Final Report

Biomechanics Gait Analysis Lab

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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 a force plate and platform, footswitches, and 3-D video system, which will give measurements to be analyzed by 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 plate 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. The current video system only uses one camera, which provides a 2-D image to analyze. The new lab will incorporate two cameras into the set-up, to provide a 3-D image to analyze. This will allow the student to calculate the moments, forces, velocity, acceleration, and angles in the three directions of x, y, and z. Currently, the 2-D system only allows for these measurements to be taken in the x and y direction. 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 components to the gait analysis is a true-life measure of ground reaction forces exerted on the foot strike, which are applied in multiple directions, and a 3-D analysis of the gait cycle.

1.2 Project Purpose

Dr. Enderle has requested an expansion of the gait analysis lab by utilizing a force measurement system, a 3-D video 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 in 3-D. 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, along with a 3-D video 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 in 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.

Compression closing switches 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 Shriner’s 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.

This patent is for another type of pressure insole that consists of outer layers that are conductive and an inner layer that is nonconductive.

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.

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 measuring devices and 3-D video system, which will give measurements to be analyzed by National Instruments devices and the LabVIEW® program.

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 for the third alternative design, 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 for 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 16 week time constraints of this design project. Fabricating a force plate is a great choice for the optimal design because the UConn Biomedical Engineering department previously purchased four load cells, which is exactly what we need 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 and safety issues for this design, we are opting to purchase the footswitches from a manufacturer instead of fabricating them ourselves. We came to this decision because fabricating and testing the footswitches ourselves would be extremely time consuming feat and since we are already building a force plate for this design project we feel that purchasing the footswitches is the best option.

The current video system only uses one camera, which provides a 2-D image to analyze. The new lab will incorporate two cameras into the set-up, to provide a 3-D image to analyze. This will allow the student to calculate the moments, forces, velocity, acceleration, and angles in the three directions of x, y, and z. Currently, the 2-D system only allows for these measurements to be taken in the x and y direction. The LabVIEW® program used in this all of the designs will be able to receive the digital signal, or bytes of data, from the digital cameras and force measuring device(s). Also, 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.

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® software 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](image-url)
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](image)

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.
The load cell dimensions are shown in Figure 4 and Table 2.

**Table 1: Thames Side-Maywood 350a Load Cell Technical Specifications**

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

**Figure 4:** Thames Side-Maywood 350a Load Cell Dimensions

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1b
Table 2: Thames Side-Maywood 350a Load Cell Dimensions

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.5</td>
<td>15</td>
<td>24.6</td>
<td>51.6</td>
<td>31.5</td>
<td>130</td>
<td>13.5</td>
<td>18</td>
<td>M12</td>
<td>76.2</td>
<td>25.4</td>
<td>15.8</td>
<td>0.9 kg</td>
</tr>
</tbody>
</table>

All dimensions are in mm

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 analysis laboratory is 6061 aluminum alloy and 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>
<thead>
<tr>
<th>Table 3: Composition of 6061 Aluminum Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Percent (wt%)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>97.9</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4: Mechanical Properties of 6061 Aluminum Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition (Temper Designation)</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Heat Treated (T4)</td>
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</table>

<table>
<thead>
<tr>
<th>Table 5: Composition of 304L Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Percent (wt%)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>0.03 max</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>0.75</td>
</tr>
<tr>
<td>0.045</td>
</tr>
<tr>
<td>0.03</td>
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<td>18-20</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>0.1</td>
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<td>67.045-65.045</td>
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<table>
<thead>
<tr>
<th>Table 6: Mechanical Properties of 304L Stainless Steel</th>
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<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
</tr>
<tr>
<td>Compression Strength (MPa)</td>
</tr>
<tr>
<td>Proof Stress 0.2% (MPa)</td>
</tr>
<tr>
<td>Elongation A5 (%)</td>
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<td>Hardness Rockwell B</td>
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</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
2.1.1.2.1.4 Ground Reaction Forces and Center of Pressure

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 10: Ground Reaction Force](image)

Figure 10d shows a single force, $F$ ($F_1 + F_2 + F_3 + F_4$), and a torque, $T_z$. $F$ here is the ground reaction force. $T_z$ 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), $F + T_z$, 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 ($F$) 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 0. The moment measured from the plate is equal to the moment caused by \( \mathbf{F} \) about the true origin plus \( \mathbf{T}_z \):

![Figure 11: True Origin of Center of Pressure](image)

**Equations:**

\[
\mathbf{M} = [x-a, y-b, -c] \times [F_x, F_y, F_z] + [0, 0, T_z]
\]

or:

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

Eventually:

\[
x = \frac{M_y + cF_y}{F_z} + a \\
y = \frac{M_x - cF_y}{F_z} + b
\]

\[
T_z = M_z - (x-a)F_y + (y-b)F_x
\]
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.

![Sony Handycam DCR-TRV27](image)

**Figure 12:** Sony Handycam DCR-TRV27\(^{3b}\)

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

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.
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.
2.1.1.2.3 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

Figure 17: National Instruments PXI-1031
Figure 1-1. Front View of the PXI-1031 Chassis

Figure 18: National Instruments PXI-1031 Front View

Figure 19: National Instruments PXI-1031 Rear View
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.

**Figure 21:** National Instruments SC-2345

**Figure 22:** National Instruments LEMO Panellete

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.

<table>
<thead>
<tr>
<th>Operating System</th>
<th>Windows XP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td>Pentium(R)4 CPU 1700 MHz Celeron</td>
</tr>
<tr>
<td></td>
<td>Microsoft Internet Explorer 6.0</td>
</tr>
<tr>
<td></td>
<td>256 MB of RAM</td>
</tr>
<tr>
<td>Software Applications</td>
<td>National Instruments LabVIEW® 8.0</td>
</tr>
<tr>
<td></td>
<td>National Instruments Vision Development Module</td>
</tr>
<tr>
<td></td>
<td>- IMAQ Vision 8.0</td>
</tr>
<tr>
<td></td>
<td>- Vision Builder for Automated Inspection (AI)</td>
</tr>
</tbody>
</table>

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 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.

