DEVICE FOR AXIAL FORCE MEASUREMENT DURING SURGERY: A LOW-COST AND PORTABLE ALTERNATIVE FOR DATA COLLECTION

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ABSTRACT
Our device was designed with the purpose of collecting axial force data for ACL injury on mice. Utilizing computer-aided-design, two 3D printed parts were designed, which formed the structure of the device. The two parts were connected with an aluminum beam, which was subject to bending moment when an axial force was applied. A strain gauge circuit was designed to collect the beam's strain data, which is linearly proportional to axial load. The prototype was tested, and results indicated that it functioned well in ideal conditions. To test the functionality of the device in a non-ideal setting, an ACL rupture experiment was performed on five mice, and force data was collected.

Keywords: Device, Axial Load, Design

NOMENCLATURE

D_{out}	Digital output
E	Modulus of Elasticity
σ	Stress
ϵ	Strain

1. INTRODUCTION AND OBJECTIVES
This text is a technical report on a portable, low-cost device to measure axial force during surgery. Our device was specifically designed for controlled ACL injury on mouse specimens, but it can be customized to perform measurements on any operation as long as the force being measured is axial and below 98 Newtons. An example for prevalent tools currently in use to carry out the same function as our device is an MTS machine (Christiansen, et al.). Compared to an MTS machine, our device is portable and significantly cheaper. An important distinction to make is that our device is handheld, as opposed to an MTS machine which applies a fine-controlled load.

Our device measures axial force by utilizing a half-bridge strain gauge integrated into the handheld tool. It outputs a voltage that is linearly proportional to axial force. Output data can be stored as a vector and given the sample rate force overtime can be calculated.

1.1 Problem Scope
Dr. Alex Kotelsky needed a method for measuring force values while inducing controlled non-invasive ACL rupture on mouse specimens. The initial approach was to use non-electronic means to measure force, i.e. a spring system which relied on the spring constant to deliver a known load. After unsuccessful attempts, our device was designed as an alternative.

1.2 Design Requirements
Function: Device must measure and store force data during operation, while not compromising tool ergonomics. Must be operated by a human hand. Maximum load should be greater than 35 Newtons (N). *Reliability:* Device must accurately reproduce the same voltage throughout different trials. Voltage output shall not be affected by ambient temperature. *Dimensions:* Device must have an extruded part through which force will be applied, with the following constraints: (a) regular hexagon, (b) short diagonal of hexagon 6.15 mm, (c) extrude height should provide enough space for easy visual observation. *Features:* Device must be easily operated without any training. It must have a tare function. It must be cleaned without taking damage. *Safety:* Must not cause unwanted injury to the mouse, must not use dangerous voltages.

2. MATERIALS AND METHODS

TABLE 1
TOOLS AND MATERIALS

Tool/Material	Company	Detail/Description
3D printer (FDM) with PLA or ABS	Creality 3D, Co., Ltd. (Shenzhen, China)	≤0.4 mm nozzle, Minimum dim.: 50x50x120 mm
Aluminum beam	UXCell, Co., Ltd. (Hong Kong)	Strain will occur on this beam
Strain gauge	UXCell, Co., Ltd.	Small
Arduino Uno	Arduino, LLC (Ivera, Italy)	Programmed with Arduino IDE (C++)
HX711 Load Cell Amplifier	Arceli AG (Bonn, Germany)	N/A
Metric bolts/nuts	Vigrue, Co., Ltd. (Shenzhen, China)	4 count M2x12 2 count M3x3

An aluminum beam was chosen as the location at which strain occurred. A half-bridge strain gauge was integrated on the beam. The beam was secured to a 3D printed structure that was designed carefully to satisfy the Design Requirements (Figure 1). Solidworks by Dassault Systèmes SE (Vélizy-Villacoublay, France) was utilized to design the structure. A circuit was designed to acquire a voltage change linearly proportional to the load (Figure 2).

Upon receiving the desired voltage behavior through circuit design, the device was calibrated to create an equation where the domain is the D_{out} of the circuit, and the range is the force (N) corresponding to the specific D_{out}. D_{out} is a digital signal because the HX711 utilizes an ADC. D_{out} is proportional to the voltage output (V_{out}) of the circuit and can be used interchangeably.

