UNIVERSITY OF WISCONSIN – MADISON
DEPARTMENT OF BIOMEDICAL ENGINEERING
BME 400 – DESIGN

Self-Measuring Orthopedic Drill System

Mid-Semester Report

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10/26/2011

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Abstract

In many orthopedic procedures, the use of screws is necessary to hold a severely fractured bone together. In order to utilize these screws the surgeon must predrill holes into the bone and accurately measure their depth in order to choose the correct length of screw. A minor problem occurs in this procedure as the surgeon must not drill too far through the bone into the soft tissue to minimize tissue damage. Currently this is done completely by the surgeons' feel of where the bone ends and soft tissue begins. Another problem arises as the surgeon must take an additional step to measure the depth of the hole with the depth gauge. This process can become tedious and time consuming when multiple screws must be inserted into the fracture. In the current surgery, a soft tissue protector is utilized to protect the soft tissue in the insertion from the drill bit. A prototype flesh protector and drill bit interface has been developed that can prevent plunging into the soft tissue and accurately measure the depth of the hole in one step. This design utilizes non-Newtonian fluid used as a hydraulic system to prevent plunging and a slider design to accurately measure the depth of the hole. This prototype will remove the step of measuring the hole depth with the depth gauge and save time in the operating room, saving both the patient and hospital money.

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 a hard cast is not enough to keep it in place throughout the healing process. For this reason, screws or plates and screws must be inserted into the bone to hold it in place during healing (Figure 1).

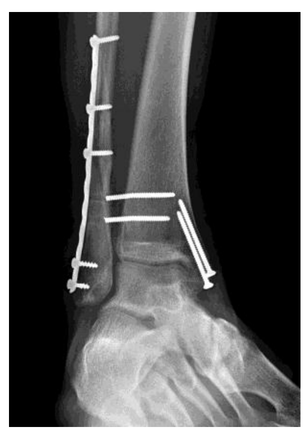

Figure 1. Orthopedic screws and plate in a fibula and tibia [1]

To insert these screws, the surgeon must drill into the bone with a surgical hand-held drill and drill bit. The drill used in this procedure is similar to a wireless 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 connect shaft for easy changing [4].

The surgeon drills through the bone carefully as not to break through the opposite side of the bone too quickly leading to trauma to the soft tissue. Breaking through the bone and cutting into soft tissue is known as plunging. Plunging can cause bleeding and other damage when working on smaller bones. Also, the plunging depth should not be taken into consideration when measuring the depth of the hole that was drilled [3].

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 around the incision from the sharp edges of the drill bit [3].

Figure 2. Tissue protector on long bone [2]

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

Figure 3. Depth gauge client currently uses [3]

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]. These 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 and improper healing and if the screw is too long, it could protrude out the backside of the bone and interfere with muscles and nerves causing the patient unnecessary pain [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 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. The next layer of bone is dependent on where in the bone the surgeon is drilling. If they are drilling through the diaphysis they will go through the bone marrow cavity and if they are drilling through the epiphysis they will go through the spongy or cancellous bone (Figure 4). Both of these layers are considerably less dense than the cortical bone and much easier to drill through [3, 5].

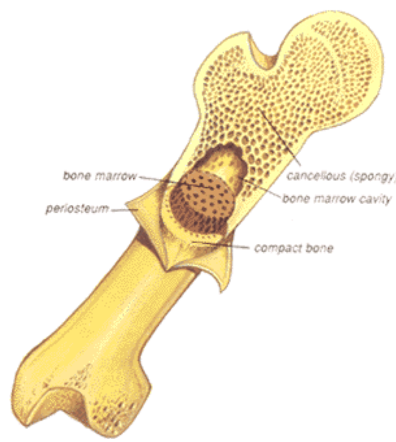

Figure 4.Different layers in a long bone [6].

Current Products on the Market

The tool currently used to measure the hole's depth 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 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. 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 up to an overestimate of 2 mm during the time of drilling. Mechanical options that have been developed can only measure as accurately as plugging is minimized due to the continuation of the drill through the soft tissue after breaching the opposing hard bone. For this reason plunging magnitude must be reduced to a 2 mm maximum which is shorter than the 5 mm that is considered safe and the 1 mm that is needed because of the tapered end of the drill bit and need to create a hole with constant cross sectional area.

More generally, 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 ability 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 [7]

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 as precise as the tick mark intervals. The problem is that plunging could not be accounted for with this device alone as the drill continues to travel 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 lacing of the drill bit. This option has the same precision as the slider with the advantage of a digital readout (Figure 6). However, it could add the complication of small interlocking parts that could

Figure 6. Lap counter [8]

easily clog and incur wear in the surgical environment and they are hard to manufacture. This option is also only as accurate as plunging can be minimized because its lack of a stopping mechanism.

