Kinematic Tester for Knee Replacements

A Major Qualifying Project Report
Submitted to the Faculty
of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Mechanical Engineering

Submitted By:

____
Jared Breton

____
Victoria Carlson

____
Nicholas Perez

Date: April 23, 2015

Approved By:

____

Professor Eben Cobb, Project Advisor

Abstract

Knee replacement surgery has become one of the most common orthopedic procedures performed on older people suffering from osteoarthritis. In an aging society, the demand for knee replacement surgery is predicted to rise. The goal of this project was to design a mechanism for evaluating knee replacements that simulates the motion of a knee replacement during walking. The team designed a mechanism that accommodates a 3D printed total knee replacement. The knee replacement within the mechanism reproduces the correct angular displacement between the tibia and femur and the angular displacement of the femur swing according to our kinematic analyses. It is hoped that future iterations of this mechanism can be used for the evaluation of knee replacement designs.

Acknowledgements

Professor Eben Cobb of Worcester Polytechnic Institute

For overseeing our project and providing guidance and direction.

Michael Strickland of Worcester Polytechnic Institute

For working with us to get our knee replacement 3D printed in a reasonable timetable.

Scott Breton of Sparton Technology

For allowing us to utilize Sparton to manufacture our links and get most of our hardware at a discounted price.

Steven Breton of Sparton Technology

For providing insight into hole clearance and slip fit holes used in our linkage nodes.

Larry Dugan of Sparton Technology

For teaching us how to properly use a Bridgeport to ream our links' holes to the proper size.

Table of Contents

Abstract i
Acknowledgements ii
Table of Contents iii
List of Figures v
List of Tables viii
1 Introduction 1
2 Background Research 2
2.1 Biology of the Human Knee 2
2.2 Kinematic Mechanisms 8
2.3 Knee Replacements 12
2.4 Knee Replacement Testing 15
3 Project Objectives 20
3.1 Goal Statement 20
3.2 Task Specifications 20
4 Design Concepts 22
4.1 Concept 1 – Hrones & Nelson Sixbar 22
4.2 Concept 2 – Theo Jansen's Linkage 28
5 Design Selection 34
6 Proof of Concept 35
7 Detailed Design 36
7.1 Linkage 36
7.2 Knee Replacement 37
7.3 Motor 42
7.4 Frame 47
8 Prototype Construction 51
8.1 Frame Construction 51
8.2 Motor and Electrical Components 53
8.3 Femur and Tibia Subassembly Construction 54
8.4 Linkage Construction 56
8.5 Alterations to the Final Prototype Design 58
9 Prototype Testing 63

10 Conclusions ... 69
11 Future Recommendations ... 70
11.1 Allow the Mechanism to be Completely Customizable per Patient ... 70
11.2 Apply Sensors to the Mechanism ... 70
11.3 Apply Accurate Forces on the Knee Replacement ... 70
11.4 Recommendations for Ordering Components ... 71
11.5 Improving Upon the Frame ... 71
11.6 Drafting ... 73
11.7 Alternate Axle Components for Use in Pin Joints ... 74
11.8 Possible Alternative Designs ... 77
Bibliography ... 81
Appendices ... a
Appendix A: Selecting the Hrones and Nelson Atlas Fourbar ... a
Appendix B: Detailed Drawings of the Final Linkage Subassembly ... c
Appendix C: Dimension Drawing of the Precision Gear Motor ... ee
Appendix D: Specifications of the Precision Gear Motor ... ff
Appendix E: Results of the SolidWorks Simulation for Torque ... gg
Appendix F: Dimension Drawing of the Motor Mount ... jj
Appendix G: Frame Design Alternatives ... kk
Appendix H: Quote for Anchor-Fastened Frame Option ... nn
Appendix I: Quote for Standard End-Fastened Frame Option ... aaa
Appendix J: Steps to Implement 80/20 End Fasteners ... mmm
Appendix K: Detailed Drawings of Final Top-Level Assembly ... nnn
Appendix L: Position Data and Calculations from the Tracker Program ... www

List of Figures

Figure 1: Anterior skeletal view of the human knee [2]. 3
Figure 2: Anterior (Left) and Posterior (Right) view of knee muscle groups [3]........................ 4
Figure 3: (A) Front view of the knee showing the patella and quadriceps tendons. (B) Back view of the knee showing the PCL and ACL ligaments.. 4
Figure 4: Positional diagram of the knee undergoing flexion, extension, rolling, and gliding motions... 5
Figure 5: Knee Movement through a walking gait cycle [7]. 6
Figure 6: Spatial Parameters of the foot while walking [7]. 7
Figure 7: OpenSim Normal to Crouching Gaits Example [10]. 8
Figure 8: Typical Hrones Nelson fourbar linkage. The numbering system is shown on the linkage. The links are labeled 1-4 with link 1 as the ground, link 2 as the crank, link 3 as the coupler, and link 4 as the rocker. The trace curve of the crank, coupler, and rocker are also depicted. 9
Figure 9: Coupler curve shapes and terminology [6].. 10
Figure 10: Theo Jansen's Mechanism with links and nodes labeled. The path of each node is traced [11]. 11
Figure 11: Time evolution of Theo Jansen mechanism for one cycle. Foot trace curve is shown [12]. 12
Figure 12: (Left) Shows a healthy knee with normal joint space. (Right) shows a knee effected by osteoarthritis. The radiograph indicates presence of bone spurs and loss of joint space [21]. 13
Figure 13: Knee Replacement Types: (Left) Unicompartmental knee replacement (Right) Total Knee Replacement [23].. 14
Figure 14: Distribution of Total Knee Replacements by Age. Data was collected from CDC Inpatient surgery from 2007- 2010 [25]... 15
Figure 15: Sign convention specified by ISO 14243-2 for forces, torques and motion of a left TKR [27]. 16
Figure 16: Kansas Knee Simulator [29]... 17
Figure 17: Vermont Knee Simulator [29]. 18
Figure 18. (Left) Stanmore/Instron Simulator. (Right) Single testing station of simulator [29]. . 18
Figure 19. Femur Swing Trace curve with 50 degree maximum swing angle. Maximum swing angle was measured using a protractor from the femur trace curve obtained from OpenSim...... 20
Figure 20: Preliminary Sketch of the Hrones and Nelson Sixbar Concept.................................. 22
Figure 21: Trace Curve of the Ankle, Captured from an OpenSim Simulation 23
Figure 22: The Page of the Hrones and Nelson Atlas Which Includes the Final Sixbar Chosen for Concept 1 24
Figure 23: Trace Curve of the Hip, Captured from an OpenSim Simulation 25
Figure 24: The Results of Finding the Location of the Third Ground Node (Hip Joint) in Concept 1.. 26
Figure 25: The Final Model of the Hrones and Nelson Sixbar Concept 27
Figure 26: The Angle of the Femur from Vertical Over One Cycle in Design Concept 1 27
Figure 27: The Angle Between the Tibia and Femur Links Over One Cycle in Design Concept 1 28

Figure 28: Model of an Example Theo Jansen's Linkage 29
Figure 29: The Adjustable Theo Jansen's Linkage Used to Increase the Accuracy of the Linkage to the Human Walking Gait 30
Figure 30: Angular Displacement of the Femur with Respect to Vertical Over One Cycle. 30
Figure 31: Angular Displacement of the Knee Joint Over One Cycle 31
Figure 32: Alternative Theo Jansen's Linkage with an Accurate Trace Curve but a Hyperextended Knee Angle 32
Figure 33: Ankle Trace Curve of the Final Theo Jansen's Linkage Concept Which More Accurately Follows the Joint Angles.. 33
Figure 34: Constructed Theo Jansen proof of concept model 35
Figure 35 - Angular displacement of the femur with respect to horizontal. The femur displaces 50 degrees. 36
Figure 36 - Angular displacement of the knee joint is 68 degrees... 36
Figure 37: SolidWorks .stl model of femur bone for 3D printing. 38
Figure 38: Attachment of femur and tibia links the mechanism.. 39
Figure 39: Example of a screw post (also known as a binding post) from Grainger's online store 39
Figure 40: (Left) Linkage with the femur and tibia bones at nearly 180 degrees. (Right) Linkage with the femur and tibia bones at an angle, resulting in a collision between the femoral and tibial components. 40
Figure 41: Slot joint for the femur link to prevent interference... 40
Figure 42: The red lines denote where the rubber bands mimic the tendons and ligaments. (Left) the X-shaped cruciate ligaments (ACL and PCL). (Right) the patellar and quadriceps tendons. 41
Figure 43: Positional Evolution of the Final Linkage over one complete cycle.......................... 42
Figure 44: Motor from ServoCity to be used in prototype. 43
Figure 45: Crank Torque over one cycle 45
Figure 46: ServoCity Motor Mount 46
Figure 47: ServoCity clamping hub 46
Figure 48: Power Switch for motor 47
Figure 49: Dimensioned cross section of a standard 80/20 10-series extrusion.......................... 48
Figure 50: End fasteners used to attach 80/20 extrusion together 49
Figure 51: Assembly of fastener screws with 10-series extrusion.. 49
Figure 52: Acrylic plate design to be laser cut for mounting of the motor and linage ground..... 50
Figure 53: Acrylic plates used to mount power switch and motor. 50
Figure 54: Components of the Frame from 80/20. 51
Figure 55: The Assembled 80/20 Component of the Frame... 52
Figure 56: The Acrylic Screwed into the Sides of the 80/20 Extrusions using T-Nuts................ 52
Figure 57: The Switch is Hot-Glued into the Rectangular Cutout in the Side Acrylic Plate with the Stop Label to its Right 53
Figure 58: The Suggested Wiring Schematic Offered from ServoCity's Website....................... 53
Figure 59: The Motor and Switch Mounted to the Frame and Wired Together 54
Figure 60: Exploded View of the Femur Assembly. 55
Figure 61: Exploded View of the Tibia Assembly 55

Figure 62: The Final Mechanism's Tendons and Ligaments.. 56
Figure 63: Assembled Node of the Final Prototype.. 57
Figure 64: Assembly of the Shaft Hub to the Crank on the Final Prototype. 57
Figure 65: The Bottom Node of the Linkage Impacts the Frame due to a Moment on the Ground Nodes. 58
Figure 66: Free Body Diagram of the Hex Screw which Comprises the Left-Most Ground Node. 59
Figure 67: Free Body Diagram of the Hex Screw after Implementing the Counterbalance......... 60
Figure 68: The Final Iteration of the Left-Most Ground Node.. 60
Figure 69: Model of the Acrylic Guide Plate Attached to the Frame 61
Figure 70: Picture of the Complete Assembly.. 62
Figure 71: The femur swing angle measured with the Tracker program was found to be 49.7 degrees. 64
Figure 72: Knee (blue) and Ankle (white) joint trace curves for one complete cycle. 65
Figure 73: Tibia and femur angular displacement of prototype. The maximum angular displacement was calculated to be 75.51 degrees. 66
Figure 74: Measured prototype knee angle at maximum extension 67
Figure 75: Trace curve of knee. (Top) OpenSim trace curve (Bottom) Prototype trace curve 68
Figure 76: Trace curve of ankle. (Top) OpenSim trace curve (Bottom) Prototype trace curve ... 68
Figure 77: Cabinet-style frame design 72
Figure 78: (a) shown at left is an isometric view of the slot intended to reduce the knee joint's 3rd degree of freedom; (b) shown at right is a cross-sectional view of how the slot is assembled. ... 73
Figure 79: Image of aluminum screw binding post. The red line denotes the flare at the bottom of the barrel near the cap screw and the green line denotes the flare at the top of the barrel post.... 74
Figure 80: Image of the screw binding post's barrel in a hole (indicated by the gray box in the top of the image). The red circle identifies a stress concentration point caused by the barrel's flared end... 75
Figure 81: Cross section of a joint in which the screw binding post acts as an axle about which links rotate. The cyan line denotes the Loctite adhesive used to hold the posts together............. 75
Figure 82: Image of different style bronze oil-impregnated bushings from www.woodworkingonline.com 76
Figure 83: Image of a rolling-element ball bearing from McMaster Carr's website 76
Figure 84: Sketch of the Cam-Driven Mechanism Concept 78
Figure 85: Rough incomplete sketch of anatomically correct sixteen or eighteen bar lower human extremities mechanism.. 79
Figure 86: Fourbar knee mechanism as shown on www.heritage-medical.com 79
Figure 87: Camshaft articulated human leg design.. 80

List of Tables

Table 1: Step to Distance Conversion Chart from the American College of Sports Medicine [8]. 7
Table 2: Lengths Used to Determine the Location of the Hip Joint 26
Table 3: Length of Each Link (with a 2/3 scale) in the Final Theo Jansen's Linkage Concept.... 33
Table 4: Design Concept Decision Matrix... 34
Table 5: 2/3 Scale link lengths for final linkage 37
Table 6: Definition of Each Variable in the Virtual Work Equation 43
Table 7: Excel Spreadsheet used in determining required power for linkage. 44
Table 8: Sum of the dot products determined from the virtual work equation............................ 45
Table 9: Sample of the excel data used to calculate the angular displacement of the knee joint. 66

1 Introduction

Knee replacement surgery is one of the most common orthopedic procedures performed on older people suffering from debilitating osteoarthritis. Osteoarthritis causes the bones of the knee to rub together and is the number one cause for knee replacements. Most people undergo knee replacement surgery later in life at the age of 45 or older. It is vital to have a healthy knee joint so that daily functions and motions such as walking, sitting, laying down, etc. can be performed. Knee replacements restore this functionality that was once lost due to osteoarthritis or trauma. Due to the high usage of the knee, it is important that the knee replacement design has a long lifespan and can withstand long term wear which it will be subjected to in the human body. To test the knee replacement, knee simulator machines have been built, and the International Standards Organization has defined standards for testing knee replacements.

This project designs a mechanism for evaluating knee replacements that simulates the motion of a knee during walking. It is the foundation for later iterations to be used for evaluating knee replacement designs.

This project was completed by first researching the biomechanics of the human knee. Next, possible linkage concepts such as Hrones-Nelson six bar and Theo Jansen mechanisms were explored. After considering both concepts, we rated each mechanism in a decision matrix and decided that the Theo Jansen mechanism would be a better choice for replicating the motions of the knee. The desired motions of the mechanism included the angular displacement of the tibia and femur bones, and the angular displacement of the femur swing. These data were obtained through research and from the program OpenSim. A proof-of-concept prototype of a Theo Jansen mechanism was built, then the team designed and constructed a working prototype. The mechanism was built to accommodate a 3D printed total knee replacement. A motor was chosen to drive the crank and a frame was designed to support the mechanism. From kinematic analysis and testing of the prototype, it was determined that our mechanism did reach the desired angular displacement of the femur. However, the angular displacement of the knee was outside the desired range, but within 8% error. This error could be the result of poor video or the motion analysis tool. Overall the team is satisfied with the results of the project and believe it is a good stepping stone for future iterations.

2 Background Research

In the following sections, we present the information necessary to understand our project. This information is separated into four main sections. The first is the biology of the human knee which includes the physical anatomy and also the motion and kinematics of the knee during gait. Next, the Hrones-Nelson fourbar and Theo Jansen mechanisms are examined for possible models of knee motion. Finally knee replacements and existing knee replacement testing devices are highlighted.

2.1 Biology of the Human Knee

The human knee provides a hinge-like motion, allowing the lower leg to bend so that humans can change body position. Without the motions of the knee, daily functions like walking, sitting, laying down, reaching, etc. cannot be performed, making it difficult to go about everyday life. In the following sections the anatomy of the knee and the kinematics behind walking are detailed. Having a basic understanding of how the human knee functions will better the team's design of a mechanism that mimics the knee's motion.

2.1.1 Anatomy of the Human Knee

The skeletal and muscular components of the knee will be described in the following sections to give a better understanding of the complexity and functionality of the knee joint.

2.1.1.1 Skeletal

The human knee, depicted in Figure 1, is located below the waistline at the junction between the femur, patella, tibia, and fibula [1]. The femur, tibia, and fibula bones help support and provide strength of the human body. The patella is a small triangular bone that rests on fatty tissue between the femur and tibia and protects the knee joint from contact injury along with helping to extend the knee so it straightens but is not hyperextended. Articular cartilage cushions the ends of the tibia and femur bones and also helps to reduce friction. The two menisci between the tibia and femur bones function as shock absorbers. The cruciate ligaments attach the femur and tibia bones together. The anterior cruciate ligament (ACL) prevents the femur from sliding backward on the tibia while the posterior cruciate ligament (PCL) prevents the femur from sliding forward on the tibia. The ACL and PCL are inside the knee joint and form an "X" (see Figure 3). Additionally, the lateral motion of the knee is minimized by the collateral ligaments, which prevent excessive back and forth motion while still allowing the knee to go through the flexion and extension motions.

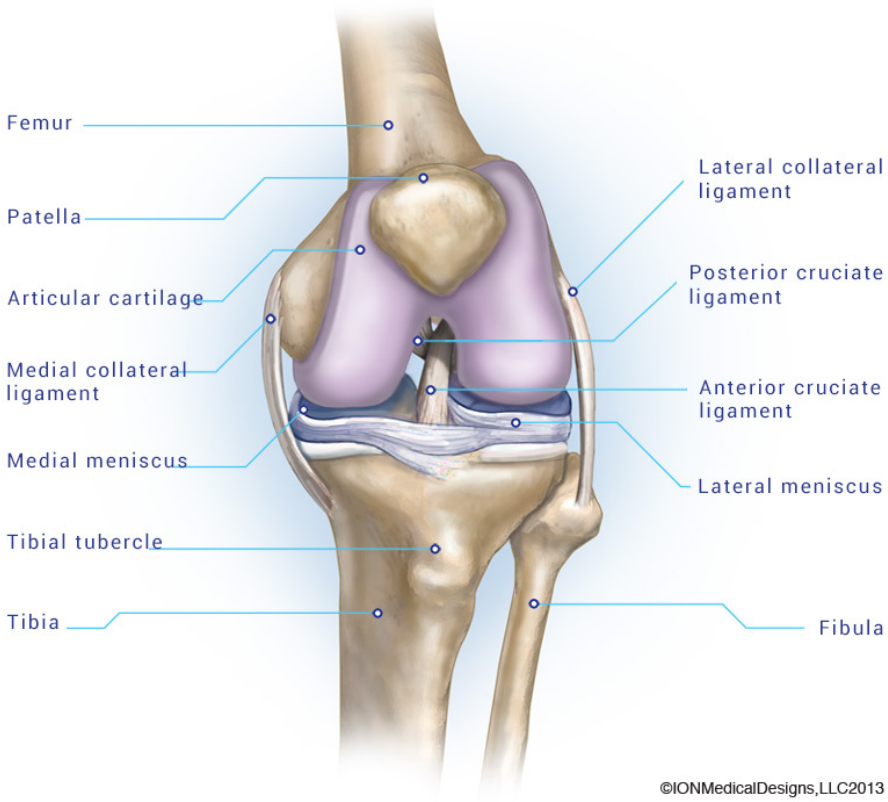


Figure 1: Anterior skeletal view of the human knee [2].

2.1.1.2 Muscular

The muscles of the knee, pictured in Figure 2, work to flex, extend, and stabilize the knee joint allowing the body to perform motions such as walking and running. There are two large muscle groups that help to control the knee directly: the quadriceps and hamstrings. The quadriceps is a group of four muscles located in the anterior (front) of the femur which functions to extend the knee. The hamstrings is a group of three muscles located at the posterior (back) of the femur that guide knee and hip movement. However, the motion of the knee is complicated for it depends on the rotation of the hip joint, the motion of the ankle, and the lengths of both the fibula, tibia, and femoral regions of the leg.

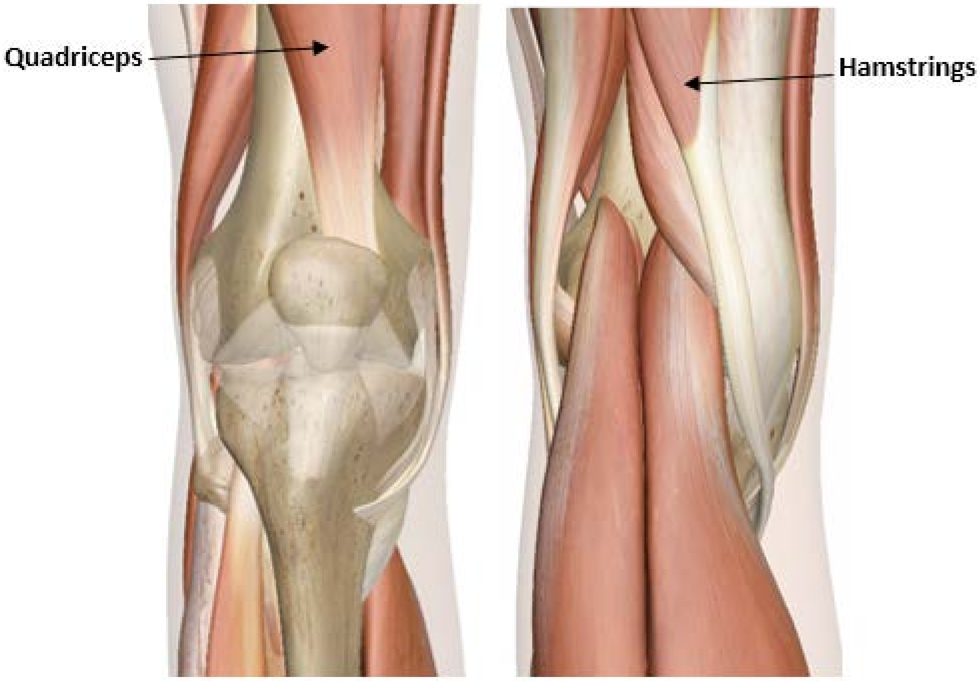


Figure 2: Anterior (Left) and Posterior (Right) view of knee muscle groups [3].

Tendons of the knee attach muscles to bones. In addition to the muscles, the quadriceps and patella tendons work together to help straighten the knee (See Figure 3).

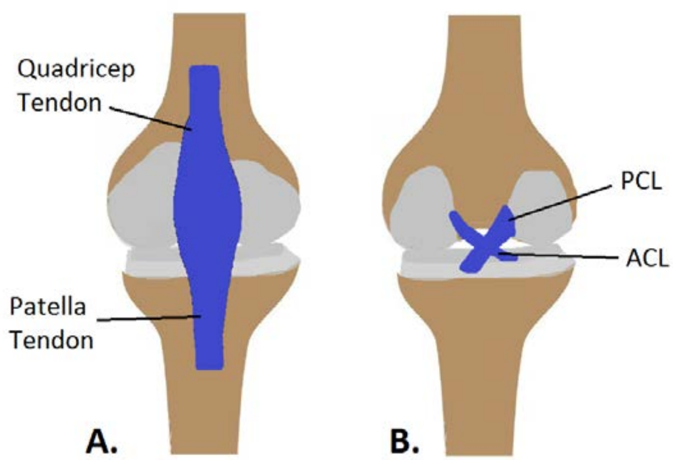


Figure 3: (A) Front view of the knee showing the patella and quadriceps tendons. (B) Back view of the knee showing the PCL and ACL ligaments.

2.1.2 Human Gait

The pattern of how humans move is called gait [4]. Human gait differs from person to person, and is affected by the extent, speed, and direction of knee joint and body segment movements [5]. For the purpose of this project, we will focus on the kinematics of the human gait cycle while walking an average speed. Kinematics is the study of motion with no reference to forces [6]. This section will focus on the motion of the knee, the kinematics of human gait, and how the OpenSim program can be used as a tool to help model gait.

2.1.2.1 Motion of the Human Knee

The knee is a hinged diarthrosis joint, meaning that the body has enough range of mobility to change positions. Due to the knee's hinge-like nature, the movement occurs mainly in one plane where the knee undergoes motion called extension and flexion, with the exception of minor gliding and rotation of the joint (see Figure 4).

The main point of emphasis in this report is the motion of the knee during flexion, extension, the transition between flexion and extension, and visa-versa. During flexion, several bones experience an inward rotation while the tibia glides behind the end of the femur. At the end of this motion, there is room for acute additional rotation. This rotation also takes place during extension.

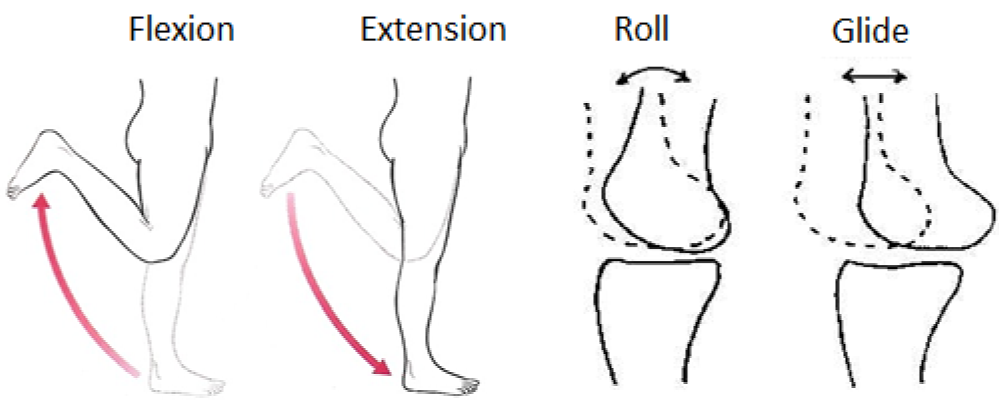


Figure 4: Positional diagram of the knee undergoing flexion, extension, rolling, and gliding motions.

2.1.2.2 Kinematics of Human Gait

The flexion and extension of the knee joint is cyclic and varies between 0 and 70 degrees. The exact amount of peak flexion varies depending on the person and their respective walking speeds [7]. During normal walking there is a period of time when the foot is in contact with the ground and when it is not. These phases are respectfully known as the stance phase and swing phase. Additionally, there are five phases that characterize human walking gait which are illustrated in Figure 5 [7].

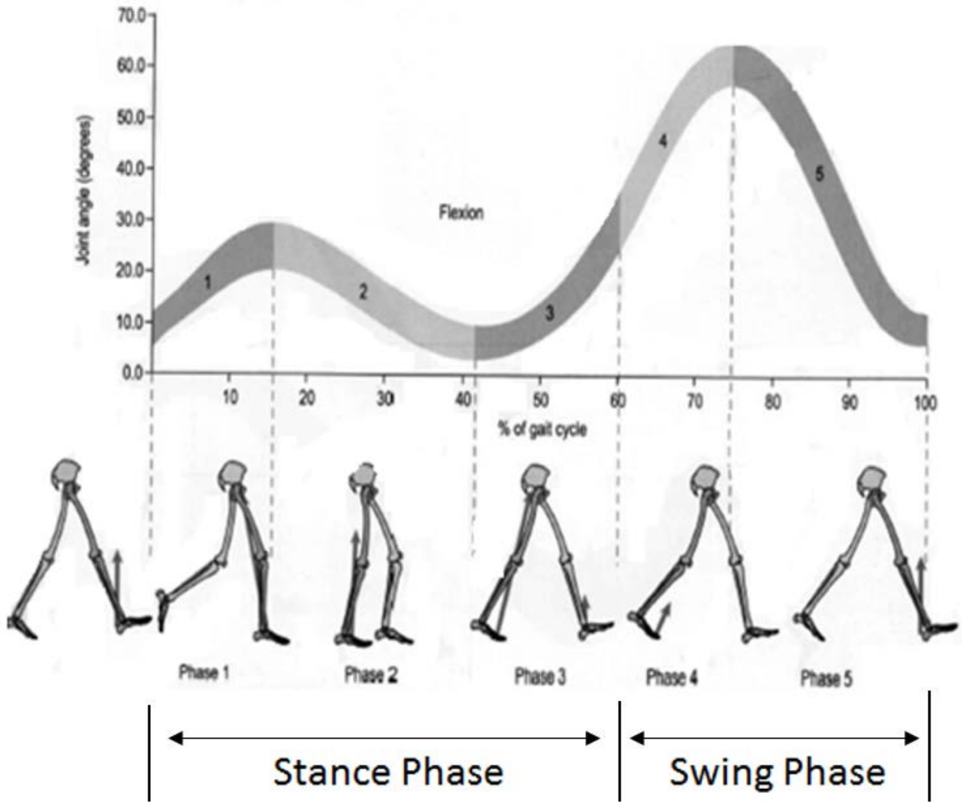


Figure 5: Knee Movement through a walking gait cycle [7].

In phase one after initial contact has been made the knee is flexed under maximum weight-bearing load to about 25 degrees. In phase two, the knee join extends to an almost full extension of nearly 180 degrees. A second flexion phase begins in phase three coinciding with a heel lift. In phase four, the lower leg and knee are preparing for the swing phase. The toe off occurs when the flexion of the knee is roughly 40 degrees. The knee joint continues to flex along with the ankle joint which allows the toes to clear the ground. During this mid-swing the knee flexes to a maximum of 65-70 degrees. In phase five, during late swing the knee joint goes through extension in preparation for the second heel to strike the ground [7].

The spatial parameters of the foot during contact can be described by step length, the distance between two consecutive heel strikes, and the stride length, the distance between two consecutive heel strikes by the same leg [7]. See Figure 6 for a visualization of the step and stride lengths.