Figure 25: 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.
Figure 27: Digital Waveform Graph (graphical indicator from National Instruments LabVIEW® 7.1)

Figure 28: Waveform Graph (graphical indicator from National Instruments LabVIEW® 7.1)
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.
Figure 29: Complete System Drawing
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.
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 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 30:** Physical Structure of a Basic FSR

**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.

**Figure 32**: Conductance as a function of force for a typical force sensitive resistor

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, Rth is used to set the sensitivity of the switch.

**Figure 33**: An FSR in a Switch Configuration, Using a Comparator
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 in 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
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 7: Closed Cell Neoprene - Styrene Butadiene Rubber
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Elongation, Break (%) (min)</td>
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<td>Tensile Strength (kg/cm²) (min)</td>
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<td>Tear Strength (kg/cm²) (min)</td>
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<td>Compression Set (compressed 50% - 25ºC)</td>
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| Table 8: Nashua 398 Duct Tape Specifications
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<tr>
<td>Backing Material</td>
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<tr>
<td>Tensile Strength</td>
</tr>
<tr>
<td>Adhesion to Steel</td>
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<tr>
<td>Unwind Force</td>
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</table>
2.1.2.2 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.

The cameras provide the following performance abilities:

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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).

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.
2.1.2.4.1 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.

2.1.2.4.2 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 material. 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, atypical 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 Resistors
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

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 though 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.
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 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.

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 an integrated force plate, platform, footswitches, two digital camcorders, 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.

A drawing of the overall system design is shown in Figure 44. 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. The footswitches will be thin insoles, built using four footswitches. 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.

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.
Figure 44: Complete System Drawing
2.2.2 Subunits

2.2.2.1 Force Measuring Devices – Force Plate & Footswitches

2.2.2.1.1 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.

2.2.2.1.2 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.

The technical specifications for the load cells are shown in Table 1.

The load cell dimensions are shown in Figure 4 and Table 2.

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.

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 $350 \pm 3.5 \, \Omega$ (Ohms); if the resistance readings are 'out of spec' than the load cell requires repair.

2.2.2.1.3 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 analysis laboratory is 6061 aluminum alloy and 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. The composition and mechanical properties for 6061 aluminum alloy are shown in Table 5 and Table 6.

The Schematics of the force plate for the gait analysis laboratory is shown below in Figures 6, 7, 8, and 9.

2.2.2.1.4 Ground Reaction Forces and Center of Pressure
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 shows the reference frame of the force plate, with the Z-axis being the vertical while Figure 10b 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, \( \mathbf{F} (F_1 + F_2 + F_3 + F_4) \), 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 \textbf{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: \( \mathbf{F}_x, \mathbf{F}_y \) & \( \mathbf{F}_z \). Among these, \( \mathbf{F}_y \) is along the direction of the motion which reflects the propulsive or braking force. \( \mathbf{F}_z \) always thrusts the body upward.

As Shown in Figure 10, 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 0. The moment measured from the plate is equal to the moment caused by \( \mathbf{F} \) about the true origin plus \( \mathbf{T}_z \):

**Equations:**

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

or:

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

Eventually:

\[
x = -\frac{M_y + cF_x}{F_z} + a \quad y = \frac{M_x - cF_y}{F_z} + b \\
T_z = M_z - (x-a)F_y + (y-b)F_x
\]
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$^{2b}$.

2.2.2.1.5 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$^{1c}$.

2.2.2.1.6 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$^{2c}$. 
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.

For this design, switches will be implemented based upon the force sensitive resistors. The circuit for the switch is shown in Figure 33. The variable resistor, \( Rth \) is used to set the sensitivity of the switch

### 2.2.2.1.7 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).

The output of the footswitches can be visualized as a basographic signal shown in Figure 36. The analysis of the timing of this signal is referred to as basographic analysis

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).
2.2.2.2. 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.
- 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 snapshot of the laboratory set-up in section 2.1.1.1.

2.2.2.3 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 force plate and the footswitches, 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 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 footswitches and 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 footswitches and 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.

2.2.2.4 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, force plate, 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.
2.2.2.4.1 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.

2.2.2.4.2 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 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.
2.2.2.4.3 Footswitch Signal Processing

The signals from the footswitches will need to go through the National Instruments SC-2345 and PXI-6040E to produce data that will be used by the LabVIEW® program. Once the signals from the footswitches are received by 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 above in Figs. 27-28.

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. Also, we are utilizing basic static laws of applied loads, moments, and points of application in order to analyze the raw data that is output from the footswitches and the force plate.

Some economic considerations for this design project include the proposed budget (although not yet specified) and the longevity of the device itself. Although currently we do not have a limited budget, our design needs to be within a reasonable cost, ranging from approximately $450 to $1,500. The gait analysis laboratory that is being designed will need to 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 at least five years of operation.

A major environmental consideration for this design project is the weather conditions and temperature ranges in Connecticut. The gait analysis laboratory will need to be stored in a closet that may or may not have a good source of heat and will hence need to survive the relatively harsh temperatures of Connecticut winters.

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 subjects and testers’ 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 things ourselves which is more cost-effective than purchasing from suppliers.

4. Safety Issues

Safety consideration is one of the most important issues in any project and especially when dealing with electricity. 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 primarily be in contact with the force plate. In addition to walking and stepping on the force plate, students will have to run the PXI-1031 and BNC-2120 equipment, which were built by National Instruments. The safety of these devices, taken into consideration by National Instruments, were assured prior to building and during the testing of those devices.

