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Dynamic Device for Real Time Acquisition of Angular Flexion of the Knee Joint During Race Walking

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Abstract

This project report describes the design, construction, and testing of a device that measures knee flexion angle for the competitive sport of Race Walking. The goal is to provide the sport with a means of indisputable angular measurement for the purpose of improved rule enforcement. The device is designed to aid both judging officials and competitors alike in their respective training through real time accurate angular readout with both visual and audible alerts. Data analysis compares the three angular measurement mediums: the human eye, the device, and high-definition video recording. The results of this analysis show general agreement for all modes, complemented by personal recommendations for future improvements.

Executive Summary

Novice and veteran race walkers alike must keep their knee at a zero degree flexion angle while their leg is in contact with the ground in order to properly participate in the sport of race walking without disqualification. Currently, there is only one method of judging to declare whether or not the leg is straight and this method consists of the human eye and human experience. However, there have been thoughts throughout the sport of using video to better decide whether or not the racer has a “bent knee”.

Through the design, implementation, and testing of a real time data acquisition system incorporated into a knee device, it has been shown that a device that physically measures the knee flexion angle through a voltage measurement converted to angles is more accurate than video measurements from a stationary position. The device produced an average difference of 5.06 ± 1.41 degrees whereas the video analysis produced an average difference of 6.34 ± 2.82. The video could theoretically achieve a smaller average difference than the device, but it was concluded that the device was more accurate for the portion of the stride where the subject was in contact with the ground. The larger video difference is mainly due to the fact that the viewing angle of the racer changes too much if the video camera is stationary. Although it is highly unlikely that the device could be implemented into actual races anytime in the near future, the device can be used as a training method for not only race walkers, but for judges as well.

It is recommended that the device be used in conjunction with a wireless data logger that can send real-time graphical measurements to an iPhone, iPad, or computer within the vicinity of the trainee. This would also allow for judges-in-training to simultaneously see the race walkers leg in motion and the corresponding data to help differentiate between a straight and bent knee. Another recommendation is the use of a 3V voltage regulator to generate more consistent data

output from the potentiometer on the device. With suggested improvements the device will be very useful and invaluable in the training of judges and walkers alike.

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1. Introduction

Knee flexion is the act of bending one's knee using flexor muscles and ligaments from the straight position to a bent position. A corresponding angular measurement can be made on knee flexion in order to quantify how far a knee is actually bending. On the other end of the spectrum, there is knee extension, which is the act of extending one's knee from the bent position to the straight position.

Knee flexion measurements can help in the understanding of biomechanics in a variety of activities and sports. This project is specifically interested in measuring knee flexion angle for the sport of race walking. In the sport the athlete's knee flexion angle is critical in their effort to avoid disqualification. If the knee is not straightened, or at a flexion angle of roughly zero degrees, when the heel strikes the ground, the athlete can be disqualified for what judges call a "bent knee." Another race walking rule that may lead to disqualification is whether or not both the athlete's feet leave the ground during their stride. These two infractions are caught by judges that are placed randomly throughout the 1000 meter course. Some controversy revolves around the method that the judges use to identify bent-knees or feet leaving the ground. The method consists of the judges using their human eye which can process an average of 24-30 frames per second, depending on the person (source). Although it takes three separate judges to disqualify a race-walker via red cards, there has been evidence showing that some race walkers that were disqualified for "bent knees" actually had straight knees when reviewed by video. With almost every judging system, in many different sports, there is always bound to be controversy over imperfect judging methods. Race walking judging is far from perfect, but like anything it has much room for improvement through new technology.

In order for race walkers to consistently keep straight legs, or a knee flexion angle of approximately zero degrees, they must practice their race walking while trying to abide by the rules of the sport. If a race walker is training by his or herself, it is very difficult to personally judge whether or not the knee is completely straight. The goal was to design and implement a knee flexion angle measurement device that was lightweight, accurate, and consistent in order to help race walkers train properly to prevent disqualification by a bent knee. The device may further aid the sport by potentially adding to the judging system, replacing human judges all-together, or even be used to help train judges.

2. Background and Literature Review

One of the biggest problems in the sport of race-walking is bent-knee disqualification. Both novice and veteran race-walkers must keep their leg at a zero degree flexion angle while their leg is in contact with the ground in order to properly participate in the sport without disqualification. This chapter will discuss the ins-and-outs of race-walking along with the concept of knee flexion and how these two go hand-in-hand.

2.1 Race Walking

Although ancient Egyptian hieroglyphics suggest the earliest competitive walking began in 2500 B.C., it was not until 1904 that race walking made its début in the Olympics. Race walking is a sport of technique. Wrong utilization of race walking technique will result in your disqualification from the race. According to the United States of America Track and Field (USATF), "Race walking is a progression of steps so taken that the walker makes contact with the ground so that no visible (to the human eye) loss of contact occurs. The advancing leg must be straightened (i.e., not bent at the knee) from the moment of first contact with the ground until in the vertical upright position." Judging is conducted completely by the sight of the judge, which can result in uncertainty due to judging variables.

2.1.1 Disqualifications

All disqualifications presented by the judges are final. There is no appeal process. There are two types of cards or paddles used when judging race walking. A yellow paddle represents a caution. Cautions are given to a competitor when they are close to failing either of the two rules of race walking: maintaining contact with the ground and keeping a straight knee. A paddle with a "~" symbol represents loss of contact with the ground and a ">" symbol represents a bent knee.

Judges cannot issue the same offense to a walker more than once. When a yellow paddle is issued, the judge records the offense on the Judge's Tally Sheet. A red card or paddle represents failure of the correct technique. As with yellow paddles, red cards of the same offense cannot be given twice to a competitor by the same judge. Once a red card is given, it is recorded on the Tally Sheet and the Chief Judge is notified. In larger competitions, an electronic board will notify competitors of their red card status. Once a competitor receives three red cards, the Chief Judge informs and disqualifies the walker with a red paddle and he or she must remove themselves from the race.

Race walking competitions are held on either tracks or road courses. The number of judges depends on the length of the course. According to the USATF race walk officiating handbook, five judges will be necessary for track races and six to nine judges for road races. All of the appointed judges vote and elect a Chief Judge for the particular race. The Chief Judge is in charge of assigning judging areas and the method they will follow for presenting and communicating of cautions and disqualifications.

Judging a race walking event can be a difficult task to complete. The capability of the human eye can be considered subpar compared to the great speed that the racers' legs are moving. Zhen Wang won the men's 20 kilometer in the 18th Race Walking Grand Prix in Dublin, Ireland. His official time was 1:19:46. That translates to a 3.99 minute kilometer (6.42min/mile) (International Association of Athletics Federations, 2009). To become a great competitor, the racer needs to increase the number of steps per minute, not the length of his or her stride. An Olympic gold medalist obtained one hundred, eight-six steps per minute (eRaceWalk, 2011). At that speed, it is exceptionally difficult for the human eye to focus on straight legs and maintaining contact for multiple racers at a time.

Because of the above difficulty, certain cues have been created to help judges notice loss of contact or bent knees. To determine if the racer has lost contact with the ground, the judges look at the level of their head. If the racers' heads remain level, it is assumed they are keeping contact with the ground. If their head is bobbing up and down, it is assumed that they have lost contact with the ground and thus their body is moving in a vertical motion. Another method is to look at the shoulders of the racer. There should be little to no horizontal rotation of the shoulders while race walking. Rotating your shoulders while keeping your hips aligned causes your body to propel forward. In the case of race walking, however, this may causes loss of contact with the ground. There are also cues for bent knee. When walking with a straight leg, your quadriceps will not contract when your heel contacts the ground. To visually notice this cue, a judge stands at a bend in the course where he can see the racers straight on to obtain an anterior view of the racers' leg. Figure 1 shows this view of the relaxed quad muscles in a group of race walkers.

Figure 1. Correct race walking technique.

At a competitive level, race walking races are held all over the world. The International Association of Athletics Federation (IAAF) holds series of races in three different categories to qualify the walker for the Race Walking Challenge Final. At the recent 2011 IAAF World Championships Athletics race in Daegu, Korea, three races were held: 20K for women, 20K for men, and 50K for men. In the women's race, six contestants were disqualified. Of the eighteen red cards given out to those disqualified, fourteen were due to a bent leg infraction. In the men's 20K, four walkers were disqualified. Eight out of the twelve cards were given due to bent knees. In the men's 50K, twelve contestants were disqualified due to thirty-five red cards for bent knees. This pattern holds true to a majority of disqualifications; most disqualifications are due to bent leg infractions.

2.2 Biomechanics of the Knee

The knee is the largest and most complicated joint in the body. The joint can be viewed as a hinge joint with a rotational component. It bears a large amount of weight and pressure through its complex series of connected bones, ligaments, tendons, and muscles. It acts as a stabilizer for the lower extremities, and allows for a large range of motion for physical activities. The four basic movements of this joint are flexion, extension, external rotation, and internal rotation. Each movement uses a specific combination of these bones, muscles, and ligaments, which will be explained in detail in the following sections.

2.2.1 Anatomy

There are four skeletal bones that meet at the knee; the femur, the tibia, the fibula, and the patella (seen in Figure 2). The four bones meet at the knee to form two joints: the Tibiofemoral Joint, and the Patellofemoral Joint. The complicated nature of the knee arises from its ability to provide both a hinge movement in addition to supple twisting and gliding movement.

Figure 2: Diagram of bones of the knee joint

The tibiofemoral joint is the largest and most vulnerable in the body. It moves in the sagittal plane to flex and extend the knee, and moves in the transverse plane to rotate when the knee is bent. The movement of this joint is controlled by a number of ligaments, which serve to support and strengthen such joints (Farlex Inc, 2012). Ligaments are bands of tissue that connect bones or cartilages to prevent excessive movement and dislocation (IDEA Health and Fitness Association, 2012). The four main ligaments which control the tibiofemoral joint are the medial collateral ligament (MCL), the lateral collateral ligament (LCL), the anterior cruciate ligament (ACL), and the posterior cruciate ligament (PCL) (Netdoctor, 2012). The collateral ligaments are located on the medial (inner) and lateral (outer) sides of the knee. The MCL provides restraint to valgus, or outward, angulations of the knee, and the LCL provides restraint to the various, or inward, angulations (Medscape Reference, 2012). These two ligaments, with the assistance of a number of other smaller ligaments and tendons, play a large role in keeping the tibiofemoral joint from rotating unnecessarily and limit it to a strictly lateral direction. The cruciate ligaments are located within the tibiofemoral joint itself. The anterior cruciate ligament, displayed in red in Figure 3, restrains the knee's anterior, or frontward, displacement, and limits the tibial rotation upon the femur. It prevents the femur from sliding posteriorly on the tibia, or the tibia from sliding anteriorly on the femur. Likewise, the posterior cruciate ligament, displayed in blue in Figure 3, restrains the knee's posterior, or backward, displacement, and also aids in limiting the tibial rotation upon the femur. The PCL prevents the femur from sliding anteriorly on the tibia, and the tibia from sliding posteriorly on the femur. It also resists hyperextension.

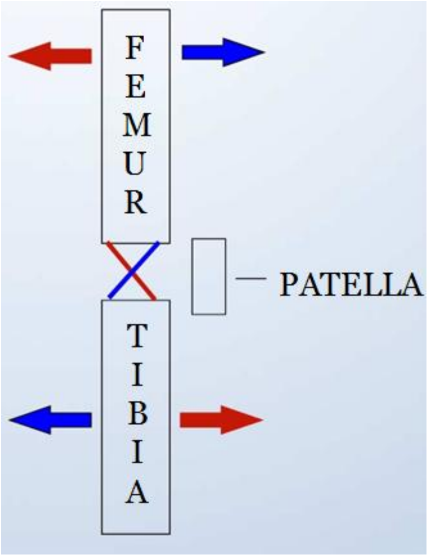


Figure 3: Diagram of Cruciate Ligament Functions

The patellofemoral joint is another component of the knee and is a saddle joint. It slides up when the knee extends, and down when the knee flexes. It is stabilized by a number of smaller ligaments, as well as retinacular tissue (IDEA Health and Fitness Association, 2012). At this joint, the medial and lateral facets of the femoral condyles, the rounded ends of the bone, are connected with the patella. The patella increases the angle of pull of the quadriceps muscles to allow for knee extension. It also provides protection for the anterior components of the knee.

There are additional components to the anatomy of the knee that influence its movement and kinesiology. Menisci are among such components and make a major contribution to the distribution of force loads on the knee joint. Menisci are disks of cartilage that act as cushions between the ends of bones in joints (Farlex Inc., 2012). Their function is to distribute the load at the knee and to absorb shock during physical activity. As much as 71% of the load on the knee joint can be absorbed through the menisci, which aids in protecting the bones and cartilage from significant damage (Beaufils, 2010). They also increase stability of the knee, decrease friction within the knee, and balance the pressure of muscle action.

The anatomical components that have the greatest contribution to kinesiology are the muscles. The knee joint is connected to a number of muscles, which coordinate to move the leg in a variety of directions. The two main muscle groups involved in knee movement are located in the upper half of the leg; the hamstrings and the quadriceps displayed in Figures 4 and 5 respectively.

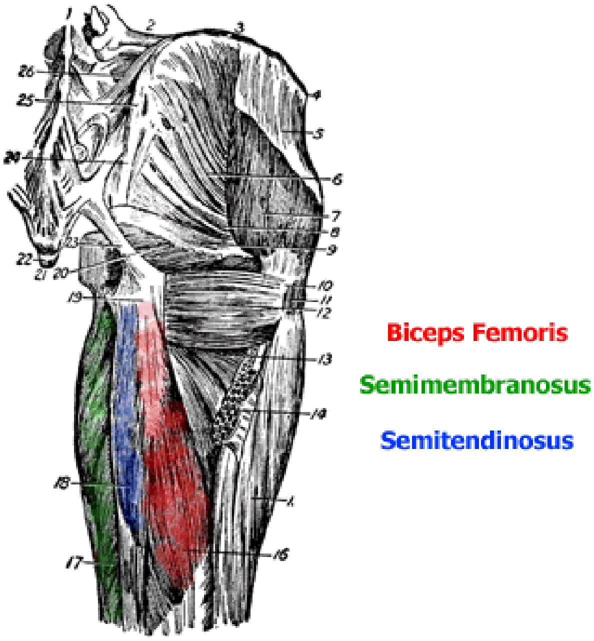


Figure 4: Diagram of the Hamstring Muscles

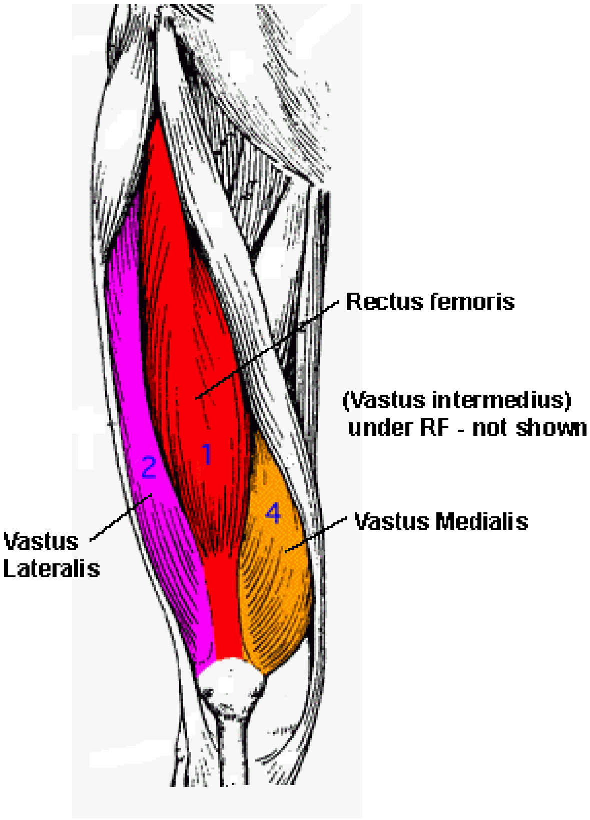


Figure 5. Diagram of the Quadriceps Muscles

The hamstring group is comprised of three different muscles; the biceps femoris, the semimembranosus, and the semitendinosus. The biceps femoris has two heads, one arising from the hip and the other from the femur and both inserting on the tibia. The semimembranosus muscle arises on the biceps femoris, and inserts on the fibula. The third hamstring muscle is the semitendinosus muscle. It arises from the hip and inserts on the tibia.   The semitendinosus muscle is a very broad muscle, and runs on a deeper plane within the leg than the others. These three muscles together form what is referred to as the hamstring group. The anterior thigh muscles, referred to as the quadriceps, are responsible for leg extension. This muscle groups is comprised of four different muscles; the vastus intermedius, the vastus medialis, the vastus lateralis, and the rectus femoris. All four quadriceps muscles insert on the patella and originate from the pelvic region.

The legs bear the most force within in body on a daily basis, and have a complex system of components that allow them to move. While the leg generally moves along one plane on the hinge joint at the knee, there are a number of other less obvious motions that it can experience. The anatomy of the knee allows such movements to occur under large loads, without major damage or injury occurring. Each anatomical component plays a specific role, and each is crucial for motion to occur.

2.2.2 Kinesiology

The knee allows the leg to move in two general directions; flexion or extension. In terms of biomechanics, flexion is the movement in a joint that decreases the angle between two bones. Likewise, extension is the movement in a joint that increases the angle between two bones (Medscape Reference, 2012). In terms of the knee, generally one muscle group is responsible for each action. The hamstring group is most involved in knee flexion, as displayed in Figure 6, whereas the quadriceps group is most involved in knee extension.

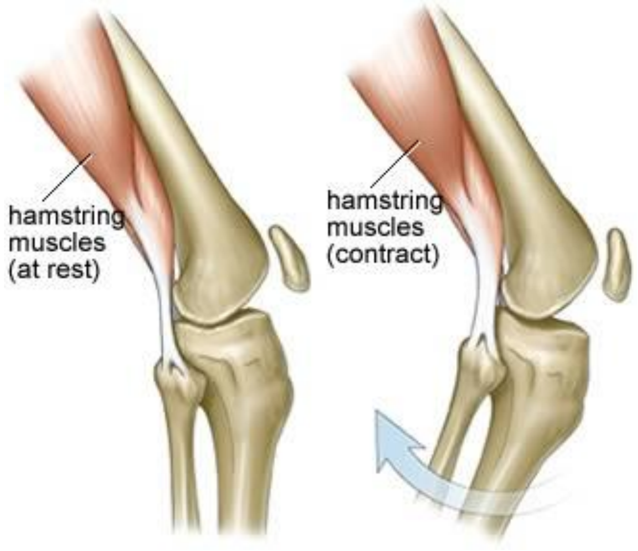


Figure 6. Knee Flexion

Each of the hamstring muscles attaches from the pelvic region to the tibia or fibula, the bones of the lower leg (below the knee joint). Muscles are only physically capable of contraction, never expansion. The connection between the pelvic region and the posterior lower leg causes knee flexion to occur when these muscles are contracted, as can be seen in Figure 6**.**

The range of motion for knee flexion is generally between 0-140° (Chai, 2004). In addition to the hamstrings, the quadriceps and the posterior cruciate ligament are passively tensed during knee flexion. The contraction of the PCL plays a contributing factor to knee flexion, as it keeps the components of the knee joint properly aligned and secure.

Similarly to the posterior muscle group holding responsibility for knee flexion, the anterior muscle groups is responsible for knee extension; the quadriceps which are represented in Figure 7. Each quadriceps muscle attaches from the pelvic region to the patella. The patellar tendon then attaches from the patella to the anterior tibia. Contraction of the quadriceps therefore causes the tibial bone to be lifted via the connection at the patella, which in turn extends the leg. Similarly to knee flexion, during the extension of the knee there is passive tension in the hamstrings. The anterior cruciate ligament is also tensed during extension, keeping the remaining components knee joint aligned and secure.

Figure 7. Knee Extension

The unique combinations of muscle and tendon contractions facilitate the motions that are necessary for leg mobility. Extension and flexion are naturally opposing motions, and therefore require the work of opposing muscle and tendon groups. It is the analysis of these movements that has influenced many of the regulations in the sport of race walking. As was discussed in the background research pertaining to race walking, the rules have been created so that specific muscles are engaged throughout the walking motion. The kinesiology of the knee throughout this motion was a primary focus in the design of the device and the goal to aid in race walking judging.

2.3 Current Measurement Devices

It is important to measure knee angle in race walking because of the stated rule regarding a straightened leg. Judging is a significant aspect of race walking and the fact that judges solely use their eyes as measuring devices may result in unfair disqualifications. Therefore a second form of judging, where the knee angle of the competitor is monitored, may be beneficial to the sport. Furthermore the device could be used for training purposes for athletes interested in monitoring their knee flexion angles.

Knee angle is commonly measured for purposes of orthopedics and rehabilitation applications. The measurement of knee flexion and extension angles can aid professionals in determining the severity of a disease or condition and also in determining the level of recovery an individual is at during a rehabilitation period following an injury or a surgery. Therefore, there are numerous devices used to successfully measure knee angle for medical and clinical applications. The various technologies utilized all have their advantages and disadvantages. Current knee angle measurement methods and devices were explored in order to acquire the necessary knowledge and ideas to develop a knee angle measurement device to be used for the sport of race walking.