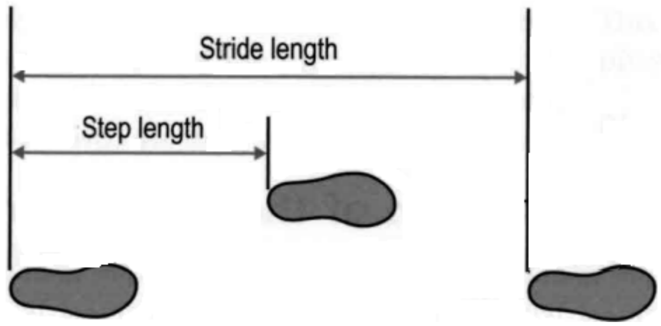


Figure 6: Spatial Parameters of the foot while walking [7].

Researchers from the American College of Sports Medicine calculated the number of steps it took humans to walk one mile and found that the typical person makes approximately 2000 steps. In turn, the typical step length is approximately 31 inches, which means the typical stride length is approximately 62 inches [8]. These conversions are displayed in Table 1. Also, according to the University of California wellness program, Walking Fit, the average person takes 133 steps in a minute. Therefore, the average human takes approximately 66.5 strides in one minute [9].

Table 1: Step to Distance Conversion Chart from the American College of Sports Medicine [8].

STEPS	MILES	KM		STEPS	MILES	KM
500	.25	.40		5500	2.75	4.43
1000	.50	.80		6000	3.00	4.83
1500	.75	1.21		6500	3.25	5.23
2000	1.00	1.61		7000	3.50	5.63
2500	1.25	2.01		7500	3.75	6.03
3000	1.50	2.41		8000	4.00	6.44
3500	1.75	2.82		8500	4.25	6.84
4000	2.00	3.22		9000	4.50	7.24
4500	2.25	3.62		9500	4.75	7.64
5000	2.50	4.02		10000	5.00	8.05

In recent years, the presence of modeling and simulations has increased as tools to study biomechanics and treatments for ailments that affect a human's movement. In 2006, the National Center for Simulation in Rehabilitation Research began developing an open-source modeling tool called OpenSim. OpenSim is a free software that simulates and evaluated musculoskeletal activity. The program uses community data that is collected using human tests, and this allows for a collaborative effort towards surgery planning or running dynamic and kinematic simulations [10].

OpenSim has been used to address numerous areas in medicine or rehabilitation. The OpenSim website lists a few applications: "stroke, spinal cord injury, cerebral palsy, prosthetics, orthotics, and osteoarthritis" [10].One specific example they detail on their site is using the program to examine how a crouch gait affects the muscle strength required to walk. Figure 7 displays models from OpenSim and how the normal gait differs from the crouch gait. The bones are clearly displayed, and the red string-like features represent simplified muscles and tendons. In this example, the researchers were able to alter the kinematics of the model and use a reverse dynamics program within OpenSim to find the forces and displacements experienced in the muscles and tendons.

Figure 7: OpenSim Normal to Crouching Gaits Example [10].

With the community of data available on OpenSim's website, it may be possible to collect an average or typical gait measured from actual humans walking. The software comes with additional downloadable models and motions based on experimental measurements. The research-grade musculoskeletal models used in this project were based on the muscle architecture of 21 cadavers and intended for kinematic analysis, as well as simulation of 3D motion. The motion simulations used are supplied and maintained by the OpenSim team at Stanford, and are based on the biomechanical examination of humans walking. OpenSim is a reliable source of data to obtain accurate human motion of legs while walking, which will be beneficial for this project [10].

2.2 Kinematic Mechanisms

Kinematics is the study of motion without forces [6]. Without first designing a system that achieves the desired motions, it is difficult to effectively design a system to put out the desired forces. Kinematics is a critical part of designing an effective knee testing solution because the motion of the knee depends on the rotation of the hip joint, the motion of the ankle, and the lengths of both the fibula, tibia, and femoral regions of the leg. The lengths of these regions depends on the anatomy of the human leg. However, achieving the desired knee motion is not so easily solved. It requires the design of a mechanism that emulates the motion. In the following sections a Hrones-Nelson fourbar linkage and Theo Jansen's mechanism will be described as possible crank based walking linkages for modeling human gait.

2.2.1 Hrones and Nelson Fourbar Linkage

The fourbar linkage is the “simplest possible pin-jointed mechanism for single-degree-of-freedom controlled motion” [6]. Because they are the simplest solutions, they are also inexpensive. An example fourbar is illustrated in Figure 8.

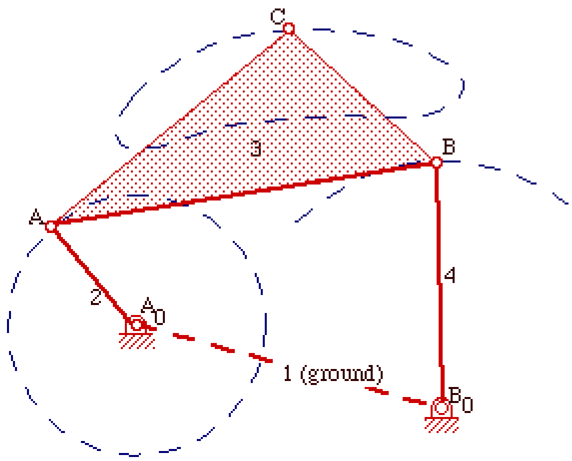


Figure 8: Typical Hrones Nelson fourbar linkage. The numbering system is shown on the linkage. The links are labeled 1-4 with link 1 as the ground, link 2 as the crank, link 3 as the coupler, and link 4 as the rocker. The trace curve of the crank, coupler, and rocker are also depicted.

A four bar mechanism consists of four links connected by joints and has one degree of freedom. The degree of freedom (DOF) of a mechanism is a function of the number of n links and the number of g joints. It is calculated by the following equation:

$$DOF = 3(n - 1) - 2g$$

In the standard numbering convention, the first link is ground which is a fixed link. The input motion of the mechanism is applied to the second link known as a driver and is connected to the ground. If link two makes a full rotation, it is known as a crank. The output motion is also connected to the ground and commonly referred to as a rocker. The link connecting these two links is called a coupler. Often the coupler is triangular in shape and has a unique trace path, known as a coupler curve [6].

The Grashof condition characterizes every four bar linkage by at least one link’s ability to make a full revolution with respect to the linkage’s ground plane. To determine if a linkage is Grashof, use the following variables and equations given in Norton’s “Design of Machinery”:

Let:

S = length of the shortest link
L = length of longest link
P = length of one remaining link
Q = length of other remaining link

Then plug the values for the variables above into this equation: $S + L \leq P + Q$

If the equation proves to be true and S + L is less than or equal to P + Q, then the linkage is Grashof [6].

Four bar mechanisms are commonly designed for their coupler curve motions. The shapes of paths created by couplers is diverse. The Hrones and Nelson atlas is a compilation of Grashof crank-rocker fourbar linkages and their respective coupler curves. In addition to over 7,000 coupler curves, the atlas provides length ratios for all links based on the crank being one unit length [6]. Figure 9 shows different coupler curve shapes, which will play a vital role in determining how the team designs the knee tester.

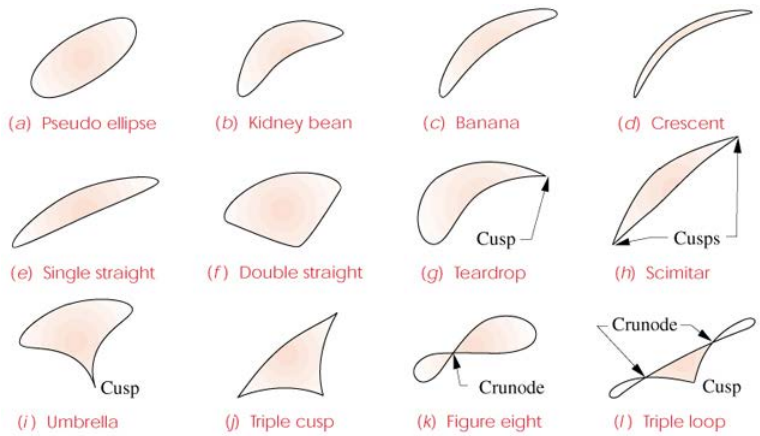


Figure 9: Coupler curve shapes and terminology [6].

2.2.2 Theo Jansen's Crank Based Walking Mechanism

In the early 1990's artist and physicist Theo Jansen created a moving sculpture which moved using a walking motion inspired by nature. In the process, Jansen created a twelve-bar mechanism that would be used by many walking machines to follow [11]. This linkage is illustrated in Figure 10.

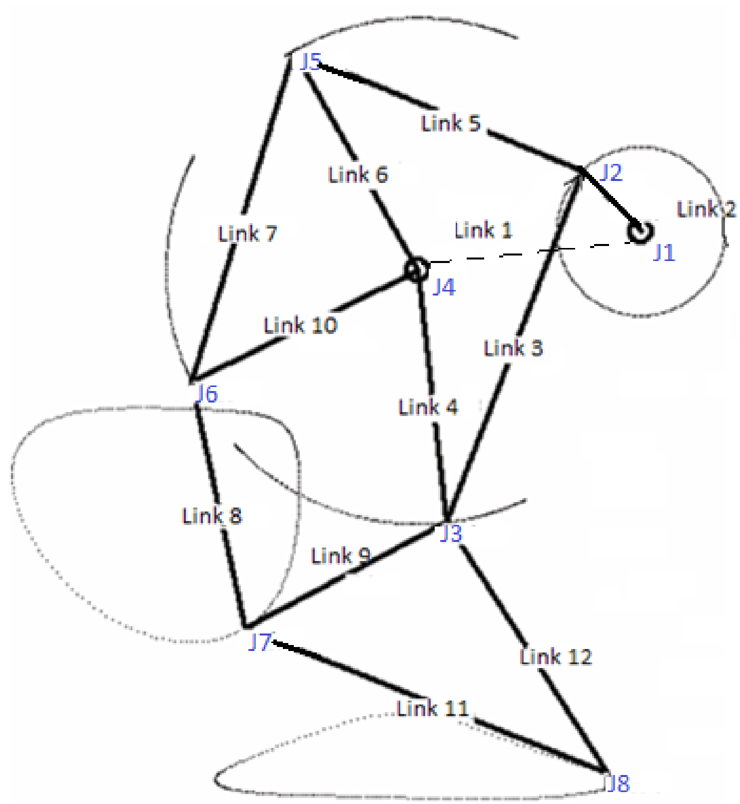


Figure 10: Theo Jansen's Mechanism with links and nodes labeled. The path of each node is traced [11].

Each linkage consists of a ground link, a crank, and ten binary links. A typical walking machine consists of multiples of this mechanism, with one crankshaft driving all of the mechanisms simultaneously. The Theo Jansen linkage comprises of two four bar mechanisms; the first is made up of the ground link (link 1), crank (link 2), link 5, and link 6, and the second is made up of the ground link (link 1), crank (link 2), link 3, and link 4. Then, there is a four bar parallelogram linkage consisting of links 4, 8, 9, and 10. This parallelogram is driven by the coupler of the first four bar mechanism, and in turn drives a ternary link comprised of links 11, 12, and 9 (see Figure 10 for link and node numbers) [13, 14]. The resulting linkage has one degree of freedom, allowing a kinematic analysis of each link with respect to the crank motion. In comparison to humans, links 4 and 12 represent the femur and tibia, respectively, while joints 3 and 8 represent the knee and foot, respectively [14].

Figure 11 demonstrates the positional time evolution of the Theo Jansen mechanism in one cycle to illustrate the motion of the mechanism.

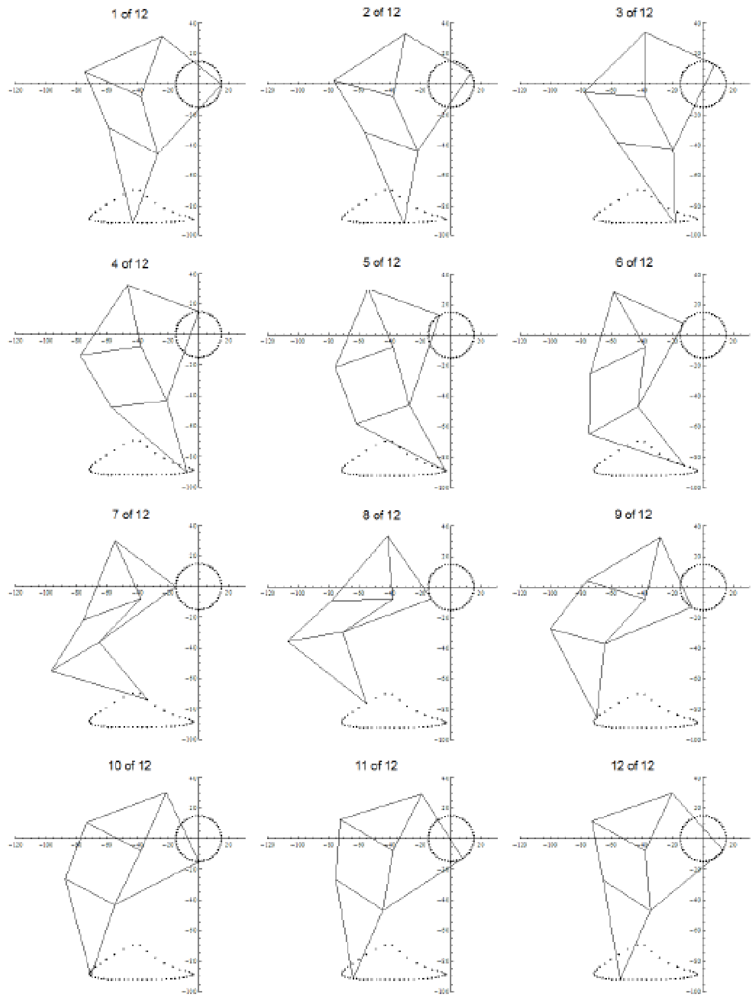


Figure 11: Time evolution of Theo Jansen mechanism for one cycle. Foot trace curve is shown [12].

Several variations of the Theo Jansen linkage exist depending upon the task it is meant to accomplish: Komoda and Wagatsuma demonstrated that moving the linkage center (see ‘Pin’ node in Figure 10) periodically will increase the orbit and ensure that the mechanism will climb over uneven terrain [15]. Giebrecht et al used force analyses to optimize the length of the linkage’s stride verse the power required to run the mechanism [13]. Additionally, Nansai et al compiled a table of link lengths that correspond to different patterns of motion, such as obstacle avoidance, step climbing, or drilling [16].

2.3 Knee Replacements

Almost half of the American adults in the United States will develop symptomatic knee osteoarthritis over their lifetime. Knee replacements have become an effective tool to reduce pain and improve physical function for those suffering from debilitating osteoarthritis or trauma. Total knee replacement surgery has become one of the most common orthopedic procedures performed in older persons and is projected to grow in the coming years. In the following sections the need, the types, and the surgery for knee replacements will be discussed.

2.3.1 Need for Knee Replacement Surgery

The main reason people seek knee replacement surgery is to ease the pain caused by advanced arthritis or trauma. Osteoarthritis and rheumatoid arthritis severely damage the knee joint to the point where it needs to be replaced. Rheumatoid arthritis is when the body's immune system attacks the membrane lining the joint causing pain, inflammation, and damage [17]. Osteoarthritis is the number one cause of knee replacements and accounts for 94-97% of all operations [18]. Osteoarthritis (OA) occurs when the cartilage of the joint breaks down, causing the bones of the knee to rub together [19]. The rubbing leads to pain, stiffness, decreased mobility, and bone growths called spurs [17, 19].

Figure 12 illustrates the difference between a healthy knee and a knee affected by osteoarthritis.The most common cause of OA is age. The chances of developing OA rises over the age of 45 due to the decreasing ability of cartilage to heal as a person gets older [20]. OA can occur in younger people, although the majority develop it later in life. OA is a progressive disease that can be diagnosed by radiographs or MRI scans [19]. Obesity, age, female gender, genetics, injuries, and congenital deformations are risk factors for knee OA [20].

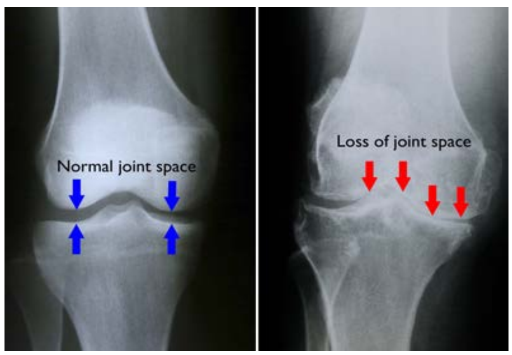


Figure 12: (Left) Shows a healthy knee with normal joint space. (Right) shows a knee effected by osteoarthritis. The radiograph indicates presence of bone spurs and loss of joint space [21].

Often those with OA are treated with a combination of physical therapy, exercise, weight loss, orthotics, walking aids, and or medicine [17, 19]. Only when OA has reached the end stage of disease and the patient experiences persistent pain, is the patient considered for knee replacement surgery [19].

2.3.2 Types of Knee Replacements

The surgeon must decide what type of knee replacement to use for the patient, either a total knee replacement (TKR) or a partial knee replacement. With a TKR, the whole knee joint surface is replaced whereas a partial knee replacement replaces only the part of the knee that is affected by disease [19]. Partial knee replacements can be done in the lateral, medial, or patella-femoral compartments of the knee and only about 10% of knee replacement surgeries are partial [19, 22]. Total knee replacements are considered the gold standard in knee replacement surgery [18]. Examples of a partial and TKR are shown in Figure 13.

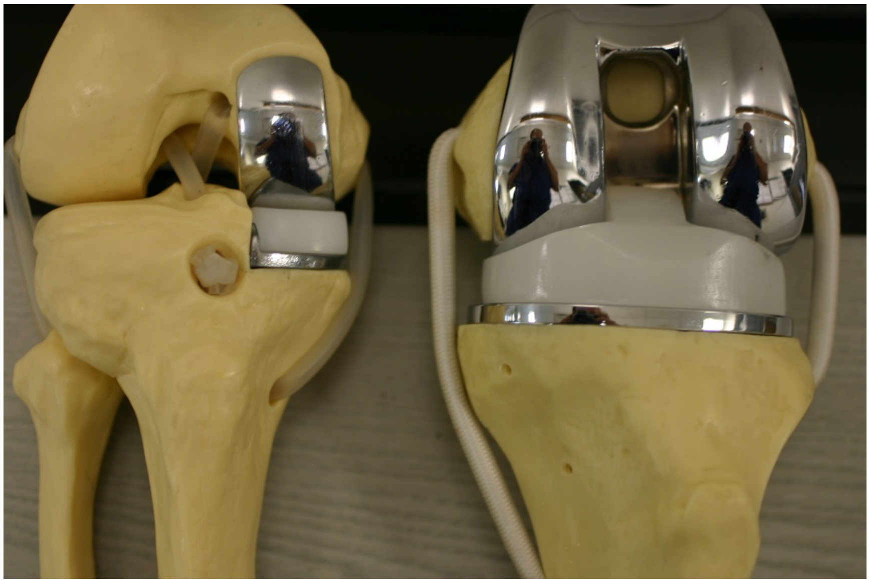


Figure 13: Knee Replacement Types: (Left) Unicompartmental knee replacement (Right) Total Knee Replacement [23].

A TKR resurfaces three bones: the lower end of the femur, the top surface of the tibia, and the back surface of the patella. The metal femoral component attaches to the end of the femur bone and is grooved to fit the condyles which allow smooth movement of the kneecap [22].The top surface of the tibia is a metal platform often referred to as the tibia tray with a cushion of plastic commonly referred to as the plastic spacer [22]. There are variations in this component design, some designs attach the plastic directly to the bone while others insert the metal part into the center of the tibia [22]. The back surface of the patella is a dome- shaped plastic piece that mimics the shape of the patella [22]. Typically titanium or cobalt-chrome alloys are used for the metal parts of the knee replacement while polyethylene is used for the plastic components [24]. Components are designed with metal being attached to plastic to provide smooth movement and minimal wear [22].

2.3.3 Knee Replacement Surgery

Knee replacement surgery was popularized in the 1970s [17]. Knee replacement surgery or knee arthroplasty has become increasingly popular with 719,000 knee replacements completed in 2010 in the USA and it is projected to increase to 3.5 million replacements by the year 2030 [17, 21]. Adults who are 45 years or older make up the majority of knee replacement surgeries, with the largest percentage being 65 and older as seen in Figure 14 [18, 25].

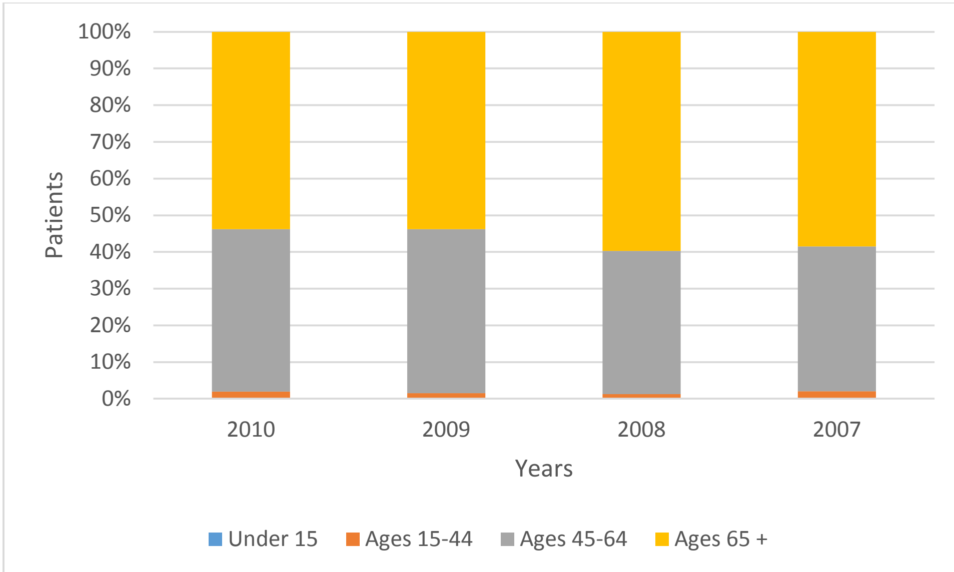


Figure 14: Distribution of Total Knee Replacements by Age. Data was collected from CDC Inpatient surgery from 2007- 2010 [25].

Overall today's knee replacement designs have changed little within the past decade, but have improved in terms of reliability and lifetime of implant materials because the material wear and biocompatibility of the material is better understood [24]. Although longevity of the implant also depends on activity level, weight, and health of the patient [19].

There are three major manufacturers of knee implants in the United States: Zimmer, DePuy, and Stryker, with more than 150 knee replacement designs available in the market today [22]. The surgeon is responsible for deciding which implant to use based on the patient's needs, the surgeon's experience with the implant, and the overall cost and performance of the implant [22]. During the knee replacement surgery, the orthopedic surgeon will first prepare the bone by removing any damaged cartilage and bone then they will position the new implants to restore function and alignment of the knee [22].

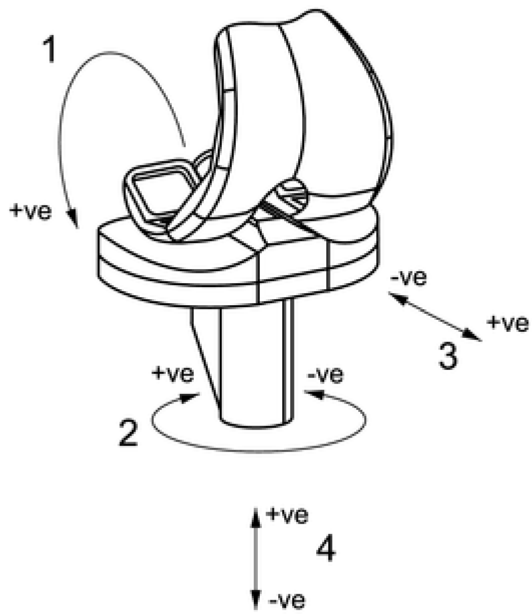
2.4 Knee Replacement Testing

To guarantee knee replacements restore mechanical function of the knee, TKR designs should be tested and evaluated for correct kinematics and long term wear. Testing of the TKR should occur prior to implantation because it becomes difficult to test while in vivo [26]. The knee simulation results should be compared to in vivo TKR performance in patients [26]. The International Standards Organization (ISO) has created a standard that provides specifications to ensure all knee replacement prosthesis are consistently measured to protect patients. These specifications should be considered while developing a knee simulation machine.

2.4.1 ISO-14243-2

The ISO standard 14243-2 specifies "the flexion/extension relative angular movement between articulating components, the pattern of the applied force, speed and duration of testing, sample configuration and test environment to be used for the wear testing of total knee-joint prostheses in wear-testing machines with load control" [27].

The standard defines forces, torques, and motions the TKR should be subjected to (see Figure 15). This includes flexion/extension of the femoral component relative to the tibial component. The condyles of the femoral component should be perpendicular to the tibial axis when the femoral component is at 30 and 60 degrees of flexion. Additionally it includes the axial force applied to the tibial component of the TKR. It specifies the anterior posterior (AP) displacement offset of the axial force from the flexion/extension axis measured perpendicular to these axes along with the force applied to the tibial component perpendicular to the tibial axis. Lastly it specifies the tibial rotation of the tibia component about the axial force axis along with the tibial rotation torque applied to the TKR component [27].



KEY

1 Flexion (of femoral component)

2 Tibial rotation, tibial rotation torque

3 Anterior Posterior (AP) displacement by tibial component, AP force on tibial component

4 Axial Force

Figure 15: Sign convention specified by ISO 14243-2 for forces, torques and motion of a left TKR [27].

2.4.2 Existing TKR Testing Machines

TKR testing or motion simulator machines have been developed over the years by researchers. Quasi-static devices achieve the desired knee-flexion angle and are loaded through the bones and muscles. The DOF can be controlled in this type of simulation. An advantage of this type of simulation is the robustness of simulating many knee muscles. Another type of knee testing machine is a wear simulator. These machines are designed to apply a large number of loading cycles to a variety of knee replacements, but are unable to simulate the load of the femur, tibia, and patella at the same time [28]. In this section three simulators and their working methods will be highlighted.

The first is the Purdue Mark II/Kansas Knee simulator. The Purdue Mark II was the original machine while the Kansas Knee simulator was a later iteration (shown in Figure 16). Both machines were built to study the effect of fast implant loading such as jogging or other quick movements. The TKR are tested in a vertical/standing position and has independently moving femur and tibia attached to the machine with moveable hip and ankle plates. The knee operates with limited direct control. There are a total of five inputs- a vertical load, a quadriceps load, torque about the center ankle joint, ankle flexion, and adduction/abduction of tibia. A Kevlar strap was used to simulate the quadriceps tendons and patellar ligaments when testing [29].

Figure 16: Kansas Knee Simulator [29].

The Vermont Knee simulator (pictured in Figure 17) was developed by researchers at the University of Vermont to gain a better understanding of the knee biomechanics to enhance the designs of TKR, fracture fixation, and rehabilitation. They developed a mechanically actuated prosthetic leg that consisted of three main parts- the frame, the muscle actuation method, and motion analysis system [29].

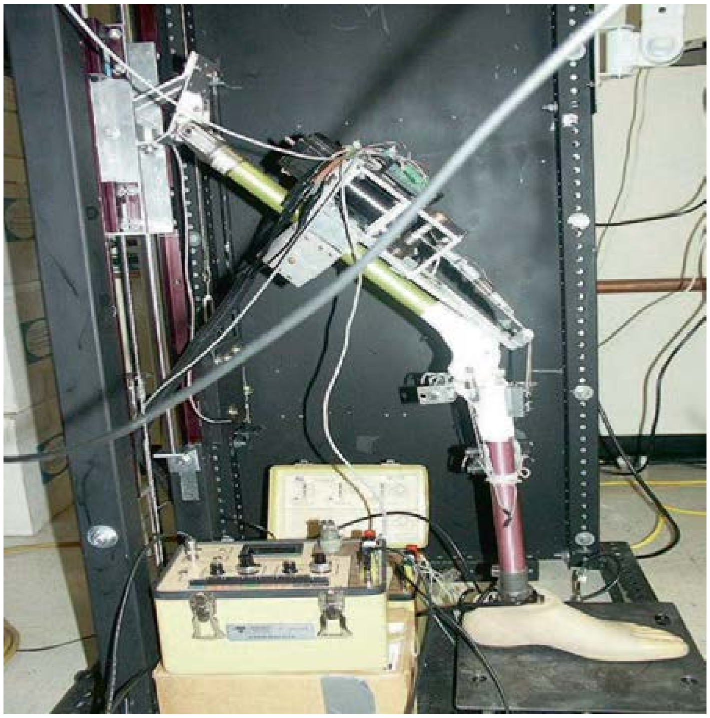


Figure 17: Vermont Knee Simulator [29].

The Stanmore/Instron simulator is a four station TKR wear tester (shown in Figure 18). It is a force controlled simulator with six degrees of freedom. It fits different TKR geometry and delivers a femoral and three tibial force waveforms to control axial tibial compression, AP tibial shear and tibial torque [29].

