Biomechanics Gait Analysis Lab

Final Report

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Abstract
The University of Connecticut’s Biomedical Engineering department has requested an upgraded gait analysis laboratory for use in the program’s Biomechanics course. The upgraded laboratory will allow the students to gain a more hands-on understanding of the hardware and applications of gait analysis, similar to the features found in a clinical setting of a gait analysis laboratory. Currently, the biomechanics gait analysis lab consists of the students participating in processing acquired data through software applications. The new laboratory would allow students to learn both the hardware applications as well as the software applications and make use of some of the existing equipment.

The upgraded laboratory will include footswitches and force sensitive resistor insoles, which will provide measurements that will be transmitted by telemetry to National Instruments devices and the LabVIEW® program. To measure the force exerted on the ground, the current lab uses a weigh scale to take a static measurement, whereas the upgraded lab will use the force sensitive resistors to take a dynamic measurement. The footswitches are a new feature, not mirrored by any device currently in use in the lab, which will show the students the pattern (or gait cycle) of foot strike on the ground over the duration of the gait cycle. This device will also allow the student to calculate the velocity, acceleration, and complete cycle time. The LabVIEW® program will have portions of the program that are left out and given to the students to fill in the gap, as an exercise to further their understanding of programs that are used in industry.

Gait analysis entails the measurement of parameters that characterize a person’s gait pattern, followed by an interpretation of the collected and processed data. In a clinical setting, it would be expected that a recommendation of treatment would follow, but for the Biomechanics laboratory, the students would be investigating the ‘how’ and ‘why’ of gait analysis. The new laboratory set-up is expected to be available for the Biomechanics class beginning in the fall of 2007.
1. Introduction

1.1 Background (client and disability)
Dr. John D. Enderle is the Editor-in-Chief of the EMBS Magazine, Biomedical Engineering Book Series Editor for Morgan and Claypool Publishers, and the Program Director & Professor for Biomedical Engineering at the University of Connecticut. Dr. Enderle needs improvements and additions made to the gait analysis lab for the undergraduate Biomedical Engineering program’s Biomechanics laboratory.

Currently, the biomechanics gait analysis lab consists of student participation in the process of acquiring data through software applications, which limits the students to only obtain or calculate 2-D measurements of distance, acceleration, speed, angles, and to determine joint moments using the assumption that the ground force reactions exerted during the gait cycle is static. The missing parameter for the current gait analysis is a true-life measure of ground reaction forces exerted on the foot strike.

1.2 Project Purpose
Dr. Enderle has requested an expansion of the gait analysis lab by using a force measurement system and National Instruments devices and programs. This improvement will afford students the opportunity to obtain an accurate measurement of the affects of dynamic gait motion. The new system will record and provide data on the affects of foot strike. The addition of a force measurement system will add value to the lab and the Biomedical Engineering program by allowing for a more “real world” biomechanics laboratory experience. Many gait analysis laboratories across the world have a force measurement system.

1.3 Previous Work Done by Others
There are three categories for the collection of gait analysis data that will be considered in this section; foot pressure, force plates, and motion systems. The acquired data from these devices or systems are sent to a computer software program, of which, the type of program is dependent upon the brand of gait analysis devices used and the desired program features, to synthesize data and display the results. Two of the foot pressure options consist of pressure mats and insoles. The force exerted on the ground can be collected by force plates and the motion
systems can include electromyography (EMG) and a video system.

**Foot Pressure**

Tekscan, Inc., located in South Boston, MA, has designed and manufactured many gait analysis products, including a few models of pressure insoles and mats. Pressure insoles can be used in a clinical setting for evaluating patients before and after surgery, screen for neuropathic disorders such as diabetes, and measure any length discrepancies in lower limbs, which could potentially be useful in assessing patients prior to hip replacement surgery for determining implant specifications. The insoles work by a method similar to pressure mats, which consist of capacitive or force sensitive resistor (FSR) switches placed in between two pieces of material that are either placed on the floor as a mat or on the inside or outside of a shoe.

B&L Engineering manufactures footswitches, which are compression closing switches that have two sheets of brass shim rock, a thin sheet of brass that has been cold rolled, with a compressible, non-conductive foam rubber insole, which has holes containing conductive rubber cylinders, in between the shim rock. The conductive rubber cylinders make contact with both sheets of sham rock and close an electric circuit upon application of pressure.

Force sensitive resistor (FSR) switches have a similar sandwich approach that uses flexible plastic for the outer layers, with circuits printed on the inside of the two plastic sheets. In between the plastic sheets, there is a slender layer of double-sided adhesive, with holes that allow for areas of contact. Similar to the compression closing switch, pressure causes the electric circuit to close, with the exception that this device has a resistive electric circuit, so that when pressure is increased, the resistance decreases.

**Force Plate Device**

Several models of force plates have been designed and produced by Bertec Corporation, based in Columbus, OH, Advanced Medical Technology, Inc., based in Watertown, MA, and Kistler Instrumente AG, based in Winterthur, Switzerland. Ground reaction forces can be measured by using a force plate. These devices include a top plate and a bottom plate or frame, which are separated by force transducers attached to each corner of the rectangular or
square plates. The entire device is installed into a platform so that the top plate is flush with the surface of the platform to prevent changes in a subject’s gait. As the subject walks along the platform and strikes the top plate, the exerted force is transferred to the transducers.

There are two types of force plates called piezoelectric and strain gauge. The piezoelectric force plate uses quartz transducers that create an electric charge when force is exerted on the top plate. The strain gauge force plates have load cells that measure stress when a force is exerted on the top plate. In both types, the devices provide vertical and shear forces, as well as the "center of pressure" during gait.

**Motion Systems**

Electromyography (EMG) utilizes electrogoniometers that are attached to the proximal and distal ends of the limb segments that are to be evaluated. One manufacturer of electrogoniometer is Biometrics Ltd., located in the United Kingdom and the United States, and another is Noraxon, located in the United States and Germany. These devices are electro-mechanical devices that provide an output voltage proportional to the angular change between the two attachment surfaces.” This system for motion analysis makes the assumption that the devices move in sync with the midline of the segment being measured and therefore, give an accurate representation of the angular change at the joints of the segments under consideration. The disadvantage is the tracking (or in sync motion with the midline) is affected when the person is not a lean individual, so that any type of bulky-ness will affect the accuracy of the results due to skin or muscle movement. ViconPeak is a manufacturer and supplier of motion systems and is based in the United Kingdom, with two locations in the United States. 3-D video systems, also referred to as optoelectronic systems or stereophotogrammetry, use two or more digital video cameras to track markers that are placed on the body of a subject. The types of markers used include infrared (IR) light-emitting diodes (LEDs) and reflective markers. The infrared (IR) light-emitting diodes (LEDs) require the use of a battery, circuits, and cables that can be cumbersome to use, but alleviate the issue of a camera losing sight of the marker. The reflective markers are much simpler to use and can be just as effective, even under the restraints of the user maintaining marker visibility by the camera.
Complete Analysis

The foot pressure devices and the force plate device can be used in conjunction with the motion systems to offer a more comprehensive analysis of a gait cycle, which is the focus of this gait analysis project, and are used clinically. There are numerous laboratories that utilize gait analysis, some examples include the Derby Gait and Movement Laboratory (www.gait.com), the Hugh Williamson Gait Analysis Laboratory (www.rch.org.au/gait/index.cfm?doc_id=1595) as part of the Royal Children’s Hospital in Melbourne, Australia, and the Shriners Hospital for Children. One company that provides entire gait analysis systems is Ariel Dynamics, at www.arielnet.com.

1.3.1 Products

Tekscan, Inc. Products for Foot Pressure Devices:

F-Scan® System
Bipedal In-Shoe Plantar Pressure/Force Measurement
www.tekscan.com

Walkway™ System
Floor Mat-based Pressure/Force Measurement
www.tekscan.com

Bertec Corporation Products for Force Plates:

4060 Force Plate Series
www.bertec.com
Dimensions in mm (342A X 552B X 29C X 24D)
4060-08 model is made of solid aluminum

4060-NC Force Plate Series
Dimensions in mm (342A X 552B X 29C X 24D)
Non-conductive and made of resin impregnated wood.
www.bertec.com

NorAngle Electrogoniometer System (for Electromyography EMG)
www.noraxon.com

ViconPeak High Speed Video Camera
Model HSC-200 PM
www.vicon.com

1.3.2 Patent Search Results
Searching for United States patents prior to undertaking an engineering project or design is obligatory. A patent restricts the use of any part of a patented invention, in that, another company or person cannot make, use, or sell the invention in the United States for a period of time that depends on the type of invention. For a design patent, the term period is 14 years from the grant date of the patent.

A quick search through the US Patent database of patents since 1975 can be done at www.uspto.gov/patft/index.html. Using the term ‘gait analysis,’ in the quick search field, brought up 110 filed patents with that term in the text of the patent form. Some of the patents include:

This patent covers an invention that includes methods and devices for monitoring and acquiring specific data from a subject’s movement and physiological measurements, which, in part, involves the use of an accelerometer.

The patent describes an invention for a portable gait analyzer which uses a type of pressure insole with detachable parts.

5,408,873 Foot force sensor – April 25, 1995 – Schmidt, et
This patent is for another type of pressure insole that consists of outer layers that are conductive and an inner layer that is nonconductive.

4,631,676 Computerized video gait and motion analysis system and method – December 23, 1986 – Pugh; James W. This patent describes a computerized video gait and motion analysis system and method that use reflective markers, Sony Video Motion Analyzers, video recorders and displays, and computer system for displaying the results obtained from the data.

6,543,299 Pressure measurement sensor with piezoresistive thread lattice – June 26, 2001 – Taylor; Geoffrey L. (Winnipeg, Manitoba, CA) This sensor measures force or pressure which varies inversely with the pressure that is exerted on the sensor.

1.4 Map for the Rest of the Report
In the remainder of this report, the project design process, decisions, and methods will be covered. The design section includes the three alternative designs, and their differences, as well as the optimal design. The optimal design incorporates selected portions of the first three alternative designs, based on specifications and realistic constraints, along with the budget and timeline required to complete the project. The design section will be followed by team member contribution highlights, and a conclusion to summarize the project. References and acknowledgements are provided, followed by the project specifications, purchase requisitions and fax quotes.

2. Project Design
The objective for this design project was to design and build an upgraded gait analysis laboratory for use in the University of Connecticut’s Biomedical Engineering Biomechanics course. The upgraded laboratory will allow the students to gain a more hands on understanding of the hardware and applications of gait analysis, similar to the features found in a clinical setting of a gait analysis laboratory. Currently, the biomechanics gait analysis lab consists of the students participating in processing acquired data through software applications. The new laboratory would allow students to learn both the hardware applications as well as the software applications and make use of some of the existing equipment. The upgraded
laboratory will include force sensitive resistor insoles and wireless footswitches, which will give measurements to be analyzed by National Instruments devices and the LabVIEW® program. After the first semester of senior design, it was decided that we would be required to use 3-D load cells for the force plate, instead of the 1-D load cells provided to us. After conducting extensive research into the cost of 3-D load cells, we found that four load cells would cost $10,000 to $12,000, which is out of our budget limit. The project was change to designing and building wireless footswitches and force sensitive resistor insoles, using the National Instruments equipment and LabVIEW® program as before. This new design and finished product will be described in the optimal design section.

In the prior semester, we researched and provided three alternative designs for consideration and an optimal design, as follows. For the first alternative design, a force plate was used as the force measuring device in the laboratory. For the second alternative design, footswitches were used as the force measuring device in the laboratory. And the third alternative design had a pressure mat was used for the force measuring device in the laboratory. For the optimal design, a combination of both the force plate and footswitches was determined to be the best option for this design project. Unfortunately, the pressure mat was not a feasible option or this design project due to the immense amount of circuitry and testing that would be required to produce a reliable and safe device and therefore, it was ruled out due to the 6 week time constraints of this design project. Fabricating the force plate is the better choice for the optimal design because the University of Connecticut Biomedical Engineering department previously purchased four load cells, which is exactly what is needed to construct the force plate. The force plate is also an ideal force measuring device for the gait analysis lab because it will be durable and portable which are two constraints of this design project. The use of the footswitches as a force measuring device in the gait analysis lab will give the user a better understanding of temporal measurements seen during gait.

Due to time constraints brought on by changing our project focus, we opted to purchase the footswitches from B&L Engineering instead of fabricating them ourselves. We came to this decision because fabricating and testing the footswitches ourselves would have been extremely time
consuming and since we were starting our second semester doing research on our new project focus, this would save valuable time that was need for researching the telemetry and force sensitive resistors, which were used in the insoles that we built. Also due to our time constraints, we did not have time to work on upgrading the optical system to 3-D, but we hope that will be picked up by another design group in the future as it will add value to the laboratory experience.

2.1 Design Alternatives

2.1.1 Design 1

2.1.1.1 Objective
The gait analysis laboratory design one will incorporate a hands-on approach to gait analysis through the use of an integrated force plate, platform, two digital camcorders, National Instruments equipment, and an interactive National Instruments LabVIEW® program.

A drawing of the overall system design is shown in Figure 1. The force plate will be designed and built using four load cells that were previously purchased by the department and withstands up to 300kg each. Data acquisition will be accomplished using the two digital cameras, a force plate, and the National Instruments PXI-1031 and SC-2345. The LabVIEW® program will be able to determine the acceleration, velocity, position, angles, and forces for one complete gait cycle.

To accurately measure the ground force reaction from foot strike, a force plate, imbedded flush into a platform, will be used in this design. The force plate will use four load cells that will measure the exerted force and send this data to the National Instruments SC-2345, which houses the SCC-SG24 modules, and the SC-2345 will be connected to the PXI-6040E data acquisition card in the National Instruments PXI-1031, from which the data acquired, will be sent to the LabVIEW® program. This force measurement device will allow the user to determine the dynamic forces exerted on the ground during the gait cycle, where previously this measurement was taken statically using a weigh scale. Digital cameras will be used to record a full gait cycle, each providing 2-D data. External markers will be placed laterally on the hip, knee, ankle, and toe of the right leg. In considering the use of multiple cameras, two
cameras will provide the software with the data necessary to create 3-D analysis. The use of more than two cameras would aid in keeping the markers in view as they become obscured by arm swing or patient rotation, improving the tracking accuracy, but the markers could still be missed during parts of the gait cycle. A white screen will be placed behind the person walking, to reduce glare, picked up by the cameras from natural light, and prevent any unwanted circular shapes to be picked up by the LabVIEW® program. The walkway location, as shown in Figure 2, was chosen to accommodate for the proper placement of the cameras.

Each camera records the gait cycle and the software determines the horizontal and vertical coordinates for each marker throughout the gait cycle, which is transformed into 3-D by the computer software. Tracking the markers provides the data needed to determine angles and distance over a gait cycle time period, which will further allow for determining velocity and acceleration. The images acquired will be received by the National Instruments PXI-1411 and sent to the LabVIEW® program.

The LabVIEW® program, along with Vision Development Module, will aggregate and synthesize the data received from the National Instruments PXI-1031 and display angles, forces, and acceleration vs. time, velocity vs. time, and position vs. time graphs, as well as the average acceleration and velocity. This portion of the lab is unique in that, some components of this program will allow the opportunity for students to build certain portions of the program, such as the force measurement function.
**Figure 1:** Complete System Drawing
**Figure 2:** Laboratory Layout

2.1.1.2 Subunits
2.1.1.2.1 Force Measuring Device – Force Plate

2.1.1.2.1.1 Background – Force Plate
A force plate is a device that measures the ground reaction forces exerted by a subject as they step on it during gait. Force plates consist of a top plate which is separated from the bottom frame by force transducers at each corner. The forces exerted on the top surface are transmitted through the force transducers. Force plates allocate the measurement of both vertical and shear forces, as well as the center of pressure for the subject throughout gait.

