UNIVERSITY OF WISCONSIN – MADISON

DEPARTMENT OF BIOMEDICAL ENGINEERING

BME 400 – DESIGN

Self-Measuring Orthopedic Drill System

Final Report

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Abstract

In many orthopedic repairs, screws are necessary to hold a severely fractured bone together. In order to utilize these screws the surgeon must pre-drill holes into the bone and accurately measure their depths to choose the correct length of screw. The main problem arises as the surgeon must take an additional step to measure the depth of the hole with the depth gauge. This process becomes tedious and time consuming when multiple screws must be inserted into the fracture. Another major problem occurs in this procedure as the surgeon must not drill too far through the bone into the soft tissue (plunging) to minimize tissue damage. Currently this is done solely by the surgeons' perception of where the bone ends and soft tissue begins. In these surgeries, a soft tissue protector is utilized to protect the soft tissue around the insertion from the drill bit. A prototype flesh protector and drill bit interface has been developed that can reduce plunging into the soft tissue and accurately measure the depth of the hole in one step. This design utilizes a viscous fluid used in a hydraulic system to reduce plunging and a slider design to accurately measure the depth of the hole. This prototype removes the step of measuring the hole depth with the depth gauge and dramatically reduces plunging. This device will not only save time in the operating room, saving both the patient and hospital money, but will also prevent unnecessary pain and trauma due to plunging.

Background

Procedure – Long Bone Orthopedic Surgery

There exist many different types of orthopedic surgeries; one of the most well-known orthopedic surgeries involves mending a fractured bone in the arm or leg. Often when a bone is severely fractured and a hard cast is not enough to keep it in place throughout the healing process. For this reason, plates and screws must be employed to hold the bone in place during the healing process (Figure 1).

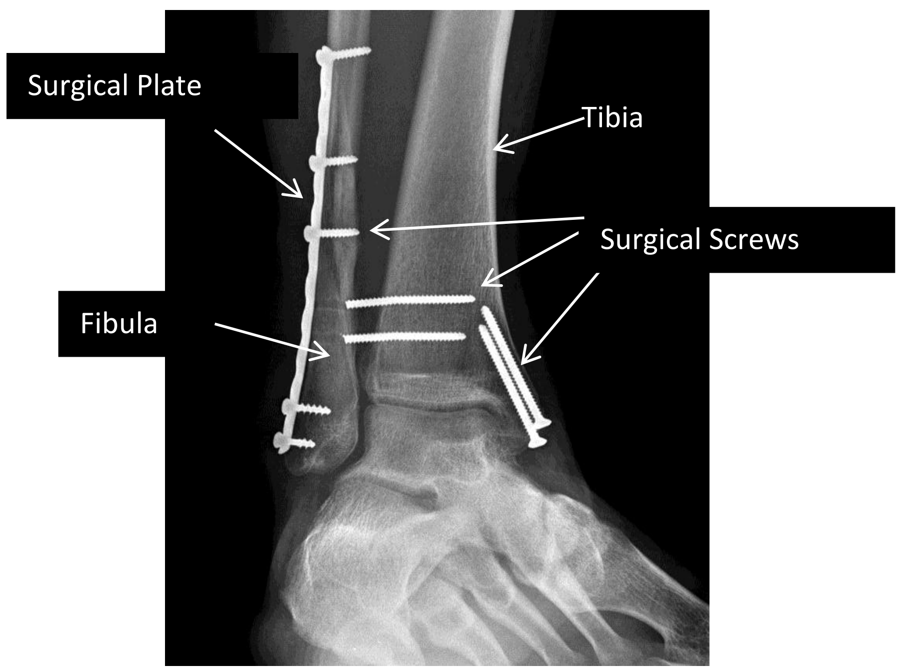

Figure 1: x-ray of orthopedic screws and plate in a fibula and tibia [1]

To insert these screws, the surgeon must drill into the bone with a surgical hand-held power drill. The drill used in this procedure is similar to a cordless drill for home use. It is a high torque, variable speed drill that utilizes a quick connect and release chuck to easily change drill bits [2, 3]. The drill bits used in these procedures are slightly different than the average wood or metal working drill bits. These are 455 or 440A stainless steel that is designed to be corrosion resistant, have high strength and toughness, and designed to hold a better edge than the average drill bit. The drill bit is fastened with a quick lock shaft for easy changing [4].

Plunging is when the surgeon breaks through the bone and begins to penetrate through the soft tissue on the distal side. The surgeon carefully drills through the bone while trying not to plunge more than 2 mm, which causes trauma to the soft tissue. Plunging causes bleeding, soft tissue damage, or neurological injuries. These injuries lead to pain, additional healing times for the patient, and scar formation [5]. Also, the plunging depth should not be taken into consideration when measuring the depth of the hole that was drilled as any amount of plunging will cause an error in the hole depth measurement [3].

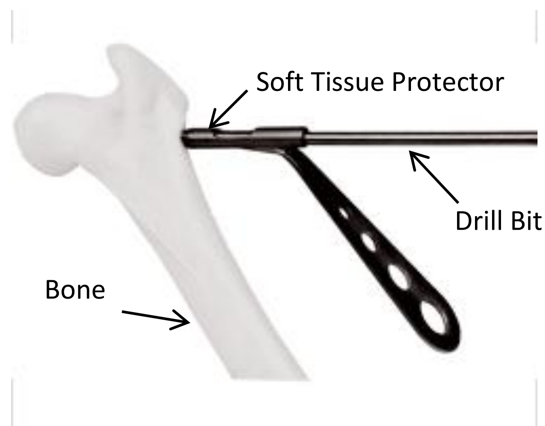

Figure 2: Tissue protector on long bone [2]

To help guide the surgeons as he drills, a soft tissue protector is utilized. This device sits flush on the bone and allows easy access in directing the drill bit to the bone as well as stabilizing the surgeon's path (Figure 2). The soft tissue protector additionally serves to protect the soft tissue and flesh around the incision from the sharp edges of the drill bit [3].

Once the hole is drilled, the depth of the hole must be measured using a depth gauge (Figure 3). The drill bit and soft tissue protector are removed from the hole and the depth gauge's shaft is inserted into the hole in the bone. A small hook on the end of the shaft catches the distal side of the bone.

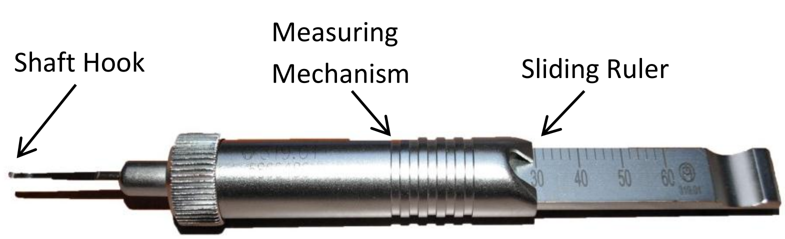

Figure 3: Depth gauge client currently uses [3]

The measuring mechanism is then slid down until it touches the entry point of the bone. The surgeon can then read the depth from the sliding ruler.

Once the hole's depth has been measured, the plate can be placed and the screws inserted through the drilled holes. The screws and plates used in these fracture surgeries are typically composed of stainless steel, but can also be made from Titanium, Cobalt Chrome Moly, or other metals depending on the surgery [4]. The screws come in 2mm increments and using the correct size screw is extremely important in the healing process. If the screw is too short, it can come loose, allowing the bone to move, resulting in improper healing. If the screw is too long, it could protrude out the distal surface of the bone and interfere with muscles and nerves causing the patient unnecessary pain, longer healing times, and scarring [3].

Layers of Bone

A long bone is composed of multiple layers of varying thicknesses and densities. A long bone has two main pieces: a shaft or diaphysis, which is in the middle of the bone, and a thicker head or epiphysis at each of the ends. The outer-most layer of the bone is a very strong thin membrane called the periosteum. This layer has a large number of blood vessels that supply the bone with nutrients. The second outermost layer is called the compact or cortical bone. This layer is extremely dense and is hard for the surgeon to drill through and ranges from 3 mm to over 12 mm. The next layer of bone is dependent on where in the bone the surgeon is drilling. The diaphysis' innermost layer is a bone marrow cavity filled with bone marrow and ranges from 10 mm to about 30 mm in size. The epiphysis' innermost layer is composed of spongy or cancellous bone, and its size is highly dependent on the size of the bone and can be from 8mm to over 30 mm [8, 9] (Figure 4). Cortical bone has a density in humans of about 1.5-2 g/cm^3, spongy bone has density of about 0.2-0.6 g/cm^3, and bone marrow has a density of about 1.0 g/cm^3. However, the elastic modulus of cortical bone is around 20 GPa, spongy bone is about 11.5 GPa,

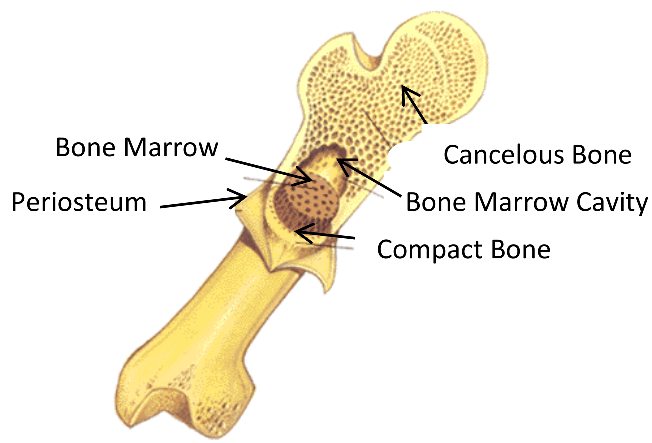

Figure 4: Different layers in a long bone [7].

and bone marrow 9 kPA [10, 11, 12, 13]. This means both the spongy bone and bone marrow are considerably less hard than the cortical bone and are therefore much easier to drill through [3, 6].