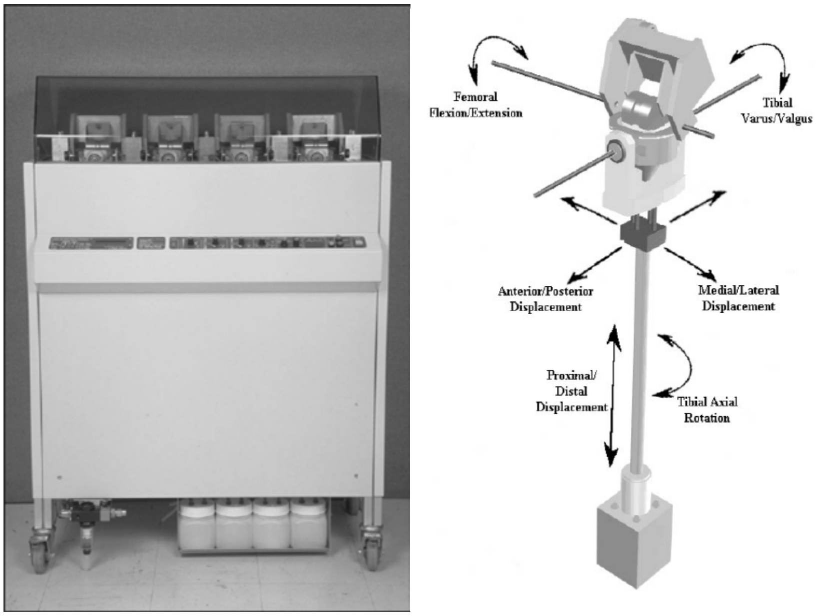


Figure 18. (Left) Stanmore/Instron Simulator. (Right) Single testing station of simulator [29].

Knee simulator machines must run for millions of cycles to test the long term wear of knee replacements. Approximately thirty million cycles represents 10-20 years of in vivo use [30]. Tests of designs with well-known clinical histories are tested to 10 million cycles according to Walker *et. Al* [30]. While designing a knee simulator machine, reduced cycle time for testing TKR is an important consideration that will not only save time but will also improve the lifetime of the machine.

3 Project Objectives

3.1 Goal Statement

The goal of this project was to design a mechanism for evaluating knee replacements that simulates the motion of a knee in a walking gait. This project will provide the groundwork for future iterations with the ultimate goal of using this device for testing the performance and long term wear of knee replacement devices.

3.2 Task Specifications

The following task specifications are the requirements set in place to define a standard by which the final design should perform:

- The femur-equivalent link must have a 50 degree rocker motion.

The team performed an analysis of the position of the knee over a human's walking gait using the OpenSim simulation software. In this analysis, the position of the knee was tracked by advancing the walking gait forward in small increments and drawing a small dot on tracing paper. After connecting these dots, a compass was used to find the centroid of the arc that the knee motion makes. Then, the team was able to use a protractor with the center of the arc to find the angle at which the knee moves during walking. The sketch that resulted from this process is illustrated in Figure 19 below.

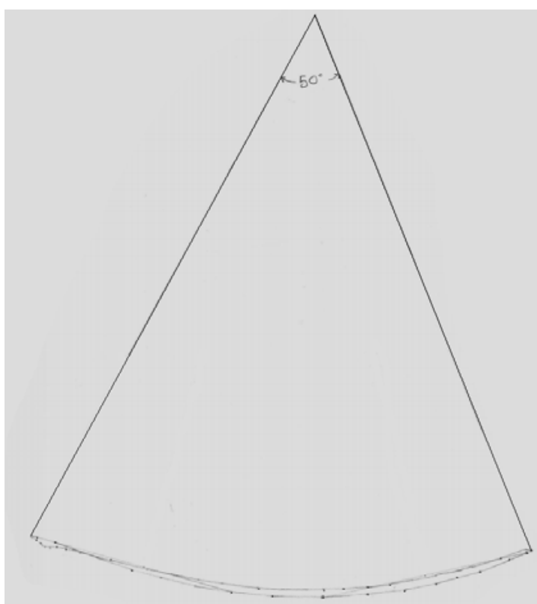


Figure 19. Femur Swing Trace curve with 50 degree maximum swing angle. Maximum swing angle was measured using a protractor from the femur trace curve obtained from OpenSim.

- The angle between the tibia and femur links must displace 65-70 degrees during flexion. During extension the links should be collinear at nearly 180 degrees.

According to the research from Tidy's Physiology textbook, detailed in Kinematics of Human Gait background section, Motion of the knee is cyclic and ranges from 180 degrees at extension (tibia and femur are collinear) to a maximum angular displacement of approximately 65 to 70 degrees at flexion [7]. This specification is necessary to ensure the final design is accurate to the human gait.

- The mechanism must have one degree of freedom.

It is important for the linkage design to only exhibit one predictable motion. If the mechanism has two degrees of freedom, then it can take a path that isn't biomechanically accurate. Instead, the linkage should be forced to exhibit the path that fulfills the previous two task specifications that define the femur and tibia angles.

- The mechanism must run for at least 2-10 million cycles.

According to DesJardins et. Al, a person can walk up to thirty million strides in ten to twenty years [26]. Since knee replacement devices are intended for this longevity, it is important for the testing device to run for the entirety of a device's lifetime. Most current testing devices test approximately two to 10 million cycles according to studies by DesJardins et. Al and Maletsky et. Al [26, 28]. While the team will most likely not be able to test the device for this length, durability of materials and lifetime of instruments in the final product will be an important consideration to fulfill this task specification.

- The mechanism must be driven by one motor.

It is good practice to simplify a mechanism to one motor, because two separate motors can produce unpredictable outcomes. It is difficult to sync to motions to each other, and if they operate at even a slight difference in speed, they will desynchronize over a long period of time. Since this mechanism is intended for long-term testing of knee replacements, this unpredictability should be avoided by using a single motor.

- The mechanism must accommodate a total knee replacement for future testing.

In order to meet the goal of this project, the mechanism must be able to attach a knee replacement. Ideally, the knee replacement parts should be interchangeable to fit multiple designs since there are many designs available on the market from different manufacturers.

- The mechanism must run at a speed of 66.5 cycles per minute.

Since the goal of this project is to simulate the human's natural walking gait, it must run at the same frequency of a human stride. According to Kinematics of Human Gait background section, humans on average walk at 66.5 strides per minute.

4 Design Concepts

4.1 Concept 1 – Hrones & Nelson Sixbar

4.1.1 Concept Overview

The first design that was considered uses a linkage that drives the ankle along its known path, which would drive tibia and femur links through an accurate gait. The Hrones and Nelson atlas contains a collection of fourbars which create a wide variety of coupler curves. This design utilizes a fourbar which has a coupler curve very similar to the ankle path. The tibia is joined to the coupler point, which is joined to the femur link at a node which represents the knee, and the femur link is fixed to a ground node which represents the hip. The resulting linkage is a sixbar. Figure 20 below illustrates this concept in its final iteration. Link 1 represents the ground link, while link 2 is the crank driven by a motor. Link 3 is the coupler which drives the ankle, represented by node C. Links 5 and 6 denote the tibia and femur bones, respectively, while nodes D and O3 represent the knee and hip joints, respectively.

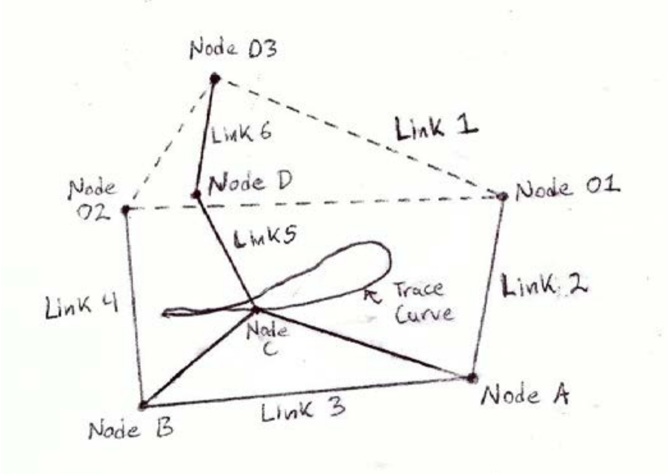


Figure 20: Preliminary Sketch of the Hrones and Nelson Sixbar Concept

To ensure that this design has only one degree of freedom, its mobility must equal one. To check this, use the DOF equation and plug in the number of links and joints this linkage consists of. This concept has six links and seven full joints. Thus, the mobility (M) is calculated as followed:

$$M = 3 * (6 - 1) - 2 * (7) - 1 * (0) = 1$$

Since this linkage has one degree of freedom, it can only follow one predictable path. This is desirable for the project, because if the ankle follows one curve which is similar to that of a human during natural gait, then the knee should also follow its natural motion. In order to recreate the human gait using this concept, five data are needed: the trace curve of the ankle during human gait, the lengths of the tibia and femur, the step length, and the position of the hip relative to the ankle trace curve.

4.1.2 Steps to the Conceptual Prototype

The team used a combination of research and biomechanical analysis to find the aforementioned five sets of data. As described in Kinematics of Human Gait, the human stride length is approximately 31 inches. The In order to find the remaining four values, position analysis was used on an OpenSim simulation.

Next, the team followed the path of the talus bone in the ankle through the length of a leftward-facing gait. To track the point, a piece of tracing paper was placed over the computer screen, and the axes in the OpenSim display were traced on the paper. Then, the motion was run step-wise, and the center of mass of the talus was traced at each step. The resulting image traced onto this tracing paper is illustrated in Figure 21 (the horizontal and vertical axes are represented by the arrows).

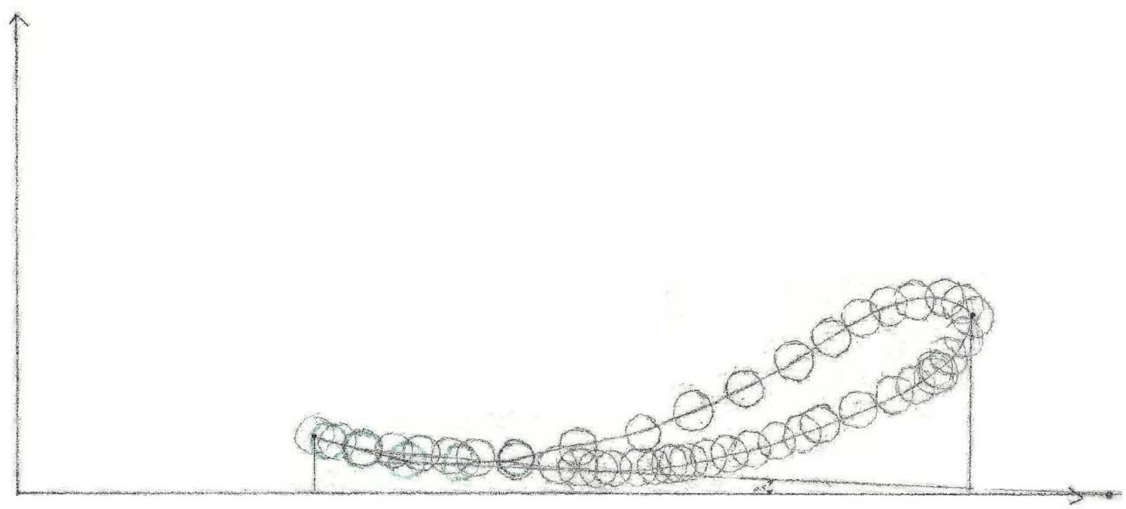


Figure 21: Trace Curve of the Ankle, Captured from an OpenSim Simulation

With this trace curve, the team read the entire Hrones & Nelson Atlas to search for possible four bar and coupler dimensions that would produce the ankle motion that was traced. Each team member checked one third of the atlas and made a note of page numbers in which a coupler curve was similar to the ankle trace curve. Then, the group combined the page numbers and voted to eliminate four bars in rounds until only three viable options remained. Since the three four bars produced such a similar coupler curve, the smallest linkage was chosen to keep the cost of materials as low as possible. The list of page numbers and rounds in which they were eliminated are listed in Appendix A: Selecting the Hrones and Nelson Atlas Fourbar.

As seen in the list, the team chose the fourbar linkage from the 9th node on page 623 of the Hrones & Nelson pdf (which corresponds to page 610 in the physical atlas). This page is displayed in Figure 22 below, and the path of this linkage is highlighted in yellow. Each link's length is determined in a ratio to the length of the crank; in this case, the crank has a length of 1, link A has a length of 4.0, link B has a length of 3.0, and link C has a length of 3.5. To determine the actual size of this linkage, the team used the known length of a human's step to properly size the coupler curve, then scaled up the rest of the linkage accordingly. This resulted in a linkage with a 55.621

inch ground link, 15.897 inch crank, 63.59 inch coupler, and 47.692 inch rocker. The coupler point (Node C) is 19 degrees from node A and 47 degrees node B.

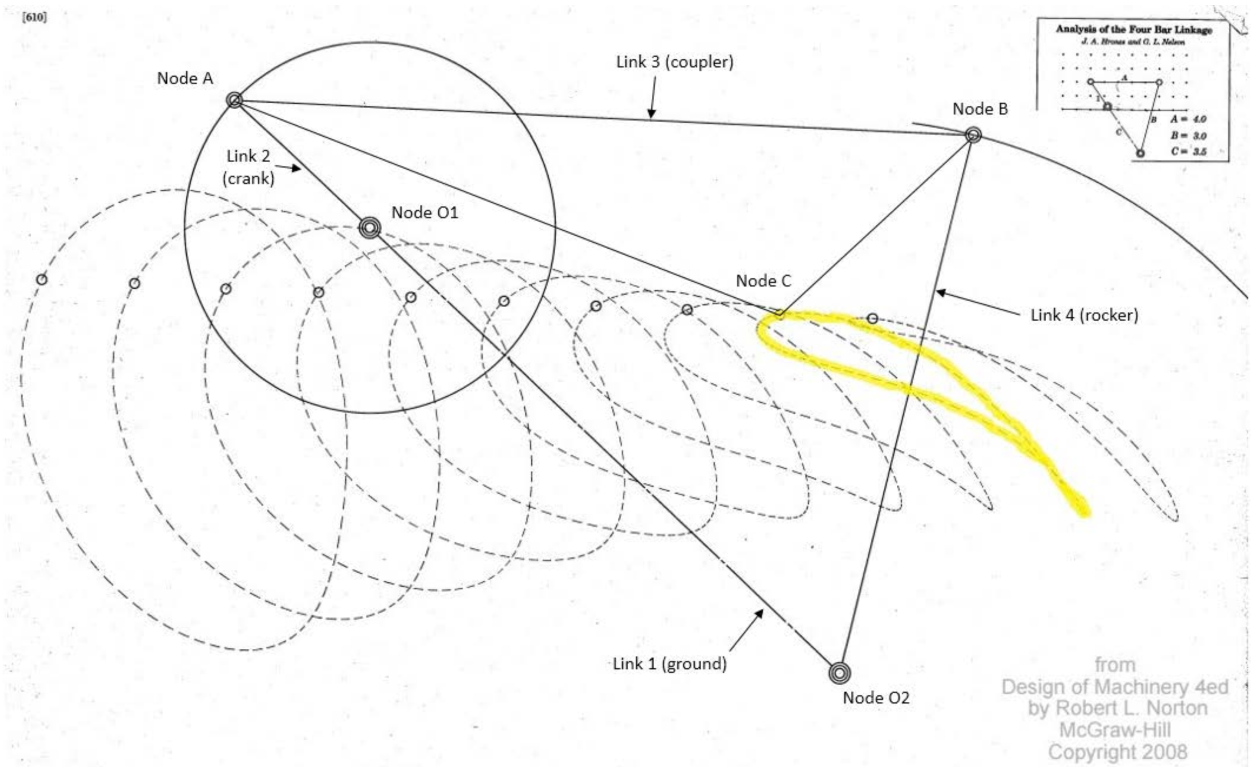


Figure 22: The Page of the Hrones and Nelson Atlas Which Includes the Final Sixbar Chosen for Concept 1

The final step to completing this concept is determining the location of the fixed hip. Early iterations of this design attempted to create a small linkage to also recreate the motion of the hip. The team followed the same steps as the ankle trace curve in order to draw a hip trace curve, which can be viewed in Figure 23 below. However, the work required to design a second linkage and drive both with one motor was too difficult for the effect of a negligible motion, in comparison to the ankle curve.

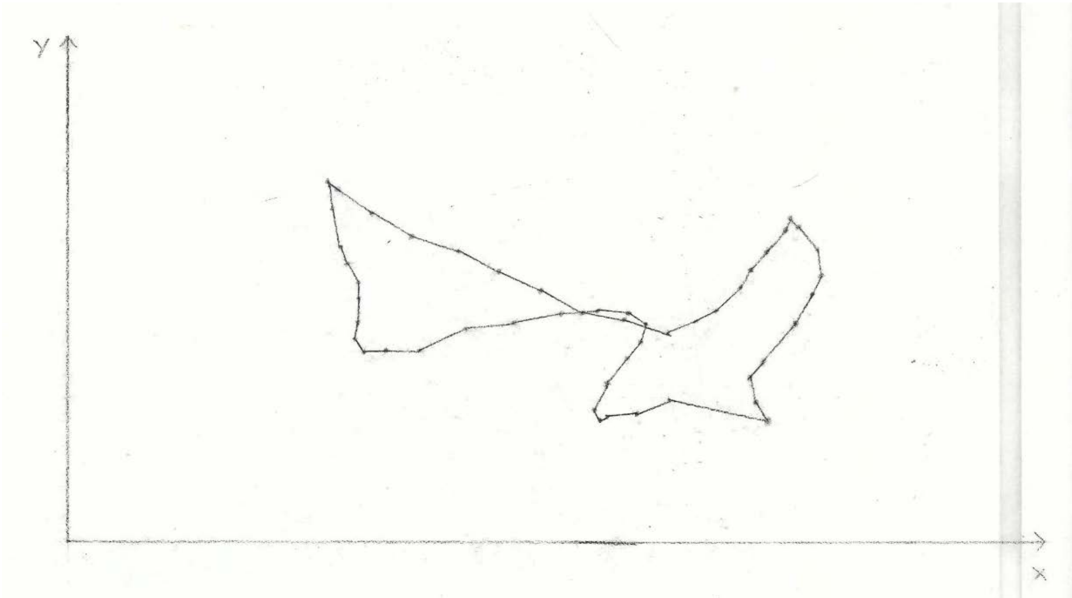


Figure 23: Trace Curve of the Hip, Captured from an OpenSim Simulation

In order to find a fixed hip node, the team traced the ankle curve through its entire cycle, and then also traced the knee and hip positions at three positions: the front-most position, a vertical position, and the back-most position. Then, the lengths from the ankle to the hip were calculated at the front and back positions using the bone lengths as a scale. These values were 33.494 inches in the front and 32.425 inches in the back. With these two lengths at each end of the ankle trace curve, it is possible to triangulate the hip location by using a compass, as seen in Figure 24 below.

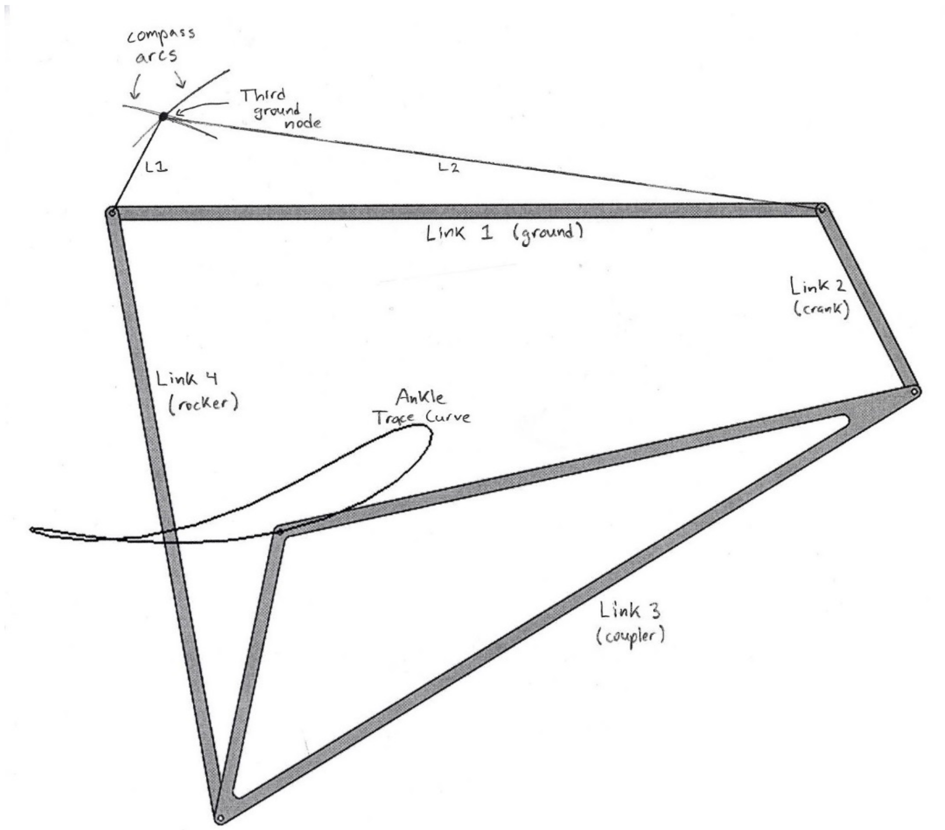


Figure 24: The Results of Finding the Location of the Third Ground Node (Hip Joint) in Concept 1

The lengths between the hip and the other ground nodes (denoted as L1 and L2 in Figure 24) were determined graphically using ratios between the lengths on the paper and the known length of the original ground link. The ratio was found to be 2.75076 mm/in. These data, as well as the values for the front and rear reference, were tabulated into Table 2, displayed below.

Table 2: Lengths Used to Determine the Location of the Hip Joint

	Paper	**Actual**
Ground	153 mm	55.621 in
Front Reference	92 mm	33.494 in
Rear Reference	89 mm	32.425 in
Ground Length 1 (L1)	23 mm	8.361 in
Ground Length 2 (L2)	143.5 mm	52.167 in

The final linkage can be designed with these known values. The result is pictured in Figure 25 below. The linkage is a sixbar, consisting of a ground link with three nodes (colored dark gray), the fourbar from the Hrones & Nelson atlas (coupler colored light blue, crank and rocker colored yellow), and the two links representing the tibia and femur (colored red).

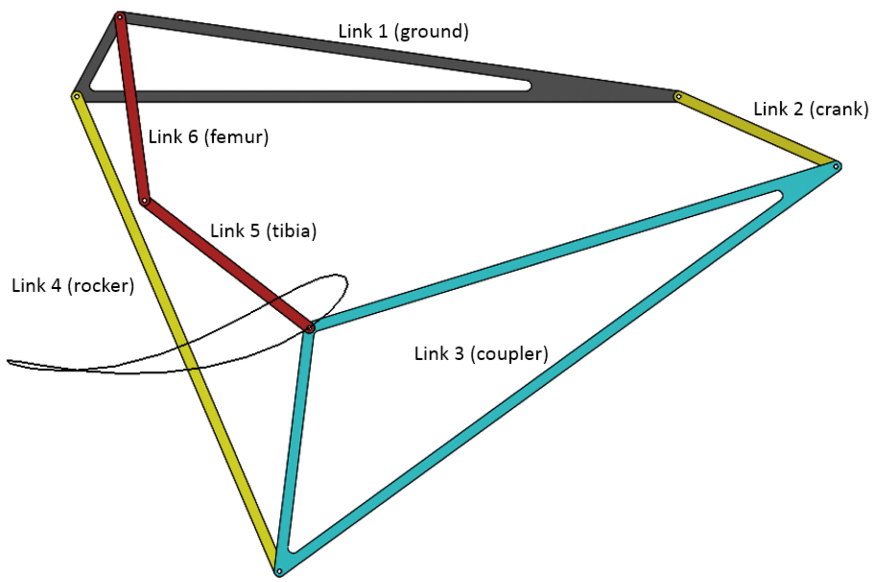


Figure 25: The Final Model of the Hrones and Nelson Sixbar Concept

A motion analysis was performed on the linkage to determine how well the links performed in relation to the 50 degree femur swing and 65-70 degree knee flexion, as described in the task specifications. These values were measured in SolidWorks Motion, and graphed in Excel. The results of the femur and knee analyses are illustrated in Figure 26 and Figure 27, respectively. The femur swing obtains an angular displacement of about 55 degrees, which is close to the task specification, but the knee flexion resulted an angular displacement of only about 26 degrees. This is unacceptable for a successful knee replacement testing device because it's not natural.

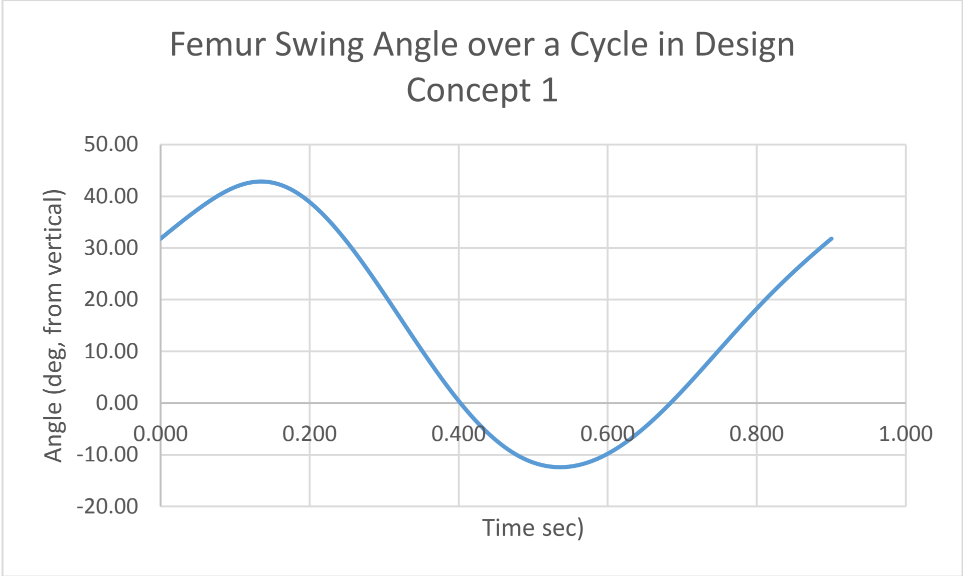


Figure 26: The Angle of the Femur from Vertical Over One Cycle in Design Concept 1

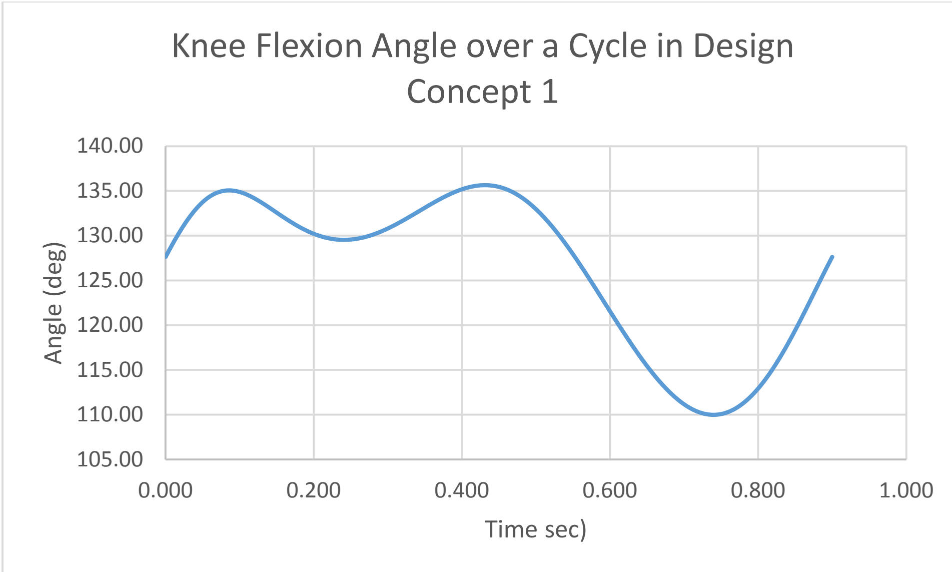


Figure 27: The Angle Between the Tibia and Femur Links Over One Cycle in Design Concept 1

4.2 Concept 2 – Theo Jansen's Linkage

4.2.1 Concept Overview

The second design that was considered is a twelve bar mechanism that was created by Theo Jansen. This design is comprised of two four bar linkages attached to each other in series with only one of the four bar linkages driven directly by the crank [12]. The four bars are separated by a rigid triangle and an additional triangle is attached to create the foot of the mechanism [12]. The mechanism creates a rocking motion for the femur and tibia links. 2.2.2 provides further detail on how the mechanism works. Figure 28 below illustrates the mechanism in a sketch. Links 4 and 12 represent the femur and tibia respectively, while joints 3 and 8 represent the knee and foot respectively.

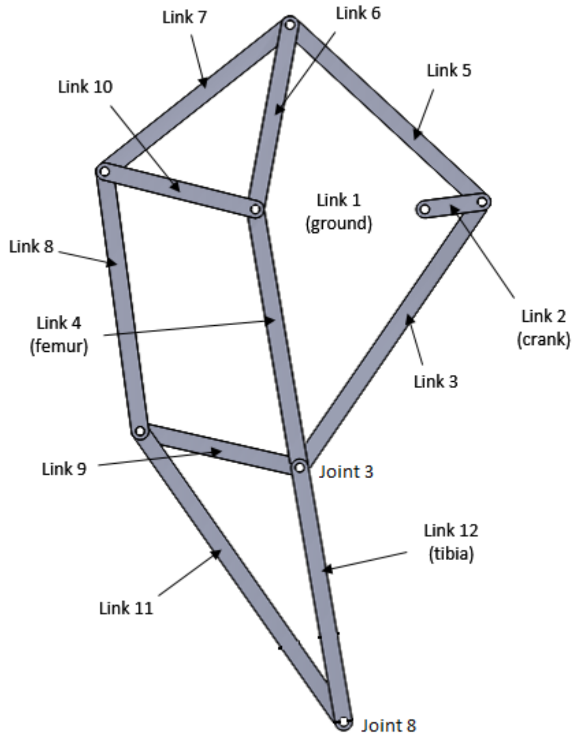


Figure 28: Model of an Example Theo Jansen's Linkage

To ensure that this design has only one degree of freedom, its mobility must equal one. To check this, use the DOF equation and plug in the number of links and joints this linkage consists of. This concept has twelve links and sixteen full joints. Thus, the mobility (M) is calculated as followed:

$$M = 3 * (12 - 1) - 2 * (16) - 1 * (0) = 1$$

The linkage has one degree of freedom, so it can only follow one predictable path. This is desirable for the project, because the mechanism can be designed to replicate the trace curve of the ankle.