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 and stop the saw blade from spinning quickly enough to prevent serious injuries [9]. The inventor of the saw stop is eager to license his 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 signal on the blade that is altered when it comes in contact with other materials [9, 10]. 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. For this reason, the saw stop was not included as a final design option or in the design matrix.

Hydraulic Design

The hydraulic design reduces the amount of plunging experienced by the drill. The technology itself has no measuring apparatus and must be coupled with one of the previous measuring designs such as the slider or interlocking gears to meet the client's requirements. The design works similarly to a door stop, offering increased resistance when experiencing increased velocity by using a non-Newtonian fluid. A non-Newtonian fluid (green curve in Figure 7) experiences an exponential increase in velocity with an increase in stress.

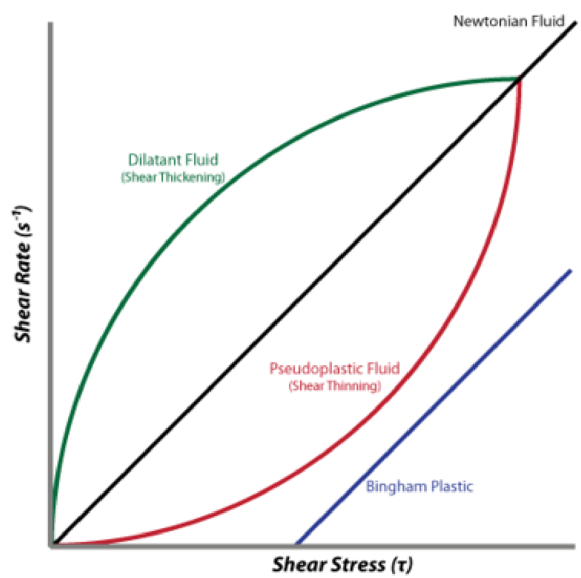

Figure 7. Reactions of various fluids to an increase in shear. Note the green line, indicating the exponential increase in shear rate as shear stress is raised [11]

In the equation shown in Figure 8, ŋ represents the viscosity of the fluid. K and n are material based constants and γ̇ is the applied shear rate. The shear rate applied to the liquid will be directly proportional to the axial force felt by the drill bit. Therefore, when the surgeon punctures through either layer of cortical bone, the liquid will respond with increased resistance if n > 1, as is the case with all non-Newtonian fluids. The result is a decrease in involuntary plunge depth. This will, in turn, substantially increase the accuracy provided by the measuring device.

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

Figure 8. The equation for viscosity of a liquid. Non-Newtonian liquids exhibit a material property of n>1.

Overall, this design uses an inherent property of hydraulics to accomplish half of our client's goals. However, the operation of the hydraulic is indiscriminate, so it will activate during the first puncture of cortical bone as well as the second. A relief switch must be implemented to allow the surgeon to continue drilling after the initial reaction of the hydraulic. Additionally, because the hydraulic will be directly above the surgical site, special care must be taken to seal the device properly, ensuring no excess fluid is spilled.

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 in response to an applied force. When placed in a circuit, the voltage of the sensor can be used to transfer physical measurements into an electrical signal.

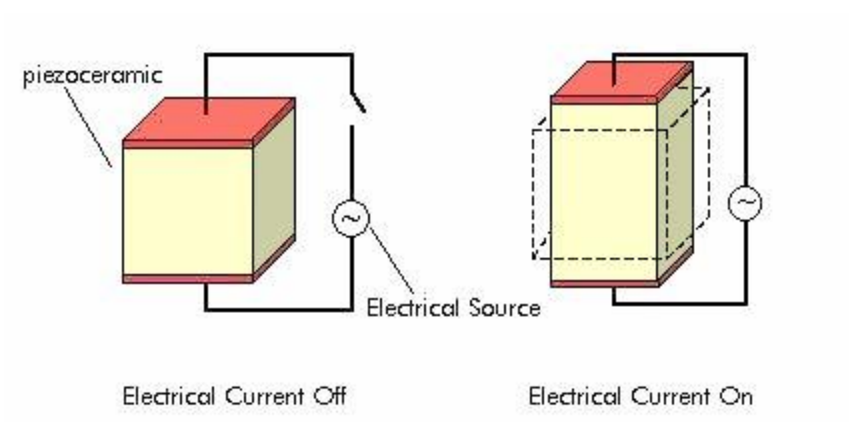

Figure 9. A model of a piezoelectric sensor relating mechanical change with electrical response [13]

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 [12]. 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).