Current Products on the Market

The tool currently used to measure the hole's depth (depth gauge) was detailed previously in the procedure section. The problem with this device is it represents an additional step during surgery before the surgeon is able to gather an accurate measurement of the depth of the hole. Despite this, the depth gauge is very accurate in its measurement of the hole's depth.

Motivation

The motivation for this project stems from the incentives of eliminating a step and the number of tools used during surgery. The addition of an anti-plunging mechanism would make the proposed product even more favorable as there is no such device currently in use. Fulfilling these goals will reduce surgical time and pain for the patient, saving the patient and hospital both time and money.

Design Criteria

The main goal of this project is the accurate detection of the depth of the hole drilled through the bone within 2 mm of the actual depth. Mechanical options that have been developed can only measure as accurately as plugging is minimized due to the continuation of the drill bit through the soft tissue after breaching the distal surface of the second cortical layer. For this reason, the plunging magnitude must be reduced to a 2 mm maximum. This maximum is much shorter than the 5mm that is considered safe and more than the 1 mm that is required for the tapered end of the drill bit to create a hole with constant cross sectional area through the entirety of the second layer of cortical bone.

Holistically, the final design must be integrated either into the drill itself or the soft tissue protector if not replacing the soft tissue protector completely. In these modifications, the final product must not compromise either the drill's function or the surgeon's vision. Finally, the final product must be constructed from an autoclavable material to enable sterilization for reuse.

Design Alternatives

Slider

Figure 5: Slide rule design [14]

The first design assessed was similar to a sliding ruler. It would have two sliders (Figure 5); the first of which zeros or calibrates the measurement and the second slider would measure the depth. This design would give a precise measurement for the depth of the drill.. The problem is that plunging could not be accounted for with this device alone as the slider continues to travel and measure during plunging.

Interlocking gears

Alongside the design of the slider, a mechanical option with a series of interlocking gears that turned a counter was conceived. The gears would turn by interlocking with the helical grooves of the drill bit. This option has the same precision as the slider with the advantage of a digital readout such as a lap counter (Figure 6). However, it could add the complication of small interlocking parts that could easily clog and incur wear in the surgical environment and they are hard to manufacture. This option is also only as accurate if plunging can be minimized because its lack of a stopping mechanism.

Figure 6: Lap counter [15].

Saw Stop Technology

The SawStop is a commercially available table saw that has the ability to detect the presence of biological or wet materials in the path of its blade. This device stops the saw blade from spinning quickly enough to prevent serious injuries [16]. The inventor of the saw stop is eager to license this technology and make it an industry standard, which is interesting from a repurposing approach to the design problem: can we implement this technology with a hand drill to detect a difference in the environment to stop the drill? The technology works by imparting a small current on the blade that is altered when it comes in close proximity with other materials [16, 17]. The amplitude of the signal is detected and processed with a set threshold that determines if the interacting material is biological or of a similar composition to biological material.

After further investigation of the SawStop, it was realized the adaptation of the technology was incompatible with our design problem. This technology relies on a probing current that would have to be placed on the drill bit. There could be no detection of the change in current because the environment would cause short-circuiting due to the vast moisture content present in the body. For this reason, the saw stop was not included as a final design option.

Hydraulic Design

The hydraulic design utilizes a well and a plunger design. As the sliding portion that contains the plunger moves down in the well, the viscous or non-Newtonian fluid inside the well would provide a feedback force to the user, slowing down movements (specifically rapid movements). This is technology is mainly used to prevent sudden movements as seen in applications such as a hydraulic or pneumatic door closer. A non-Newtonian fluid, specifically a dilatant fluid is ideal for this application because this type of fluid thickens with an increasing shear rate (top curve in Figure 7). This translates to an extremely effective method of plunge reduction as soon as the drill bit breaks through the distal side of the second layer of compact bone.

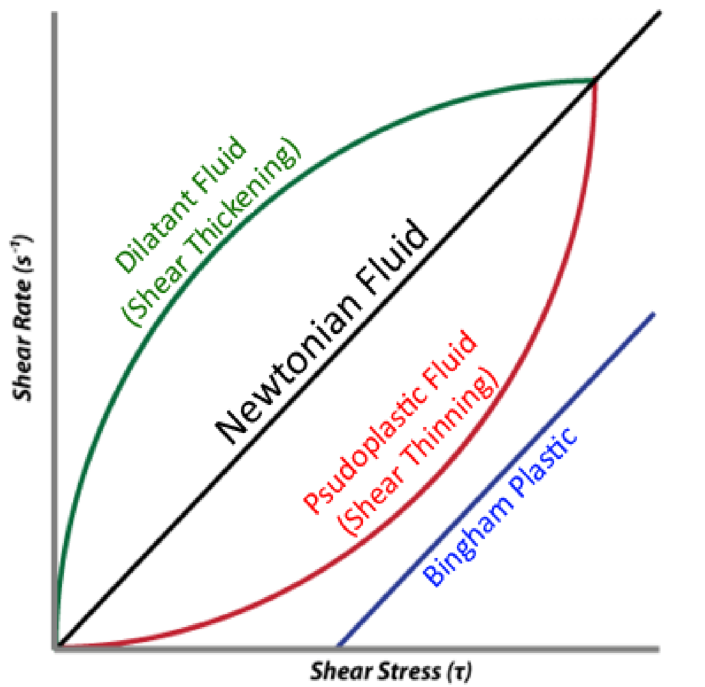

Figure 7: Reactions of various fluids to an increase in shear (x-axis). Note the top line labeled "Dilatant Fluid" that exhibits shear thickening in relation to shear stress [18].

In the equation shown in Figure 8, η represents the viscosity of the fluid, K and n are material based constants and γ is the applied shear rate. The viscosity of the liquid will increase as shear the shear rate increases. When the drill bit penetrates the second layer of cortical bone, and starts the plunge, the shear rate will increase which will result in thickening of the non-newtonian fluid and a stronger feedback force compared to that of a Newtonian

$$\eta = K\gamma^{n-1}$$

Figure 8: The equation for the viscosity of a fluid. Non-Newtonian fluids exhibit the material property of n>1.

fluid. This will result in a decrease in involuntary plunge depth and an increase in the measurement accuracy on the measuring device.

Overall, this design uses the inherent property of hydraulics to accomplish our client's goal of reducing plunging. But, currently there is no way to measure the depth of the hole. So, a measuring device such as the slider or interlocking gears will have to be added to fulfill the clients requirement of obtaining an accurate hole depth measurement. It is important to note that although technically the measurement of plunge reduction and depth measurement are unrelated, in practice, a smaller average plunge distance will result in a more accurate depth measurement as the aspect of the randomness in plunge distance is reduced.

Piezoelectric Sensor

This approach utilizes a standard piezoelectric quartz force sensor (Figure 9) to decrease the plunge and measure screw length. A piezoelectric force sensor houses a material which accumulates an electrical charge (due to orientation of internal electric dipoles) in response to an applied force. When placed in a circuit, the output voltage of the sensor can be used to determine stress measurements.

When implanted internally in the drill, this voltage would be proportional to the experienced axial force. The piezoelectric approach to detect the drill bit environment has been used by previous researchers [19]. Additionally, it has been shown that a plot of this axial force shows distinguishable behavior when the drill is forcing itself through cortical bone (Figure 10).

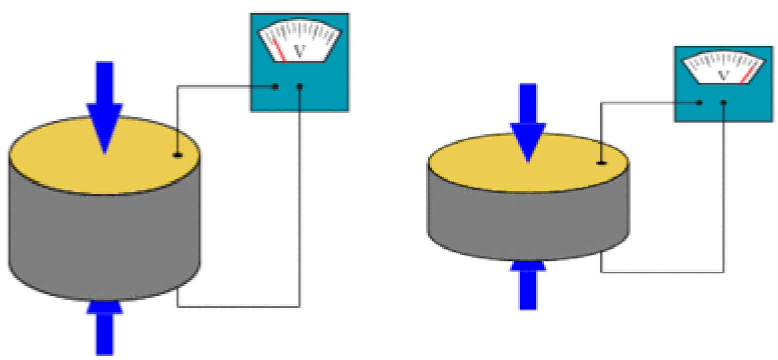

Figure 9: A model of a piezoelectric sensor relating mechanical change with electrical (voltage) response, as the sensor is compressed, the resistance changes resulting in an increase in the voltage output [20].