All of the wires that are connected to the force plate, National Instruments devices, digital cameras, and computer, will be placed in a cable tunnel or conduits, as shown in Fig. 37 and will be taped to the floor using duct tape, so that the wires are not hazardously placed in such a way that a student may trip on them. This will also reduce the chance of an electrical shock to a student.

Figure 37: Cable Tunnels and Conduits¹
Additionally, the correct size will be selected for the electrical cables used, so that the power voltage will not be so great as to cause the cables to heat up and potentially produce a fire. By using conduits to arrange the wires and the right voltage source, students will be safe when using the laboratory set-up.

Another safety issue to take into consideration is the material that will be used in the force plate and the connection circuitry of the load cells. In this design, the force plate will be created using metal. Metal is a good electrical conductor and could be dangerous if the circuitry is not set-up properly. For that reason, the circuitry that is connecting the load cells should be isolated from contact with the metal force plate.

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. Some of those impacts will be discussed next.

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 gait analysis processes in general, including ‘what is gait analysis?’ and ‘what is it used for in the medical field?’ We also learned about the gait cycle and how is it divided into different parts. We have increased our understanding of this process and will highlight some of the knowledge gained with comparisons to what we had previously learned.

During the biomechanics lab, we built a simple LabVIEW® program to process the information recorded from the digital camera. In this design, by building the gait analysis program, we acquire more details and learn more about the different parts of the program and how each part functions and communicates to produce the desired, complex results.

By building the program, we will learn more modules in LabVIEW® and gain more in-depth knowledge of the data the program receives and how it is used. The difference between
creating this program and the one used in the biomechanics class is that we are building the program and not simply using it. The students using the new design will be given portions of the program to get started and will be expected to build a portion of it. Due to time constraints, were students only have one lab section, building the entire program and finishing the entire lab would be impossible.

For the optical devices, we learned the differences between using one or two cameras, and which one is the better option. We have also learned how the cameras should be placed, to include how far apart the two cameras should be placed in order to give an accurate motion recording. Also getting to know the quality of the cameras and how the quality affects the results has been a learning experience.

Concerning the markers used in gait analysis lab, we have found that, in order to detect 3-D motion properly using the cameras, three markers should be placed on each body segment instead of one, as was done in the previous Biomechanics gait analysis lab.

The PXI-1031 and SC-2345 national instrument equipments are being used for the first time in this lab, meaning that we had no prior knowledge about these devices. After creating the first alternative design for the new lab, we have gained more knowledge about how these instruments functions to transform the data from the cameras and the footswitches, so that the collected data can be analyzed.

Adding to all of this new information that we gain in designing the gait lab, we also learned about footswitches and what kind of material is best to use, how many switches are used, and how the switches connect and send data through the system. We also learned about the force plate and what kind of material is best to use and how thick it should be in order to assure lab safety.
7. Budget and Timeline

7.1 Budget

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<th>Items</th>
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<th>Retail (each)</th>
<th>Est. Project</th>
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Total Cost $2,835.15
### 7.2 Timeline

The following table was copied directly from the Microsoft Office Project file we created for the timeline.

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Project Finish Date: Fri 12/1/06