2.1.1.2.1.2 Force Transducers
For this design we will use four Thames Side-Maywood (Southwood, Farnborough, England) 350a strain gauges/load cells that were previously purchased by the University of Connecticut Biomedical Engineering program shown in Figure 3 below.

![Thames Side-Maywood 350a Load Cell](a) & (b)

**Figure 3** (a) & (b): Thames Side-Maywood 350a Load Cell

The technical specifications for the load cells are shown in Table 1 on the top of the next page.
### Thames Side-Maywood 350a Load Cell Technical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Load Cell Capacity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Load Ranges</td>
<td>300</td>
<td>kg</td>
</tr>
<tr>
<td>Rated Output</td>
<td>2</td>
<td>mV/V ± 0.1%</td>
</tr>
<tr>
<td>Accuracy Class</td>
<td>3000</td>
<td>n.OIML</td>
</tr>
<tr>
<td>Combined Error</td>
<td>&lt; ± 0.017</td>
<td>%*</td>
</tr>
<tr>
<td>Non-repeatability</td>
<td>&lt; ± 0.015</td>
<td>%*</td>
</tr>
<tr>
<td>Creep (30 minutes)</td>
<td>&lt; ± 0.016</td>
<td>%*</td>
</tr>
<tr>
<td>Temperature Effect on Zero Balance</td>
<td>&lt; ± 0.01</td>
<td>%*/°C</td>
</tr>
<tr>
<td>Temperature Effect on Span</td>
<td>&lt; ± 0.006</td>
<td>%*/°C</td>
</tr>
<tr>
<td>Compensated Temperature Range</td>
<td>-10 to +40</td>
<td>°C</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-20 to +70</td>
<td>°C</td>
</tr>
<tr>
<td>Safe Overload</td>
<td>150</td>
<td>%*</td>
</tr>
<tr>
<td>Ultimate Overload</td>
<td>200</td>
<td>%*</td>
</tr>
<tr>
<td>Zero Balance</td>
<td>&lt; ± 2</td>
<td>%*</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>400</td>
<td>Ω ± 30</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>350</td>
<td>Ω ± 1.5</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>&gt; 5000</td>
<td>MΩ @ 100V</td>
</tr>
<tr>
<td>Recommended Supply Voltage</td>
<td>10</td>
<td>V</td>
</tr>
<tr>
<td>Maximum Supply Voltage</td>
<td>15</td>
<td>V</td>
</tr>
<tr>
<td>Environmental Protection</td>
<td>IP66</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 1:** Thames Side-Maywood 350a Load Cell Technical Specifications
The load cell dimensions are shown in Figure 4 and Table 2.

<table>
<thead>
<tr>
<th>Thames Side-Maywood 350a Load Cell Dimensions</th>
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<tr>
<td>A</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>31.5</td>
</tr>
</tbody>
</table>

Table 2: Thames Side-Maywood 350a Load Cell Dimensions

In order to measure strain with a bonded resistance strain gauge, it must be connected to an electrical circuit that is capable of measuring the minute changes in resistance corresponding to strain. The Thames Side-Maywood strain gauge transducers employ four strain gauge elements electronically connected to form a Wheatstone bridge circuit shown in Figure 5 below.

![Figure 5: Thames Side-Maywood 350a Load Cell Electrical Circuit](image)

### Testing the Load Cells

To test the load cells at zero balance (electrical output with no load) a millivoltmeter is used to measure the load cell’s output under a “no load” condition. The output of a trimmed cell should typically be within ± 0.1% of the rated output.

To test for bridge resistance the resistance across each pair of input and output leads is measured. The input and output resistance is typically 350 ± 3.5 Ω (Ohms); if the resistance readings are 'out of spec' than the load cell requires repair.

#### 2.1.1.2.1.3 Top Plate and Platform

The top plate for the force plate and platform need to be made out of a material that is relatively light weight, durable, strong, and cost-efficient. The material that will be used for the top plate of the force plate in this gait
The material that will be used for the platform is 304L stainless steel. The composition and mechanical properties for 304L stainless steel are shown in Table 3 and Table 4 below. The composition and mechanical properties for 6061 aluminum alloy are shown in Table 5 and Table 6 below.

**Table 3: Composition of 6061 Aluminum Alloy**

<table>
<thead>
<tr>
<th>Weight Percent (wt%)</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>97.9</td>
<td>Aluminum (Al)</td>
</tr>
<tr>
<td>1.0</td>
<td>Mercury (Mg)</td>
</tr>
<tr>
<td>0.6</td>
<td>Silicon (Si)</td>
</tr>
<tr>
<td>0.3</td>
<td>Copper (Cu)</td>
</tr>
<tr>
<td>0.2</td>
<td>Chromium (Cr)</td>
</tr>
</tbody>
</table>

**Table 4: Mechanical Properties of 6061 Aluminum Alloy**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Ductility (%EL in 50 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Treated (T4)</td>
<td>240</td>
<td>145</td>
<td>22-25</td>
</tr>
</tbody>
</table>

**Table 5: Composition of 304L Stainless Steel**

<table>
<thead>
<tr>
<th>Weight Percent (wt%)</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03 max</td>
<td>Carbon (C)</td>
</tr>
<tr>
<td>2.0</td>
<td>Manganese (Mn)</td>
</tr>
<tr>
<td>0.75</td>
<td>Silicon (Si)</td>
</tr>
<tr>
<td>0.045</td>
<td>Phosphorus (P)</td>
</tr>
<tr>
<td>0.03</td>
<td>Sulfur (S)</td>
</tr>
<tr>
<td>18-20</td>
<td>Chromium (Cr)</td>
</tr>
<tr>
<td>12</td>
<td>Nickel (Ni)</td>
</tr>
<tr>
<td>0.1</td>
<td>Nitrogen (N)</td>
</tr>
<tr>
<td>67.045-65.045</td>
<td>Iron (Fe)</td>
</tr>
</tbody>
</table>

**Table 6: Mechanical Properties of 304L Stainless Steel**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>500</td>
</tr>
<tr>
<td>Compression Strength (MPa)</td>
<td>210</td>
</tr>
<tr>
<td>Proof Stress 0.2% (MPa)</td>
<td>200</td>
</tr>
<tr>
<td>Elongation A5 (%)</td>
<td>45</td>
</tr>
<tr>
<td>Hardness Rockwell B</td>
<td>92</td>
</tr>
</tbody>
</table>

The Schematics of the force plate for the gait analysis laboratory is shown below in Figures 6, 7, 8, and 9.
Figure 6: Top View of Force Plate

Figure 7: Side View of Force Plate and Platform

Figure 8: Front View of Force Plate and Platform
Due to gravity, we constantly maintain contact with the ground, and therefore, interactions occur between the body and the ground. The ground reaction force (GRF) is the reaction force supplied by the ground and is basically the reaction to the force that the body exerts on the ground. The GRF of a subject can be calculated using a force plate and Figure 10a below shows the reference frame of the force plate, with the Z-axis being the vertical while Figure 10b below shows the reaction force vectors acting on small areas. A force plate has four tri-axial force sensors embedded that measure the force acting between the foot and the ground in three axes: transverse (X), anteroposterior (Y), and vertical (Z). Figure 10c below shows the four reaction force vectors measured by the sensors. Since the sum of all of the reaction forces from the ground (Figure 10b) is equivalent to the sum of the four forces measured by the sensors $F_1$, $F_2$, $F_3$, and $F_4$ (Figure 10c), the system is equivalent to the system in Figure 10c.
Figure 10d shows a single force, $\mathbf{F} (\mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \mathbf{F}_4)$, and a torque, $\mathbf{T}_z$. $\mathbf{F}$ here is the ground reaction force. $\mathbf{T}_z$ shown in the figure is the so-called free torque and has the vertical ($Z$) component only. The free torque is caused by the coupling effects of the forces about the vertical axis. System (d), $\mathbf{F} + \mathbf{T}_z$, is again equivalent to system (c). The ground reaction force has three components: $F_x$, $F_y$ & $F_z$. Among these, $F_y$ is along the direction of the motion which reflects the propulsive or braking force. $F_z$ always thrusts the body upward.

As shown in Figure 10 above, all of the forces acting between the foot and the ground can be summed up to yield a single ground reaction force vector ($\mathbf{F}$) and a free torque vector ($\mathbf{T}_z$). The point of application of the ground reaction force on the plate is the center of pressure (CP).

All the small reaction forces collectively exert on the surface of the plate at the CP. Generally, the true origin of the strain gauge force-plate is not at the geometric center of the plate surface. Here, we assume that the true origin ($O'$ shown in Figure 11) is at $(a, b, c)$. The $Z$ component of the CP position is always zero. The moment
measured from the plate is equal to the moment caused by $\mathbf{F}$ about the true origin plus $\mathbf{T}_z$:

![Diagram](image)

**Figure 11**: True Origin of Center of Pressure

**Equations:**

$$
\mathbf{M} = \begin{bmatrix} x - a, y - b, -c \end{bmatrix} \times \begin{bmatrix} F_x, F_y, F_z \end{bmatrix} + \begin{bmatrix} 0, 0, T_z \end{bmatrix}
$$  

(1)

or:

$$
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
0 & c & y - b \\
-c & 0 & -(x - a) \\
-(y - b) & x - a & 0
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
T_z
\end{bmatrix}
= \begin{bmatrix}
(y - b)F_z + cF_y \\
-cF_x - (x - a)F_z \\
(x - a)F_y - (y - b)F_x + T_z
\end{bmatrix}
$$  

(2)

Eventually:

$$
x = -\frac{M_y + cF_x}{F_z} + a \\
y = \frac{M_x - cF_y}{F_z} + b
$$  

(3)

Therefore, the position of the CP can be computed from the moment caused by the ground reaction force about the true origin, $M_x, M_y$ & $M_z$, the ground reaction force, $F_x, F_y$ & $F_z$, and the location of the true origin, $a, b$ & $c$. $M_x, M_y, M_z, F_x, F_y$ & $F_z$ can be directly measured from the data output from the force transducers 2b.

2.1.1.2.2 The Optical System

Two digital cameras, Sony Handycam DCR-TRV27 shown in Figs. 12-13, will be used in this design. The digital cameras are
used to record the instantaneous position of each marker in order to analyze the movement of the body in a 3-D system.

**Figure 12: Sony Handycam DCR-TRV27**

The cameras provide the following performance abilities:

- An advanced hole accumulation diode imager with 690k pixels, which will provide highly detailed images with great clarity.
- MiniDV digital recording format that delivers 3 times the color bandwidth of VHS and lower signal-to-noise ratio compared to analog formats, which will provide stunning video performances comparable to DVD.
- A clear color view of video subjects, which makes spotting or following subjects easier.
- A high speed bi-directional digital video and audio communication between two compatible devices equipped with an IEEE-1394 interface, including camcorders, digital VTRs, capture cards, and PCs.
- Converts and records any analog NTSC video source to digital video via the analog inputs.
- A digital still memory mode captures high quality Megapixel still images at 1152 * 864 or 640 * 480 resolution directly to memory stick media.
- Playback zoom: during video playback, pause mode or while viewing still images stored on memory stick media, it can zoom up to 5x closer.
- An MPEG movie EX mode, which will allow the recording to be uninterrupted to the full capacity of the memory stick media. For example a 128MB memory stick will record up to 85 minutes of non-stop MPEG1 video.
- 10X Optical/120X Precision digital zoom: the optical zoom brings the action close up from far away.
• Precision digital zoom interpolation technology means that extreme digital zooming is clearer, with less distortion than previous types of digital zoom.

![Figure 13: Sony Handycam DCR-TRV27](image)

The cameras will be connected directly to the National Instruments PXI-1031, each to its own dedicated PXI-1411 card. The National Instruments PXI-1031 contains the National Instruments PXI-1411 data acquisition device that is responsible of transforming the digital input from the camera that will be sent to the computer to be analyzed using the National Instruments LabVIEW® program.

Four Styrofoam balls, shown in Fig. 14, will be used as motion markers. The markers are used so that the images from the cameras can be used to detect the motion of the different segments of the body, which can be tracked by the program. In capturing the 3-D coordinates, these markers will be placed on the ankle, knee, hip, and the toe of each body segment.

![Figure 14: Styrofoam balls used as motion markers](image)

The cameras will record a complete gait cycle of the subject, as depicted in Fig. 15. The gait cycle may also be referred to as a walking cycle. A complete gait cycle includes the heel-strike-to-heel-strike of a single leg,
but also involves the person’s stance and swing phases for each leg. In the complete gait cycle, movements can be divided into the instances when a foot strikes the ground, also referred to as the stance phase and makes up about 62% of a gait cycle, and when the foot is not on the ground, also referred to as the swing phase and makes up the remaining portion of the gait cycle. The stance phase of a gait cycle can be separated into the initial foot strike (shown as HS for ‘heel strike’ in Fig. 15), the instance that the entire foot is on the ground (shown as MidStance in Fig. 15) and the instance where the phase ends (shown as TO for ‘toe off’ in Fig. 15). Figure 15 is further divided into ‘single support,’ which indicates that the body is supported by only one foot during this time interval, and ‘double support,’ which indicates that the body is supported by both feet. The green shaded areas indicate the left foot and the yellow shaded areas indicate the right foot.

**Figure 15: Complete Gait Cycle**

In order to achieve a high-quality recording that will lead to optimal results; the digital cameras will be spaced as shown in Fig. 16, which is a snap shot of the laboratory set-up in section 2.1.1.1.
Figure 16: Camera Spacing Diagram

2.1.1.2.3 National Instrument Devices

Figure 17: National Instruments PXI-1031

The PXI-1031, as shown in Figs. 17-19, combines 4-slots PXI backplane with a structural design that gives it the
ability to be used in a wide range of applications. The key features include the following:

- Accepts 3U PXI and Compact PCI (PICMG 2.0 R 3.0) modules
- 4-slot chassis with universal AC input, and automatic voltage/frequency ranging
- DC power input (PXI-1031DC only)
- On/Off (Standby) power switch on the front panel for easy access
- AUTO/HIGH temperature-controlled fan speed based on air intake temperature to minimize audible noise
- Optional Carrying handle for portability
- Rack mountable

![Figure 18: National Instruments PXI-1031 Front View](image1)

![Figure 19: National Instruments PXI-1031 Rear View](image2)
Figures 18-19 show the rear and front view of the PXI-1031. As mentioned before, this device contains 4 different slots. One of these slots contains the NI-1411, shown in Fig. 20, which consists of a PXI plug-in image acquisition device that accepts digital video input from standard color or monochrome cameras. It also includes image acquisition driver software. The PXI-1411 Series includes features that improve overall image acquisition and image processing speed, using the onboard programmable ROI feature, only a portion of the image would be acquired. The National Instruments PXI-1411 can be used with several different software programs include LabVIEW®, Measurement Studio, and C/C++.

**Figure 20: National Instruments PXI-1411**

The National Instruments PXI-1411 will receive images from only one camera and send it to the computer. Since the PXI-1031 contains only one PXI-1411, and because two digital cameras will be used, a second PXI-1411 will need to be added to the PXI-1031 so the results from both cameras can be sent to the computer.