After conversion to a voltage, the signal would be sent to a microcontroller internal to the drill or a computer for analysis. At this juncture, logic, behavior recognition, or another algorithmic detection system will recognize when the drill pierces the cortical bone. Upon the second detection of cortical puncture, a feedback signal onto the motor of the drill will be sent. The signal will stop the spinning of the drill bit, by cutting the current to the motor, in turn decreasing the plunge and alleviating the post-cortical soft tissue from unnecessary trauma. This design also offers a method to measure screw distance without use of a depth gauge. Retrospective analysis of the voltage data will show the time difference between velocity increases. This time difference would be used to get an accurate hole depth measurement which would be displayed on a digital readout so the surgeon could select the correct size screw.

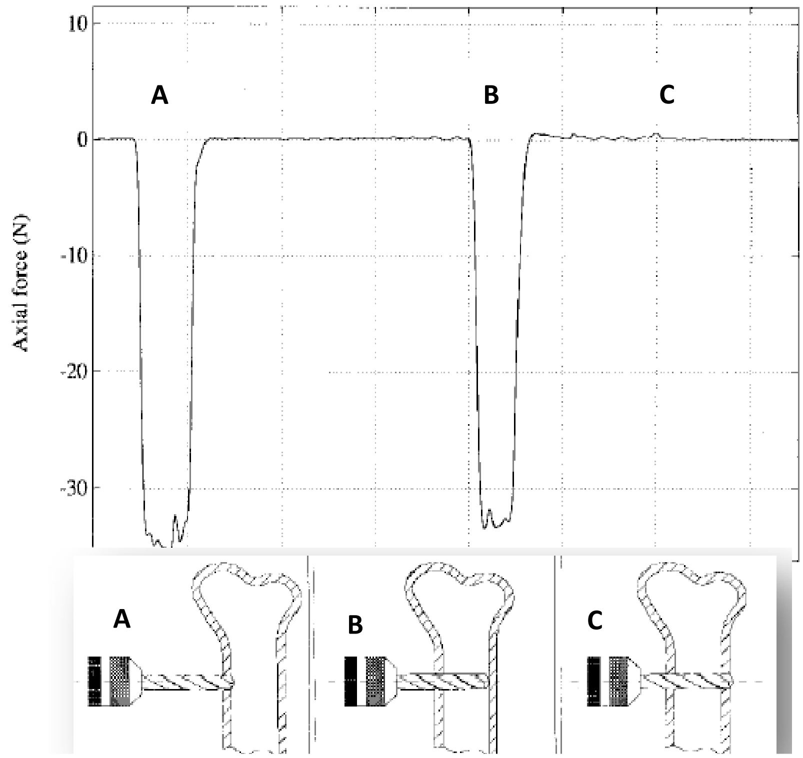

Figure 10: Axial force while drilling through long bone on top and depiction of where drill bit is when those forces occur on bottom [19]. **A&B)** Diagram and quantify the resistive forces when drilling through the first and second layers of cortical bone respectively. In these areas the axial forces are approximately -35N. **C)** Diagrams and quantifies the resistive force after drilling through the second layer of cortical bone. Here the resistive forces are around 0 N.

Unfortunately, neither of the referenced drills which contain piezoelectric sensors underwent commercial production. Because of this, the circuitry, drill modifications, and algorithmic detection must all be researched and implemented. This approach does, however, offer a high degree of versatility, as the microcontroller programming can be changed to vary the behavior of the drill. The complexity of the design will likely demand the use of a PC for algorithm implementation. The modifications this requires, a coaxial cable for PC-drill communication, may pose an inconvenience in the operating room.

Velocity Profiling

The velocity profiling design shares many elements with the piezoelectric design. Like the piezoelectric design, the velocity profiling approach will use a direct current power supply, a reed switch, magnets, a microcontroller, and a feedback device to stop the drill bit from spinning at the time of the second cortical bone breakthrough. It also functions to both reduce plunging and measures screw length. The velocity profiling approach uses a reed switch mounted to the drill with magnets mounts adjacent to the reed switch on the drill's chuck. The reed switch will detect the magnets on the spinning chuck and feed this signal, as a voltage, to a microcontroller. The signal is processed for peaks giving counts for frequency. This frequency can be used to indirectly determine the rotational velocity of the drill chuck (Figure 11).

The properties of the material being drilled (bone or soft tissue) can be determined empirically by analysis of the chuck speed. In theory, the chuck velocity will undergo a velocity increase once puncture of the cortical bone is complete. It is at this point which the microcontroller will feed a stop signal to cut off the current to the motor of the drill. This design is very similar to the piezoelectric idea after conversion of the signal into a voltage. Therefore, the same method for screw measurement can be used. This design does, however, require more extensive modifications to the outside of the drill casing. The external magnets and sensor mounted on the drill may block the surgeon's view or hinder the drills range of use.

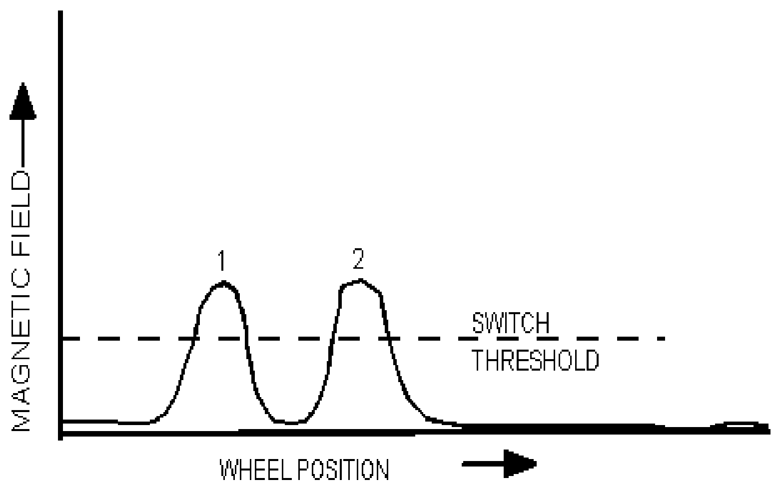

Figure 11: A graph showing the effect of a spinning wheel on a bike magnet. Each rotation of the wheel is detected. This can be converted into a voltage and ultimately a rotational speed with proper hardware [21].

Design Matrix

Each design alternative's score was based off a total of 100 points. The highest ranking categories are to prevent plunging and to retrieve an accurate measurement. These two categories were stressed at each of the client meetings by Dr. Crow. In addition, the client was given each of the designs and he provided his personal opinion. The hydraulic design was given the most points due to the high client preference and its ability to prevent plunging. However, as mentioned earlier, this design only prevents plunging; it has no measuring apparatus. It was therefore paired with the leading measurement device, the slider, to fulfill the design requirements.

Table 1: The Design matrix

	Prevent Plunging (30)	Accurate Measure (30)	Manurafact-urable (10)	Feasible (10)	Client Input (20)	Total
Hydraulic	24	15	10	10	20	**79**
Slider	8	25	10	10	20	**73**
Cog	8	25	7	10	15	65
Piezo	20	10	2	3	5	40
Velocity Profiling	20	30	5	2	10	**67**

Final Designs

Hydraulic Slider

A design that incorporated the anti-plunging capabilities of the hydraulic system and the measuring capabilities of the slider system was chosen for one of the final designs. An easily achievable hybrid of the two was created by simply add a sliding mechanism to the existing hydraulic system (Figure 12). The slider (rectangular upper section) contained a plunger that slides down the base section (lower section) as the drill bit is lowered through the hole at the top of the slider. Ruler etchings on the side of the inner tube allow for direct measurement of the hole depth as it slides down. Previously, there was a locking device that was made conceptually but was not translated into this version as we wanted to attain proof of concept for plunge prevention first.

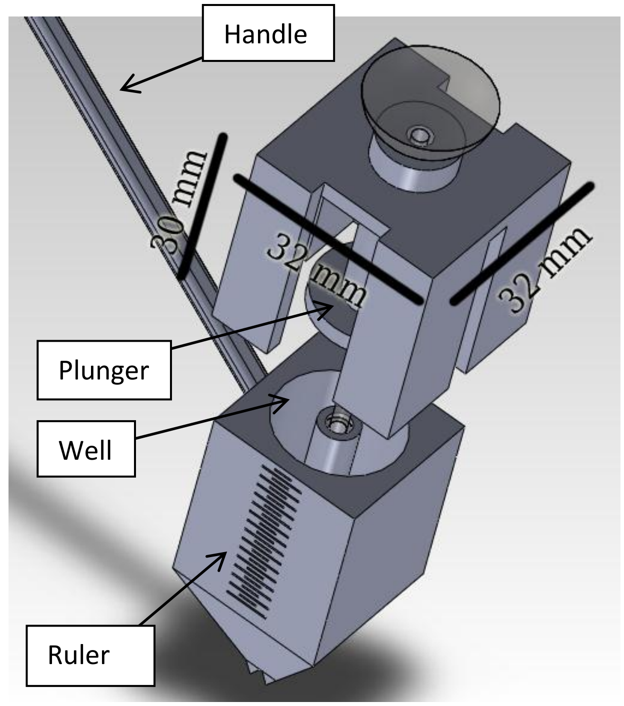

Figure 12: Solidworks of v6.2 of the hydraulic slider, the dark grey piece represents the drill bit and chuck while the light grey pieces are the slider (top) and base (below).

