QUANTIFICATION AND ANALYSIS OF UPPER-EXTREMITY HEMIPARESIS USING A NOVEL HUMAN-COMPUTER INTERFACE

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ABSTRACT OF THE THESIS

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A new device, DynaWand was designed, fabricated, and programmed, to register grip force while simultaneously controlling a computer cursor. DynaWand was tested on 12 children with Cerebral Palsy (CP) ages 5-13 (mean = 7.3, Std = 2.3) and 18 age matched controls ages 5-11 (mean 8.2, Std = 1.9). The two tests administered were a Fitts tests and a Grip Precision test. The Fitts test was conducted using the DynaWand's imbedded accelerometer as a tilt sensor, capable of controlling a computer cursor. The results from the Fitts test were used to calculate the Psychomotor Delay (PMD) associated with the movement trials. The Grip Precision test used the DynaWand's Force Sensitive Resistors (FSRs) and accelerometer to measure the grip force to load force onset latency and grip force at load force onset. Results from the Fitts test show that PMD for the impaired arms of the CP group averaged 184 ± 80ms and 165 ± 11ms on day 1 and day 2 of testing, respectively. The unimpaired arms of that group averaged 132 ± 108ms and 127 ± 100ms. The average PMD value for the control group was 130 ± 92ms. The grip-to-load force onset latency for the impaired and unimpaired arms of the CP group averaged 171 ±114ms and 39 ± 25ms, respectively. Controls averaged 45 ± 45ms. The grip force at load force onset for the impaired and unimpaired arms of the CP group was 215 ± 172 and 17 ±16 relative force units, respectively. Controls averaged 57

± 76 relative force units. These results show the unimpaired arms of the CP group had similar PMD values to the control and these delays were shorter than the impaired arms. The grip-to-load force onset latency for the impaired arms of the CP group was substantially higher than the unimpaired arms and controls. This suggests the DynaWand may be capable of quantifying temporal and force-related aspects of coordination deficits in children with hemiparetic injuries.

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1. Introduction

1.1 Statement of Need

The emergence of video games directed towards motivating players to move their bodies in order to control the game-play has opened the opportunity for therapists to use them for rehabilitation tools. These games offer higher adherence to rehabilitation protocols than do conventional, non-video game based rehabilitation techniques. However, the current games are not designed to address a particular activity of daily living, but rather they focus more on sports such as baseball, tennis, and bowling. Moreover, the quantitative feedback provided to therapists is based on scores in such games and are not linked to the underlying motor control mechanisms. Injuries causing unilateral, upper-extremity dysfunction, such as a Cerebral Palsy, provide an excellent platform for study because many physically interactive video games require the use of at least one hand for operation.

Traditionally, video games are operated by input devices requiring only a small range of motion or the use of only a distal part of the body. For example, a mouse or gaming controller may only use the fingers and small wrist movements to achieve control of a game. However, many therapists prefer the use of input devices which have their patients moving larger limbs. One of the more popular gaming consoles used by therapists is the Nintendo Wii system. The controller, a wand fitted with accelerometers, gyroscopes, and infrared cameras, allows players to control video games in a more dynamic way. This provides a greater range of motion in the rehabilitation process.

While the Wii system and other gaming consoles provide an interactive and rich gaming experience, the games developed by their manufacturers are used solely for entertainment purposes. Therefore, there is a need for video games and input devices specifically tailored to the rehabilitation of patients with upper-extremity hemiparesis in order for therapists to compare quantitative results in an inter- and intra-patient fashion.

1.2 Background of Speed-Accuracy Tradeoff

The relationship between the speed and accuracy of a planned movement has been applied to human movement for decades. The seminal work done by Paul Fitts characterized this relationship by providing evidence suggesting the time required to complete a movement task is limited by the information capacity of the motor system [1]. Fitts' research modeled the movement time using a linear regression complete with two experimentally determined coefficients. Emerging research has focused on the use of Fitts' paradigm as a way for users and therapists to use the paradigm's coefficients to assess the level of dysfunction in stroke patients[2].

Additionally, Fitts' paradigm is a guiding force behind the development of video game and computer interfaces [3]. ISO regulations state that the determining factor in how well an input device can control a computer is the throughput calculated from only the slope of the Fitts regression. This method does not use the second coefficient and therefore under-represents the full potential of Fitts' Law. Therefore, it is worthwhile to integrate these concepts into a platform capable of quantifying the level of impairment experienced by persons with hemiparetic injury. A successful utilization of Fitts' Law in order to combine Cerebral Palsy patient's motor control and the operation of Human-Computer Interfaces (HCI) will rely on using both regression coefficients.

One promising method for combining both regression coefficients is determining the Psychomotor Delay (PMD). PMD is calculated by passing these Fitts coefficients into a delayed feedback circuit. This circuit is based on converting spatial target information into neural commands. The difference between the targets' position and the present position of the pointing device, in this case the computer's cursor, is continuously updated. The updating process suffers from two separate delays which are added to determine the PMD. Recently, Beamish et al. applied this circuit to data presented in previous work by several researchers and determined the PMD for many different test protocols. These PMD values for unimpaired subjects ranged from 80ms during mouse pointing tasks to 90ms for Fitts' original disk transfer tests [4]. This quantitative delay can then be used by therapists to assess the level of impairment suffered by persons with hemiparetic injury. Clinicians can implement this approach with confidence that not only does the metric conform to underlying motor control mechanisms, but the full robustness of Fitts' Law is used.

1.3 Grip Impairment in persons with hemiparetic injury

In order to pick up an object, one must grasp the object before lifting it. This simple observation may seem trivial, but the temporal coordination of such a movement can provide information about the health of a person's motor system. One common metric used in such an assessment is the latency between the onset of grip force and the onset of the load force required to lift the object, referred to as the duration of the preload phase. Additionally, this type of movement can also provide insight into temporal coordination of a grasping and lifting task by measuring the magnitude of the grip force at load force onset. It has been shown that children with high functioning autism have an increased latency between grip force onset and load force onset as well as elevated grip forces at the time of load force onset [5]. Other researchers have found this trend in children suffering from cerebral palsy where the onset latency and grip force at load force onset metrics were increased in the child's affected arm compared to the unaffected arm. Additionally, these metrics were also larger in CP subjects compared to unimpaired children ([6], [7], [8], [9, 10]). This well established testing protocol motivates the development of a novel device fitted with force sensor capable of measuring the temporal coordination of grip and load force.

2. Hypotheses

(1): Psychomotor Delay (PMD) in children with cerebral palsy is greater in their impaired arm compared to their unimpaired arm. Additionally, the PMD will be greater in the impaired arm compared to a control population without CP.

When performing targeting tasks, persons with Cerebral Palsy injury will follow the log-linear regression fit similar to healthy individuals, however, the Psychomotor Delay calculated from the regression coefficients will be higher with respect to healthy persons. Subjects will perform a Fitts targeting task using a custom input device used to control a computer’s cursor. Developed software will be used to administer the test, record targeting times, and calculate the regression fit. The empirically calculated regression coefficients will be fed into the delayed feedback circuit model to determine the subject’s Psychomotor Delay.

(2): The grip force to load force onset latency and the grip force at the onset of load force will both be greater in children with cerebral palsy compared to unimpaired children.

It is well known that there exists a latency between when one grasps an object and when that object is lifted. What is lesser known is that children with cerebral palsy exhibit a greater latency compared to unimpaired children. Moreover, this latency is larger when comparing an individual CP patient's affected arm to his/her unaffected arm. In addition to this temporal coordination abnormality, increased grip forces at the onset of load force can give researchers clues to the force-related impairments suffered by children with CP.

Therefore, it is proposed that the device under development will be capable of measuring the grip force to load force onset latency as well as the grip force at load force onset. The expectation is that when compared to unimpaired children, children with CP will have greater latency and greater grip force at load force onset. Additionally, these two metrics will also be increased when comparing the affected arm to the unaffected arm of an individual CP patient.

3. Literature Review

3.1 Fitts' Paradigm: The Speed Accuracy Tradeoff (SAT)

For nearly sixty years Fitts' Law has been the hallmark of describing motor behavior in humans. Fitts set out to quantify the notion that the faster an action is performed, the less accurate that movement becomes. He further investigated this speed-accuracy tradeoff by empirically determining that the movement time required to perform a movement is based on constraints of how far a person must move and to what accuracy that movement required. Fitts' characterization of the speed-accuracy tradeoff proves to be a fundamental principle in determining the efficiency of motor behavior as it describes many physiological cases such as transferring disks between pegs, tapping a stylus, and placing pins into holes ([1], [11], [12]).

Fitts' original SAT test consisted of reciprocally tapping a stylus between two stationary, rectangular targets. Targets were separated by a movement amplitude (A), each with a constant width (W). The height of each target was much larger than its width, ensuring that the limiting factor in the size of each target only depended on the width. The task presented to the subjects was to record as many alternated target hits as he could in an allotted amount of time. Fitts recorded the time between hits and found a logarithmic relationship between these values and the physical arrangement of the targets.

$$MT = \mathrm{a} + \mathrm{b} * \log_2 \frac{2A}{W} = a + b * ID \qquad \text{Eq. 3-1}$$

Where MT = movement time

A = center-to-center distance between targets

W = Width of targets

a, b = empirically determined coefficients

The $\log_2 \frac{2A}{W}$ term is called the index of difficulty (ID) because as the targets are separated by a greater amplitude (A), or are reduced in size (W), the action becomes more difficult to perform.

Fitts' motivation for selecting this logarithmic relationship is based on his representing the motor system as a continuous channel carrying motion information from the motor cortex to the distal muscles. This produces the movement, and the afferent information coming back from these muscles represents the position of the moving limb. The ability of the motor system to transmit and process this information represents one's ability to produce one class of movements from many alternatives, and the number of alternatives specifies the information capacity of that system [1]. Since the measurable quantities such as time, amplitude, and width are continuous variables, it is possible to deduce the information capacity of the motor system using Shannon's Information Theory [13].