In addition to the PXI-1411, the SC-2345 module (Fig. 21) will be added to the design set-up. The SC-2345 module is an accessory module consisting of a high-speed, high precision amplifier that conditions signals from the force plate, prior to sending the signal to the PXI-6040E. The force transducers will connect to the SCC-SG24 strain gauge connectors, which are located inside the SC-2345 with a BNC input panelette (Fig. 22). The SCC-SG24 strain gauge connector will condition the signal and provide the necessary excitation to the transducers, which will allow the transducers to produce a signal.
The force plate will be connected to the SC-2345, as well as the National Instruments PXI-1031, so the data will be received from the force plate through the SC-2345 to the PXI-6040E, Fig. 23, in the PXI-1031, where the data will be read and converted to digital data that the computer will be able to read.
2.1.1.2.4 Computer Program

The LabVIEW® program used in this design will be able to receive the digital signal, or bytes of data, from the digital cameras and force plate. The products and specifications required to accomplish the necessary data acquisition to produce the desired results, are listed as follows in Fig. 24.

**Operating System**
Windows XP

**Hardware**
Pentium(R)4 CPU 1700 MHz Celeron
Microsoft Internet Explorer 6.0
256 MB of RAM

**Software Applications**
National Instruments LabVIEW® 8.0
National Instruments Vision Development Module
- IMAQ Vision 8.0
- Vision Builder for Automated Inspection (AI)

**Figure 23:** National Instruments PXI-6040E

**Figure 24:** Operating System, Hardware and Software Application Requirements
All software applications are produced by National Instruments and will be referred to by the application name, through the remainder of section 2.1.1.2.4.

2.1.1.2.4.1 Digital Image Acquisition and Displays
The digital data or bytes of data, from the cameras are received from the National Instruments PXI-1031 by the Vision Development Module, IMAQ software, serving as the interface path between the LabVIEW® program and the PXI-1411, to deal with any issues such as programming interrupts, and performs the functions that acquire and save the images. IMAQ Vision performs functions such as image analysis, interpretation, manipulation, processing, storage and display. IMAQ Vision Builder for Automated Inspection has many abilities, which include setting up coordinate systems, performing pattern matching, geometric analysis, and measurements. Examples of the IMAQ Vision Builder for Automated Inspection are shown in Figs. 25-26. The program will be able to match a shape of a defined size and color, which will be based on the size and color of the markers used for the lab, and follow the markers on the person recorded to measure the location change in the recorded frames. By determining the location changes in the frames, data will be acquired that is required for producing the position, velocity, acceleration, and angles over the recorded timeframe.

![IMAQ Vision Builder for Automated Inspection](image)

**Figure 25:** IMAQ Vision Builder for Automated Inspection
Figure 26: IMAQ Vision Builder for Automated Inspection

The Vision Builder for Automated Inspection generates LabVIEW® code that allows for custom and optimal inspection algorithms that, used in conjunction with the LabVIEW® software, will meet our application and display requirements.

2.1.1.2.4.2 Force Signal Processing

The signal received from the force transducers will need to go through the National Instruments SC-2345, and the National Instrument PXI-6040E, located in the PXI-1031, to produce data that will be used by the LabVIEW® program. Once the signal from the force plate is sent to the computer, the LabVIEW® software will translate this data into a displayable measurement in engineering units. An example of a displayable measurement is a graph, such as the graphs shown in Figs. 27-28.
2.1.2 Design 2

2.1.1.1 Objective
The gait analysis laboratory design will incorporate a hands-on approach to gait analysis through the use of footswitches, two digital camcorders, National Instruments equipment, and an interactive National Instruments LabVIEW® software program. A drawing of the overall system design is shown in Fig. 29. The footswitches will be designed as thin insoles and built using four footswitches. Data acquisition will be accomplished using the two digital cameras, footswitches, and National Instruments PXI-1031 and SC-2345. The LabVIEW® program will be able to determine the acceleration, velocity, position, angles, and forces for one complete gait cycle.
Footswitches are placed as insoles in the shoes or adhered to the bottom of the feet and have contact areas, or footswitches, on the heel, great toe, and the first and fifth metatarsals of each foot. There is a cable with a lead for each footswitch. The signals from each lead indicate that pressure has been applied to a particular area, which can be tracked by the computer over the course of the entire gait cycle. This device will show which area, or areas, of the foot are exerting forces on the ground during the gait cycle.

Digital cameras will be used to record a full gait cycle, each providing 2-D data. External markers will be placed laterally on the hip, knee, ankle, and toe of the right leg. In considering the use of multiple cameras, two cameras will provide the software with the data necessary to create 3-D analysis. The use of more than two cameras would aid in keeping the markers in view as they become obscured by arm swing or patient rotation, improving the tracking accuracy, but the markers could still be missed during parts of the gait cycle. A white screen will be placed behind the person walking, to reduce glare, picked up by the cameras from natural light, and prevent any unwanted circular shapes to be picked up by the LabVIEW® program. The walkway location, as shown in Figure 2, was chosen to accommodate for the proper placement of the cameras, as well as allow for ease in movement when using the footswitches that are connected to the PXI-1031 through the leads.

Each camera records the gait cycle and the software determines the horizontal and vertical coordinates for each marker throughout the gait cycle, which is transformed into 3-D by the computer software. Tracking the markers provides the data needed to determine angles and distance over a gait cycle time period, which will further allow for determining velocity and acceleration. The images acquired will be received by the National Instruments PXI-1411 and sent to the LabVIEW® program.

The LabVIEW® program, along with Vision Development Module, will aggregate and synthesize the data received from the National Instruments PXI-1031 and display angles, forces, and acceleration vs. time, velocity vs. time, and position vs. time graphs, as well as the average acceleration and velocity. This portion of the lab is unique in that, some
components of this program will allow the opportunity for students to build certain portions of the program, such as the force measurement function.

2.1.2.2 Subunits

2.1.2.2.1 Force Measuring Device – Footswitches

2.1.2.2.1.1 Background
Since gait is recurring in nature, temporal gait measurement systems provide the clinician with a valuable
analytical tool in gait analysis by quantifying the timing of important events in the cycle. Some of the typical parameters that are measured include: gait cycle duration, stance and swing times, single limb support, cadence, and initial and terminal double limb support. Also, by producing the measurements over a defined walking distance, the average velocity and stride length can be defined. Measuring only the velocity and single limb support can reveal a great deal about a subject’s functional ability to ambulate; as the subject gets weaker, has painful joints, or feels unstable, velocity will decrease and less time will be spent in single limb support on the affected side. Footswitches are a convenient and inexpensive way of obtaining temporal measurements during gait. Currently, there are two basic types on the market, compression closing and force sensitive resistor (FSR) switches. These footswitches are usually configured as thin insoles that can be placed between the bottom of the subject’s foot and shoe, or taped to the bottom of their bare feet.

2.1.2.2.1.2 Force Sensitive Resistors

For this design, we will use FSR switches to construct the footswitches. FSR switches consist of two thin layers of flexible plastic, with printed circuits on the inner surfaces, separated by a thin layer of double-sided adhesive (Figure 30). Holes in the adhesive create contact areas and as pressure is applied, carbon on one surface contacts a metal pattern on the other surface, creating a resistive electrical circuit. As more pressure is applied, the resistance drops and the associated circuitry triggers at a predefined resistance value indicating a switch closure.

Figure 30: Physical Structure of a Basic FSR

Over a wide range of forces, one can determine that the conductivity is approximately a linear function of force (F $\alpha$ C, F $\alpha$ 1/R). Figure 31 shows the resistance of the sensor.
as a function of force. Also, it is important to note the three regions of operation of the sensor. The first is the abrupt transition which occurs somewhere in the vicinity of 10 grams (g) of force, in this region the resistance changes very rapidly. The second region is above the first region where the force in directly proportional to \( 1/R \) until the third region where saturation is reached. When forces reach this magnitude, additional forces do not decrease the resistance substantially.

**Figure 31:** Resistance as a function of force for a typical force sensitive resistor.

Figure 32 below shows a plot of conductance versus force for a typical FSR sensor. Notice that the x-axis is now a linear axis, and that above the break-point, conductance is approximately linear with force.
For this design, switches will be implemented based upon the force sensitive resistors. The circuit for the switch is shown in Figure 33 below. The variable resistor, $R_{th}$ is used to set the sensitivity of the switch.

1.2.1.7 Footswitches

The footswitches for this design are to be worn as insoles in the subject’s shoes or taped to the bottom of their bare feet, and will indicate the total time each foot is and is not bearing weight. The footswitches will have contact areas in the Heel, Fifth Metatarsal, First Metatarsal, and Great Toe areas to indicate when these areas of the foot are bearing weight (Figure 34). The heel section of the insole is designed to be separated from the forefoot section so that one pair of footswitches can accommodate a
range of shoe sizes. Each footswitch has a thin cable with five leads, one for each switch and a common (Figure 35).

**Figure 34**: Contact areas for footswitches
The output of the footswitches can be visualized as a basographic signal shown in Figure 36 below. The analysis of the timing of this signal is referred to as basographic analysis.

Figure 35: Cable for footswitches with five leads

Figure 36: Electromyographic plots of seven different muscles of the same leg and basographic signal of the leg under examination. RF = rectus femoris, VM = vastus

Male Female
medialis, ST = semitendinosus, TA = tibialis anterior, PL = peroneus longus, GM = gastrocnemius medialis, SO = soleus, BA = basographic signal with four-level coding: foot-flat, push-off, swing, and break.

The force sensitive resistor sensors are connected to the insole which is made up of a closed cell neoprene material (Table 7) with conductive rubber modules that is covered entirely by duct tape (Table 8).

<table>
<thead>
<tr>
<th>Table 7: Closed Cell Neoprene - Styrene Butadiene Rubber</th>
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<tr>
<td><strong>Elongation, Break</strong> (%) (min)</td>
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<tr>
<td><strong>Tensile Strength</strong> (kg/cm²) (min)</td>
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<tr>
<td><strong>Tear Strength</strong> (kg/cm²) (min)</td>
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<td><strong>Hardness</strong> (Type C)</td>
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<td><strong>Density</strong> (G/cm³)</td>
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<tr>
<td><strong>Modulus at 200% Elongation</strong> (kg/cm²)</td>
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<tr>
<td><strong>Water Absorption By Weight</strong> (%) (max)</td>
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<tr>
<td><strong>Shrinkage</strong> (70°C, 24 hrs) (max)</td>
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<tr>
<td><strong>Compression Set</strong> (compressed 50% - 25°C)</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Table 8: Nashua 398 Duct Tape Specifications</th>
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</thead>
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<tr>
<td><strong>Backin Material</strong></td>
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<td><strong>Total Tape Thickness</strong></td>
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<tr>
<td><strong>Tensile Strength</strong></td>
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<tr>
<td><strong>Adhesion to Steel</strong></td>
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<tr>
<td><strong>Unwind Force</strong></td>
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2.1.2.2.2 The Optical System
Two digital cameras, Sony Handycam DCR-TRV27 shown in Figs. 12-13, will be used in this design. The digital cameras are used to record the instantaneous position of each marker in order to analyze the movement of the body in a 3-D system. The cameras provide the following performance abilities:

- An advanced hole accumulation diode imager with 690k pixels, which will provide highly detailed images with great clarity.
- MiniDV digital recording format that delivers 3 times the color bandwidth of VHS and lower signal-to-noise ratio compared to analog formats, which will provide stunning video performances comparable to DVD.
- A clear color view of video subjects, which makes spotting or following subjects easier.
- A high speed bi-directional digital video and audio communication between two compatible devices equipped with an IEEE-1394 interface, including camcorders, digital VTRs, capture cards, and PCs.
- Converts and records any analog NTSC video source to digital video via the analog inputs.
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- 10X Optical/120X Precision digital zoom: the optical zoom brings the action close up from far away.
- Precision digital zoom interpolation technology means that extreme digital zooming is clearer, with less distortion than previous types of digital zoom.

The cameras will be connected directly to the National Instruments PXI-1031, each to its own dedicated PXI-1411 card. The National Instruments PXI-1031 contains the National Instruments PXI-1411 data acquisition device that is responsible of transforming the digital input from the camera that will be sent to the computer to be analyzed using the National Instruments LabVIEW® program.
Four Styrofoam balls, shown in Fig. 14, will be used as motion markers. The markers are used so that the images from the cameras can be used to detect the motion of the different segments of the body, which can be tracked by the program. In capturing the 3-D coordinates, these markers will be placed on the ankle, knee, hip, and the toe of each body segment.

The cameras will record a complete gait cycle of the subject, as depicted in Fig. 15. The gait cycle may also be referred to as a walking cycle. A complete gait cycle includes the heel-strike-to-heel-strike of a single leg, but also involves the person’s stance and swing phases for each leg. In the complete gait cycle, movements can be divided into the instances when a foot strikes the ground, also referred to the stance phase and makes up about 62% of a gait cycle, and when the foot is not on the ground, also referred to as the swing phase and makes up the remaining portion of the gait cycle. The stance phase of a gait cycle can be separated into the initial foot strike (shown as HS for ‘heel strike’ in Fig. 15), the instance that the entire foot is on the ground (shown as MidStance in Fig. 15) and the instance where the phase ends (shown as TO for ‘toe off’ in Fig. 15). Figure 15 is further divided into ‘single support,’ which indicates that the body is supported by only one foot during this time interval, and ‘double support,’ which indicates that the body is supported by both feet. The green shaded areas indicate the left foot and the yellow shaded areas indicate the right foot.

In order to achieve a high-quality recording that will lead to optimal results; the digital cameras will be spaced as shown in Fig. 16, which is a snap shot of the laboratory set-up in section 2.1.1.1.

2.1.2.2.3 National Instrument Devices
The PXI-1031, as shown in Figs. 17-19, combines 4-slots PXI backplane with a structural design that gives it the ability to be used in a wide range of applications. The key features include the following:

- Accepts 3U PXI and Compact PCI (PICMG 2.0 R 3.0) modules
- 4-slot chassis with universal AC input, and automatic voltage/frequency ranging
- DC power input (PXI-1031DC only)
- On/Off (Standby) power switch on the front panel for easy access
• AUTO/HIGH temperature-controlled fan speed based on air intake temperature to minimize audible noise
• Optional Carrying handle for portability
• Rack mountable

Figures 18-19 show the rear and front view of the PXI-1031. As mentioned before, this device contains 4 different slots. One of these slots contains the NI-1411, shown in Fig. 20, which consists of a PXI plug-in image acquisition device that accepts digital video input from standard color or monochrome cameras. It also includes image acquisition driver software. The PXI-1411 Series includes features that improve overall image acquisition and image processing speed, using the onboard programmable ROI feature, only a portion of the image would be acquired. The National Instruments PXI-1411 can be used with several different software programs include LabVIEW®, Measurement Studio, and C/C++.

The National Instruments PXI-1411 will receive images from only one camera and send it to the computer. Since the PXI-1031 contains only one PXI-1411, and because two digital cameras will be used, a second PXI-1411 will need to be added to the PXI-1031 so the results from both cameras can be sent to the computer.

In addition to the PXI-1411, the SC-2345 module (Fig. 21) will be added to the design set-up. The SC-2345 module is an accessory module consisting of a high-speed, high precision amplifier that conditions signals from the footswitches, prior to sending the signal to the PXI-6040E. The SC-2345 can be further customized to accommodate the footswitches by adding the SCC-AG04 strain gauge connectors and LEMO B-Series panelettes (Fig. 37).

![LEMO (B-Series)]

**Figure 37:** National Instruments LEMO Panellete

The footswitches will be connected to the SC-2345, as well as the National Instruments PXI-1031, so the data will be received from the footswitches through the SC-2345 to the
PXI-6040E, Fig. 23, in the PXI-1031, where the data will be read and converted to digital data that the computer will be able to read.

### 2.1.2.2.4 Computer Program

The LabVIEW® program used in this design will be able to receive the digital signal, or bytes of data, from the digital cameras and footswitches. The products and specifications required to accomplish the necessary data acquisition to produce the desired results, are listed as follows in Fig. 24. All software applications are produced by National Instruments and will be referred to by the application name, through the remainder of section 2.1.2.2.4.