Traditional methods of angle measurement include protractors and goniometers. These devices offer a mechanical means of measuring knee angle. They can produce errors when not placed correctly over the joint. Updated versions of these devices have been developed more recently. Bosch has developed a digital protractor that determines angles for carpentry purposes. Similar digital goniometer devices can be seen as well. The technology used in these devices has the possibility of being applied to a wearable knee angle measurement device. Electric goniometer advancement has led to their extensive use for joint angle measurement.

2.3.1 Electrogoniometer

An electrogoniometer measures an angle electronically and produces a visual reading. An example of their use for medical applications was exhibited by Amir, Kuiken & Sheidt. The team developed of a computerized knee goniometer with biofeedback capabilities. The device provides audio and visual feedback when the measured joint angle passes the present threshold goal. The goniometer was constructed of two anatomically aligned metal stabilizers with a potentiometer at the hinge and was contained within a knee brace. The measurements from the goniometer were sent to a small data logger that the patient wears around their waist, shown in Figure 8.

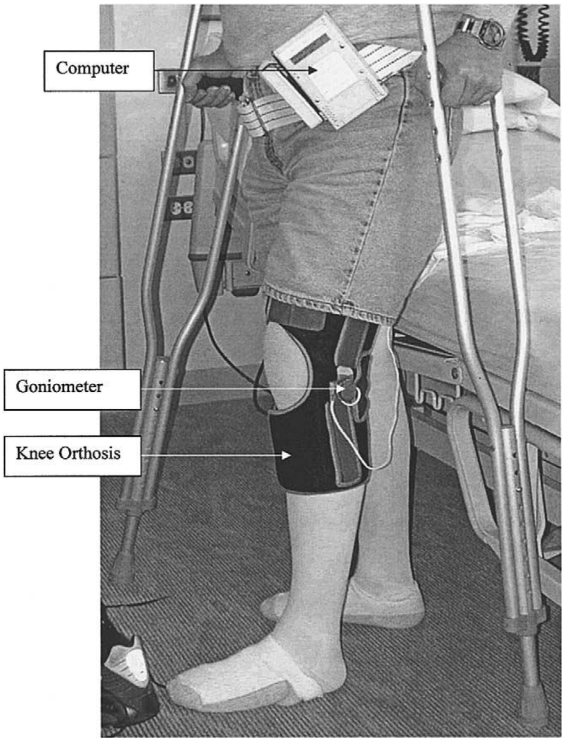


Figure 8. Computerized Biofeedback Knee Goniometer (Amir, Kuiken & Sheidt, 2004)

It was applied to patients of Total Knee Arthroplasty (TKA) and claim that the device encourages patients to continue self-exercise programs given to them by physical therapists.

However, the knee goniometer was said to give inaccurate measurements when measuring flexion angles between 110º and 160º because the brace and the patient’s skin was being stretched (Amir, Kuiken & Sheidt, 2004). This study measures much smaller flexion angles than this, but considerations were still made for the movement of the sensing device during motion.

One company that produces electric goniometer sensors is Biometrics Ltd. They manufacture an arrangement of goniometers with both twin and single axis devices such as the F35 goniometer.

Figure 9. Biometrics Ltd. F35 Single-Axis Goniometer (Biometrics Ltd., 2011)

For these goniometers, the sensor must reach across the joint so that the two end blocks can be mounted where the least amount of movement occurs between the skin and underlying bone. The device can be used for a wide range of applications and no specific method of attachment is required. The goniometer uses a series of strain gauges along its length that output measurements of strain related to the bend radius. There is also an LCD angle display unit available for use in conjunction with the goniometer. The drawback to this system are that the goniometer can only be used with the Biometrics manufactured equipment and software which is fairly expensive. Additionally the goniometer cannot be moved in a way other than the specified bend pattern without resulting in damage to the device (Biometrics Ltd., 2011). Their devices are lightweight and not very cumbersome, which are prominent design specifications.

2.3.2 Video Analysis

Analyzing a recorded video is another method of measuring knee angle. In this method, the only devices connected to the knee are some sort of skin markers or colored dots. Using video allows for the visualization of the center of the knee in a two-dimensional plane making angle measurement easier. It has also been shown that valid flexion angles can be measure through this photographic method (Naylor, Ko, Adie, Gaskin, Walker, Harris & Mittal (2011). This could was a possible design route for the race walking application because it would be unnoticeable to the athlete. The real time measurement of each athlete's knee angle would also have to be considered. Video analysis also offers a means of validation for other angle measurement methods.

2.3.3 Kinematic Sensor

An additional type of device used to measure knee angle is a pair of kinematic sensors each containing an accelerometer and a gyroscope. Dejnabadi, Jolles & Aminian used sensors each containing a biaxial accelerometer and a gyroscope to measure knee angle. They assumed human body segments to be rigid bodies and were able to construct a mathematical model that could obtain knee angle from the measurements of their kinematic sensors. Dejnabadi et al. showed this method has a very small error and also that it has minimal sensor hardware, the sensors dimensions being 20mm x 20mm x 10mm. This size is advantageous in the case of race walking where the measurement device should not hinder the performance of the athlete.

Comparable sensors were used by Farve, Jolles, Aissaoui & Aminian in their trials where they referred to them as Internal Measuring Units (IMU). The sensors required to be realigned for each new attachment and the angle measured was based off the initial sensor position. If a similar concept were applied to race walking the initial position may correspond to a straight leg and any variation in this measurement during a period the leg is supposed to be straight would be considered a disqualification. Although this system offered some desired qualities, significant noise is produced when using kinematic sensors. This would lead to inaccurate angle measurement if sufficient filtering was not conducted and with an abundance of small angle measurements this method would have produced a fair amount of error.

2.3.4 Other Transducer Types

Background research uncovered various other possibilities to be explored for measuring angles that are not commonly used in devices to measure knee angle. Through the use of a transducer, one form of energy can be converted into another. In the case of angle measurement, an array of sensors can be used to achieve a measurement of a parameter, force or pressure for instance, and utilizing a transducer it can be correlated to an angle. For the purposes of this project, research was done on two transducer types that convert their initial measurements into a voltage reading which are piezoelectric sensors and potentiometers.

Piezoelectric materials possess the unique ability to generate a voltage analogous to an applied compressive force. They are used extensively in force sensors where they provide an output voltage that is easily measured. These sensors are advantageous because their strength and stiffness allows direct incorporation of the sensor into a mechanical device. Piezoelectric sensors are commercially available in a wide range of sizes and are relatively inexpensive. Furthermore, there is no need for a voltage source with these sensors which makes them attractive for use in a streamlined design. Problems with this method could have resulted from insufficient voltage changes causing low sensitivity and indistinguishable angles.

Potentiometers were also considered as a potential transducer candidate. A potentiometer is a variable resistor commonly using a rotating knob mounted on a base to change the resistance. If a voltage is supplied to the potentiometer and the resistance is varied, the resulting output voltage correlates with the change in resistance. Using a series of codes and a microprocessor the changes in voltage can be equated to a specific angle. Countless sizes of potentiometers are available allowing simple integration into an angle measurement device. The potential drawback of using a potentiometer as a transducer is the fact that an external voltage source is needed which may lead to a more cumbersome knee angle measurement device. Even though the voltage source added extra weight, this transducer type was eventually chosen for prototype construction.

3. Methodology

Having a process that dictates when and how certain tasks are carried out was critical to complete the project. The project goal was to design and implement a knee flexion angle measuring device that was lightweight, accurate and consistent in order to help race walkers train properly to prevent disqualification by a bent knee. The following section chronologically describes how the project was completed using the knee flexion angle measurement device to ultimately reach the goal statement.

In order to choose the best design, a specific process was utilized that included three parts. First, design specifications needed to be created so that each design would ideally be able to meet each specification. Once these design specifications were finalized, three refined designs were created. After these three initial designs were created, a decision matrix was used to select the best possible solution from the three that were created.

3.1 Design Specifications

The device was designed around a certain set of criteria based on the problem statement in order to obtain a viable solution. These criteria are described as “Design Specifications”. A list of design specifications was created for the device to meet and to help steer the design process in the proper direction. The list of the specifications is displayed in this section including a brief description of each.

1. Readout of an angle from 90° to -5° of knee flexion

   The device should encompass all of the angles that a race walker’s knee might flex too. For this reason, a 90 degree flexion angle to -5 degree flexion angle was chosen.

Some people have abnormal knee flexion and can hyperextend their knee past straight, or what is considered a zero degree flexion angle.

2. Does not restrict motion on the walker

   Any restrictive motion for the race walker could make the difference between 1st and 2nd place. For this reason, the device must not measurably restrict the motion of the knee flexing at all.

3. Weight of less than two pounds

   The device needs to be lightweight in order to not add weight to the leg. Any added weight puts more of a strain on the race walker's leg muscles which in turn could make the difference between a certain finish.

4. Be able to endure one entire race (durable)

   A durable device should be able to easily withstand at least one race, if not more. It must not fail during the race, or it could make unfair circumstances relative to other race walkers.

5. Comfortable for the walker

   The device must be comfortable and not irritate any part of the knee or surrounding area during the entirety of its use.

6. Ssecurely attach to the leg around the knee

   The key word for this design specification is "securely." The act of race walking involves excessive movement of the legs which may the device to shift out of position. Accuracy of position is important for precision of measurements.

7. Easy for the walker and/or judge to operate

Not every person is mechanically or technically inclined. For this reason, the device needs to be simple enough for an average person to operate without malfunction.

8. Powered by a 9V or less battery

   Batteries over 9 volts have significant weight. Specifying that the battery must be fewer than 9 volts relates back to the design specification of the device being less than two pounds. With this specification, the possibility of the user being harmfully shocked by the electrical voltage is minimal.

9. Have an audible cue for achieving a straight-leg

   In order for the judge or the athlete to know that the leg is straight, there must be some sort of audible cue. This buzzer cue alerts the interested party that the leg is straight.

10. Safe to use and have no pinch points

    In order for the device to be usable it is important that it is safe. The goal of the device was to aid in the sport of race walking and to improve the means by which the sport is moderated. This would not have been possible if the device is harmful to the user or inhibits their range of motion in any way. Safety is a primary component in the design of any device.

3.2 Design Options

There were three different initial designs that were brainstormed. Each design was named after the transducer the design utilized to produce a measurement of knee flexion angle. For example, the first design used piezoelectric sensors as a transducer with a mechanical linkage aspect. This design was called “Piezoelectric/Mechanical Design”, and the other two were dubbed “Goniometer Design” and “Potentiometer Design”. All of the designs included an LED angle readout that is part of the chosen development board which is detailed later in the report.

3.2.1 Piezoelectric/Mechanical Design

The piezoelectric/mechanical design would use a piezoelectric sensor that measures a spring force being acted on the sensor by a spring. The spring variably pushes against the piezoelectric sensor as the knee is bent via a mechanical linkage. As the piezoelectric crystals are deformed, they would produce a very small change in voltage. This change in voltage could be measured and compared to angle measurements at specific points along the knee flexion path. Once a corresponding angle is given to a specific voltage, a circuit can be configured to display the knee flexion angle based on the specific voltage reading. A rough sketch of this initial design is shown below in Figure 10.

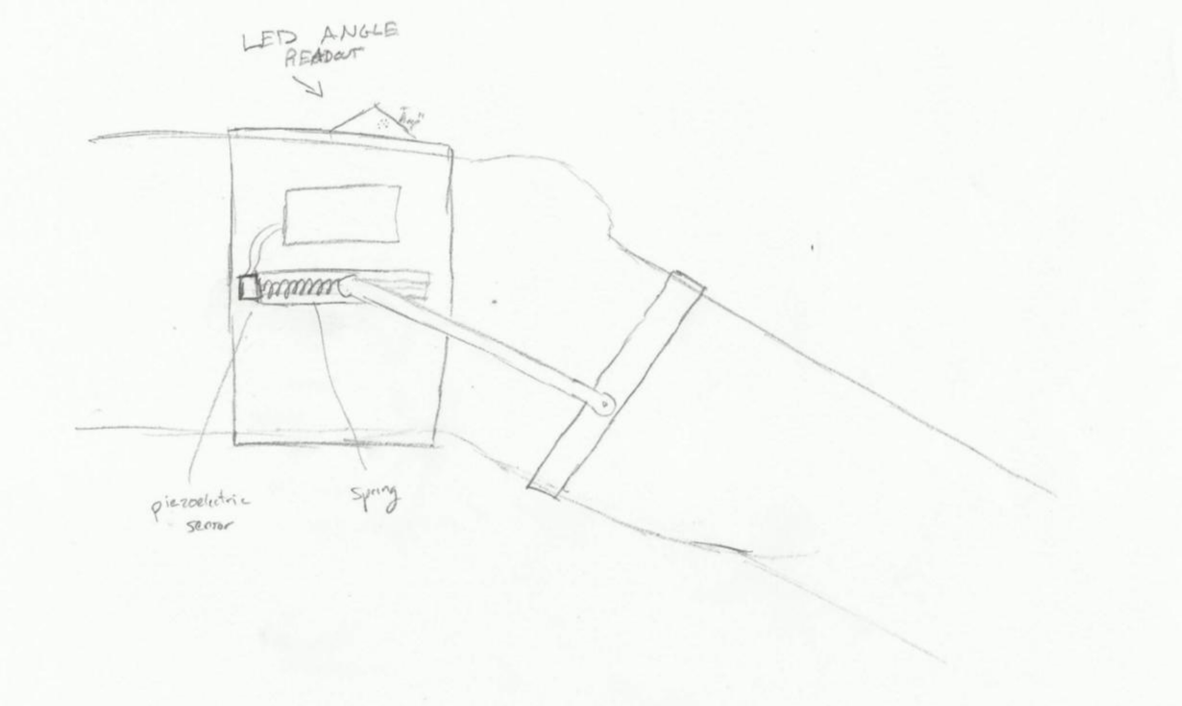


Figure 10. Piezoelectric/Mechanical Initial Design

The mechanical “linkage” would have consisted of a durable, but lightweight beam that traveled from below the knee to above the knee. It would attach to a square or cylindrical casing with a rail slot on the outside where the beam would slide back and forth. This sliding motion back and forth is where the spring would be compressed in order to place a force on the piezoelectric sensor.

The beam would be held to the leg by a neoprene-like material that is comfortable against the skin of the leg. The material would have Velcro, also known as hook-and-loop, to firmly secure the “strap” to the leg. The upper “strap” would be made of the same neoprene-like material; however, this “strap” would be much wider and would consist of some encasings for a battery, a circuit, and an LED readout display.

3.2.2 Potentiometer Design

The second initial design was called the “Potentiometer Design” because it measures the knee flexion angle using a variable resistor as a transducer, also known as a potentiometer (pot). Most small potentiometers have a base with a rotating knob on top. When the knob is turned clockwise (CW) or counterclockwise (CCW), it changes the resistance, increasing or decreasing the voltage dropped across the resistor.

Our group thought that if knee flexion could be transferred to the rotation of a potentiometer knob, the voltage could be measured and correlated to a specific knee flexion angle. To do this, the potentiometer needed to be directly at the knee’s inflection point with the base attached to one of the leg supports. The potentiometer would then need to be attached to the part of the other leg support. A rough sketch of this design can be seen below in Figure 11.

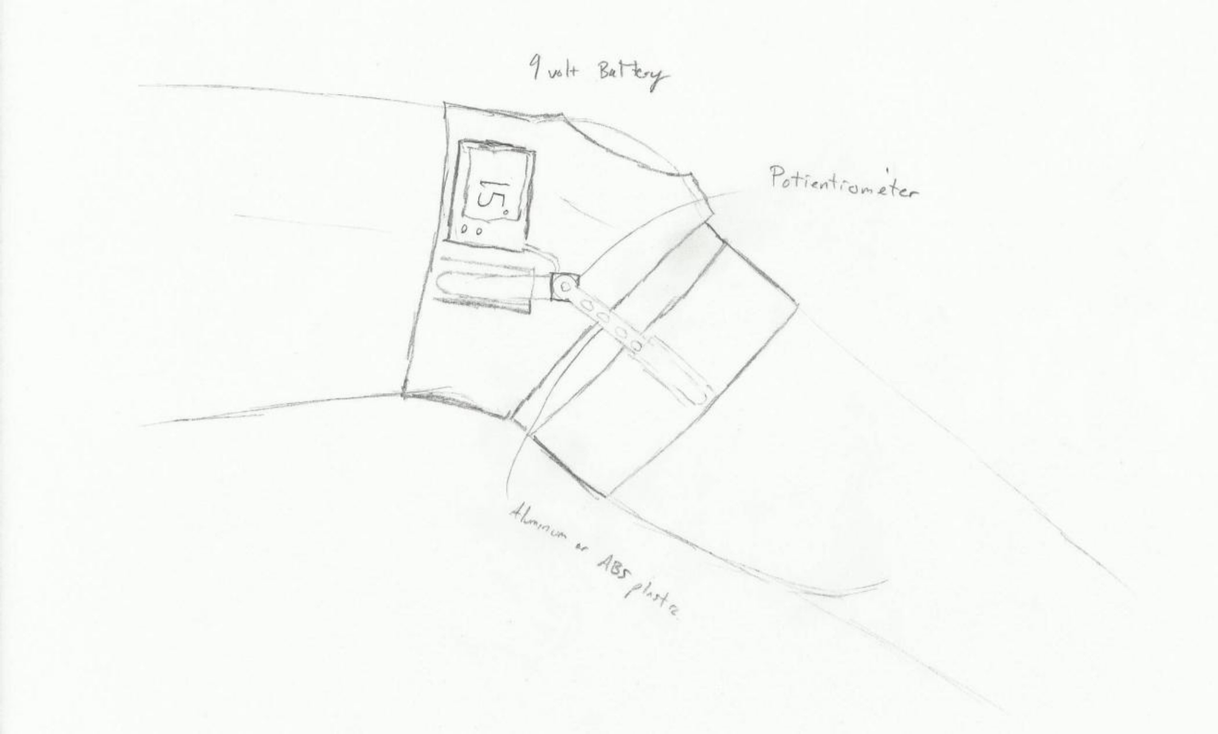


Figure 11. Potentiometer Design

This device would have straps similar to the ones on the piezoelectric/mechanical design; however they would travel longer down each part of the leg in order to transfer as much knee bending motion as possible to the potentiometer. The longer the straps are, the longer the rods or beams are that essentially capture the knee flexion angle. Longer rods or beams would have result in a more accurate reading, as a longer rod or beam would follow the contour of the leg more closely. A similar circuit would be designed to display the knee flexion angle using the development board, but this circuit would measure a change in voltage caused by the varying of the potentiometer as opposed to the change in voltage caused by a force in the piezoelectric/mechanical design.

3.2.3 Goniometer Design

The Goniometer Design uses an electric Goniometer to measure the knee flexion angle. This design would incorporate a goniometer similar to those produced by Biometrics Ltd. or BioLab that were previously explored in the background research section. These goniometers use a series of strain gauges as a transducer to achieve angle measurement. In the design it was desired that these measurements be displayed on an easily visible angle readout screen. This design uses a similar method of attachment as the two previous designs using neoprene and Velcro to secure the goniometer to the athlete seen below in Figure 12.

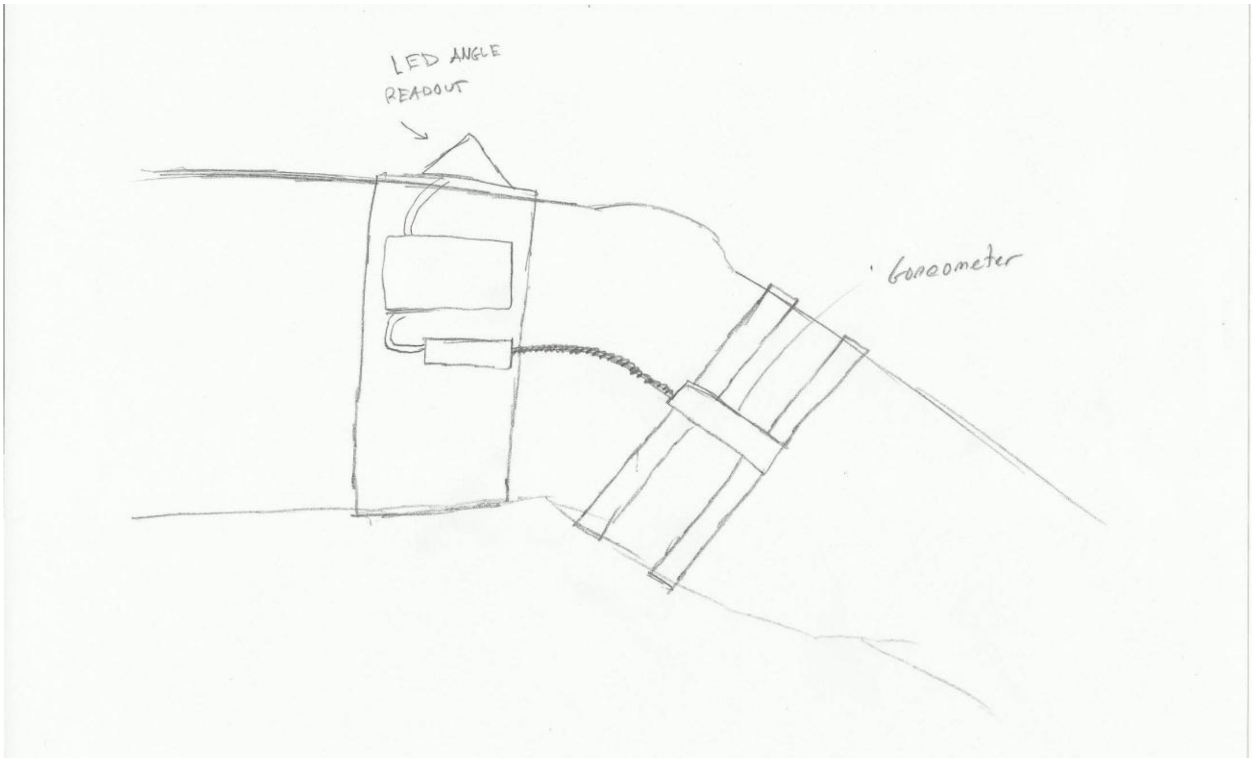


Figure 12. Initial Goniometer Design

The upper portion of the device would have a thicker strap that the led screen, the upper portion of the goniometer, and the required electronics would be attached to. To secure the lower portion of the device, two separate thinner straps were considered to ensure the device would not move when subjected to motion. The use of a commercially available electric goniometer that is proven to provide accurate angle measurements provided an advantage in reliability for this design.