3.1.1 Shannon's Information Theory

Theorem 17 from Shannon's *A Mathematical Theory of Communication* states that the capacity of a continuous channel is described by the difference in entropy between the ensemble signal, one containing transmitted signal plus white thermal noise, and the average power of that noise [13]. The mathematical similarity to Fitts' law cannot be understated for Shannon's representation of the continuous channel is

$$C = H(ensemble\ signal) - H(noise) = W \log_2 \frac{S+N}{N} \qquad \text{Eq. 3-2}$$

where C = channel capacity

H = entropy

W = channel bandwidth

S = average signal power

N = average noise power

Fitts chose this for the basis of his law because noise alone, in the continuous variables mentioned above, will provide the alternative movements quantifying the information capacity of the motor system. This is realized by assuming the signal (S) in Shannon's theorem is analogous to the amplitude of the movement task (A) in Fitts' law, while the noise is analogous to the endpoint variability in the movement task defined by the target width (W). Therefore, many researchers define the index of difficulty (ID) of a movement task as $\log_2(\frac{A}{W} + 1)$ ([14], [15], [16], [17]). The choice of which ID formulation to use has been the topic of debate ever since Fitts first published his findings. Fitts' rationale for using the 2A/W instead of (A/W +1) is somewhat nebulous. He states that his use of 2A rather than A ensures that the ID will be non-zero for practical situations and adds one bit of information per response. In addition, Fitts states this choice makes the ID correspond to the "number of fractionations required to specify a tolerance range derived from a range extending equidistant on the opposite side of the target" [1]. Moreover, the confusion is compounded by his statement that the choice of the numerator in his ID is arbitrary because the range of possible amplitudes must by empirically inferred.

Therefore, more recent studies using Fitts' law almost entirely use Shannon's formulation to describe the ID ([18], [4], [19], [20]). One advantage to using the Shannon formulation is that, regardless of the choice of amplitudes and target sizes, the ID will always retain a positive, non-zero value. Additionally, the Shannon formulation exactly mimics the underlying information theory while providing a better fit to experimental data when compared to the Fitts' formulation [20]. In fact, the International Organization for Standardization (ISO) adopted the Shannon formulation for ID to describe the control of non-keyboard computer input devices such as a mouse, joystick, or tablet inputs to name a few [3].

3.1.2 International Standards for computer input devices: ISO 9241-9

There are two distinct advantages of using ISO guidelines to describe the function of a novel computer input device. Firstly, any device developed in accordance with ISO guidelines in one part of the world may be used elsewhere without changing the device's parameters. Secondly, the device may be evaluated using any of the ISO's other standardized tests [23]. One of the most important metrics outlined in ISO 9241-9 is throughput (TP). TP is a measure of a devices' capacity for transmitting information to a computer through that device ([2], [3]). TP is defined as 1/b where b is the channel bandwidth taken from Shannon's formulation of Fitts' Law (Eq 3-2). From equations 3-1 and 3-2, one can see that the $\log_2$ representation of the ID will have units of bits. Therefore, assuming the y-intercept is zero, 1/b will give rise to a throughput whose units will be bits/second. However, this requirement that the y-intercept must be zero has led researchers to question the ISO standard of throughput.

Zhai et al perform detailed analyses of different throughput metrics including the ISO guideline's 1/b representation. They conclude that for a given non-zero intercept value, a, TP asymptotically approaches the ISO's 1/b representation only as the mean ID level increases [21]. Therefore, it can be inferred that the ISO's description of TP depends on the relative ID level and the y-intercept; however, the stated 1/b representation does not address these two issues directly. Through Zhai's analysis of this problem, they suggest several reasons why one might encounter non-zero intercept values.

Firstly, Zhai suggests that a non-zero intercept may arise due to modeling or regression errors. Regression analyses are fundamentally subject to noise, and selecting a narrow range of ID levels lessens the robustness of the MT vs. ID regression leading to a less reliable estimation of a, the y-intercept [21]. Also, designing tests where the ID levels are less than 2 bits likely shifts the task towards an open-loop behavior and veers away from Fitts' Law [18]. Additionally, Zhai suggests a non-zero a value could arise from a component of motor performance independent of target size or separation distance. One example of this can be seen in Fitts' original paper where subjects performed a disk transfer test. In this test, subject were to move metal washers from one peg to another as quickly as possible. The distance between pegs along with the relative sizes of washer inner-diameter and peg diameter defined the ID levels tested. The results showed that the disk transfer tests produced intercept values of 150-223ms while the more simple stylus tapping test produced intercept values ranging from -37 to 12ms [1].

Finally, Zhai suggests "a component of human visual, cognitive or motor reaction/activation process that is independent of movement task parameters" may contribute to a non-zero intercept value [21]. One obvious example of this issue is the reaction time required to recognize a target an initiate movement. Fitts' recognized reaction time as being a parameter that could not be fully explained by his original test. Therefore, he developed a test where subjects performed a non-reciprocal aiming test. Subjects held a stylus on a starting position between two targets. One of two LEDs would light up specifying which of the two targets the subject must hit, and the time between the separation of the stylus from the starting position and when the target was successfully hit represented the movement time. This procedure was designed to quantify reaction time and was found to slightly increase with increasing ID level. However, Fitts concluded that this increase was very minor, and that reaction time remained rather constant [11]. Therefore, if reaction time is not explicitly measured, it will be one source of a non-zero intercept.

The question then becomes: what are the underlying cognitive and physiological components of human movement that aggregate to form Fitts' behavioral law? The answer to this question may provide a better representation of the input performance of humans using computer input devices compared to TP, and this new representation may lead to better quantifying impairment experienced by persons with hemiparetic injury.

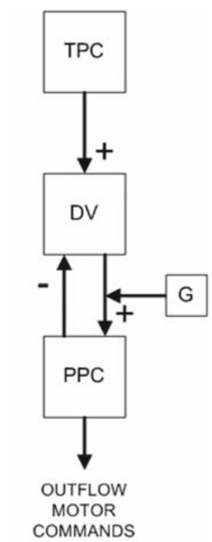

Figure 1: The Vector-Integration To Endpoint (VITE) Circuit. TPC = Target Position Command. PPC = Present Position Command. DV = Difference Vector and is calculated by PPC-TPC. G= variable Gain. Figure taken from Beamish, et al.

3.1.3 The Vector-Integration To Endpoint (VITE) circuit: estimation of psychomotor delay

In the hopes of defining the underlying cognitive and physiological control mechanisms by which Fitts' Law is based, researchers have studied the neural characteristics of movement tasks and how they relate to the overall behavioral outcomes. While Fitts' Law is the hallmark of determining the behavioral aspects of planned movement tasks by testing the aggregate effect of many muscles producing a movement, the individual contributions from each muscle is not well defined. These individual motor unit contributions may contract variable amounts to achieve an overall synergy consistent with Fitts' Law, but Fitts' Law need not apply to each subunit independently. The combination of neural subsets can be described using the Vector-Integration To Endpoint (VITE) circuit [22].

The VITE circuit is a delayed feedback circuit based on the fact that neuromuscular signals are not sent instantaneously through the motor channels. Therefore, it is proposed that the VITE circuit is capable of quantifying these delay times giving rise to the speed-accuracy tradeoff ([22], [4]). A schematic of the VITE circuit is presented in Figure 1.

Motor planning starts by generating a Target Position Command (TPC) which is the cognitive representation of the target's location in space. The Present Position Command (PPC) specifies the internal representation of the current position of the targeting apparatus, in most cases a finger, or in the case of Fitts' original test, the tapping stylus. The PPC is generated in two ways, Outflow Motor Commands and Inflow Motor Commands.

Outflow motor commands are used in at least three ways. Firstly, they send movement signals to the muscles to generate contraction. They also send corollary discharges branching off the efferent pathway which are coupled with Inflow motor commands in an afferent manner to ensure a linear muscle contraction even though an individual muscle plant may fire non-linearly. Finally, the corollary discharges generated are matched with the TPC to provide synchronous trajectories [22]. Inflow motor commands are afferent signals from the muscle to the brain generated by proprioceptors and provide information on the current configuration of the muscle. Along with coupling to the corollary discharges, these inflow commands are used in the learning process to provide automatic gain control in response to familiar objects [22]. For example, when one reaches to pick up a briefcase or pen, the information about the size, mass, and orientation of the object can be sent via the inflow signal to adaptively configure the gain to produce the desired motion.

The Difference Vector (DV) is aptly named for it represents the difference between the TPC and PPC, or DV=TPC-PPC. Moreover, the DV is based on cell populations residing in the motor cortex of the brain called vector cells. These cells are tuned to fire in response to a broad range of directions. Therefore, not only does the DV encode the magnitude of distance between the TPC and PPC, these vector cells provide directional information to the DV. These vector quantities are then fed into the PPC which continuously adds, or integrates through time, all the DVs giving rise to the name Vector-Integration to Endpoint (VITE) circuit [22].

Beamish et al. took this model one step further by providing a set of nonlinear delayed differential equations under certain constraints. Firstly, they propose that the feedback circuit will suffer from two separate delays: the delay in response of the motor plant to outflow commands by the PPC; and the delay with which the DV population responds to signals sent back from the PPC [4]. The second constraint is that the DV signal will be non-zero only for positive DV values. This is based on the assumption that DV information is provided by the directionally tuned vector cells residing in the motor cortex and that excitatory signals only come from those cells registering a positive difference between TPC and PPC [22]. The simplest model consistent with these constraints can be solved with the two following equations

$$\frac{dV}{dt} = \alpha[-V(t) + T(t) - P(t-\tau_1)] \qquad \text{Eq. 3-3}$$

$$\frac{dP}{dt} = G[V(t-\tau_2)]^+ \qquad \text{Eq. 3-4}$$

where T(t) and P(t) represent the TPC and PPC activities respectively, V(t) represents the DV population activity, G represents the gain signal, and

$$[V(t)]^+ = \{0 \; if \; V(t) \leq 0.$$

Equation 3.3 says that the activity of the DV population averages the difference between the TPC and PPC by bringing V(t) toward the equilibrium value of V(t)=T(t)-P(t) with a rate constant α, but having a delayed response to PPC of τ_1. Equation 3.4 says the PPC continuously integrates through time the DV signals multiplied by gain, G, and delayed by τ_2 resulting from responses from the outflow motor commands. Beamish and Grossberg assert that the sum of these two delays will provide the total psychomotor delay (PMD) experienced by the motor system [4].

In order to calculate PMD, Beamish et al. provided with their 2009 paper a MatLab code which takes experimentally measured movement times based on Fitts' tests, and through non-linear regression, determines the model parameters α and τ [4]. The estimation of α and τ minimizes the least-squares difference between empirical data and the speed-accuracy tradeoff of the VITE circuit using the following equation

$$\Delta(\alpha,\tau) = \sqrt{\sum_{i=1}^{n}(MT_{\alpha,\tau}(ID_i) - MT_i)^2} \qquad \text{Eq. 3-5}$$

where α is the rate constant of units 1/ms, and $\tau = \tau_1 + \tau_2$ is the psychomotor delay.

PMD is a metric that may give clues to the human motor system's ability to control planned movements and may provide researchers and therapists with a quantitative metric to assess the level of impairment experienced by persons with hemiparetic injury. Moreover, one could obtain values for PMD in order to document the level of improvement different modalities of therapy provide.