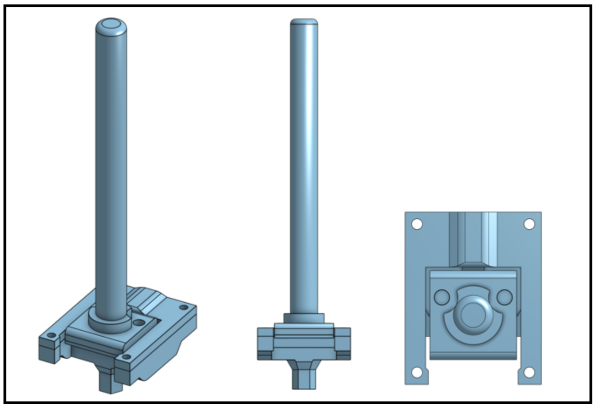

FIGURE 1: CAD view of structure encasing the aluminum beam connected to the circuit shown in Figure 2.

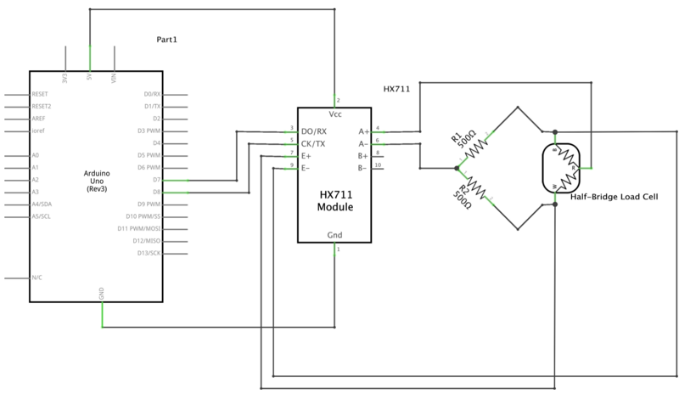

FIGURE 2: Fritzing sketch of Arduino system (larger image available in Annex B)

To achieve this, known loads were applied to the device and the digital output was recorded over a 15 second period. Output remained constant under a constant load. This process was repeated for 12 different loads ranging from 0 to 22 N. The data structures were in vector form. This output data was averaged for easier data analysis, which resulted in 12 data points. The data points were Known Load vs. D_{out} for 12 loads. The 12 loads were applied using an MTS Machine by MTS Systems Corporation (Eden Prairie, MN, USA). A possible alternative to an MTS machine is laboratory mass sets.

A linear equation was acquired by applying simple linear regression in MATLAB via the `polyfit(x,y,n)` function, by MathWorks, Inc. (Natick, MA, USA).

$$Force(x) = (0.015734x - 1.6638) \quad (1)$$

Equation (1) was acquired with very high confidence, with $R^2 = 0.9983$ and $p<0.001$. Figure (3) shows a plot for the data points. This equation is important because data collection will be in terms of the raw D_{out}. It is required for data analysis.

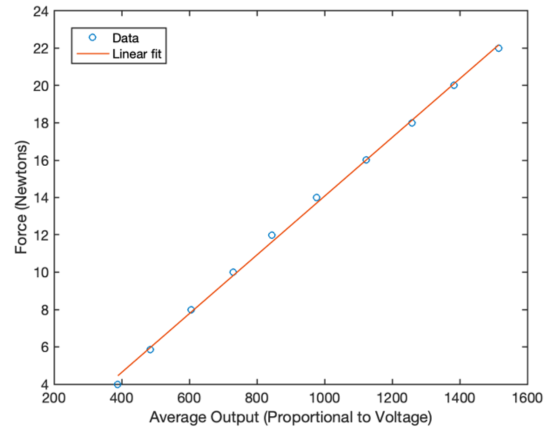

FIGURE 3: Force vs. Average Digital Output

3. RESULTS AND DISCUSSION

Tests on the functionality of the device were performed under ideal conditions (MTS machine). To test the functionality of the device, ACL injury procedure was carried out on mouse specimens with the help of Dr. Alex Kotelsky. Results indicated that the device functioned as designed.