#### 2.1.2.2.4.1 Digital Image Acquisition and Displays

The digital data or bytes of data, from the cameras are received from the National Instruments PXI-1031 by the Vision Development Module, IMAQ software, serving as the interface path between the LabVIEW® program and the PXI-1411, to deal with any issues such as programming interrupts, and performs the functions that acquire and saves the images. IMAQ Vision performs functions such as image analysis, interpretation, manipulation, processing, storage and display. IMAQ Vision Builder for Automated Inspection has many abilities, which include setting up coordinate systems, performing pattern matching, geometric analysis, and measurements. Examples of the IMAQ Vision Builder for Automated Inspection are shown in Figs. 25-26. The program will be able to match a shape of a defined size and color, which will be based on the size and color of the markers used for the lab, and follow the markers on the person recorded to measure the location change in the recorded frames. By determining the location changes in the frames, data will be acquired that is required for producing the position, velocity, acceleration, and angles over the recorded timeframe.

The Vision Builder for Automated Inspection generates LabVIEW® code that allows for custom and optimal inspection algorithms that, used in conjunction with the LabVIEW® software, will meet our application and display requirements.

#### 2.1.2.2.4.2 Force Signal Processing

The signal received from the footswitches will need to go through the National Instruments SC-2345, and the National
Instrument PXI-6040E, located in the PXI-1031, to produce data that will be used by the LabVIEW® program. Once the signal from the footswitches is sent to the computer, the LabVIEW® software will translate this data into a displayable measurement in engineering units. An example of a displayable measurement is a graph, such as the graphs shown in Figs. 27-28.

2.1.3 Design 3

2.1.3.1 Objective
The gait analysis laboratory design will incorporate a hands-on approach to gait analysis through the use of a pressure mat, digital cameras, National Instruments equipment, and an interactive National Instruments LabVIEW® software program. A drawing of the overall system design is shown in Fig. 38 and the laboratory set-up is shown in Fig. 2. The pressure mat will be designed with two thin layers of material with an array of pressure sensors that are imbedded between the materials. Data acquisition will be accomplished using digital cameras, a pressure mat, and the National Instruments PXI-1031 and BNC-2120. The LabVIEW® program will be able to determine the acceleration, velocity, position, angles, and forces for one complete walking cycle.

Digital cameras will be used to record a full gait cycle, each providing 2-D data. External markers will be placed laterally on the hip, knee, and ankle of the right leg. In considering the use of multiple cameras, two cameras will provide the software with the data necessary to create 3-D analysis. The use of more than two cameras would aid in keeping the markers in view as they become obscured by arm swing or patient rotation, improving the tracking accuracy, but the markers could still be missed during parts of the gait cycle. Each camera records the gait cycle and the software determines the horizontal and vertical coordinates for each marker throughout the gait cycle, which is transformed into 3-D by the computer software. Tracking the markers provides the data needed to determine angles and distance over a gait cycle time period, which will further allow for determining velocity and acceleration. The images acquired will be received by the National Instruments PXI-1411 and sent to the LabVIEW® program. The major advantage of a pressure mat is its portability. Pressure mats provide a plantar pressure picture, force and pressure measurements versus time, and gait lines. The pressure mat also allows
for determining areas of high and low pressure, and the center of force and how it travels down the foot. As a person walks on the mat, the feet strike the sensors, which send signals to the computer.

These signals will vary depending on the amount of force applied to each of the sensors. The sensors act as variable resistors in a circuit with its resistance changing in inverse proportion to the applied force. In other words, as the force increases, the resistance decreases. These data are sent through the PXI-4220 for signal conditioning, then to the BNC-2120, followed by the PXI-6040E, located within the PXI-1031, and finally to the computer.

The LabVIEW® program, along with Vision Development Modules, will aggregate and synthesize the data received from the National Instruments PXI-1031 and display the angles, forces, and acceleration vs. time, velocity vs. time, and position vs. time graphs, as well as the average acceleration and velocity. This portion of the lab is unique in that, some components of this program will give the opportunity for students to build certain portions of the program, such as the force measurement function.

![Figure 38: Complete System Drawing](image-url)
2.1.3.2 Subunits

2.1.3.2.1 Force Measuring Device – Pressure Mat

2.1.3.2.1.1 Background
For clinical gait analysis, measurements of plantar pressure provide an indication of both ankle and foot functioning during gait and other similar activities, since the ankle and foot provide: 1) the necessary support and 2) flexibility for weight bearing and weight shifting while performing these activities. Plantar pressure data has been recognized as an important element in the assessment of subjects with diabetes and peripheral neuropathy as well as in determining and managing the impairments associated with various musculoskeletal, integumentary, and neurological disorders. When evaluating patients, a typical amounts or patterns of loading may be reflective of a systemic pathology that acts as indicators or risk factors for further or worsening pathology. Also, plantar pressure measurement systems offer the clinician a high degree of portability, allowing operation among several clinical sites.

Pressure mats provide a quick and easy way of obtaining plantar pressure pictures as a subject walks across it during gait. Currently, there are two basic types of transducers used in a pressure mat system, compression transducers and force sensitive resistor (FSR) transducers. Since the area of the transducer is known, the applied force can be calculated by adding up the force computed from each active sensor at a given point in time. These systems are valuable because they provide an immediate method for determining the areas of high pressure on the plantar surface of the foot, which may have resulted from tissue breakdown.

2.1.3.2.1.2 Force Sensitive Resisters
For this design, we will use FSR transducers to construct the pressure mat. FSR transducers consist of two thin layers of flexible plastic which have electrically conductive electrodes deposited in varying patterns (Figure 30). In Figure 39 below, the inside surface of one sheet forms a row pattern, while the inner surface of the other employs a column pattern. The spacing between the rows and columns varies according to sensor application and can be as small as ~0.5 millimeters. Prior to assembly, a thin
semi-conductive coating is applied as an intermediate layer between the electrical contacts (rows and columns) and provides an electrical resistance change at each of the intersecting points. By measuring the changes in current flow at each intersection point, the applied force distribution pattern can be measured and displayed on a computer screen. The force measurements can be made either statically or dynamically and the information can be seen graphically in 2-D or 3-D displays. The 2-D and 3-D displays show the location and magnitude of the forces exerted on the surface of the sensor at each sensing location. Force and pressure changes can be observed, measured, recorded, and analyzed throughout the test, providing a powerful engineering tool.

![Figure 39: FSR Transducer Surface Structure](image)

Over a wide range of forces, one can determine that the conductivity is approximately a linear function of force \( F \propto C, F \propto 1/R \). Figure 31 shows the resistance of the sensor as a function of force. Also, it is important to note the three regions of operation of the sensor. The first is the abrupt transition which occurs somewhere in the vicinity of 10 grams (g) of force, in this region the resistance changes very rapidly. The second region is above the first
region where the force is directly proportional to 1/R until the third region where saturation is reached. When forces reach this magnitude, additional forces do not decrease the resistance substantially.

Figure 32 shows a plot of conductance versus force for a typical FSR sensor. Notice that the x-axis is now a linear axis, and that above the break-point, conductance is approximately linear with force.

2.1.3.2.1.3 Pressure Mat
The pressure mat for this design will provide static and dynamic barefoot pressure and force measurements over several steps during gait. The mat dimensions for this design are 1468 mm x 442 mm x 5 mm (57.8 in x 17.4 in x 0.2 in). It is comprised of 25,056 sensing elements and it has a spatial resolution of 4 Sensels/cm². Some applications of the pressure mat include:

- Capture multiple foot strikes on walkway
- Quantify continuous gait patterns over many strides
- Identify pressure profile discrepancies between left and right feet
- Observe gait abnormalities
- Identify asymmetries during stance phase
- Assist in writing orthotic prescriptions
- Monitor improvements in balance & sway, strength & weight bearing
- Monitor degenerative foot disorders
- Assess high pressures and deviated Center of Force trajectories due to pronation, supination, or other foot and/or gait related disorders

The Schematics of the pressure mat for the gait analysis laboratory are shown below in Figures 40, 41, and 42.
For the pressure mat, an 8-bit electronics system is used to scan the intersecting points of the sensor’s rows and columns as well as to measure the resistance at each contact point. The points are read in the presence of multiple contacts, while simultaneously limiting the possible current flow through the device. Figure 43 below illustrates the sensing system where each contact location is represented by a variable resistor whose value is high when no force is applied to it.\textsuperscript{2d}
2.1.3.2.2 The Optical System

Two digital cameras, Sony Handycam DCR-TRV27 shown in Figs. 12-13, will be used in this design. The digital cameras are used to record the instantaneous position of each marker in order to analyze the movement of the body in a 3-D system. The cameras provide the following performance abilities:

- An advanced hole accumulation diode imager with 690k pixels, which will provide highly detailed images with great clarity.
- MiniDV digital recording format that delivers 3 times the color bandwidth of VHS and lower signal-to-noise ratio compared to analog formats, which will provide stunning video performances comparable to DVD.
- A clear color view of video subjects, which makes spotting or following subjects easier.
- A high speed bi-directional digital video and audio communication between two compatible devices equipped with an IEEE-1394 interface, including camcorders, digital VTRs, capture cards, and PCs.
• Converts and records any analog NTSC video source to digital video via the analog inputs.
• A digital still memory mode captures high quality Megapixel still images at 1152 * 864 or 640 * 480 resolution directly to memory stick media.
• Playback zoom: during video playback, pause mode or while viewing still images stored on memory stick media, it can zoom up to 5x closer.
• An MPEG movie EX mode, which will allow the recording to be uninterrupted to the full capacity of the memory stick media. For example a 128MB memory stick will record up to 85 minutes of non-stop MPEG1 video.
• 10X Optical/120X Precision digital zoom: the optical zoom brings the action close up from far away.
• Precision digital zoom interpolation technology means that extreme digital zooming is clearer, with less distortion than previous types of digital zoom.

The cameras will be connected directly to the National Instruments PXI-1031, each to its own dedicated PXI-1411 card. The National Instruments PXI-1031 contains the National Instruments PXI-1411 data acquisition device that is responsible of transforming the digital input from the camera that will be sent to the computer to be analyzed using the National Instruments LabVIEW® program.

Four Styrofoam balls, shown in Fig. 14, will be used as motion markers. The markers are used so that the images from the cameras can be used to detect the motion of the different segments of the body, which can be tracked by the program. In capturing the 3-D coordinates, these markers will be placed on the ankle, knee, hip, and the toe of each body segment.

The cameras will record a complete gait cycle of the subject, as depicted in Fig. 15. The gait cycle may also be referred to as a walking cycle. A complete gait cycle includes the heel-strike-to-heel-strike of a single leg, but also involves the person’s stance and swing phases for each leg. In the complete gait cycle, movements can be divided into the instances when a foot strikes the ground, also referred to the stance phase and makes up about 62% of a gait cycle, and when the foot is not on the ground, also referred to as the swing phase and makes up the remaining portion of the gait cycle. The stance phase of a gait cycle can be separated into the initial foot strike (shown as HS for ‘heel strike’ in Fig. 15), the instance that the entire
foot is on the ground (shown as MidStance in Fig. 15) and the instance where the phase ends (shown as TO for ‘toe off’ in Fig. 15). Figure 15 is further divided into ‘single support,’ which indicates that the body is supported by only one foot during this time interval, and ‘double support,’ which indicates that the body is supported by both feet. The green shaded areas indicate the left foot and the yellow shaded areas indicate the right foot.

In order to achieve a high-quality recording that will lead to optimal results; the digital cameras will be spaced as shown in Fig. 16, which is a snap shot of the laboratory set-up in section 2.1.1.1.

2.1.3.2.3 National Instrument Devices
The PXI-1031, as shown in Figs. 17-19, combines 4-slots PXI backplane with a structural design that gives it the ability to be used in a wide range of applications. The key features include the following:

- Accepts 3U PXI and Compact PCI (PICMG 2.0 R 3.0) modules
- 4-slot chassis with universal AC input, and automatic voltage/frequency ranging
- DC power input (PXI-1031DC only)
- On/Off (Standby) power switch on the front panel for easy access
- AUTO/HIGH temperature-controlled fan speed based on air intake temperature to minimize audible noise
- Optional Carrying handle for portability
- Rack mountable

Figures 18-19 show the rear and front view of the PXI-1031. As mentioned before, this device contains 4 different slots. One of these slots contains the NI-1411, shown in Fig. 20, which consists of a PXI plug-in image acquisition device that accepts digital video input from standard color or monochrome cameras. It also includes image acquisition driver software. The PXI-1411 Series includes features that improve overall image acquisition and image processing speed, using the onboard programmable ROI feature, only a portion of the image would be acquired. The National Instruments PXI-1411 can be used with several different software programs include LabVIEW®, Measurement Studio, and C/C++.

The National Instruments PXI-1411 will receive images from only one camera and send it to the computer. Since the PXI-
1031 contains only one PXI-1411, and because two digital cameras will be used, a second PXI-1411 will need to be added to the PXI-1031 so the results from both cameras can be sent to the computer.

In addition to the PXI-1411, the SC-2345 module (Fig. 21) will be added to the design set-up. The SC-2345 module is an accessory module consisting of a high-speed, high precision amplifier that conditions signals from the pressure mat, prior to sending the signal to the PXI-6040E. The SC-2345 can be further customized to accommodate the pressure mat by adding the SCC-AG04 strain gauge connectors and LEMO B-Series panelettes (Fig. 37).

The pressure mat will be connected to the SC-2345, as well as the National Instruments PXI-1031, so the data will be received from the pressure mat through the SC-2345 to the PXI-6040E, Fig. 23, in the PXI-1031, where the data will be read and converted to digital data that the computer will be able to read.

### 2.1.2.2.4 Computer Program

The LabVIEW® program used in this design will be able to receive the digital signal, or bytes of data, from the digital cameras and pressure mat. The products and specifications required to accomplish the necessary data acquisition to produce the desired results, are listed as follows in Fig. 24.

All software applications are produced by National Instruments and will be referred to by the application name, through the remainder of section 2.1.2.2.4.

#### 2.1.3.2.4.1 Digital Image Acquisition and Displays

The digital data or bytes of data, from the cameras are received from the National Instruments PXI-1031 by the Vision Development Module, IMAQ software, serving as the interface path between the LabVIEW® program and the PXI-1411, to deal with any issues such as programming interrupts, and performs the functions that acquire and saves the images. IMAQ Vision performs functions such as image analysis, interpretation, manipulation, processing, storage and display. IMAQ Vision Builder for Automated Inspection has many abilities, which include setting up coordinate systems, performing pattern matching, geometric analysis, and measurements. Examples of the IMAQ Vision Builder for Automated Inspection are shown in Figs. 25-26.
The program will be able to match a shape of a defined size and color, which will be based on the size and color of the markers used for the lab, and follow the markers on the person recorded to measure the location change in the recorded frames. By determining the location changes in the frames, data will be acquired that is required for producing the position, velocity, acceleration, and angles over the recorded timeframe. The Vision Builder for Automated Inspection generates LabVIEW® code that allows for custom and optimal inspection algorithms that, used in conjunction with the LabVIEW® software, will meet our application and display requirements.

2.1.3.2.4.2 Force Signal Processing
The signal received from the pressure mat will need to go through the National Instruments SC-2345, and the National Instrument PXI-6040E, located in the PXI-1031, to produce data that will be used by the LabVIEW® program. Once the signal from the pressure mat is sent to the computer, the LabVIEW® software will translate this data into a displayable measurement in engineering units. An example of a displayable measurement is a graph, such as the graphs shown in Figs. 27-28.