3.2 Grip Precision Tasks

The role injuries to the cerebellum have on prehensile activities has been investigated extensively in recent years. One of the most well tested prehensile motions is the act of grasping and lifting an object, most commonly referred to as a grip precision task. The task is used by many researchers because it can be completed quickly, it is easily understood by subjects, and has been related to current clinical measures of impairment ([8], [10], [23]). Another attractive aspect of testing grip precision is the ability to test temporal as well as force coordination. This simple test is capable of providing a wealth of information quickly and easily, but more importantly, the test is directly related to activities of daily living (ADL).

The grip precision test is administered by first having the subject reach out and grasp an object placed directly in front of the grasping hand. Then, the subject is to lift the object off the table and either places it back on the starting position or directly in front of the starting position. A plethora of data can be obtained from this test including temporal aspects such as the duration of the preload phase and load phase; as well as force-related aspects such as grip force at load force onset. For this study, the grip force to load force onset latency is considered the total duration of the preload phase and load phase, summed.

As for the temporal aspects, the preload phase is initiated when the object is grasped and grip forces start to rise; the preload phase ends with the onset of positive load forces. The load phase starts with the onset of load forces and ends when the load force overcomes the weight of the object and liftoff occurs. For healthy individuals with no history of motor impairment, it has been reported that the preload phase lasts for short durations of approximately 50ms; the load phase lasts for approximately 300ms in children ages 6-8 years [9]. As for children with CP, values of preload duration were reported to be 405ms and load phase durations of 275ms for the same age range [7]. This suggests the presence of dysfunctional coordination between gripping and lifting an object, but CP should not affect the lifting of the object off the table.

The force-related aspects of the grip precision task provide additional information about the level of impairment experienced by children with CP. The grip force at the onset of load force is greater in the affected arm of a child with CP compared to the less-affected arm. Steenbergen, et al. tested children ages 4-13 years with CP and found the grip force at load force onset was 3N with the affected arm while the less-affected arm performed the task with only 1.5N [6]. This disparity in force control provides an opportunity to investigate more fully the role CP plays in force coordination.

4. Instrumentation

4.1 DynaWand Design and Operation

The implementation of rehabilitation devices should follow the tenants of any good engineering device. The device must provide the user with the desired operation, and the device should be designed to test for what is being investigated. In this context, the device must ensure the subject operates at a sufficiently large range of motion to provide the desired rehabilitation to the patient. Additionally, the focus on activities of daily living (ADL) is of paramount concern so that continued use of the device will assist the user in developing translational skills needed to live a more normal life. To this end, the device must not put the user in harm's way which could set the patient back in their rehabilitation.

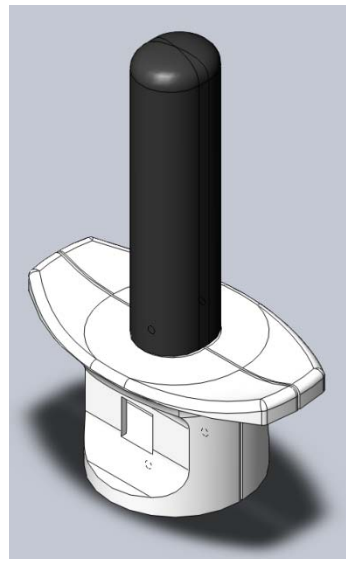

Figure 2: The DynaWand Computer-Aided Design Schematic complete with foam cover. Rocker-bottom excluded.

Generating quantitative information about the level of impairment of the user is the goal of the device from the researcher/clinician's point of view. The challenge is to obtain this data by minimizing the device's effect on the system. Moreover, it is of upmost importance for the testing platform to generate the same testing conditions time and time again. This ensures the data can be used in an inter- and intra-subject basis which allows for quantifying improvements for each subject and comparisons between subject populations.

4.1.1 Design and Development

Three dimensional design of the device was conducted in SolidWorks CAD. Two final versions were produced: one child version and one adult version. Figure 2 shows the rendering of the child's version which was used exclusively during this research. The device consists of a base made from ABS plastic and generated via Fused Deposition Modeling. The black cover, made from VITON rubber, loosely fits over the stem of the device holding the two mated halves together. Figure 3 shows one half of the base. The two halves are nearly identical with the only difference being the saw-tooth connections at the top and bottom of the device. The scalloped design allows for force sensing with the Force Sensitive Resistors (FSR), see section 4.1.2, while the mated saw-tooth projections limit shear forces. The cover is fitted to hold the two halves together, producing very little force on the force sensing region along the stem of the device.

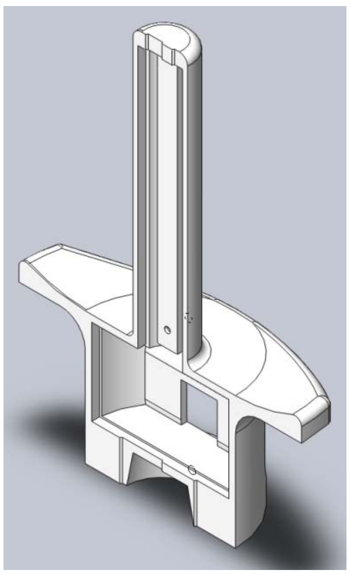

Figure 3: One half of the DynaWand exposed to show cutout used to house the printed circuit board. The Stem running the length of the shaft is used to contact the FSR.

From top to bottom, the stem of the device houses the force sensing region of the printed circuit board (PCB), section 4.1.4. The stem, length of 97mm and radius 10mm, contains a longitudinal, recessed rib used to contact the FSRs. Fitted to the rib on each half of the device is a strip of one side adhesive foam allowing the device to displace slightly with the application of force. This is an important feature because, if the outer radius of one half of the device contacts the other half, an increase in applied force will not be transmitted to the FSRs. The application of the sticky foam ensures that the rib-foam-FSR contacts allow for the greatest possible range of force measurement.

Just below the stem is the hand guard. This feature allows the user to rest his or her hand comfortably, while ensuring each user operates the device in the same manner. Below this is the lower bell region. This widened area allows for the PCB circuitry as well as an entry space for the RJ-11 cable used to transmit signal to the computer. On the very bottom of the device is a notch allowing for the insertion of a rubber 'rocker-bottom'. The rocker-bottom allows the device to act like a joystick for the control of a computer cursor (Figure 4).

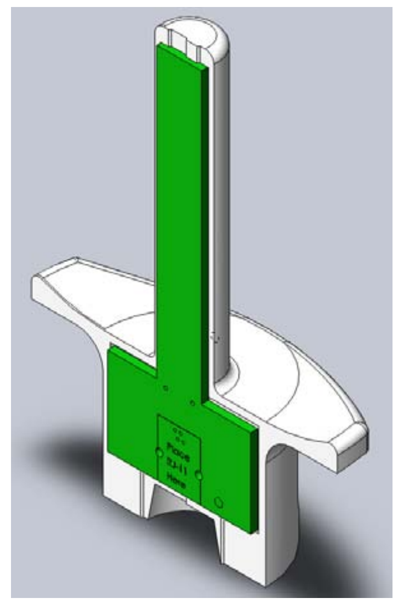

Figure 4: Printed circuit (PCB) board housed within the DynaWand. Circuitry and the FSR both face the occluded cavity. The FSR extends to the top of the PCB.

4.1.2 Force Sensitive Resistor (FSR)

The force sensing component of the device comes from the use of a force sensitive resistor (FSR) attached to the region of the PCB extending up the stem of the device. The FSR (Interlink Electronics) is a piezoelectric strip which changes its resistivity proportionally to applied normal force. The FSR is powered from the RJ-11 supply voltage, and the voltage across the FSR is measured to determine the applied force. FSRs are ideal for this application because they are inexpensive and a mere fraction of a millimeter in thickness. One important aspect of FSRs is that the voltage reading is not linearly proportional to applied force. Shain characterized these sensors in a similar device using an Instron. His work shows the FSRs are capable of a linear response up to 80 lbs of applied force. Shain concludes that FSRs are capable of providing reproducible outputs to applied force even days apart. However, he suggests calibrating the FSR once a week [24].

4.1.3 Accelerometer (ADXL327)

The use of an accelerometer in the device has two main purposes. Firstly, the accelerometer provides data pertaining to the translational acceleration experienced by the device. This information is used to determine the load force during the grip precision test. Secondly, the accelerometer can be used as a tilt sensor. This allows the device to act like a joystick, allowing the user to control the cursor of a computer needed to perform the Fitts test. The accelerometer used in the device is the ADXL-327 3-axis accelerometer (Analog Devices, Inc, Norwood, MA). The ADXL-327 is a micro-electric mechanical sensor (MEMS) device capable of measuring a maximum of ±2g of translational acceleration and reporting this information as an analog signal.

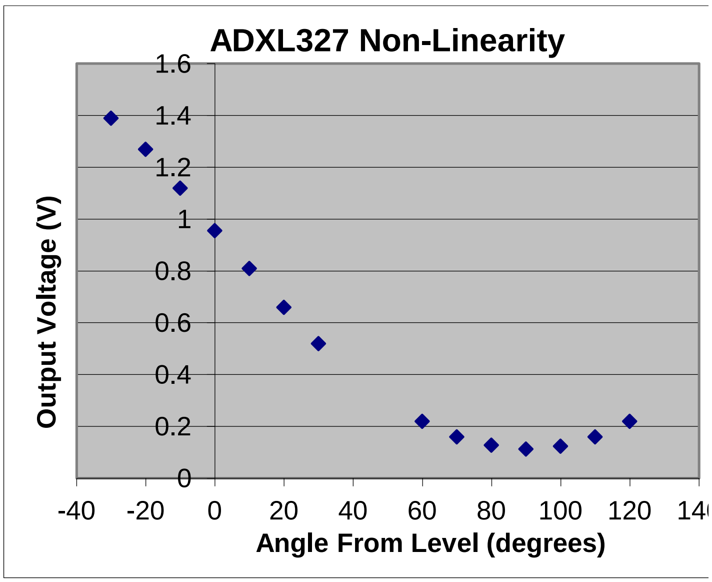

Figure 5: Graph of the accelerometer's non-linearity while acting as a tilt sensor. Output voltage is linear in a range from -30 degrees to +30 degrees from level.

Additionally, the ADXL-327 can be used as a tilt sensor by using the acceleration of gravity as a reference. Orienting the accelerometer so that two of its sensing channels are perpendicular to gravity allows the measurement of pitch and roll. When either of the two channels is perpendicular to gravity, the output will be a voltage half that of the supply voltage. As the channel is tilted, the output of that channel will increase or decrease due to the component of gravity in that channel's direction. This is an effective way to measure the tilt of the accelerometer because each channel is mutually orthogonal to the other channels. This ensures the accelerometer can measure pitch independent of roll, and vice versa. However, since tilt is measured using the contribution of gravity, the response from either channel will be non-linear. In fact, it can be assumed that gravity's contribution will follow as the sine of the angle deviated from level. This is a strong assumption, but for verification purposes, Figure 5 shows the y-channel output vs. degrees from level. It can be seen in Figure 5 that the output responds quite linearly $\pm 30^{o}$ from level; therefore, the use of the ADXL-327 as a tilt sensor should be limited to this range.