4.2.2 Steps to the Conceptual Prototype

The trace curve for the ankle can be adjusted by changing the lengths of links 9, 11, and 12. In order to recreate the ankle trace curve (see Figure 21 above), the team designed a linkage with adjustable links, shown in Figure 29 below. As seen in the image, there are multiple holes on links 9, 11, and 12, which can be mated to each other in different configurations to obtain different trace curves.

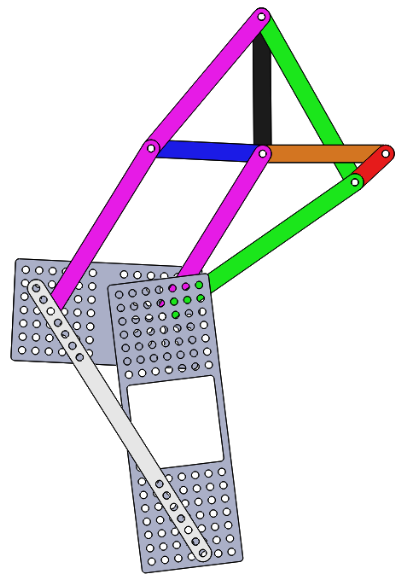


Figure 29: The Adjustable Theo Jansen's Linkage Used to Increase the Accuracy of the Linkage to the Human Walking Gait

This concept design is not limited to just simulating the ankle trace curve. In addition, the mechanism can be designed to obtain desirable angular displacement of the tibia and femur bones and the angular displacement of the femur swing. To obtain the desired 50 degree femur motion and 65 – 70 degree knee motion, the team modified the adjustable linkage and ran motion analysis tests in SolidWorks until the desirable angles were obtained. These tests produced graphs of the femur angle and knee angle, which can be viewed in Figure 30 and Figure 31, respectively. Note that the femur displaces exactly 50 degrees, and the knee displaces 67 degrees and reaches nearly 180 degrees at max extension.

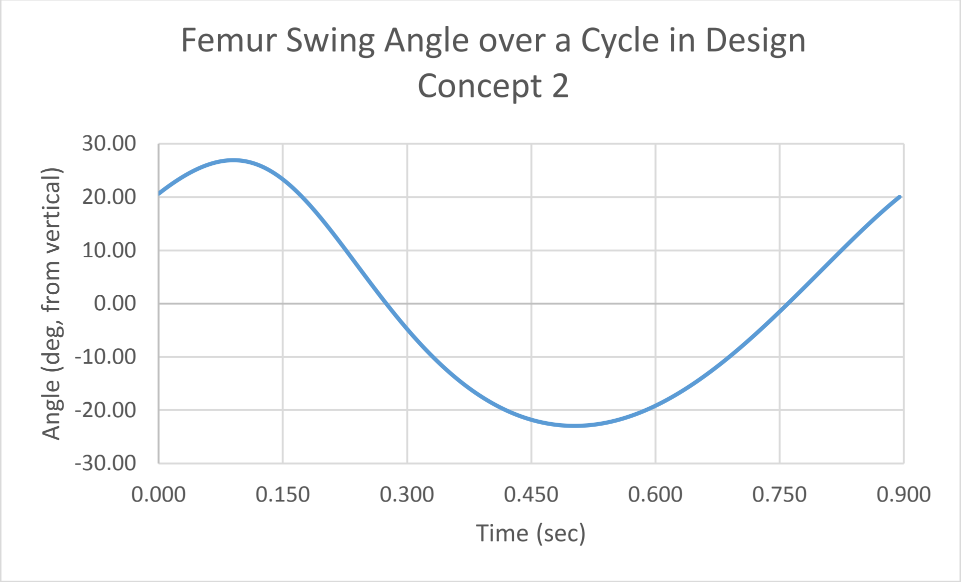


Figure 30: Angular Displacement of the Femur with Respect to Vertical Over One Cycle.

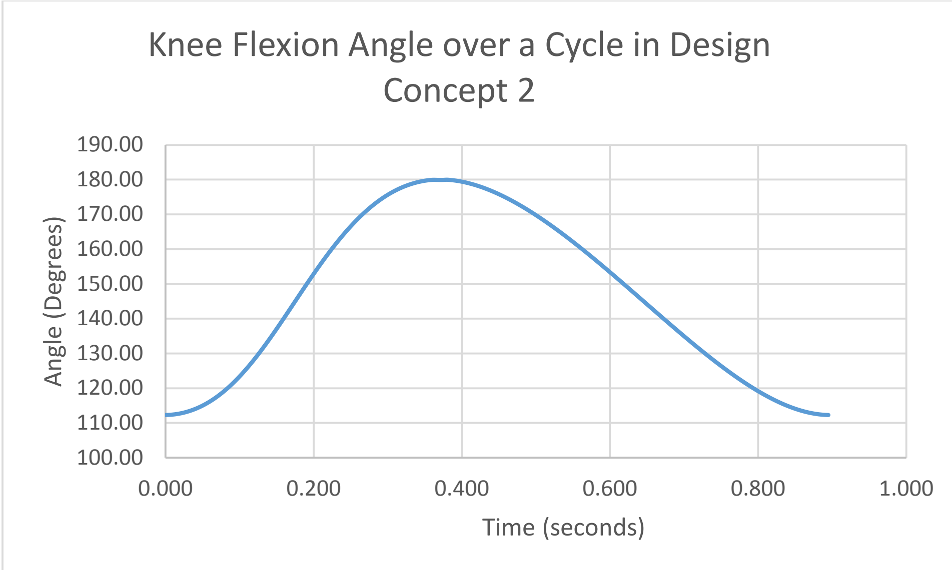


Figure 31: Angular Displacement of the Knee Joint Over One Cycle

The team found difficulty in achieving both the desired ankle trace curve and knee angle; a linkage which would satisfy the ankle curve would produce knee angles which aren't humanly possible, and linkages which satisfy the angles would produce ankle curves which aren't similar to the trace curve from OpenSim. Figure 32 shows a mechanism with the desirable ankle trace curve, but with unnatural knee angles. This is most likely because the actual angle graph of the knee doesn't experience a near-harmonic motion which the Theo Jansen linkage produces, seen in the graph from Figure 30 above.

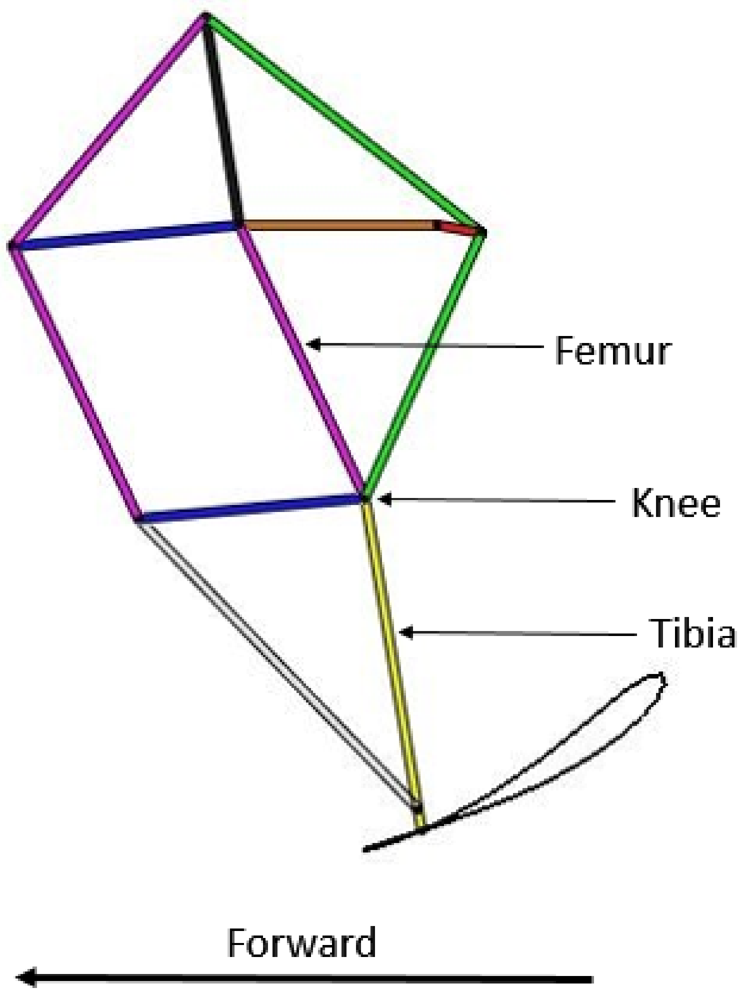


Figure 32: Alternative Theo Jansen's Linkage with an Accurate Trace Curve but a Hyperextended Knee Angle

The team decided it was more important to match the angles of the knee and femur than it was to match the ankle trace curve. This resulted in the angular trace curve illustrated in Figure 33 below.

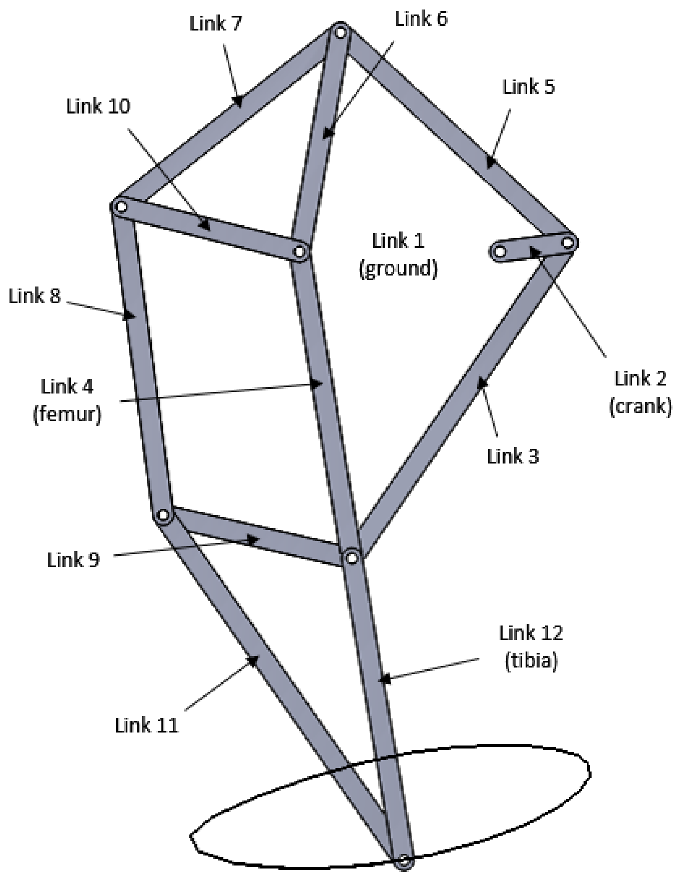


Figure 33: Ankle Trace Curve of the Final Theo Jansen's Linkage Concept Which More Accurately Follows the Joint Angles.

The final concept contains the link lengths (with a 2/3 scale) as described in Table 3 (reference Figure 33 for the link numbers). The links were scaled to stay within budget.

Table 3: Length of Each Link (with a 2/3 scale) in the Final Theo Jansen's Linkage Concept

Link Number	**Length (in.)**
1 (distance between ground nodes)	7.330
2	2.500
3	14.000
4	11.402
5	11.333
6	8.167
7	10.250
8	11.402
9	7.085
10	6.725
11	16.945
12	12.827

5 Design Selection

To decide what design concept to use, the team weighed each concept's pros and cons in a decision matrix. The decision matrix compares the designs against one another using specific criteria that is based on the project's task specifications and overall goal. Each design was rated on a scale of 1 (worst) to 5 (Best). The design that scored the highest was chosen.

The decision matrix that was used to determine the best design is shown in Table 4.

Table 4: Design Concept Decision Matrix

	Hrone-Nelson Sixbar Concept	**Theo Jansen Mechanism**
Compact Link Size	1	4
Development Time	3	4
Complexity	3	2
Accurate Ankle Trace Curve	5	1
50 Degree Femur rocker motion	2	5
Maximum angle of the knee during flexion is between 65-70 degrees	2	5
During extension the knee reaches 180 degrees and is not hyperextended.	1	5
Mechanism has only one Degree of Freedom	5	5
Driven by only one Motor	5	5
TOTAL	27	36

Note: Scale of 1 (Worst) and 5 (Best).

As a result of the decision matrix the Theo Jansen mechanism scored the highest, thus it was chosen. The Theo Jansen mechanism better simulates the anatomically correct angles of the knee while walking, which the team decided was more important than producing the correct ankle trace curve.

6 Proof of Concept

The team built a proof of concept model for the Theo Jansen mechanism. The model included a linkage and a frame, both of which were laser cut from 0.22 inch acrylic. Figure 34 shows the proof of concept model that was built. This model required the crank to be hand driven, but allowed the team to test out the linkage and verify that it would work for our final prototype. The joints for the linkage were plastic screw posts, which we purchased at Bay State Hardware in Worcester, MA.

Figure 34: Constructed Theo Jansen proof of concept model

While building the model the team learned valuable insight on how to assemble the links, the importance of spacing, and how to attach the linkage to a frame concept. These lessons learned would become important for developing and further designing the final prototype.

7 Detailed Design

In this section the final design for the prototype will be detailed including the linkage, knee replacement, frame, and motor.

7.1 Linkage

The final mechanism satisfies the angular displacement of the knee joint and the femur swing with respect to the horizontal according to the SolidWorks motion analysis. Motion analysis in SolidWorks (Figure 35) shows the femur displaces nearly 50 degrees: 27-(-23) = 50 degrees. Figure 36 shows the knee displaces 68 degrees and is straight during extension (180 degrees): 180-112=68 degrees. In humans the knee experiences a small 25 degree flexion in the stance phase of gait before the larger 65-70 degree flexion during the swing phase (Refer to Figure 5). However, the mechanism was unable to recreate the first 25 degree flexion. This is most likely because the Theo Jansen mechanism experiences a near harmonic motion while the knee does not.

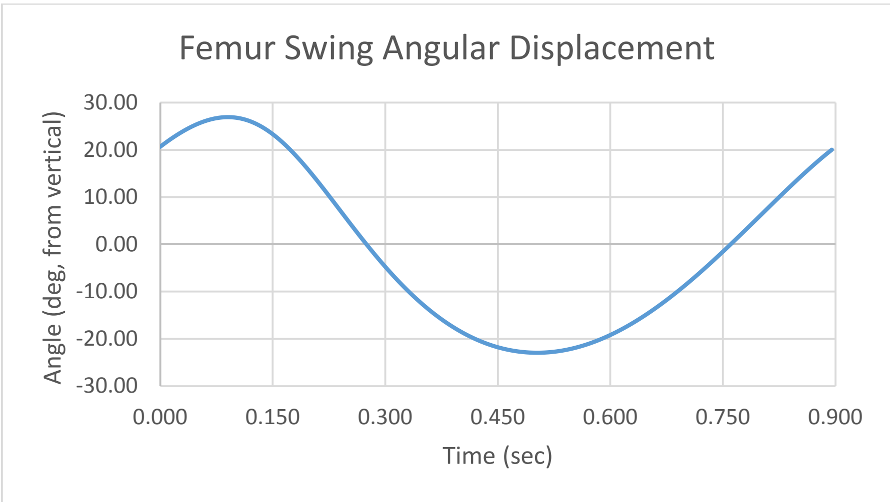


Figure 35 - Angular displacement of the femur with respect to horizontal. The femur displaces 50 degrees.

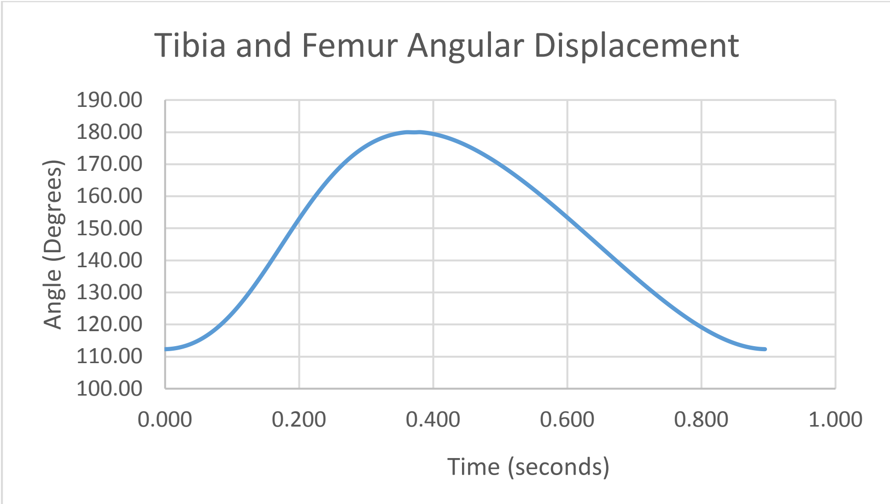


Figure 36 - Angular displacement of the knee joint is 68 degrees.

A 2/3 scale was applied to the mechanism in order to stay within budget and to produce a mechanism that was not oversized. Table 5 lists the link lengths. A detailed drawing of each link can be viewed in Appendix B.

Table 5: 2/3 Scale link lengths for final linkage

Link Number	Length (in.)
1 (distance between ground nodes)	7.330
2	2.500
3	14.000
4	11.402
5	11.333
6	8.167
7	10.250
8	11.402
9	7.085
10	6.725
11	16.945
12	12.827

7.2 Knee Replacement

7.2.1 3D Printing Objects

The TKR design was chosen because the majority of knee replacement surgeries use this. The team was unable to obtain an actual TKR so a 3D printed model was used from MakerBot's Thingiverse. Thingiverse is a design community for making and sharing 3D printable objects [31]. We found a 3D assembled model of a knee replacement which was created from a real 3D scan. The model included the femoral component, the tibia tray, the plastic spacer, and the tibia and femur bones which were modeled from a CT scan and cut to be assembled with the knee replacement [31].

The TKR needed to be scaled in SolidWorks to actual human size. The team used data from a study by Elsner *et al* that used MRI scans of 118 people to measure and analyze the dimensions of bone anatomy for size matching knee replacement implants [32]. Appendix B shows the 3D printed parts and their respective dimensions.

Additionally, the femur and tibia bones were edited to accommodate attachment to the linkage mechanism. The ends of the bone were cut and holes were created in the file to allow screws to attach the 3D printed parts to the femur and tibia links. Figure 37 below illustrates the cuts and holes in the femur part in a SolidWorks model.

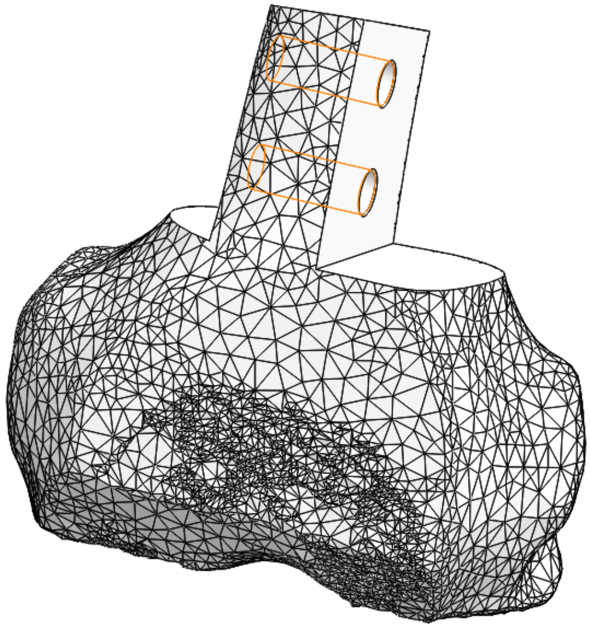


Figure 37: SolidWorks .stl model of femur bone for 3D printing.

7.2.2 Attachment of Knee Replacement to Mechanism

The team decided that the best method to attach the knee parts was to attach them in a separate plane to the mechanism. Four hexagonal standoffs connect the knee replacement to the femur and tibia links in the mechanism (see Figure 38). The hexagonal standoffs attach to an 80/20 piece, which has two plates bolted to either end that hold the 3D printed bone.

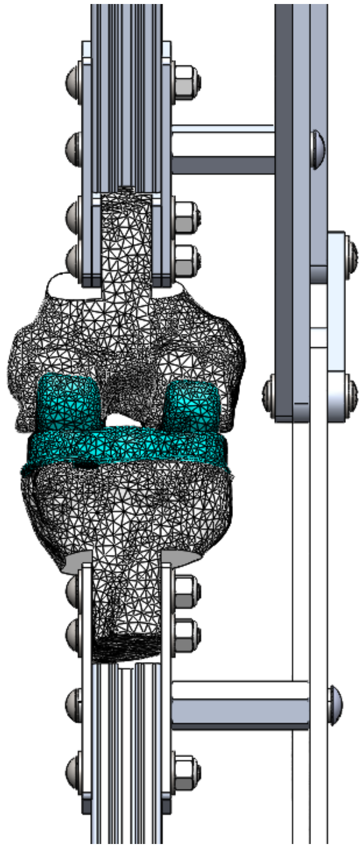


Figure 38: Attachment of femur and tibia links the mechanism

7.2.3 Joints

The mechanism uses screw posts (see Figure 39) as pin joints to connect the links together. Node three is attached to the ground by a long partially threaded hex cap screw.

Figure 39: Example of a screw post (also known as a binding post) from Grainger's online store

When the team attached the femur and tibia links to the final mechanism in SolidWorks, it was found that the femur and tibia parts would collide Figure 40.

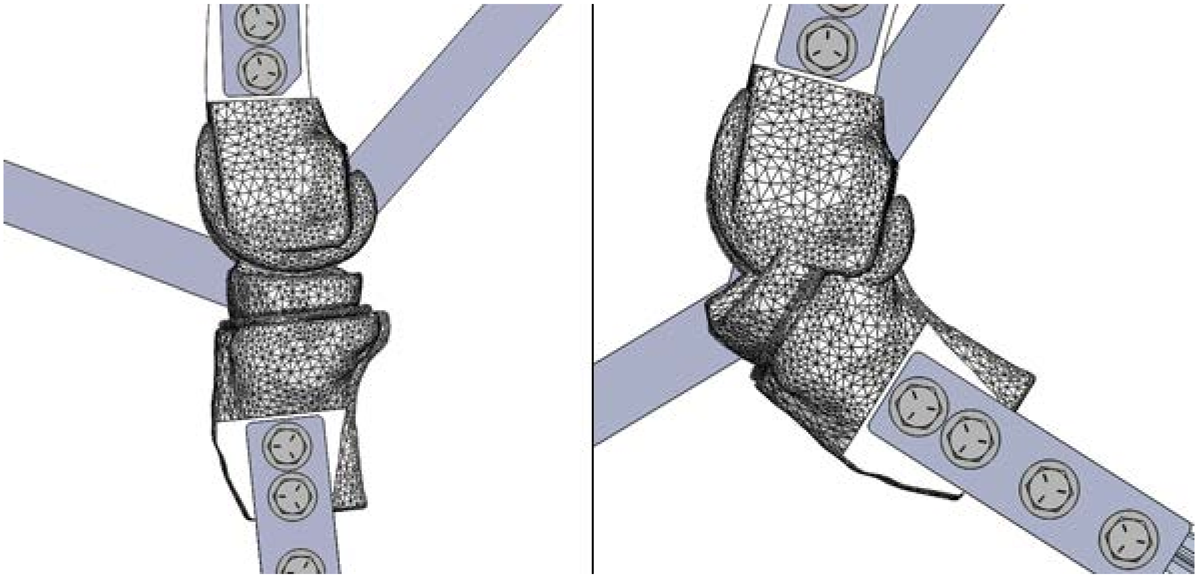


Figure 40: (Left) Linkage with the femur and tibia bones at nearly 180 degrees. (Right) Linkage with the femur and tibia bones at an angle, resulting in a collision between the femoral and tibial components.

To solve this interference problem, a slot replaced the joint on link 12 (see Figure 41). The size of the slot was determined to be 0.875 inches at maximum length. This is just more than the minimum distance needed for tibia and femur links to not collide with one another at the position of maximum interference.

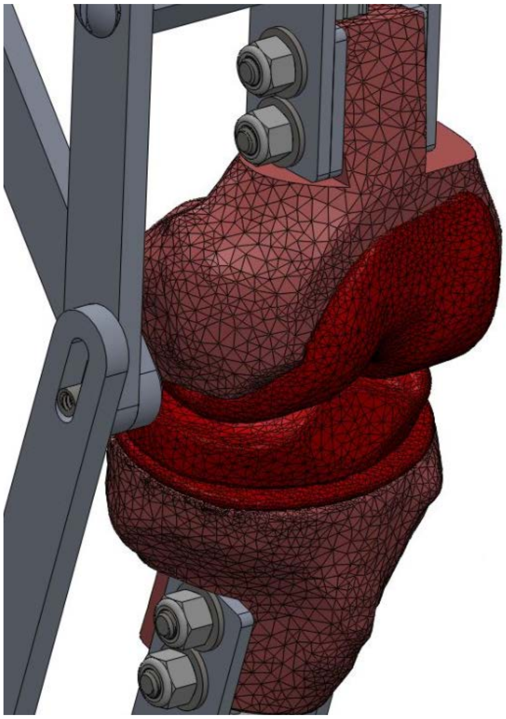


Figure 41: Slot joint for the femur link to prevent interference.

7.2.4 Tendons and Ligaments

To help keep the knee replacement parts together during the cycle so the tibia link does not stay at the bottom of the slot due to gravity, models of the patella and quadriceps tendons along with the posterior and anterior cruciate ligaments were attached to the 3D printed bone assemblies for the final prototype (See Figure 42). The tendons and ligaments were recreated using rubber bands that can withstand one pounds of force. Adding the ligaments and tendons will help keep the knee replacement parts together, which will create a roll-slide half joint. The rubber bands will be attached to the 80/20 extrusions with t-nuts.

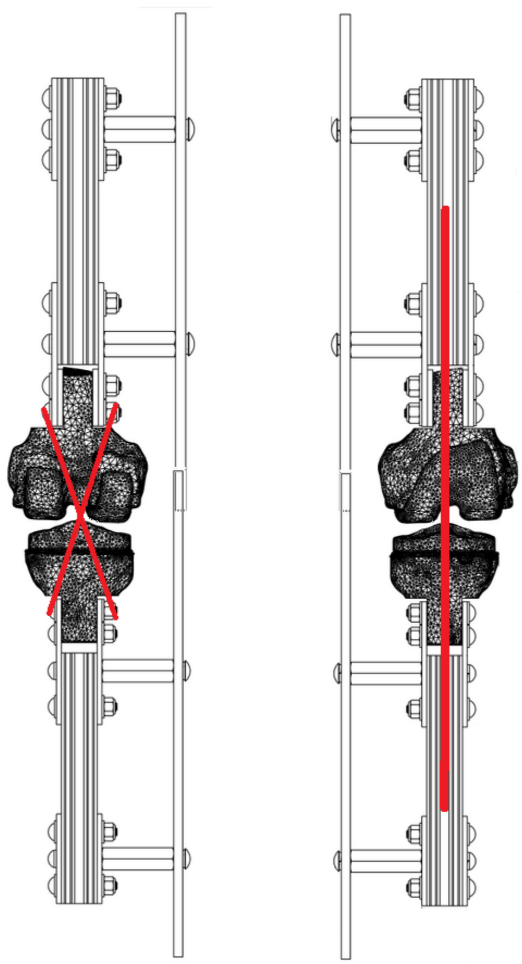


Figure 42: The red lines denote where the rubber bands mimic the tendons and ligaments. (Left) the X-shaped cruciate ligaments (ACL and PCL). (Right) the patellar and quadriceps tendons.

Overall the mechanism theoretically has 1 DOF. The mechanism has twelve links, 15 full joints, and 2 half joints. One half joint is the slot and the second half joint is the roll-slide joint created from the muscles and ligaments. Thus, the mobility is calculated using the DOF equation as followed:

$$M = 3 * (12 - 1) - 2 * (15) - 1 * (2) = 1$$

An evolutional image of the final linkage mechanism including the attached knee replacement is shown in Figure 43. Using the team's connection at Sparton Technology, the mechanism links were laser cut out of aluminum.