3.3 Decision Matrix

Table 1. Decision Matrix

	Weight	Piezoelectric/Mechanical Design	Potentiometer Design	Goniometer Design
Readout of an angle from 90° to -5°	10%	4	5	5
Will not restrict motion of the walker	10%	2	4	4
The device must be under two pounds	5%	4	4	1
Must last one entire race(durability)	15%	3	4	2
Must be comfortable for the walker	15%	3	3	2
Must be able to be attached to the leg	10%	4	5	5
Must be easy for the walker or judge to operate	5%	4	5	4
Must be powered by a 9V or less battery	5%	4	5	2
Must have a visual cue for straight-leg failure	10%	5	5	3
Must have no pinch points and be safe	15%	3	3	4
Total	100%	3.45	4.10	3.25

Based on the above Decision Matrix in Table 1, the potentiometer design has the greatest overall benefits for the necessary design specifications. It rated above average for the majority of specifications, while the other two designs had areas that were not as attractive. The design is the least cumbersome allowing for superior comfort which also provides reliability because of the decreased number of parts compared to the piezoelectric design. It also is much less expensive than the available electro goniometers on the market and proved to be fairly accurate. In addition to the evidence provided in the Design Matrix, the potentiometer design was the most logical choice for prototype construction.

3.3 Final Design and Prototype Construction

In order to implement the final design, several steps needed to be taken to ensure a proper prototype build process. First, a SolidWorks Computer Aided Design (CAD) model was created based off the initial design drawing. Once a CAD model was created, a dimensioned drawing was generated for each part of the assembly. These dimensioned drawings displayed different views of each part with dimensions and necessary information. There was also an assembly drawing that allowed the group to see what the final prototype should visibly resemble upon completion. Then, based off of the CAD model, a Bill of Materials was generated to provide an accurate description of the materials needed to create the prototype. The materials were then ordered through several different vendors. Lastly, the construction of the prototype was document with pictures are taken of each step of the build process.

3.3.1 Computer Aided Design (CAD) Model and Drawings

A Computer Aided Design (CAD) model was constructed as part of the design process. The model allowed for superior visualization with accurate dimensions that could be readily altered. The CAD model was also very useful because specific materials could be applied to any part which allows that material’s properties to become evident in how the prototype functions. The CAD model for the final design, the potentiometer design, actually used some small aspects from the other initial designs. The final design CAD model without neoprene straps can be seen below in Figure 13. The final design CAD model with the neoprene straps added is displayed in Figure 14. The center of mass was also calculated in SolidWorks and displayed to ensure that the device would not hinder an athlete’s performance by throwing them off balance.

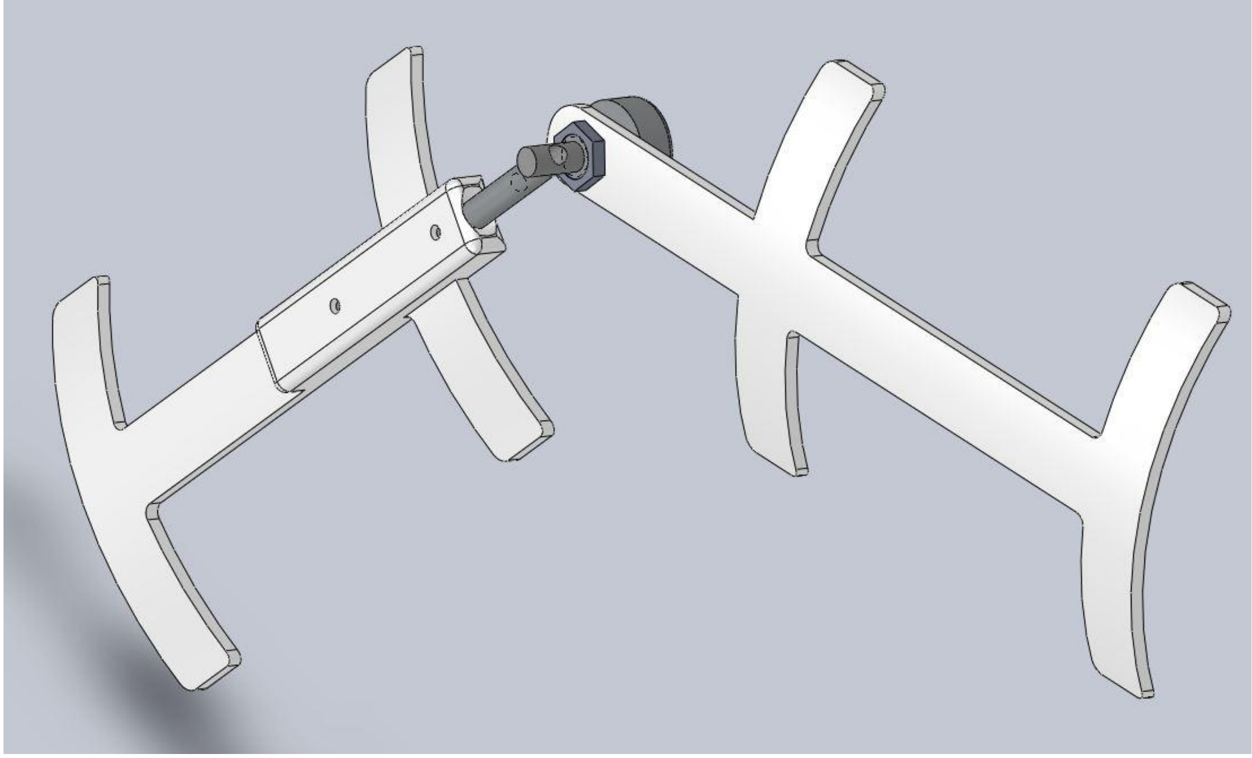
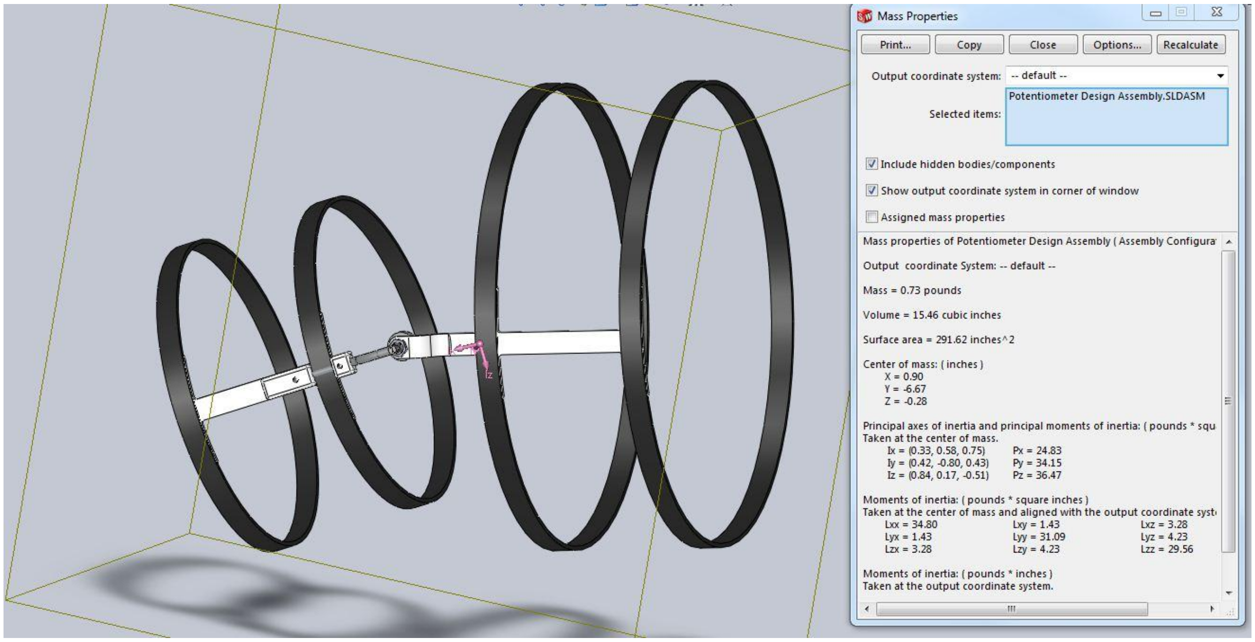


Figure 13. CAD model of Final Design Assembly



Output coordinate system: -- default --

Selected items: Potentiometer Design Assembly.SLDASM

☑ Include hidden bodies/components

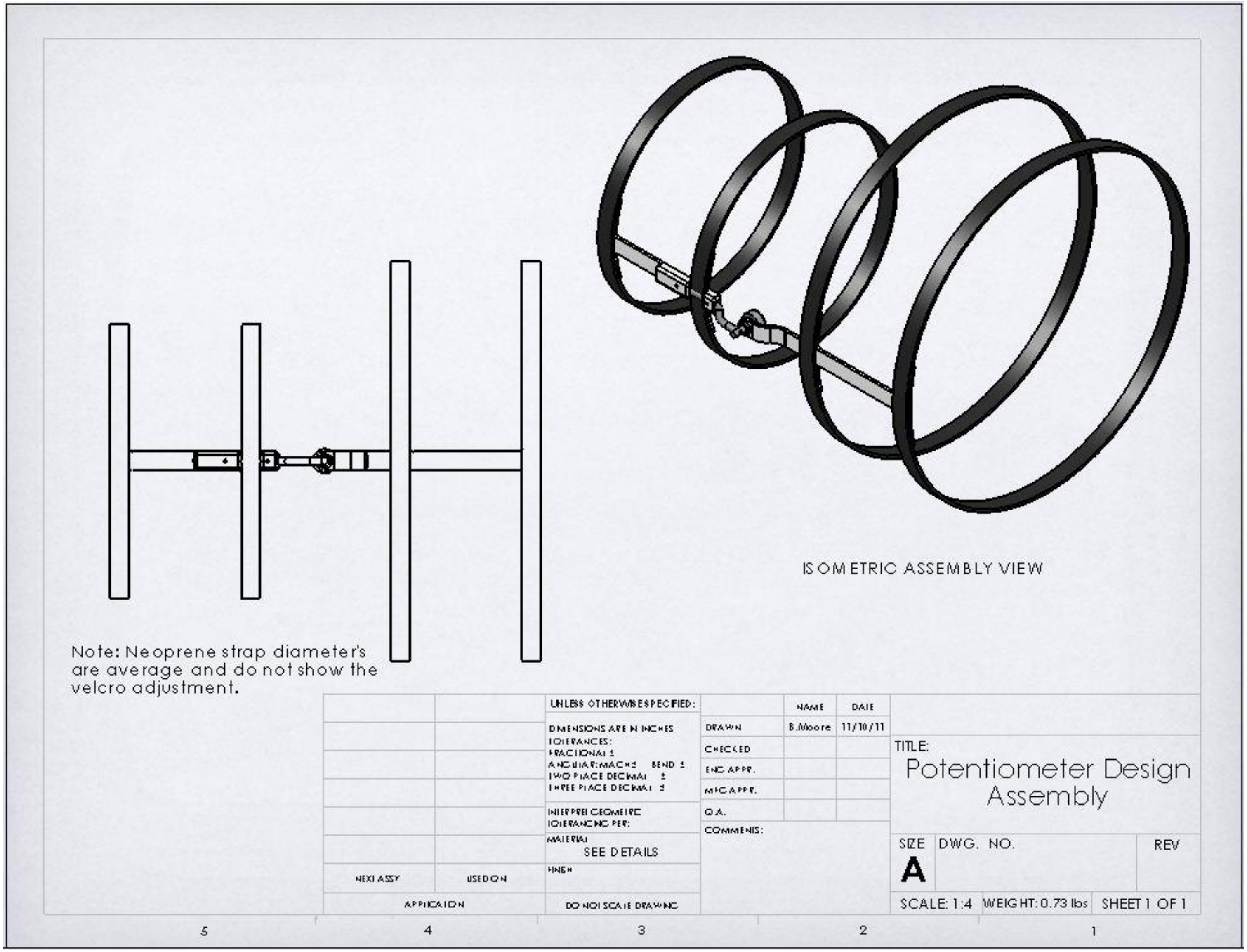
☑ Show output coordinate system in corner of window

☐ Assigned mass properties

```
Mass properties of Potentiometer Design Assembly ( Assembly Configura

Output  coordinate System: -- default --

Mass = 0.73 pounds

Volume = 15.46 cubic inches

Surface area = 291.62 inches^2

Center of mass: ( inches )
	X = 0.90
	Y = -6.67
	Z = -0.28

Principal axes of inertia and principal moments of inertia: ( pounds * squ
Taken at the center of mass.
	 Ix = (0.33, 0.58, 0.75)  	Px = 24.83
	 Iy = (0.42, -0.80, 0.43)  	Py = 34.15
	 Iz = (0.84, 0.17, -0.51)  	Pz = 36.47

Moments of inertia: ( pounds * square inches )
Taken at the center of mass and aligned with the output coordinate syst
	Lxx = 34.80	Lxy = 1.43	Lxz = 3.28
	Lyx = 1.43	Lyy = 31.09	Lyz = 4.23
	Lzx = 3.28	Lzy = 4.23	Lzz = 29.56

Moments of inertia: ( pounds * inches )
Taken at the output coordinate system.
```

Figure 14. CAD Model of Final Design Assembly with Neoprene Straps and Center of Mass

Once the CAD model was finalized, it was then put into a CAD drawing. As stated earlier, the CAD drawing usually shows four views: front, right, top, and isometric. These views allow for the proper dimensions to be placed on each part, which ultimately allows for ease in manufacturing the part. The CAD drawings for the final design show the main functioning parts of the device, but there are also a few arbitrary parts that have changing dimensions and do not need to be shown. Shown below in Figures 15 through 19 are all the CAD drawings for the final design.



Note: Neoprene strap diameter's are average and do not show the velcro adjustment.