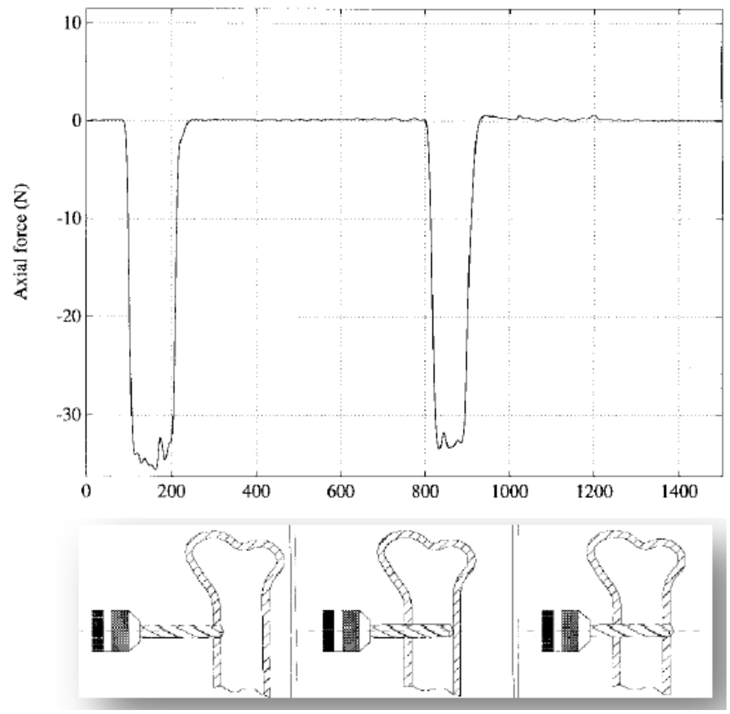

Figure 10. Axial force while drilling through long bone on top and depiction of where drill bit is when those forces occur [12]

After conversion to a voltage, the signal will be sent to a microcontroller internal to the drill or a PC computer for analysis. At this juncture, fuzzy 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, decreasing the plunge and saving 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 then be displayed on a digital readout for the surgeon's convenience.

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, likely a coaxial cable for 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 voltage, microcontroller, and 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 magnetic mount adjacent to the drill to detect chuck velocity. The magnet will detect the chuck spinning around and feed this signal, as a voltage, to a microcontroller. The signal is detected for peaks giving counts for time, indirectly determining the rotational velocity of the drill chuck (Figure 11).

The material being drilled through (bone or soft tissue) can be determined empirically by analysis of the chuck speed. In theory, the chuck velocity will undergo a jerk increase once puncture of the cortical bone is complete. It is at this point which the microcontroller or PC will feed a stop signal 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 magnet mounted on the chuck may block the surgeon's field and view or range of use.

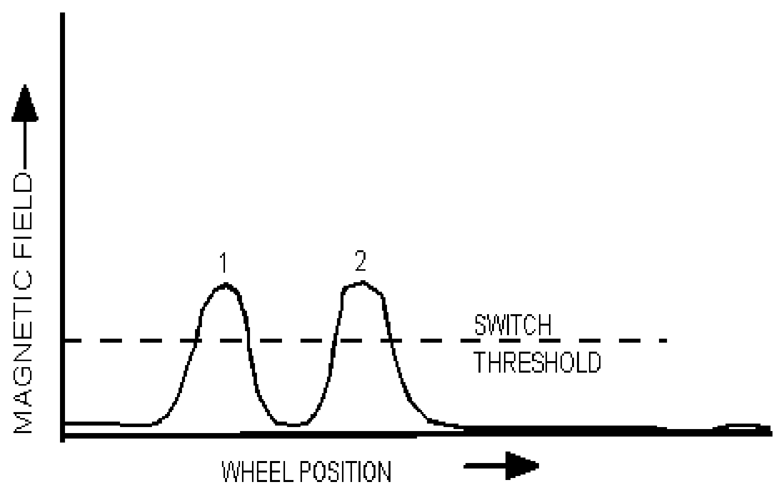

Figure 11. A graph showing the effect of a spinning wheel on a bike magnet. Each rotation of the wheel is detected. This can be converted into a voltage and ultimately a rotational speed with proper hardware [14].