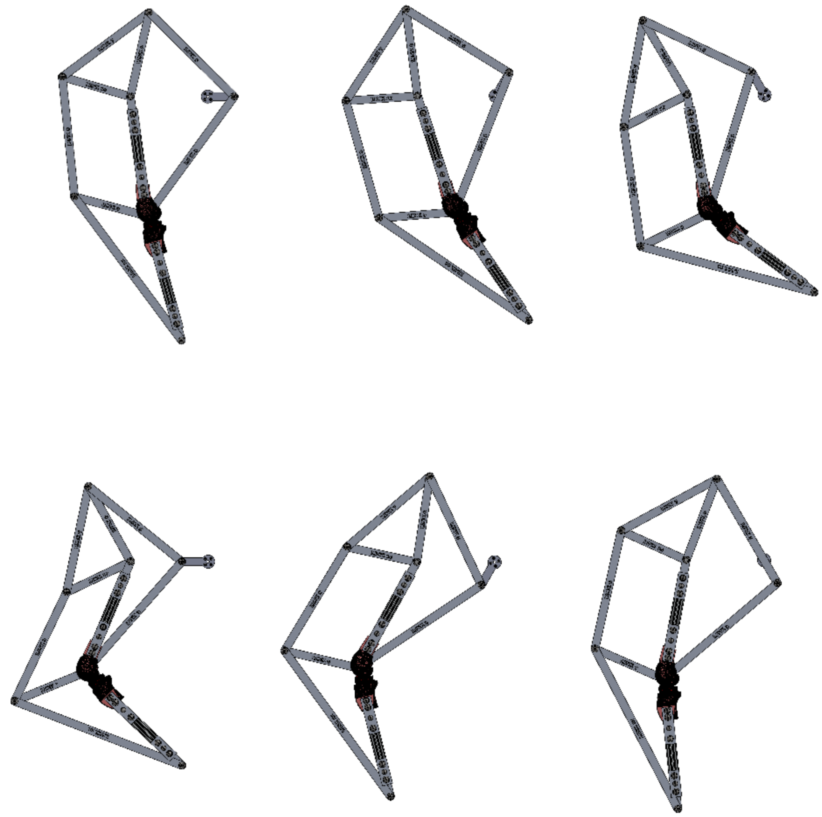


Figure 43: Positional Evolution of the Final Linkage over one complete cycle.

7.3 Motor

The motor used to drive the mechanism is a 75 rpm precision gear motor from ServoCity. Figure 44 displays the motor with no accessories. This motor operates between six and twelve volts, and at maximum voltage it has a stall torque of 166.6 oz.-in. See Dimension Drawing of the Precision Gear Motor for a dimension drawing of the motor (note that the dimensional drawing is in metric units; this motor was only available with this unit system), and Appendix D: Specifications of the Precision Gear Motor for a complete list of specifications.

Figure 44: Motor from ServoCity to be used in prototype.

In order to choose the motor for the final design, the team performed a kinematic simulation in SolidWorks and used the results in the virtual work method to find torque. Then, several accessories to the motor were necessary to supply power and attach the shaft to the linkage.

7.3.1 Virtual Work Method

The virtual work method is a type of energy method of dynamic force analysis in which external forces are computed and internal forces are ignored. It uses the law of conservation of energy to state that, in the absence of losses, the rate of change of energy stored in the system is equal to the energy which is external supplied to it. This relationship is expressed by equating the sum of the changes in external forces and torques to the changes in inertia forces and torques. The resulting equation is as follows (bolded variables denote a vector):

$$\sum_{k=2}^{n} \boldsymbol{F_k} \cdot \boldsymbol{v_k} + \sum_{k=2}^{n} \boldsymbol{T_k} \cdot \boldsymbol{\omega_k} = \sum_{k=2}^{n} m_k \boldsymbol{a_k} \cdot \boldsymbol{v_k} + \sum_{k=2}^{n} I_k \boldsymbol{\alpha_k} \cdot \boldsymbol{\omega_k}$$

The variables in this equations are described in Table 6.

Table 6: Definition of Each Variable in the Virtual Work Equation

Variable	Description
k (subscript)	Link number (beginning at 2 because link 1 is the stationary ground link)
n	Total number of links
F	External force on the link
v	Linear velocity on the link
T	External torque on the link
ω	Angular velocity of the link
m	Mass of the link
a	Linear acceleration of the link
I	Moment of Intertia of the link
α	Angular acceleration of the link

This equation is true at all points in the linkage's cycle, but it can only be analyzed at one position at a time. In order to find the change in torque over the entire cycle, the equation must be solved at multiple positions and interpolated with a trend line. The team decided to use the virtual work method every π/6 radian turn of the crank, thus having 12 total points across the cycle. At each π/6 radian increment, all values listed in the equation must be known, in vector form if necessary, for every link. The team created a excel spreadsheet to organize this data and perform the calculations necessary to calculate the crank torque. A sample of the excel spreadsheet at one increment can be seen in Table 7 below. The torque on link 2 in the z-direction is highlighted in green since that is the value being calculated.

Table 7: Excel Spreadsheet used in determining required power for linkage.

Position	Link #	X - Direction						Y - Direction						Z - Direction					
		F	T	v	ω	a	α	F	T	v	ω	a	α	F	T	v	ω	a	α
	2	0	0	-0.00557	0	0.63951	0	0	0	-0.14357	0	-0.28808	0	0		0	4.525321	0	8.28628
	3	0	0	-0.33629	0	2.07656	0	0	0	-0.01277	0	0.08288	0	0	0	0	-2.39283	0	1.03774
	4	0	0	-0.33072	0	1.43705	0	0	0	0.1308	0	0.37096	0	0	0	0	-2.45603	0	8.28628
	5	0	0	0.188572	0	3.11928	0	0	0	-0.03057	0	0.59238	0	0	0	0	-2.25891	0	-14.2598
0 rad	6	0	0	0.194139	0	2.47977	0	0	0	0.113	0	0.88046	0	0	0	0	-2.16581	0	-24.934
or	7	0	0	0.111248	0	1.88363	0	0	0	0.27837	0	2.96375	0	0	0	0	-2.16581	0	-24.934
0 sec	8	0	0	-0.4965	0	0.24478	0	0	0	0.46153	0	4.53755	0	0	0	0	-2.45603	0	8.28628
	9	0	0	-0.74433	0	2.27796	0	0	0	0.42696	0	2.82522	0	0	0	0	-2.16581	0	-24.934
	10	0	0	-0.08289	0	-0.59613	0	0	0	0.16536	0	2.08329	0	0	0	0	-2.16581	0	-24.934
	11	0	0	-0.95536	0	-0.7639	0	0	0	0.1442	0	0.02696	0	0	0	0	-2.16581	0	-24.934
	12	0	0	-0.87247	0	-0.16776	0	0	0	-0.02117	0	-2.05634	0	0	0	0	-2.16581	0	-24.934

The values included in this table were found using a motion simulation in SolidWorks. The SolidWorks Motion plug-in was used for this analysis because it allows the user to graph kinematic data over a cycle of motion. The team placed a motor on the crank that rotated at 66.67 rpm, because the cycle time needed to be easily divisible by 12. This speed allows the cycle to be 0.90 seconds long, which is divisible into 0.075 second increments, and it is close enough to 66.5 rpm for the data to be valid.

To fill the table seen above in Table 7, the team ran the simulation for one entire cycle, focusing on the results for one link at a time to minimize the computer memory used by SolidWorks. The results only observed the linear and angular velocities and accelerations, since no external forces or torques are acting on the linkage besides the unknown torque from the motor. These results were exported into excel spreadsheets so they could easily be copied into the table. After repeating this process for all 11 links, the table was filled with all the values needed to solve for the crank torque. This complete table can be seen in Appendix E.

After filling the table with data, a new table was made which calculated the sums of the dot products found in the virtual work equation. This table is displayed in Table 8 below. Note that there is no value for the F·v terms; since no external force is acting upon the linkage, that term is always zero. The crank torque was calculated by adding the ma·v and Iα ·ω terms, then dividing by the angular velocity of the crank. Since there is no external torque acting on the linkage other than the motor on the crank, then the torque required to run the machine is equal to this value of torque on link 2.

Table 8: Sum of the dot products determined from the virtual work equation

Results					
Position	Σ F · v	Σ ma · v	Σ Iα · ω	Σ T · ω	Crank Torque
0	0	2.04377	0.64926	2.69303	**0.595102867**
π/6	0	3.52106	1.03586	4.55693	**0.804616394**
π/3	0	5.84809	0.94298	6.79108	**0.849345274**
π/2	0	7.70388	1.24931	8.95319	**0.874441696**
2π/3	0	4.88914	0.42526	5.3144	**0.506905224**
5π/6	0	3.82108	0.58838	4.40946	**0.465429283**
π	0	3.11204	0.26501	3.37705	**0.409355493**
7π/6	0	1.9994	0.1534	2.1528	**0.303163258**
4π/3	0	1.10238	0.27933	1.38171	**0.227946078**
3π/2	0	1.63846	0.30827	1.94674	**0.376057721**
5π/3	0	1.93769	0.21712	2.15481	**0.474630518**
11π/6	0	1.55477	0.12722	1.68198	**0.394288419**

The results of this analysis are shown in the right-most column of Table 8. To visualize the torque required over time, a scatter plot with smooth lines was produced in Excel. This plot can be viewed in Figure 45 below.

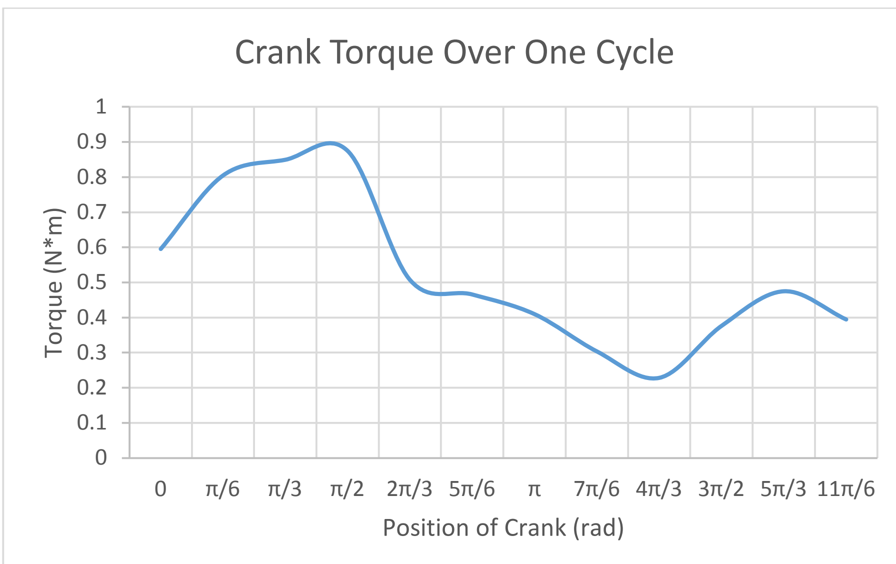


Figure 45: Crank Torque over one cycle

As seen in the plot, the peak torque necessary for the crank to drive the linkage at 66.67 rpm is roughly 0.90 N*m. Since most motors which operate at this level are rated in oz*in, this value was converted to 127.4 oz*in. This value, as well as the 66.5 rpm shaft speed, guided the team's research into a motor best suited for this application. The motor described above was selected because the torque it can achieve is 166.6 oz*in, roughly 1.3 times the highest torque value produced from the virtual work method. This should account for any extra friction experienced in the physical linkage. Also, since the motor is rated for 75 rpm when it has no torque load on the shaft, the load of the linkage will slow the rotational velocity nearer to the average human's stride frequency of 66.5 strides per minute. This motor was considered the best option at its price point for this application.

7.3.2 Motor Accessory Selection

After selecting a motor to power the mechanism, several motor accessories were required to serve additional functions: mount the motor to the frame, attach the motor shaft to the crank, allow an easy shut-off for safety, and convert a 120 VAC wall outlet to 12 VDC, which the motor is rated for.

ServoCity sells many accessories that can fulfil some of these functions. A mount for this machine must serve two purposes: it must attach to the front side of the motor, then also attach to a plate directly in front of the motor. ServoCity's Aluminum Motor Mount B, pictured in Figure 46 below, satisfied both purposes. It is compatible with the precision gear motor used in our mechanism, and comes with two mounting screws that screw directly into the motor. A dimension drawing of this part is displayed in Appendix F.

Figure 46: ServoCity Motor Mount

In order to attach the motor shaft to the crank, the team decided to use ServoCity's 0.770 in. Clamping Hub, displayed in Figure 47. This hub tightens around a shaft with the included 6-32 screw, pictured next to the shaft hub, which does not damage the motor's shaft and offers high holding power with a high torque application. This part comes in a 6mm shaft size, which fits the motor perfectly. Since the four holes are tapped with 6-32 female threads, this hub can mount to the crank by inserting four screws through the crank, as displayed in the crank subassembly drawing in Appendix B.

Figure 47: ServoCity clamping hub

Having an emergency shut-off for a machine is a necessary safety feature for this machine. ServoCity offers non-momentary switches which will only connect the circuit if the switch is in a specific position. This way, if one needs to turn off the motor, he or she can simply flick the switch down. This switch is illustrated in Figure 48 below. With the addition of a visible sign stating the direction that will shut off the machine, this switch will suffice as an emergency shut-off.

Figure 48: Power Switch for motor

The final accessory is a converter from 120 VAC to 12 VDC. The Electrical and Computer Engineering department donated a wall converter. This converter is wired directly to the switch, which acts as a gate to completing the circuit with the motor.

7.4 Frame

The frame must satisfy three requirements to successfully support the mechanism: it must carry the weight of the linkage and motor, it must be easy enough to assemble with simple tools, and it must allow the fixation of the ground nodes on the linkage. By recommendation from the project advisor, the team looked towards 80/20, Inc. to satisfy the first two requirements. This company manufactures extrusions and fasteners for the intended use as industrial frames, but the parts are designed for easy assembly. Additionally, all parts in their product catalog are available as CAD files for the customer to design his or herself, and the company offers consultation on projects included with any orders (80/20 website).

After consulting with the 80/20 professional, the team decided that their 10-series, which includes extrusions that are 1 in. x 1 in., would successfully support the linkage and the motor for extended use. A dimensioned cross section of a standard 10-series extrusion from 80/20's product catalog is displayed in Figure 49. These extrusions are available in pre-cut lengths of 48 or 72 inches, or 80/20 offers labor to pre-cut them to the length required by the consumer.

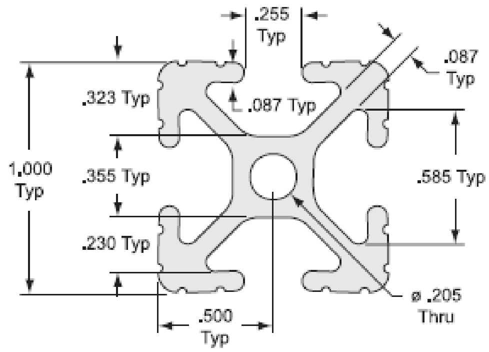


Figure 49: Dimensioned cross section of a standard 80/20 10-series extrusion.

The team then brainstormed two design alternatives, displayed in

Appendix G: Frame Design Alternatives, using the 10-series extrusions. One design used only 90 degree cuts, and the other utilizes four extrusions with 45 degree cuts. The design with 45 degree cuts was chosen in order to reduce the length of extrusions needed and, in turn, reduce the cost. Then, the team sent two quotes to the 80/20 consultant including all components of the final frame, but using two different fasteners: anchor fasteners (Appendix H: Quote for Anchor-Fastened Frame Option) and standard end fasteners (Appendix I: Quote for Standard End-Fastened Frame Option). The standard end-fastened frame option was cheaper, so these were used in the final frame.

These parts are attached to one another perpendicularly using standard end fasteners, pictured in Figure 50. The standard end fastener consists of the cap screw and the wing clip. This fastener screws into the 0.205 inch hole in the center of the 10-series extrusion (see Figure 49 above). Then, the wing clip slides through the side of another extrusion, and the screw is tightened through a hole in the second extrusion. The pressure from the wing clip after tightening the screw is high enough to fix the two extrusions together. Appendix J displays the steps found in the 80/20 product catalog to implement the end fasteners.

Figure 50: End fasteners used to attach 80/20 extrusion together

Additionally, 80/20, Inc. offers T-nuts which slide into the ends of the extrusions to allow plates to be screwed on to the surface. Figure 51 displays a cross-section of how these fasteners attach to the extrusions.

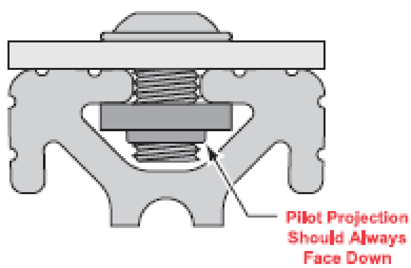


Figure 51: Assembly of fastener screws with 10-series extrusion

The team decided to use these T-nuts to fasten an acrylic plate to the front of the frame, which may be laser-cut to insert the ground nodes to the frame. Figure 52 displays the design of the acrylic plate on the front face of the frame. This strategy satisfies the third requirement of this frame, which is to allow the frame to fix the ground nodes. One of these ground nodes is the motor shaft, which is displayed on the right side of the acrylic plate. Note the four small holes that surround the motor's ground node. These holes are intended for four 6-32 screws which thread into the motor mount, described in 7.3.2. The node on the left side of the acrylic plate is 7.330 in. from the motor mount.

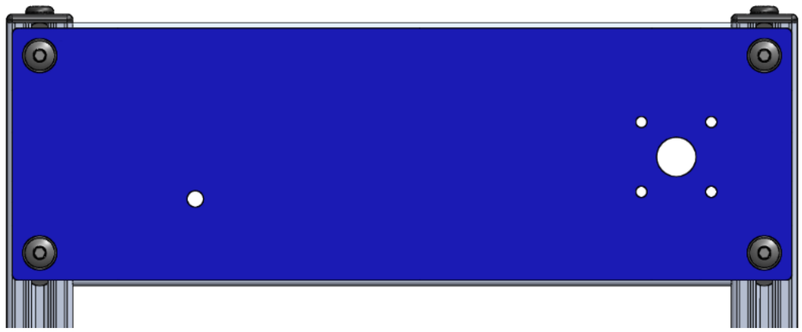


Figure 52: Acrylic plate design to be laser cut for mounting of the motor and linage ground.

In addition to the acrylic plate in the front of the frame, an acrylic plate was fastened to the right side of the frame to mount the switch. This plate simply has a rectangular hole which houses the switch near the motor to wire them together. The switch is glued in place with hot glue. A model of the top of the frame is displayed in Figure 53 with translucent acrylic plates, the motor mounted, and the power switch included.

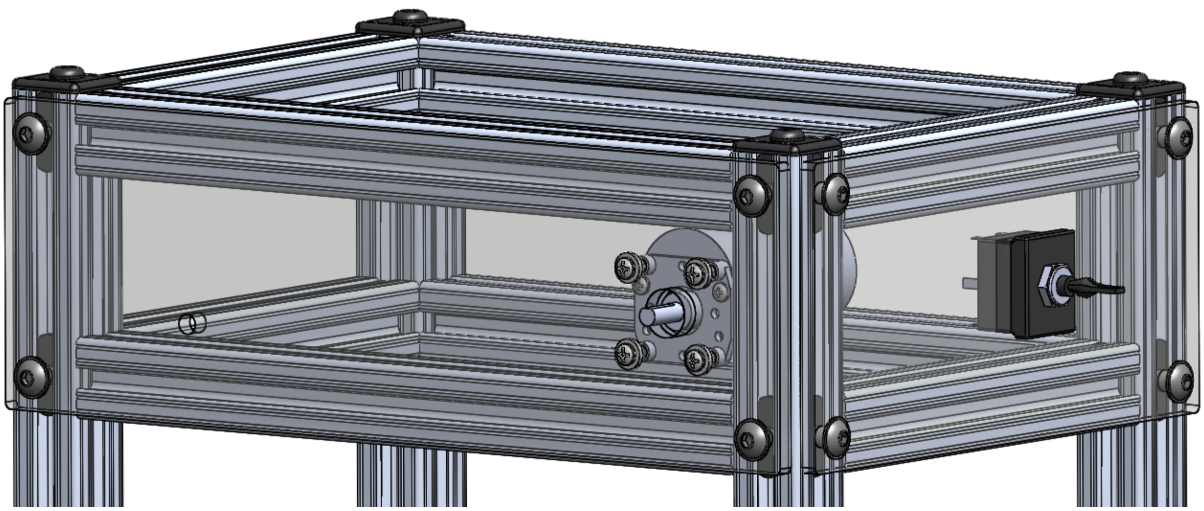


Figure 53: Acrylic plates used to mount power switch and motor.

Appendix K displays dimensioned drawings for each part of the frame assembly.

8 Prototype Construction

In the following sections the team provides brief assembly instructions for the mechanism's frame, linkage, tibia and femur sub assembly, motor and electrical components. Additionally, changes made to paper design and lessons learned during construction were described.

8.1 Frame Construction

The frame components were the first parts to be delivered, so the team began assembly of the prototype with the frame construction. All parts from 80/20 were laid on a table and identified as seen in Figure 54 to make them easier to find, then the team referenced a SolidWorks assembly of the frame to help guide the assembly.

Figure 54: Components of the Frame from 80/20.

The frame was built from the bottom up, allowing the rest of the frame to be built upon a base and stand upright. The team only encountered minor difficulties in fitting the pieces together. This may be due to slight bending or other irregularities in the 80/20 extrusions which is not accounted for in the CAD model. Regardless, it took only some small force to fit the pieces together correctly and fix them in place. The complete 80/20 component of the frame is displayed in Figure 55.

Figure 55: The Assembled 80/20 Component of the Frame.

Next, the team laser cut 0.22" acrylic sheets into the front and side plates designed for this frame. The T-nuts were loosely screwed into the plate, then slid down the 80/20 extrusions. Then, the screws were tightened, fixing the acrylic into the 80/20 parts. The result is displayed in Figure 56.

Figure 56: The Acrylic Screwed into the Sides of the 80/20 Extrusions using T-Nuts.

8.2 Motor and Electrical Components

With the frame assembly completed, the motor and switch could then be attached to the acrylic plates. The motor mount was screwed on to the front face of the motor, which was then screwed into the front plate through the four small holes. Next, the switch was glued to the side plate using a hot glue gun. The team placed a strip of bright red duct tape in the shape of a downwards-facing arrow with the word "STOP" written in permanent marker. This label is meant to notify anyone running the machine which direction shuts off the machine in case of an emergency. The acrylic plate with the switch glued and stop label is depicted in Figure 57.

Figure 57: The Switch is Hot-Glued into the Rectangular Cutout in the Side Acrylic Plate with the Stop Label to its Right

The wall converter came with a long length of extra wire. The team utilized this wire to cut off small pieces to complete the circuit between the 120 VAC power supply, the converter to 12 VDC, the non-momentary switch, and the motor. The wires were connected to the switch according to the image in Figure 58.

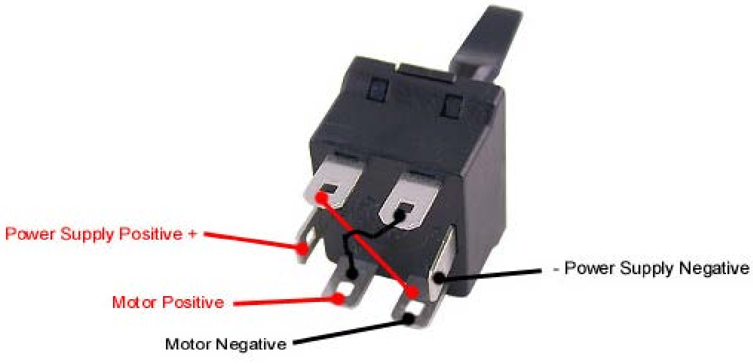


Figure 58: The Suggested Wiring Schematic Offered from ServoCity's Website

While the image suggests the switch should be wired to run the motor in both directions, the team did not intend for our linkage to run backwards. Therefore, the wires which connect the motor positive and negative pins to the opposite ends on the switch are not present in the prototype assembly. The wiring of the motor to the switch are illustrated in Figure 59.

Figure 59: The Motor and Switch Mounted to the Frame and Wired Together

8.3 Femur and Tibia Subassembly Construction

The team assembled the femur and tibia subassemblies by referencing the exploded assembly drawings shown in Figure 60 and detailed in Appendix B. The 3D printed femur and tibia assemblies were connected to the 80/20 links by four hexagonal standoffs which attached to the plates of the 3D Printed Knee Replacements.

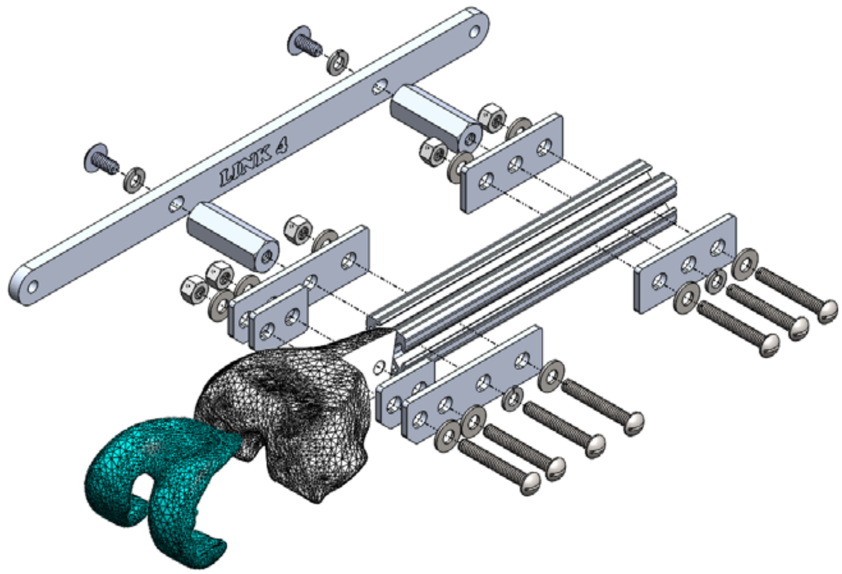


Figure 60: Exploded View of the Femur Assembly.

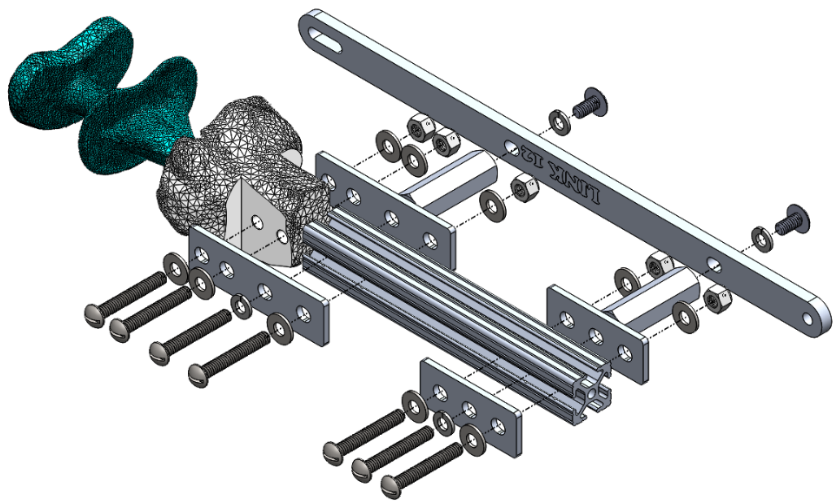


Figure 61: Exploded View of the Tibia Assembly

Additionally, the rubber bands modeling the tendons and ligaments of the knee joint were attached with t-nuts and washers. Figure 62 shows the final prototype construction.

Figure 62: The Final Mechanism's Tendons and Ligaments

8.4 Linkage Construction

The team constructed the linkage from eleven laser-cut aluminum links. To ensure that the links were in their proper positions relative to each other, reference pictures of each node were available to view at any time during assembly. Each node was attached using a screw post with a washer on each end. White lithium grease was applied to any two surfaces which slid across each other, and Loctite was utilized inside the screw posts to keep them from unscrewing. A finished joint can be seen in Figure 63.

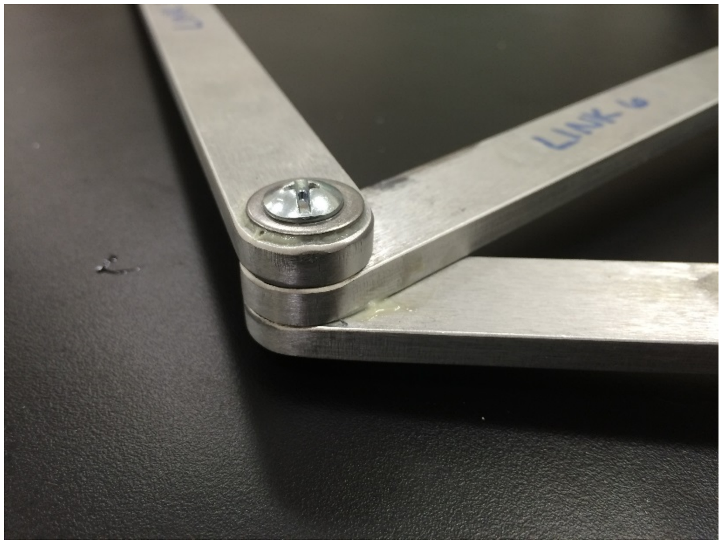


Figure 63: Assembled Node of the Final Prototype.

The joint which connects links 4, 6, and 10 to the ground node used a partially threaded hex cap screw instead of the screw post. The hex screw feeds through the left-most ground node cut into the front acrylic plate, and is locked on with a lock screw. This constitutes the first ground node of the linkage. After all the links have been joined at the nodes, the crank was screwed into the shaft hub with 6-32 screws. The crank/shaft hub assembly is displayed in Figure 64. The hub was tightened on to the motor shaft which reaches through the front acrylic plate, acting as the second ground node of the linkage.

Figure 64: Assembly of the Shaft Hub to the Crank on the Final Prototype.

8.5 Alterations to the Final Prototype Design

8.5.1 Implementing a Counterbalance on a Ground Node

The major problem encountered after assembling the entire mechanism was the moment which forced the bottom of the linkage to turn inwards, towards the frame, and impact the 80/20 extrusions while running. Figure 65 below illustrates how the linkage bends in to touch the frame.