DRAWN B.Moore 11/10/11

MATERIAL SEE DETAILS

TITLE: Potentiometer Design Assembly

SIZE A

SCALE: 1:4 WEIGHT: 0.73 lbs SHEET 1 OF 1

Figure 15. Potentiometer Design Assembly

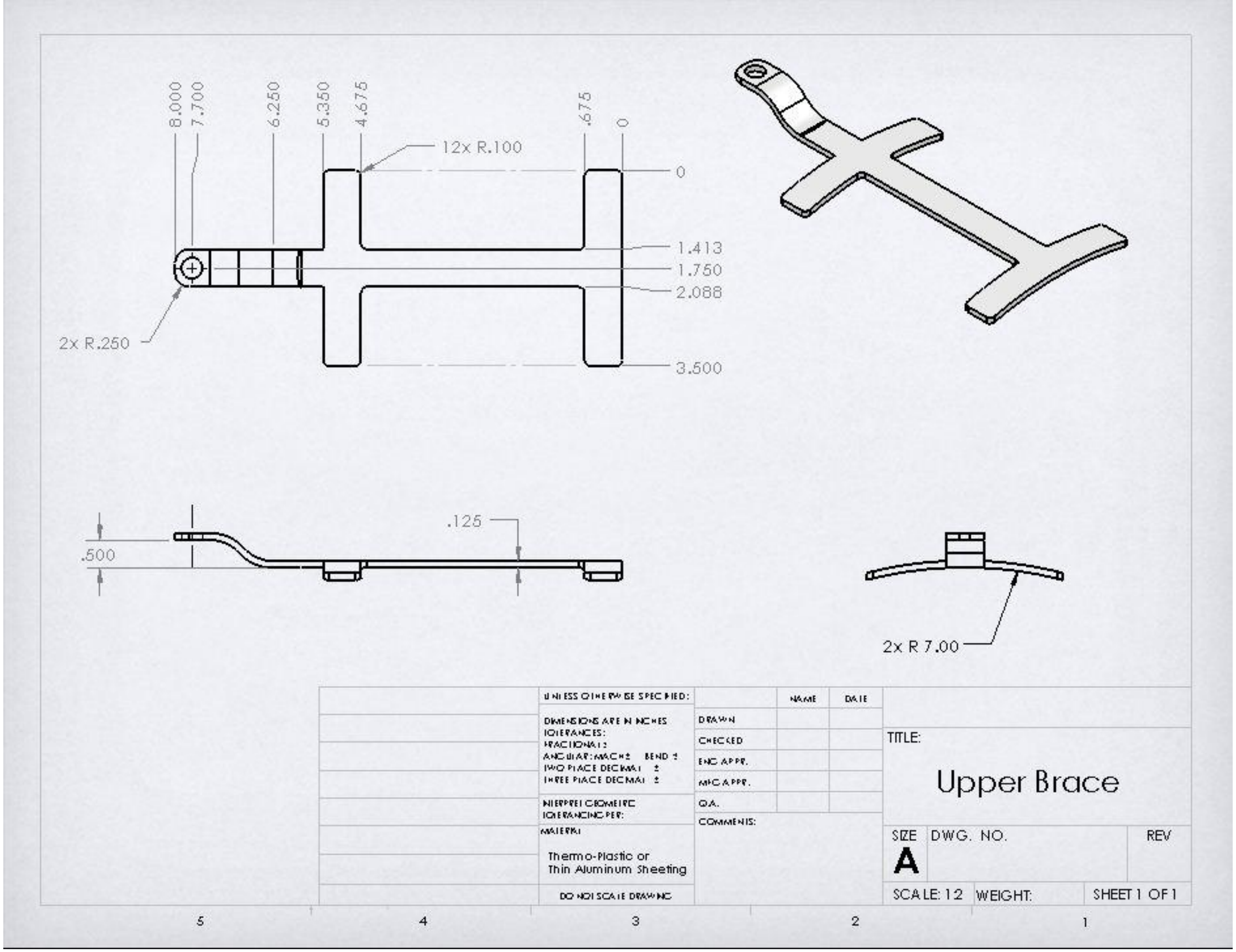


Figure 16. Upper Brace Drawing

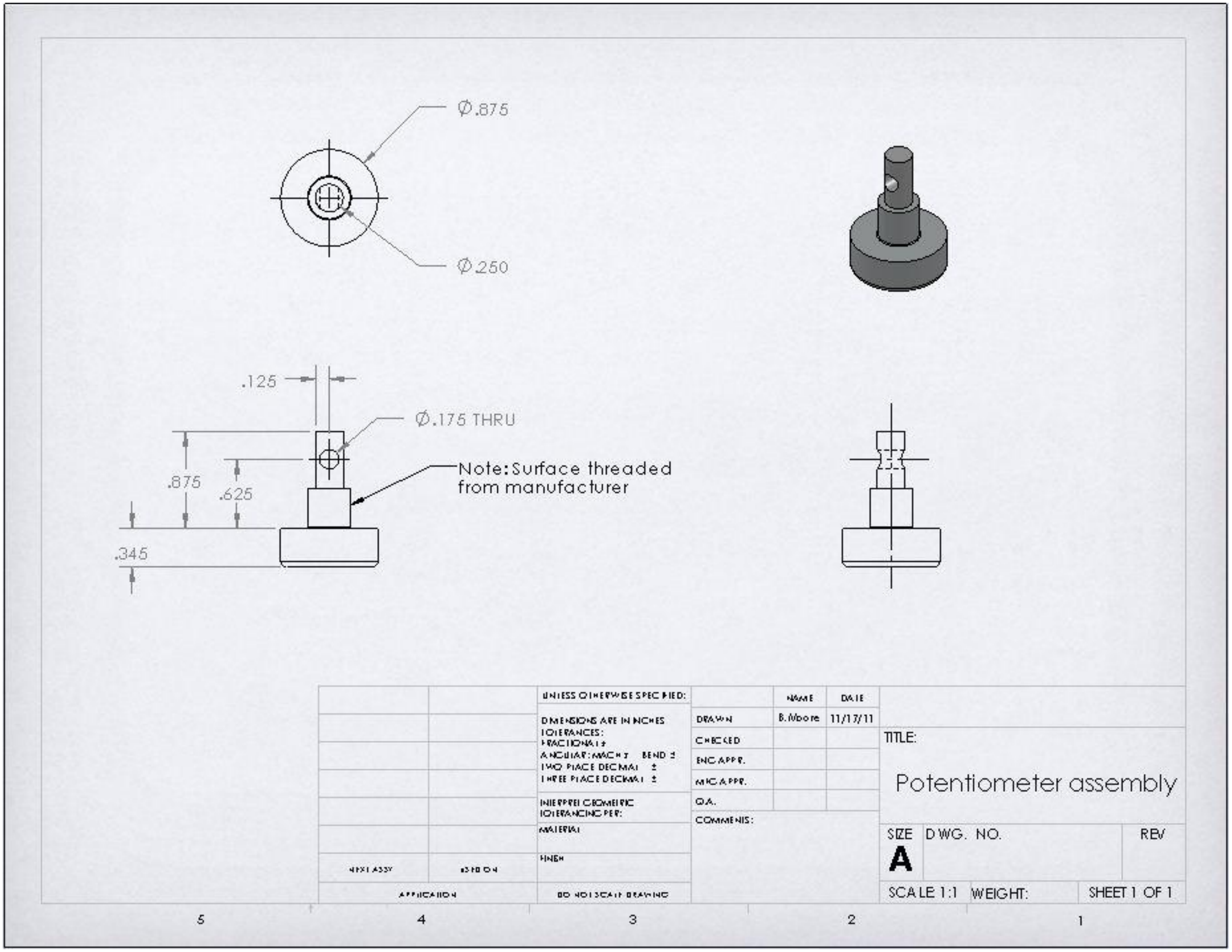
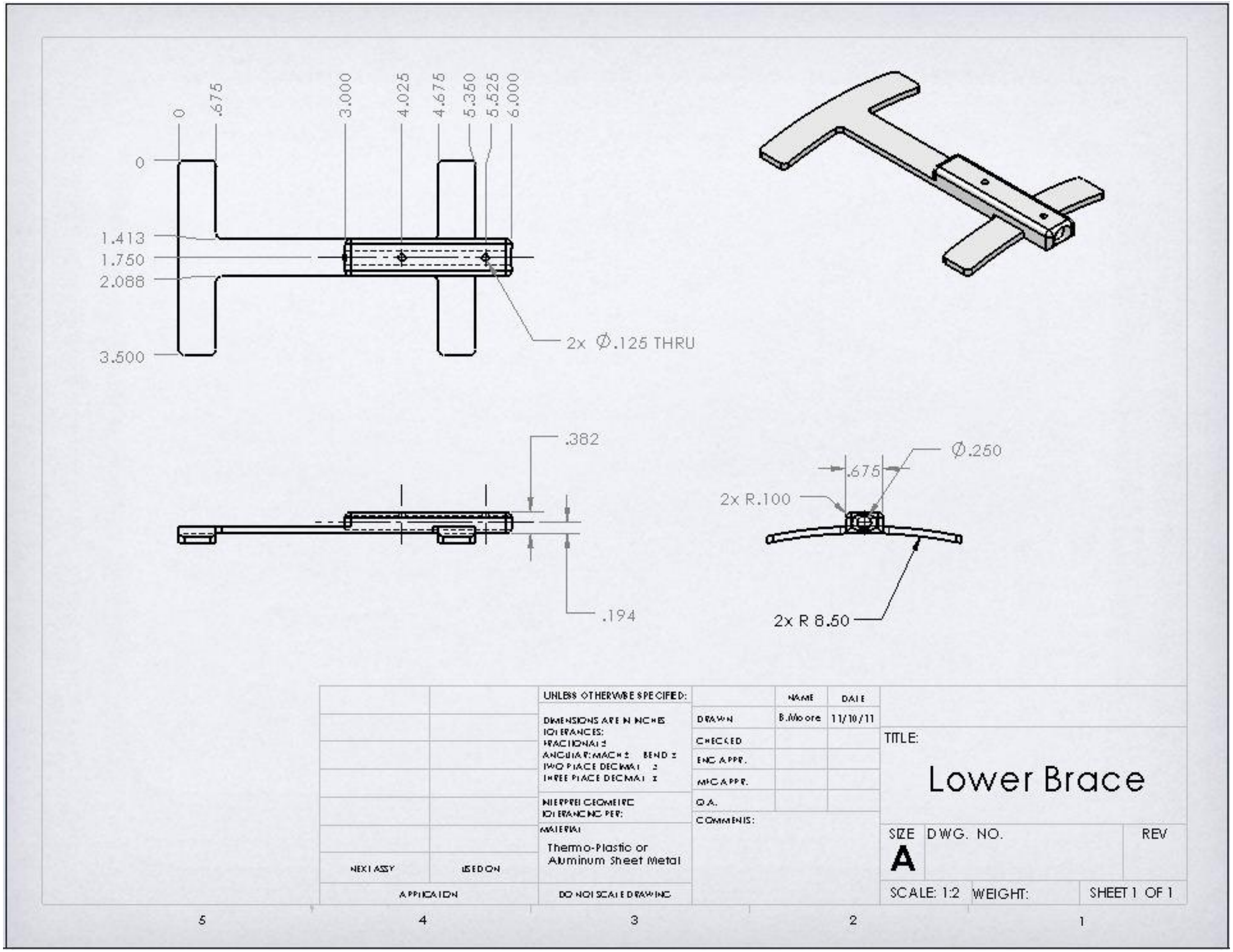


Figure 17. Potentiometer Assembly Drawing



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Thermo-Plastic or
Aluminum Sheet Metal
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

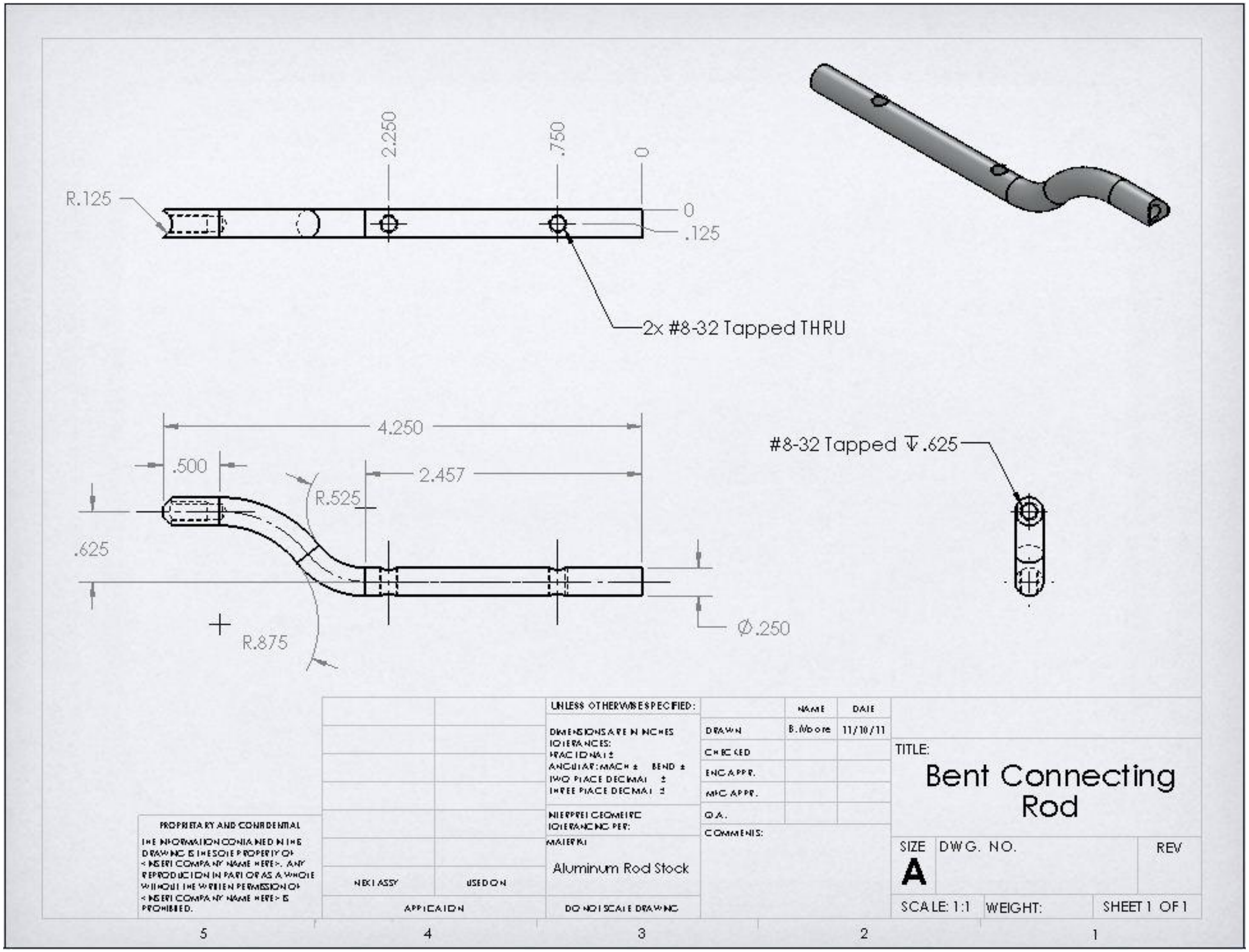
	NAME	DATE
DRAWN	B.Moore	11/10/11
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Lower Brace

SIZE A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

Figure 18. Lower Brace Drawing



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum Rod Stock
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN	B.Moore	11/10/11
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Bent Connecting Rod

SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

Figure 19. Bent Connecting Rod Drawing

Bill of Materials

Table 2. Bill of Materials

Manufacturer	Item Description	Quantity	Unit Price ($)	Total Price ($)
Vishay	2K Ω Potentiometer	1	22.04	22.04
Ultimate Plastics	4'x2' Thermoplastic Sheet	1	36.00	36.00
Olimex	MSP430F449 Development Board	1	88.00	88.00
Select	¼" x 72" Aluminum round stock	1	8.39	8.39
	1" Velcro Tape	1	8.99	8.99
JoAnn Fabrics	1 sq. yd. Neoprene Fabric	1	36.00	36.00
	Metal "D" Rings 1" 4/Pkg	1	2.29	2.29
3M	Electrical Tape	1	1.13	1.13
	Metal Tri-Glides	4	1.00	2.00
	#6-40 SHCS	1	0.25	0.25
Wal-Mart	AA Battery 12-Pack	1	14.47	14.47
			Total Price	**219.56**

The total price for the prototype is displayed in Table 2. It does not take into account that there was a large amount of Thermoplastic, as well as Neoprene Fabric, left over for future use. Each Item in the Bill of Materials is based off the smallest possible quantity available for purchase. If the prototype were to go into production, many of these unit prices would be reduced due to bulk purchasing and whole sale prices instead of retail prices.

3.3.2 Main Assembly Prototype Construction

To begin the construction of a prototype for the main assembly of the knee flexion measurement device, proper material selection was required. Polypropylene thermoplastic was picked for its light weight and stiffness, as well as its ability to be molded to a desired shape after being heated any number of times. Once re-cooled the thermoplastic returns to its lightweight, rigid form and maintains the desired shape. The material is stiff when bent along its width, but flexes enough laterally to comfortably contour to the leg. The 1/8 inch thick sheet of thermoplastic was cut into two separate pieces and molded to form the components shown in Figure 20 and Figure 22.

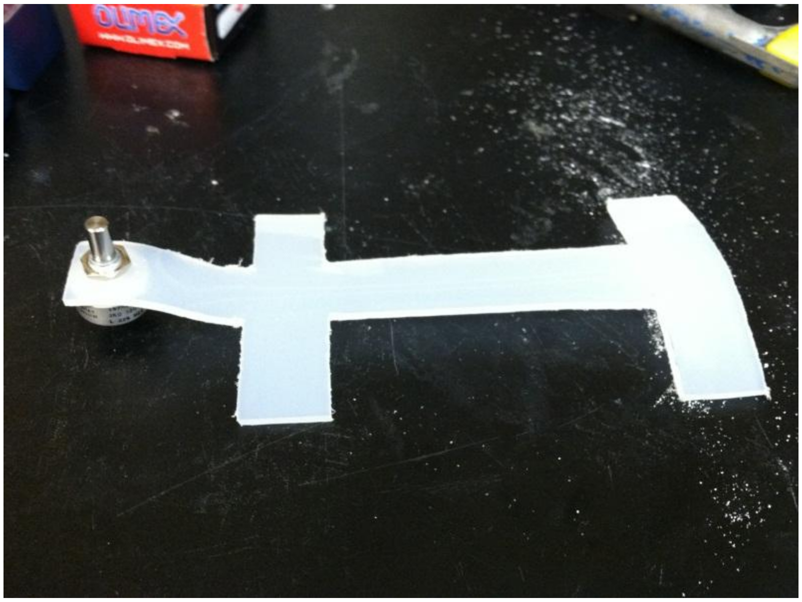


Figure 20. Upper leg support with potentiometer

The two pieces made were designed as an upper leg support and a lower leg support. The upper leg support is 8” in length, and the lower leg support is 7.5” in length. Both supports are approximately 4” wide, and were contoured to fit around the leg through the use of a heat gun. A hole was drilled into the upper leg support, shown in Figure 20, to allow a 2KΩ potentiometer to be attached to the device. The potentiometer is secured to the plastic using a lock washer and a nut.**Error! Reference source not found.** In order to prevent interference with the leg, the protruding end of the upper leg support was molded away from the leg, shown in **Error! Reference source not found.**1.

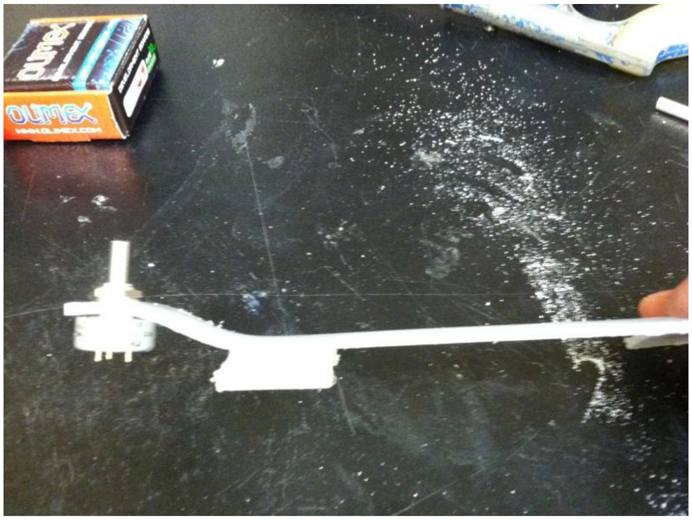


Figure 21 Side view of the upper leg support with potentiometer

The upper and lower leg supports are connected with a 1/8” diameter solid stock aluminum rod. The top end of the lower leg support was molded to fit around the aluminum rod. **Error! Reference source not found.**2 displays the lower leg support prior to molding, with an excess amount of material on the top to allow to ideal shaping with the rod.

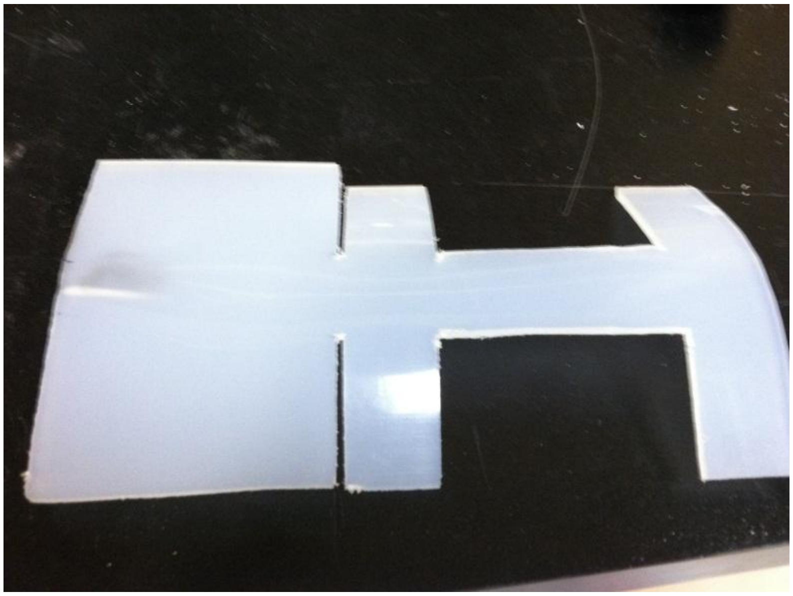


Figure 22 Lower leg support

The potentiometer chosen for the prototype was a Vishay/Spectrol 2KΩ Top-Adjustment Model shown below in Figure 23. This model was purchased because of its durable design and the large knob diameter allowed for a thru hole to be drilled. Figure 23 also displays the 0.138 ±0.005 inches thru hole that was drilled in the potentiometer knob that was used to attach the aluminum rod with a #6-40 Socket Head Cap Screw.

Figure 23. Potentiometer with thru hole

The ¼ inch diameter aluminum bar stock was cut to a length of 4 ¾ inches; one end was drilled and tapped with a #6-40 UNF thread shown in Figure 25. Figure 24 displays how the tapped end of the aluminum connecting rod was then contoured to abut flush with the ¼ inch diameter potentiometer knob. A ½ inch long #6-40 socket head cap screw was used to join the connecting rod and the potentiometer creating the potentiometer assembly seen in **Error! Reference source not found.**. While constructing the prototype, it was realized that the aluminum bar stock did not need to be bent as originally planned in the generated CAD drawings.

Figure 24. Aluminum bar stock after machining

Figure 25. Aluminum bar stock after machining (side view)

Figure 26. Potentiometer attached to the aluminum bar stock

Before the finally assembly began, the upper and lower leg supports were covered with neoprene fabric. The neoprene was sewn on following the outer edge of the pieces in order to provide more comfort for the wearer and also allowed for the construction of leg straps. The leg straps are part of the same piece of neoprene that covers each of the supports. Velcro was sown on one side of the straps and on the opposing side buckles were sown allowing for greater adjustability and comfort. The neoprene fabric covered upper leg support is showcased in Figure 27 without the potentiometer attached. Figure 28 displays the neoprene fabric covered lower leg support without the aluminum connecting rod inserted. It also clearly exhibits how the top end of the lower leg support was molded to snuggly hold the aluminum rod. It also allows it to slide for adjustment from person to person.

Figure 27. Upper leg portion with neoprene and adjustable Velcro straps

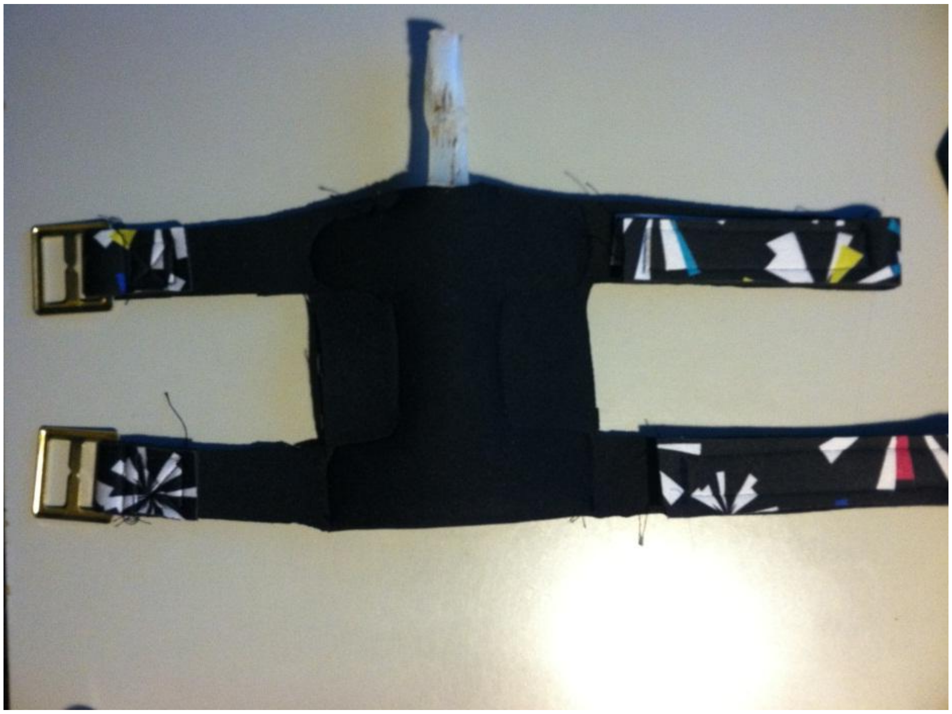


Figure 28. Lower leg portion with neoprene and adjustable Velcro straps

Once the supports were wrapped in neoprene fabric the potentiometer assembly was reintroduced and the device was assembled. Figure 29 shows how the entire main assembly of the knee angle measurement device attaches to the right leg of an individual.