3.1 Mouse ACL Injury Test

Five mice were euthanized. Three tests were performed on days 0, 7, and 14. Days 7 and 14 had two specimens each. Day 0 only had one specimen in order to preserve mouse lives if the device functions poorly in application. The mouse undergoing operation was first fastened onto the operation platform. Leg fur was removed using generic hair removal cream. ACL injury was performed using the injury method Dr. Alex Kotelsky uses for his own ACL injury study. Force data was collected during the injury. The knee of the mouse was dissected post-injury and checked for ACL rupture and surrounding tissue damage.

Results indicated that the device was measuring axial force accurately. The range for axial load at ACL rupture was 9.34–18.8 N. Sample size was too small for statistically significant mean and median values. Other studies recorded ACL rupture at a similar range, with a mean value of 12 N (Christiansen, et al., 774). The comparison of Christiansen's study to tests of our device is not scientifically rigorous. Christiansen's method varied in multiple ways from Kotelsky's.

TABLE 2
ACL INJURY LOADS

		Load at ACL Rupture	
Specimen	Injury Day	Right Knee	Left Knee
(1)	Day 0	15.0 N	9.50 N
(2)	Day 7	16.1 N	Sham Injury
(3)	Day 7	9.55 N	9.34 N
(4)	Day 14	13.6 N	Sham Injury
(5)	Day 14	18.8 N	13.4 N

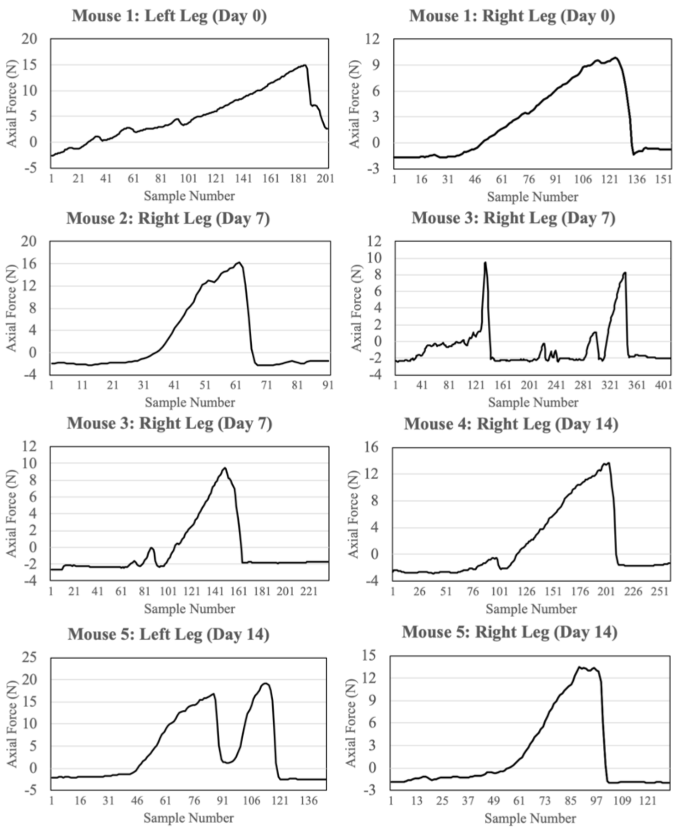

FIGURE 4: Force vs. Average Digital Output

Figure 4 demonstrates the capabilities of our device for force measurement during surgery. Upon generating graphs, it was possible to determine the point of ACL injury, as it occurs at local maxima.

ACL rupture samples were qualitatively compared to sham injury by Dr. Alex Kotelsky. ACL rupture checks indicated rupture in every leg except sham injury samples. Surrounding tissue damage was inconclusive. This comparison has low scientific significance.

3.2 Theory

Our device can measure axial load because of the properties of the aluminum beam holding the device together. When a load is applied during surgery, the load goes through the beam. There is a moment applied to the beam via this load, which causes bending stress, given by Equation (2):

$$\sigma = -\frac{My}{I} \tag{2}$$

where M is the moment, I is the area moment of inertia, and y is the distance from the neutral axis to the location of interest. In this case, the location of interest is the outer surface of the beam where two strain gauges are located. The bending stress can be converted to strain, given by Equation (3):

$$\epsilon = \frac{\sigma}{E} \tag{3}$$

which is the strain measured by the strain gauge system. This strain results in a small resistance change in the circuit. This resistance causes a very small voltage difference. Without the HX711 load cell amplifier, the resistance change is only 1-2 Ohms, therefore the resolution of the signal was very poor. With the HX711 integrated in the circuit, the resolution of the signal was amplified significantly.