Design Matrix

Each design alternative was weighed out of 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 meetings with the client. In addition, the client was given each of the designs and provided his personal opinion. The hydraulic design was given the most points. However, as mentioned earlier, this design only prevents plunging, it has no measuring apparatus. Therefore, it was 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	28	10	2	3	5	48
Mag	28	30	5	2	10	75

Final Design

Hydraulic Slider

A design that incorporated the anti-plunging capabilities of the hydraulic system and the measuring ability of the slider system was initially sought. An easily achievable hybrid of the two would simply add a sliding mechanism to the existing hydraulic system (Figure 12). The outer tube (white) contains a pump that slides down the inner tube (gray) as the drill bit is lowered through the

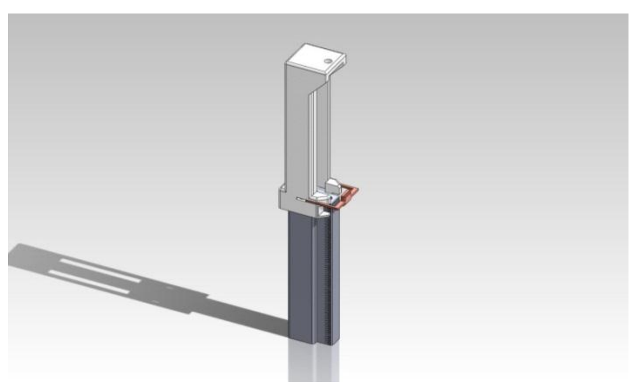

Figure 12. SolidWorks drawing of the hydraulic slider design.

hole at the top of the outer tube. Ruler etchings on the side of the inner tube allow for direct measurement of this system as it slides down. The bronze piece in the middle of the two tubes provides a locking mechanism to prevent the top tube from further plunging.

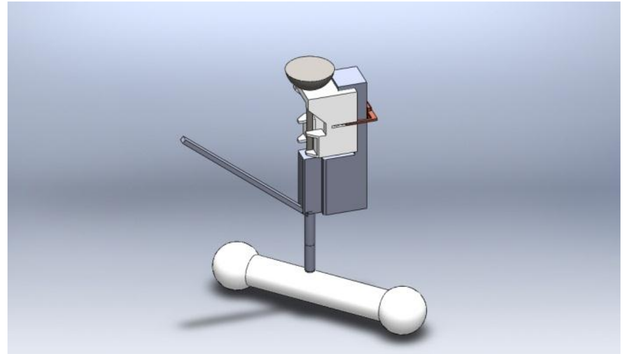

Figure 13. SolidWorks drawing of the hydraulic slider design. The slider is at its top most point demonstrating when the surgeon would begin drilling.

Initially, the team was quite infatuated with this idea as it contained the necessities for the two requirements the client specified. However, upon further evaluation, it became clear that this design's dimensions would not allow functionality as the inner tube spanned the entire length of the drill bit. Basically, when the drill bit reached the end of the plunger's length, the tip of the drill bit would just barely protrude from the bottom of the inner tube, leaving no room for the flesh protector or actual drilling function.

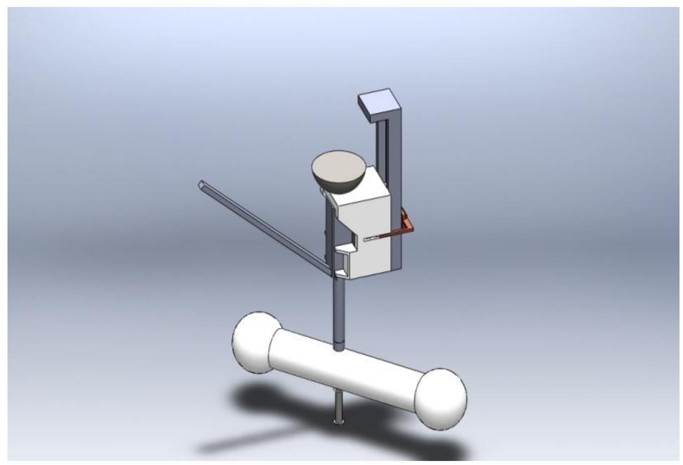

Figure 14. SolidWorks drawing of the hydraulic slider design. The slider is at its lowest point demonstrating when the surgeon has drilled through the bone.

Upon reworking, the hydraulic slider system v4.0 was developed (Figure 13-14). It was clear that the length of the well needed to be reduced and reasonable to assume plunging prevention is only needed when drilling through the second layer of cortical bone. As the drill bits were only 12 to 30 cm in length and the anti-plunging well had a length of 18 cm with an extra 5 cm for the surgeon to experience the feeling of going through the liquid as a control. Besides the lock now being situated on the back, all other components remain the same. Figure 13 also contains the bone, flesh protector and drill bit and the outer tube is positioned at the top of its travel.