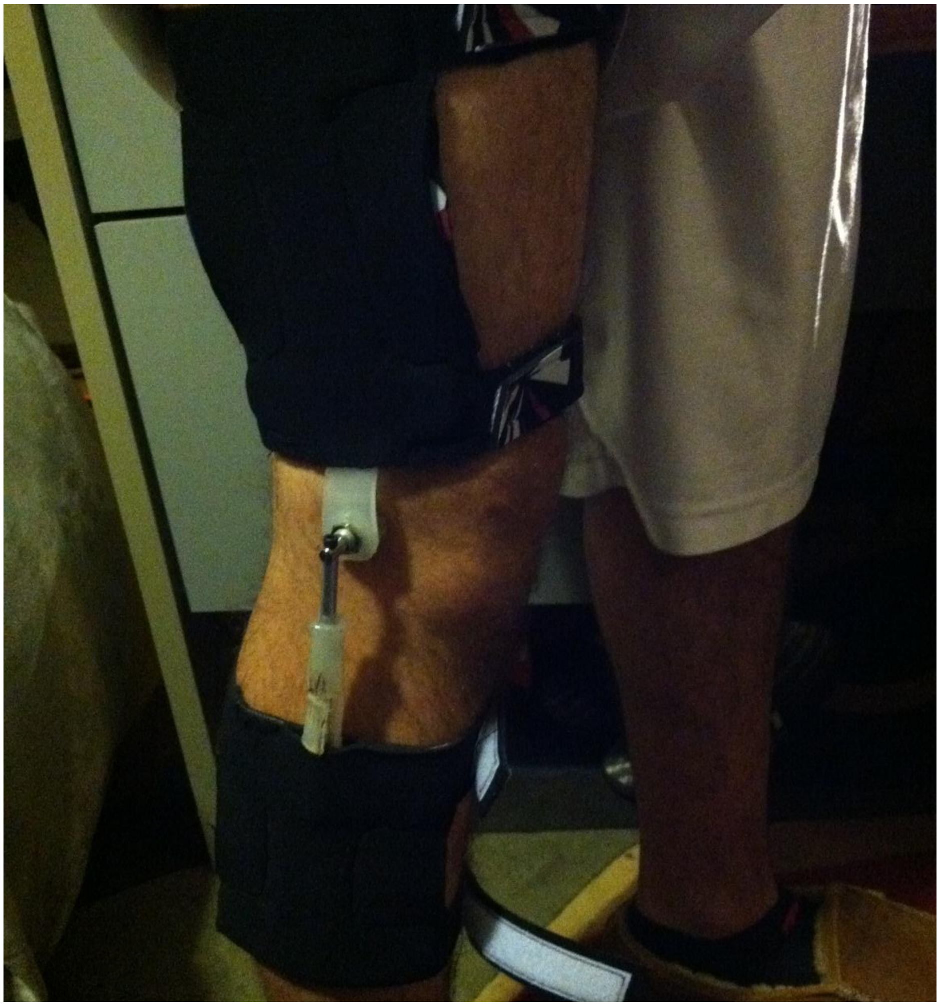


Figure 29. Device attached to leg

The main assembly shown in Figure 29 excludes the development board and the data acqu electronics a housing for the microprocessor was also constructed out of the same 1/8-inch thick thermoplastic as the leg supports. The microprocessor, including the 2 AA batteries that power it, together with the housing weighs about 150g.

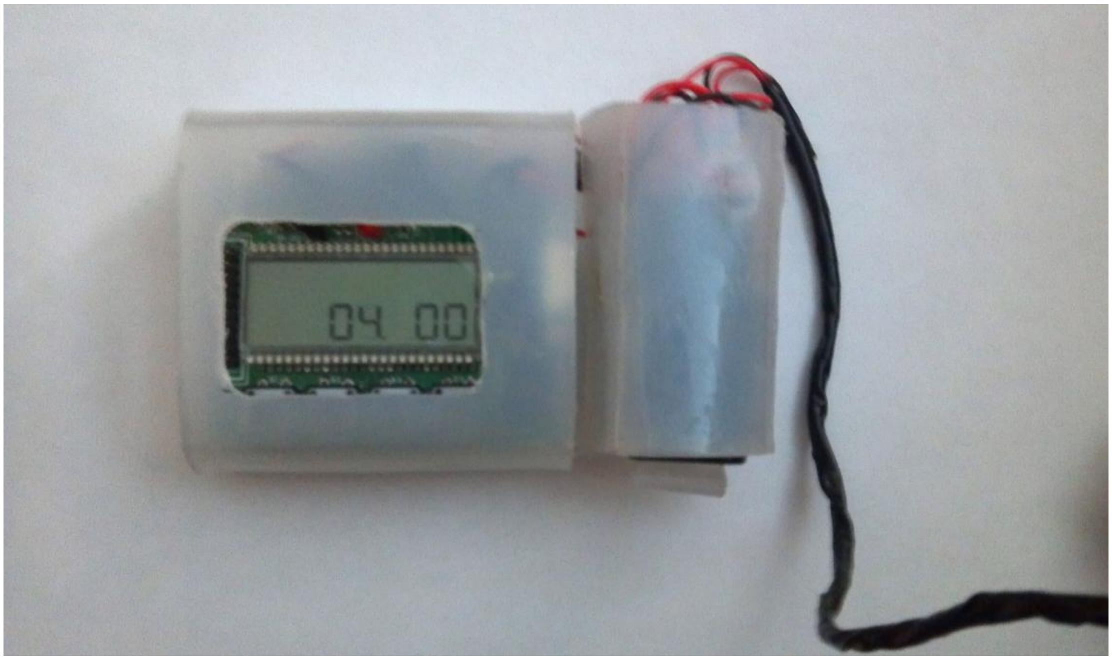


Figure 30. Development board housing

Since the microprocessor and housing would have almost doubled the weight strapped to an individual’s leg the group decided against attaching it directly to the main assembly and opted for a belt clip. In order to form a belt clip the thermoplastic was cut, heated, and then molded. The same process was done to bend the rest of the housing into shape shown in Figure 28. A rectangle was then cut out of the front face of the housing to allow the LCD to be viewed. Once the housing was completed, focus was turned to wiring the electrical components of the knee flexion measurement device. There are two different configurations of the electrical components, and each configuration has its own function.

3.3.3 Development Board

One configuration consists of the device with a voltage source (+3V) and the Olimex MSP430F449 Development Board which hosts a microprocessor and an LED display. Figure 31 displays two electrical components wired to the 3V voltage supply, although both components are not used in conjunction with one another. The development board is the component on the left side of the figure and a data acquisition device (DAQ) is showcased on the right. This configuration, with only the development board connected, is meant to be used as a training device for race walking competitors who seek to train independently.

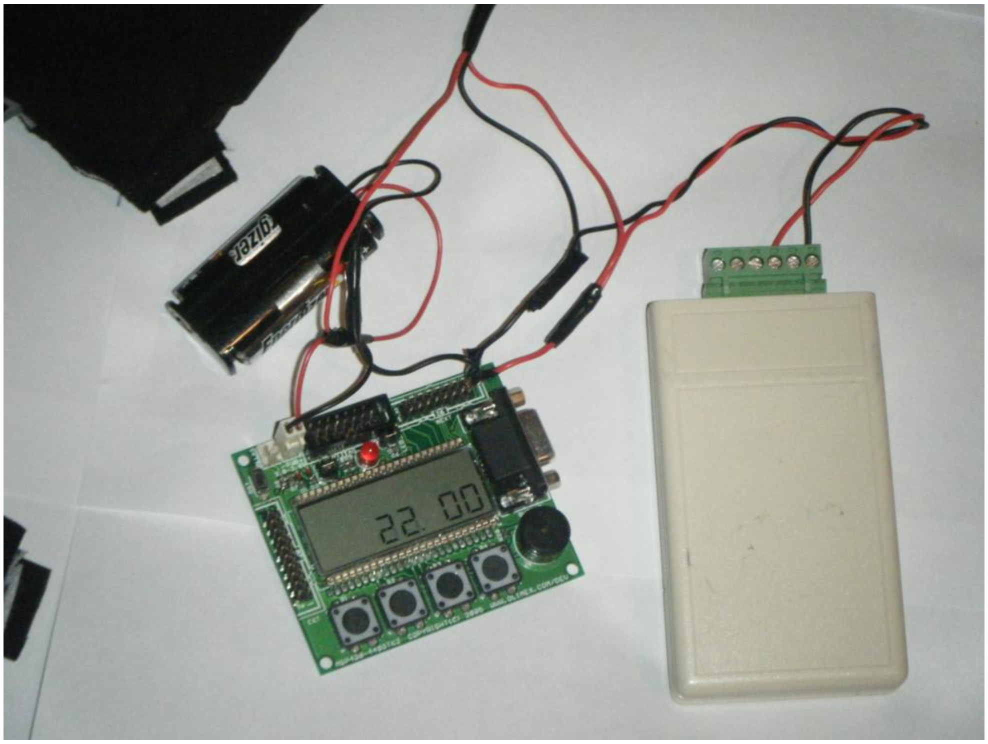


Figure 31. Development board and DAQ

The pin diagram for the MSP430F449 Development Board included in Appendix A was helpful for wiring of the device.

11. Two wires with single-pin connectors attached to them were plugged into the one and two pins of the JTAG connection on the development board.
12. The batteries were then connected to the development board using the white double-pin clip.
13. The wire going from the voltage source to the development board was spliced so wires could be soldered in to allow for an alternative supply of voltage to the data acquisition module and the potentiometer.
14. The voltage going into the microprocessor from the 3V voltage source powers the chip.
15. The output pins on the potentiometer were soldered to wires that were long enough to reach an average person's waist line from the knee joint. These wires were soldered to the single-pin connectors that were plugged into the development board.
16. These secondary battery terminals are connected in series to the original battery terminals. This allows voltage from the two AA batteries to also pass through the potentiometer, creating a voltage drop when the potentiometer is turned by the leg.

A simple wiring schematic for all of the components on the device can be seen below in Figure 32. There are two wires with connectors where the DAQ box would normally be hooked up, but these do not be attached to anything.

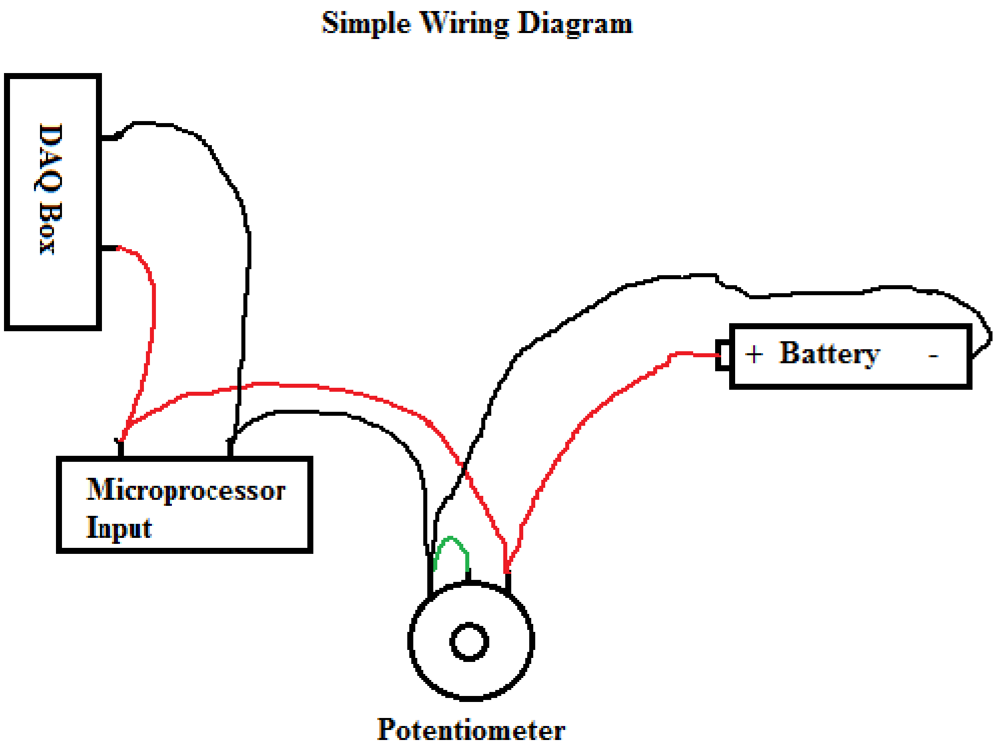


Figure 32. Simple Wiring Schematic of all components in the device

While the main focus of the testing is for the device as a judging tool, it can also be used as a training tool for avid race walkers acting as their own personal judge. Not only can the race walker see the angle that their leg is at on the LED display, but the development board beeps and illuminate a red LED when the leg is “straight”, which is classified as -1 degrees to 1 degrees. This may help during the Race Walker’s strides in determining whether or not they have a straight leg when they are touching the ground. If the Development Board does not beep, they can assume that they did not reach the required “zero” angle knee flexion. The race walker can then continue to work on his form on his own, without having a judge or anyone else present.

Development Board Code

The code for the Olimex Development Board Microprocessor is written in the programing language of C. IAR Imbedded Workbench is used to write the code to the MSP430F449 microprocessor via JTAG connection. The code follows a simple process to display the relevant angles per voltage, described in Figure 33 below.

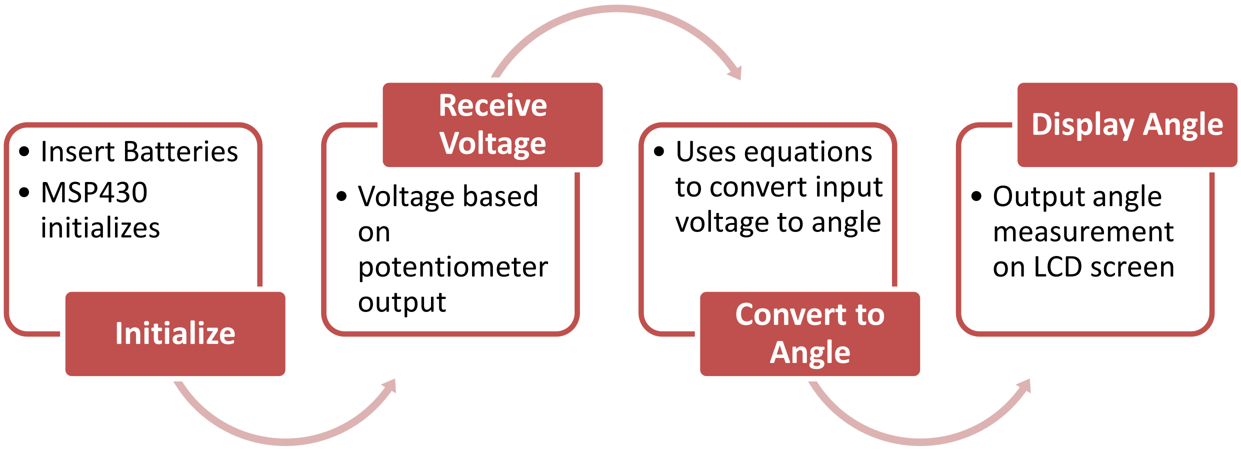


Figure 33 Diagram of Function of MSP430F449 Development Board

Through the process shown above, the program converts the output voltages of the potentiometer to their respective angle measurement. The equation used to determine each angle was found via a best-fit curve of the graph below (Figure 34).

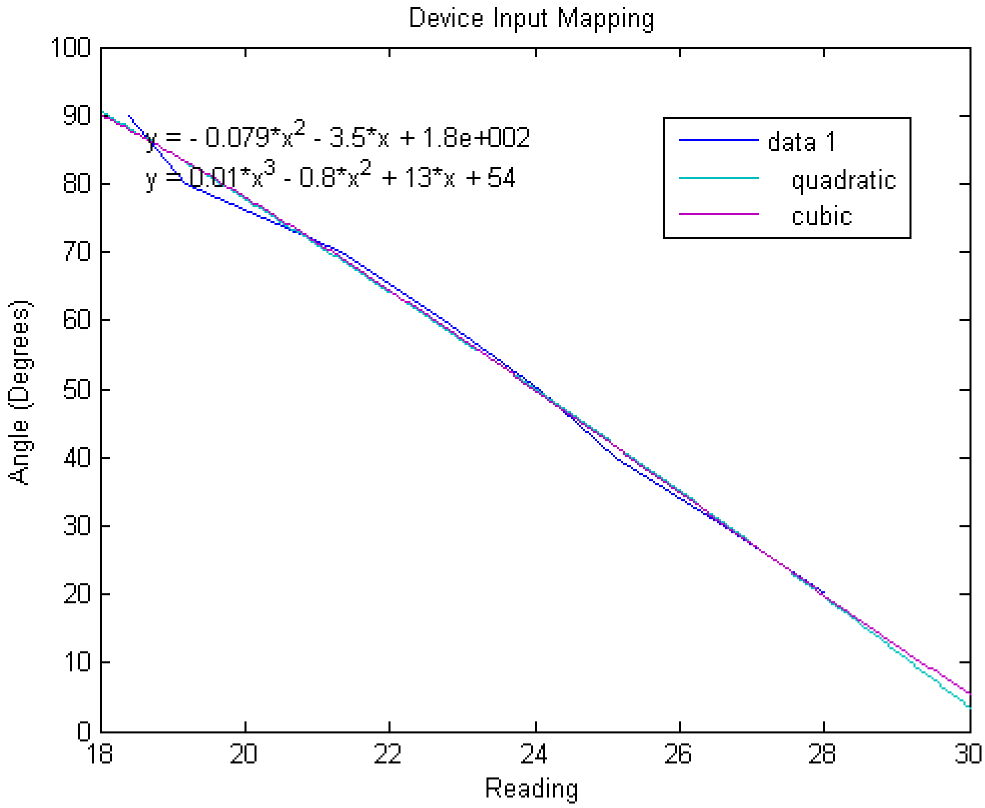


Figure 34. Graph for coding purposes

The data represented in Figure 34 was found using a protractor and volt meter. Voltage measurements were taken at ten degree intervals between 0°-90° and plotted on the graph shown above. Both quadratic and cubic best-fit approximations were used to determine the most accurate equation to convert each voltage to an angle measurement. Of the two equations, the cubic equation found to best represent the obtained data (equation shown below).

Equation 1: $0.01x^3 - 0.8x^2 + 13x + 54$

Using this equation, each angle was calculated by the program from the voltages received from the potentiometer. These angles were displayed on the LCD screen located on the MSP430F449 Development Board. The development board was also programmed to alert its user when they have reached an angle between -1° and 1°. Within this range an audible alarm sounds and a red LED light on the development board illuminates, informing the user that their angle of knee flexion is currently within the set range. This feature was designed to inform the user when their leg is within the range considered by officials to be straight. When the entire device is worn appropriately by a Race Walker, its program will facilitate a real-time angle measurement readout that both walker and judges can benefit from.

3.3.4 Data Acquisition Module

The second configuration consists of the device with the same voltage source (+3V), but instead a PACE XR440 Data Acquisition system was wired in to store the data rather than process it with the development board. This configuration of the device is an attempt to eliminate the human judging error within the sport of race walking.

In order to obtain better visual results of the output voltages and corresponding angles, the data needs to be stored. Once stored, the data can be converted to an excel format and graphed for a better visual representation and comparison. To store the data, a Data Acquisition system (DAQ) was utilized. The DAQ records voltage readings from the potentiometer and converts them to digital values that can be processed by a computer. A program called Pocket Logger was used to control the DAQ and actually collect the data. Pocket Logger allows you to change the DAQ settings such as the sampling rate and resolution. The sampling rate can be changed from 200 readings a second all the way up to one reading every twelve hours. Changing the sampling rate and resolution also changes the amount of time that the DAQ ran for, ranging from a few minutes to a few days.

3.4 Testing of the Device

Two different phases of testing were performed with the knee flexion angle measurement device. The first test, explained in Section 3.4.1, used a mechanical goniometer and was designed to verify the accuracy of the Development Board readout. The second phase of testing, explained in Section 3.4.2, was performed with multiple volunteer participants and compared the measurements obtained by the device with those obtained by a HD video camera. The data sets obtained through those mediums were compared to manual measurements of each video frame for the relevant region of the walker’s stride (heel strike to vertical). All videos were shown to a race walking judge to obtain his professional opinion of the legality of each stride as another mode of comparison.

3.4.1 Phase 1: Real Time Angle Measurement Testing

The device was tested to ensure accuracy of angle readout and reliability of mechanical design. The following procedure was used to perform each test. A mechanical goniometer was used as the comparative “true” value, and the readout of the device was compared against it.

Test Procedure:

1. Attach two halves of device; insert aluminum rod into appropriate thermoplastic insert so that the two pieces connect at the potentiometer.
2. Connect device to MSP430F449 Development Board.
3. Insert two AA batteries into the battery pack located on the device. Place battery pack into its appropriate housing. The MSP430F449 Development Board will turn on as soon as the batteries are secured into position and the device will immediately begin displaying angle measurements.

4. Set goniometer to an angle of 90°.
5. Hold the vertex of the goniometer directly above or on top of the potentiometer. Reposition the device so that the metal rods are lined up exactly with the axes of the goniometer. This positions the device at a 90° angle as well.
6. Record the angle displayed on the MSP430F449 LED Screen at that instant, as well as the angle of the goniometer.
7. Repeat steps 4 through 6 at increments of 5° until 0° is reached.