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</tr>
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<td>use the machine shop to form the platform</td>
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<td>take picture of the platform</td>
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<td>implant the PXI-6040E in the PXI-1031</td>
<td>1 day</td>
<td>Fri 10/6/06</td>
<td>Fri 10/6/06</td>
<td>34</td>
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<td>1 day</td>
<td>Fri 10/6/06</td>
<td>Fri 10/6/06</td>
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</tr>
<tr>
<td>install 8.1 labview software</td>
<td>1 day</td>
<td>Mon 10/9/06</td>
<td>Mon 10/9/06</td>
<td>36</td>
</tr>
<tr>
<td>start building labview program</td>
<td>30 days</td>
<td>Tue 10/10/06</td>
<td>Mon 11/20/06</td>
<td>37</td>
</tr>
<tr>
<td>group meeting</td>
<td>1 day</td>
<td>Tue 10/10/06</td>
<td>Tue 10/10/06</td>
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<tr>
<td>gather information on labview program</td>
<td>7 days</td>
<td>Tue 10/10/06</td>
<td>Wed 10/18/06</td>
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<tr>
<td>finishing labview program</td>
<td>1 day</td>
<td>Mon 11/20/06</td>
<td>Mon 11/20/06</td>
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<tr>
<td>testing labview program</td>
<td>2 days</td>
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<td>Wed 11/22/06</td>
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<td>Fri 10/13/06</td>
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<td>update the website</td>
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<td>Mon 10/16/06</td>
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<tr>
<td>take pictures of the NI devices</td>
<td>1 day</td>
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<td>1 day</td>
<td>Tue 10/17/06</td>
<td>Tue 10/17/06</td>
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<td>first visit for gait analysis clinic</td>
<td>1 day</td>
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<td>Wed 10/18/06</td>
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<td>test the video cameras</td>
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<td>take pictures of the video cameras</td>
<td>1 day</td>
<td>Thu 10/19/06</td>
<td>Thu 10/19/06</td>
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<td>Fri 10/20/06</td>
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<td>double check on the lab set up</td>
<td>1 day</td>
<td>Mon 10/23/06</td>
<td>Mon 10/23/06</td>
<td>50</td>
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<td>put all the wires in a conduits</td>
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<td>Tue 10/24/06</td>
<td>Wed 10/25/06</td>
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<tr>
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<td>1 day</td>
<td>Tue 10/24/06</td>
<td>Tue 10/24/06</td>
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<tr>
<td>connect the cameras to the PXI-1031</td>
<td>1 day</td>
<td>Wed 10/25/06</td>
<td>Wed 10/25/06</td>
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<td>gather more information about the NI SC-2345</td>
<td>2 days</td>
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<td>connect the force plate to the SC-2345</td>
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<td>Fri 10/27/06</td>
<td>Fri 10/27/06</td>
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<td>connect the footswitches to the SC-2345</td>
<td>1 day</td>
<td>Mon 10/30/06</td>
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<td>connect the SC-2345 to the PXI-1031</td>
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<td>Fri 11/3/06</td>
<td>Fri 11/3/06</td>
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<td>find a way of attaching the markers</td>
<td>2 days</td>
<td>Mon 11/6/06</td>
<td>Tue 11/7/06</td>
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<td>meet with Bharat Sandhu(from NI)</td>
<td>1 day</td>
<td>Tue 11/7/06</td>
<td>Tue 11/7/06</td>
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<td>1 day</td>
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<td>moving and setting up all the equipement to room 215</td>
<td>1 day</td>
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<td>connecting all the wires</td>
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<td>Thu 11/9/06</td>
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<td>68</td>
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<td>take pictures of the lab</td>
<td>1 day</td>
<td>Thu 11/9/06</td>
<td>Thu 11/9/06</td>
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<td>70</td>
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<td>recheck all the circuit</td>
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<td>covering the lab windows with shades</td>
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<td>update the website</td>
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<td>1 day</td>
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<td>1 day</td>
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<td>Fri 11/17/06</td>
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</tr>
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<td>taking pictures when testing</td>
<td>2 days</td>
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<td>Fri 11/17/06</td>
<td></td>
</tr>
<tr>
<td>work on solving any problems that occurs</td>
<td>5 days</td>
<td>Fri 11/17/06</td>
<td>Thu 11/23/06</td>
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<td>Tue 11/21/06</td>
<td>Tue 11/21/06</td>
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<td>5 days</td>
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<td>1 day</td>
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<td>Fri 11/24/06</td>
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<td>start preparing for final report</td>
<td>5 days</td>
<td>Fri 11/24/06</td>
<td>Thu 11/30/06</td>
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</tr>
<tr>
<td>start preparing for final presentation</td>
<td>5 days</td>
<td>Fri 11/24/06</td>
<td>Thu 11/30/06</td>
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<tr>
<td>cleaning up the lab before open house</td>
<td>1 day</td>
<td>Mon 11/27/06</td>
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<td>1 day</td>
<td>Tue 11/28/06</td>
<td>Tue 11/28/06</td>
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<td>do final testing</td>
<td>1 day</td>
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<td>Wed 11/29/06</td>
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<td>final lab report due</td>
<td>1 day</td>
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<td>1 day</td>
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<td>invite our client to the presentation</td>
<td>1 day</td>
<td>Mon 11/27/06</td>
<td>Mon 11/27/06</td>
<td></td>
</tr>
<tr>
<td>invite people who helped us in the project</td>
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<td>Mon 11/27/06</td>
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<tr>
<td>taking pictures during final demonstration</td>
<td>1 day</td>
<td>Fri 12/1/06</td>
<td>Fri 12/1/06</td>
<td>90</td>
</tr>
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<td>final demonstration to our client</td>
<td>1 day</td>
<td>Thu 11/30/06</td>
<td>Thu 11/30/06</td>
<td>91</td>
</tr>
<tr>
<td>create a show board of the project</td>
<td>3 days</td>
<td>Mon 11/27/06</td>
<td>Wed 11/29/06</td>
<td></td>
</tr>
<tr>
<td>submitting new ideas of improving the lab in the future</td>
<td>1 day</td>
<td>Thu 11/30/06</td>
<td>Thu 11/30/06</td>
<td>96</td>
</tr>
<tr>
<td>final update of the website</td>
<td>1 day</td>
<td>Wed 11/29/06</td>
<td>Wed 11/29/06</td>
<td></td>
</tr>
<tr>
<td>final meeting of the group</td>
<td>1 day</td>
<td>Tue 11/28/06</td>
<td>Tue 11/28/06</td>
<td>93</td>
</tr>
<tr>
<td>given the final presentation</td>
<td>1 day</td>
<td>Fri 12/1/06</td>
<td>Fri 12/1/06</td>
<td>97</td>
</tr>
</tbody>
</table>
8. Team Members Contributions to the Project

The four components of the project were divided among the three members, each being responsible for the extensive details of the assigned component. The purpose for dividing up the components was to ensure that each component was thoroughly investigated, with the concurrence that each member is responsible for assisting one another, which requires each member to pursue an understanding of each member’s elected component. All team members met on a weekly basis to plan and coordinate their efforts and remained in communication between meetings through e-mail and instant messaging.

Team Member 1: Kimberly Carr

Kimberly’s main component was the force measuring devices and the platform. Extensive research was done by Kimberly to determine force measuring devices that are commonly used to analyze a subject’s gait and which one would be the best option for the University of Connecticut’s Biomechanics laboratory. Following Kimberly’s research, she concluded that force plates, pressure mats, footswitches, and gait mats are the force measuring devices most often used in clinical gait settings. Kimberly met with David Kaputa, the Teaching assistant for the Biomechanics lab as well as one of our clients, several times to gain a better understanding of what the biomechanics lab needed to learn from the force measuring device as well as the limitations of size and weight the device had to follow. After much deliberation, Kimberly decided to focus on the force plate, footswitches, and pressure mat for the three alternative designs of the design project. Additionally, Kimberly contributed by writing portions of the project documents and assisted her fellow team members by editing documents for grammar and spelling. She also helped by putting everyone’s components together into one cohesive document.
Team Member 2: Angela Ensor

Angela’s main component was the National Instruments LabVIEW® program and modules. In order to understand the computer program requirements, a thorough research of the other components was required, so that she would know what type of information was to be received by the program. She used resources online, attended a National Instruments seminar on measurement and control devices, and consulted with Bharat Sandhu, National Instruments’ Field Engineer for Western New England. In attending the National Instruments seminar, she was able to discover the optimal devices needed for conditioning the signals received from the measuring devices, showing the importance of assisting her team members, while ascertaining through the live demonstration that the software applications will perform the necessary tasks for gait analysis. She also consulted with David Kaputa on the features of LabVIEW and the features available at the school, as well as the layout of the room for the set-up of the gait analysis lab. Additionally, Angela contributed by writing portions of the project documents and assisted her fellow team members by editing documents for grammar and spelling for a team member, and sending useful information on the other components that was discovered in researching for her assigned component.