Figure 65: The Bottom Node of the Linkage Impacts the Frame due to a Moment on the Ground Nodes.

This phenomenon can be explained with a free body diagram of the linkage. Figure 66 below shows the 12-bar linkage with the two major forces acting upon it; F_N denotes the normal force from the ground nodes holding the linkage up, and F_G denotes the sum of the forces of gravity on the linkage and knee replacement parts. As shown in this figure, the forces acting in opposite directions create a counterclockwise moment, M, for the linkage to rotate around. Any leeway in the ground nodes in the front acrylic plate will allow the ground nodes to tilt. This moment causes the bottom of the linkage to impact the frame.

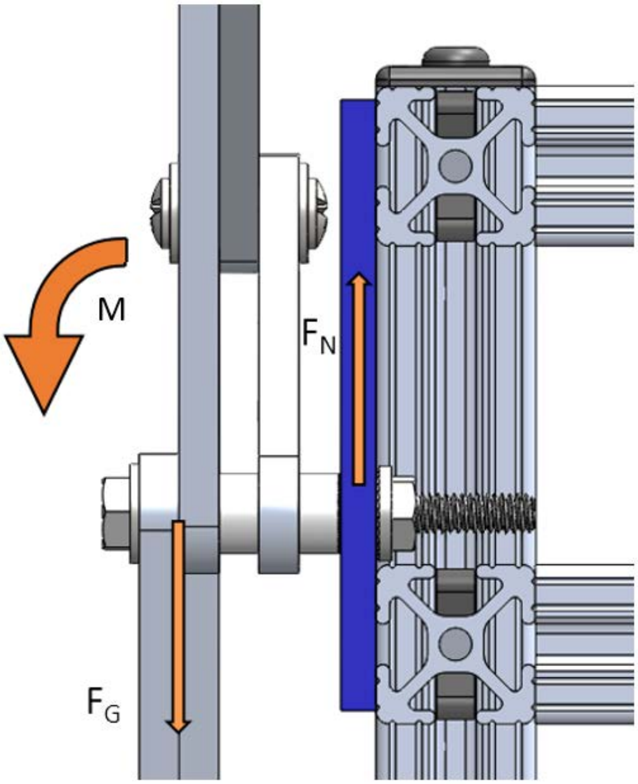


Figure 66: Free Body Diagram of the Hex Screw which Comprises the Left-Most Ground Node.

A solution to this problem is to create a double-paned ground node which does not allow the shaft or hex screw to tilt and rotate inwards. This second pane of acrylic would act as a counterbalance to the linkage, and the downward force would cancel the moment created by the gravity and normal forces. To further avoid any tilt in the hex screw, the holes in the acrylic plate was tightened to a very close clearance. The resulting free body diagram is displayed in Figure 67; F_C denotes the force of the counterbalance.

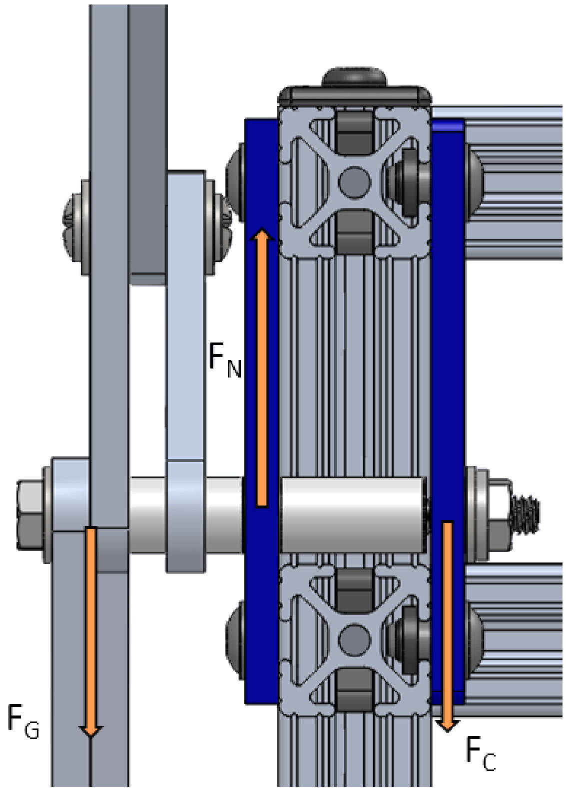


Figure 67: Free Body Diagram of the Hex Screw after Implementing the Counterbalance.

The team laser cut the new acrylic plates and installed them with extra T-Nuts supplied from the Robotics department. A one inch spacer was also placed between the two acrylic plates so they would not buckle inwards if the nut was screwed on too tightly. The finished ground node with the two acrylic plates is illustrated below in Figure 68.

Figure 68: The Final Iteration of the Left-Most Ground Node.

8.5.2 Installing a Collision Plate in Front of the Frame

After implementing the counterbalance, the linkage turned to a more vertical position, but after running several cycles, it began to impact the frame slightly. Since even a small impact like this is unacceptable for long-term testing, a second method was required to keep the linkage vertical while running. The team decided to attach an acrylic plate to the front of the frame which would lightly contact with the bottom of the linkage (see Figure 69). To make the plate more aesthetically pleasing, the team cut the Worcester Polytechnic Institute logo at a location where the linkage wouldn't touch the plate. This prevents the links from touching the gaps that make up the logo.

Figure 69: Model of the Acrylic Guide Plate Attached to the Frame

When the mechanism is experiencing high moments which would cause the lower links to collide with the 80/20 extrusions, it will instead touch the flat plate. This prevents the linkage from rotating too far inwards, and from having a site of high impact since the plate is parallel with the intended motion of the links. Additionally, since there is very little friction experienced between the acrylic plate and metal screw post which slides across it, it will not add too much torque load on the motor. This plate was laser cut and attached to the frame using additional T-Nuts. An image of the plate joined to the front of the frame, completing the prototype's assembly, is depicted in Figure 70.

Figure 70: Picture of the Complete Assembly

9 Prototype Testing

The prototype was tested to assess if the team successfully met the tasks specifications that were set at the beginning of the project and to identify any areas for future improvement. The goal of this project was to create a mechanism that simulated the motions of the knee while walking, thus the prototype was tested to see if the mechanism functioned the way it was intended.

A checklist was created to see if the prototype satisfies the checks. The checklist includes the following points:

- Was a knee replacement successfully attached?

Yes, the knee replacement was successfully attached to the mechanism. The knee replacement was attached so that it undergoes similar motions of the knee.

- Did the mechanism jam?

No, the mechanism did not jam. The slot on link # prevented the tibia and femur 3D printed parts from colliding with each other. Overall, the mechanism ran smoothly. Applying grease to the joints helped to insure this.

- Was the motor powerful enough to drive the mechanism?

Yes, the motor was powerful enough to drive the mechanism.

- Did the mechanism run at 66.5 cycles per minute?

After using a counter to count the number of cycles the mechanism ran in a full minute, the team determined that it runs at 77 cycles per minute. While the motor was rated at 75 rpm without any load, the team found that the motor actually runs at 100 rpm unloaded.

- Did the emergency stop work properly?

Yes, the emergency stop does work properly. The switch located on the side of the mechanism powers on and off the motor.

- Did the motion of the knee match the SolidWorks motion analysis, in terms of angular displacement of the knee and femur swing?

Through video analysis we were able to determine the femur swing angular displacement was achieved while the knee joint angular displacement was within 8% error of the anatomically correct range. A video recording of the mechanism going through one complete cycle was used for motion analysis. Tracker, a free open source physics program, was used to perform the motion analysis. Two tools were used within the program. The first was the ‘Protractor’ tool which was used to measure the femur swing. The femur swing angle was measured to be 49.7 degrees (See Figure 71).

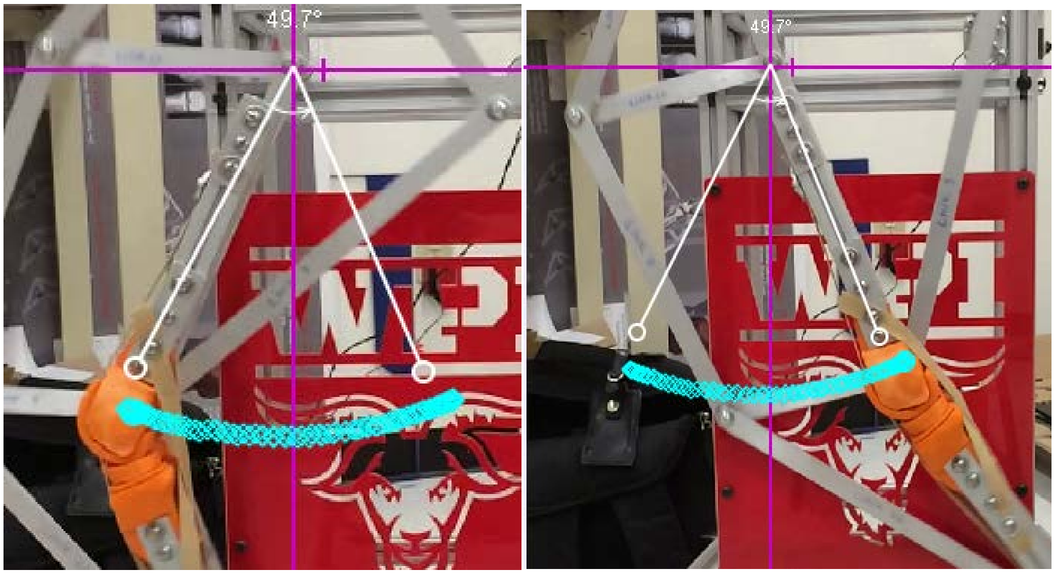


Figure 71: The femur swing angle measured with the Tracker program was found to be 49.7 degrees.

The second tool was the ‘Point Mass’ tool, which allows frames of the video to be isolated and frozen enabling the user to select a mass of interest and track the mass of interest through the selected video frames. To determine the angular displacement of the tibia and femur, the knee and ankle joints were tracked with respect to a defined origin over the length of the video frame. Duct tape was used as an indicator to highlight joints 3 and 8 on the mechanism for ease of tracking. As a result, the trace curves of the knee and ankle joints were obtained along with the x and y positional coordinates of each data point with respect to the defined origin. The trace curves of the knee and ankle in the Tracker program are shown below in Figure 72.

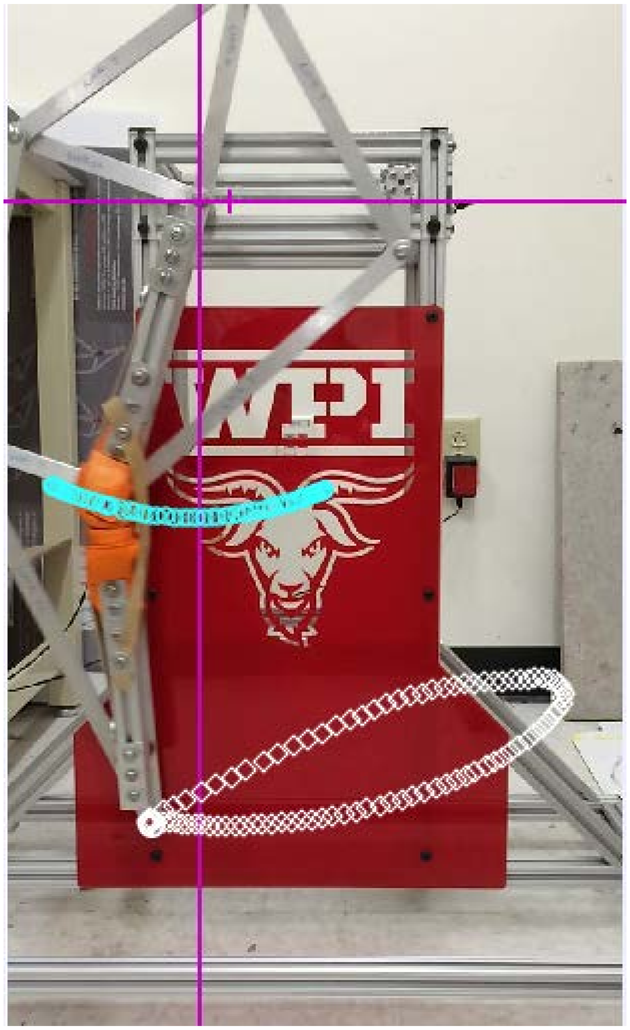


Figure 72: Knee (blue) and Ankle (white) joint trace curves for one complete cycle.

The positional coordinates of the knee and ankle were copied into an excel file. These positional coordinates were translated into vectors of the femur and tibia. Using the formula below, the excel sheet was able to calculate the angle between the femur and tibia vectors. This calculation was performed at a total of 88 steps, which comprised an entire cycle.

$$\cos(\theta) = \frac{(\vec{u} \cdot \vec{v})}{(\|\vec{u}\|\|\vec{v}\|)}$$

Where,

$\vec{u} \cdot \vec{v}$ is the dot product of the two vectors

$\|\vec{u}\|, \|\vec{v}\|$ is the length of the vector u and v respectively

Table 9 below shows some of the data from the excel spreadsheet used to calculate the angular displacement of the knee. Refer to Appendix L for the entire excel knee angular displacement data.

Table 9: Sample of the excel data used to calculate the angular displacement of the knee joint.

Step #	Knee Position		Ankle Position		Femur Vector			Tibia Vector			Dot Product	Magnitude Product	Cos(θ)	θ (rad)	θ (deg)	Actual θ (deg)
	X	Y	X	Y	X-Component	Y-Component	Magnitude	X-Component	Y-Component	Magnitude						
1	-70.09	-330.32	-31.90	-693.81	70.09	330.32	337.67	38.19	-363.49	365.49	-117390.78	123415.60	-0.95	2.83	162.02	**162.02**
2	-61.36	-331.29	-25.76	-695.47	61.36	331.29	336.93	35.60	-364.18	365.92	-118466.63	123287.42	-0.96	2.86	163.92	**163.92**
3	-53.27	-333.18	-19.93	-696.61	53.27	333.18	337.41	33.34	-363.44	364.96	-119312.32	123141.39	-0.97	2.89	165.67	**165.67**
4	-44.70	-334.30	-13.46	-697.36	44.70	334.30	337.28	31.24	-363.06	364.40	-119974.26	122903.92	-0.98	2.92	167.46	**167.46**
5	-35.28	-334.26	-7.70	-697.95	35.28	334.26	336.12	27.58	-363.69	364.73	-120595.19	122593.95	-0.98	2.96	169.64	**169.64**
6	-26.79	-335.35	0.40	-698.83	26.79	335.35	336.42	27.19	-363.48	364.50	-121165.14	122623.14	-0.99	2.99	171.16	**171.16**

The maximum angular displacement of the knee was found to be: 180.96 – 105.45 = 75.51 degrees. 75.51 degrees is outside the maximum flexion range a typical human knee experiences, but is within 8% error. The angular displacement of the knee was graphed over the video frame steps to show the angle of the knee over time (Figure 73).

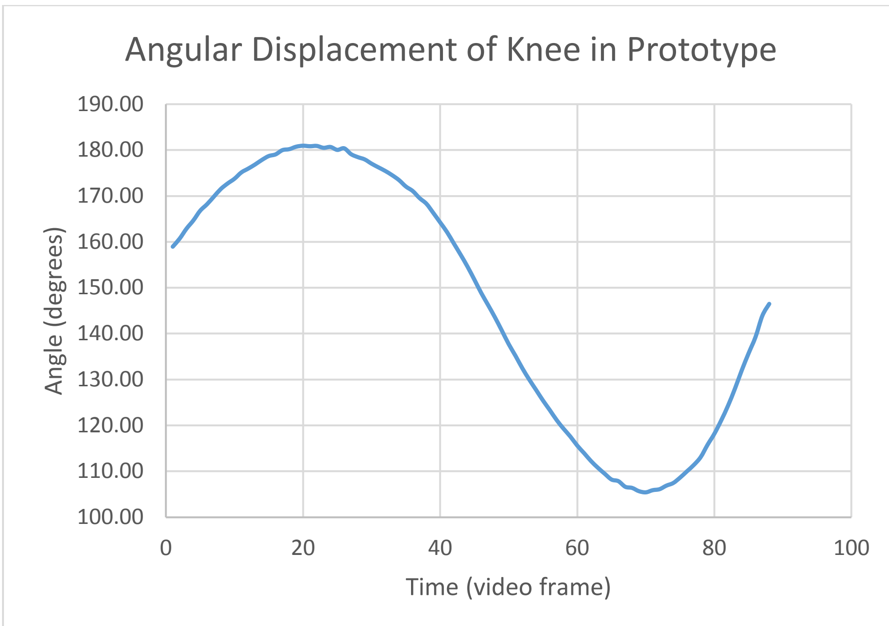


Figure 73: Tibia and femur angular displacement of prototype. The maximum angular displacement was calculated to be 75.51 degrees.

It is important to note that although the data collected from the Tracker program suggests the knee undergoes unnatural knee angles, the data may not be 100% accurate. The data collected from the tracker program was collected using the auto-tracker function. Auto-tracker works by "creating one or more template images of a feature of interest and then searching for each frame for the best match to that template" [33]. The data can be skewed if the same mass of interest point is not selected every time.

- Did the knee hyperextend?

According to visual conformation, the knee never hyperextends. The protractor within the Tracker program measures that the knee is 180 degrees at the maximum point of extension as seen in Figure 74. However, according to the positional coordinate calculations for the knee angle, the knee slightly hyperextends at maximum extension by 0.92 degrees. This 0.5% error and discrepancy could be due to a variety of factors including the precision of the video and the program to measure the data.

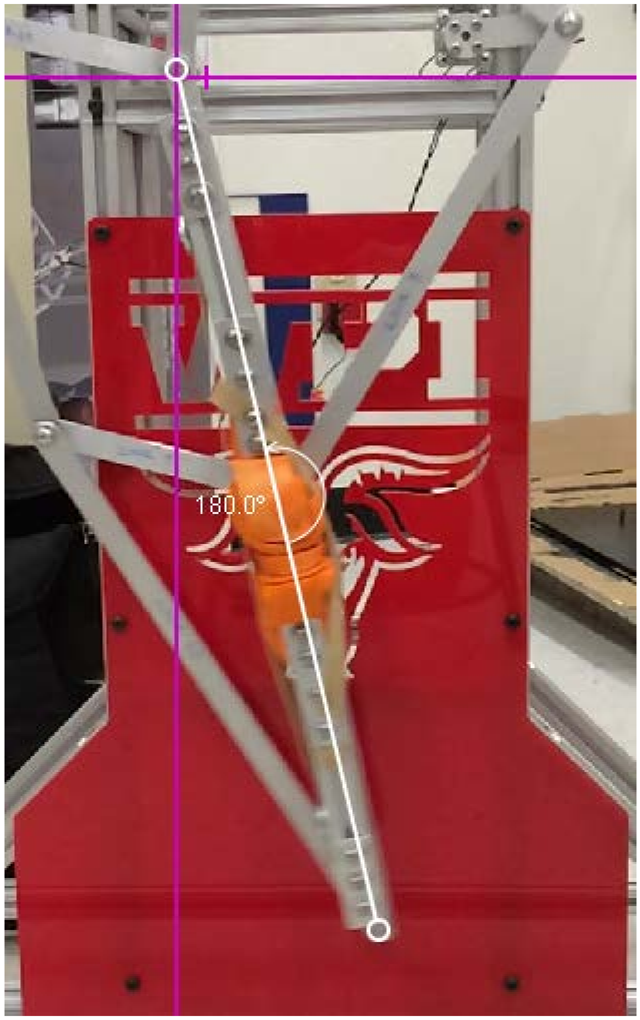


Figure 74: Measured prototype knee angle at maximum extension

- Does the prototype produce accurate trace curves of knee and ankle?

Using the Tracker program the joints representing the knee and ankle were traced over one complete cycle. Markers on the video highlight the position of the joint during the frame. Upon visual comparison between the trace curves obtained in OpenSim and Tracker, the trace curve of the knee appears to be the same while the ankle trace curve is off; this result was expected. Figure 75 and Figure 76 below show the comparison between knee and hip trace curves, respectively.

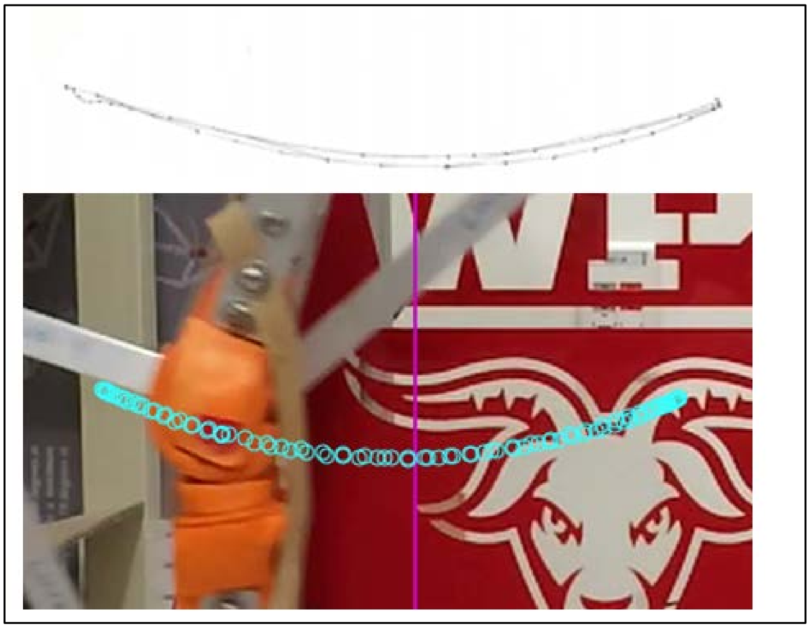


Figure 75: Trace curve of knee. (Top) OpenSim trace curve (Bottom) Prototype trace curve

Figure 76: Trace curve of ankle. (Top) OpenSim trace curve (Bottom) Prototype trace curve

10 Conclusions

The prototype passed many criteria during its testing: it doesn't jam, the knee doesn't hyperextend, the motor's torque is sufficient to run the machine, and it successfully shuts off in case of emergency. For these reasons, the team concludes that this prototype is a successful representation of the design concept.

While the prototype did fulfil much of the criteria, there are areas in which the design can be improved to perform better as a machine and more closely simulate the human gait. For example, the machine runs at 77 cycles per minute instead of the researched 66.5 cycles per minute that the average human walks. However, according to research detailed in Section 2.4, it is not necessary for testing devices to run at the actual gait speed. In fact, it is sometimes preferred to run at a higher speed in order to lessen testing time.

Additionally, while Theo Jansen's linkage does mimic the range of motion of the knee, it doesn't mimic the behavior of the knee bending over a cycle. As described in Section 2.1, the knee displaces roughly 15 degrees during the stance phase before the larger displacement during the swing phase (see Figure 5) for a graph of the knee angle over one cycle of the walking gait). Instead, Theo Jansen's linkage generates a more harmonic knee displacement over a cycle. Recommendations and solutions to this problem, among others, are detailed in Section 11.

The results of realizing this concept were generally expected. The team anticipated that this prototype would run similarly to the conceptual model. The simulations ran in SolidWorks and the proof of concept helped ensure that the physical prototype would assemble and perform as smoothly as possible. While there were some unexpected difficulties in assembly of the prototype (see Section 8.5), the team assessed them and implemented fixes by the deadline of the project.

In conclusion, the design successfully met the goal of the project. The team's prototype proves that this mechanism simulates the human gait by running a knee replacement device through the knee and femur angle displacements, and this design is an effective foundation for future iterations to eventually meet the goal of using this device to test knee replacements.

11 Future Recommendations

11.1 Allow the Mechanism to be Completely Customizable per Patient

One design factor that was not taken into account for this iteration of the prototype was the fact that not only do men and women have different stride lengths but also people of different heights and even the same height have different stride lengths. Each person is unique, therefore there is a wide spectrum of stride lengths that should be accounted for in designing a linkage to test knee replacements. How long until a female patient begins to feel discomfort? How long until a male patient begins to feel discomfort? How does stride length affect the forces applied to the knee replacement? These questions all need answering and the first step is to incorporate this into the design of the testing mechanism.

One such design option could be an adjustable ground link; one in which the tester can change the angle or distance of the ground node where the hip is located and lock it in place. Then, the tester could load up a linkage designed for that desired ground link size and test. This enables the device to test many different stride lengths and even to incorporate running, which occurs at more of an angle than walking. However, the main downfall of this is that it is not an easy task to dismount one linkage in exchange for another, and the cost of creating multiple linkages increases costs.

11.2 Apply Sensors to the Mechanism

While not imperative for this iteration of the project, applying sensors on the mechanism would allow the team to track motion and forces at select nodes, like the knee and ankle joints. For this iteration, the team used an image-based motion open-source tracking software called Tracker. It provided positional results for the knee and ankle that were sufficient for this iteration, but in future iterations, more exact results will be imperative. The reason being is that in order to properly determine how the knee replacement is withstanding wear and tear during testing, the knee needs to be undergoing the exact motion it would undergo while walking. The only way to know this is to have positional sensors that accurately indicate the angular displacement of the femur and tibia, femur swing, and ankle trace curve.

Once the team has tested and proved the knee is demonstrating all the desired kinematics, the team must then determine what the forces are both externally from the knee joint (loads from impact traveling up the tibia and reaction from the femur) and internally as the femur insert glides over the tibial spacer. Only then can the team determine if the measured forces correlate with the actual forces on a knee and how well the knee replacement responds to them as the number of cycles increases.

11.3 Apply Accurate Forces on the Knee Replacement

Applying accurate forces on the knee replacement improves results when testing how well it withstands wear and tear over time. The knee replacement itself must last years and there is no way for the body to lubricate the high-density polyethylene of the spacer component. Even though this component is rated for low friction, how long before it begins to erode and cause discomfort for the patient? The team can determine this by applying proper loads from the hip joint and impact loads to simulate a foot striking the ground during walking. One way to accomplish this is to bring the device closer to an anatomically correct walking leg by making the linkage full scale and attaching a foot to it. By doing so, as the foot strikes the ground it would generate a force up through the tibia and a reaction force traveling down the femur towards the knee. This combination of forces plays a significant role in determining how long the knee replacement lasts and should be implemented in future iterations.

11.4 Recommendations for Ordering Components

11.4.1 Double Check Quotes before Placing Orders

In the future when ordering components, keep these few things in mind. First, always double check quotes before placing an order. One of the difficulties the team experienced getting different frame designs quoted was that it did not catch a mistake within the quote. There was a tooling charge for component 7061, a ¼-20 tapped hole at the end of the 80/20 components designed to accommodate end fasteners used to fasten the extrusions together. When analyzing the quotes the team got for the same frame accommodating different end fasteners with the intention of identifying which style end fasteners would be cheaper, it did not identify that component 7061 was missing. Since that style was cheapest, the team placed an order. The correction to the quote was made the next day, but that style frame became more expensive with the correction. This mistake falls on the team for not catching the error in time and not alerting WPI’s purchasing department as soon as it was discovered. People make mistakes, but this one could have been prevented had the team checked item-for-item and service-for-service to assure everything was accounted for.

11.4.2 Component Tolerances

Always check with a company before ordering components designed to fit together in an assembly. In this case, the team designed a frame made using 80/20 aluminum extrusions and fasteners. The extrusions were cut to exact size with no clearance built in because the extrusions were cut to size using standard shop equipment like a band saw, table saw, miter saw, etc. There are no guarantees that the components are cut to the exact size and clearance for these fluctuations should always be accounted for. Luckily, assembling the frame was nearly seamless, with only one component needing to be muscled in place. This could have been avoided by asking the 80/20 supplier, Air Inc. what their tolerance for cut lengths are. The team could then account for them and avoid the need to muscle a component in place.

11.5 Improving Upon the Frame

11.5.1 Enclosing the Linkage

Perhaps the most important modification to the frame’s design is enclosing the linkage. This prevents people viewing the linkage from sticking their hands in and potentially injuring fingers, prevents people from walking by and being kicked in the knee or groin by the device, and overall just prevents accidental injuries. A rough mockup of the concept is shown below in Figure 77.

Figure 77: Cabinet-style frame design

While the frame is enclosed with glass, acrylic, or some other clear material that allows viewers to observe the linkage in motion, the frame must still provide access to the device. Therefore, a clear acrylic door is shown attached on the front of the frame using the two black hinges shown at the left-hand side of the frame.

11.5.2 Reducing the Slotted Knee Joint's 3rd Degree of Freedom

Once the linkage was fully assembled, the team realized a problem that could only be identified through experience with a physical slot. The slotted joint used to give the knee its rotational and translational gliding motion had a third degree of freedom not discussed when it is shown in a two-dimensional plane. That third degree of freedom caused the lower section of the linkage by the ankle joint to collide as the knee transitioned from flexion to extension. In order to solve this, a point of contact with the linkage was created. Ideally, this slot shown in Figure 78 would be attached to the tibia subassembly, close to the knee joint. The reason being is that just underneath the axle is where the moment is created that allows the tibia to travel towards the frame, causing a collision. Placing this feature below the axle stabilizes the knee. However, the ideal solution would be a slot on both the medial and lateral sides of the knee to completely lock the femur, tibia, and knee in their respective planes.

