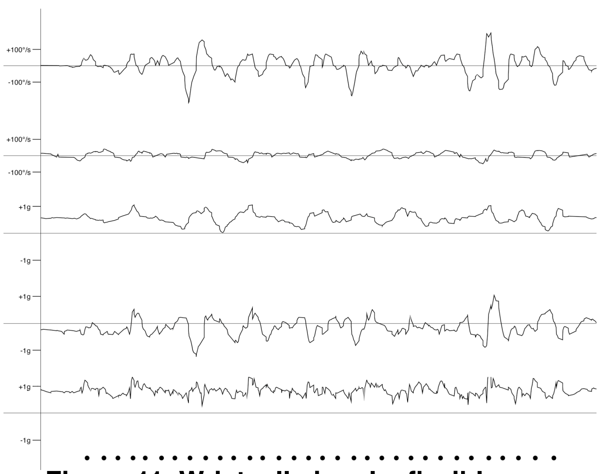

Figure 11. Wrist, all signals, flexible arm

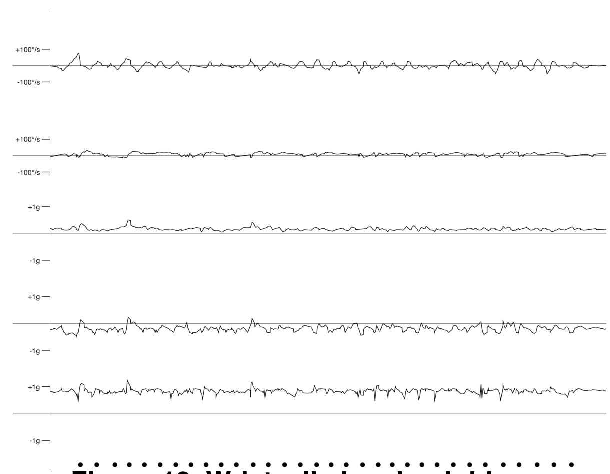

Figure 12. Wrist, all signals, rigid arm

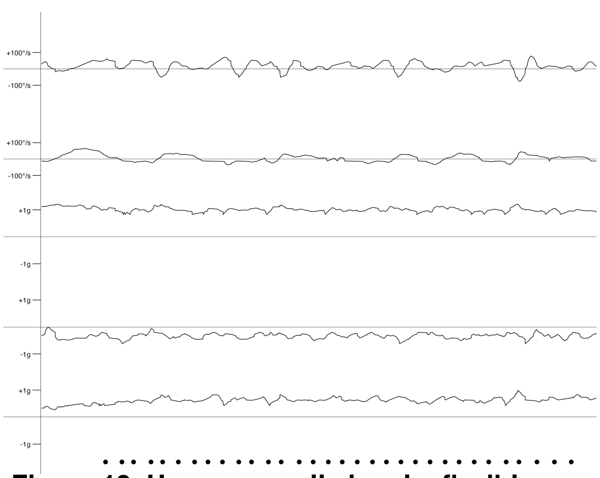

Figure 13. Upper arm, all signals, flexible arm

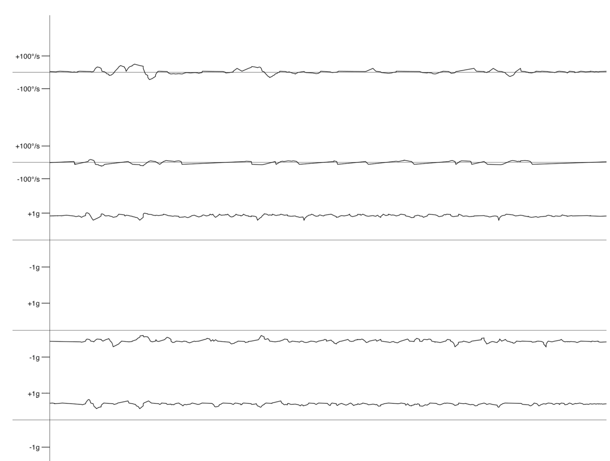

Figure 14. Upper arm, all signals, rigid arm