Figure 14 shows v4.0 with the outer tube at the bottom of its travel. The back extension of the inner tube allows for measurement and gives the inner tube a track to slide down when it moves.

Locking Mechanism

The locking mechanism (Figure 15) features a notch system that forces the bronze locking piece (Figures 12-14) to flex outwards as it slides and pop into place at the end of its travel (B). It is originally situated at position A. This system needs to be further considered and tested for functionality as it is currently an artistic rendering.

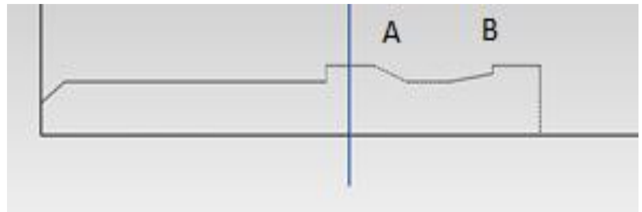

Figure 15. SolidWorks drawing of the hydraulic slider's locking mechanism.

Future Work

One of the major concerns is the viability of the pump in its ability to generate the necessary force to resist the force from the surgeon and his downward momentum. Proper testing has not been conducted to estimate the amount of resistance needed to stop the forward movement of the drill given the cross-sectional area of the plunging piece coming in contact with the hydraulic. If resistant force is not sufficient, the well dimensions and the surface area of the plunger can be modified as needed. Theoretical measurements following trial and error should be sufficient to determine the necessary force before clinical testing. The SolidWorks design can be printed free of charge with the stronger 3D printing polymer ABS through university resources.

To determine a value for force expected to be placed on the design, we will drill through a bone on a common scale and graph the resulting forces as a function of bone length. It will also be useful to test the different dilatant forces available and test how varying non-Newtonian fluids affect the anti-plunging capabilities. Perhaps modeling the ratio of water to cornstarch with respect to viscosity increases could give a clearer picture on just what kind of viscous characteristics are needed.

The design of the current hydraulic slider system has yet to be optimized and made to accommodate the large forces it might encounter. This includes, removing excess parts, improving ergonomics, creating a functional locking mechanism, and modifying either the well or plunger to develop sufficient resistant force. After this work is completed, 3-D printing using ABS will create a prototype to assess problems to improve upon the entirety of the design following redesign and continuing with this process until the printed prototype meets expectations.

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Appendix

Product Design Specifications

Product Design Specifications - Orthopedic Drill

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Client: Dr. Austin Crow, Department of Orthopedic Surgery
Advisor: Mitch Tyler, PhD., Department of Biomedical Engineering
Last Updated: 10/25/11

Function:

Orthopedic surgery for the application of installing screws into bones requires precisely drilled holes through the diameter of the bone. A minor problem occurs in this process as the surgeon must not drill too far into the soft tissue past the bone to minimize tissue damage. This is entirely gauged on the surgeon's feel of where the bone ends and the soft tissue begins. The hole's depth must be measured afterwards, using a depth gauge, adding unnecessary time during surgery. 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 saving the time of surgeon, patient and all others involved.

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 use or surgeon's vision

Design Requirements:

1) **Physical and Operational Characteristics**
   a. *Performance requirements* – Must be able to drill through bone and obviate measurement necessity.
   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 and cause infection.

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 or less. The mechanism must reduce plunging into the soft tissue on the backside of the bone to less than 2mm.
   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 and soft tissue.

g. *Ergonomics* - Must be able to be used comfortably in conjunction with the drill and not impede drill use or distract operator while in use.
h. *Size* – Varies based on drill bit and flesh protector.
i. *Weight* – The design must be light enough to not disturb the drilling accuracy. The weight must be under 1.25 kilograms.
j. *Materials* – Must be nontoxic and corrosion resistant. All materials used must be compatible with standard O.R. sterilization procedures.
k. *Aesthetics* – Besides being safe, the aesthetics of this design are of minimal importance.

2) Product Characteristics

a. *Quantity: number of units needed* – One initially with prototype but more in the second semester in varying lengths for varying tissue work and with the intention and designs to produce more if necessary.
b. *Target Prototype Cost* – Under $1,000 USD.

3) Miscellaneous

a. *Standards and Specifications* – Should allow the operator to measure the depth of the drilled bone without the use of depth gauge.
b. Customer – Orthopedic surgeons.
c. Patient-related concerns – Nontoxic flesh protector that allows for accurate measuring of drill bit.
d. Competition – A depth gauge is currently in use that we are trying to replace. Additionally, there are several anti-plunge mechanisms which we may incorporate into the final design. If successful, our system will replace the depth gauge entirely and save OR time.