3.3 Limitations and Improvements

Our device needs to be subject to more testing before it can accurately be described as reliable. An MTS machine for instance, is tremendously more reliable. Furthermore, our device can only measure axial force up to 98 Newtons. Another limitation is that the device was designed for a specific application, which is to cause ACL injury in mice via an axial load. It was previously mentioned that this is a customizable device. It can be customized for other surgical applications because 3D printed parts are very versatile, and the CAD files can be edited. However, this process would take multiple hours of design and manufacturing. This is a limitation.

Though these limitations exist, they're contrasted by some strengths, which are elaborated in the **3.4 Discussion** section.

One possible improvement is to use a full bridge strain gauge setup. This would further decrease noise in the digital output. As clearly indicated in Figure 2, the circuit uses a half-bridge setup. Moreover, customized parts can be designed upon determining other applications of the device. Another improvement is removing the necessity of a computer. This can be done by adding a SD card module to the circuit and storing the data with serial communication. This would make the device more portable and accessible.

An improvement that has already been applied to the device after testing was concluded was soldering the circuit. Prior to soldering, the circuit connections consisted of jumper wires and a breadboard. Because of this, noise was present in the circuit and digital output continuously fluctuated up to 40 units, which corresponds to up to 0.62 N of fluctuation. Upon soldering, fluctuation drastically lowered. The highest amount observed was around 5 units, which is <0.1 N. Unfortunately, this improvement wasn't made until after the device was tested.

3.4 Discussion

Our device is highly portable and low cost. The size of the device can be viewed in ANNEX C. Our prototype cost 75 USD to manufacture (excluding 3D printer and CAD software, which is accessible in most research facilities). Portability is an important feature, especially in clinical settings. Another aspect is that our device can be controlled with a human hand. This gives the advantage of utilizing human fine motor control to conduct the operation.

The resistance of a strain gauge is affected by ambient temperature. A small temperature change can have a large effect on the digital output. The circuit design takes this into account by utilizing a half bridge design. Therefore, the voltage output isn't affected by a temperature change.

In addition to designing a circuit that would give our device the desired function, careful mechanical design is also necessary. The most important requirement was delivering the axial force through a beam that undergoes bending moment caused by the axial load. The CAD parts were designed to account for this. Another design focus was the stability of the tool. Stability is determined by two moments.

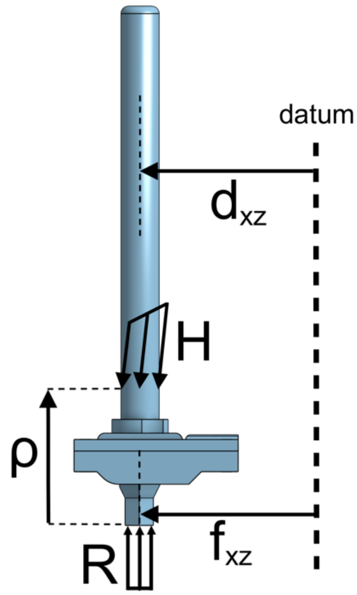

FIGURE 5: Forces acting on the device during usage

This is a view that is normal to the *xz-plane*. H is the force applied by the hand, and R is the reaction force opposing the vertical component of H. H_{XY} is defined as the projection of vector H onto the *xy-plane*. There is a vertical datum, which is a displacement d_{XZ} away from the central axis of the handle, and displacement f_{XZ} away from the central axis of the extruded tip. Displacement ρ is the vector originating from the reaction location and terminating at the location where force is applied by the hand.

$$\overrightarrow{M_1} = \vec{\rho} \times \overrightarrow{H_{XY}} \tag{4}$$

In order to minimize this moment and maximize stability, the magnitude of ρ was minimized. Due to non-ideal conditions of human control, vector H always has a projection on the *xy-plane*, therefore M_1 is inevitable.