2.2 Optimal Design

2.2.1 Objective

The optimal gait analysis laboratory design will incorporate a hands-on approach to gait analysis through the use of footswitches, force sensitive resistor (FSR) insoles, National Instruments equipment, and an interactive National Instruments LabVIEW™ software program. This design will provide students with an understanding of two different types of measuring devices that are used in a clinical setting, which were not previously available for use in the Biomechanics lab.

2.2.2 Subunits

2.2.2.1 Force Measuring Devices

2.2.2.1.1 Force Sensors Background
The force sensor acts as a force sensing resistor in an electrical circuit, so that when it’s unloaded, the resistance is very high, and when it’s loaded, the resistance is very low. When the force sensor is
calibrated, the level of resistance can be correlated inversely to the amount of force applied. By placing the force sensor into an insole, the amount of force a person exerts on the sensor can be track over time.

Over a wide range of forces, one can determine that the conductivity is approximately a linear function of force \( F \propto C, F \propto 1/R \). Figure 44 shows the resistance of the sensor as a function of force. Also, it is important to note the three regions of operation of the sensor. The first is the abrupt transition which occurs somewhere in the vicinity of 10 grams (g) of force, in this region the resistance changes very rapidly. The second region is above the first region where the force in directly proportional to \( 1/R \) until the third region where saturation is reached. When forces reach this magnitude, additional forces do not decrease the resistance substantially.

![Resistance vs. Force](image)

**Figure 44:** Resistance as a function of force for a force sensitive resistor

Figure 45 below shows a plot of conductance versus force for a typical FSR sensor. Notice that the x-axis is now a linear axis, and that above the break-point, conductance is approximately linear with force.
2.2.2.1.1.2 Force Sensitive Resistor Insoles

The FSR insoles are comprised of force sensitive resistors, sandwiched between cut-to-size shoe insoles and taped together with Gorilla brand duct tape. The idea for this design was, in part, taken from the simple design of the footswitches. A diagram of an FSR insole is shown in figure 46. Rubber disks are placed on either side of the sensing area to concentrate the force directly onto the sensing area to provide a better reading, which is indicated in figure 47. The FSR has a three male square pin connector, also shown in figure 47 and figure 46. The middle connector is connected to ground and the two outer pins are used for the voltage supply input and the voltage output. The two outer pins can be either used as the input or the output. The force sensor is an extremely thin, flexible printed circuit. The force sensor is made of two layers of a polyester/polyimide substrate sheet. For each layer, conductive silver is applied, on top of which a layer of pressure-sensitive ink is applied. An adhesive joins the two layers of substrate together to complete the force sensor. The active sensing area is outlined by the silver circle around the pressure-sensitive ink, which can be seen in figure 47. The silver lines extend from the

Figure 45: Conductance as a function of force for a force sensitive resistor

![Conductance vs. Force Graph](image_url)

\[ y = 6\times10^6x + 34.942 \]
sensing area to the two outer connector male square pins to form the leads.

The sensors act as a force sensing resistors in an electrical circuit, so that when it’s unloaded, the resistance is quite high, and when it’s loaded, the resistance is rather low. The resistance will vary as the sensor is loaded and unloaded. Using a digital multimeter, the resistance or force can be read by connecting the probes to the outer two pins, and then apply a force to the sensing area. The digital multimeter must be turned on and the dial set to the resistance or voltage reading option. The FSRs can range up to 1000 lbs by reducing the resistor value and/or voltage of a driver circuit, which is used in this design, shown in figure 50, and will be described next.

Figure 46: FSR Insole design
Figure 47: FlexiForce FSR® (force sensitive resistor)

FSR Insole Lead Wire Connectors

The connectors used for the FSR insoles are the same type as the footswitches, except that they have only four pins, since we have only one input, two outputs, and ground to wires to connect. Shown in figure 48, male 4-pin LEMO (FGG.0B.304.CLAD52Z) connectors were used to connect the lead wires from the FSR insoles to the transmitter box. The lead wires were soldered into the holes, which can be seen in the rear view drawing in figure 48C.

Figure 3.6: Male 4-Pin LEMO Connector

The following table gives the dimensions for the LEMO connector shown in Figure 48.

<table>
<thead>
<tr>
<th>Metric</th>
<th>A</th>
<th>L</th>
<th>M</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm.</td>
<td>9.5</td>
<td>35.0</td>
<td>25.0</td>
<td>8.0</td>
<td>7.0</td>
</tr>
<tr>
<td>in.</td>
<td>0.37</td>
<td>1.38</td>
<td>0.98</td>
<td>0.31</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 9: Measurements for figure 3.6A
The male LEMO connector fits to the female LEMO connector (ECG.0B.304.CLL), which is attached to the printed circuited board in the transmitter box and shown in figure 49 below.

![Figure 49: Female LEMO Connector](image)

The following table gives the dimensions for the LEMO connector shown in Figure 49.

<table>
<thead>
<tr>
<th>Metric</th>
<th>A</th>
<th>B</th>
<th>e</th>
<th>E</th>
<th>L</th>
<th>M</th>
<th>N</th>
<th>S1</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm.</td>
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<td>12.5</td>
<td>M9X0.6</td>
<td>5.5</td>
<td>20.7</td>
<td>2.5</td>
<td>19.1</td>
<td>8.2</td>
<td>11.0</td>
</tr>
<tr>
<td>in.</td>
<td>0.47</td>
<td>0.49</td>
<td>-</td>
<td>0.22</td>
<td>0.81</td>
<td>0.10</td>
<td>0.75</td>
<td>0.32</td>
<td>0.43</td>
</tr>
</tbody>
</table>

**Table 10: Measurements for figure 3.7A**

2.2.2.1.1.3 FSR Insole Driver Circuit

The output voltage from the force sensitive resistor is relayed to the drive circuit, where it goes through three inverting operational amplifiers (TL072), then run to the microprocessor (PIC16F874), where it is converted from analog to digital data before it can be transmitted via telemetry. The FSR output voltage can range about 5V, but the microprocessor can only receive up to 5V. In order to make the FSR voltage output range between 0V-5V so the microprocessor can receive the data, we need to use three inverting operational amplifiers (TL072), which is show in figure 50. The inverting amplifiers require a +9V and −9V power source in put at pins 8 and 4, respectively.

The first inverting amplifier consists of the force sensitive resistor, with a varying resistance, and an 8.99KΩ reference resistor. This amplifier should have a positive output voltage on pins 1 and 7. The second
inverting amplifier will have a 9.82kΩ input resistor and a 2.65kΩ reference resistor to give an inverse gain of -2.65. This amplifier should have a negative output voltage on pins 1 and 7. Then the third inverting amplifier will have equally valued input resistor and reference resistor to give a gain of -1, making the final inverse gain of the last two inverting amplifiers 2.65. So, the final output voltage should be positive on pins 1 and 7. Equations for each inverting amplifier are given in figure 52.

The input from the heel and toe sections of the FSR insoles come into pins 2 and 6, respectively. The output to the BNC-2120, described in the National Instruments section, for the heel and toe comes from pins 1 and 7 on that last inverting amplifier depicted in figure 50.

In order to use telemetry for the FSR insoles, they must be connected to the microprocessor through Pin 2 and Pin 3, shown in figure 51. The microprocessor requires a 5V power source input at pin VDD. The microprocessor is capable of 10-bit analog-to-digital conversion. Analog-to-digital (A/D) conversion is the method of converting an analog voltage into a discrete digital count of ones and zeros, which can be transmitted by the telemetry system. Unfortunately, due to changing our project, there was not enough time in the last semester to troubleshoot the A/D program part of the design, so it is not currently working. Instead, the FSR insoles are connected directly to the BNC-2120, through the transmitter box.
**Figure 50:** Transmitter Telemetry Device: Drive Circuit for FSR Insoles Outlined in Blue, Footswitch Insoles in Green
**Figure 51:** Microprocessor Circuit for FSR Insoles (PIC16F873)

### Equation for 1st Inverting Amplifier

\[
V_{(R\text{Heel})1} = -V_{FSR}(R_6/R_{FSR}) \quad \text{Eq. 1}
\]

### Equation for 1st Inverting Amplifier

\[
V_{(R\text{Heel})2} = -V_{(R\text{Heel})1}(R_9/R_8) \quad \text{Eq. 2}
\]

### Equation for 1st Inverting Amplifier

\[
V_{(R\text{Heel})3} = -V_{(R\text{Heel})2}(R_{13}/R_{12}) \quad \text{Eq. 3}
\]

**Definition of Variables**

- \(R_{FSR}\): Force Sensitive Resistor
- \(R\): All other resistors are numbered according to fig. 3.3
- \(V_{(R\text{Heel})X}\): X represents output of matching inverting amplifier
- \(V_{FSR}\): Output Voltage from FSR

**Figure 52:** Inverting Amplifier Equations as Shown in Figure 50
2.2.2.1.1.4 Calibrating the FSR Insoles

Devices that measure force require calibration, which is the process by which force is related to the output voltage as the resistance varies with changing force. Using the Tinius Olsen machine in compression, the following is the procedure for calibration and requires two people to perform.

1. Place one half of an insole between two hard plastic plates
2. Place them between the two grips on the Tinius Olsen machine and a pad in the larger empty spaces, so pressure is applied evenly.
3. Make sure that the sensor end of the FSR is in the middle of the grips, for even force application.
4. Set-up two speeds on the Tinius Olsen machine (fig. 53), speed 1 at 0.01 and speed 2 at 0.005 (see manual for Tinius Olsen machine to set-up speeds)
5. Hook up the insole to the transmitter telemetry device, attach probes from a digital multimeter to the output of the receiver box, and turn on both telemetry boxes.
6. On person starts speed 1, and calls out the force every 10 lbs starting at 40 lbs, while the other person writes down the output voltage reading. At 200 lbs select speed 2, and continue until 350 lbs is reached.
7. Turn all devices off when done

From this data determine the FSR resistance value at each voltage reading, using the equations in figure 3.5, and divide the resistance by 1 to get conductance. Using the conductance data and its matching force output, plot conductance vs. force in Excel and use linear regression to extrapolate the equation that will relate output force to conductance.
2.2.2.1.2 Footswitches

2.2.2.1.2.1 Background - Footswitches
Since gait is recurring in nature, temporal gait measurement systems provide the clinician with a valuable analytical tool in gait analysis by quantifying the timing of important events in the cycle. Some of the typical parameters that are measured include: gait cycle duration, stance and swing times, single limb support, cadence, and initial and terminal double limb support. Also, by producing the measurements over a defined walking distance, the average velocity and stride length can be defined. Measuring only the velocity and single limb support can reveal a great deal about a subject’s functional ability to ambulate; as the subject gets weaker, has painful joints, or feels unstable, velocity will decrease and less time will be spent in single limb support on the affected side.

Footswitches are a convenient and inexpensive way of obtaining temporal measurements during gait. Currently, there are two basic types on the market, compression closing and force sensitive resistor (FSR) switches. These footswitches are usually configured as thin insoles that can be placed between the bottom of the subject’s foot and shoe, or taped to the bottom of their bare feet. 

Figure 53: Tinius Olsen Machine
The footswitches for this design are to be worn as insoles in the subject’s shoes or taped to the bottom of their bare feet, and will indicate the total time each foot is and is not bearing weight. The footswitches will have contact areas in the Heel, Fifth Metatarsal, First Metatarsal, and Great Toe areas to indicate when these areas of the foot are bearing weight (Figure 54). The heel section of the insole is designed to be separated from the forefoot section so that one pair of footswitches can accommodate a range of shoe sizes. Each footswitch has a thin cable with five leads, one for each switch and a common.

2.2.2.1.2.2 Footswitch Design

The footswitch insoles consist of four compression closing switches, at the heel, 1st metatarsal, 5th metatarsal, and toe, as shown in figure 54. These switches act as an open or closed electric circuit, which requires an input of 5 volts. When pressure is applied to the switches, two rubber cylinders contact pieces of brass sheets on each side of the insole, which acts to close the electric circuit, as shown in figure 55. The only information that this will provide is that pressure is being applied and the length of time that pressure is applied. This will not show variations in applied pressure. The footswitches can provide velocity, cadence, stride length, and information on gait cycle, single limb support, swing, and stance. The footswitches do not need to be calibrated, which is a difficult and lengthy process.

The drive circuit for the footswitch insoles is simply a +9V battery connected to a voltage regulator to reduce the input voltage to +5V, which is shown in figure 50. The footswitches are connected to the transmitter with a pull-down resistor in between. The pull-down resistor is need to supply a very small voltage (less than 0.01V) because the transmitter cannot process no input and would send a default number which causes the program to give erroneous outputs. The pull down resistor set-up is shown in figure 56.
Figure 54: Footswitch diagram
The LEMO connectors for the footswitches are similar to the FSR insoles, except they have five pins instead of four. The footswitches were purchased from B&L Engineering and came with the male LEMO connectors attached. The male LEMO connector (FGG.0B.305.CLAD52Z) is shown in figure 57.
The following table gives the dimensions for the LEMO connector shown in Figure 57.

<table>
<thead>
<tr>
<th>Metric</th>
<th>A</th>
<th>L</th>
<th>M</th>
<th>S1</th>
<th>S2</th>
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<tr>
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<td>35.0</td>
<td>25.0</td>
<td>8.0</td>
<td>7.0</td>
</tr>
<tr>
<td>in.</td>
<td>0.37</td>
<td>1.38</td>
<td>0.98</td>
<td>0.31</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 11: Measurements for figure 57A

The female LEMO connector was soldered to the printed circuit board in the transmitter box and is shown in figure 58. The layout for the lead input is shown in figure 59, which shows the sections of the foot coming into each pin as well as the input voltage.
The following table gives the dimensions for the LEMO connector shown in Figure 58.

<table>
<thead>
<tr>
<th>Metric</th>
<th>A</th>
<th>B</th>
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**Table 12**: Measurements for figure 58A

**Figure 59**: Female LEMO Lead Wire Layout

### 2.2.2.2 Telemetry

The purpose of telemetry is to reduce the amount of wires and allow the freedom of movement that cannot be achieved using wires that are directly connected to a computer. The telemetry system is comprised of a transmitter box and receiver box. The transmitter box includes the 418MHz transmitter/encoder chip (TXE-418-KH), 10-pin dip switch (SDA10H1KD), and 418MHz Splatch antenna (ANT-418-SP-1), which is shown in figure 60A-B. The box also has the circuitry that provides the data to be sent wirelessly. The receiver box has a 418MHz receiver/decoder chip (RXE-418-KH), 10-pin dip switch (SDA10H1KD), and 418MHz Splatch antenna (ANT-418-SP-1), which is shown in figure 61A-B. The receiver/decoder chip is also wired to connect to the BNC-2120, which will be described later in the National Instruments equipment section. The transmitter/encoder and receiver/decoder are powered by a 3V coin battery at pin 5 for both chips.
Figure 60A: Transmitter Set-up
Figure 60B: Transmitter PCB
Figure 61A: Receiver Set-up
The 418MHz transmitter/encoder chip and Splatch antenna was purchased from Linx Technologies and are shown in figure 62. The transmitter receives the analog data and evaluates it using binary, true or false, assessment, which determines if it’s receiving a signal or not. The evaluation by the transmitter generates a series of zeros and ones, which is then encoded, sent through the 10-pin dip switch, and finally sent by the antenna to the receiver box. The transmitter and receiver set-up must both be at the same frequency or the signal will not be received. The frequency of the antennas must be the same, but the type of antenna can be different.
The transmitter/encoder allows for the secure transmission of up to 8 parallel binary outputs and has \(3^{10}\) address lines for security. The signals from the footswitches are sent to pins 7-10 on the transmitter/encoder, shown in figure 60. If the FSR insoles were made wireless, the data would be input into pin 2. When the pressure is applied to a section of the footswitch, the input to the transmitter on that line should show about 3V and nearly 0V if no pressure is applied. As explained previously, the pull-down resistor provides a very small voltage input (less than 0.001), which is determined to be a false signal by the transmitter.