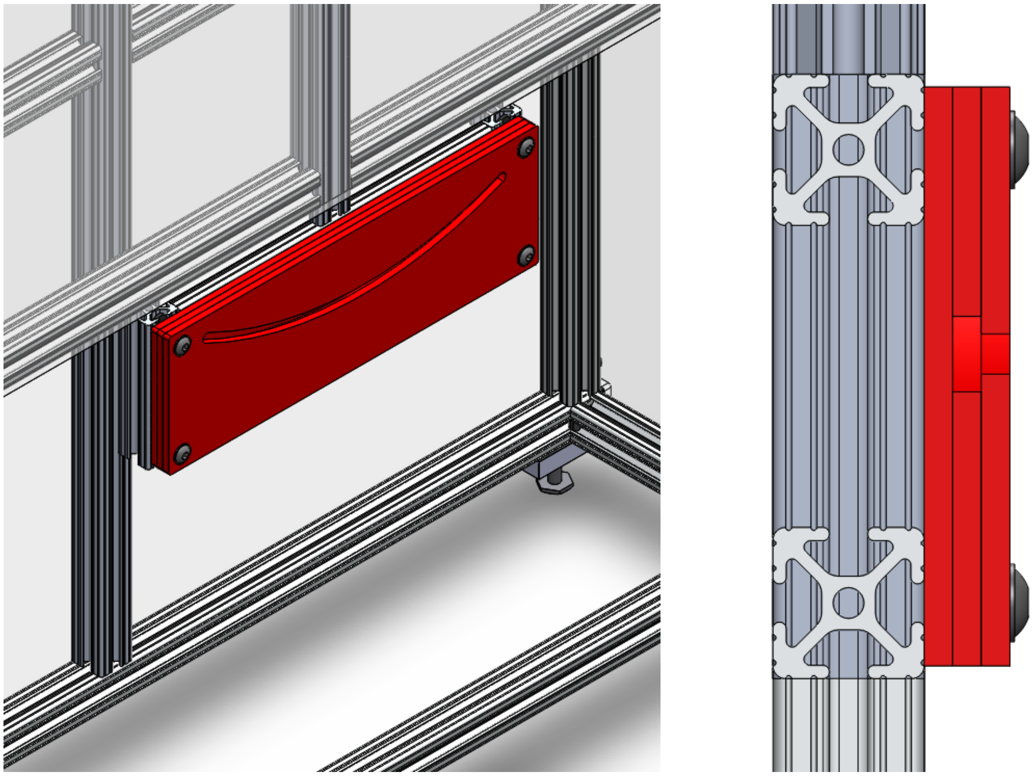


Figure 78: (a) shown at left is an isometric view of the slot intended to reduce the knee joint's 3rd degree of freedom; (b) shown at right is a cross-sectional view of how the slot is assembled.

This feature is composed of an 80/20 window frame style assembly that allows for t-nuts to be inserted into the 80/20's guide channels without disassembling other frame components. It uses three sheets of laser cut acrylic or sheet metal fastened together using four ¼"-20 screws and econ t-nuts. The first sheet, located on the left of Figure 78b, acts as a backboard for the bolt head or fastener connected to the tibia link. The middle sheet has a slot that acts as a track with a diameter that accommodates the head of the bolt or fastener, allowing it to move along its intended path. The outermost sheet on the right side of Figure 78b has a slot that accommodates the barrel diameter of the bolt or fastener.

One conceptual idea to implement this design is to use a bolt with a round head and fasten it in the track. Then it would be fastened to the tibia link (link 12) using a nut and washer on the inside, and a washer and locknut on the outside. This would completely secure the bolt to the linkage and to the slot feature so that the tibia would only move in its intended two degrees of freedom.

11.6 Drafting

Throughout most of this project, the team used Dassault Systèmes SolidWorks 2014 3D computer-aided drafting software to design the frame, linkage, etc. The decision was made to use SolidWorks because of its ability to easily suppress features, components, and change dimensions using its configurations feature. This allowed the team to easily adjust frame concepts and 80/20 components with subtle differences, without saving them as new parts. However, SolidWorks has limited finite element analysis capabilities. While it can plot trace curves, angular displacement, and the like, it is not as user-friendly as its modeling, assembly, and drawing platforms. This became most apparent when the team struggled to get the 3D printed femur bone and tibia bones to stay together as a normal human knee does. The team used elastic rubber bands to hold the physical knee together, but SolidWorks cannot simulate these.

The team used a Path Mate to hold the knee replacement together in SolidWorks and it displayed all the motion of a human knee. However, when SolidWorks Motion Analysis was turned on, the assembly did not work because Motion Analysis cannot use a freely constrained Path Mate. Path Mates have different constraints that can be applied; the team needed it to be set to “free” to prevent over-defining the assembly.

11.7 Alternate Axle Components for Use in Pin Joints

11.7.1 The Use of Screw Binding Posts for Axles

To keep the cost of this project down, the team elected to use aluminum screw binding posts as axles. While a cheap solution at first, the manufacturing process used to make them creates a flared edge at both the top of the barrel post and at the bottom by the cap screw (shown in Figure 79).

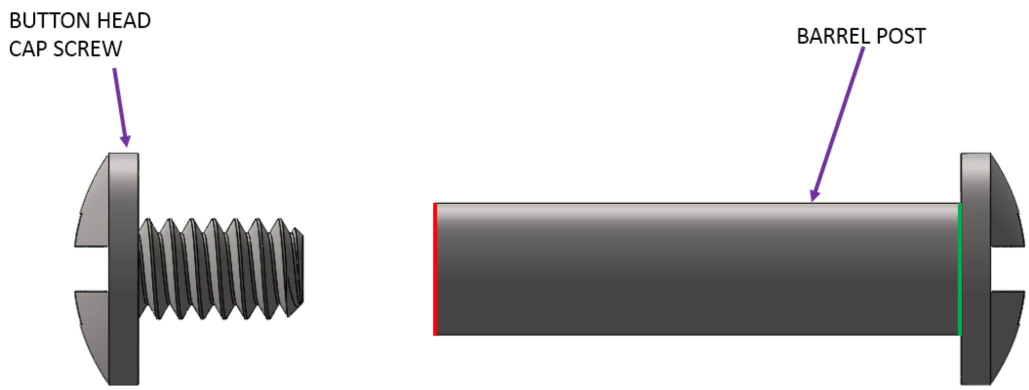


Figure 79: Image of aluminum screw binding post. The red line denotes the flare at the bottom of the barrel near the cap screw and the green line denotes the flare at the top of the barrel post.

Because the flared sections have different diameters than the rest of the barrel, there are stress concentrations throughout the hole where the flares contact the hole face while the rest of the barrel does not. In Figure 80, shows a hole designed for a slip fit between the barrel and hole face, meaning that the hole is approximately one thousandth of an inch larger than the measured diameter of the barrel. The tight clearance allows for minimal additional movement outside of the intended movement. However, due to the flare shown below, the barrel no longer fits squarely within the hole and the point of contact becomes a point of stress concentration, which would previously be dispersed through the entire hole-axle meeting surface. To counter this, the team reamed holes one thousandth larger than the flared diameter and heavily greased the barrel with white lithium grease to reduce friction.

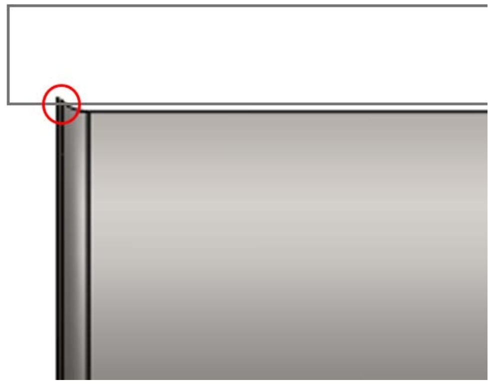


Figure 80: Image of the screw binding post's barrel in a hole (indicated by the gray box in the top of the image). The red circle identifies a stress concentration point caused by the barrel's flared end.

While this combatted the friction and stress concentrations, another problem arose from using the binding posts. In order to firmly secure the posts in place, the cap screw must be tightly screwed into the barrel component. This clamping force on the joint creates a friction large enough that the linkage does not move and the motor axle spins within the crank hub. After undergoing several manually operated revolutions, the joint loosens to the point where the motor can drive it. However, the cap screw also loosens with the rest of the joint, which is why the friction force loads reduce. To securely lock the posts in place without tightening them to the point where the joint has no motion, the team applied Loctite thread locker inside the barrel (denoted in cyan in Figure 81). The Loctite adhesive creates a semi-permanent hold on the threads, securing them in place for the team's purposes.

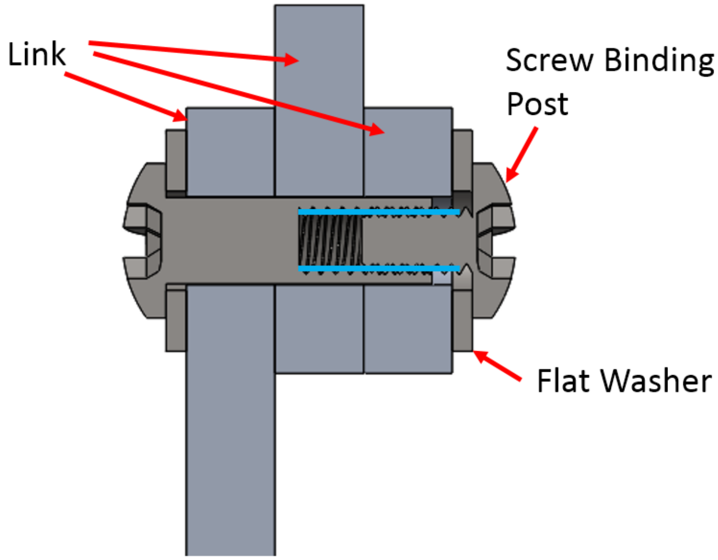


Figure 81: Cross section of a joint in which the screw binding post acts as an axle about which links rotate. The cyan line denotes the Loctite adhesive used to hold the posts together.

Given the experience with using screw binding posts as axles, which compromise the effectiveness of the design, the team has a few recommendations for better options.

11.7.2 The Use of Oil-Impregnated Bushings and Slip Fit Machined Pins for Axles

Two effective ways to reduce friction in the linkage joints are to use oil-impregnated bushings or rolling element bearings. Oil-impregnated bearings, like the screw binding posts the team used in this iteration, operate via a slip fit. The main difference is that instead of the slip fit being with the aluminum link, which will wear down over time due to aluminum being soft, the bushing is inserted into the hole and creates a lubricated slip fit with a machined pin. This ensures that both the bushing and pin remain true (straight, constant diameter throughout) while also retaining the integrity of the link. Using a harder material like steel would also help maintain the integrity of the link's hole.

Figure 82: Image of different style bronze oil-impregnated bushings from www.woodworkingonline.com

11.7.3 The Use of Rolling-Element Bearings and Machined Pins for Axles

The other alternative, rolling-element bearings, are commonly used in standard pin joints from exercise equipment to wind turbine main shafts. They eliminate the need for a slip fit, come lubricated, and have pre-determined equations to calculate cycles to failure. The main significance with these is that while they are more expensive, eliminating the slip fit pin joint reduces the amount of friction on the entire system, meaning less of the motor's output torque is lost to internal forces. Additionally, calculating the number of cycles to failure allows the designer to determine which style and size bearing would last the number of cycles needed to properly test a knee replacement. As for what pin to use, a steel machined pin provides the hardness needed to withstand wear while also maintaining a true diameter. This solution eliminates the problems the team encountered with the screw binding posts. The main downside to rolling-element bearings is that they are expensive (listed at around $5.00 on McMaster Carr's website for ball bearings designed for 0.250 inch shafts).

Figure 83: Image of a rolling-element ball bearing from McMaster Carr's website

11.8 Possible Alternative Designs

11.8.1 Cam-Driven Mechanism

The two design alternatives discussed in this report make use of a crank link which drives the linkage through a walking motion. However, later into the project, a design alternative was discussed among group members which was driven by a cam and a follower. While this design was formulated too late to be considered as a design concept, it may be useful to others who wish to accomplish the same goal of testing knee replacements.

Cams are useful in designing machines because they can specify virtually any output function, whereas linkages are limited to certain motions corresponding to a variety of configurations. However, there are many more considerations in designing a cam, including follower types, method of keeping contact with the cam, and manufacturing methods. They require more extensive design to fully realize the cam, and they can be difficult to manufacture to the specific dimensions that it requires. However, the result is an extremely useful and versatile tool for machines [4].

The particular reason a cam could be useful for this application because it can be designed to recreate the knee angle very closely over the course of its cycle. In 10, the team detailed the problem of the prototype's inability to recreate the actual knee angle vs time chart. The cam solution solves this problem.

A sketch of the design concept is displayed below in Figure 84. Note how the cam's motion translates to the motion of the rocker, which rotates the tibial component of the knee replacement device around its center of rotation. It is likely that there will need to be a slot and tendon-like materials to solve the same knee replacement impacting problem which the team encountered with Theo Jansen's linkage, as described in Joints. However, if this slot allows the femur to move freely, it opens up the opportunity to also test a knee replacement device's performance from the forces of walking. If a spring or hydraulic cylinder is introduced to create a downwards force, it can essentially recreate the weight of the human body pushing downward. This spring or hydraulic cylinder would likely also be driven by a second cam which produces a displacement curve similar to the force curve humans experience while walking. These two cams can still be driven by one motor with the use of a belt or chain.

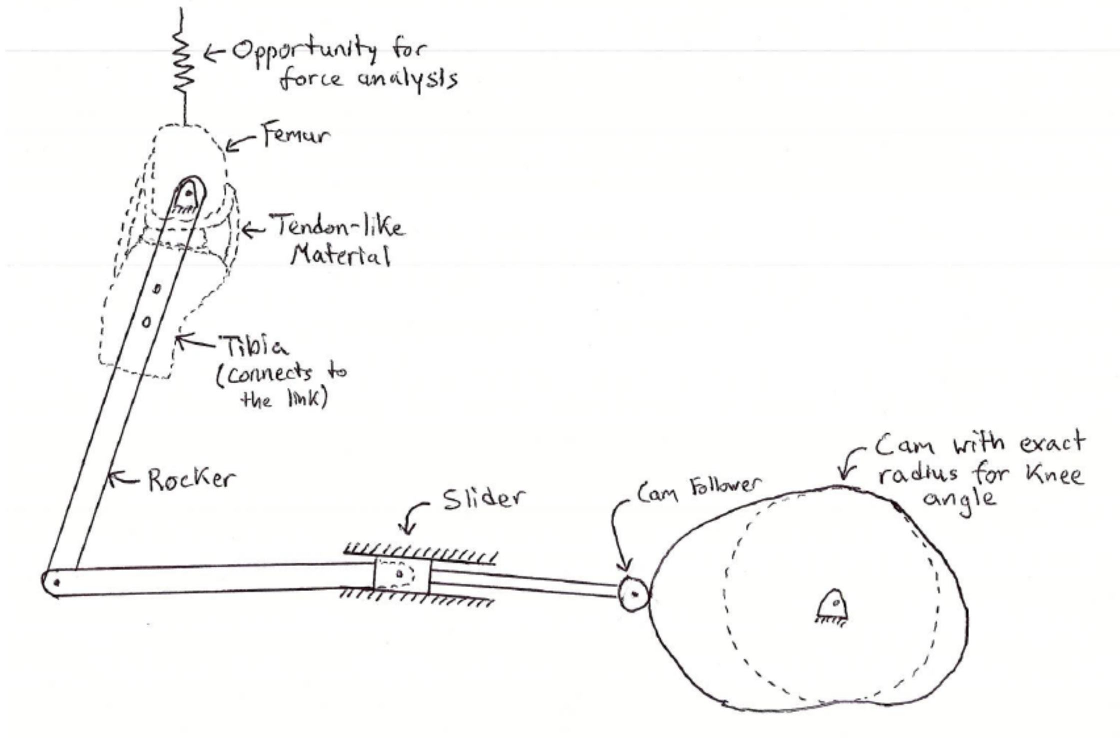


Figure 84: Sketch of the Cam-Driven Mechanism Concept

This design alternative has the potential to create a very accurate simulation of the human gait, but the difficulty in design and manufacturability may render this design infeasible with the team's limited resources.

11.8.2 Sixteen or Eighteen Bar Linkage Design

One of the main shortcomings the team's current mechanism has is that it does not exhibit the exact motion of a full human leg. It is driven by a fourbar in which the femur is pushed and pulled by a link on the backside where the hamstring would be, and the tibia is pushed and pulled by a link where the quadriceps are located. Human anatomy does not work like this.

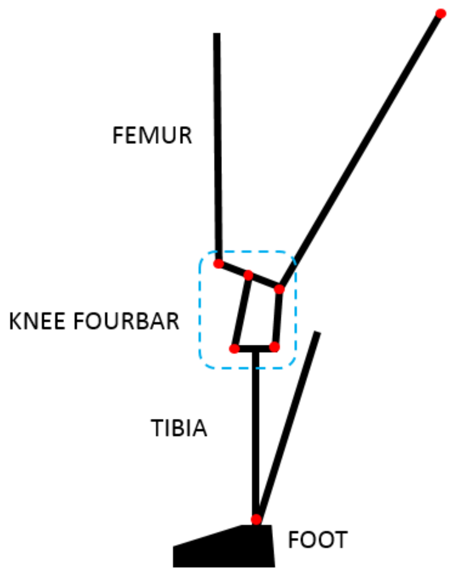


Figure 85: Rough incomplete sketch of anatomically correct sixteen or eighteen bar lower human extremities mechanism.

As a way to make the linkage more anatomically correct, this sixteen or eighteen-bar mechanism, depicted in Figure 85, would start with the ground link located around the belly button. From here, the lower back and abdominal muscles exert work in unison with the quadriceps and pelvic muscles to generate the femur's swinging motion. This design intends to use a series of links powered by a single motor to perform the actions of these muscles. However, the femur also has a gliding node at the hip joint, which is a socket-style joint. The linkage incorporates a series of links connected to the upper section of the linkage (abdominals and lower back) to perform the actions exhibited by the quadriceps (which exert a pushing force during extension) and hamstring (which exert a pulling force during flexion). Additionally, a fourbar mechanism like the one shown in Figure 86. To finish the pulling motion enacted by the hamstring, a link that performs the calf muscle's duties would be attached to the ankle joint and link back up to the hamstring portion of the mechanism.

Figure 86: Fourbar knee mechanism as shown on www.heritage-medical.com

11.8.3 Camshaft Articulated Motion Design

Another alternative to the complex system of links in the sixteen or eighteen bar design is a camshaft driven human leg. The leg itself has the femur fully within a functioning hip socket, which aims to demonstrate a more accurate gliding motion of the hip joint. The knee joint, like the previous design, uses a standard knee fourbar mechanism to get the rotational and translational motion a real human knee demonstrates. The tibia is then connected to the bottom of the knee fourbar and has a spring-mass-damper system that acts as the shock-absorbing component of the ankle while also providing an opportunity to measure the forces of the foot (mass) striking the ground.

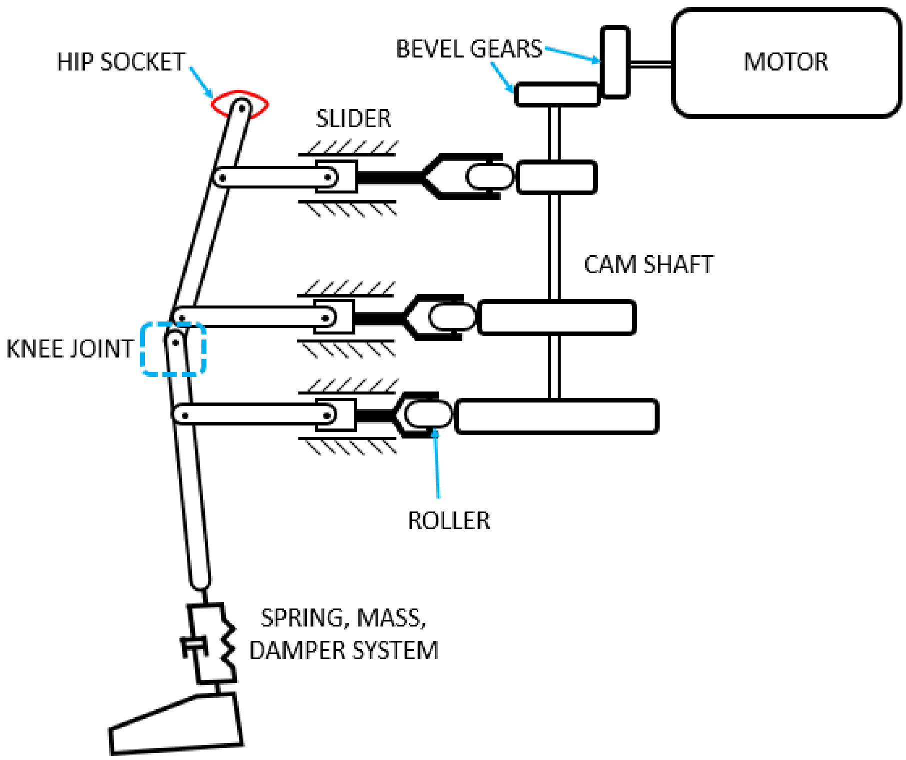


Figure 87: Camshaft articulated human leg design

The mechanism, shown in Figure 87, is powered by a single motor with a speed control switch. The speed control switch allows viewers to slow the motion of the mechanism down, which makes it easier for viewing. It also allows the user to set the speed to the expected speed the patient would be walking with. This ensures more realistic results when testing the knee replacements. Attached to the motor are a series of two bevel gears, which transfer the rotational motion to a vertically oriented camshaft. The each cam along the shaft has the exact radius of curvature needed to generate the desired trace curve at the corresponding point it is located at on the leg linkage. To limit the number of degrees of freedom, each cam is outfitted with a roller, slider, and link with the ability to rotate as the leg moves, ensuring it exhibits the desired motion.

Bibliography

[1] (2006, November 2). *Skeletal Structure*. Available: https://www.nauticus.org/activities/bones/images/skeleton1.jpg

[2] http://www.josephbermanmd.com/anatomy-of-the-knee/meniscus-cartilage/

[3] http://www.innerbody.com/image/musc09.html

[4] L. Jasmine. (2013). *Walking Abnormalities*.

[5] D. Thompson. (2002). *Kinematics of Human Gait*.

[6] R. L. Norton, Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines, Fifth Edition ed.: McGraw-Hill, 2012.

[7] J. Richards, *Tidy's physiotherapy*, "Biomechancis," pp. 331-368, 2013.

[8] J. Johnson. (2013). The Average Walking Distance.

[9] R. F. University of California. (2011). *Walking Fit*.

[10] (2010). OpenSim - See the Work.

[11] T. Jansen, *Theo Jansen: The Great Pretender*. Rotterdam: 010 Publishers, 2007.

[12] A. Ghassaei, P. Choi, and D. Whitaker, "The Design and Optimization of a Crank-Based Leg Mechanism," ed, 2011.

[13] D. Giesbrecht, C. Q. Wu, and N. Sepehri, "Design and Optimization of an Eight-Bar Legged Walking Mechanism Imitating a Kinetic Scupture, "Wind Beast"," *Canadian Society for Mechanical Engineering*, vol. 36, pp. 343-355, 2012.

[14] A. J. Ingram, "Numerical kinematic and kinetic analysis of a new class of twelve bar linkage for walking machines," Rand Afrikaans University, Johannesburg2004.

[15] K. Komoda and H. Wagatsuma, "A proposal of the extended mechanism for Theo Jansen linkage to modify the walking elliptic orbit and a study of cyclic base function," Kyushu Institute of Technology.

[16] S. Nansai, N. Rojas, M. R. Elara, and R. Sosa, "Exploration of Adaptive Gait Patterns with a Reconfigurable Linkage Mechanism," presented at the International Conference on Intelligent Robots and Systems, Tokyo, 2013.

[17] National Institute of Health. *Knee Replacement*. Available: http://nihseniorhealth.gov/kneereplacement/whoneeds/01.html

[18] A. Carr, O. Robertsson, S. Graves, and A. Price, "Knee replacement," *Lancet*, vol. *379*(9823), pp. 1331-1340, 2012.

[19] A. Liddle, E. Pegg, and H. Pandit, "Knee replacement for osteoarthritis," *Maturitas*, vol. 75, pp. 131-136, 2013.

[20] J. W. Bijlsma, F. Berenbaum, and F. P. Lafeber, "Osteoathritis: an update with relevance for clinical practice," *The Lancet,* vol. 377, pp. 2115-2126, 2011.

[21] http://orthoinfo.aaos.org/topic.cfm?topic=a00212

[22] American Academy of Orthopedic Surgeons. (AAOS). (2010). *Knee Replacement Implants*. Available: http://orthoinfo.aaos.org/topic.cfm?topic=a00221

[23] http://totalknee.org/testimonials/diana-gabaldons-new-knees/

[24] J. Bellemans, V. H., and J. Vanlauwe, "(Iv) total knee replacement," *Current Orthopaedics,* vol. 19(6), pp. 446-452, 2005.

[25] Centers for Disease Control and Prevention (CDC). Inpatient Surgery [Online]. Available: http://www.cdc.gov/nchs/fastats/inpatient-surgery.htm

[26] J. D. DesJardins, P. S. Walker, H. Haider, and J. Perry, "The use of a force-controlled dynamic knee simulator to quantify the mechanical performance of a total knee replacement designs during functional activity.," *Journal of Biomechanics,* vol. 33, 2000.

[27] International Organization for Standardization, "Implants for surgery- Wear of total knee joint prostheses," vol. 14243-1, ed, 2009.

[28] L. P. Maletsky and B. M. Hillberry, "Simulating Dynamic Activities Using a Five-Axis Knee Simulator," *Biomechanical Engineering,* vol. 127, 2005.

[29] R. B. Durairaj, J. Shanker, P. V. Kumar, and M. Sivasankar, "A Study on Development of Knee Simulator for Testing Artificial Knee Prosthesis," *Emerging Trends in Science, Engineering, Technology,* 2012.

[30] P. S. Walker, G. W. Blunn, J. P. Perry, C. Bell, and S. Sathasivam, "Methodology for long-term wear testing of total knee replacements," *Clinical Orthopaedics and Related Research,* pp. 290-301, 2000.

[31] http://www.thingiverse.com/thing:340254

[32] J. Elsner, S. Portnoy, F. Guilak, A. Shterling, and E. Linder-Ganz, "MRI- Based Characterization of Bone Ananatomy in the Human Knee for Size Matching of a Medial Meniscal Implant," *ASME,* vol. 132, 2010.

[33] Cabrillo College, "*T*racker: Video Analysis and Modeling tool," ed, 2015.

Appendices

Appendix A: Selecting the Hrones and Nelson Atlas Fourbar

These page numbers correspond to the page numbers of the PDF atlas the team used, not the page numbers in the atlas itself.

Key:

Eliminated in Round 1

Eliminated in Round 2

Eliminated due to size

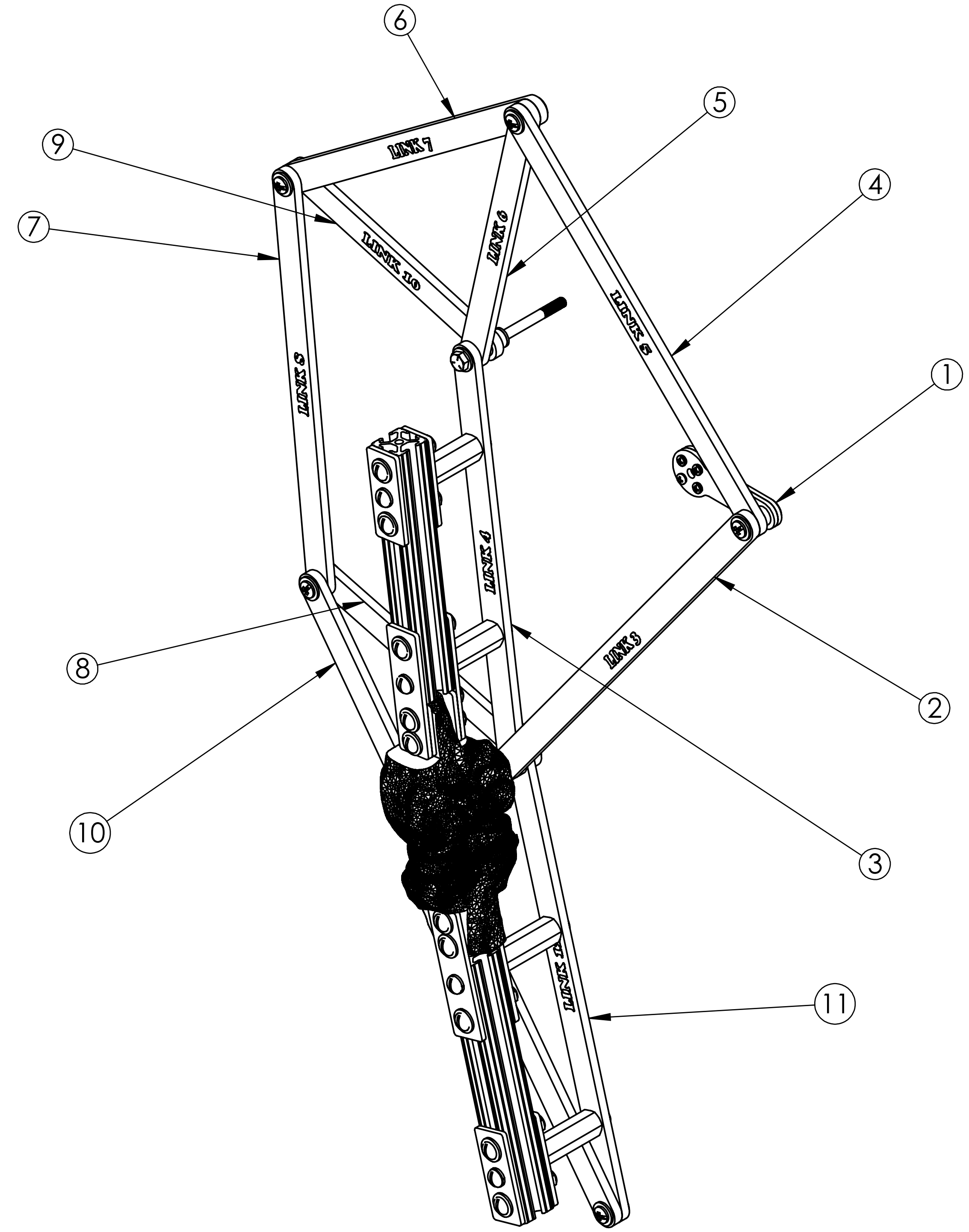
- Pg 24 6th node (mirrored)
- Pg 29 6th node (mirrored)
- Pg 34 6th node (mirrored)
- Pg 39 6th node (mirrored)
- Pg 44 6th node (mirrored)
- Pg 45 5th node
- Pg 47 7th node (mirrored)
- Pg 49 5th node
- Pg 49 6th node (mirrored)
- Pg 57 8th node
- Pg 59 6th node
- Pg 62 7th node (mirrored)*
- Pg 69 6th node
- Pg 84 6th node*
- Pg 104 7th node
- Pg 119 7th node (mirrored)*
- Pg 120 6th node
- Pg 126 8th node (mirrored)*
- Pg 127 8th node (mirrored)
- Pg 132 10th node
- Pg 137 9th node
- Pg 159 7th node*
- Pg 179 7th node*
- Pg 204 7th node
- Pg 235 7th node*
- Pg 254 8th node
- Pg 259
- Pg 260
- Pg 284

- Pg 285
- Pg 316
- Pg 349
- Pg 350
- Pg 385
- Pg 406
- Pg 428
- Pg 434
- Pg 506
- Pg 517
- Pg 518
- Pg 523
- Pg 538
- Pg 548
- Pg 563
- Pg 572
- Pg 578
- Pg 588
- Pg 592
- Pg 593
- Pg 604
- Pg 612
- Pg 618
- **Pg 623 (final choice)**
- Pg 633
- Pg 652
- Pg 653
- Pg 663
- Pg 673
- Pg 692
- Pg 693
- Pg 713

Appendix B: Detailed Drawings of the Final Linkage Subassembly

The following pages depict detailed drawings of each component in the final design of the linkage, including all necessary dimensions.