Team Member 3: Omar Chawiche

Omar’s main component was the optical system, which includes the digital video cameras, and the National Instruments devices, such as the PXI-1031, PXI-1411, PXI-6040E and SC-2345. Research was done by Omar on the optical system to gain a deeper understanding on how many cameras should be used and the differences in using more than one camera. This research also helped with determining camera placement in the laboratory, and in
which position it will provide 3-D images. Omar met with David Kaputa, the Teaching Assistant for the Biomechanics lab, several times to gain a better understanding on the way that the NI devices operate and to ascertain the number of PXI-1411 cards that are required to use to two digital video cameras. Additional research was completed by Omar on the National Instruments device to find out if another circuit was needed between the connecting of the force plate and the PXI-1031. That research was facilitated with assistance from his teammate Angela Ensor. Omar also contributed in writing portions of the project documents and in preparing and presenting a portion of the project proposal.

9. Conclusion

As described, the optimal gait analysis laboratory design will incorporate a hands-on approach to gait analysis through the use of an integrated force plate, platform, footswitches, two digital camcorders, 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 is 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 a more robust example of biomechanics applications for the purpose of bridging the gap between the classroom experience and clinical applications.
10. References

References for Section 1

1a. *Instrumented Gait Analysis Systems* by Ernest L. Bontrager, MS.


2a. www.toolsandsupplies.com/shimstockinfo.htm

3a. Tekscan, Inc.

   www.tekscan.com

Mentioned companies can be found at:

   www.teckscan.com
   www.bertec.com
   www.amti.biz
   www.kistler.com
   www.biometricsltd.com
   www.vicon.com
   www.gait.com
   www.arielnet.com

References for Section 2.1.1


4b. www.bjcraftsupplies.com


References for Section 2.1.2


2c. http://at.or.at/hans/misc/itp/pcomp/fsr.html


References for Section 2.1.3

1d. www.ptjournal.org/April00/public/ad040000399p


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
David Kaputa, Advisor
Christopher Liebler, Advisor
Bharat Sandhu, Field Engineer, National Instruments
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 mainly 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 an integrated force plate, footswitches, two digital video cameras, as well as an interactive LabVIEW® software program. The force plate is to be designed and built using four load cells that were previously purchased by the department and can withstand up to 300 kg each. Also, the data acquisition must be done using the National Instruments PXI-1031, PXI-1411, and PXI-6040E that already exist in the lab, in addition the SC-2345 will be purchase to use in the lab for measuring and providing excitation to the force measurement device. 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, angles, and forces for one complete walking cycle at the completion of their gait analysis laboratory.

Technical Specifications

Force Plate Parameters

Size: 508mm W X 464mm L X 25.4mm H
Weight: 18 pounds
Durability: Must be durable and wear resistant with a reasonably long lifetime
Load Cells: Four Thames Side-Maywood Series 350i stainless steel shear beam load cells for industrial weighing
- Load Range: 300kg each
- Combined Error: <±0.017%
- Non-repeatability: <±0.015%
- Creep: <±0.016%
- Temperature Effect on Zero Balance: <±0.01%/°C
- Operating Temperature Range: -20°C to +70°C
- Safe Overload: 150%
- Ultimate Overload: 200%
- Input Resistance: 400 Ω±30
- Output Resistance: 350 Ω±1.5
- Supply Voltage Recommended: 10V
- Supply Voltage Maximum: 15V

**Footswitches**

Size: US Men’s size 9
US Women’s size 7

Lead Connector: 5-pin LEMO

**Platform Structural Considerations**

Size - 840mm W
2440mm L
Weight - 50 pounds
Stability - Withstand load up to 600 kg

**Image and Data Acquisition**

Two Tripods for Sony Handycam DCR-TRV27
Two Digital video cameras:
- IEEE-1394 interface
- 690k pixels
- Megapixel still images at 1152 * 864 or 640 * 480
- MPEG movie EX mode
- 10X Optical/120X Precision digital zoom
- S-video cable
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-1411:
- Color or monochrome acquisition
- 1 NTSC, PAL, S-Video, RS-170, or CCIR input
- 3 by 8-bit RGB look-up table
- 1 external trigger/digital I/O line
- Transfer rates up to 132 Mbytes/s

National Instruments SC-2345:
- Signal conditioning for DAQ systems
  - 16 analog inputs
  - 8 digital I/O lines
  - 2 unconditioned counter/timers
- NI-DAQ driver software simplifies configuration, measurement, and scaling

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.
**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
National Instruments Vision Development Module
  o IMAQ Vision 8.0
  o Vision Builder for Automated Inspection (AI)

**Power Source**
Electrical Outlet – 120 Volts Alternating Current
## 12.2 Purchase Requisitions and FAX Quotes

### 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

<table>
<thead>
<tr>
<th>Date:</th>
<th>Team #</th>
<th>Student Name:</th>
<th>Total Expenses</th>
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<td>Angela Ensor</td>
<td>$1,055.87</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

**ONLY ONE COMPANY PER REQUISITION**

<table>
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<tr>
<th>Catalog #</th>
<th>Description</th>
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<th>QTY</th>
<th>Unit Price</th>
<th>Amount</th>
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<td>777459-37</td>
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**Comments**