Another characteristic of the ADXL-327 is the pervasiveness of noise. Ambient vibrations, minute tremors of the hand, and operating bandwidth are the main contributors of noise. The rocker-bottom's rubber material was selected to attenuate vibrations and provide a high coefficient of friction which reduces translational accelerations. Translational accelerations would corrupt the tilt-sensing capabilities of the accelerometer. Additionally, the hand-gaurd provides a sturdy platform on which the user can rest his or her hand that aids in the steadiness of the hand. But by far, controlling the operating bandwidth has the greatest affect on noise reduction. The noise in the accelerometer is proportinal to the square-root of operating bandwidth. The next section will provide information on the implementation of low-pass filtering to reduce the bandwidth; by extension, the noise.

4.1.4 Printed Circuit Board (PCB)

The printed circuit board was designed and manufactured by Applied Processor and Measurement, Inc., Amherst, NY. The PCB was sized to fit gently in the recessed cavity in each half of the device, Figures 3, 4. The recessed cavity allows for minimal contact with the board itself, while ensuring the foam pads running the length of the stem are the primary contact points along the FSR. This allows for maximum sensitivity and range of the FSR's force measuring capabilities.

The ADXL327 accelerometer resides as close to the bottom of the PCB as possible to reduce translational accelerations. Each of the three accelerometer channels is passed through OPA430 operational amplifiers acting as noise buffers. A 0.22 µF capacitor was selected to perform the low-pass filtering which equates to a cut-off frequency of 22.7Hz. This figure was calculated from the ADXL327 datasheet. The earliest versions of the board had a cut-off frequency of 500Hz and was found to produce an excessive amount of noise. With the 22.7Hz cut-off frequency, the noise was reduced to 21% of that of the 500Hz version.

The PCB houses a six-pin RJ-11 connector for use with a 6-foot Ethernet cable. This connector was selected because of its robustness, availability, and low cost. The six pins provide power and ground, three channels for the accelerometer, and one channel for the FSR.

4.2 Computer Hardware and Interface

Since both the FSR and accelerometer output analog signals, an MCU was used as an analog-to-digital converter (ADC). The MCU used is the Silicon Laboratories c8051f340 set at a 1000 Hz conversion rate. A program developed in C++ by Silicon Labs was modified to receive the analog signals, convert them to digital, and send these data via USB to the computer. The computer used is a Dell Studio XPS laptop with 1920x1080 LCD screen. On the computer side, the data was fed into a custom Visual Studio C# program originally developed by Dr. Nicki Ann Newby. Modifications were made to this program to utilize these data for the purposes of the study. Two Windows form applications were developed, one for each of the experiments conducted in this research.

5. Fitts Experiment

5.1 Participant Recruitment

The CP group consisted of 12 children ages 5-13 (mean = 7.3, STD = 2.3). Each of the children has Cerebral Palsy and is one-side affected with the exception of one subject, EE, who was affected on both sides. The diagnosis was confirmed by Occupational Therapist, Donna Kelly, OT. The CP group was tested at the Children's Specialized Hospital's "Open Arms Camp." This is a three week camp for "constraint-induced movement therapy" where children have their unaffected arm placed in a removable cast, forcing the children to use their affected arm for activities of daily living. These activities include playing games, painting, drawing, and other similar tasks. The cast was removed prior to testing. Parental consent was obtained on the first day of the camp, prior to testing, and adhered to the Rutgers University IRB standards. Two testing sessions were conducted per subject, once on the first day of camp, and once 17 days after the first session.

The control group consisted of 18 children ages 5-11 (mean = 8.2, STD = 1.9). Subjects were recruited through the Highland Park Family Martial Arts Academy. All subjects were asked if they had visual or motor impairments with none reporting any impairment. Parental consent was obtained for each subject prior to testing, and adhered to the Rutgers University IRB standards.

5.2 Fitts Experiment Windows Application

For this experiment, only the accelerometer channels were used from the DynaWand. The accelerometer's tilt sensitive channels were mapped to pixel locations on the computer screen. This allowed the Visual Studio C# program to define the computer cursor location to be moved in accordance with the device's tilt with respect to vertical. One target is displayed on-screen at any given time, and once the cursor resides within the target for 250ms, a successful 'hit' is registered. This 250ms check ensures the target was in fact targeted and was not just passed through by the subject. The 250ms check was subtracted from all data prior to processing, and the time between two successive target hits determines the Movement Time (MT). Upon a successful target hit, a new target is generated with a new location and diameter. The location was randomly generated on the screen within a boundary ensuring the device did not have to tilt more than +/- 30 degrees from vertical. This was selected so that the device was operating within the linear region of the accelerometer (see Figure 5). The following equation

$$D = \frac{A}{2^{ID} - 1} \qquad \text{Eq 5-1}$$

determines the diameter (D) of the newly generated target based on the Cartesian distance, or amplitude (A), between the new target's center and the previous target's center at a given Index of Difficulty (ID). A total of 35 targets are generated at 7 ID levels ranging from 1-4 bits with an interval of 0.5 bits. Target diameters were restricted to a range of 125/ID to 250/ID pixels, or 31 to 250 pixels.

5.3 Fitts Experiment Methods

Subjects were seated at a table with the computer centered in front of them. The device was placed in hand with the rocker bottom Velcroed to the bottom of the device. Subjects were instructed to hold the device comfortably with their elbow and shoulder in-line. For the CP subjects, an adjustable chair was raised or lowered to ensure the elbow made a 90 degree angle between forearm and upper-arm. The control subjects were not tested using the adjustable chair, but subjects were instructed to make an effort to adjust themselves to ensure a 90 degree elbow angle.

A practice trial consisting of five targets at ID = 1 was performed prior to each arm's testing to familiarize the subject to the device's control of the cursor. A short break was given to the subject as the experimenter entered the subject's filename into the Windows application. Subjects were told the experiment was a computer game called "Bubble Burst" and that the goal of the game was to pop the bubbles as quickly as possible. Subjects were informed that the game had 35 bubbles and that they would be timed. Timing started once the first bubble was popped and stopped at the targeting of the 35th bubble. The amplitude between targets, diameter of each target, and time between hits was recorded to a .csv file created with the subject's initials and tested arm. Subjects were not given information about their performance on the game, but positive verbal reinforcement was given after the completion of the game. Once the first arm was tested, a short (~30s) break was given to the subject, and the protocol was carried out for the other arm. The CP group was tested with their unaffected arm first, while the control group was tested on their dominant hand first. One full trial of the game lasted approximately two minutes depending on the subject's performance. It is important to note that the maximum grip force test and the grip precision test were conducted prior to the Fitts experiment. See Appendix for a full script. One subject from the CP group, JS, performed the Fitts Experiment three times with each arm. The average of these three trials is reported for each testing session. Data from five subjects in the CP group is removed from analysis due to several factors. Three subjects chose not to finish the trials, one subject refused to perform the experiment with her affected arm, and one subject broke her arm before the second testing date. The latter subject broke her arm in an event unrelated to this study or the Open Arms Camp. The remaining 7 subjects in the CP group have an average age of 8 ± 2 years.

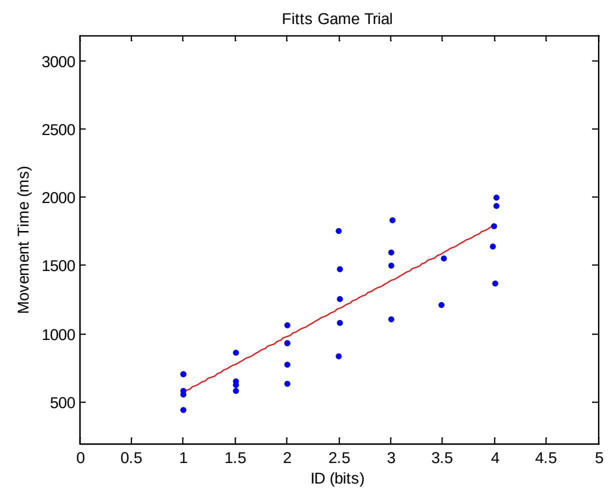

Figure 6: One example of a Fitts Game trial. Each blue dot represents a successful target hit. The Movement Time (ms) is the time elapsed between successful target hits. ID is the Index of Difficulty given by the ID term in Equation 2.1. The red line is the line of best fit calculated by MatLab's robustfit.

Each target's diameter, the amplitude between successive targets, and the movement time between target hits were recorded during the trails. Post-hoc analysis of the data was conducted for each subject's arm. These data were read to a MatLab program which determined the ID level for each target (see section 3.1.1) and paired this number to the movement time. A scatter plot is generated with MT represented on the ordinate and ID level on the abscissa. An example can be seen in Figure 6. A linear regression is computed using MatLab's *robustfit* function which performs a multilinear regression on the MT, ID pairings. The *robustfit* function was chosen because this method of linear regression is less susceptible to outlying data points. In fact, outliers are removed using the 'w' value calculated by *robustfit*, which is a weight parameter applied to each data point in the set. A w value of one (1) represents the case where that data point resides exactly on the regression line, while a w value close to zero (0) corresponds to a point that is highly uncorrelated to the data set. For these data, any w value less than 0.5 is considered an outlier and is removed from the data set. The *robustfit* function also provides the y-intercept and slope for the regression line. Once the outliers are removed, the remaining MT, ID pairs are fed into Beamish et al.'s program to calculate the PMD (see Appendix).

Paired, two-sided t-tests are performed for day 1 impaired vs. unimpaired, day 2 impaired vs. unimpaired, impaired day 1 vs. day 2, and unimpaired day 1 vs. day 2 for each of the metrics: y-intercept, slope, and PMD. In addition, t-tests are performed for impaired vs. control and unimpaired vs. control for each day and each metric. A total of 24 t-tests are performed, and a p value less than 0.05 will be considered statistically significant.

Table 1: Regression Coefficients and PMD for Fitts Test						
	Unimpaired			Impaired		
CP Group (n=7*)	PMD (ms)	Slope (ms/bit)	Y-int (ms)	PMD (ms)	Slope (ms/bit)	Y-int (ms)
Day 1	132 ± 108	906 ± 753	-73 ± 884	184 ± 80	912 ± 415	280 ± 497
Day 2	127 ± 100	609 ± 241	205 ± 424	165 ± 111	856 ± 364	213 ± 529
Control (n=17)	130 ± 92	580 ± 230	219 ± 366			

Table 1: These data are the Psychomotor Delay (PMD) and regression coefficients calculated from the Fitts Game. Averages +/- Std are reported for the unimpaired and impaired arms of 7 children with Cerebral Palsy on the two testing days. Data from both arms of 17 control subjects are reported as well.