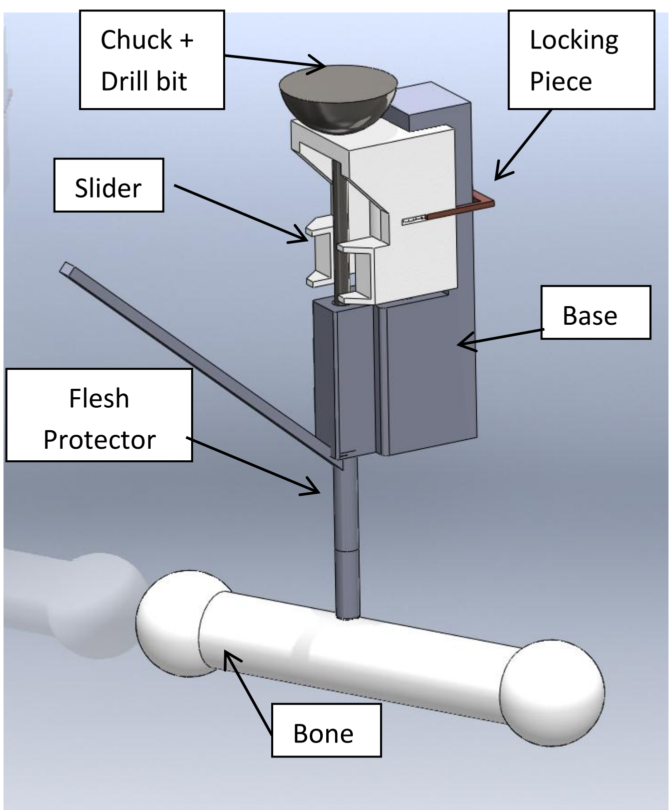

Figure 13: Solidworks of v4.0 of the hydraulic slider. The figure contains the drill bit and chuck, base, slider, bone, flesh protector and locking piece.

Compared to v4.0 (Figure 13) of the hydraulic slider, this new version makes several improvements based on updated client requirements. Firstly, the external flesh protector was removed and integrated into the system while simultaneously being significantly shortened. With this change, significantly more room was created to allow a longer well which would allow the surgeon to experience going through the liquid first for a longer period before plunging. Our client also stated that the length of screws would only be 10 to 20 mm's. This means that only 10mm's must be accounted for as far as plunge reduction is concerned. A 30 mm well was made so this system could accommodate a wider range of screw lengths. Additionally, the hole which the drill bit went through was shifted to the middle of the plunger rather than to the side of the plunger to remove any moments created by the drill bit.

Finally, the well size was significantly increased from a 9mm diameter to a 20 mm diameter. With a larger well size, the effects having a viscous or Non-Newtonian fluid could be felt to a greater extent allowing finer tuning of the liquid and the adjustment of the plunger size. Currently, the plunger is 19.3 mm's which roughly takes up 93.5% of the total well space. This was determined through testing of the first two printed prototypes. Additional figures of the final design with dimensions can be found in Appendix E.

Reed Switch Design

The second final design utilizes a reed switch and a processor to determine drill chuck velocity. A reed switch is an electrical switch operated by a magnetic field. The reed switch (Figure 14) consists of two ferromagnetic blades slightly offset from each other. In this configuration, a reed switch would cause an open circuit, allowing no current to flow. However, when in the vicinity of a magnet, the ferromagnetic blades are attracted to each other. If this attraction is strong enough (i.e. if the magnet is close enough), the blades make contact, allowing the flow of electrons and completing the circuit. A resistor is added in series to the reed switch to allow for voltage change detection (Figure 15). Also, the power supplied to the circuit can vary, as long as the voltage divided by the resistance of the resistor used yields current low enough to be under the current tolerance of the reed switch, which is 2.5 Amps.

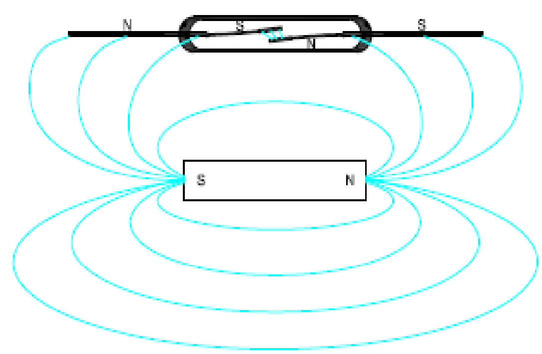

Figure14: A diagram of a reed switch in the presence of a magnetic field [22].

For testing purposes, a *National Instruments myDAQ* device (Figure 16) was used for voltage monitoring and power supply. This device is relatively compact, and it may act as a model when designing future circuitry necessary to reduce the overall size and obstruction of the reed switch design.

Through this process, the reed switch allowed an easily implemented detection circuit. Specifically, magnets mounted on the chuck of the drill placed within close proximity of the reed switch gave an indirect reading of drill chuck velocity. This chuck velocity is believed to display a characteristic difference depending on the medium that is being drilled. For instance, when drilling through the cortical layer of bone, the chuck speed will noticeably slow down. Each spike in voltage output represents a magnet on the drill chuck passing the reed switch sensor. A simple algorithm will be created which detects these peaks and performs a simple division operation to yield rotations/second. This value will be monitored over time, and any sudden variations in this metric will trigger a feedback system to cut current to the drill motor and therefore preventing plunging. This feedback system is still being designed.

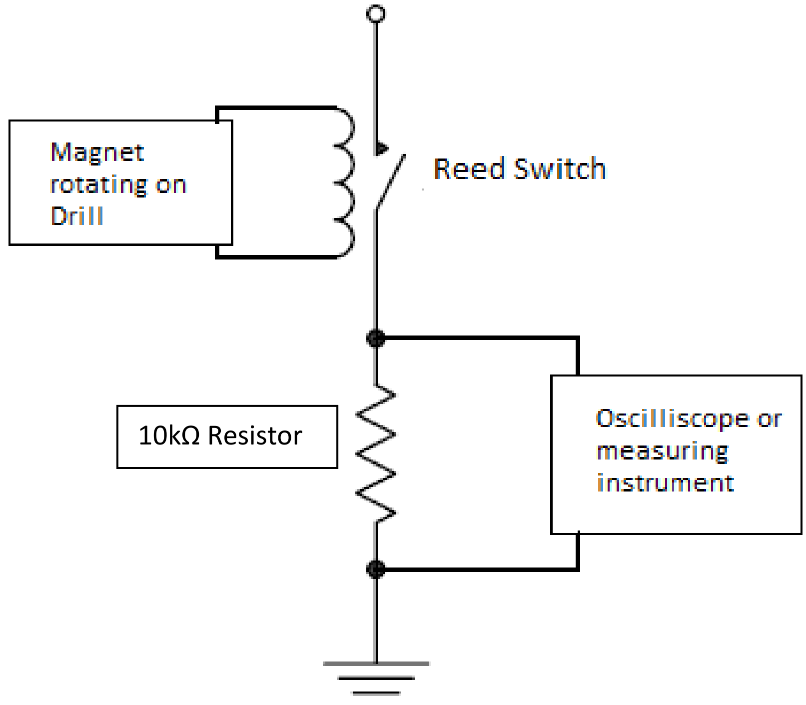

Figure 15: The completed reed switch circuit, including the reed switch, a 10kΩ resistor and the measuring instrument (myDAQ).

Figure 16: The NI myDAQ data acquisition tool used for testing purposes [23].

Testing

Tests were performed to gain understanding of the mechanical environment during orthopedic procedures, to develop a correlation factor between axial velocity and vertical translation, and to test the effectiveness of the hydraulic slider. All instances of drilling in testing were performed by the same individual to keep drilling forces as constant as possible.

Force Measurement

The first set of tests involved understanding the forces developed on the drill during the orthopedic procedure by drilling through bone on top of a force plate. The procedure detailing the use of the force plate and data acquisition is shown in Appendix B1, and the Matlab code for analyzing the data is shown in Appendix C1. The drill was cordless and bovine femurs were purchased from a butcher. The bone was placed on a block of wood on top of the force plate and data was acquired during drilling.

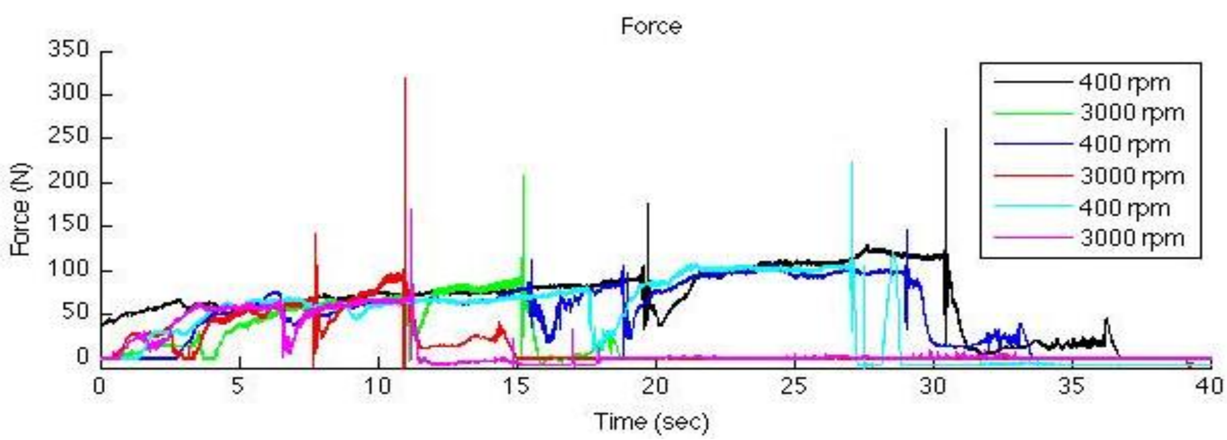

Figure 17: Drilling forces - Forces developed while drilling through bovine femur at slow and fast speeds. Measurements were recorded from a force plate and analyzed in Matlab.