- Price Quote: $1,055.87
- File Name: 632937
- Yes or No Vendor Accepts Purchase Orders: No

**Shipping**: $38.87

**Total**: $1,055.87

**Vendor:**

- National Instruments

**Address:**

- Sales Office
- 11500 N Mopac Expwy
- Austin, TX 78759-3504

**Phone:**

- (512) 683-0100

**Contact Name:**

- Nicole Link

**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

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<th>Total Expenses</th>
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<tbody>
<tr>
<td>April 20, 2006</td>
<td>3</td>
<td>$196.62</td>
</tr>
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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

---

**ONLY ONE COMPANY PER REQUISITION**

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**Comments**

**Price Quote:** $196.62

**Shipping:** $5.50

**Vendor Accepts Purchase Orders?**

**Vendor:** Sony

**Address:** SonyStyle.com

**Phone:** (877) 865-7669

**Authorization:**

---

Page 93
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

<table>
<thead>
<tr>
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<tr>
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Ship to: University of Connecticut
Biomedical Engineering
U-2247, 260 Glenbrook Road
Storrs, CT 06269-2247

Attn: Kimberly Carr

Project Name: Biomechanics Gait Analysis Lab

ONLY ONE COMPANY PER REQUISITION

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Price Quote: $402.00
File Name: 041906A
Vendor Accepts Purchase Orders?: Yes
Vendor: B & L Engineering
Address: Sales Office
3002 Dow Avenue, Suite 416
Tustin, CA 92780
Phone: (714)505-9492
Contact Name: Lee Barnes

Authorization:

Shipping: $12.00
Total: $402.00
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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**ONLY ONE COMPANY PER REQUISITION**

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Comments

Price Quote $950.15

File Name: Q60420PH005

Vendor Accepts Purchase Orders?

Vendor: Yarde Metals

Address: Sales Office

45 Newell Street

Southington, CT 06489

Phone: (860)406-6061

Contact Name: Kevin Pryor

Shipping $12.00

Total: $950.15

Authorization:
Quotation No. 632937

Please indicate the above quote number when ordering for faster processing.

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Shipping and Handling: $38.87
Total: $1,055.87

Currency quoted in: U.S. Dollars

To ensure the highest quality service in order processing and support after delivery, please provide end-user information with your purchase order.

Payment Terms: Net 30
Quote Valid Until: 20-MAY-06
Freight Terms: Flat Rate Shipping Fee Charge

All sales are subject to the enclosed National Instruments terms and conditions of quotation and sale. National Instruments shall not be bound by any conflicting or additional Terms and Conditions. Standard shipping dates are based on product availability at time of quotation and are subject to change without notice. Not all products produced by National Instruments are made in the U.S.A.

Yours sincerely,
National Instruments Corporate
Link, Nicole Catherine
National Instruments Terms and Conditions of Sale

Customer and National Instruments ("NI") agree that the purchase and sales of NI hardware and software products ("the Products") are made under these terms and conditions, and that NI SHALL NOT BE BOUND BY CUSTOMER'S ADDITIONAL OR DIFFERENT TERMS. Customer's order and purchase of the Products shall constitute acceptance of these terms and conditions.

1. TITLE. Title to the Products shall pass at NI's plant; however, if Customer is the United States or any political subdivision of the United States, title shall pass at Customer's plant. NI retains a security interest and right of possession in the Products until Customer makes full payment.

2. TAXES. Product prices are exclusive of, and Customer shall pay, applicable sales, use, service, value added or like taxes, unless Customer has provided NI with an appropriate exemption certificate for the delivery destination acceptable to the applicable taxing authorities. For all Canadian orders, 7% GST will be added to the invoice amount. For customers in Nova Scotia, New Brunswick, and Newfoundland and Labrador, 15% HST will be added to the invoice amount where applicable. For customers in Quebec, 7% GST and 6.955% QST will be added to the invoice amount where applicable. Customers who are exempt from HST or QST must provide proof of exemption.

   - GST No.: R140637471
   - QST No.: 10-1095-4823TQ0002

3. PRICES AND PAYMENT. All quotations shall expire thirty (30) days from date of issuance, unless otherwise set forth on the quotation or agreed in writing. Customer shall make payment in full prior to or upon delivery by cashier's check, credit card, or money order, unless NI approves Customer for credit terms. If NI approves Customer's credit application, payment shall be due no later than 30 days from the date of NI's invoice. All sums not paid when due shall accrue interest daily at the lesser of a monthly rate of 1.5% or the highest rate permissible by law on the unpaid balance until paid in full. Payments for orders accepted in the United States shall be made in U.S. Dollars. In the event of any order for several units, each unit(s) will be invoiced when shipped. Exceptions will be made for government purchase orders.

3.1 Canadian customers placing orders in Canadian dollars must remit payment to:

   - National Instruments T9646, PO Box 9600, Postal Station A, Toronto, Ontario M5W 1P8

Canadian customers placing orders in US dollars must remit payment to:

   - National Instruments, PO Box 840909, Dallas, TX 75284-0909

4. ORDERS. All orders are subject to acceptance by NI. NI's booking of an order shall constitute its acceptance of an order.

5. DELIVERY. NI shall deliver the Products to a carrier at NI's plant and, if the Products are sold to a Customer outside the United States, shall clear the Products for export destined outside the United States. Customer shall pay all freight charges, applicable import duties, and other necessary fees and shall bear the risks of carrying out customs formalities and clearance. Orders are entered as close as possible to the Customer's requested shipment date, if any. Shipment dates are scheduled after acceptance of orders and receipt of necessary documents. Claims for shipment shortage shall be deemed waived unless presented to NI in writing within forty-five (45) days of shipment.