Figure 6 shows displacement vectors originating from two datums and terminating in the central axis of the handle. Vector d_{XZ} is parallel to the *xz-plane* (as also shown by Figure 5), and d_{YZ} is parallel to the *yz-plane*. Vectors d_{XZ} and d_{YZ} have equivalents for the extruded tip, f_{XZ} (shown in Figure 5) and f_{YZ}, which originate at the same datum but terminate at the central axis of the tip of the extrude. The vast majority of force H is in the *-z direction*. Force R is opposing that force and acting in the *+z direction*. These forces form a couple and form a couple moment if the two parts of the device don't share a central axis.

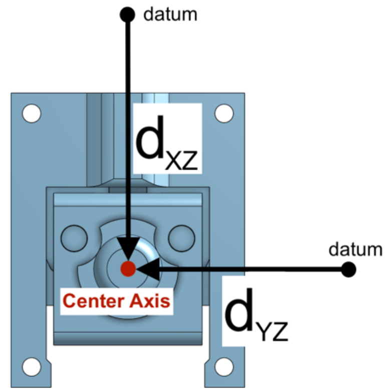

FIGURE 6: Moment arms for M_2

The couple moment will result in more instability during force application.

$$\vec{d} = \overrightarrow{d_{XZ}} + \overrightarrow{d_{YZ}} \tag{5}$$

$$\vec{f} = \overrightarrow{f_{XZ}} + \overrightarrow{f_{YZ}} \tag{6}$$

$$\vec{\Delta} = \vec{d} + \vec{f} \tag{7}$$

In the case that the two central axes don't coincide, vector Δ is nonzero. Another moment exists:

$$\overrightarrow{M_2} = \vec{\Delta} \times \vec{R} \tag{8}$$

In order to prevent this moment, axes were aligned during computer-aided-design.

CONCLUSION

Our device is able to serve as an alternative to preexisting axial force measurement tools for loads under 98 Newtons. Our device has shown to be effective for measuring force while inducing ACL injury on mice. Our device has significant limitations and needs lots of testing and improvement to be scientifically reliable.

ACKNOWLEDGMENTS

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REFERENCES

Christiansen, B.A., et al. "Non-invasive mouse models of post-traumatic osteoarthritis." Osteoarthritis and Cartilage vol. 23,10 (2015): 1627-38. doi:10.1016/j.joca.2015.05.009

Christiansen, B.A., Anderson, M.J., et al. "Musculoskeletal changes following non-invasive knee injury using a novel mouse model of post-traumatic osteoarthritis." Osteoarthritis and Cartilage vol. 20,7 (2012): 773-782. doi:10.1016/j.joca.2012.04.014.