5.4 Fitts Experiment Results

The regression coefficients obtained from *robustfit*, along with the PMD results, are shown in Table 1. Values reported are the averages and standard deviations for both the CP group and control group. The CP group consists of data from the 7 children who were able to complete the testing on both days and with both their impaired and unimpaired arms. However, the values listed for this group include the average of the three trials performed by JS. The values reported for the control group consist of 34 measurements from 17 of the 18 control subjects. The values for both arms of each subject are shown, with one subject's data lost due to file corruption.

There were no significant differences found when t-tests were performed on the above data. However, Table 2 shows PMD values obtained for both the impaired and unimpaired arms on both days of testing (Table 2, Columns A, B). Additionally, Table 2 shows the difference in PMD between Day 1 and Day 2 for each arm as well as differences between the impaired and unimpaired arm for each day (Table 2, Columns C,D). A negative value is Table 2 Column C indicates a decrease in PMD between Day 1 and Day 2. A positive value in Table 2 Column D signifies a greater PMD in the impaired arm compared to the unimpaired arm. Additionally, Column D shows that 6 of the 7

Table 2: PMD Values (ms)		A.) Day 1 (d1)		B.) Day 2 (d2)		C.) [PMD(d2) - PMD(d1)]		D.) [PMD(Imp) - PMD(Uimp)]	
Subject	Age (y)	Uimp PMD	Imp PMD	Uimp PMD	Imp PMD	Unimpaired	Impaired	Day 1	Day 2
an	7	49	249	140	84	91	-165	200	-
dm	7	44	75	79	182	35	107	31	1
jg	6	229	259	347	110	118	-149	30	-2
js - av of 3 trials	13	93	94	69	110	-24	16	1	
pg	9	328	259	90	127	-238	-132	-69	
ss	9	126	217	61	139	-65	-78	91	
vv	8	58	138	105	407	47	269	80	3

Table 2: Psychomotor Delay Vales for 7 children with Cerebral Palsy. A.) PMD values for both the impaired and unimpaired arms on Day 1 of testing. B.) PMD values for both the impaired and unimpaired arms on Day 2 of testing. C.) The change in PMD values from Day 1 to Day 2 of testing. D.) The difference in PMD values between the impaired and unimpaired arms for each day of testing. The two testing days

subjects showed greater PMD in the impaired arm compared to the unimpaired arm on Day 1. Five of the seven showed this same result on Day 2.

5.5 Discussion of Fitts Experiment

Psychomotor Delay (PMD) is a metric that could potentially be used to assess the level of impairment experienced by persons with hemiparesis. This experiment was conducted to develop a Human Computer Interface (HCI) capable of quantifying PMD and be used as a potential rehabilitation device. It was hypothesized that PMD would be greater in the impaired arm of subjects with hemiparesis compared to their unimpaired arm. Furthermore, it was expected that the PMD in the impaired arm of children with Cerebral Palsy (CP) would be greater than that of a control population without motor impairment.

Table 1 shows that, on both testing days, average PMD values in the impaired arm were higher than that of the unimpaired arm. Additionally, the average PMD of the unimpaired arm of the CP group across both days is very similar to the PMD of the control group, while the impaired values are consistently higher than control. Table 1 also shows a decrease in the average PMD values for the impaired arm from Day 1 to Day 2 of testing, but the PMD value for the unimpaired arm stayed constant. This suggests a potential role for the device and the PMD metric to quantify motor impairment and improvements to motor control through rehabilitation.

However, such large standard deviations generated from a small sample size makes it challenging to support the hypothesis. The large standard deviations in PMD values are most likely a result of the noise in the device's accelerometer (see Section 4.1.3). The noise in the accelerometer causes the cursor to be jittery. As a result of this jitter, it is difficult to keep the cursor stationary within the target. Coupled with the 250ms 'check' (see Section 5.2), this leads to a situation where the subject has clearly targeted the target, but a successful hit is not registered by the program because the cursor is constantly jumping out of the target. As a result, this problem acts to artificially increase the recorded time between hits especially at high ID levels when targets tend to be small. This issue affected each subject differently. Some subjects were able to fight through the jitter and remain fully engaged on completing the test, while others became frustrated and their performance suffered. Due to the high variability shown in Table 1, comparing intra-subject PMD values may prove more informative than these averaged values.

Therefore, Table 2 lists PMD values, Day 1 to Day 2 changes in PMD, and the difference in PMD between the impaired and unimpaired arms for each subject. In Table 2, Column C reports the difference in PMD for each CP subject across the two testing days. Four of the seven subjects recorded a decrease in PMD in their impaired arm indicated by the negative values listed in Column C, impaired. A negative value here represents an improvement in motor function by signifying a decrease in latency when sending motor information to the hand and faster processing of feedback information at the brain. Column D shows the difference in PMD between the impaired and unimpaired arm for each subject on both testing days. Six of the subjects on Day 1, as well as five subjects on Day 2, recorded positive values suggesting the device and PMD metric may be capable of quantifying the level of impairment.

However, the issue of repeatability should be noted when interpreting these results. Column C, unimpaired in Table 2 shows values that stray from zero both positively and negatively. Ideally, this column should report values close to zero for two reasons. First of all, these data are reported on each subject's unimpaired arm which did not receive treatment. Additionally, learning should not play a role in a subject's ability to complete the test since the two testing days were 17 days apart. Given these two factors, the circumstances under which the test was performed by each subject's unimpaired arm did not change from Day 1 to Day 2. However, it should be noted that the unimpaired arm of each subject was placed in a removable cast while he or she attended camp. This could have unpredictable consequences on the unimpaired arm, potentially leading to non-zero values reported in this data set.

Psychomotor Delay (PMD) could be a better representation of the underlying motor control pathways than previously described by Throughput. Preliminary data show that PMD may distinguish and quantify motor impairment in children with Cerebral Palsy. However, this limited data set did not show any significant differences between groups indicating the need for more testing to determine the efficacy of the device. This new HCI, in addition to allowing users to play computer games, is specifically designed to rehabilitate neuromuscular injury.

6. Grip Precision Experiment

6.1 Participant Recruitment

All individuals who performed the Fitts' Experiment also performed the Grip Precision Experiment.

6.2 Grip Precision Experiment Methods

Prior to performing the Fitts' Experiment, each subject completed the Grip Precision Experiment. In addition to the Grip Precision experiment, subjects were asked to perform a maximum grip force test. This test was simply to squeeze the device as hard as possible and immediately relax to avoid fatigue. The subjects were seated facing the device with the rocker-bottom removed. The device was placed in front of the tested arm on one of two pieces of tape. The proximal piece of tape was used to position the device 3cm from the edge of the table, and the distal tape was placed 15cm from the proximal tape. This marking procedure was mirrored for the other arm.

To begin, an auditory countdown from 3 was followed by the word "go" at which time the subjects were instructed to begin the test. The experimenter began collecting data on "2". For the maximum grip force test, the cue "relax" was given so that the subject did not hold this grip force for too long. For the Grip Precision test, the subject was instructed to lift the device off the proximal tape at the cue "go" and place it gently on the distal tape. Three trials were conducted for each test starting with the unimpaired arm for the CP population and the dominant hand for the control population. The maximum grip force and Grip Precision tests were blocked so that each subject finished the maximum grip test for both arms before moving to the Grip Precision trials. For a complete protocol and script, see Appendix.

Data were continuously recorded during each trial at a variable sampling rate using the C# *timer* routine. It was attempted to maximize the sampling rate of the timer routine; however, the fastest sampling rate was determined to be approximately 64Hz. The sampled data included the FSR Vout, the z-axis channel of the accelerometer, and the elapsed time of the timer routine.

Data analysis was performed using a custom MatLab program which first filters noise using a 3-point moving average on both the acceleration channel and FSR channel. Next, two offset values were obtained by averaging the first three data points of each channel and subtracting this value from the respective channel's data. This centered the data about zero in the y-direction. A scatter plot graph was produced for each trial's offset data.

Once the scatter plots were produced for all trials, three exclusion criteria were applied by the experimenter to discard trials for which the grip force at load force onset or the grip force to load force onset latency were incalculable. The three exclusion criteria are as follows:

1. No baseline measurements in either grip force or load force.
2. No measured increase in grip force or load force.
3. Grip force increase occurred after load force increase.

Failure to pass any one of the three results in a trial's omission.

Using the remaining trials, the MatLab function *ginput* was used to determine a region of interest (ROI) which included the initial grip force increase, initial load force increase, and the maximum of each channel during the lifting portion of the test only. The ROI is necessary because each trial contains spurious data such as when the device strikes the table and generates a large spike in the acceleration channel. Using data from the ROI, the grip force onset and load force onset were calculated by determining the point in time where the response of either channel reached 5% of the maximum increase above baseline in that channel. The grip force to load force onset latency was calculated by subtracting the grip force onset time from the load force onset time. The grip force at load force onset was calculated by indexing the grip force at the point in time when the load force was initiated.

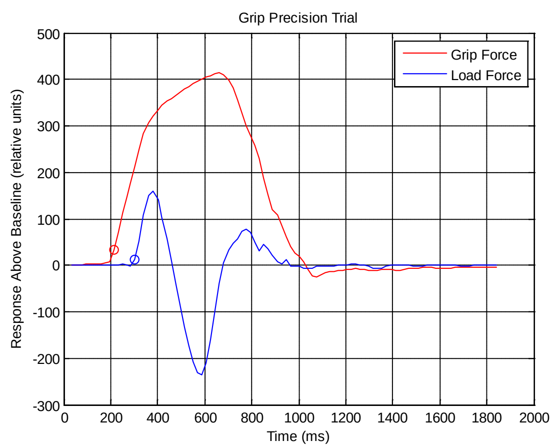

Figure 7: Example of a Grip Precision trial. The Grip Force (red) is the normal force applied to the DynaWand's force sensitive resistor. The load force (blue) is the output from the DynaWand's accelerometer channel oriented in the vertical position. The red and blue circles represent the onset of the grip force and load force respectively. The signals are reported as forces above their baselines in relative units.

6.3 Grip Precision Experiment Results

Figure 7 shows the entire trial of one of the control subjects. The response of both the device's accelerometer and FSR channels represent the load force and grip force respectively. The trial begins with a baseline of approximately 200 ms where the device is stationary on the testing surface and the subject is awaiting the cue to begin gripping and lifting the device.