Figure 17 shows the forces developed during drilling. When drilling at a slower speed of 400 rpm, the forces ranged from 50 to 130 N. When drilling at a higher speed of 1,300 rpm, the forces ranged from 40 N to 90 N. The time it took to drill at 1,300 rpm was 2 – 3 fold less than the time it took to drill at 400 rpm. The peaks in the graph correspond to the drill hitting the layer of bone or wood block following a plunge and have a maximum force of 300 N.

The forces acquired through force plate testing are what we need to counteract by varying the cross sectional area of the plunger and the viscosity of the fluid in the well of the hydraulic pump. A maximum of 300 N will be used to determine what cross sectional area of the plunger in the hydraulic slider is needed with our testing fluid being honey. Honey is a Newtonian fluid with a high viscosity (76.3 centistokes at 100 degrees F) [23]. This fluid was used for testing because previous experiments with cornstarch and water solutions settled out and we were unable to create a non-Newtonian fluid from polyethylene glycol (PEG) and silica despite repeated attempts. A greater cross sectional area will create a greater resistive force during plunging.

The area of the current hydraulic slider plunger cross section is 3 cm^2. A correlation between the fluid in the well and the force generated into time still needs to be found.

Velocity Profiling to Determine Hole Depth

Testing of the velocity profiling system was needed to find a correlation factor to relate the axial velocity of the chuck to vertical translation of the drill. Testing was conducted as detailed in Appendix B2 and the signal was analyzed by processing in Matlab as detailed in Appendix C2. Appendix D, Figure 1 shows an example of signal visualization. The number of peaks produced was counted and related to the actual distance traveled by the drill during drilling. Assumptions made in this calculation include that the dill operator was drilling at a constant force and that the bite of the drill bite was constant throughout drilling.

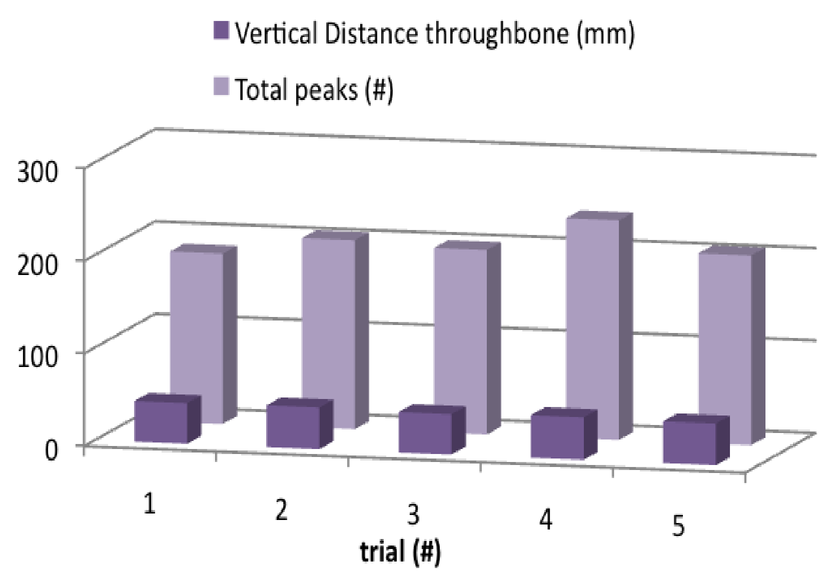

Figure 19: Peaks during drilling and vertical translation - The total number of peaks seen while drilling through bone and the actual distance the drill traveled through bone.

A correlation factor of 0.218 mm/peak with a standard deviation of 0.016 mm/peak was measured from 5 trials shown in Figure 19 and can be used to translate the total number of peaks observed to a distance traveled by the drill. The system could experience ± 5 peaks and still be accurate to within 1 mm of the actual hole depth.

The correlation found is only relevant to the bovine femur and can only properly account for the distance traveled through the cortical bone. The bones used in testing had the bone marrow carved out and the drill experienced a maximum velocity in this section. Testing in fresh bone is needed and multiple bone types are needed to find a more all-encompassing correlation. Additionally the mechanical properties of bovine bone present a greater density and hardness. Observing orthopedic procedures in human with the velocity profiling system in place is necessary to make the system applicable to cases of human bone.

Plunge Testing with the Hydraulic Slider

To test the effectiveness of the hydraulic plunger, trials with and without the device were preformed. We drilled through bone on top of a piece of raw meat to represent soft tissue damaged in plunging. After drilling through the bone and plunging into the meat, the bone and drill was lifted to measure the length of the drill bit that protruded from the bone. The raw data can be found in Appendix D Table 2. Figure 20 shows a threefold decrease in the plunging distance experienced.

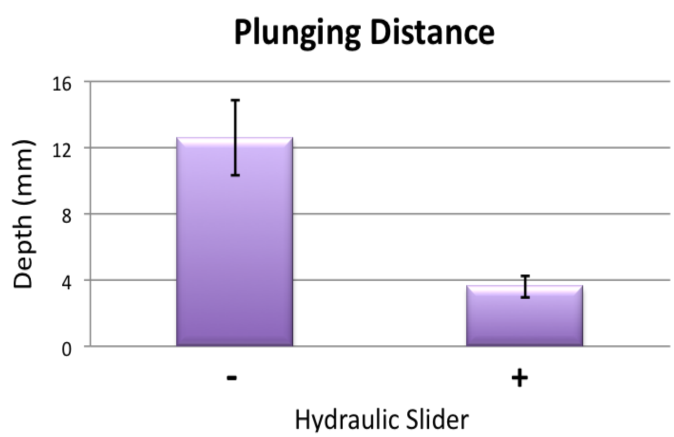

Figure 20: Plunging improvement with hydraulic slider - The average plunging depth without the hydraulic plunger was 12.6 mm. The addition of the hydraulic slider reduced plunging to 3.6 mm. Honey was the viscous fluid in the hydraulic slider well.

Conclusion

In conclusion, each of the designs pursued have shown promise in fulfilling the client's requirements. The hydraulic slider design has performed well at reducing plunging depth during all test trials. However, the mechanism in place approximates the screw length, because of the plunging that still occurs, requires redesigning. In case the redesign of this model should prove difficult, the reed switch design will be pursued. The reed switch design has successfully generated a profile of the rotations of the drill of the chuck. From this, the velocity of the chuck has been calculated. Designs are in place which would allow follow through on this design, allowing for accurate screw length approximation and plunge reduction.

Future Work

Hydraulic Slider

One of the major concerns is the viability of the pump in its ability to generate the necessary force to resist the additional force of the surgeon during plunging but not impede normal drilling. Proper testing has shown that the hydraulic slider design has accomplished this task to a great extent. However, more testing is required with a more accurate model actual drilling in order to get more useful results. Additionally, finding a proper plunger, well size, and an actual dilatant fluid will help reduce plunging even more. Therefore, multiple types of dilatant fluid could be tested along with varying plunger and well sizes in order to find an optimal combination that maximally reduces plunging given current size and money restraints.

A few other minor problems with the ergonomics and functionality of the device still need to be addressed. Firstly, the device is not a closed system and thus the feedback fluid has the possibility of spilling if not properly positioned. This can be fixed with 2 O-rings. Next, the chuck grinds against the top of the slider as it is pushing it down. This can be fixed with a female mold of the chuck's contact location attached to a bearing. Along with greatly reducing friction, the device would also perform better as extraneous vibration would be reduced. Constant force springs could also be attached to the slider so that the slider would automatically contract back to its pre-depressed state after use, saving time between drilling. The idea of having two sliders, one to zero the device to multiple sized drill bits and the other to measure could also be brought back so that this system could fit a larger range of drill bits. A locking mechanism will also be implemented so that the surgeon can lock the slider in place after they experience plunging and accurately read the depth measurement. Finally, in the far future, the device would be constructed from stainless steel instead of the ABS which would give it increased durability, decreased wall thickness, improved aesthetics and allow the device to be autoclavable for sterilization.

Velocity Profiling

Now that we have recovered a velocity profile for the rotating chuck, we plan on extrapolating our results so that the coefficient we generated can be applied to varying types of bone, drill bits, and drill operators. The magnet configuration on the chuck of the drill will change to a gear shape for a higher resolution of chuck velocity. Additionally, internalization of all components of the reed switch system must be completed to minimize invasiveness during surgery. This includes completing circuitry able to detect the peaks in the velocity profile, monitoring the velocity of the chuck, and detecting sudden changes in this velocity. An algorithm determining cortical breakthrough will trigger an attenuation of the drill motor output. The lack of power to the drill bit will prevent further rotation, reducing the plunge depth. Furthermore, analysis of the chuck velocity changes will yield an estimate of screw length regardless of plunge depth. This value will be output to an LED display. Other modifications include a design of a power source to supply all of the above components, an unobtrusive mount to keep the reed switch in close proximity to the magnet, and programming of the “plunge-decision” algorithm.