The Splatch antenna in the receiver box picks up the radio frequency signal sent by the transmitter antenna, and then sends the data to the 10-pin dip switch, which can only receive data that came from a dip switch with the same pin setting to reduce unwanted data from other radio frequency devices operating at the same level. If the settings match, the data is sent to the receiver/decoder, which was also purchase from Linx Technologies and shown in figure 62. The data is decoded and sent to the BNC-2120 by wires that are soldered to the receiver outputs on pins 7, 8, 9, and 12, shown in figure 61. If the FSR insoles were made wireless, the data would be output from pins 2 and 3.

**Figure 62:** A) 418MHz Splatch Antenna; B) 10-Pin Dip Switch; C) 418MHz Transmitter/Encoder; D) 418MHz Receiver/Decoder
2.2.2.3 National Instrument Devices

The data acquisition devices used are the National Instruments BNC-2120 and PXI-6040E, which is housed in the PXI-1031, shown in figures 63, 64, and 65, respectively.

The BNC-2120 is a shielded connector block that connects the up to 8 analog and 8 digital inputs to the PXI-6040E. The FSR input signals are connected to the BNC-2120 using BNC connectors, which have a red lead that connects to the wire that extends from the FSR driver circuit and the black lead, is connected to ground. The footswitch output wires, extending from the receiver box, are attached to the digital inputs on the BNC-2120. The BNC-2120 sends the data through a DAQ Card connector cable to the PXI-6040E.
The PXI-6040E is a data acquisition device that performs high speed continuous data logging and supplies the data to the computer to be received and displayed using the LabVIEW® 8.1 program’s data acquisition assistant (DAQ Assist) module, which creates, edits, and runs task that allows manipulation and displays of the data received.

**Figure 64:** National Instruments PXI-6040E

The PXI-1031, as shown in Figs. 65-67, combines 4-slots PXI backplane with a structural design that gives it the ability to be used in a wide range of applications.

**Figure 65:** National Instruments PXI-1031
The key features include the following:

- Accepts 3U PXI and Compact PCI (PICMG 2.0 R 3.0) modules
- 4-slot chassis with universal AC input, and automatic voltage/frequency ranging
- DC power input (PXI-1031DC only)
- On/Off (Standby) power switch on the front panel for easy access
- AUTO/HIGH temperature-controlled fan speed based on air-intake temperature to minimize audible noise
- Optional) Carrying handle for portability
- Rack mountable

Figures 66–67 show the rear and front view of the PXI-1031.

![Diagram of PXI-1031 Chassis](image)

**Figure 1-1.** Front View of the PXI-1031 Chassis

**Figure 66:** National Instruments PXI-1031 Front View
2.2.2.4 Computer Program

The National Instruments LabVIEW™ computer program used in this design is able to receive and analyze the digital data that is transmitted from the footswitch insoles and the analog data from the FSR insoles in real-time, during one complete gait cycle. The LabVIEW™ program can calculate the following gait parameters:

**Footswitch Insoles**

- total gait cycle duration
- stance phase duration
- swing phase duration
- time of toe contact
- time of 1st metatarsal contact
- time of 5th metatarsal contact
- time of heel contact
- total gait cycle length
- stance phase length
- swing phase length
- % of time on toe during stance phase
- % of time on 1st metatarsal during stance phase
- % of time on 5th metatarsal during stance phase
- % of time on heel during stance phase
- cadence
- total gait cycle velocity
- stance phase velocity
- swing phase velocity

**FSR Insoles**

- weight distribution on toe during stance phase
- weight distribution on heel during stance phase

The LabVIEW™ programs for both the footswitch and FSR insoles utilize the DAQ Assistant Express VI (Figure 68) to read and configure the analog and digital data coming from the National Instruments BNC-2120 and PXI-1031 devices. For both insoles the sampling rate was set to acquire 1000 samples continuously at a 1 kHz frequency.

**Figure 68:** DAQ Assistant Express VI LabVIEW™ Function

The LabVIEW™ program for the footswitch insoles also incorporates the Tick Count (ms) (Figure 69), which is a millisecond timer that returns the number of milliseconds since 01/01/1990. This timer is used to calculate the total gait cycle duration, stance phase duration, swing phase duration, time of toe contact, time of 1\textsuperscript{st} metatarsal contact, time of 5\textsuperscript{th} metatarsal contact, and time of heel contact.

**Figure 69:** Tick Count (ms) LabVIEW™ Function
The footswitch program also uses the Digital to Analog Express VI (Figure 70) to convert the digital waveform data from the receiver to analog waveform data that can be sent to a measurement file spreadsheet.

![Digital to Analog Express VI LabVIEW™ Function](image)

**Figure 70:** Digital to Analog Express VI LabVIEW™ Function

Finally, the footswitch program employs the Write to Measurement File Express VI (Figure 71) to combine the millisecond time data from the Tick Count function with the converted analog data from the footswitch sensors. This VI writes the files in an LVM format which can be opened and viewed in Microsoft® Excel.

![Write to Measurement File Express VI LabVIEW™ Function](image)

**Figure 72:** Write to Measurement File Express VI LabVIEW™ Function
The Front Panel of the Gait Analysis Footswitch Insoles System LabVIEW™ computer program is shown in Figure 73 below.

**Figure 73:** Footswitch Insoles LabVIEW™ Program Front Panel
The block diagram of the Gait Analysis Footswitch Insoles System LabVIEW™ computer program is shown in Figure 74 below.

**Figure 74:** Footswitch Insoles LabVIEW™ Program Block Diagram
After a Subject has completed the data acquisition portion of the footswitch insole program, they will have 4 Excel spreadsheets (Toe spreadsheets shown in Figures 75-76) they will need to extract data from it in order to complete the data analysis portion of the laboratory.

**Figure 75: Original Toe Sensor Data File**
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**Figure 76:** Corrected Toe Sensor Data File
In the four spreadsheets, the 1st column is the sensor data and when pressure is applied to the sensor the output is 0 and when no pressure is applied to the sensor the output is -1. From this information and measured information from the exercise, the following values are input into the footswitch data area of the LabVIEW™ program front panel (blue = input values, black = output values):

- Time @ First Toe Contact
- Time @ Last Toe Contact
- Time @ First 1st Metatarsal Contact
- Time @ Last 1st Metatarsal Contact
- Time @ First 5th Metatarsal Contact
- Time @ Last 5th Metatarsal Contact
- Time @ First Heel Contact
- Time @ First Heel Contact (Swing Phase)
- Time @ Last Heel Contact (Stance Phase)
- Total Gait Cycle Length
- Stance Phase Length/Shoe Size

The resulting information from the input data is the:

- total gait cycle duration
- stance phase duration
- swing phase duration
- time of toe contact
- time of 1st metatarsal contact
- time of 5th metatarsal contact
- time of heel contact
- total gait cycle length
- stance phase length
- swing phase length
- % of time on toe during stance phase
- % of time on 1st metatarsal during stance phase
- % of time on 5th metatarsal during stance phase
- % of time on heel during stance phase
- cadence
- total gait cycle velocity
- stance phase velocity
- swing phase velocity
The Front Panel of the Men’s Force Sensitive Resistor (FSR) Insoles System LabVIEW™ computer program is shown in Figure 77 below.

**Figure 77:** Men’s FSR Insoles LabVIEW™ Program Front Panel
The Block Diagram of the Men’s Force Sensitive Resistor (FSR) Insoles System LabVIEW™ computer program is shown in Figure 78 below.

Figure 78: Men’s FSR Insoles LabVIEW™ Program Block Diagram
The Front Panel of the Women’s Force Sensitive Resistor (FSR) Insoles System LabVIEW™ computer program is shown in Figure 79 below.

**Figure 79:** Women’s FSR Insoles LabVIEW™ Program Front Panel
The Block Diagram of the Women’s Force Sensitive Resistor (FSR) Insoles System LabVIEW™ computer program is shown in Figure 80 below.

Figure 80: Womens FSR Insoles LabVIEW™ Program Block Diagram
After a Subject has completed the data acquisition portion of the FSR insole program, they will have 1 Excel spreadsheet and they will need to extract the data to compute the maximum force exerted by the subject on the toe and heel during one complete gait cycle.

2.3 Prototype

Prototype

Footswitch Drive Circuit Prototype

Prototypes were created and tested for the footswitch and FSR insole drive circuits and the telemetry evaluation kit. The prototype drive circuit for the FSR insole was also used to calibrate the FSR insoles, test the LabVIEW® program until the telemetry was completed, and test the telemetry evaluation kit. The footswitch prototype drive circuit was created and tested and used to test the LabVIEW® program as well as the telemetry evaluation kit. Once the telemetry boards were completed, both of the insoles were used to test the telemetry set-up, and the telemetry evaluation kit was used to troubleshoot the functioning of the telemetry boards.

FSR Insole Drive Circuit

The first FSR insole drive circuit consisted of an inverting amplifier connected to a +9V and -9V battery and an input voltage of -5V connected supplied to pin 3 of the force sensitive resistor. As shown in figure 81, a TL072 operational amplifier (black) and potentiometer (blue) were used for the circuit. The input voltage was supplied by two BK Precision® DC Power Supplies and connected to the protoboard using alligator clips, which can be seen in figure 82. The schematic for the first FSR insole is shown in figure 83.

The set-up shown in figure 82 and 83 was used to test all of the force sensitive resistors before the insoles were constructed. The output of the set-up, pin 1 on the LT072 operational amplifier, was connected to a digital multimeter probe using alligator clips as shown in figure 84. The force sensitive resistors were tested by applying pressure on the sensor area using the thumb and 1st
metacarpal (pointer finger) and looking for a voltage read out on the digital multimeter.

The potentiometer was used to find the appropriate reference resistor value for the force sensitive resistor, which would allow the resistance to change beyond 350 lbs. If the resistor is set too high, the output would saturate, meaning that no more change in resistance would occur. It was important to find a common resistor value that allowed all eight force sensitive resistors to surpass 350 lbs without saturating, since there is only one reference resistor for each insole in the drive circuit design. This made the circuit simple and kept the number of input receptacles to just one. It was determined that a 9kΩ reference resistor was small enough to suit all eight force sensitive resistors. Figure 85 shows the schematic with the 9kΩ reference resistor and figure 86 is a picture showing the set-up on a protoboard.

Figure 81: First Prototype - TL072 operational amplifier and potentiometer with Connections Shown
Figure 82: First Prototype - Power Supply Set-up
Figure 83: 1st FSR Drive Circuit Schematic with Potentiometer
Figure 84: Testing the Force Sensitive Resistors
Figure 85: 1st FSR Drive Circuit Schematic with 9kΩ Reference Resistor
Once the force sensitive resistors were tested and the FSR insoles were built, the first drive circuit was used in calibrating the insoles and testing the LabVIEW® program, using the output from the calibration procedure. Figure 87 shows the set-up for the calibration and LabVIEW® program testing. Although it is not shown in figure 87, the insole was placed into the Tinius Olson machine and compression force was applied up to 350 lbs.
After the calibration was completed, it was learned that the microprocessor and transmitter/encoder cannot receive voltage inputs greater than +5V. Some of the insoles showed voltage outputs of several volts higher, with some nearly 8V. It was determined that using another inverting amplifier with the proper resistor values would reduce the output voltage to far under the maximum input for the microprocessor and transmitter/encoder, but the output of the second inverting amplifier would be negative. To overcome this problem, another inverting amplifier with no gain (both resistors are the same) was added to the circuit design, so the output would be positive. The schematic showing the three inverting amplifiers is given in figure 88 and a picture of the set-up is shown in figure 89.
Figure 88: FSR Insole 3 Inverting Amplifier Schematic
The telemetry evaluation kit was tested using the design shown in figure 88. The transmitter kit board was attached to a wire at the output on pin 1 of the TL072 operational amplifier using an alligator clip, which was attached to the input to the transmitter/encoder on the transmitter kit board. The transmitter set-up is shown in figure 90. The receiver board was attached to the BNC-2120 Connector board at the output pin of the receiver/decoder using a BNC probe that has an alligator clip at the end. The BNC probe also has a ground clip, which was attached to ground on the DC Power Supply by using an alligator clip. The receiver set-up is shown in figure 91. Another BNC probe, attached to another analog input on the BNC-2120, was attached directly to the drive circuit output using an alligator clip. The direct connection was made so that the telemetry output could be compared to the direct output from the circuit. Both outputs, from the direct connection and telemetry, were exactly the same. This led us to conclude that the microprocessor was not necessary, so we update our transmitter schematic as shown in figure 92. A week later, we discovered that the BNC will take data from another
input, to compensate for no data coming into another, and that the outputs were the same as a result of a drawback to the data acquisition system. Unfortunately, there was not enough time to change our schematic for the printed circuit board (PCB) order, so we constructed a separate board with the microprocessor set-up which is shown in figure 93. As mentioned in the optimal design section, we did not have enough time to troubleshoot the microprocessor program or set-up to get the FSR insole working wirelessly.

Figure 90: Transmitter Telemetry Protoboard Set-up
Figure 91: Receiver Telemetry Set-up for FSR Insoles
Figure 92: FSR Insole Schematic without Microprocessor
Footswitch Drive Circuit

At first the drive circuit consisted of a +5V input, which is shown in figure 94, but it was discovered that the transmitter/encoder would receive no input when pressure was not applied and so, the transmitter/encoder would not have any data to send. Looking at a laboratory exercise, we found that a pull-down resistor would provide an extremely small input to the transmitter/receiver that would be taken to be zero. The pull-down resistor set-up consists of a resistor in parallel between the footswitch output and the transmitter/encoder input. Figure 95 shows the set-up and figure 96 gives the schematic for the drive circuit.
Figure 94: Footswitch - First Drive Circuit
Figure 95: Footswitch Set-up with Pull-Down Resistors
Figure 96: Footswitch Schematic with Pull-Down Resistors
The telemetry evaluation kit was tested using the design shown in figure 97. The input to the transmitter/encoder on the transmitter kit board was attached to an input wire located on the LEMO connector. The transmitter set-up is shown in figure 98. The receiver board was attached to the BNC-2120 Connector board at the output pin of the receiver/decoder using an alligator clip, which was attached to a wire that was inserted into the digital input on the BNC-2120. The BNC-2120 digital inputs also have one input for ground, which was attached to ground on the DC Power Supply by using an alligator clip that was attached to a wire that was inserted into the ground input on the BNC-2120. The receiver set-up is shown in figure 99. The driver circuit was also tested by directly connecting the output to the digital input of the BNC-2120.
Figure 97: Telemetry Schematic for Footswitches
Figure 98: Transmitter Set-up for Footswitches
LabVIEW® Program Prototypes

The first prototype program for the footswitch insoles consisted of the DAQ Assist VI with a graph indicator, as show in figure 100. Another program, used to test each output from the insoles is shown in figure 101. The final program is given in the optimal design section of this report.

The first FSR insole program also consisted of the DAQ Assist VI with a graph indicator, as show in figure 100. In order to perform some troubleshooting, we used the set up in figure 102, which also has a Filter VI, FFT-based Spectral Measurement VI, along with their respective graphical indicators. This program was used to determine the source of the noise that was showing on our first program. It was discovered that the was at 60MHz, indicating power line interference, which was not be a problem once the project was built since the FSR insoles would be powered by a battery. In figure 103, the program
in figure 102 is expanded to include a calibration equation output to a graph and Excel file, so that the output data from the equation could be analyzed.

Figure 100: First Prototype Program (Block Diagram)
Figure 101: Second Footswitch Program to Test Each Output
Figure 102: FSR Insole Program for Troubleshooting Noise
Figure 103: FSR Insole Program for Filtering Noise and Testing Calibration Equations
3. Realistic Constraints

Engineering standards are very important when designing a biomedical device. For this design project, we are using the International System of Units (SI units) as well as US customary units in order to keep with engineering standards around the world.