3.4.2 Phase 2: Measurement of Knee Flexion Angle During Race Walking

The device was used in further testing to compare its measurements against those of other mediums. The angle of knee flexion during Race Walking was measured by the following mediums; the device, the analysis of simultaneous video recording, the opinion of a certified Race Walking judge, and the manual angle measurement of each video frame. The test procedure used to obtain these measurements is outlined below. For the purposes of this project, a Sony HdR-XR550 Camcorder was used for all video recordings. A Pace Scientific XR440 Data Logger (DAQ) was used to record the measurements of the device.

Test Procedure:

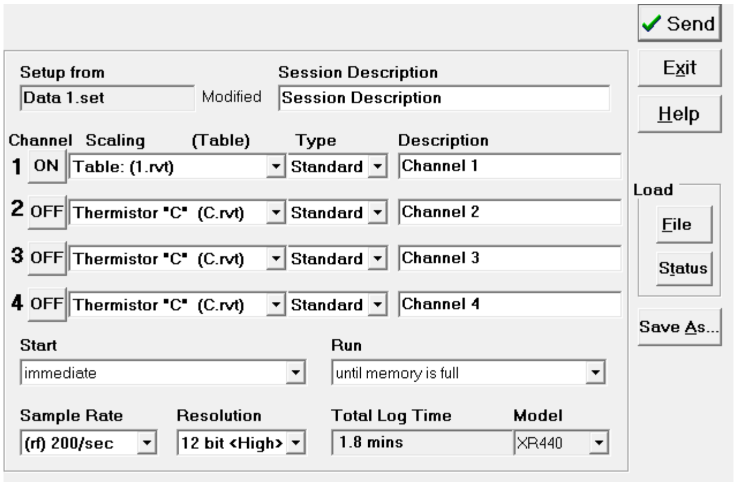
Initial Setup:

1. Attach two halves of device; insert aluminum rod into appropriate thermoplastic insert so that the two pieces connect at the potentiometer.
2. Insert two AA batteries into the battery pack located on the device.
3. Connect the device to the Pace Scientific XR440 DAQ (Data Acquisition device)

4. Connect DAQ to computer using USB cord, and open PocketLogger software (available on the Pace Scientific website for the XR440 DAQ Model).
5. Open Control Panel of computer and proceed to Devices and Printers. The DAQ should appear as a device. Select the DAQ and view its properties. Record the displayed Baud Rate and COM Port.
6. Proceed back to PocketLogger Program. Under “Settings”, ensure that the appropriate COM Port and Baud Rate are selected based on those found in the previous step. Once they have been selected, press “OK”.
7. Under the “Send” Menu in PocketLogger, select “Send Baud Rate” and ensure that the computer has successfully sent the information to the connected DAQ.
8. Attach the High Definition Video Recorder to its respective tripod. Position the tripod and recorder so that they are viewing the path that the test subject will be walking. Ensure that all appropriate settings are selected and that the video recorder is set to High Definition.
9. Using cones or marker, mark off the area of test path that is viewable by the video recorder.

Calibration:

10. Position the electric goniometer device to a 90° angle using the protractor. Hold in this position and proceed to initiate DAQ recording.
11. Under the “Send” Menu in PocketLogger, select “Setup” displayed in Figure 35. Alter the configurations so that they are the same as those in Figure X below. After appropriate adjusting each of the settings, select “Send”. At this point the DAQ will immediately begin recording data.



Setup from: Data 1.set (Modified)

Session Description: Session Description

Channel		Scaling (Table)	Type	Description
1	ON	Table: (1.rvt)	Standard	Channel 1
2	OFF	Thermistor "C" (C.rvt)	Standard	Channel 2
3	OFF	Thermistor "C" (C.rvt)	Standard	Channel 3
4	OFF	Thermistor "C" (C.rvt)	Standard	Channel 4

Start: immediate

Run: until memory is full

Sample Rate: (rf) 200/sec

Resolution: 12 bit <High>

Total Log Time: 1.8 mins

Model: XR440

Figure 35. Pocket Logger setup

12. Unplug the USB cord from the DAQ.
13. The device should be positioned at exactly 90° using the protractor, as specified in step 7. Hold the device in this position for 10 seconds after the DAQ has begun recording.
14. After the 10 second period has elapsed, quickly reposition the device to an 80° angle. Hold for an additional 10 seconds.
15. Repeat step 10 at 10° increments until 0° has been reached (and recorded for its appropriate 10-second interval).
16. The DAQ will continue recording data until 1 minute and 48 seconds has elapsed from the moment it was initiated (time is dependent on the Total Log Time displayed on the Setup screen). After this period of time has elapsed, plug the DAQ into the computer. Under the "Receive" Menu in the PocketLogger program, select "Data". This will download all data to the computer and will be available as a graph in the program. Graph should appear as a step-wise function.

Test Subject Walk:

17. Fasten electric goniometer device onto the right leg of the test subject. Ensure the colored markers located on the leg straps are lined up with the axes of the test subject's leg. These markers will be tracked so it is important that they are placed accurately.
18. Turn on video recorder and prepare for recording. Do not press record yet.
19. DAQ should be connected to computer already. Repeat steps 10 and 11 to initiate DAQ recording. DAQ should be unplugged from the device at this time.
20. Begin recording video.
21. Instruct test subject to Race Walk from his starting point (which should be just to the left of the view of the video recorder) until he/she has reached the marker which signifies the right-most boundary of the video recorder's view. Be sure to count which step from his starting point is the first one that is viewable by the camera and record the information for later use. The test subject should walk with regulation form and at a comparable speed to that of a race.
22. Stop recording video.
23. Once the test subject has reached the second marker, instruct he/she to stop and remain standing still for 10 seconds; moving the knee as little as possible. After the 10-second period of time has elapsed, he/she may walk (normally) back to the starting point (next to the computer).
24. Similarly to Step 15, after the length of the Total Log Time has elapsed (1 minute and 48 seconds for the settings recommended for this test) plug the DAQ into the computer and receive the data. Be sure to save the graphs after each test run.
25. Repeat steps 18 through 23 three times in total.

26. Detach the device from the test subject’s leg. This completes the test procedure.

A total of eight test subjects participated in the completion of this testing; the four members of the group as well as four experienced Race Walkers. The videos obtained during testing were analyzed using Adobe AfterEffects, a program which facilitated the tracking of each of the markers on the test subject’s leg. The videos obtained during this testing procedure were played for a certified Race Walking judge, and analyzed based on his professional opinion. This test procedure effectively produced three mediums of data to be compared, in addition to the opinions of the judge. The measurements obtained were analyzed and compared over a specified time interval to determine the accuracy of each medium.

4. Results

Two separate aspects of the device were evaluated through the conducted test procedures. The methodology detailed in Section 3 served as a guide for the team in obtaining useable data for analysis. Attaching the MSP430F449 Development Board to the device provided real time angle knee flexion angle measurement for each subject. When wired to the XR440 Data Logger (DAQ) the data first required analysis before an angle measurement could be generated. Two separate analyses were completed in order to examine the validity of the measurements. Both analyses used manually angle measurements as a control, providing a source of comparison for the obtained data.

4.1 Phase One Testing: Real Time Angle Measurement Results

To validate the real time angle measurement that is produced by the LED screen on the development board, the test procedure described in section 3.4.1 was conducted. The graph in Figure 36 shows the results of the real time angle measurement analysis.

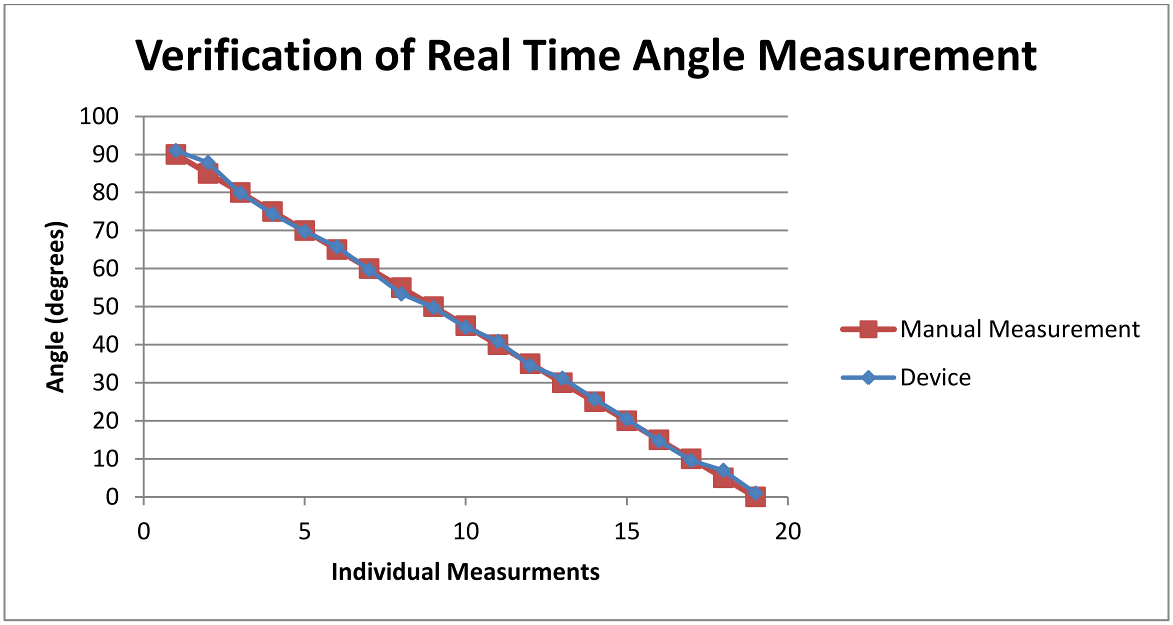


Figure 36. Real time angle measurement graph

Eighteen measurements were performed and a t-test was performed on the two sets of data obtained during the test. The t-test produced a value of 0.974, showing a high correlation between the two data sets. This verified the overall accuracy of both the design of the device as well as the internal coding of the development board. The development board program uses the output voltage of the potentiometer to compute the respective angle. It was important throughout this series of testing that new batteries be used for each test. The slightest change of voltage, due to the loss of life in either battery, altered the angle readout and produced inaccurate measurements. All findings for future improvements were recorded throughout the test process and are described in Section 4 of the report.

4.2 Phase Two Testing Results

Two separate rounds were done when testing the device for race walking. The first consisted of group members as test subjects and the second consisted of experienced race walkers. The first round was done to ensure proper operation of the device and ensure efficient data collection methods. Completion of testing produced three different sets of data for each subject; one from motion tracking of the video, one from the device voltage readings recorded by the DAQ, and one obtained through manual angle measurement with a mechanical goniometer of each video frame. Once all of the data was analyzed an error analysis was reported and discussed.

4.2.1 Round One Testing: Group Members

The first phase of testing consisted of four test subjects, all of whom had never race walked previously. For each subject the three different mediums of data collection were analyzed and overlaid on a single graph in order to display the differences in each medium of measurement. The process of analysis was repeated for both rounds of device testing. The analysis procedure is explained in detail in order to clearly exhibit the process.

Video Data Analysis

- The motion tracking capabilities of Adobe After Effects made it possible to track the three separate pink colored indicators located on the device.
- In each frame of video the indicators were converted to three separate points, each with an individual set of x-y coordinates.
- The data was exported to Microsoft Excel spreadsheet and input into an equation which yielded the corresponding angle of knee flexion for each frame. The equation uses the dot product of the resultant vectors of the motion trackers to yield the angle of the middle point, the knee.

$$Angle = \cos^{-1}\frac{(x_2 - x_1)(x_3 - x_2) + (y_2 - y_1)(y_3 - y_2)}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} * \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}}$$

- Resulted in a series of angle measurements for the subject over the distance of the predetermined test track. However, with no set time scale until the device data was analyzed.

Device Data Analysis

- The device data was obtained through the DAQ module which recorded voltage readings
- Calibration was performed as described in Section 3.4.2 in order to properly correlate a voltage reading to a specific angle measurement.

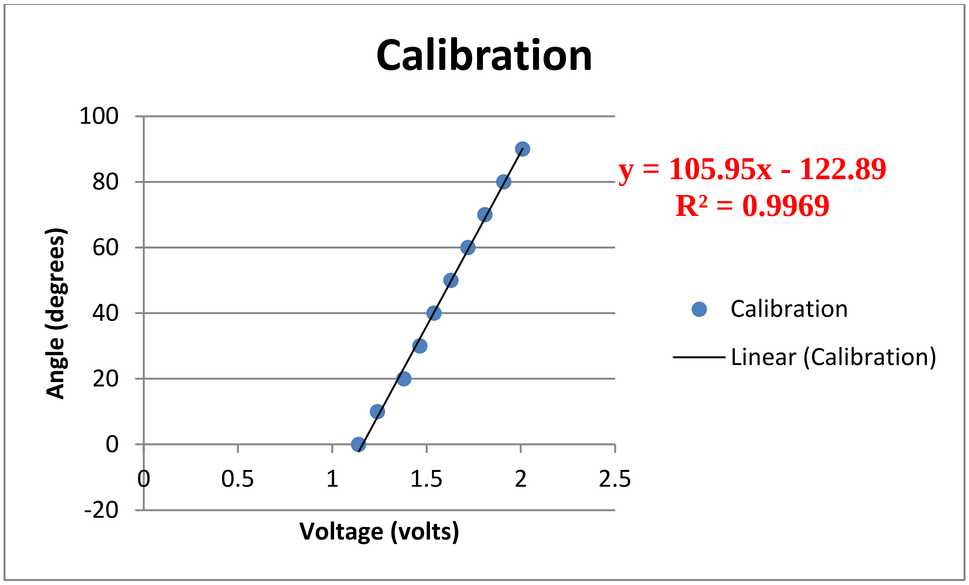


Figure 37. Calibration graph

- In a Microsoft Excel spreadsheet a trendline was fit to the data shown in Figure 37 and the equation of the trendline correlates a specific voltage to a single angle measurement.
- It was used to convert all of the DAQ voltage readings into angle measurements resulting in a data set from the knee flexion angle measurement device.
- The DAQ sampled 200 readings in a minute which means it was taking a voltage reading every 0.005 seconds. This time scale was applied to the device data and plotted providing a great visualization of all the data stored in the device.
- The only relevant data was for the participant’s test run for the distance of the predetermined track, so the device data was trimmed to only include the three to five strides taken by the participant.
- The time it took the participant to traverse the test track served as the time frame for the video data.

- In order to match the device data with the video data, the time it took the participant to walk the marked section of track was divided by how many frames of video were analyzed.
- This set the video data from each frame and the device data on the same time scale allowing the two collection methods to be overlaid on a single plot.

Manual Measurement

For the last part of analysis a mechanical goniometer was used to manually measure angles in each frame of video. During the analysis it was discovered that the center stride of each run was the most accurate for comparison of all the data collection methods. The center stride refers to the stride in which the participant was directly in front of the camera and at the center of the test track. It was found that for the other strides the subject was positioned at an angle to the stationary camera causing a parallax.

- Manually measured angles of each frame of video for only the center stride were analyzed
- The video frames ranged from the initial heel strike of the stride through to the point where the subject's leg was directly beneath their center of gravity. This was approximately 7 or 8 frames depending on the test participant.
- Each of the relevant frames were taken from the AfterEffects program and converted to picture files.
- The knee flexion angle of each frame was then measured manually using a mechanical goniometer
- Figure 38 displays the lines that were drawn on each screenshot for manual measurement.

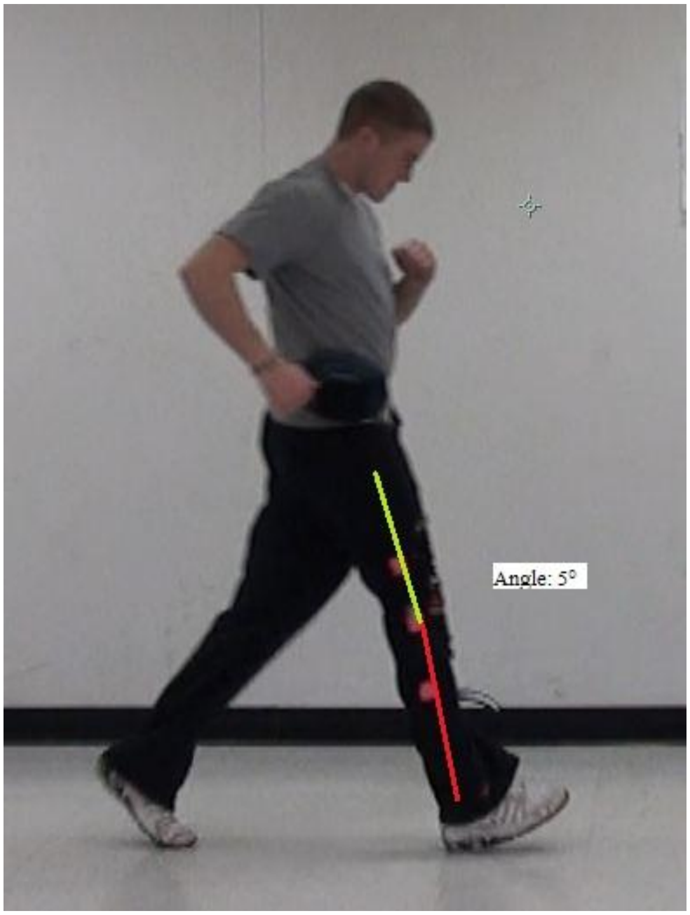


Figure 38. Example screenshot with lines drawn

- The figure also shows how lines were drawn that did not necessarily follow the colored indicators placed on the device. The purpose of these manual measurements was to create a set of data to serve as a control for means of comparison.
- The manually measured angles were then incorporated into the existing plot of the video and device data. A graph displaying all three measurement mediums was generated for each test subject.

Group Member 1

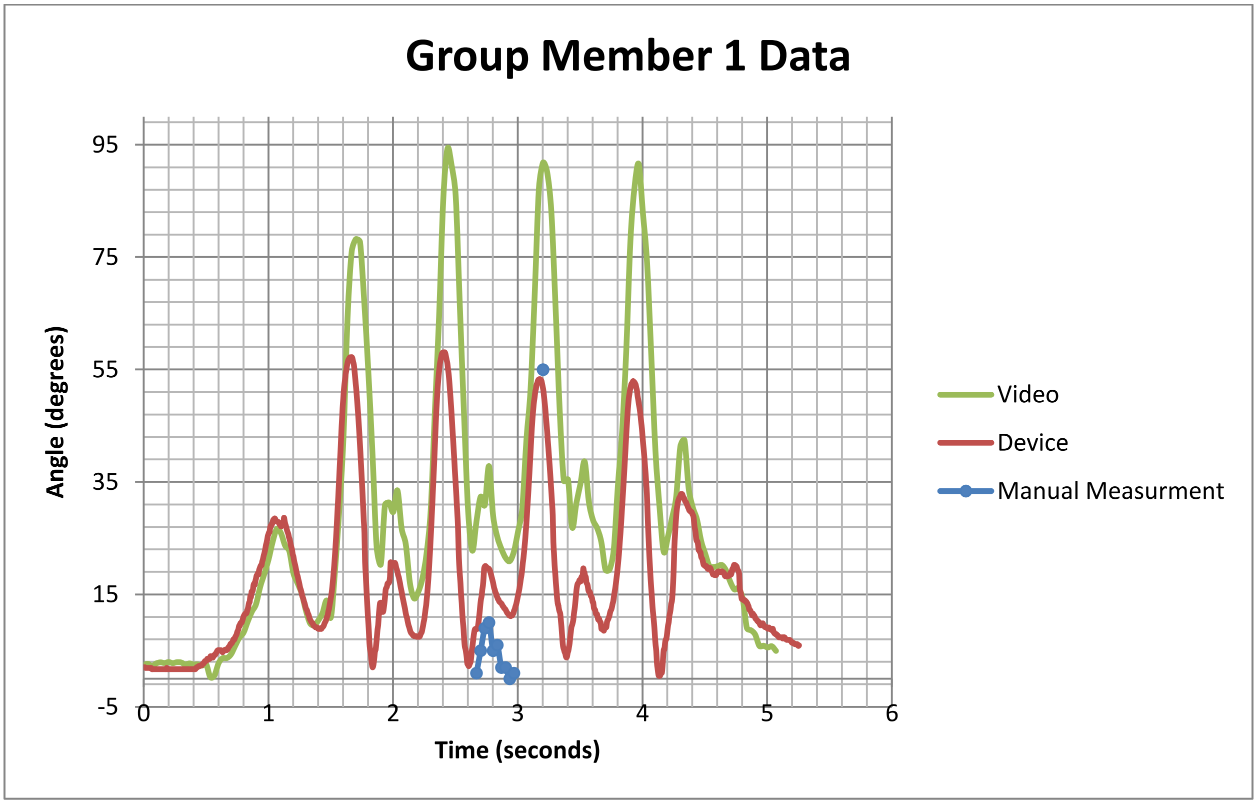


Figure 39. Group member 1 graph

A single graph was showcased of each subject's test runs with all three data collection mediums displayed. Figure 39 shows the first group member's test run. The red plot corresponds to the device data, the green plot is video, and the small blue portion is the manual angle measurements. This graph shows four steps; the valleys correspond to where the subject's leg should have a knee flexion angle close to zero. This particular group member did not hold a straight leg for the entire period of contact which is displayed by the varying valleys of each stride. This was of course expected having no race walking experience. It can also be seen that the device data is significantly under the video values in the valleys and at the peaks of each stride. The goniometer measurement is fairly close to that of the measurements from the data acquisition module for both the initial heel strike and the peak value where the knee is at its largest flexion angle. However the device data does not match as closely throughout the valley of this portion of the graph.