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Appendices

A. Product Design Specifications

Product Design Specifications - Orthopedic Drill

Josh Kolz, Kenneth O. Xu, John Refrew, Sarah Sandock
Client: Dr. Austin Crow, Department of Orthopedic Surgery
Advisor: Mitch Tyler, PhD., Department of Biomedical Engineering
Last Updated: 12/13/11

Function:

Orthopedic surgery for the application of installing screws into bones requires precisely drilled holes through the diameter of the bone. The hole's depth must be measured afterwards, using a depth gauge, adding unnecessary time during surgery. Another problem occurs in this process as the surgeon must not drill too far into the soft tissue past the bone to minimize tissue damage (plunging). Currently this is gauged entirely on the surgeon's feel of where the bone ends and the soft tissue begins. A flesh protector is used during the drilling process to prevent soft tissue damage around the drill as it perforates the bone. A prototype of a flesh protector and drill bit interface system that is safe, cost effective and consistent in measuring the depth of the hole would be greatly beneficial to orthopedic surgeons in saving time during surgery. If this prototype is successful, it would allow the step involving the depth gauge to be removed entirely and decrease plunging, reducing pain and recovery time for the patient along with reducing cost to the hospital and patient.

Client Requirements:

- Accurate detection of depth
- Reduces plunging into soft tissue
- Interface between flesh protector and drill bit
- Cost efficient
- Autoclavable materials
- Does not compromise drill function or surgeon's vision

Design Requirements:

1) Physical and Operational Characteristics

a. *Performance requirements* – Must retain drill's ability to drill through bone, remove the need for the depth gauge, and reduce plunging.

b. *Safety* – Must be electrically safe to contact for both operator and patient. Must be made of sterilizable materials and not generate excessive heat that would burn bone or cause any irritation. Must also be non-toxic and corrosion-free.

The modified drill/drill bit must remain within current safety guidelines for drill orthopedic drill systems. The added material must

c. *Accuracy and Reliability* – Depth measurement resolution must be 2 mm's or less. The mechanism must reduce plunging into the soft tissue on the backside of the bone to less than 5 mm's.

d. *Life in service* – The soft tissue protector must be reusable. The drill bit must be reusable until the cutting portion becomes dull.

e. *Shelf Life* – Indefinite

f. *Operating Environment* – The device will be used in a sterile operating environment and will come into contact with human blood, bone and soft tissue.
g. *Ergonomics* - Must be able to be used comfortably in conjunction with the drill and must not block vision of the operator more than the current system.
h. *Size* –The device must fit between the chuck and the drill bit and must not obstruct the surgeons view.
i. *Weight* – The design must be light enough to not disturb the drilling accuracy. The weight of the device must be under 500 grams (if attached to the drill bit) to reduce any impact on drilling. Any extraneous components must be less than 1.5 kilograms for easy transportation.

B. Testing procedures

B1. Force plate

The force plate used was a Bertec model FP 4060-10 and was positioned at the bottom of a pit and even with the concrete floor. The coordinate system for this plate was three dimensional with the z-axis oriented into the floor, the x-axis oriented in the direction facing the rear of the subject (away from the door), and the y-axis pointing towards the left of the subject (towards Camp Randall stadium) (Figure 1a). This type of force plate uses strain gages at the corners. When one of these gages deforms, it causes a change in resistance and therefore the deformation can be measured as a voltage. For this reason the measurements were converted to forces and moments using scaling factors according to the Product Data Sheet (Table 1).

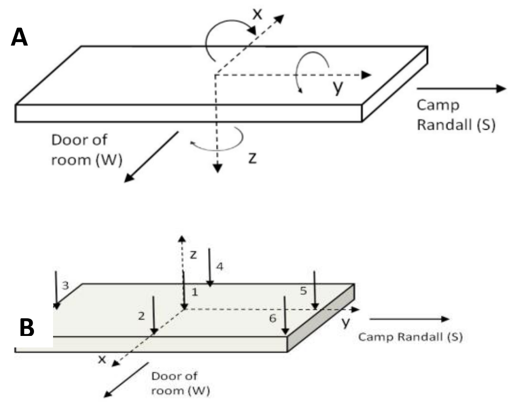


Figure 1: Bertec force plate and coordinate system in room 3034 Mechanical Engineering **A)** showing coordinate system and **B)** showing the six locations the 10lb weight was set to determine the COP (wrong coordinate system) (Thelen & Decker, 2011)

Table 1: Force plate calibration parameters according to the Bertec Product Data Sheet

Quantity	Scaling Factor	Units
Fx, Fy	1000	N/V
Fz	2000	N/V
Mx	600	N-m/V
My	400	N-m/V
Mz	300	N-m/V

In order to record the data from the force plate, the information from the plate must first be amplified and converted from a digital signal to an analog signal using the Bertec D/A converter (Bertec AM650X). This signal is then sent to a computer program called LabVIEW by National Instruments using a data acquisition box also created by National Instruments (DAQ box NI USP-6299). This computer program is set to obtain data at a rate of 1000Hz from the force plate and acquired six sets of data, force in the x, y, and z directions as well as the moments in the x, y, and z directions. This data was then saved and processed in a different computer program called MATLAB created by Mathworks. Matlab code is show in Appendix C.

B2. Velocity profiling

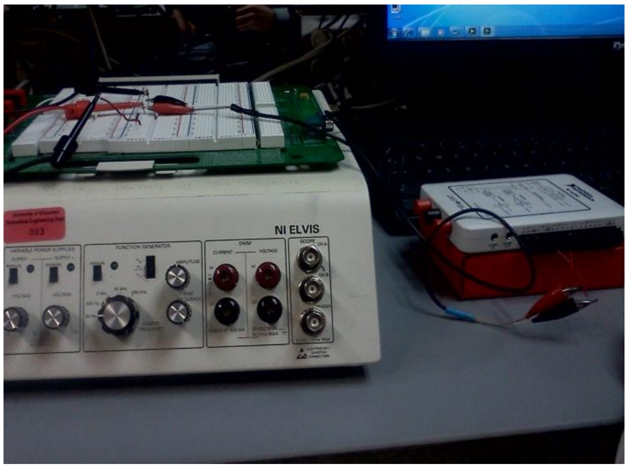


Figure 1: Velocity profiling set-up with the breadboard with resistor and reed switch on the

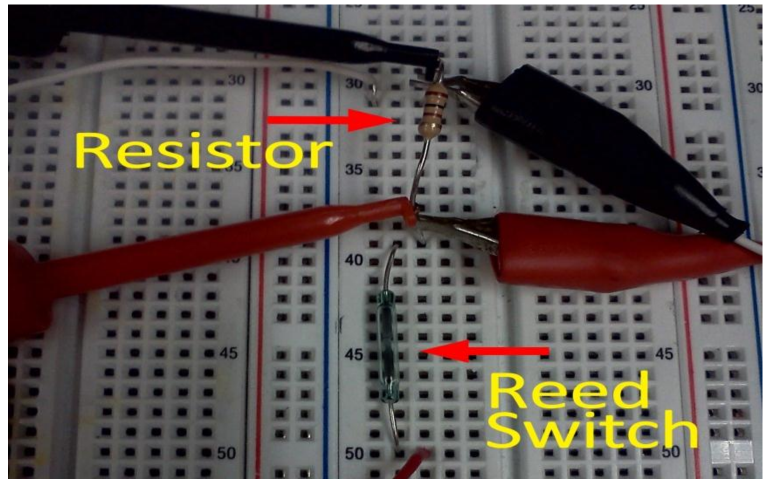


Figure 2: Close up view of the breadboard showing the 10kΩ resistor and the reed switch. The clips connected to

The circuit used is Figure 15 in the body of the report. This figure used the National Instruments myDAQ as the data acquisition system and power supply. The device provided 5 Volts of power. Using the myDAQ, the voltage across a 10 kΩ resistor was measured and monitored using LabVIEW. The sampling frequency of the myDAQ unit is capped at 200kHz, which is what was used during testing. All subsequent processing to be performed on the voltage signal will first be emulated in LabVIEW, and eventually the processing will be engineered into the hardware of the final design. For initial analysis, the data was processed in matlab as noted in appendix C2.