The grip force is the first channel to experience change once the subject begins manipulating the device. The grip force onset is marked by a red circle in Figure 7 near 200 ms. This increase in grip force in followed by an increase in load force, and its onset is marked by the blue circle near 300ms. This load force onset marks the point in time when the device has been lifted off the table. The device then accelerates upward indicated by the time span where the load force is positive. Once the device has reached its maximum elevation, the acceleration turns negative at approximately 450ms and the device is brought back to the table. At the 650ms mark in Figure 7, the load force channel crosses back to positive values that is most likely a result of the device striking the table and rebounding slightly.

In order to determine the grip force to load force onset latency and grip force at load force onset, data from the entire trial is not needed, but rather a region of interest. This region of interest (ROI) is defined by the time span including the grip force and load force onsets as well as the maximum in response of each channel during the movement phase. It can be seen that in Figure 8, the ROI contains only the segment of the trial from the beginning of data acquisition to the point in time where the device has been placed back on the table. This figure captures the grip force onset, load force onset, as well as the maximum in both load force and grip force during the movement phase.

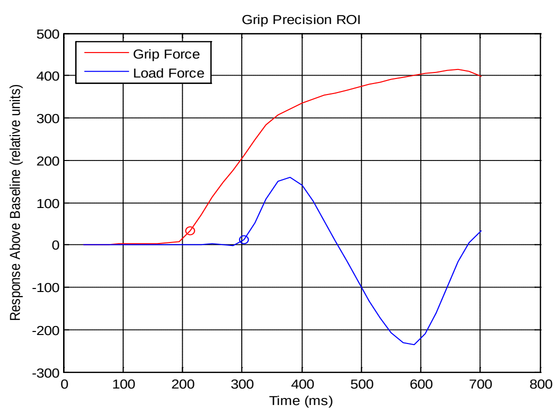

Figure 8: The region of interest (ROI) of the trial presented in Figure 7. The ROI includes the baseline measurements for each channel, the grip force and load force onset, as well as the maximum values of each during the movement phase.

A total of 238 Grip Precision trials were performed for this study. Sixty four (64) trials on Day 1 of the Open Arms Camp, 60 on Day 2, and 114 trials from the control group. Data from 11 subjects from Day 1 and 10 subjects from Day 2 of the camp were analyzed, as well as data from all 18 control subjects. Of the 238 trials, 27 passed the exclusion criteria.

The grip force to load force onset latency (Latency) and grip force at load force onset (GF@LF) were calculated for all trials which passed the exclusion criteria. The average and standard deviation of each of these values is shown in Table 3.

Table 3: Grip Precision Experiment Results

Population	CP - Unimpaired	CP Impaired	Control
n (number of trials)	5	3	19
Latency (ms)	39 ± 25	171 ± 114	45 ± 45
GF@LF (relative force units)	17 ± 16	215 ± 172	57 ± 76

Table 3: Averages ± Std for the 27 trials that passed the exclusion criteria. Latency is the grip force to load force onset latency and GF@LF is the grip force at load force onset. GF@LF is reported as the relative force above baseline. CP = Cerebral Palsy population.

The data presented in Table 3 from the CP population come exclusively from Day 2 of the Open Arms Camp. None of the trials from Day 1 passed the exclusion criteria. The 5 unimpaired trials come from 4 subjects. Three (3) different subjects provided the three trials for the impaired data, while 8 subjects from the control population produced the 19 trials presented.

6.4 Discussion of Grip Precision Experiment

The Grip Precision test is a well established measurement adopted by many researchers to measure prehensile and grasping coordination. The test is well liked in part because it can be administered quickly, it is easily understood by participants, and has been correlated to existing clinical measurements of motor control and impairment ([8],[10],[23]). Two of the most popular quantities that can be measured during the Grip Precision test are the grip force to load force onset latency and the grip force at load force onset. These two measurements test the temporal coordination of gripping and lifting tasks as well as force-related coordination.

The experiment conducted for this research required children with Cerebral Palsy, ages 5-13, grasp and lift a device capable of measuring the applied grip force and the load force needed to lift the device. From these two forces, the temporal and force-related components of coordination were calculated and compared to an age-matched population of unimpaired children. Previous work on Grip Precision experiments have shown that both the grip force to load force onset latency and the grip force at load force onset were larger when children with motor impairments, such as CP, compared to unimpaired populations ([9, 10], [7], [6], [8]). Moreover, this work set out to investigate if the novel device developed is capable of measuring this disparity between groups as well as differences between the impaired and unimpaired arms within the CP group.

The grip force to load force onset latency, which is the sum of the preload phase and load phase (section 4.2), and the grip force at load force onset could be measured using the DynaWand. Table 3 shows both metrics were larger for the impaired arm of the CP population compared to a similar population's unimpaired arm. Also, the data from the impaired arm showed greater latency and greater grip force at load force onset compared to the control population. This was the expected result; however, the small sample size and large standard deviations make it difficult to support the hypothesis.

The reason for the small sample size is a result of only 27 of the 238 trials passing the exclusion criteria. The exclusion criteria were adopted for several reasons.

1. **No baseline measurements in either grip force or load force.**

Without baseline measurements, the onset in those responses could not be calculated. Since the Latency metric is calculated by determining the time lag between onsets of the two responses, both onsets need to be detected. Even if the load force baseline and load force onset are both present, determining the grip force at load force onset could not take place because the metric is measured as relative force above baseline. The reason there would be no baseline is if the subject started the trial before data acquisition began. This would often occur when the subject would anticipate the experimenter's pressing the start button, rather than beginning on the GO command (Section 6.2).

2. **No measured increase in grip force or load force.**

Not having an increase in force means the onset was not present. It was rare for there to be no increase in load force, but rather no increase in grip force was the main reason for not passing this criterion. This is most likely due to the subject applying a grip force large enough to lift the device before data acquisition started.

3. **Grip force increase occurred after load force increase.**

In some cases, the grip force would increase well after the device was lifted off the table. An increase in grip force measured here suggests the subject was gripping the device with sufficient force for lifting, and as he or she brought the device to the table, the grip force would increase in anticipation of collision with the table.

Despite the low throughput, the device was able to measure the grip force to load force onset latency and grip force at load force onset. In addition, the small number of trials passing the exclusion criteria did show the expected result that these two metrics were larger in the impaired arm of children with Cerebral Palsy compared to the unimpaired arm of a similar population. This result was also seen when comparing the impaired arm to a population without motor impairment. For future work, a number of improvements to the device and the experimental protocol should be implemented and may provide more quality results.

7. Future Directions

7.1 Improvements to the DynaWand

One of the most challenging aspects of using this device for these experiments was the noise from the accelerometer. During the Fitts' Experiment it acted as a tilt sensor to control the cursor on a computer screen. Even after hardware and software filtering, the noise made cursor extremely jittery. Since the Fitts Experiment required the targeting of small targets, the noise made some of those nearly impossible to hit. Subjects would be hovering over the target, but the cursor would jump in and out, resetting the 250ms check time (section 5.2). This resulted in poor linear regression fitting and large standard deviations in the calculation of PMD. An early attempt at correcting this was to use a MEMs gyroscope instead of the accelerometer. The gyroscope measures angular velocities and did not produce the jitter. However, these suffered from a drift in the zero-velocity offset. Therefore, when the device housed one of these gyroscopes, the cursor would drift to a corner of the computer screen by the end of the Fitts game. The ideal component would be a 6 degree-of-freedom sensor called an Inertial Measurement Unit (IMU). The IMUs combine the inputs from an accelerometer and gyroscope to better represent the device's physical orientation. IMUs are the standard component in most video game devices currently on the market.

In order to report values of force in the Grip Precision experiment, more calibration must be done on the FSR. This allows the researcher to report values in terms of Newtons or pounds of force which could be compared to previous work. Calibration was carried out for this project, however, several weeks elapsed between calibration and testing. Shain reports drift in the FSR’s voltage output to applied force over the course of days, and he concludes that calibration should be carried out once a week [24]. Therefore, future testing should include a calibration the day of or at most one week prior to testing.

In this report, the grip force to load force onset latency was reported to investigate the temporal aspects of motor coordination. The metric is considered to be the time delay between when the grip force is initiated to the point when the device is lifted from the table. This value represents the sum of the preload and load phase durations (section 3.2). In order to distinguish between these two phases, an additional FSR should be present on the bottom of the device. As the device stands now, the load force is measured by the output of the accelerometer. This signal is unchanging until the device separates from the table. Therefore, in this study, the load force onset is when the device actually separates from the table; not when the subject is beginning to apply an upward force.

7.2 Improvements to Fitts Experiment

Augmenting the 250ms 'check' (section 5.2) is one improvement that could reduce the large standard deviations seen in the PMD data. Discussed in Section 5.5, the noise in the accelerometer's channels would cause the cursor to jump in and out of the target, resulting in the inflation of the time between hits. Reducing this value by several milliseconds would diminish this affect. However, removing this check time, while maintaining a way to ensure a target was actually targeted, would be the most applicable. One approach would be to have the subject click on the targets using a mouse held off the table in the opposite hand. Unfortunately, this would introduce bilateral input from the arms, and one main function of the device is to measure the disparity between the impaired and unimpaired arms independently. This could be circumvented by adding a button to the device. Another option would be to register a successful hit if the cursor is residing in the target, and the subject grips the device with a percentage of his or her maximum grip force.

Another improvement would be to avoid presenting small targets to the subjects. Increasing the minimum target diameter is the obvious correction. For this to be implemented, the 'gameplay' region would have to be increased as well since the target diameter is proportional to the target separation (Equation 5.1). This would risk operating the device outside of the linear region of the accelerometer (Sections 4.1.3 & 5.2). To get around this, one could obtain a computer with a higher resolution and scale the accelerometer's output accordingly. This would undoubtedly increase the contribution from noise in the accelerometer. Therefore, the greatest improvements would still result increasing the signal to noise ratio of the accelerometer. This only bolsters the argument for implementing the IMU (Section 7.1).

7.3 Improvement to Grip Precision Experiment

Improvements to the Grip Precision Experiment center around avoiding the need for the exclusion criteria listed in Section 6.2. Starting to collect data well before the GO signal would ensure baseline measurements are captured. This would drastically reduce the number of trials excluded by criterion 1. In order to avoid subjects anticipating the start of the test, a randomized signal could be used for the GO command. This could be a visual or auditory cue programmed into the testing software.

A better option would be to instruct the subject not to hold the device prior to the start of the trial. Not only would this ensure baseline measurements, criteria 2 and 3 would be addressed as well. This would remove the possibility of the subject applying a grip force sufficient to lift the device prior to data collection.