Group Member 2

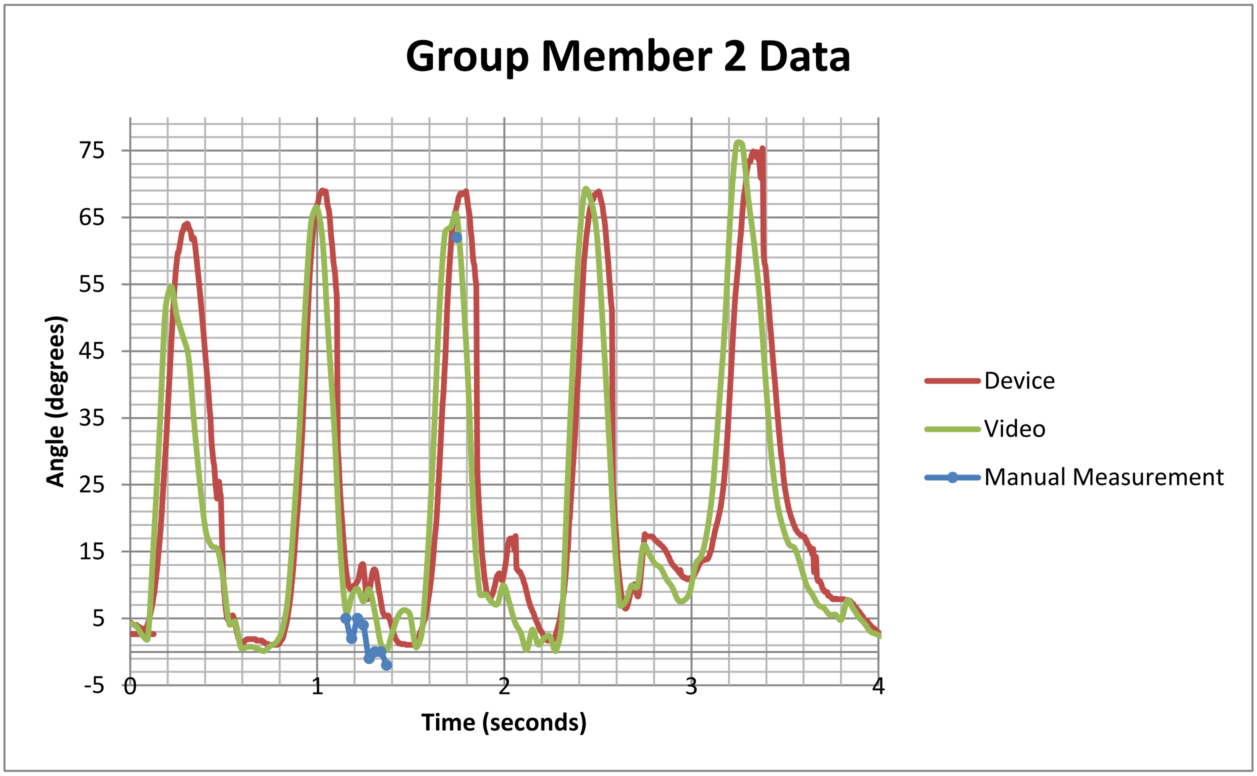


Figure 40. Group member 2 graph

The graph of the second group member shown in Figure 40 is very closely matched throughout the entirety of the test run. The initial heel strike manual measurement is much closer to the video than the device data and the peak value holds the same characteristic. The manually measured values in the valley of the stride center stride seem to follow the same gradual decline as the other two measurement methods, but it appears to be shifted down slightly. For the Group Member the device data produced larger angle measurements than the video analysis throughout the whole test run.

Group Member 3

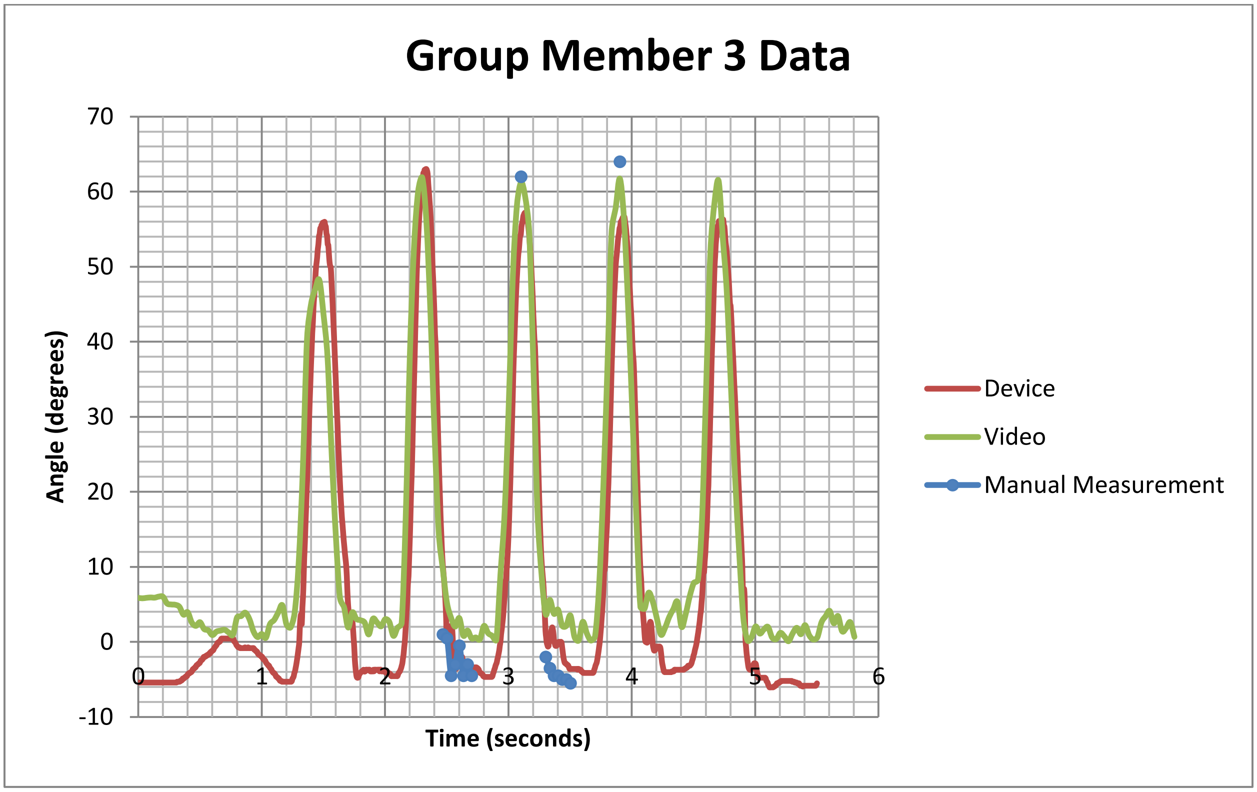


Figure 41. Group member 3 graph

The analysis of the graph of the third member was slightly different than the other analyses in the fact that two strides were manually measured with the goniometer. Figure 41 shows that the manual measurements clearly follow the device data closer on the first of the manually measured strides than the second stride. The video measurement on both of these strides visually differs from the other two collection mediums. This difference is within 5 degrees, which means that in a race walking event this would qualify as a bent knee and may have been misinterpreted through video analysis. Both of the cases of inconsistency in the data collection were likely caused by the angle produced when recording the video of each run. The camera was stationed at the center of the test track causing a parallax for the strides on either ends of the track.

The valley of the center stride, the first manually measured stride, indicates that the group member was fairly proficient in keeping a straight leg throughout ground contact. The video data shows that the group member held a consistent knee flexion angle almost at zero. Although the device data and the goniometer data match up, they indicate a knee flexion angle less than zero. This would mean that the group member hyperextends their knee when contacting the ground which is common in some race walkers.

Group Member 4

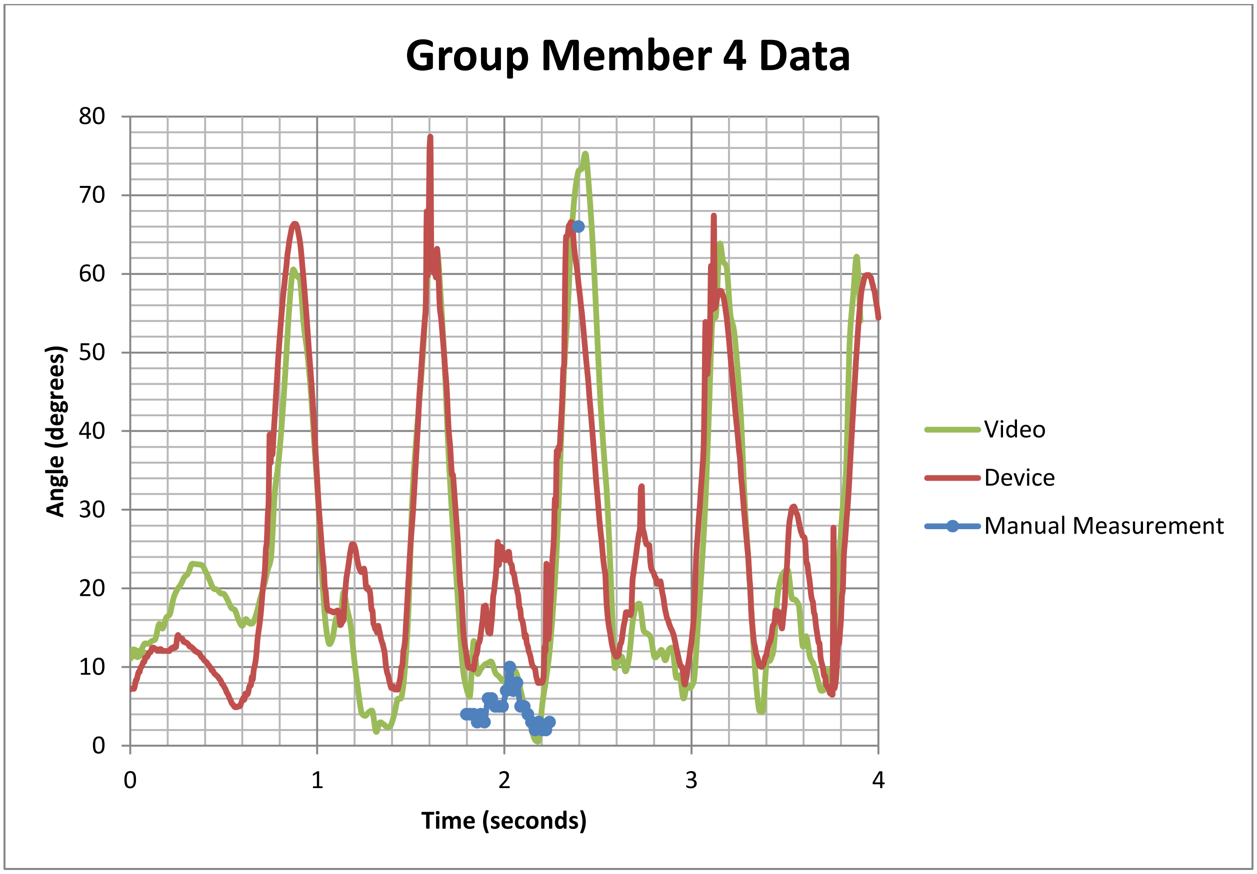


Figure 42. Group member 4 graph

The resultant graph from the data analysis of Group Member 4 is displayed in Figure 42. The data from this group member displays a bent knee part way through the valley portion of each stride and then returns to a somewhat straight leg. In this graph the video and device data are somewhat comparable. The video measurements were found to be lower at the valley of each stride. The video data is more consistent with the manually measured angles than the device data is in both the valley and peak measurements of the center stride. According to the goniometer measurements the group member did come close to a zero degree knee flexion angle, but the device data does not reflect this.

4.2.2 Round Two Testing: Race Walker Test Participants

The second phase of testing consisted of a group of four subjects who were familiar with the sport of race walking and whom had proper race walking form. Each of the subjects was asked to perform three runs and each was analyzed. The best of these runs was chosen to display and discuss for the project. The process of analyzing the data for this second round of testing is identical to the first round. When a knowledgeable race walker viewed this set of videos it was indicated that the majority of the test runs would pass for the straight leg rule in a race walking event.

Subject 1

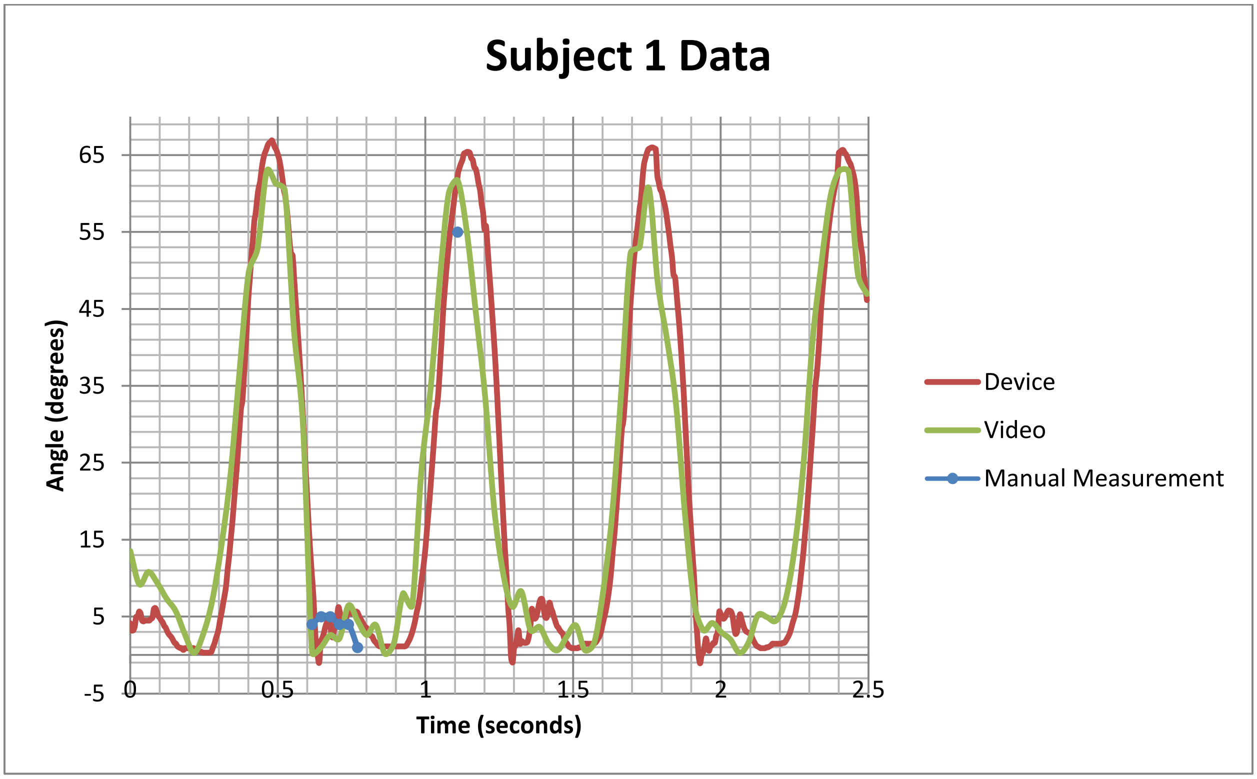


Figure 43. Subject 1 graph

The results obtained from the first test subjects for the second phase of testing is displayed above in Figure 43. It is evident from the graph that the subject retained a knee flexion angle close to zero degrees throughout ground contact on each stride. The methods of data collection did produce discrepancies in the valley of each stride, but they are relatively smooth for this subject. All three mediums of data collection are consistent at the valley of the center stride and the peak value is below both the device and video data. The device and video data are consistent for the most part except at the peaks where the video measurements were found to be lower than the device measurements.

Subject 2

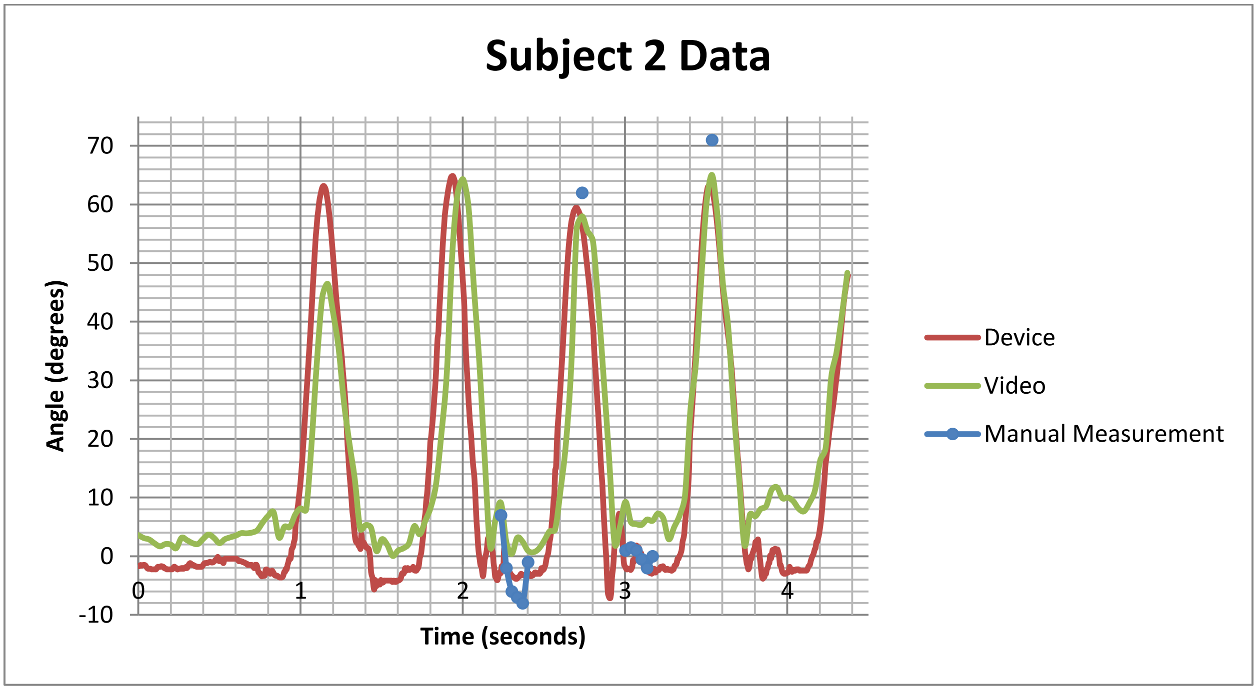


Figure 44. Subject 2 graph

Again the data displayed in Figure 44 exhibits proper race walking form for subject 2. The device measurements are lower than then video measurements at the valleys of each stride. For this subject's data the center stride as well as the proceeding stride was analyzed. According to both the manually measured angles and the device data this subject achieves hyperextension when contacting the ground. The video data is slightly above the other two data collection methods in the graph. For the center stride, the manual data does not compare well with either the device or video data. It does however very closely match the video data for the heel strike of the center stride. The proceeding stride was found to be more consistent where the manually measured data was very close to the device data.

