The Actuated Guitar: Implementation and User Test on Children with Hemiplegia

Jeppe V. Larsen
Aalborg University
Sofiendalsvej 11
9200 Aalborg SV
Denmark
jvl@create.aau.dk

Dan Overholt
Aalborg University
A. C. Meyers Vænge 15, B4
2450, København SV
Denmark
dano@create.aau.dk

Thomas B. Moeslund
Aalborg University
Sofiendalsvej 11
9200 Aalborg SV
Denmark
tbm@create.aau.dk

ABSTRACT
People with a physical handicap are often not able to engage and embrace the world of music on the same terms as normal functioning people. Traditional musical instruments have been refined over the last centuries, developing highly specialized and powerful interfaces; but nearly all require two functioning hands. In this study we try to enable people with Hemiplegia to play a real electrical guitar, by modifying it in a way that allows people with Hemiplegia able to actually use the instrument. We developed a guitar platform utilizing sensors to capture the rhythmic motion of alternate fully functioning limbs, such as a foot, knee or the head to activate a motorized fader moving a pick back and forth across the strings. This approach employs the flexibility of a programmable digital system which allows us to scale and map different ranges of data from various sensors to the motion of the actuator, thereby making it easier to adapt to individual users. To validate and test the instrument platform we collaborated with the Helena Elsass Center in Copenhagen, Denmark during their 2013 Summer Camp, to see if we actually succeeded in creating an electrical guitar that children with Hemiplegia could play. The initial user studies showed that children with Hemiplegia were able to play the actuated guitar by producing rhythmical movement across the strings, enabling them to enter a world of music they so often see as closed.

Keywords
Interactive performance systems; Interfaces for sound and music; Music and robotics; Social interaction in sound and music computing; Actuated instruments; Actuated guitar; Musical instruments for the disabled.

1. INTRODUCTION
Music is a big part of human culture. Music is consumed, performed and enjoyed by nearly everyone in every layer of society. But the feat of performing music is more of a challenge to some than others. Those of us living without disabilities can just pick and choose an instrument of our liking and start learning. Some people succeed and actually learn to play an instrument, but many give up along the way when they realize what it takes in time and effort to actually learn to play a musical instrument well. People with disabilities might not be able to use an arm or a leg, and thereby are unable to use the instrument.

In this work, we continue the development of the Actuated Guitar [1] that began to address these issues via development of a solution for people with one side of their body paralyzed – for example, those with Cerebral Palsy Hemiplegia or stroke victims – to start learning to play the guitar or regain the ability to play. While it is still likely that they will be unable to reach the instrument's full potential, just enabling them to actually play a guitar that otherwise would be out of reach is viewed as a huge accomplishment.

The focus of this research is to use technology in combination with existing instruments to enable alternative methods of playing the guitar for people with cerebra Palsy Hemiplegia. By using small linear actuators, feedback systems, and flexible / adaptive interaction design techniques, we present a novel design optimized for easy customization.

In terms of therapy, playing music can be a good activity for "Forced Hand Use" training [2]. This method encourages those with Cerebral Palsy or stroke patients, for example, to use their affected arm, with the aim that they will begin using that arm more in daily life or regain control with the arm or hand.

1.1 Related Work
A wide range of approaches to either customizing existing instruments, or designing entirely new music interfaces exists. These range from simple mechanical aids [3] to advanced bioelectric controllers allowing users to produce computer-generated music [4]. Many of the customized instruments focus on percussion-like input modalities, such as simple tap-pad interfaces developed for disabled users. One such example is the TouchTone [5]. However, our research focuses on stringed instruments, in this case the electric guitar, not percussion, wind, or other families of musical instruments.

The work described here involves creating a semi-robotic musical instrument. A historical view of robotic musical instruments is included in [6]. Robotic instruments focused on the guitar include the League of Electronic Musical Urban Robots (LEMUR's) GuitarBot [7], among others. While the GuitarBot is much more capable of completely automating the motions needed to play a guitar than our current work, it discards any affordances of direct human playing skills, due to a design that places each string on a separate 'neck'. We purposefully aim our development at traditional guitar bodies, thus enabling users to develops skills that are as close to the normal techniques as possible. This also follows in some of the author's related past work with actuated instruments [8].