6. LIMITED WARRANTY. NI hardware Products are warranted against defects in materials and workmanship for a limited period of time from the date NI ships the Products to Customer ("Delivery Date") as follows: non-IEEE 488 hardware Products (one (1) year); IEEE 488 hardware Products (two (2) years); and cables (ninety (90) days). All software Products are licensed to Customer under the terms of the appropriate National Instruments license. For a period of ninety (90) days from the Delivery Date, NI software Products (when properly installed on NI hardware Products) (a) will perform substantially in accordance with the
accompanying written materials, and (b) the medium on which the software product is recorded will be free from defects in materials and workmanship under normal use and service. Any replacement of a licensed software product will be warranted for the remainder of the original warrant period or thirty (30) days, whichever is longer. Customer must obtain a Return Material Authorization number from NI before returning any Products under warranty to NI. Customer shall pay expenses for shipment of repaired or replacement Products to and from NI. After examining and testing a returned product, if NI concludes that a returned product is not defective, Customer will be notified, the product returned at Customer’s expense, and a charge made for examination and testing. This Limited Warranty is void if failure of the Products has resulted from accident, abuse, misapplication, improper calibration by Customer. Customer supplied third party software not intended for use with the applicable NI software, utilization of an improper hardware or software key or unauthorized maintenance or repair.

7. CUSTOMER REMEDIES. NI’s sole obligation (and Customer’s sole remedy) with respect to the foregoing Limited Warranty shall be to, at its option, return the fees paid or repair/replace any defective Products, provided that NI receives written notice of such defects during the applicable warranty period. Customer may not bring an action to enforce its remedies under the foregoing Limited Warranty more than one (1) year after the accrual of such cause of action.

8. RETURN/CANCELLATION/CHANGE POLICY. Customer may return unwanted Products within thirty (30) days of the Delivery Date. Customer shall pay a fifteen percent (15%) restocking charge on any unwanted Products returned to NI. No returns will be accepted after the thirty (30) day period has expired. Where special equipment or services are involved, Customer shall be responsible for all related work in progress; however, NI shall take reasonable steps to mitigate damages immediately upon receipt of a written cancellation notice from Customer. A Return Material Authorization number must be obtained from NI for return of any Products. NI may terminate any order if any representations made by Customer to NI are false or misleading. Changes to orders shall not be binding upon nor be put into effect by NI unless confirmed in writing by NI’s appropriate representative.

9. NO OTHER WARRANTIES. EXCEPT AS EXPRESSLY SET FORTH ABOVE, THE PRODUCTS ARE PROVIDED “AS IS” WITHOUT WARRANTY OF ANY KIND, AND NO OTHER WARRANTIES, EITHER EXPRESSED OR IMPLIED ARE MADE WITH RESPECT TO THE PRODUCTS, INCLUDING BUT NOT LIMITED TO ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, TITLE OR NON-INFRINGEMENT OR ANY OTHER WARRANTIES THAT MAY ARISE FROM USAGE OF TRADE OR COURSE OF DEALING. NI DOES NOT WARRANT, GUARANTEE, OR MAKE ANY REPRESENTATIONS REGARDING THE USE OF OR THE RESULTS OF THE USE OF THE PRODUCTS IN TERMS OF CORRECTNESS, ACCURACY, RELIABILITY, OR OTHERWISE AND DOES NOT WARRANT THAT THE OPERATION OF THE PRODUCTS WILL BE UNINTERRUPTED OR ERROR FREE. NI EXPRESSLY DISCLAIMS ANY WARRANTIES NOT STATED HEREIN.

10. NO LIABILITY FOR CONSEQUENTIAL DAMAGES. The entire liability of NI and its licensors, distributors, and suppliers (including its and their directors, officers, employees, and agents) is set forth above. To the maximum extent permitted by applicable law, no event shall NI and its licensors, distributors, and suppliers (including its and their directors, officers, employees, and agents) be liable for any damages, including, but not limited to, any special, direct, indirect, incidental, exemplary, or consequential damages, expenses, lost profits, lost savings, business interruption, lost business information, or any other damages arising out of the use or inability to use the Products, even if NI or its licensors, distributors, and suppliers has been advised of the possibility of such damages. Customer acknowledges that the applicable purchase price or license fee for the Products reflects this allocation of risk. Because some states/jurisdictions do not allow the exclusion or limitation of liability for consequential or incidental damages, the above limitation may not apply. If the foregoing limitation of liability is not enforceable because an NI product sold or licensed to Customer is determined by a court of competent jurisdiction in a final, non-appealable judgment to be defective and to have directly caused bodily injury, death, or property damage, in no event shall NI’s liability for property damage exceed the greater of $50,000 or fees paid for the specific product that caused such damage.