C. Matlab Code

C1. Drilling force visualization

```
%-- BME 400 Force Plate Data --%
close all; clear all;

Fx_sf = 1000;  % N/V
Fy_sf = 1000;  % N/V
Fz_sf = 2000;  % N/mV
Mx_sf = 600;   % N-m/V
My_sf = 400;   % N-m/V
Mz_sf = 300;   % N-m/V
colors = ['kgbrcmygkb'];
g = 9.8;

for k =1:10


    data = load([num2str(k) '.txt']);

    time = data(:,1);
    fx_v = data(:,2);
    fy_v = data(:,3);
    fz_v = data(:,4);
    Mx_v = data(:,5);
    My_v = data(:,6);
    Mz_v = data(:,7);

    t = time;                % seconds
    fx = fx_v.*Fx_sf-14.8;           % N
    fy = fy_v.*Fy_sf;          % N
    fz = fz_v.*Fz_sf;          % N
    Mx = Mx_v.*Mx_sf;          % N-m
    My = My_v.*My_sf;          % N-m
    Mz = Mz_v.*Mz_sf;          % N-m

    mass = fz(1)/g;
    accel = (1/mass)*(fz-mass*g);
    velocity = cumtrapz(t,accel);
    distance = cumtrapz(t,velocity);
    %distance2 = (Mz/fz);

    if k == 7:10
    figure(1); hold on; plot(t, fz-13, colors(k))
    title('Force');
    xlabel('Time (sec)');
    ylabel('Force (N)');
    axis ([0 40 -10 350]);
    %legend('Trial 1','Trial 2', 'Trial 3','Trial 4', 'Trial 5', 'Trial 6',);
    legend('400 rpm','3000 rpm', '400 rpm','3000 rpm', '400 rpm', '3000 rpm');

    end

end
```

C2. Signal Visualization

```
%-- BME 400 Force Plate Data --%
close all; clear all;

data = load('5seconds.txt');
```

```
time = data(:,1);
voltage= data(:,2);

figure(1); hold on; plot(time, voltage-2.4);
title('Reed Switch System Output');
xlabel('Time (sec)');
ylabel('Voltage (V)');
axis ([0 4 0 2]);
%legend('Trial 1','Trial 2', 'Trial 3','Trial 4', 'Trial 5', 'Trial 6',);
%legend('400 rpm','3000 rpm', '400 rpm','3000 rpm', '400 rpm', '3000 rpm');
```

C3. Plunging Forces

```
%-- BME 400 Force Plate Data --%
close all; clear all;
ad = [0, 1, 0.4, 0.3];

Fx_sf = 1000;  % N/V
Fy_sf = 1000;  % N/V
Fz_sf = 2000;  % N/mV
Mx_sf = 600;   % N-m/V
My_sf = 400;   % N-m/V
Mz_sf = 300;   % N-m/V
colors = ['kgbrcmygkb'];
g = 9.8;
for k =1:3
    data = load([num2str(k) '.txt']);

    time = data(:,1);
    fx_v = data(:,2);
    fy_v = data(:,3);
    fz_v = data(:,4);
    Mx_v = data(:,5);
    My_v = data(:,6);
    Mz_v = data(:,7);
    t = time;                   % seconds
    fx = fx_v.*Fx_sf-14.8;               % N
    fy = fy_v.*Fy_sf;          % N
    fz = fz_v.*Fz_sf;          % N
    Mx = Mx_v.*Mx_sf;          % N-m
    My = My_v.*My_sf;          % N-m
    Mz = Mz_v.*Mz_sf;          % N-m

    figure(1); hold on; plot(t-ad(k), fz-5, colors(k));
    title('Force');
    xlabel('Time (sec)');
    ylabel('Force (N)');
    axis ([0 9.5 -5 100]);
    legend('Low Density','Medium Density', 'High Density','3000 rpm');
    end
```

D. Testing Data

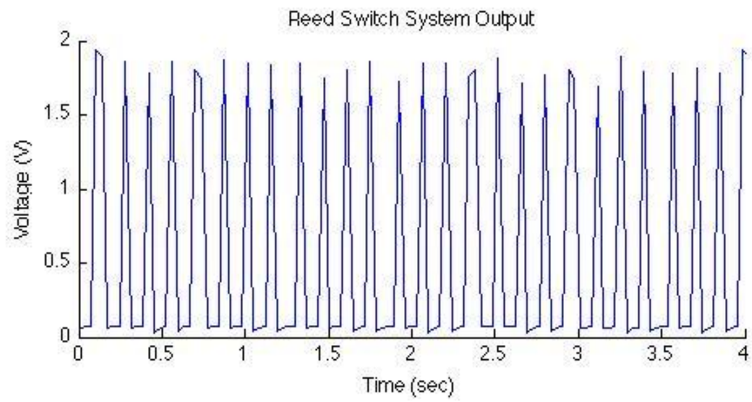


Figure 1: Signal from magnet passing reed switch for four seconds during drilling showing ~7 peaks/sec acquired through National Instrument's myDAQ.

Table 1: Raw data from drilling trials using velocity profiling system

Trial	Time (sec)	Peeks (#)	Actual (mm)	Coef (mm/peak)
1	26.3	184.1	44	0.23900
2	29.2	204.4	45	0.22016
3	28.5	199.5	43.5	0.21805
4	33.9	237.3	46	0.19385
4	29.3	205.1	45	0.21941
			avg	0.21809
			std	0.01605

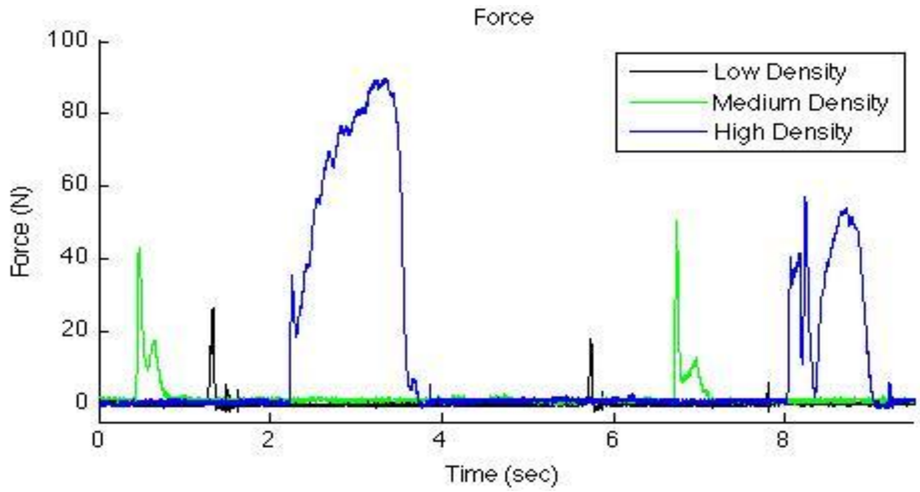


Figure 2: Forces developed while plunging (2mm diameter plunger) fast (first signal) and slow (second signal) into cornstarch and water solution (oobleck). The procedure for this experimentation is explained in appendix B1 and the matlab code used is in appendix C3.

Table 2. Raw data from tests with and without hydraulic slider

	Depth (mm)	
	control	**resistive slider**
	15	3
	9	4
	12	3
	14	4
	13	4
avg	12.6	3.6
std dev	2.302172887	0.547722558

E. Final Design Solidworks Drawings

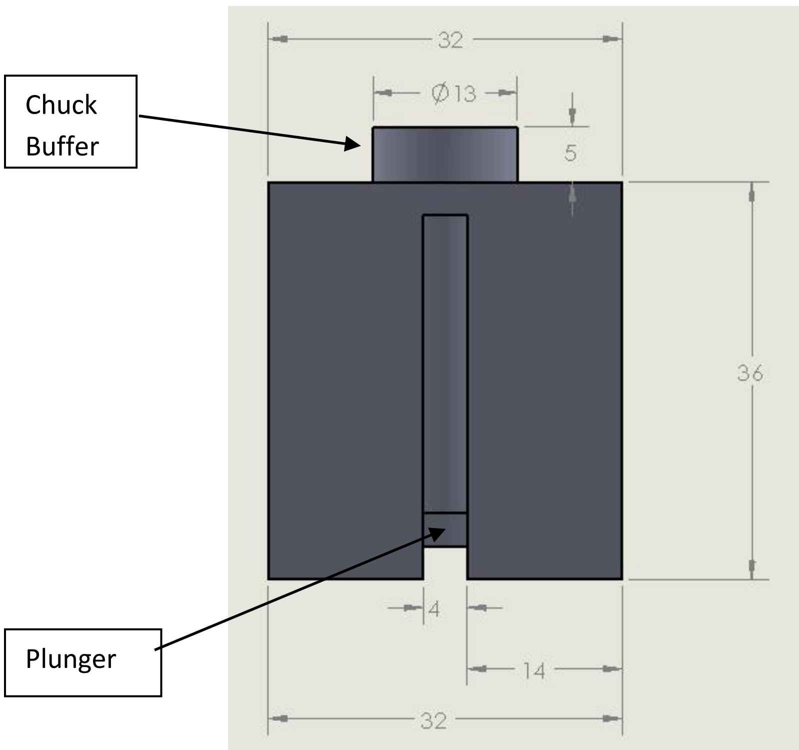


Figure 1: The frontal view of the slider. The plunger isn't shown fully but has a diameter of 19.3 mm's. All values shown in this figure is in millimeters. A chuck buffer is located at the top that and is simply a placeholder for the bearing. It is damaged by the chuck instead the actual slider. The narrow slit in the middle is where the slider accommodates for the handle of the integrated flesh protector. All measurements are in millimeters.