2. METHODS
Playing a guitar traditionally requires the use of both hands. The right hand does the strumming and the fingers of the left hand are used for fretting the strings. As stated in the introduction, the scope for this research is to enable or re-enable people who are not able (or lost the ability), to play the

guitar. This approach focuses on the right hand's strumming motion, and how it interacts with the guitar. The are some common and complex interactions of the right hand that have been divided into three stages:

Stage 1: Simple strumming up and down movement
Stage 2: Individual string picking and string skipping
Stage 3: String muting both multiple and individual strings

The research approach has been divided into the above stages, based on their complexity where *stage 1* is the simplest form of interaction and *stage 3* the most difficult. We have focused on the strumming as the best candidate for a proof of concept to investigate the possibilities, before including the other types of right hand interaction. Next we describe and discuss our approaches to strumming a guitar when the user does not have full control of the right hand.

2.1 Suited Body parts for Rhythmic Movement

As one hand, right or left depending on the user, is occupied fretting the strings, possible limbs for control of our actuated strumming include the legs, feet, head or neck. These parts of the body do not offer any realistic means of physically strumming the strings in a normal playing position. One of the simpler main tasks of the strumming hand is moving in a continuous rhythmic pattern. While most limbs can offer a similar type of motion, the feet or legs are likely the best options, as humans are accustomed to naturally moving these body parts in rhythmic patters for long periods of time (e.g. when walking, running or dancing). For people with no control of their legs nor right arm, the head could also be used to move in a rhythmic pattern, but as the muscles in the neck are made for stabilizing the head and not for prolonged rhythmic movements, this is not optimal due to possible fatigue or injury. Nevertheless, over shorter periods of time this could still give such individuals the ability to strum the guitar.

2.2 Interpreting Rhythmic Motion

Because rhythmic movement of the suited parts of the body is not able to physically strum the strings in a conventional fashion, the system somehow needs to capture and interpret the motions. This can be done through the use of various sensors that can be mounted on the desired parts of the body, in order to capture the rhythmic moment made by the user. One example would be a user with a partially paralyzed leg, but who can still stomp their foot. Mounting a sensor on the foot will translate that motion into input for a microcontroller, which can then map this input to control the actuator's full range of motion. This gives us the possibility of amplifying small motions to move the output actuators an entire strum-length, translate rotation motions into linear motions (if using angular sensors such as a gyroscope), etc. Doing such by purely mechanical means would require highly complex constructions and be difficult to quickly modify to fit different users with different needs. Therefore electronic sensors and actuators prove very useful when combined with programmable microcontrollers in this eontext.

2.3 Implementation of Development Platform

One of the most important aspects when working with any form of interaction design is latency. This is even more important when you need to control the sound produced by your interactions. To determine which sensor was the best fit for realizing the construction and playability of the guitar, we ran a series of prototype development iterations with each sensor. The three initial candidates were an infrared distance sensor from Sharp (GP2D12), an accelerometer from Analog Devices (ADXL322) and a simple momentary push button, see Figure 1.

For prototyping, sensors can be fitted, with e.g. a velcro armband and strapped onto various parts of the body. Many other types of sensors can also work as input for the actuated guitar, such as Inertial Measurement Units (IMUs), which capture orientation changes, sensors to capture blinking, etc.. An individual that can only rotate their head, for example, could use an IMU, with the orientation data translated to the actuator's linear output. However, the chosen candidates were used because of availability and time constraints in this initial prototype implementation.

To interpret the sensor signals an Arduino Nano V.3 board with an ATmega328 microcontroller was used, because of its small form factor and simple usage. To drive the actuator, we used a '2motor' controller board from Gravitech, Inc., which has an L298 dual H-Bridge driver on-board. For the actuator, we chose a Penny+Giles PGFM3200 motorized fader due to it's specification with the strongest linear force we could find. The firmware used on the Arduino in order to drive the motorized fader was inspired by the FireFader project [3].