Two economic considerations for this design project include the budget and the longevity of the device. Our design needed to be within a reasonable amount, which is the main reason that we could no longer build the force plate. When we presented the cost for the load cells, which was $9,000-$11,000 over the expected investment for the entire project, we proposed the force sensitive resistor insoles and footswitches because they were more economical and provided similar data to our original project. The gait analysis laboratory that we designed will be used in the University of Connecticut’s biomechanics laboratory which is presently offered in the fall semesters. Therefore, our device should be able to last for a few years of operation, so that the biomechanics laboratory gets a return on the investment.

A major environmental consideration for this design project is the weather conditions and temperature ranges in Connecticut. Should the insoles be used outside of the shoe, it will be important that the walking path for the experiment will be clear of any weather elements tracked into the room, such as snow, water, salt, and/or dirt. Although we used materials for the insoles that claim to resist weather elements, the insoles (and especially the telemetry devices) should not be exposed unnecessarily.

Two very important ethical constraints for this design project come from the Code of Ethics for Engineers. The first ethical constraint is the statement “Strive to prevent a person from being placed at risk due to the use of technology”. This constraint demands that the gait analysis laboratory be set-up in such a way that will keep the students safe at all times of operation and assembly. The second ethical constraint is the statement “Work toward the containment of costs by the better management and utilization of technology”. This constraint asks that we utilize existing materials that are on hand or that are cheaper than others on the market as well as to make devices, which is more cost effective than purchasing from suppliers, or purchasing from suppliers when making devices
is more costly. This constraint consideration is the reason we bought the footswitches and made the force sensitive resistor insoles.

4. Safety Issues
Safety consideration is one of the most important issues in any project and especially when dealing with electric circuits. In general, any equipment or device that uses electricity, and is in contact with people, must be electrically isolated from the power main or battery power. Even if the instrument is not in direct contact with a person, the device must be electrically grounded.

In this design for the gait analysis lab, the students will be in contact with the insoles and the transmitter box. In addition to walking on the insoles, students will have to run the transmitter box. The safety of the products were considered during our design phase, include insulated materials and grounded circuitry.

All of the wires that are connected to the insoles and telemetry devices were wrapped in insulated coverings and will be attached to the leg using Velcro to avoid snagging loose wire. This will also reduce the chance of an electrical shock to the student.

Additionally, a reasonable length was selected for the wires, so as to allow free motion, but not so long that a student will trip or get snagged due to loose wiring. By using insulated coverings over the wires, Velcro to secure the wires and a reasonable length, students will be safe when using the laboratory set-up.

Another safety issue to take into consideration is the material that will be used to make the force sensitive resistor insoles. In this design, the insoles were made from two rubber or foam insoles that were sandwiched and held together using duct tape. These materials are good electrical insulators.

5. Impact of Engineering Solutions
Designing a gait analysis program can have many impacts that are global, societal, economic, and environmental. Learning about gait analysis and its applications will provide a better understanding of the impact of biomedical engineering solutions for students and, hopefully, the students will be able to discover some of the global,
societal, economic, and environmental impacts in the gait analysis lab.

Globally, in researching applications of gait analysis, these types of programs were found in countries such as Australia, the United Kingdom, China, and all across the United States. The Hugh Williamson Gait Analysis Laboratory, as part of the Royal Children’s Hospital in Melbourne, Australia, uses their laboratory to perform research and to develop ways of providing useful information to surgeons and therapists, primarily for children with Cerebral Palsy and also Spina Bifida. The Derby Gait and Motion Laboratory, in the United Kingdom, evaluate adults and children with Cerebral Palsy, stroke, and amputated limbs. The Institute of Biomedical Engineering, Tsinghua University, in Beijing, China has been involved in the use of gait analysis for analyzing Cerebral Palsy. Clinical gait analysis is also used at the Gait Analysis Laboratory at the Connecticut Children's Medical Center.

The use of gait analysis to treat diseases and disabilities has a positive impact on society. By discovering ways to treat physical conditions, people with disabilities would be able to receive better medical treatment or therapy, and assistive devices. These treatments could help patients become more productive and independent. Research and use of gait analysis for patients with Cerebral Palsy has been performed on a global scale, at all of the institutes mentioned previously. Cerebral Palsy is an incurable disorder that hinders the control of muscle movement and can affect the use of one or any combination of limbs. The lack of motor control makes walking very difficult, for which gait analysis could be a great tool in determining proper treatment, allowing patients to participate more easily in society.

The economic impact can affect consumers, both patients and providers. The cost of building a gait analysis laboratory is extremely expensive. The patients that use the facilities that use “state-of-the-art” equipment often have higher fees, which would exceed insurance coverage or would not be covered at all. The benefit to the patient, and the usefulness in determining proper treatment by the health professional, must outweigh the cost. The growing expectation for a quality life, demands tools to better serve the recovery or treatment process and gait analysis
is one of those tools. A patient could require treatment in order to regain the ability to work, which could provide a better income than disability compensation, thereby improving the individual’s economic situation.

Environmentally, the impact can be found in the creation of materials and electronics that must eventually be thrown out. As materials and electronics age, they must be replaced to ensure operational safety and quality results. While some materials can be recycled, this is not true for all materials and, unless the user is environmentally conscious, all of the materials could conceivably be thrown away. Recycling is very expensive, but the cost to the environment is irreversible and every effort should be made to recycle as much of the used materials as possible.

Depending on how one views the definition of ‘environment,’ the patient’s environment could be impacted as well. The environment in which the patient lives could improve and expand greatly. This would mean the patient becomes mobile, or more easily mobile, and is able to gain access to areas of their environment that were previously restricted by their condition. The recommended treatment from gait analysis would allow the patient to re-enter the workforce and regain involvement in the environment of society.

Designing a gait analysis program has already greatly impacted the world in a global, societal, economic, and environmental sense and shows how engineering solutions can make a positive difference in the world, if put to good use.

6. Life-Long Learning
In the Biomechanics gait analysis lab, we learned about motion analysis and what it is used for in the medical field. We also learned about the gait cycle and how is it divided into different sections. We have expanded our understanding of gait analysis by learning about other devices used to analyze gait such as force plates, force/pressure mats, pressure insoles, footswitches, and electrogoniometers.

By building our program, we have learned about more modules in LabVIEW® and gained a better understanding of the data the program receives and how it is used. In the laboratory, students are taught the purpose of each module and how it works. When designing our project we had to apply what we
have learned, learn about modules on our own, and
collaborate with more experienced users to learn new
modules by means such as attending seminars.

We had no prior knowledge of telemetry devices, so we had
to research the different components and understand how
they work together. We were under severe time constraints
due to the change in our project, so we also had to seek
resources from teaching assistants and technology experts
to expedite our progress. Engineers in industry must
research, learn about, or design new products and
processes, which often require collaborating with other
industry experts, universities, or groups within the
company.

Some of the National Instruments equipment that are being
used in our design were new to us. We had to learn about
the PXI-1031 and BNC-2120 data acquisition devices and
after using them, we found that they operated in a way that
we didn’t expect and had to compensate by redesigning our
project. Since our project changed in the second semester,
we had to research, design, build, and troubleshoot as we
progressed through our project.

From this design project, we learned that in order to
progress and develop as an engineer, it is vital to keep
educated on the latest developments in the field. Lifelong
learning should be pursued by taking classes, attending
professional seminars, collaborating with other industry
experts, or some variety of sources to be able to advance
along with technology and not be left behind.
7. Budget

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Total: 1,405.20

8. Team Members Contributions to the Project

Once the project was changed a week into the beginning of the second semester, the team worked together to research, design, and build the products. Each team member had to put in an exorbitant amount of time and effort to achieve a finished working product. They were under pressure the entire semester, since the research set them back about five to six weeks, but they managed to work well together to drive results. They met on a weekly basis to plan and coordinate their efforts and remained in communication between meetings through e-mail and instant messaging. The completed project was truly a team effort.
Team Member 1: Kimberly Carr

Last semester in Senior Design I, Kimberly’s main role was to design and fabricate the force plate. Unfortunately, due to budget restrictions, the force plate aspect of the design project was scrapped within the first 2 weeks of Senior Design II. With this major set-back came an immense challenge for the team to work together and research other force measurement devices that could be used for gait analysis. The team worked together on almost every aspect of this design project and Kimberly’s main responsibilities included: making the force sensitive resistor (FSR) insoles, designing the transmitter and receiver circuits, designing the printed circuit board layouts, constructing the transmitter and receiver circuit boards, troubleshooting the telemetry system, and developing the National Instruments LabVIEW™ computer program for the footswitch insoles. Because the design team worked so well together and shared all of the responsibilities, this project was able to be completed on time.

Team Member 2: Angela Ensor

Since our project changed, we were under pressure to start and complete our research at the beginning of the second semester as quickly as possible, so each of us spent a lot of time researching. Angela had a hand in nearly every aspect of this project, as did her partners, so they each thoroughly understand each part of this project and were able to support each other. Some of Angela’s involvements, along with her partners, included researching force sensitive resistors that could reach 350lbs, researching and purchasing materials and components, understanding how the components work, building and testing the devices, building the LabVIEW® programs, finding out how to calibrate the FSR insoles and writing up the instructions, calibrating the FSR insoles and using the data to extrapolate the equation that relates output voltage to the amount of force exerted, as well as many other tasks. They each took turns presenting to Dr. Enderle and compiling their individual weekly reports into a team report. Although they each completed individual assignments, they were usually collaborating on a larger task.
Team Member 3: Omar Chawiche

In the first semester of Senior Design, Omar’s main component was the optical system of the optimal design. But since the project completely changed this semester, Omar’s main component changed to the electric circuit part of the device. However, since the team was behind in the time line, the three team members were working together on every part of this project in order to complete it on time. Research was done by Omar on how transmitters and receivers work, how FlexiForce® sensors measure force, and on microprocessors. Omar helped building and calibrating the force sensitive resistor insoles using the Tinius-Olson compressive machine. He also worked on completing the circuit board for both the transmitter and receiver. Overall, every team member put a considerable amount of effort in every part of this project which led to a finished project.

9. Conclusion
As described, the optimal gait analysis laboratory design will incorporate a hands-on approach to gait analysis through the use of wireless footswitches, force sensitive resistor insoles, National Instruments equipment, and an interactive National Instruments LabVIEW® software program. With the set-up of this design, the students will be able to gain a deeper understanding of gait analysis with the use of two different types of measuring devices that are used in a clinical setting, which are not currently available for use in the Biomechanics lab. The design also fulfills the upgrade request for the Biomechanics gait analysis lab, which is needed to provide more robust examples of biomechanics applications for the purpose of bridging the gap between the classroom experience and clinical applications.

The force sensitive resistor insoles provide real time applied force that displays on the LabVIEW® front panel and sent to an Excel file for students to create graphs of force vs. time, conductance vs. force, and resistance vs. force. The footswitches provide the amount of time pressure is applied to the heel, 1st metatarsal, 5th metatarsal, and toe over a gait cycle. This information is transmitted by telemetry to the National Instruments equipment describe in the optimal design section, then to LabVIEW®, which calculates the cadence (number of steps per minute), total gait cycle time, stride length, and
velocity. The data can be sent to an Excel file to create graphs as well.

The addition of the FSR insoles and footswitches will add an exciting element to the Biomechanics laboratory in the fall of 2007, since it has been designed and built by fellow students, and has enhance the lab by adding analysis capabilities that did not exist previously. The interactive nature of the program and devices will make the experience more rewarding for the students, as it will be more than theoretical and is similar to real clinical applications. Due to the hard work and perseverance, as a team and individually, this design project was successful in upgrading the Biomechanics laboratory.

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11. Acknowledgements
We would like to express our gratitude to the following individuals for their support and assistance in developing this design.

Dr. John D. Enderle, Client and Advisor
Bill Pruehsner, Advisor for Sr. Design II
David Kaputa, Advisor
Christopher Liebler, Advisor for Sr. Design I
Craig George, Linx Technologies
Bharat Sandhu, Field Engineer, National Instruments
Dr. Peterson, UConn Health Center
Dr. Fox, Uconn
Dr. Ayres, UConn
Robert Bires, Pratt & Whitney

12. Appendix

12.1 Updated Specifications

Introduction and Overview
Dr. John D. Enderle, director of the Biomedical Engineering Department at the University of Connecticut, has expressed his need for an upgraded gait analysis laboratory for the department’s biomechanics course. Currently, the laboratory that is in use focuses on analyzing the acquired data from the gait observations through MaxTRAQ® and MaxMATE® computer software applications. The upgraded gait analysis
laboratory will incorporate a more hands-on approach to gait analysis through the use of wireless footswitches, force sensitive resistor insoles, National Instruments equipment, as well as an interactive LabVIEW® software program. The footswitches were purchased from B&L Engineering and the force sensitive resistor insoles were designed, build, and calibrated by the team. Also, the data acquisition was accomplished using the National Instruments PXI-1031, PXI-6040E, and the BNC-2120 that already exist in the lab. The new gait analysis lab will be ready for use in the Biomechanics class beginning in the Fall of 2007. The biomechanics students will be able to determine the acceleration, velocity, position, and forces for one complete walking cycle at the completion of their gait analysis laboratory.