ANNEX A

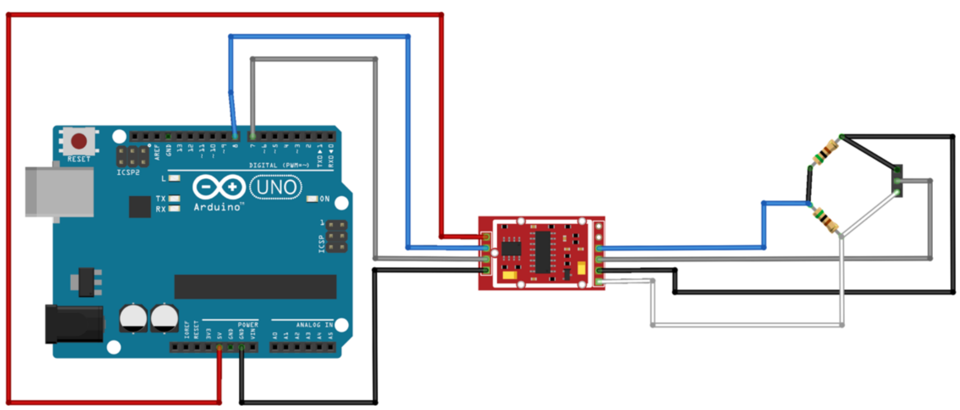
MATLAB CODE FOR DATA ANALYSIS

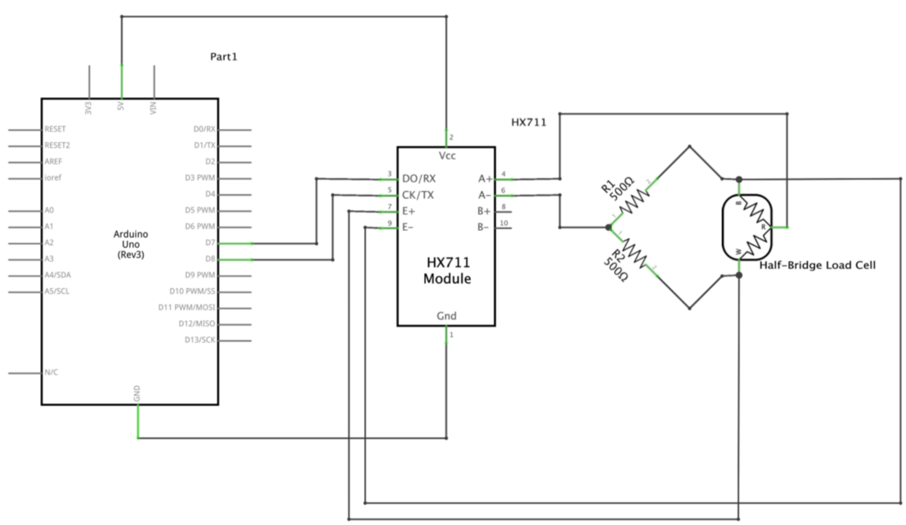
```
%{

Testing done at calibration_factor = 1000;

This code does the following:
- Import raw data from force device
- Convert string to number
- Plot data and linear fit
- Calculate R-squared

Lesson learned: don't print unwanted strings in Arduino serial monitor


RESULTS: R-squared is 0.9983 so it is very strong correlation.


Note: in case the corrcoef function is giving the wrong value, maybe double
checking the R-sqared value with Excel might be a good idea.

%}

T = readtable('01_29_20_MTS_analysis.xlsx'); %import data
rawdata = T.Variables; %convert table to 141x22 cell array


%readings at serial monitor as cell array
cell_array = [rawdata(:,2) rawdata(:,4) rawdata(:,6) rawdata(:,8)...
    rawdata(:,10) rawdata(:,12) rawdata(:,14) rawdata(:,16)...
    rawdata(:,18) rawdata(:,20) rawdata(:,22)];
%type rawdata in command window to inspect which row belongs to which load


pure_array = erase(cell_array,"Reading: "); %remove unwanted string from cell array
array = str2double(pure_array); %convert cell array to matrix


%variable 'array' is a matrix. make a vector for each load increment:
array0 = array(:,1);
array4 = array(:,2);
array6 = array(:,3);
array8 = array(:,4);
array10 = array(:,5);
array12 = array(:,6);
array14 = array(:,7);
array16 = array(:,8);
array18 = array(:,9);
array20 = array(:,10);
array22 = array(:,11);


%DATA IS TIDY.
%BEGIN ANALYSIS:

%calculate average values:
ave0 = mean(array0);
ave4 = mean(array4);
ave6 = mean(array6);
ave8 = mean(array8);
ave10 = mean(array10);
ave12 = mean(array12);
ave14 = mean(array14);
ave16 = mean(array16);
ave18 = mean(array18);
ave20 = mean(array20);
ave22 = mean(array22);
```

```
%make vectors:
ave_output = [ave4;ave6;ave8;ave10;ave12;ave14;ave16;ave18;ave20;ave22];
force = [4;5.85;8;10;12;14;16;18;20;22];

%generate linear fit data
linear_eq = polyfit(ave_output,force,1);
linear_fit = polyval(linear_eq,ave_output);

%plot data
plot(ave_output,force,'o',ave_output,linear_fit,'-')
title("Force vs. Average Output")
xlabel("Average Output (Proportional to Voltage)")
ylabel("Force (Newtons)")
legend('Data','Linear fit')

%display r-squared value
disp(' ')
disp('R-squared is:')
R_matrix = corrcoef(ave_output,force);
R = R_matrix(2,1);
Rsq = R^2;
disp(Rsq)

%display linear equation
eqtn = ['    y=' num2str(linear_eq(1)) 'x' num2str(linear_eq(2))];
disp('Linear equation is:')
disp(eqtn)
```

ANNEX B

FRITZING SKETCH OF CIRCUIT





ANNEX C

PICTURE OF DEVICE