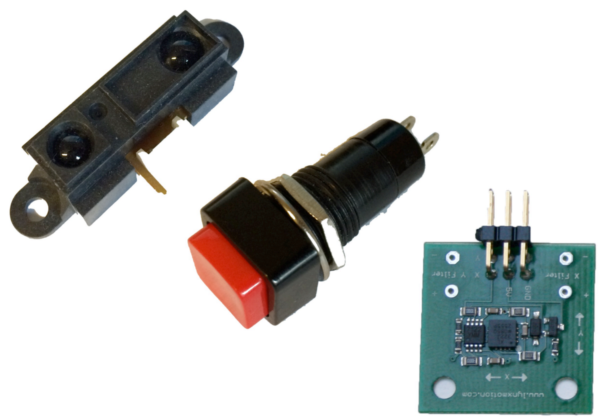

Figure 1: The three candidates for acquiring motion information from the user. To the left a Sharp GP2d12 IR Distance sensor, in the middle a momentary pushbutton and to the right the ADXL322 tilt sensor from Analog Devices.

Figure 2: Motorized fader used as the actuator for driving the pick back and forth over the strings of the guitar.

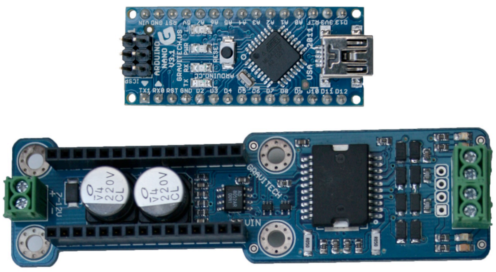

Figure 3: Top, the Arduino Nano V. 3. Bottom, the 2Motor controller.

2.3.1 Linear Mapping and sensor selection

The accelerometer (see Figure 1) was tested in a first iteration with a simple linear mapping between its tilted position and the fader's position. When the accelerometer pointed straight up, the actuator was at one of its extremes and when the accelerometer pointed straight down the actuator was at its other extreme. A problem became apparent right away, which is the inability of an accelerometer to separate accelerations due to dynamic motion from accelerations due to gravity (tilt angle). While an IMU would have solved this issue, we did not have easy access to one – so we moved on to the next prototype iteration, even though filtering of the raw sensor data was attempted. Filtering did solve the problem partially, but it also introduced a slight latency. This was still playable, but at the same time noticeable and annoying. As mentioned above, this is not optimal considering the context of its use in a musical application.

The first tests using the distance sensor (see Figure 1) showed that it had less initial problems when compared to the accelerometer, but still had some needed of filtering. A simple linear mapping was applied but the filtering again introduced a noticeable latency, so it turned out to be difficult to do a difficult to play with.

A solution instead of the linear approach to mapping, would be to set a threshold for actuation. This was tried with both of the above described sensors. It worked in such a way that when e.g., the accelerometer exceeded a certain g force it would trigger the motor to run the fader to the opposite extreme, thereby strumming the strings. The same was applied to the distance sensor. This worked a lot better in terms of playing, and seemed a lot more stable. However, these two sensors were still prone for accidental activation of the fader, which resulted in unwanted output. This threshold approach is really similar to a simple binary trigger, which led us to consider the next sensor type..

The last prototyping test used a simple push button. There are of course two types of buttons, latching and momentary. The latching type hold its state until changed again and momentary only changes state while being pressed. Momentary behavior is appropriate in this context, as there is simply no need for latching

The motorized fader itself is driven by a rubber band to pull the fader back and forth. However, the rubber band is able to stretch a bit, which results in a small overshoot of the fader's position on the linear potentiometer. This feedback is what tells the microcontroller its current position, so this needs to be taken in to consideration in the final implementation.

2.3.2 Final Development Platform

The final development platform ended up consisting of an Epiphone SG Standard electrical guitar, the Arduino Nano V.3 board, "2motor" controller board from Gravitech as described in section 2.3, a 3D printed foot pedal pushing a momentary button, see Figure 9 and a 3D printed mount used for mounting the Penny+Giles PGFM3200 motorized fader, see **Figure 5**.