Subject 3

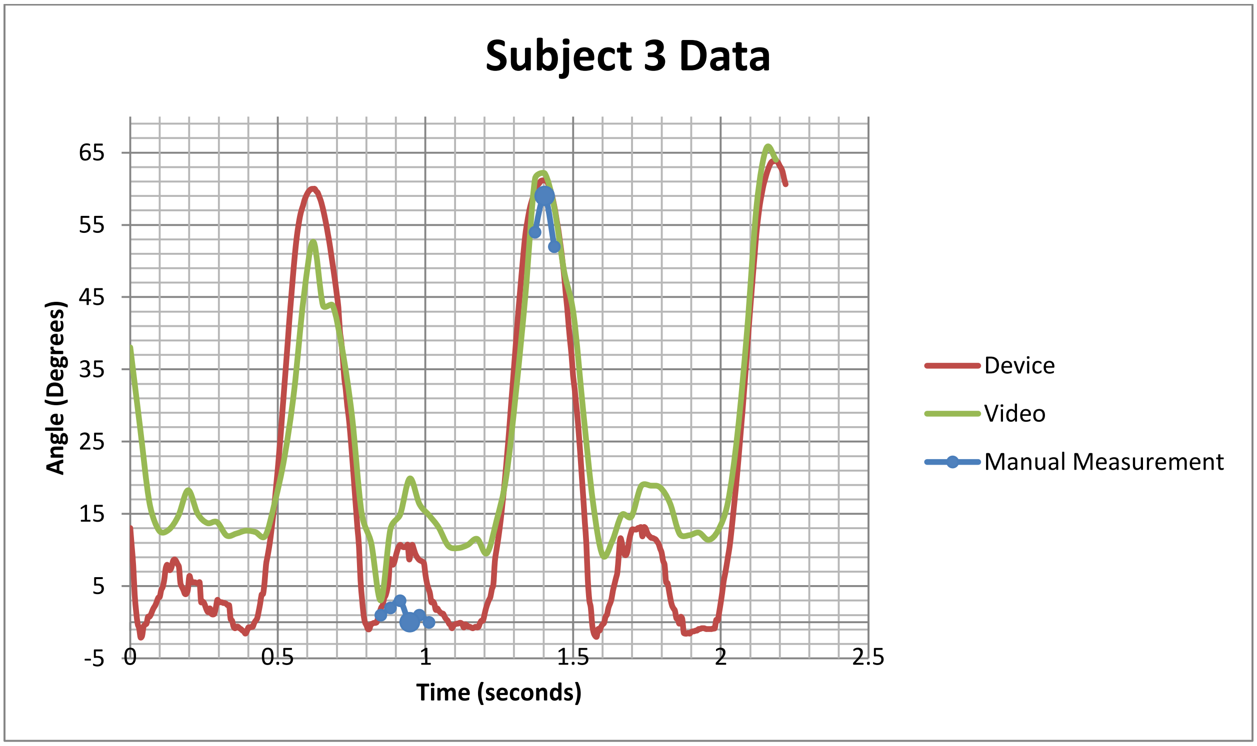


Figure 45. Subject 3 graph

Figure 45 displays the data for Subject 3. The graph shows that the walker obtained a straight leg followed by a slight bend in the knee and then returned to a straight knee flexion angle. This was also pointed out when the video analysis was viewed by the experienced race walking judge. The data acquired from the device is much closer to a zero degree knee flexion angle than the video data and is consistently lower in the valleys of each stride. The peaks of each stride are fairly close for the device and video data especially in the center stride. The manual measurement data indicated that the device was more accurate in the valley of the center stride than the video and that both mediums compared well on the peak.

Subject 4

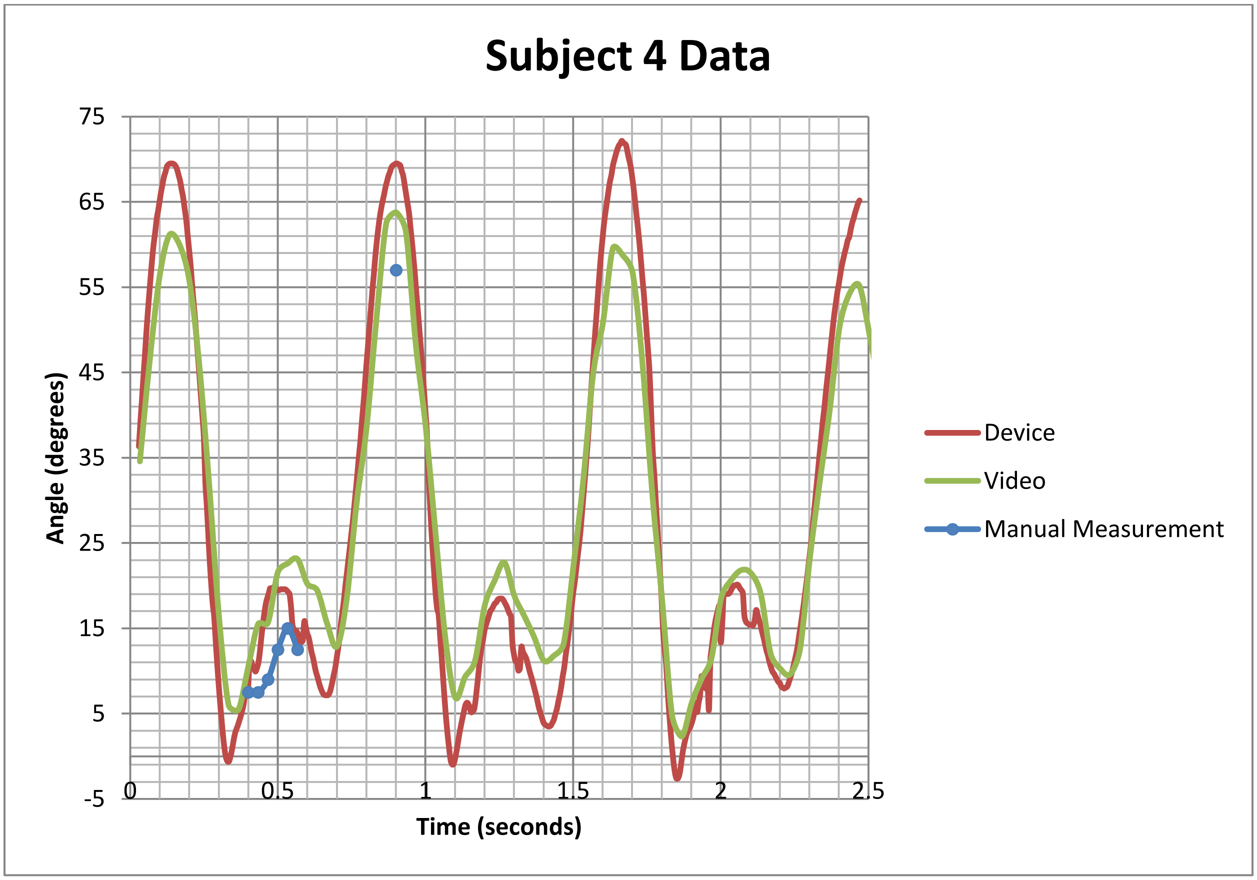


Figure 46. Subject 4 graph

Figure 46 shows the last of the four subjects that participated in the second round of testing for this phase. The valleys of each stride in this data set are erratic ranging from around zero to twenty degrees for the device data and from about five to twenty degrees for the video data. Although this subject was learned in race walking technique the data shows that proper technique was not achieved. Although the form was not exact, the device and video data are both fairly close to the manual measurements taken on the analyzed stride. The device and video data are also relatively consistent for the entirety of the test run. The device data is unswervingly above the angle measurements obtained from the video analysis for the peaks of each stride.

4.3 Error Analysis

Three different portions of each participants set of data were analyzed. For the center stride of each run and for each of the three measurement mediums, angle measurements at the heel strike, the valley, and the peak were explored. The valleys contained numerous data values some of which were negative. The absolute value of these measurements was taken followed by an average. The control manual measurements were used to indicate how the device and video data both differed from the assumed known measurement. Table 3 showcases the discrepancies in the device and video data for the heel strike, valley, and peak of each test participant as differences in degrees.

Table 3. Difference between measurement mediums

Difference (degrees)						
	Device vs. Manual			Video vs. Manual		
	Heel Strike	Valley	Peak	Heel Strike	Valley	Peak
Group Member 1	7.74	10.35	1.71	7.74	23.06	36.85
Group Member 2	4.05	4.55	4.66	1.89	0.65	3.39
Group Member 3	2.46	2.46	4.75	4.48	1.58	0.73
Group Member 4	9.44	10.83	6.92	4.85	4.41	7.05
Subject 1	6.54	0.73	7.62	3.68	0.98	6.70
Subject 2	9.90	5.88	2.60	2.08	0.01	4.03
Subject 3	0.41	0.24	2.17	2.06	12.51	3.13
Subject 4	0.66	5.41	12.37	2.98	7.48	6.76
Average	5.15	5.06	5.35	3.72	6.34	8.58
Standard Deviation	3.79	3.98	3.56	1.98	7.99	11.63
Standard Error	1.34	1.41	1.26	0.70	2.82	4.11

Table 3 displays two separate comparisons, the device versus the manual measurements and the video analysis versus the manual measurements. The heel strike, valley, and peak differences were reported for each test participant for each comparison. The values were averaged corresponding to where on the stride the analysis was performed. It was discovered that the device measured angles were overall more accurate for the valley and peak portions of the stride. The video proved better on the heel strike of the stride; however this point is also included in the valley averages which the device measured better. The valley portion of the stride is actually the most important part of the stride regarding race walking rules. The device produced an average difference of 5.06 ± 1.41 degrees and the video analysis produced an average difference of 6.34 ± 2.82. The video could theoretically achieve a smaller average difference than the device, but it was concluded that the device was more accurate for the valley portion of strides.

There seems to be differences in the device versus the control for the valley averages that are outliers. These high differences may have been caused by a rotation in the device over the course of the test run. They also could have resulted from an improper device fitment. If these two values were removed the average difference would fall to 3.21 ± 0.86 degrees. This isn’t an ideal error for the device because a bent knee may not be detected having about a possible three degree window that the measurements can be off by. Of course the device error could be improved with future developments and alternative material selection.

There are other possible sources of error that could have contributed to the difference the team experienced. The uncertainty the measurements made with the potentiometer and the mechanical goniometer could have each produced minor errors. The device itself also was found to shift during test runs which could account for differences in the device angle measurements. Also the After Effect program did not provide significant accuracy which was most likely caused by the parallax the stationary camera produced. Recommendations for future development of the knee flexion angle measurement device have been included in the following section.

5. Conclusion and Suggested Recommendations

The overall design, ideation, and construction of a functional, accurate knee flexion angle measurement device was successful. The angle readouts measured by the device were verified through a series of tests using a mechanical goniometer, and found to be very accurate. The device was further tested by each of the four group members as well as four experienced race walkers to determine their angle of knee flexion while race walking. The test procedure and analysis were conducted successfully and valuable data was obtained.

The device was found to fare better than video analysis when compared with the manual measurements. It was also discovered that in a majority of the test runs the device measured angles lower than the video analysis for the valleys of each stride. When the larger differences were removed from the valley data the device error dropped to around a three degree difference. This would be sufficient as a training device where there is no fear of being disqualified to provide the athlete with a rough estimate of when they are not achieving a straight leg. The device definitely has potential to be optimized to read angles more accurately if future development is of interest.

5.1 Device Improvements

There were several instances during testing where certain aspects of the device could have been improved. These improvements would not only help generate more reliable data, but would also make the device feasible for use in actual Race Walking events.

The first recommended device improvement is the use of a wireless data logger that will transmit the data from the device directly to a laptop, iPad or even an iPhone via Bluetooth connection. This would allow a race walker to train and see his walking data at the same time, or save it to view it after. It would also allow a person to race walk with the device on, and have a judge view the data and the walking strides at the same time. This would definitely help train judges to recognize what “bent knee” looks like, and the data would available for the judge to view as well.

A second recommended improvement to the device is the use of a 3V voltage regulator with a 9V battery. During testing it was found that even the slightest voltage drop to the potentiometer resulted in a change in angle readout. Using a 9V battery with a 3V voltage regulator will supply the device with a constant three volts for an extended time period without a change of batteries. The only con to the voltage regulator is that it may add some unnecessary weight along with the heavier battery, which is a negative factor to one of the design specifications.

One problem that arose from testing the device is that it would slide or twist on a person’s leg as they bent their leg more and more. This sliding or twisting changed the angle readout and in turn resulted in slightly inaccurate data. In order to present this, it is recommended that a non-slip rubber be used on the underside of the neoprene in order to prevent twisting or sliding. Another possible improvement is the re-design of the way that the nice attaches to the leg. If the device were attached to the leg relative to the knee cap, it would be easier to keep the device in the same place on the leg.

5.2 Testing Improvements

Through analysis of the testing, two aspects were found that would lead to more precise data. For future testing, it is recommended that a better placement of indicators be used when tracking the leg motion through the Adobe program AfterEffects. The indicators should be placed on the leg itself, along the axes of the leg bones. Proper placement would be on the femur, the tibia or ankle protrusion, and where the two bones meet at the knee for a more accurate representation of the angle of knee flexion. Also, the indicators should be made smaller for more accurate tracking of each point. With a smaller surface area, the analyzer will more precisely place the tracker in the middle of the indicator.

A second recommendation for better testing would be the use of relative camera motion. Using a stationary camera caused discrepancies in angle measurements during video analysis due to the angle of the walker's position in relation to the stationary camera. Most accurate angle measurements were found when the walker was positioned directly in front of the camera. Instead of using a stationary camera, a camera that stays parallel with the race walker at all times would produce much more accurate results. Two alternative methods are suggested. The first idea was to position the camera on a trolley to create parallel motion to the walker. Second, the use of a Go-Pro (or similar) high definition camera, which would be attached to the hip of the race walker, would also cut down the angle. As this may alter their center of gravity, the first mentioned recommendation may be a better solution.

6. References

Beaufils, Philippe, and Rene Verdonk. The Meniscus. Springer Heidelberg Dordrecht, 2010.

Bill Sellers. Functional anatomy of the lower limb. Available: http://moon.ouhsc.edu/dthompso/namics/kneeak.htm.

Biometrics ltd electrogoniometers & torsiometers Retrieved 10/3/2011, 2011, from http://www.biometricsltd.com/gonio.htm

Bosch DAF220K miterfinder digital angle finder kit Retrieved 10/3/2011, 2011, from http://www.cpotools.com/bosch-daf220k-miterfinder-digital-angle-finder-kit/bshndaf220k,default,pd.html?ref=googaw&kw={keyword}&gclid=CLC8i-jSy6sCFcYKKgodxixr1Q&keyword=bosch+digital+protractor

Clinicare, "BMI Knee Corrective Orthosis," vol. 2011, pp. 1, .

Dave Tompson PT. Biomechanics of the knee. *2011(09/23)*, pp. 1. 2000. Available: http://moon.ouhsc.edu/dthompso/namics/kneeak.htm.

Dejnabadi, H., Jolles, B., & Aminian, K. (2005). A new approach to accurate measurement of uniaxial joint angles based on a combination of accelerometers and gyroscopes. *IEEE Transactions on Biomedical Engineerings, 52*(8)

eORIF. Knee anatomy. *2011(09/29)*, pp. 1. Available: http://www.eorif.com/KneeLeg/KneeLeg%20anatomy/Kneeanatomy.html.

eRaceWalk. Technique. *2011(09/28)*, pp. 1. 2011. Available: http://www.eracewalk.com/Tech.htm.

Favre, J., Jolles, B. M., Aissaoui, R., & Aminian, K. (2008). Ambulatory measurement of 3D knee joint angle. *Journal of Biomechanics, 41*(5), 1029-1035. doi:10.1016/j.jbiomech.2007.12.003

HealthPage.org. Knee joint anatomy, function and problems. *2011(10/01)*, 2011. Available: http://healthpages.org/anatomy-function/knee-joint-structure-function-problems/#structures-of-the-knee.

Huei-Ming Chai. "Kinesiology, NTUPT." December 5 2004. <http://www.pt.ntu.edu.tw/hmchai/kines04/kinlower/Knee.htm>.

I. Farlex. The Free Dictionary. “Meniscus”. *2011(October 2)*, 2011. Available: http://medical-dictionary.thefreedictionary.com/ligament.

IAAF. "2011 IAAF worle race walking challenge handbook," in Anonymous 2011, Available: http://www.iaaf.org/mm/document/competitions/competition/05/91/93/20110201113729httppostedfile_rwchallenge2011handbook_23381.pdf.

IAAF. Race walking challenge. *2011(10/01),* 2011. Available: http://www.iaaf.org/wrc11/results/index.html#.

IDEA. IDEA health and fitness association. *2011(September 18),* 2011. Available: http://www.ideafit.com/fitness-library/knee-joint-anatomy.
Jeff Salvage, "The History of Race Walking," vol. 2011, pp. 2, 2011.

Kuiken, T. A., Amir, H. & Sheidt, R. (2004). Computerized biofeedback knee goniometer: Acceptance and effect on exercise behavior in Post–Total knee arthroplasty rehabilitation. Retrieved 10/2/2011, 2011, from http://www.eng.mu.edu/scheidtr/publications/KuikenAmirScheidt2004.PDF

Lakshmi Ananth. Hamstring muscles - flexor muscles of knee joint. *2011(10/03),* pp. 1. 2010. Available: http://lakshmiananth.suite101.com/hamstring-muscles--flexor-muscles-of-knee-joint-a219248.

Medscape Reference. "Medial Collateral and Lateral Collateral Ligament Injury." July 22 2011.<http://emedicine.medscape.com/article/307959-overview>.

Naylor, J. M., Ko, V., Adie, S., Gaskin, C., Walker, R., Harris, I. A., & Mittal, R. (2011). Validity and reliability of using photography for measuring knee range of motion: A methodological study *BMC Musculoskeletal Disorders, 12*(1), 77. doi:10.1186/1471-2474-12-77

NetDoctor. “Knee Injuries – Collateral Ligaments”. *2011(October 1),* 2011. Available: http://www.netdoctor.co.uk/diseases/facts/kneeinjuriesligaments.htm.
Racewalk.com, "The Rules of Race Walking," vol. 2011, pp. 8, 2009.

State University of New York. The functional anatomy of the knee joint. *2011(09/29),* pp. 1. Available: http://www.upstate.edu/cdb/education/grossanat/limbs8.shtml.

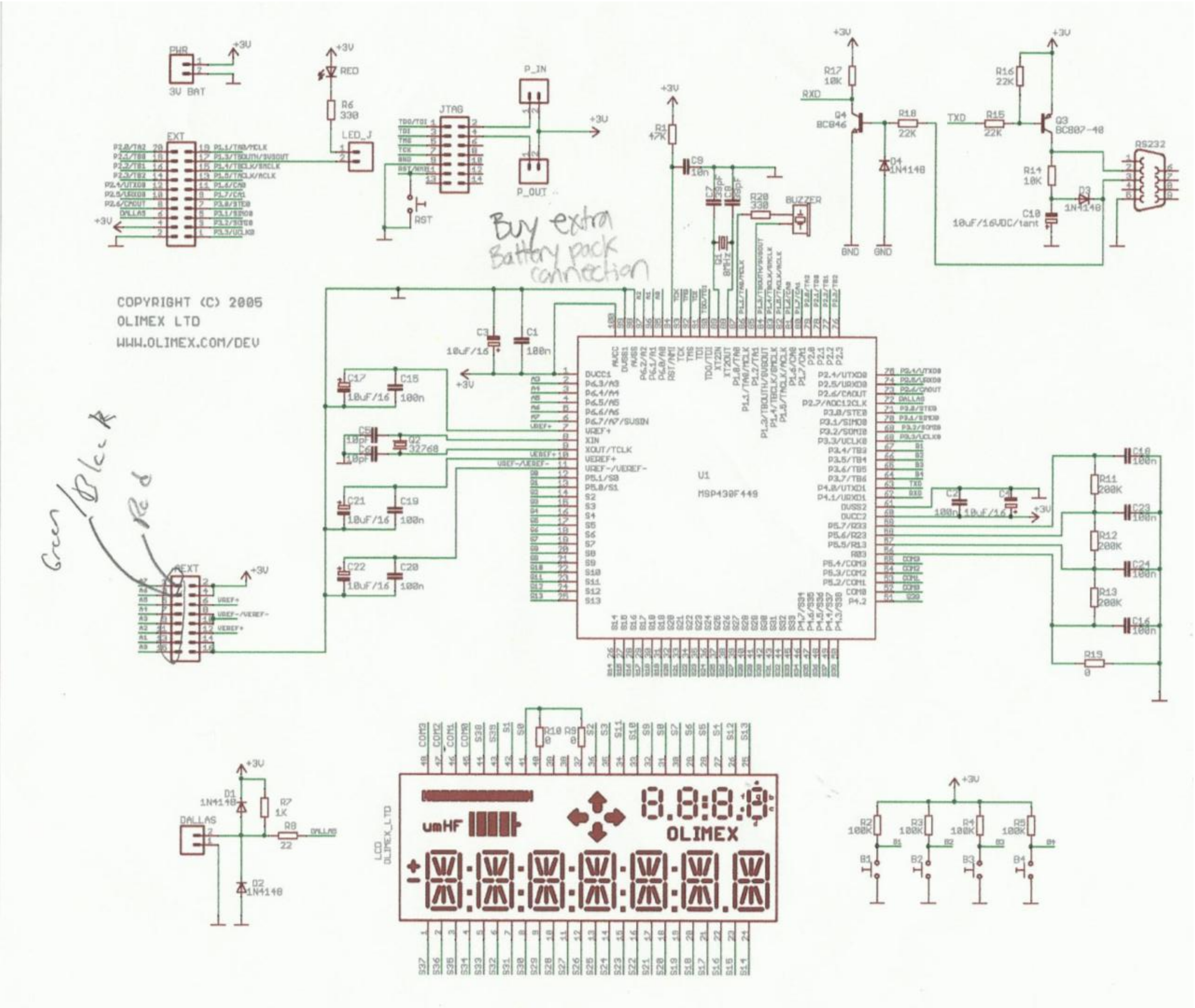
USATF. *Race Walk Officiating Handbook* 2008Available: http://www.usatf.org/groups/officials/files/resources/race-walking/2008-race-walking-officiating-handbook.pdf.

USATF. Race-walking. *2011(10/01),* 2011. Available: http://www.usatf.org/Sports/Race-Walking.aspx.

WebMD LLC. Medscape. *2011(September 20),* 2011. Available: http://emedicine.medscape.com/article/307959-overview.

7. Appendices

Appendix A: MSP430F449 Development Board Pin Diagram



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