11. WARNING: (1) NI PRODUCTS ARE NOT DESIGNED WITH COMPONENTS AND TESTING FOR A LEVEL OF RELIABILITY SUITABLE FOR USE IN OR IN CONNECTION WITH SURGICAL IMPLANTS OR AS CRITICAL COMPONENTS IN ANY LIFE SUPPORT SYSTEMS WHOSE FAILURE TO PERFORM CAN REASONABLY BE EXPECTED TO CAUSE SIGNIFICANT INJURY TO A HUMAN. (2) IN ANY APPLICATION, INCLUDING THE ABOVE, RELIABILITY OF OPERATION OF THE SOFTWARE PRODUCTS CAN BE IMPAIED BY ADVERSE FACTORS, INCLUDING BUT NOT
LIMITED TO FLUCTUATIONS IN ELECTRICAL POWER SUPPLY, COMPUTER HARDWARE MALFUNCTIONS, COMPUTER OPERATING SYSTEM SOFTWARE FITNESS, FITNESS OF COMPILERS AND DEVELOPMENT SOFTWARE USED TO DEVELOP AN APPLICATION, INSTALLATION ERRORS, SOFTWARE AND HARDWARE COMPATIBILITY PROBLEMS, MALFUNCTIONS OR FAILURES OF ELECTRONIC MONITORING OR CONTROL DEVICES, TRANSIENT FAILURES OF ELECTRONIC SYSTEMS (HARDWARE AND/OR SOFTWARE), UNANTICIPATED USES OR MISUSES, OR ERRORS ON THE PART OF THE USER OR APPLICATIONS DESIGNER (ADVERSE FACTORS SUCH AS THESE ARE HEREAFTER COLLECTIVELY TERMED “SYSTEM FAILURES”). ANY APPLICATION WHERE A SYSTEM FAILURE WOULD CREATE A RISK OF HARM TO PROPERTY OR PERSONS (INCLUDING THE RISK OF BODILY INJURY AND DEATH) SHOULD NOT BE RELIANT SOLELY UPON ONE FORM OF ELECTRONIC SYSTEM DUE TO THE RISK OF SYSTEM FAILURE TO AVOID DAMAGE, INJURY, OR DEATH, THE USER OR APPLICATION DESIGNER MUST TAKE REASONABLY PRUDENT STEPS TO PROTECT AGAINST SYSTEM FAILURES, INCLUDING BUT NOT LIMITED TO BACK-UP OR SHUT DOWN MECHANISMS. BECAUSE EACH END USER SYSTEM IS CUSTOMIZED AND DIFFERS FROM NI'S TESTING PLATFORMS AND BECAUSE A USER OR APPLICATION DESIGNER MAY USE NI PRODUCTS IN COMBINATION WITH OTHER PRODUCTS IN A MANNER NOT EVALUATED OR CONTEMPLATED BY NI, THE USER OR APPLICATION DESIGNER IS ULTIMATELY RESPONSIBLE FOR VERIFYING AND VALIDATING THE SUITABILITY OF NI PRODUCTS WHENEVER NI PRODUCTS ARE INCORPORATED IN A SYSTEM OR APPLICATION, INCLUDING, WITHOUT LIMITATION, THE APPROPRIATE DESIGN, PROCESS AND SAFETY LEVEL OF SUCH SYSTEM OR APPLICATION.

12. FORCE MAJEURE. NI shall be excused for any delay or failure to perform due to any cause beyond its reasonable control, including but not limited to acts of governments, natural catastrophes, acts of Customer, interruptions of transportation or inability to obtain necessary labor or materials. NI’s estimated shipping schedule shall be extended by a period of time equal to the time lost because of any excusable delay. In the event NI is unable to perform in whole or in part because of any excusable failure to perform, NI may cancel orders without liability to Customer.

13. LIMITED INDEMNITY AGAINST INFRINGEMENT. NI shall, at its own expense, defend any litigation resulting from sales of the Products to the extent that such litigation alleges that the Products or any part thereof infringes any United States patent, copyright, or trademark, provided that such claim does not arise from the use of the Products in combination with equipment or devices not made by NI or from modification of the Products, and further provided that Customer notifies NI immediately upon obtaining notice of such impending claim and cooperates fully with NI in preparing a defense. If Customer provides to NI the authority, assistance, and information NI needs to defend or settle such claim, NI shall pay any final award of damages in such suit and any expense Customer incurs in NI’s written request, but NI shall not be liable for a settlement made without its prior written consent. If the Products are held to be infringing and the use thereof is enjoined, NI shall, at its option, either (i) procure for the Customer the right to use the Products, (ii) replace the Products with others which do not constitute infringement, or (iii) remove the infringing Products and refund the payment(s) made therefor by Customer. The foregoing states the Customer’s sole remedy for, and NI’s entire liability and responsibility for, infringement of any patent, trademark, or copyright relating to the Products provided hereunder. THIS LIMITED INDEMNITY IS IN LIEU OF ANY OTHER STATUTORY OR IMPLIED WARRANTY AGAINST INFRINGEMENT.

14. ACKNOWLEDGMENT/GOVERNING LAW. Customer acknowledges reading these Terms and Conditions, understands them and agrees to be bound by them. A waiver of any provision of this agreement shall not be construed as a waiver or modification of any other term hereof. With respect to all orders accepted by NI in the United States, disputes arising in connection with these Terms and Conditions of Sale shall be governed by the laws of the State of Texas without regard to principles of conflicts of laws. With respect to all orders accepted by NI outside the United States, disputes arising in connection with these Terms and Conditions of Sale shall be governed by the laws of the country and locality in which NI accepts the order without regard to principles of conflicts of laws.


Rev (05/06/04)
**Shipping address**

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<tr>
<td><strong>State</strong> Connecticut</td>
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**Shipping method**

- **Ground**: 6-10 Business Days
  - Delivered Monday-Saturday, except TVs above 27" (no Saturday).
  - No P.O. boxes or APO/FPO addresses.
- **Expedited**: 3-4 Business Days
  - No weekend delivery, P.O. boxes or APO/FPO addresses.
  - No P.O. boxes or APO/FPO addresses.
Express: Two Business Days
No weekend delivery, P.O. boxes or APO/FPO addresses.

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Close  Calculate

QUOTATION (ACKNOWLEDGEMENT)
No. Q60420PH005        Date: 04/20/06
CUSTOMER'S RFQ
No. KIMBERLY CARR

Delivery Date: 4/25/06
F.O.B.: DELIVERED
SHIP VIA: OUR TRUCK

CUSTOMER: 26831

UNIVERSITY OF CONNECTICUT
PURCHASING DEPT
U-3078 181 AUDITORIUM ROAD
STORRS CT 06269-3076

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Visit us at WWW.YARDE.COM  E-mail: sales@yarde.com