Figure 4: The guitar used for this project is an Epiphone SG. [12]

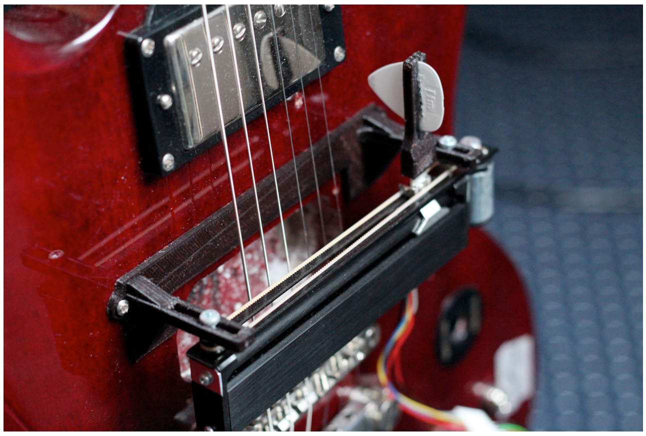

Figure 5: The finished system with the actuator mounted in the customized mount on top of the guitar body.

The Arduino Nano sits on top of the 2motor board, both of which are plugged into a simple breadboard that is adhered inside the guitar's body (part of the control cavity). The foot controller is connected to the microcontroller's input pin via connectors mounted in the existing holes (where the volume and tone knobs sat). An external power supply is plugged into the guitar body, again through one of the spare holes, which powers the Arduino, motor board and the motorized slider. The USB port on the Arduino is still accessible and allows for quick data access and easy upload of software to the Arduino during development. With a few simple modifications, the system could also be battery powered. The electronics are all protected by covering them with the original backplate on the guitar. This makes the system robust enough for testing purposes.

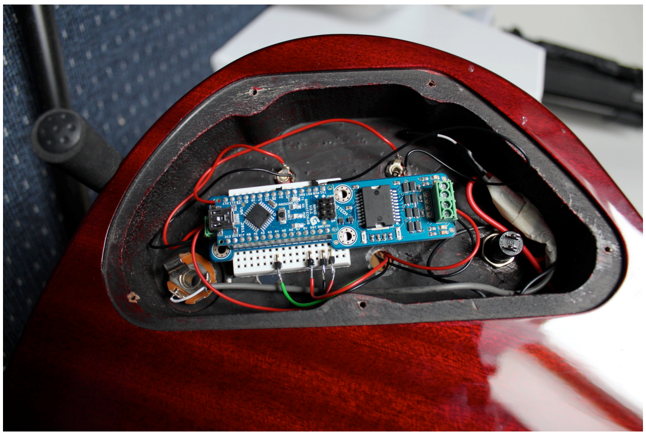

Figure 6: The Arduino and motorcontroller mounted on a breadboard inside the guitar's empty control cavity for protection (but still providing easy access to the electronics).

2.3.3 Dataflow

When a user presses the foot pedal's momentary button, the signal is sent to the Arduino. The microcontroller then reads the current position of the pick by checking the value of the fader's potentiometer. Depending on the position, it reverses the direction of the motor and drives the pick the opposite direction across the strings. The microcontroller continues reading the potentiometer's value as it moves, and stops the motor when it reaches the other end. Once there, it waits on further messages via interaction from the user. An illustration of the data flow throughout the system is shown in **Figure 7**.