Appendix

Protocol: (Total time ~15 minutes/child)

1. Hand, Forearm, Upper arm measurements
2. Task 1: Full Grip Strength Test (each hand)
    a. Subject instructed to grip joystick until reaching max grip strength, then release
3. Task 2: Pick and Place (3x each hand) with tape target
    a. Measure table and chair height so elbow is at 90 degrees
    b. Tape points 15 cm apart directly in front of the other point
    c. Measure force on FSRs
    d. Measure time delay between grip force and load force (force to lift device off table)
    e. Purpose: There is a time delay between gripping an object and lifting. We hypothesize that the time delay will be longer for CP subjects than for the control group.
4. Practice Trial of 2-D Fitts' Test
    a. Abbreviated version (5 targets each arm)
    b. No data taken
5. Task 3a: 2-D Fitts' Testing Session
    a. Start with unaffected arm for CP group, dominant hand for control
    b. Full session (35 target hits) (~35 seconds – max (90 seconds))
        i. 5 targets/ID
        ii. 7 indices of difficulty (starting at ID 1, separated by 0.5)

c. Data recorded

d. Repeat 3x (~300 seconds/5minutes each arm max)

e. Rest period (30 seconds)

6. Task 3b: Testing Session - Repeat Step 5 with opposite hand

Script:

1. Introduction:

   a. Introduce ourselves to child: Something along the lines…*"My name is Alex and this is my friend Kim. We go to the same school. We wanted to come here today to teach you a new computer game that we learned at school. Will you play the game with us?"*

   b. If child is uneasy to begin, let another child go first and allow the other to watch.

2. Participates will be asked to please sit down at the workstation, facing the computer screen. [*Adjust the chair height, so the elbow is resting on the table at 90 degrees]*.

3. Preface to tasks:

   a. *"Today you are going to play a computer game. Instead of a mouse, we have a joystick to move the cursor across the screen."*

   b. *"Before we play the computer game, we are going to try a few things so we get used to joystick."*

   c. *"Don't forget, if you get tired and want to take a break while we are playing, just tell us."*

   d. Measurements:

i. For the young ones*: "We also heard that you are ____-years-old and can't believe you are that big. May we measure your hand and arm to see if you really are ___-years-old?"*

ii. For the older ones: something age appropriate… *"May I measure your hand?"* should do.

4. Task 1: *"First, we want you to squeeze the joystick as hard as you possibly can with your [impaired/unimpaired]. Now, squeeze as hard as you can with your [unimpaired/impaired]."* (Unimpaired hand started).
5. Task 2: *"Let's try another game. If we put the joystick on this tape, will you pick it up and put it down on the other piece of tape."* [Task 2 should be run 3x on each hand as IU or UI as before]
6. Task 3a: *"Now that you are warmed up. It is time to play the computer game. During the computer game, you are going to see* ***blue and red*** *bubbles appear on the screen. Using the joystick, you want to move the cursor to the bubble and hold the cursor there until the bubble "pops!" Let me give you a hint on how to win the game: Whenever a new bubble appears, we want you to move to the bubble as quickly and as accurately as possible. Don't forget to stay on the bubble until it disappears."*
   a. *"We are going to have you set your [Imp/unimp] arm on the table while keeping your [unimp/imp] arm down at your side.*"
   b. *"We want you to comfortably grab the joystick with your [unimp/imp] hand, while keeping the bottom of the joystick on the table. For this game, you do not need to squeeze it too tightly."*

c. Practice: *"Let's practice."*

   i. Run abbreviated 2-D Fitts' test, both hands

   ii. *"Remember the hint: whenever a new bubble appears, we want you to move to the bubble as quickly and as accurately as possible. Don't forget to stay on the bubble until it disappears."*

d. Test on first hand: *"You are a fast learner. You are ready to play the game."* [Repeat 3 times, max out at 90 seconds]

e. Rest: *"Now, let's take a short break."* [about 30 seconds]

7. Task 3b: *"Since you did such a great job with the [right/left] hand. You are ready to play on the [left/right]hand."*

Beamish Code:

```
% THIS FUNCTION PERFORMS AN ANALYSIS OF EXPERIMENTAL DATA
%
% The argument should be a table of values of the form [ID MT] where
% duplicate points are allowed.
%
% Assumes the precomputed DATASET is a global variable in memory.
%
% CAUTION: THIS ASSUMES DATA POINTS ARE NO COLINEAR.
% This routine compares the least squares difference of the model to
that
% of the regression line. If the experimental data is exactly co-linear
we
% would need to modify this criteria.
function y = Estimate_Parameters(DATA_experimental)
global DATASET
```

```
    % Load the precomputed data
    Load_Precomputed_Data
    % This array will be of the form [k c leastsqr]
    difference_array = [];
    difference_minimum_forallC = [];
    % We want to find the minimizing (c,k)
    c_minimum = 99999;
    k_minimum = 99999;
    difference_minimum = 999999;
    % ID and MT values of the experimental data
    ID_experimental = DATA_experimental(:,1);
    MT_experimental = DATA_experimental(:,2);
    % Do a linear regression on the experimental data
    %fprintf('Performing linear regression on experimental data.');
    [regression_coefficients S] =
polyfit(ID_experimental,MT_experimental,1)
    regression_slope = regression_coefficients(1)
    regression_intercept = regression_coefficients(2)
    regression_difference = norm(MT_experimental-
(regression_slope*ID_experimental+regression_intercept*ones(length(ID_e
xperimental),1)),'fro')
    % For each value of k=alpha*tau in the precomputed set create a
    % graph of the minimum least squares difference.
    values_of_k = unique(DATASET(:,1))';
    %fprintf('Calculating minimum differences for %d values of the
parameter k contained in the precomputed data.\n',length(values_of_k))
    %fprintf('\nCaution: It is possible the optimal values are not
contained within this data set. \n\n');
```

```
    % Calculate a list of iterations for which to return a progress
update
    % i.e. 10% 20% 30% etc.
    iteration_list = floor([.01:.01:1]*length(values_of_k));
    iteration = 0;
    for k = values_of_k
        iteration = iteration + 1;
        % Give a progress update (since this could take a long time)
%          if ismember(iteration,iteration_list)
%              fprintf('%d percent
done.\n',ceil(iteration/length(values_of_k)*100))
%
% %             % Draw a graph of the progress
% %             cla
% %             hold on
% %             title('MINIMUM LEAST SQUARE FOR EACH k')
% %             grid on
% %             xlabel('k');
% %             ylabel('\Delta(k)');
% %             if length(difference_minimum_forallC) > 10
% %
plot(difference_minimum_forallC(:,1),difference_minimum_forallC(:,2));
% %             end
% %             F = getframe(gca);
%          end

        % For each delay in the dataset, take the corresponding data
        Performance_Data = DATASET(DATASET(:,1)==k,2:3);
```

```
        % Interpolate the values of MT predicted by the model for the
data
        % Must include duplicate values that occur in experimental data.
        for indx = 1:length(ID_experimental)
            ID_model(indx,1) = ID_experimental(indx,1);
            MT_model(indx,1) =
interp1(Performance_Data(:,1),Performance_Data(:,2), ID_model(indx,1),
'linear');
        end
        % Calculate the value of c=1/alpha which minimized for
k=alpha*tau
        % Remember, the model is linear in this parameter so we can
just
        % use regression.
        c = MT_model \ MT_experimental;
        % Calculate the difference norm
        difference = norm(c*MT_model-MT_experimental,'fro');
        % Keep track of the difference norm for each k
        difference_minimum_forallC = [difference_minimum_forallC; [k
difference]];
        % Keep track of which (k,c) are the optimal encountered so far.
        if difference < difference_minimum
            k_minimum = k;
            c_minimum = c;
            difference_minimum = difference;
            MT_model_minimum = c*MT_model; % want to plot this later
        end
```

```
    end
    %fprintf('Calculation of differences complete.\n\n')
    %subplot(1,2,1)
    %cla
    %hold on
    %grid on
    % Draw experimental data points
    %plot(ID_experimental,MT_experimental,'line','none','marker','o')
    % Draw model prediction
    alpha_min = 1/c_minimum;
    delay_min = c_minimum*k_minimum;
    Model_Prediction = Performance_Curve_Lookup(alpha_min,delay_min);
    %plot(Model_Prediction(:,1),
Model_Prediction(:,2),'color','k','LineWidth',2)
    % Draw regression line
    ID_regression = [0:.1:10]';
    %plot(ID_regression,
regression_slope*ID_regression+regression_intercept*ones(length(ID_regr
ession),1),'--','color','k');
    %xlabel('Index of Difficulty (bits)');
    %ylabel('Movement Time (ms)');
    %title(strcat('\alpha = ',num2str(1/c_minimum),', \tau =
',num2str(c_minimum*k_minimum)));
    alpha_minimum = 1/c_minimum
    delay_minimum = c_minimum*k_minimum

    % Plot the minimum difference for each k.
    %subplot(1,2,2)
```

```
    %hold on
    %plot(difference_minimum_forallC(:,1),difference_minimum_forallC(:,
2))
    %xlabel('k = \alpha \tau');
    %ylabel('Difference Norm \Delta(k)');
    %title('Dependence of difference on parameters')
    y = [alpha_minimum delay_minimum difference_minimum];
%     regression_slope
%     regression_intercept
%     regression_difference
%     difference_minimum
%     alpha_minimum
%     delay_minimum
end
```