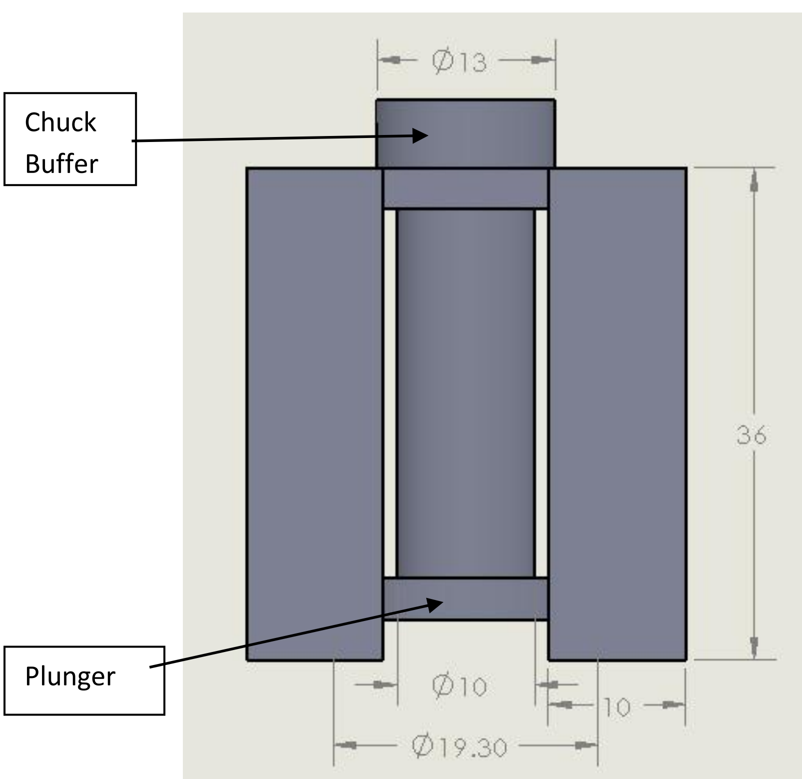


Figure 2: The side view of the slider. All values shown in this figure is in millimeters. The wide slit in the middle allows reduced weight and reveals the measuring marks on the base as the slider is depressed. All measurements are in millimeters.

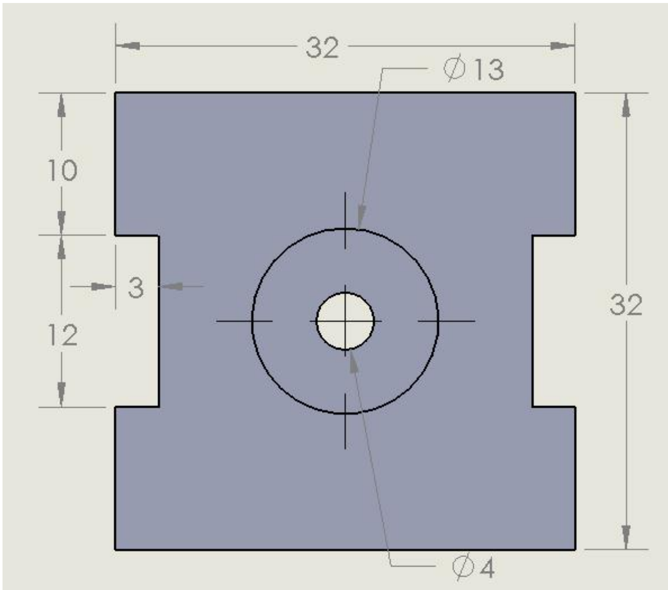


Figure 3: The top view of the slider. All values shown in this figure is in millimeters. The hole in the center is where the drill bit would enter. All measurements are in millimeters.

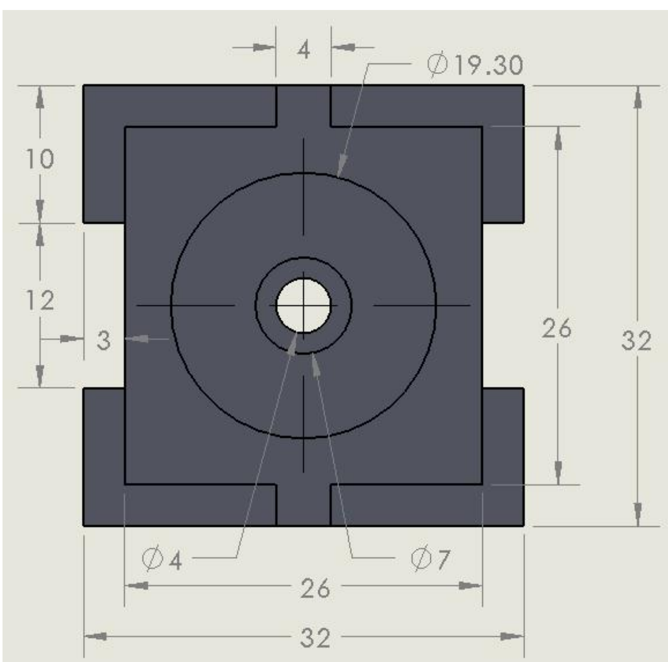
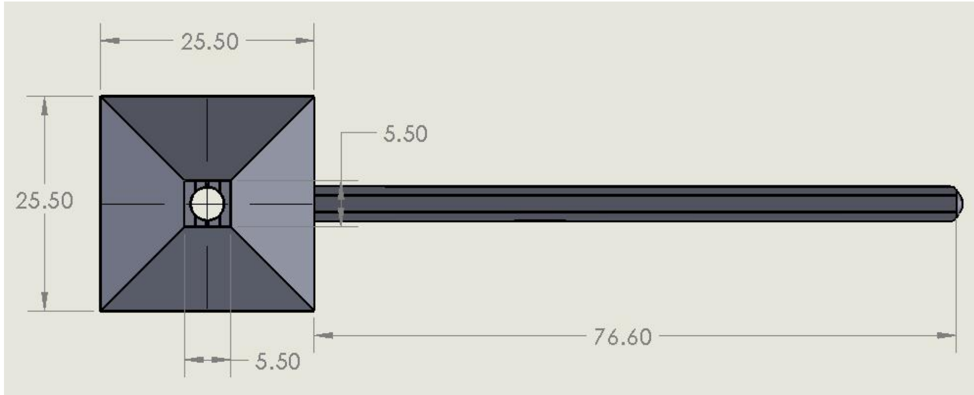


Figure 4: The top view of the slider. All values shown in this figure is in millimeters. The hole in the center is where the drill bit would exit and enter the bone. All measurements are in millimeters.



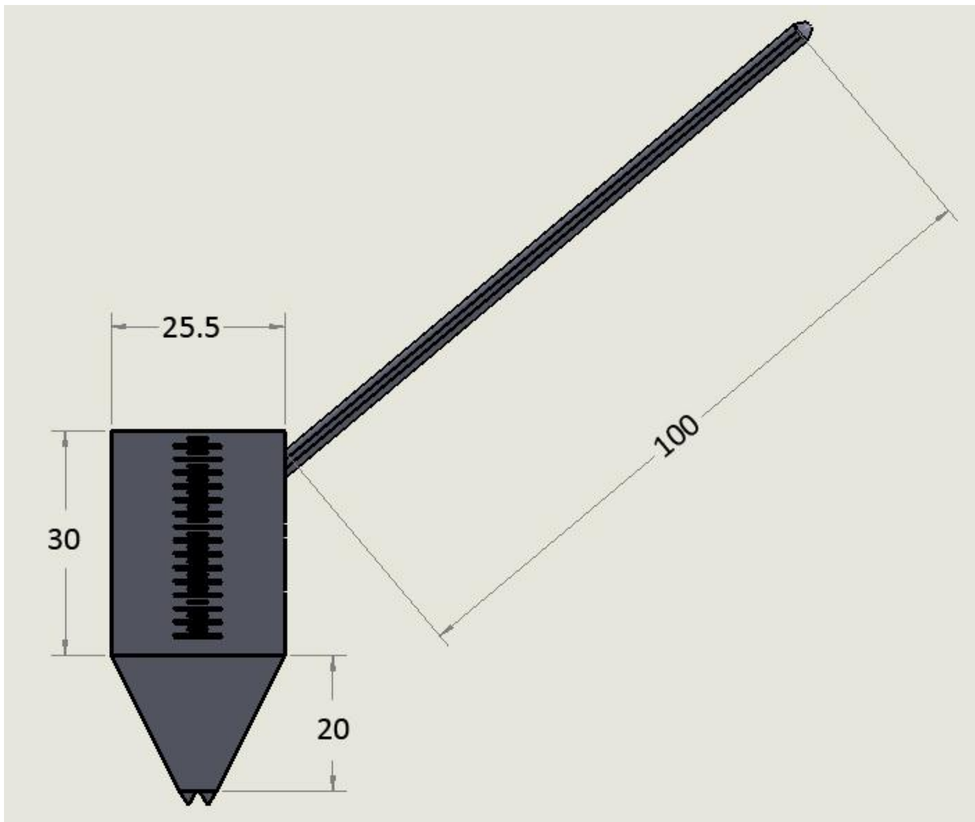


Figure 5 & 6: The bottom view (upper picture), and the side view (lower picture) of the base. A pointed tip was created to allow easier viewing of the hole. A 100 mm handle was implemented to mimic the original flesh protector. Notches on the side of the device allow for reading of depth as the slider moves downward on it. Pointed teeth were added to the bottom to prevent the device from rotating with the drill bit. All measurements are in millimeters.