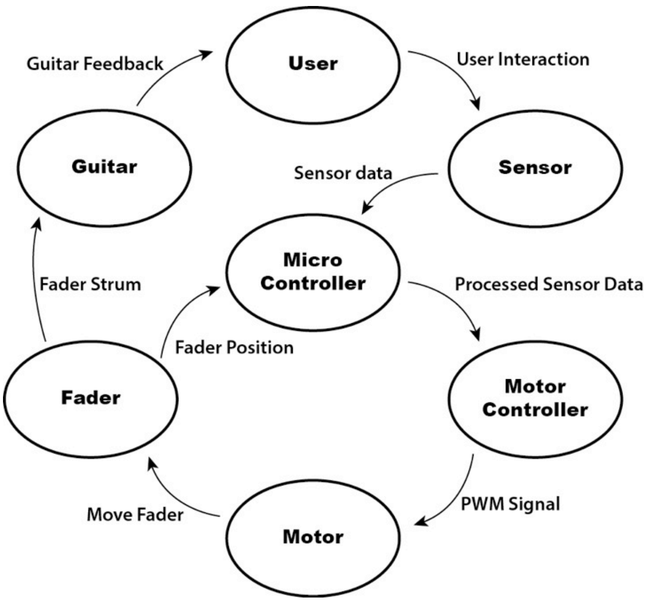

Figure 7: Simple dataflow throughout the system.

2.4 Test method

The user test was conducted at the Helena Elsass Center in Charlottenlund, Copenhagen, during the 2013 Summer Camp. This is an annual week-long camp for children with Cerebral Palsy. The goal of the summer camp is for the kids to challenge themselves through various activities, proving that they can be more physically capable than they might think. The test was not an actual part of the summer camp, but was conducted when the staff and children could find enough time in the busy schedule.

The test tried to investigate if children with Hemiplegia Cerebral Palsy were able to play the actuated guitar. It was expected that the children have no previous experience with playing traditional musical instruments; this was of course verified by asking them as well. The success criteria was two fold. The first success criteria was if they could sit with the guitar, position their hand and fingers of their non-paralyzed side on the guitar neck, fret a chord and press the foot switch producing some sound (it was not needed or expected to be pristine sounding). The second and more demanding criteria was if they were able to take it a step further and produce a continuous rhythmic motion, which might indicate an inherent musicality.

For testing these criteria, a qualitative method was used. It included observations using video and sound recordings for later in-depth observation and analyses. The observations were followed by semi-structured interviews that were used to investigate the children's familiarity and use of music. E.g., have they taken guitar or piano lessons, or if and how they listen to and use music, or if they have ever imagined/dreamed of themselves performing music and if so, what song they would like to perform.

The guitar was tuned in an open-G tuning for easier fretting of chords. This means that if you do not fret any strings and strum all strings you play a G-Major chord, and if you want to fret another Major chord you simply press all the strings on the same fret. Further simplify chording and fretboard navigation, the neck was color-coded with stickers beneath the strings to indicate certain chords. The color-coding was combined with a sheet of paper telling the children how to play "Sweet Home Alabama" by Lynyrd Skynyrd, which was chosen because of its simplicity. It only contains three Major Chords: D, C and G.

3. RESULTS

The children attending the Summer Camp were between 11 and 13 years old. They had different types of Cerebral Palsy, but mainly Hemiplegia. Because of the tight schedule and planning of the summer camp, there was only enough time for testing with five children, from ages 11-13, all with Hemiplegia, but in different sides of the body and severity stages. The semi-structured interview focused on three main areas: The children's knowledge about their own condition, their musical experience, and their own and their family's use of music in their every day life. All of the children except for one didn't know what type of paralysis they had but simply responded: "I just know I have Cerebral Palsy." This was a bit problematic, because then they were not able to answer on what level they were according to the Gross Motor Function Classification System – Expanded and Revised (GMFCS - E&R) that ranges from Level 1, best functioning to Level 5, worst functioning [11]. Based on observations during the Camp and the user tests, the children attending the Summer Camp and the test were either level 1 or 2.

None of the children had attended any prior instrument lessons, besides the mandatory music lesson at their schools. Four of the children had a desire to start learning to play an instrument, and when asked what type it ranged from guitar, piano, and drums to tambourine. None of the test participants came from homes where their parents or siblings played any instruments. Only one had a mother that had attended some piano lessons when she was younger. When asked if they listened to music, they all responded 'yes', and two said that they listened to music quite a lot. When asked how they used the music (to see if it was something that the whole family used), most answers were “just in my room, on my iPad, on youtube,” etc. Only one said “on the radio and in the car”.