Fitts Experiment Code:

```
clear all
close all
fitcoeff = [0 0 0 0 0 0 0 0];
subjectname='';
N=0;
rightaffected = {'SF' 'DM' 'SS' 'AM' 'JG'};
leftaffected = {'EE' 'KM' 'OP' 'AN' 'PG' 'VV' 'JS'};
files = dir('C:\Users\Alex\Desktop\CSH day 2 - MountainSide data');
goodfiles = struct('name', {}, 'date', {}, 'bytes', {}, 'isdir', {},
'datenum', {});
j = length(files);
for i=1:length(files)
    filename = files(i,1).name;
```

```
    if(strcmp(filename(1),'_')==1)
        goodfiles(i)=files(i,1);
        j = j-1;
    end
end
goodfiles = goodfiles';
for i=j:length(goodfiles)
    filename=goodfiles(i,1).name;
    importfile(filename);
    if ~isempty(strmatch({[filename(6) filename(7)]},leftaffected))
        affected='L';
    elseif  ~isempty(strmatch({[filename(6)  filename(7)]},rightaffected))
        affected='R';
    else
        affected='N';
    end
    testedarm=filename(13);
    if strcmpi(testedarm,affected)==1
        affectedarm=1;
    else
        affectedarm=0;
    end
    if strcmpi([filename(6) filename(7)],subjectname)==1
        subjectname=[filename(6) filename(7)];
    else
        N=N+1;
        subjectname=[filename(6) filename(7)];
    end
    A=data(2:end-1,2);
```

```
    D = data(2:end-1,1);
    ID1 = log2(2*A./D);
    ID2 = log2(A./D + 1);
    T = data(3:end,3) - 250;
    ymin = min(T - 250);
    ymax = max(T + 250);
    [b,stats] = robustfit(ID2,T);
    outlier = find(stats.w < 0.5);
    newT = T; newT(outlier)=[];
    newID= ID2; newID(outlier)=[];
    x = linspace(1,4);
    subplot(1,2,1)
    plot(newID,newT,'.');
    hold on
    plot(x,b(1) + b(2).*x)
    title({'Conditioned'; [filename(6) filename(7) '_' affected '^'
testedarm]});
    xlabel('ID');
    ylabel('Time Between Hits (ms)');
    axis([0 6 ymin ymax])
    subplot(1,2,2)
    plot(ID2,T,'.')
    hold on
     p=polyfit(ID2,T,1);
    plot(x,p(2) + p(1).*x)
    %plot(ID2,T,'.')
    %axis([0 5 0 1000])
    title({'Raw Data'; [filename(6) filename(7) '_' affected '^'
testedarm]});
```

```
    xlabel('ID');
    ylabel('Time Between Hits (ms)');
    axis([0 6 ymin ymax])
    par=estimate_parameters([newID,newT]);
    RMSE_robust = stats.robust_s;
    fitcoeff(i,:)=[b' p par(2) RMSE_robust affectedarm N];
figure
end
fitcoeff=fitcoeff(j:end,:);
tau=[];
for n=1:N
    pos=find(fitcoeff(:,7)==n);
    temp=fitcoeff(pos,6);
    posaff=find(temp==1);
    posunaff=find(temp==0);
    for j=1:length(posaff)
tau=[tau;fitcoeff(pos(posaff(j)),5);fitcoeff(pos(posunaff(j)),5)];
    end
end
tau=reshape(tau,2,length(tau)/2);
tau=tau';
slopes=[];
for n=1:N
    pos=find(fitcoeff(:,7)==n);
    temp=fitcoeff(pos,6);
    posaff=find(temp==1);
    posunaff=find(temp==0);
    for j=1:length(posaff)
```

```
slopes=[slopes;fitcoeff(pos(posaff(j)),1);fitcoeff(pos(posunaff(j)),1)];
    end
end
slopes=reshape(slopes,2,length(slopes)/2);
slopes=slopes';
yint=[];
for n=1:N
    pos=find(fitcoeff(:,7)==n);
    temp=fitcoeff(pos,6);
    posaff=find(temp==1);
    posunaff=find(temp==0);
    for j=1:length(posaff)
yint=[yint;fitcoeff(pos(posaff(j)),2);fitcoeff(pos(posunaff(j)),2)];
    end
end
yint=reshape(yint,2,length(yint)/2);
yint=yint';
```

Grip Precision Code:

```
clear all
close all
filename = 'CSH2JSdropL.csv';
importfile(filename);
trial1=[];
trial2=[];
trial3=[];

% data(:,1) = log(402.4./data(:,1) - 0.6461)./(-0.6693);
```

```
%Find Individual Trials
Tdiff = data(2:end,3) - data(1:end-1,3);
pos = find(Tdiff < 0);
if isempty(pos)
    trial1=data;
else
    trial1 = data(1:pos(1),:);
end
if length(pos)>=2
    trial2=data(pos(1)+1:pos(2),:);
    trial3=data(pos(2)+1:end,:);
elseif length(pos)==1
    trial2=data(pos(1)+1:end,:);
end
%Calculate Trial BaseLines
if ~isempty(trial1)
offset1 = mean(trial1(1:3,2));
end
if ~isempty(trial2)
offset2 = mean(trial2(1:3,2));
end
if ~isempty(trial3)
offset3 = mean(trial3(1:3,2));
end
if ~isempty(trial1)
goffset1 = mean(trial1(1:3,1));
end
if ~isempty(trial2)
goffset2 = mean(trial2(1:3,1));
```

```
end
if ~isempty(trial3)
goffset3 = mean(trial3(1:3,1));
end
%Center Data to 0 on y-axis
offsetAccel1 = trial1(:,2) - offset1;
offsetAccel2 = trial2(:,2) - offset2;
offsetAccel3 = trial3(:,2) - offset3;
offsetForce1 = trial1(:,1) - goffset1;
offsetForce2 = trial2(:,1) - goffset2;
offsetForce3 = trial3(:,1) - goffset3;
%3-Point Moving Average
averagedTime = [];
averagedAccel1 = [];
averagedAccel2 = [];
averagedAccel3 = [];
averagedForce1 = [];
averagedForce2 = [];
averagedForce3 = [];
for i = 3:length(offsetAccel1)
   averagedTime1(i-2) = (trial1((i-2),3) + trial1((i-1),3) +
trial1((i),3)) ./3;
   averagedTime2(i-2) = (trial2((i-2),3) + trial2((i-1),3) +
trial2((i),3)) ./3;
   averagedTime3(i-2) = (trial3((i-2),3) + trial3((i-1),3) +
trial3((i),3)) ./3;
```

```
    averagedAccel1(i-2) = (offsetAccel1(i-2) + offsetAccel1(i-1) +
offsetAccel1(i))./3;
    averagedAccel2(i-2) = (offsetAccel2(i-2) + offsetAccel2(i-1) +
offsetAccel2(i))./3;
    averagedAccel3(i-2) = (offsetAccel3(i-2) + offsetAccel3(i-1) +
offsetAccel3(i))./3;
    averagedForce1(i-2) = (offsetForce1(i-2) + offsetForce1(i-1) +
offsetForce1(i))./3;
    averagedForce2(i-2) = (offsetForce2(i-2) + offsetForce2(i-1) +
offsetForce2(i))./3;
    averagedForce3(i-2) = (offsetForce3(i-2) + offsetForce3(i-1) +
offsetForce3(i))./3;
end
%Plot Averaged Data
%%%%%%%%%%%%%%% Trial 1 %%%%%%%%%%%%%%
plot(averagedTime1,averagedForce1,'r');
hold on
plot(averagedTime1,averagedAccel1,'b');
title([filename(5) filename(6) ' Trial 1'  '-' filename(11)]);
legend('Grip Force','Load Force');
%Set Region of Interest (ROI)
[x1, y1] = ginput (1);
x1 = round(x1);
[row1 col1] = find(averagedTime1 < x1);
forceROI1 = averagedForce1(1:max(col1));
accelROI1 = averagedAccel1(1:max(col1));
% This is maximum force from ROI
maxForce1 = max(forceROI1);
% and maximum accel from ROI
```

```
maxAccel1 = max(accelROI1);
%Find Force Onset
forceOnset1 = 0.05*maxForce1;
forceOnset1 = round(forceOnset1);
[a b] = find(averagedForce1 > forceOnset1);
forceOnsetTime1 = averagedTime1(min(b));
hold on
plot(forceOnsetTime1,averagedForce1(min(b)),'or');
%and Accel Onset
accelOnset1 = 0.05*maxAccel1;
accelOnset1 = round(accelOnset1);
[a b] = find(averagedAccel1 > accelOnset1);
accelOnsetTime1 = averagedTime1(min(b));
hold on
plot(accelOnsetTime1,averagedAccel1(min(b)),'ob');
OnsetLatency1 = accelOnsetTime1 - forceOnsetTime1
gfAlf1 = averagedForce1(min(b))
% hold on
% plot(accelOnsetTime1,gfAlf1,'xm');
%%%%%%%%%%%%%% Trial 2 %%%%%%%%%%%%%%
if ~isempty(trial2)
figure
plot(averagedTime2,averagedForce2,'r');
hold on
plot(averagedTime2,averagedAccel2,'b');
title([filename(5) filename(6) ' Trial 2'  '-' filename(11)]);
legend('Grip Force','Load Force');
end
```

```
%Set Region of Interest (ROI)
[x2, y2] = ginput (1);
x2 = round(x2);
[row2 col2] = find(averagedTime2 < x2);
forceROI2 = averagedForce2(1:max(col2));
accelROI2 = averagedAccel2(1:max(col2));
% This is maximum force from ROI
maxForce2 = max(forceROI2);
% and maximum accel from ROI
maxAccel2 = max(accelROI2);
%Find Force Onset
forceOnset2 = 0.05*maxForce2;
forceOnset2 = round(forceOnset2);
[a b] = find(averagedForce2 > forceOnset2);
forceOnsetTime2 = averagedTime2(min(b));
hold on
plot(forceOnsetTime2,averagedForce2(min(b)),'or');
%and Accel Onset
accelOnset2 = 0.05*maxAccel2;
accelOnset2 = round(accelOnset2);
[a b] = find(averagedAccel2 > accelOnset2);
accelOnsetTime2 = averagedTime2(min(b));
hold on
plot(accelOnsetTime2,averagedAccel2(min(b)),'ob');
OnsetLatency2 = accelOnsetTime2 - forceOnsetTime2
gfAlf2 = averagedForce2(min(b))
%%%%%%%%%%%%% Trial 3 %%%%%%%%%%%%%%%%
if ~isempty(trial3)
figure
```

```
plot(averagedTime3,averagedForce3,'r');
hold on
plot(averagedTime3,averagedAccel3,'b');
title([filename(5) filename(6) ' Trial 3'  '-' filename(11)]);
legend('Grip Force','Load Force');
end
%Set Region of Interest (ROI)
[x3, y3] = ginput (1);
x3 = round(x3);
[row3 col3] = find(averagedTime3 < x3);
forceROI3 = averagedForce3(1:max(col3));
accelROI3 = averagedAccel3(1:max(col3));
% This is maximum force from ROI
maxForce3 = max(forceROI3);
% and maximum accel from ROI
maxAccel3 = max(accelROI3);
%Find Force Onset
forceOnset3 = 0.05*maxForce3;
forceOnset3 = round(forceOnset3);
[a b] = find(averagedForce3 > forceOnset3);
forceOnsetTime3 = averagedTime3(min(b));
hold on
plot(forceOnsetTime3,averagedForce3(min(b)),'or');
%and Accel Onset
accelOnset3 = 0.05*maxAccel3;
accelOnset3 = round(accelOnset3);
[a b] = find(averagedAccel3 > accelOnset3);
accelOnsetTime3 = averagedTime3(min(b));
hold on
```

```
plot(accelOnsetTime3,averagedAccel3(min(b)),'ob');

OnsetLatency3 = accelOnsetTime3 - forceOnsetTime3

gfAlf3 = averagedForce3(min(b))
```

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