**Technical Specifications**

**Footswitches**

Size: US Men’s size 9; US Women’s size 7
Materials: closed cell neoprene with conductive rubber modules placed in small holes, brass shim plates, wires, and black duct tape
Lead Connectors: female 5-pin LEMO (ECG.0B.305.CLV)
               male 5-pin LEMO (FGG.0B.305.CLAD52Z)

**Force Sensitive Resistor (FSR) Insoles**

Force Sensitive Resistors:
Tekscan FlexiForce® Sensors A201-100
Ranges up to 1000 lbs by reducing the resistor value and/or voltage of driver circuit
Storage: 15°F to 165°F
Physical Properties:
- Thickness - 0.008" (.208mm)
- Length - 8" (203mm), 6" (152mm), 4" (102mm), 2" (51mm)
- Width - 0.55" (14mm)
- Sensing Area - 0.375" diameter (9.53mm)
- Connector - 3-pin male square pin
- Thickness - 0.008" (.208mm)

Typical Performance:
- Linearity Error: +/-5%
- Repeatability: +/-2.5% of full scale (conditioned sensor, 80% force applied)
• Hysteresis: <4.5% of full scale (conditioned sensor, 80% force applied)
• Drift: <5% per logarithmic time scale (constant load of 90% sensor rating)
• Response Time: <5 microseconds
• Operating Temperatures: 15°F to 140°F (-9°C to 60°C)
• Force Range: 0-100 lbs. (440 N)
• Temperature Sensitivity: Output variance up to 0.2% per degree F (approximately 0.36% per degree C)

Insoles:
• Scotch tape, double-sided
• Duct Tape – Gorilla Tape, black, tensile strength=58 lbs/in, adhesive strength=17-18 mils, max temp=200°F, UL723
• Electrical Tape – multicolor, ACE® brand, 7.0mil, UL74HK, max 600V, max 80°C(176°F), ¾”X12’
• SOF® Comfort Insoles (Women) – one size/cut to size
• Odor-Eaters® Ultra Comfort (Men) – one size/cut to size
• Rubber disks – ACE® Red Rubber Sheet Packing# 40215 for washers and gaskets, 1/16” thick (durometer)
• Electrical Tape – RadioShack® black, abrasion resistant, water resistant, oil resistant, grease resistant, salt water resistant, 7.0mil, UL Listed, max 600V, max 80°C(176°F), ¾”X60’
• Wires – multicolor

Lead Connectors:  
female 5-pin LEMO (ECG.0B.304.CLL)  
male 5-pin LEMO (FGG.0B.304.CLAD52Z)

Circuitry Components for Driver Circuit

Operational Amplifier – TL072
• Supply voltage, VCC+ (see Note 1) 18 V
• Supply voltage, VCC– (see Note 1) -18 V
• Differential input voltage, VID (see Note 2) ±30 V
• Input voltage, VI (see Notes 1 and 3) ±15 V
• Duration of output short circuit (see Note 4) unlimited
• Operating free-air temperature range, TA: C suffix 0°C to 70°C
• I suffix -40°C to 85°C
• M suffix -55°C to 125°C
• Storage temperature range -65°C to 150°C

Microprocessor (PIC16F873)
• High performance RISC CPU
• Operating speed: DC - 20 MHz clock input
• DC - 200 ns instruction cycle
• Up to 8K x 14 words of FLASH Program Memory
• Up to 368 x 8 bytes of Data Memory (RAM)
• Up to 256 x 8 bytes of EEPROM Data Memory
• Interrupt capability (up to 14 sources)
• Programmable code protection
• Power saving SLEEP mode
• Selectable oscillator options
• Low power, high speed CMOS FLASH/EEPROM technology
• Fully static design
• In-Circuit Serial Programming (ICSP) via two pins
• Single 5V In-Circuit Serial Programming capability
• Processor read/write access to program memory
• Wide operating voltage range: 2.0V to 5.5V
• High Sink/Source Current: 25 mA
• Low-power consumption:
  o < 0.6 mA typical @ 3V, 4 MHz
  o 20 µA typical @ 3V, 32 kHz
  o < 1 µA typical standby current
• Timer0: 8-bit timer/counter with 8-bit prescaler
• Timer1: 16-bit timer/counter with prescaler, can be incremented during SLEEP via external crystal/clock
• Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler
• 10-bit multi-channel Analog-to-Digital converter
• Synchronous Serial Port (SSP) with SPI (Master mode) and I2C (Master/Slave)
• Operating Frequency DC - 20 MHz
• FLASH Program Memory (14-bit words) 4K
• Data Memory (bytes) 192
• EEPROM Data Memory 128

Voltage Regulator (UA7905)
• Ratings: 5V - 1A
• Encasement: TO220 metal
• Operating Temperature: -40° to +125°C

Capacitors (0.1µF)

Resistors (varying from 9kΩ to 10kΩ)

Toggle Switches
• 7301MD9AV2BE: 3PDT Vertical Right Angle Thru-Hole Toggle Switch
• 7201MD9AV2BE: 2PDT Vertical Right Angle Thru-Hole Toggle Switch
• Contact Rating: B contact material: 0.4VA max. @ 20V AC or DC max. Q contact material: 5 AMPS @ 120V AC or 28V DC; 2 AMPS @ 250V AC. See page G-16 for additional ratings
• Electrical Life: 7X01 and UX1 models: 100,000 make-and-break cycles at full load. All other models: 40,000 cycles
• Contact Resistance: Below 10 mΩ typ. initial @ 2-4V DC, 100 mA, for both silver and gold plated contacts
• Insulation Resistance: 109 Ω min
• Dielectric Strength: 1000Vrms min. @ sea level
• Operating Temperature: −30ºC to 85ºC
• Solderability: Per MIL-STD-202F method 208D, or EIA RS-186E method 9 (1 hour steam aging)

Coin Cell Battery Holder (BA2032)
• Press to eject feature

Battery Holders – 9V

Boxes (377-1217-ND)
• Material: ABS Thermoplastic (flammability rating of UL94V-0 at 0.080” thickness & continuous use temperature of 70ºC)

Telemetry Components

KH Basic Evaluation Kit 418Hz (EVAL-418-KH)
• Allows evaluation KH Series and testing for the design process
• Features: pre-built evaluation boards for range testing and benchmarking; extra modules
• Kit Includes: 2 Assembled evaluation boards, 2 TX/Encoder Modules*, 2 RX/Decoder Modules*, 2 CW Series Antennas, Lithium Batteries, Data Guides, FCC Part 2 & 15 Guidelines (* one mounted on demo PCB)

Transmitter/Encoder (TXE-418-KH)
<table>
<thead>
<tr>
<th>RF-Parameters</th>
<th>TXE-315-KH</th>
<th>Designation</th>
<th>Min.</th>
<th>Typical</th>
<th>Max.</th>
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<td>315.075</td>
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<td>Harmonic Emissions</td>
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<td>Output Power</td>
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<td>+4</td>
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<td>-</td>
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<td>Vdc</td>
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<td>7x$V_{CC}$</td>
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<td>26bits 3x</td>
<td>26bits 3x</td>
<td>50%</td>
<td>70</td>
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</table>

(Linx Technologies Specification Sheet for TXE-XXX-KH)

**Absolute Maximum Ratings:**

- Supply voltage $V_{CC}$: -0.3 to +6 VDC
- Operating temperature: -30°C to +70°C
- Storage temperature: -45°C to +85°C
- Soldering temperature: +225°C for 10 sec.
- Any input or output pin: -0.3 to $V_{CC}$

*NOTE:* Exceeding any of the limits of this section may lead to permanent damage to the device. Furthermore, extended operation at these maximum ratings may reduce the life of this device.

(Linx Technologies Specification Sheet for TXE-XXX-KH)

Receiver/Decoder (RXM-418-KH)
Antennas (ANT-418-SP-1)

Dip Switch (SDA10H1KD)

- 10 positions
- Contact Rating - 25mA @ 24V or 100mA @ 50V.
- Mechanical & Electrical Life: 1,000 cycles at rated loads
- Contact Resistance: 50mΩ max. initial
- Insulation Resistance: 100 MΩ between terminals
- Dielectric Withstanding Voltage: 300V min. for 1 minute
- Storage Temp.: -40°C to 85°C
- Operating Temp.: -20°C to 85°C
- Operating Force: 800g maximum
- Solderability: Dip and look solderability testing per C&K spec. #448; non-plated edges of terminals permitted

Data Acquisition
National Instruments Measuring and Test Equipment:

National Instruments PXI-1031:
• Accepts 3U PXI and Compact PCI (PICMG 2.0 R 3.0) modules.
• 4-slot chassis with universal AC input, and automatic voltage/frequency ranging.
• DC power input (PXI-1031DC only.)

National Instruments PXI-6040E:
• 16 or 64 analog inputs at up to 1.25 MS/s, 12 or 16-bit resolution
• 2 analog outputs at up to 1 MS/s
• 12 or 16-bit resolution
• 8 digital I/O lines (TTL/CMOS)
• Two 24-bit counter/timers
• Analog and digital triggering
• 14 or 15 analog input signal ranges
• NI-DAQ driver simplifies configuration and measurements.

National Instruments BNC-2120:
• Shielded connector blocks with signal-labeled BNC connectors to connect analog input/output, digital input/output
• Counter/timer signals to multifunction DAQ device
• Provides a function generator, quadrature encoder, temperature reference, thermocouple connector, and LED
• Dimensions - 26.7 by 11.2 by 6.0 cm (10.5 by 4.4 by 2.4 in.)

Computer program

Operating System
Windows XP

Hardware
Pentium(R)4 CPU 1700 MHz Celeron
Microsoft Internet Explorer 6.0
256 MB of RAM

Software Applications
National Instruments LabVIEW® 8.0
### 12.2 Purchase Requisitions and FAX Quotes

**PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB**

<table>
<thead>
<tr>
<th>Team #</th>
<th>Total Expenses</th>
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<tbody>
<tr>
<td>3</td>
<td>442</td>
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**Student Name:** Kimberly Carr  
**Date:** September 11, 2006  
**Team #:** 3  
**Total Expenses:** 442

**Ship to:** University of Connecticut  
Biomedical Engineering  
U-2247, 260 Glenbrook Road  
Storrs, CT 06269-2247

**Attn:**  
**Project Name:** Biomechanics Gait Analysis Lab

**Catalog #**  
**Description**  
**Unit**  
**QTY**  
**Unit Price**  
**Amount**

<table>
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<tr>
<th>Catalog #</th>
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<th>Unit</th>
<th>QTY</th>
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**Shipping**  
**Total:** $442.00

**Comments**

**Price Quote:** 442  
**File Name:**  
**Yes or No:** yes  
**Vendor:** B & L Engineering  
**Address:** 3002 Dow Ave, Suite 416  
Tustin, CA 92780

**Phone:** (714) 505-9492  
**Contact Name:**

**Authorization:**

---

**Instructions:** Students are to fill out boxed areas with white background  
Each Vendor will require a different purchase requisition  
ONLY ONE COMPANY PER REQUISITION
### PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

**Instructions:** Students are to fill out boxed areas with white background. Each Vendor will require a different purchase requisition.

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<tr>
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<td>Biomedical Engineering</td>
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<tr>
<td>U-2247, 260 Glenbrook Road</td>
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<td>Storrs, CT 06269-2247</td>
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**Only One Company Per Requisition**

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<th>Unit</th>
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<td>Flexi-Force A201 (0-100lb. Range) four pack of 2-2&quot; &amp; 2-4&quot; FSRs</td>
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| Comments | |
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<tr>
<th>Vendor:</th>
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<tr>
<th>Address:</th>
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<td></td>
<td>South Boston, MA 02127-1309</td>
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<th>Phone:</th>
<th>ph 800-248-1309 / fax 617-464-4266</th>
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**Total:** $120.00
Each Vendor will require a different purchase requisition.

**PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB**

**Instructions: Students are to fill out boxed areas with white background**

**Each Vendor will require a different purchase requisition**

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<td>Kimberly Carr</td>
<td>University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247</td>
<td>Biomechanics Gait Analysis Lab</td>
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<tr>
<th>Attn:</th>
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<th>Student Initial Budget</th>
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<tr>
<td></td>
<td>Address: 701 Brooks Avenue South Thief River Falls, MN 56701</td>
</tr>
<tr>
<td></td>
<td>Phone: 1 800-344-4539 or 218-681-6674</td>
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<tr>
<td></td>
<td>Contact Name:</td>
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**Authorization:**

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Page 134
### PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

**Instructions:** Students are to fill out boxed areas with white background.

Each Vendor will require a different purchase requisition.

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<td>Angela Ensor</td>
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**Ship to:** University of Connecticut
Biomedical Engineering
U-2247, 260 Glenbrook Road
Storrs, CT 06269-2247

**Attn:** Angela Ensor

**Project Name:** Biomechanics Gait Analysis Lab

**Catalog #** | **Description** | **Unit** | **QTY** | **Unit Price** | **Amount** |
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<tbody>
<tr>
<td>A201-100</td>
<td>Flexi-Force A201 (0-100lb. Range) four pack of 2-2” &amp; 2-4” FSRs</td>
<td>1</td>
<td>$65.00</td>
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**Comments**

- **Vendor:** Tekscan/FlexiForce
- **Address:** 307 W. First Street
  South Boston, MA 02127-1309
- **Phone:** 800-248-1309/ fax 617-464-4266

**Price Quote File Name:** $65.00

**Vendor Accepts Purchase Orders?** Yes or No

- **Authorization:**

**Total:** $65.00
# PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

**Instructions:** Students are to fill out boxed areas with white background. Each Vendor will require a different purchase requisition.

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**Student Name:** Angela Ensor

**Ship to:**
- University of Connecticut
- Biomedical Engineering
- U-2247, 260 Glenbrook Road
- Storrs, CT 06269-2247

**Attn.:** Angela Ensor

**Project Name:** Biomechanics Gait Analysis Lab

**Catalog #** | **Description** | **Unit** | **QTY** | **Unit Price** | **Amount** |
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**Comments:**
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- Shipping: $0.00
- Total: $2.02

**Vendor:** Digi-Key

**Address:**
- 701 Brooks Avenue South
- Thief River Falls, MN 56701

**Phone:** ph 800-344-4539/ fax 218-681-3380

**Contact Name:**

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Page 136
Each Vendor will require a different purchase requisition

**PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB**

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date: October 27, 2006
Student Name: Angela Ensor

<table>
<thead>
<tr>
<th>Team #</th>
<th>Total Expenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$38.28</td>
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</table>

Ship to: University of Connecticut
Biomedical Engineering
U-2247, 260 Glenbrook Road
Storrs, CT 06269-2247

Attn: Angela Ensor

Project Name: Biomechanics Gait Analysis Lab

### Catalog # | Description | Unit | QTY | Unit Price | Amount |
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>7301MD9AV2BE</td>
<td>3PDT Vertical Right Angle Thru-Hole Toggle Switch</td>
<td>1</td>
<td>$12.22</td>
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Comments

Price Quote: $38.28
Shipping

Vendor: OnlineComponents.com
Address: P.O. Box 25905
Los Angeles, CA 90025

Phone: ph 310-452-8516/ fax 310-450-6110

Vendor Accepts Purchase Orders?

Authorization:

Total: $38.28
Each Vendor will require a different purchase requisition

Date: October 27, 2006
Team #: 3
Total Expenses: $99.92

Student Name: Angela Ensor

Ship to:
- University of Connecticut
- Biomedical Engineering
- U-2247, 260 Glenbrook Road
- Storrs, CT 06269-2247

Lab Admin only:
- FRS #
- Student Initial Budget
- Student Current Budget
- Project Sponsor

Attn: Angela Ensor

Project Name: Biomechanics Gait Analysis Lab

<table>
<thead>
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<th>QTY</th>
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<td>Kit-LEMO 0B 4 pin solder</td>
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Comments: Quote Number 6558

Price Quote: $99.92
Shipping: Total: $99.92

Vendor: BKT Supply Co., Inc.
Address: P.O. Box 3167
Syracuse, NY 13220

Phone: ph 888-722-6258/ fax 315-463-7807
Contact Name:

Authorization: ______________________________

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

ONLY ONE COMPANY PER REQUISITION
Each Vendor will require a different purchase requisition

**PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB**

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

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<td>Student Name:</td>
<td>Angela Ensor</td>
<td>Total Expenses:</td>
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<td>Ship to:</td>
<td>University of Connecticut</td>
<td>FRS #:</td>
<td>Lab Admin only:</td>
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<tr>
<td>Attn:</td>
<td>Angela Ensor</td>
<td>Student Initial Budget:</td>
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<td>Project Name:</td>
<td>Biomechanics Gait Analysis Lab</td>
<td>Student Current Budget:</td>
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**Catalog #** | **Description** | **Unit** | **QTY** | **Unit Price** | **Amount** |
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</tr>
</tbody>
</table>

**Comments:** Must indicate in comments of online order "Wave minimum order surcharge per Jim"

**Price Quote:** $7.41

**Vendor:** OnlineComponents.com

**Address:** P.O. Box 25905
Los Angeles, CA 90025

**Phone:** ph 310-452-8516/ fax 310-450-6110

**Authorization:**

---

**File Name:** PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

---

**File Name:** PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB
Each Vendor will require a different purchase requisition

Date: November 7, 2006
Team # 3
Student Name: Angela Ensor
Total Expenses $37.00

Ship to: University of Connecticut
Biomedical Engineering
U-2247, 260 Glenbrook Road
Storrs, CT 06269-2247

Attn: Angela Ensor
Project Name: Biomechanics Gait Analysis Lab

<table>
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<tr>
<th>Catalog #</th>
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<th>Unit</th>
<th>QTY</th>
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<td>377-1217-ND</td>
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Comments
Price Quote $37.00
Shipping $21.00
Vendor Accepts Purchase Orders?
Vendor: Digi-Key
Address: 701 Brooks Avenue South
Thief River Falls, MN 56701
Phone: ph 800-344-4539/ fax 218-681-3380

File Name:

Authorization: ______________________________