The children were introduced to the actuated gjuitar with a brief explanation on how the instrument worked, and how they could operate the it. They got the sheet music showing the simplified view of how many times they should play a color to play Sweet home Alabama (1 x Green, 1 x Yellow, 2 x Blue) The instrument was placed so that their good side operated the guitar’s neck for fretting the strings and pressing the pedal. One of the children insisted on doing the opposite and using his weakened side. He was also by far the least affected child in the test, and had nearly the same strength in both sides.

From notes during the test and review of the recordings, it became clear that all of the test participants are able to interact with the guitar. They could fret the guitar and press the foot pedal to produce sound. It was obvious that it would take time to gain speed along the fret board and foot, hand and eye coordination (to lower the time between fretting and striking the strings, etc.), but nothing more substantial than normal children have when they interact with a new and unfamiliar instrument. One child stood out in the test. He was actually the most severely paralyzed. He had never played a normal instrument before, but was able to play Sweet Home Alabama by following the color-coded chart. After the test he said his mind was blown. In his wildest fantasies, he had never imagined that he would be able to play guitar and even actually able to play a song. Compared to the others rhythmic tendencies, he seemed to have an inherent musicality or talent. This does not mean that the other children couldn’t maintain consistent rhythms, but that they maybe needed a bit more convincing. Overall, the test has shown that these children are able to produce rhythmic motion, and would be able to start learning basic chords by going to regular guitar lessons like normal children.

Figure 8: A user with Hemiplegia Cerebral Palsy playing the guitar for the first time. It can be seen that the user is partially paralyzed in his right side.

4. DISCUSSION

There are many possible directions for future work that would be interesting to pursue, following this initial research. One example would be to experiment further with different types of sensors. It is likely worth pursuing Inertial Measurement Units (IMUs) that combines data from an accelerometer, gyroscope and magnetometer to provide a more precise estimation of orientation and motion. This would allow us to remove the coupling effects between gravity and dynamic motion experienced in the initial test with the accelerometer. Commercial sensor options such as e.g. the Leap Motion device, could also be interesting. This could be mounted in various locations, because if its small size, to capture player inputs.

The current implementation of the guitar foot pedal, using the momentary push button, does not facilitate coarse motor control exercises of paralysed limbs (unless it happens to be that leg). Using the pushbutton approach also limits the range of motion which might be unwanted in a rehabilitation perspective. In fact, therapeutic use may purposefully require larger motions for successful interaction. However, the system at this stage is very flexible and can easily be adjusted to accommodate many diiferent styles of interaction that might be more focused on training and rehabilitation of the paralysed or affected limb. This could e.g. be done with the alternative sensors as suggested in the interaction methods in section 2.3 or above.

When customizing the actuated guitar for people with various disabilities, our digital approach attempts to make it easy to perform the necessary mapping of data from various input sensors (simple filtering, scaling and offset operations) to give control of the strumming actuator. This is especially true when compared to the wide variety of mechanical approaches that would be needed for different scenarios and users. At the moment, these changes are managed in the firmware of the micro-controller that our system uses, but these parameters could also be changed graphically via a simple GUI presented via a small screen or a laptop running visual programming environments such as MaxMSP or PureData . This approach, which could easily be based on the FireFader system [9] would likely be preferable for individuals who wish to modify the system themselves.

Figure 9: The 3D printed foot pedal used to activate the actuator strumming the strings of the guitar. The print is fitted with a momentary button that is connected through wires to the Arduino inside the guitar.

4.1 Limitations

The fine motor control of a normal functioning human arm, hand and fingers will be extremely difficult if not impossible to replicate via this low-cost approach. A human hand can move in almost every direction of the wrist. Fingers can stretch, bend and move sideways and the hand can bend and rotate at the wrist. Furthermore, we receive sensory feedback from our hands and fingers that help immensely when touching or operating objects. As we are still in the initial stages of this research, and in this installment only focuses on strumming (coarse movements), it is clear that custom actuators would need to be designed and implemented, if more advanced and hand-like interaction should be possible (finger-picking or other playing styles).

It is also worth noting that we are working with an electrical guitar for this prototype, and that the actuator we are using can cause electrical noise in form of a electromagnetic field and audible motor noise to bleed from the motor into the guitar's pickups. This occurs due to the proximity of the electrical guitar pickup, be it single coil or humbucker design, near the plucking location on the strings (a position required to best capture the sound). This noise problem can be substantially circumvented by running the pulse-width modulation (PWM) signal that controls the motorized fader at a frequency higher than normal human hearing (more than 20kHz). While an acoustic guitar would not have this problem, the more fragile body makes it somewhat difficult to mount actuators on the guitar's body without damaging it, or compromising its ability to produce a good acoustic sound.

5. CONCLUSION

The results clearly points in a direction that children or adults with Hemiplegia can play an actuated guitar, potentially even bringing it to a traditional guitar teacher and start learning basic chord shapes with their good hand (with standard tuning). In the prototype's current state – where string skipping and muting is not possible – it has to be limited to things possible only with strumming. Nonetheless, is it a huge step for people with disabilities to simply be able to play a real guitar. It is also possible to use it as a training and rehabilitation instrument for the affected arm as a therapeutic tool with a few more iterations of prototype development. Using the motivating factor that playing guitar and learning new tunes can be fun possibly leads to more consistent training the affected arm, and thereby hopefully increase the dexterity of the affected limb more quickly.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] J. V. Larsen, D. Overholt, T. B. Moeslund, "The Actuated Guitar: A Platform Enabling Alternative Interaction Methods", in Proceedings of SMC Sound and Music Computing Conference, p. 235–238 (2013)

[2] M.D. Crocker, M. MacKay-Lyons, and E. McDonnell, "Forced Use of the Upper Extremity in Cerebral Palsy: A Single-Case Design," *American Journal of Occupational Therapy Volume 51*, November 1997 pp. 824-833.

[3] J. P. Snedeker, "Adaptive Engineering for Musical Instruments," in *Medical Problems of Performing Artists: Volume 20 Number 2*: Page 89 (June 2005).

[4] R. Benjamin Knapp and Hugh S. Lusted, "A Bioelectric Controller for Computer Music Applications," in *Computer Music Journal, Vol. 14, No. 1, New Performance Interfaces 1* (Spring, 1990), pp. 42-4, MIT Press.

[5] S. Bhat, "TouchTone: an electronic musical instrument for children with hemiplegic Cerebral Palsy," in *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10)*. ACM, New York, NY, USA, 305-306.

[6] A. Kapur, "A History of Robotic Musical Instruments," in *Proceedings of the International Computer Music Conference.* Barcelona, Spain, September 2005.

[7] E. Singer, K. Larke, and D. Bianciardi, "LEMUR GuitarBot: MIDI robotic string instrument," in *Proceedings of the 2003 conference on New interfaces for musical expression (NIME '03).* National University of Singapore, Singapore, Singapore, 188-191.

[8] D. Overholt, E. Berdahl and R. Hamilton, "Advancements in Actuated Musical Instruments" in *Organised Sound*, 16, p. 154 – 165 (2011)

[9] E. Berdahl and A. Kontogeorgakopoulos, "The FireFader Design: Simple, Open-Source, and Reconfigureable Haptics for Musicians", in *Proceedings of the ninth Sound and Music Computing Conference*, p.90-98 (2012)

[10] E. Berdahl, J. Smith III and G. Niemeyer, "Mechanical Sound Synthesis: And the new application of force-feedback teleoperation of acoustic musical instruments" *in Proceedings of the 13th int. Conference on Digital Audio Effects* (September 2010)

[11] Palisano, R., Rosenbaum, P., Bartlett, D., & Livingston, M. (2007). GMFCS - E & R. CanChild Centre for Childhood Disability Research

[12] http://www.gibson.com

[13] http://www.youtube.com/watch?v=RlNKix43ULY