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	KTKR-LK-02-02500	0	2.50" CRANK LINK	ALUMINUM	1
2	KTKR-LK-03-14000	0	LINK 3: 14.00" LONG	1/4" ALUMINUM	1
3	KTKR-FEMUR	0	FEMUR SUBASSEMBLY	ALUMINUM, STEEL, ABS	1
4	KTKR-LK-05-11333	0	LINK 5: 11.33" LONG	1/4" ALUMINUM	1
5	KTKR-LK-06-08167	0	LINK 6: 8.167" LONG	1/4" ALUMINUM	1
6	KTKR-LK-07-10250	0	LINK 7: 10.25" LONG	1/4" ALUMINUM	1
7	KTKR-LK-08-11402	0	LINK8: 10.402" LONG	1/4" ALUMINUM	1
8	KTKR-LK-09-07085	0	LINK 9: 7.085" LONG	1/4" ALUMINUM	1
9	KTKR-LK-10-06725	0	LINK 10: 6.725" LONG	1/4" ALUMINUM	1
10	KTKR-LK-11-16945	0	LINK 11: 16.945" LONG	1/4" ALUMINUM	1
11	KTKR-TIBIA	0	TIBIA SUBASSEMBLY	ALUMINUM, STEEL, ABS	1
12	WF-250-STZ-SAE-0	N/A	1/4" FLAT WASHER	STEEL	13
13	92463A406	N/A	1/4" DIA x 1" LG BINDING POST	ALUMINUM	2
14	92463A405	N/A	1/4" DIA x 3/4" LG BINDING POST	ALUMINUM	3
15	92463A403	N/A	1/4" DIA x 1/2" LG BINDING POST	ALUMINUM	1
16	N/A	N/A	1/4" ID, 1/2" OD x 1/4" LG NYLON SPACER	NYLON	3
17	00671	N/A	1/4"-20 x 3.5" HEX HEAD CAP SCREW	STAINLESS STEEL	1
18	N/A	N/A	FIBER WASHER FOR 1/4" DIA.	FIBER	1



NOTES:
1. INSTALL ALL COMPONENTS AS SHOWN USING HARDWARE INDICATED IN DRAWING.
2. USE WHITE LITHIUM GREASE TO GREASE THE AXLES BEFORE INSTALLING AND TO GREASE THE LINK COINCIDENT SURFACES.
3. APPLY LOCTITE THREADLOCKER IN BARREL OF SCREW BINDING POSTS TO SECURE THREADS IN PLACE. KEEP NEAT AND DO NOT GET ON LINKS.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM, STEEL, ABS
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

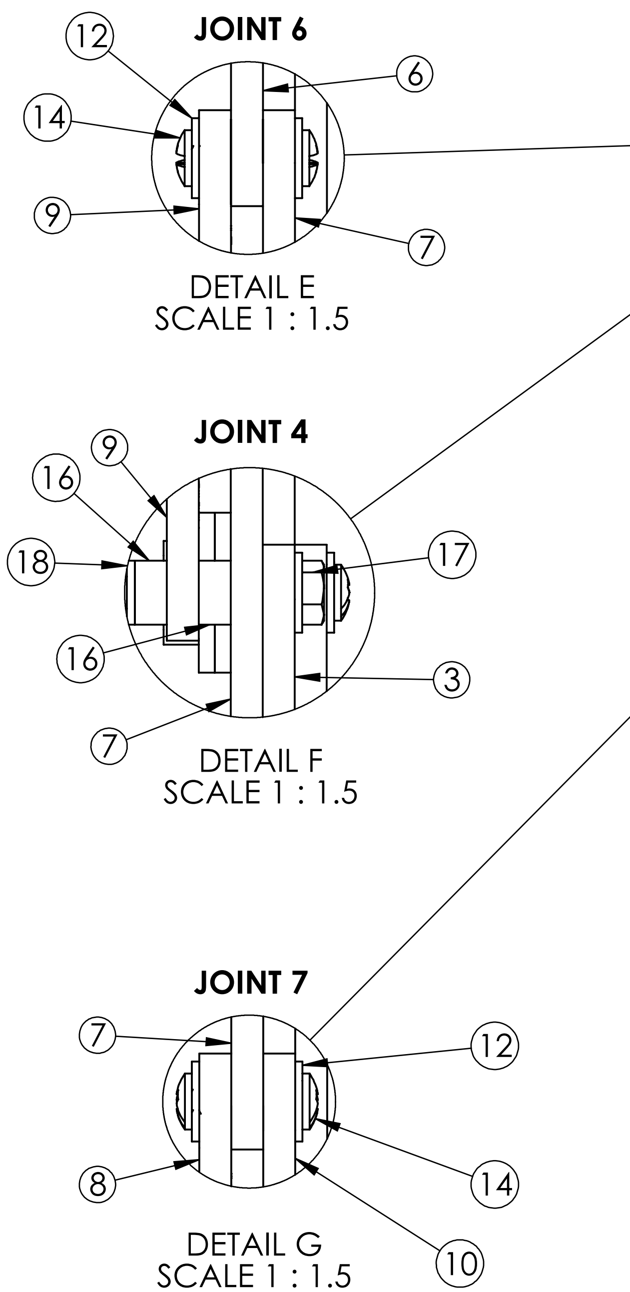
TITLE:
12 BAR KNEE TESTER LINKAGE

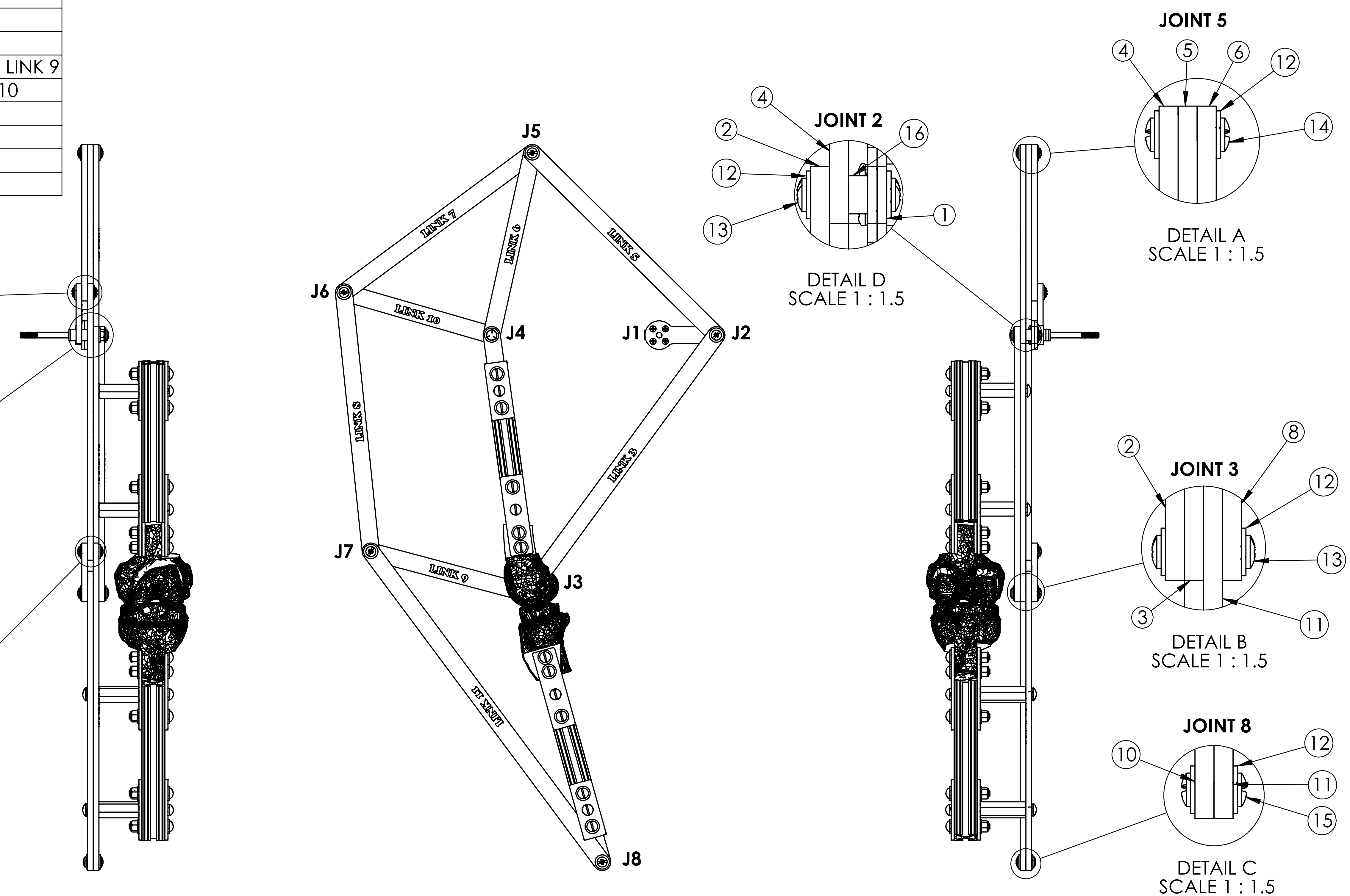
SIZE B | DWG. NO. KTKR-12-BAR | REV 0

SCALE: 1:4 | WEIGHT: 4.48 | SHEET 1 OF 2

TABLE OF JOINTS

NUMBER	HOLDS TOGETHER:
J1	ATTACHES CRANK TO MOTOR
J2	CRANK, LINK 3, LINK 5
J3	LINK 3, FEMUR SUBASSY, TIBIA SUBASSY, LINK 9
J4	FEMUR SUBASSY, LINK 6, SPACER, LINK 10
J5	LINK 5, LINK 6, LINK 7
J6	LINK 7, LINK 8, LINK 10
J7	LINK 8, LINK 9, LINK 11
J8	LINK 11, TIBIA SUBASSY





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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: ALUMINUM, STEEL, ABS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

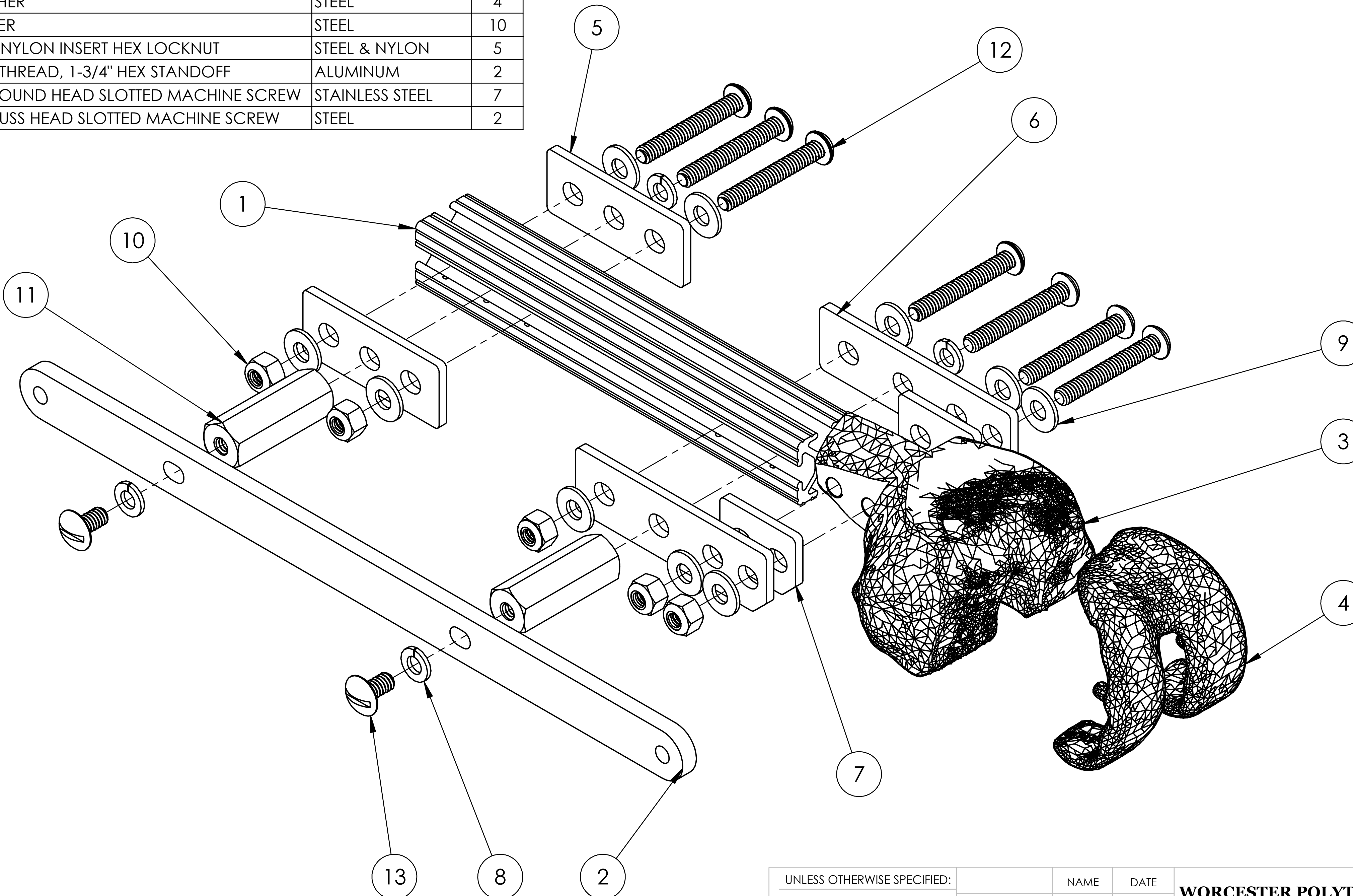
TITLE:

12 BAR KNEE TESTER LINKAGE

SIZE: B | DWG. NO.: KTKR-12-BAR | REV: 0

SCALE: 1:5 | WEIGHT: 4.48 | SHEET 2 OF 2

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	1010-07-BONE	0	1.0" x 1.0" EXTRUSION; 7" NOM WITH 17/64 TAPPED HOLES	6105-T5 ALUMINUM	1
2	KTKR-LK-11402-0	0	LINK 4 & 8: 10.402" LONG	STEEL	1
3	KTKR-RC-001-A	1	FEMUR BONE	HIGH DENSITY ABS	1
4	KTKR-RC-003-A	0	FEMUR INSERT	HIGH DENSITY ABS	1
5	KTKR-CB-001-A	0	8020 END MTG BRKT	1/8" ALUMINUM	2
6	KTKR-CB-002-A	0	BONE CONNECTING BRKT	1/8" ALUMINUM	2
7	KTKR-CB-003-A	0	FEMUR BONE MTG BRKT SPACER	1/8" ALUMINUM	2
8	WS-250-STZ-SAE-0	N/A	1/4" LOCK WASHER	STEEL	4
9	WF-250-STZ-SAE-0	N/A	1/4" FLAT WASHER	STEEL	10
10	90630A110	N/A	1/4"-20 THREAD NYLON INSERT HEX LOCKNUT	STEEL & NYLON	5
11	91780A976	N/A	FEMALE 1/4"-20 THREAD, 1-3/4" HEX STANDOFF	ALUMINUM	2
12	SE-25020-1750-BSS-S0	N/A	1/4"-20 x 1.75" ROUND HEAD SLOTTED MACHINE SCREW	STAINLESS STEEL	7
13	SE-25020-0500-TSZ-S0	N/A	1/4"-20 x 1/2" TRUSS HEAD SLOTTED MACHINE SCREW	STEEL	2



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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ALUMINUM, STEEL, ABS

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

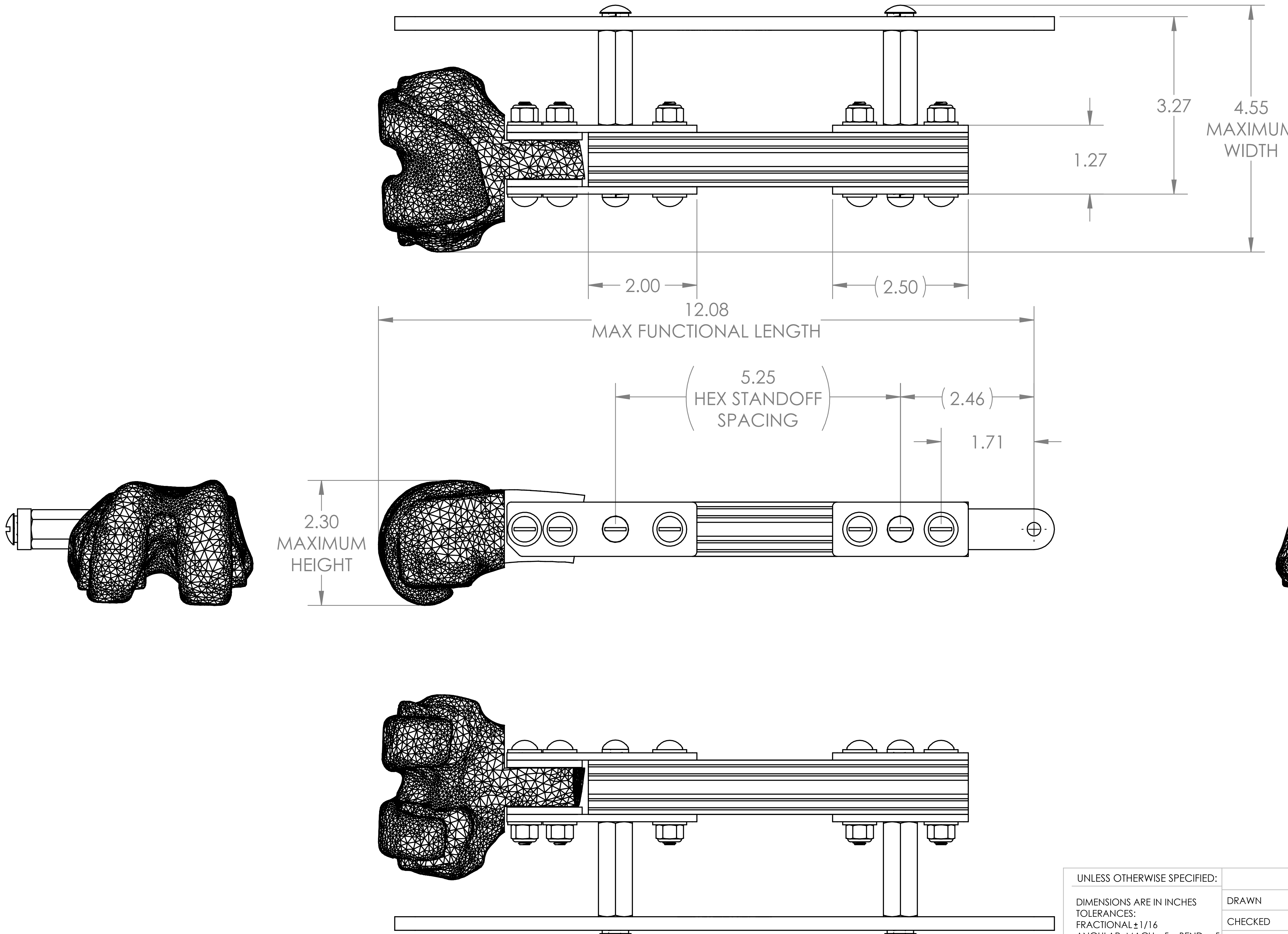
TITLE:

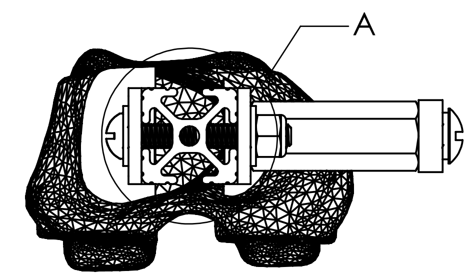
FEMUR SUBASSEMBLY

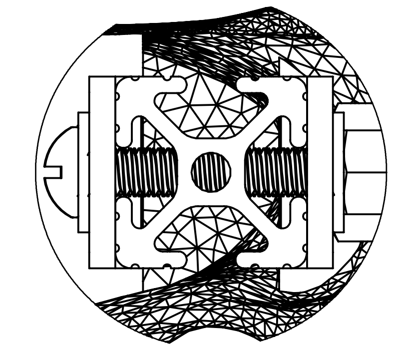
SIZE B | DWG. NO. KTKR-FEMUR | REV 0

SCALE: 3:5 | WEIGHT: 1.36 | SHEET 1 OF 2

INSTALLATION:
INSTALL ALL HARDWARE AS SHOWN TO ENSURE THE SUBASSEMBLY REMAINS COMPLETELY RIGID WHILE IN OPERATION. APPLY LOCTITE TO HEX STANDOFFS IF NECESSARY.





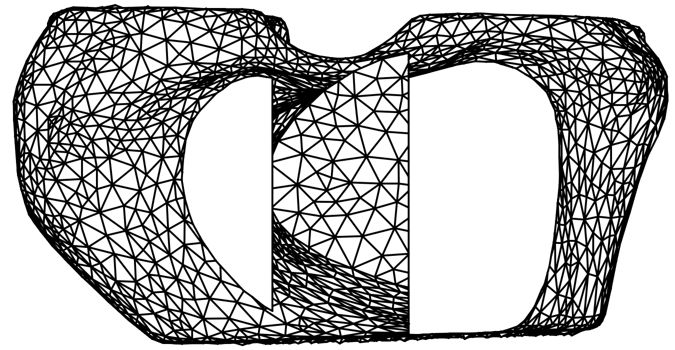


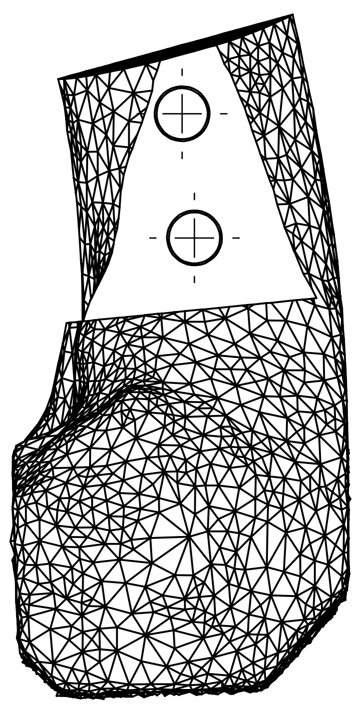
DETAIL A
SCALE 1 : 1

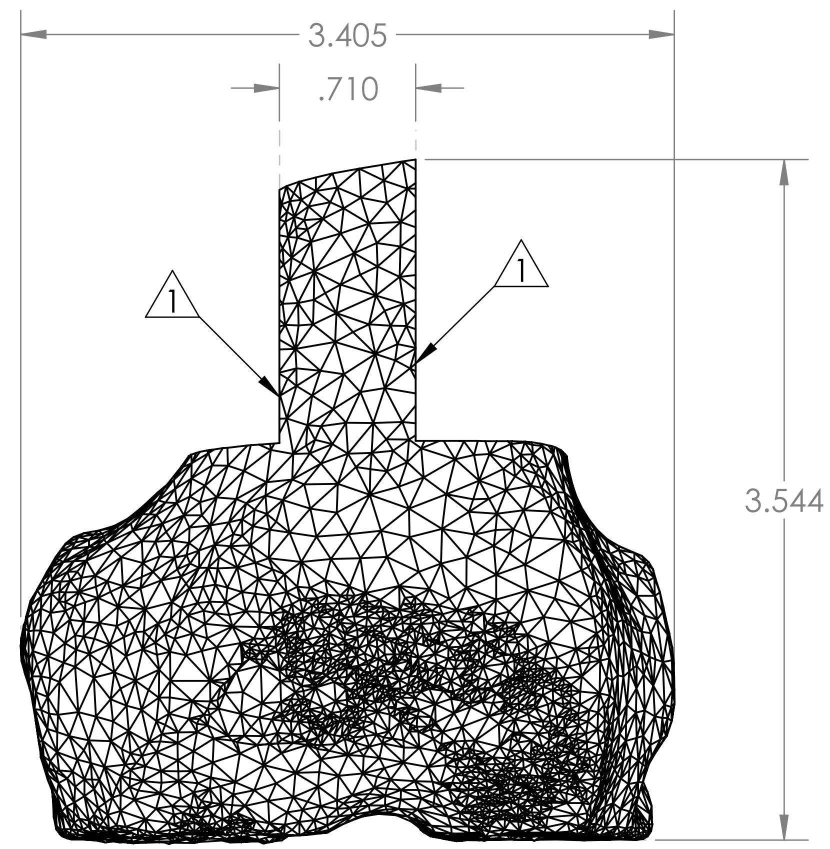
NOTES:
1. MISSING DIMENSIONS ARE NON-CRITICAL OR CANNOT BE CONTROLLED AT THIS LEVEL.
2. ASSEMBLE COMPONENTS AS SHOWN IN DRAWING VIEWS.

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	WORCESTER POLYTECHNIC INSTITUTE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/16 ANGULAR: MACH ±.5 BEND ±.5 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.015	DRAWN	JARED BRETON	3/22/2015	TITLE:
	CHECKED			FEMUR SUBASSEMBLY
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL ALUMINUM, STEEL, ABS	COMMENTS:			SIZE B
FINISH NONE				DWG. NO. KTKR-FEMUR
DO NOT SCALE DRAWING				REV 0
				SCALE: 1:2 · WEIGHT: 1.36 · SHEET 2 OF 2

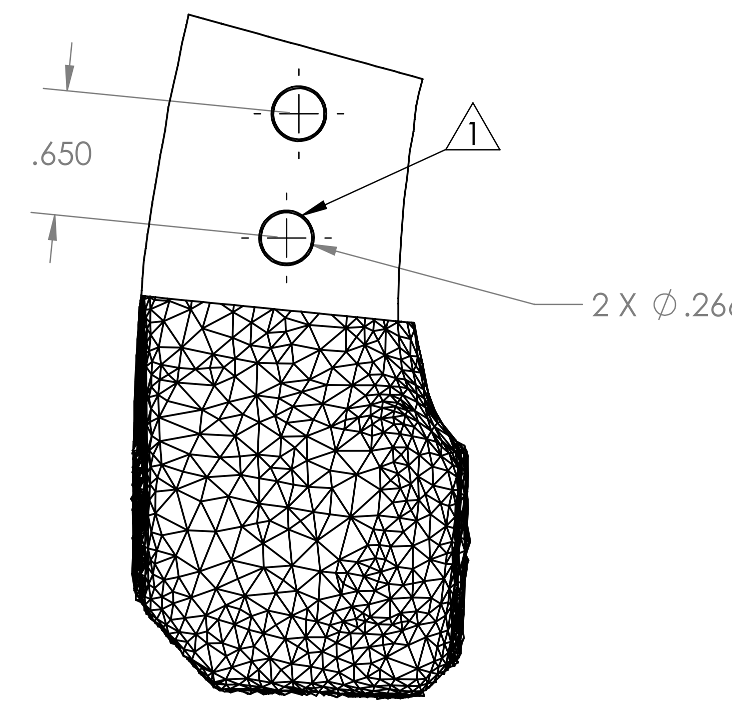
REVISIONS			
REVISION	DESCRIPTION	DATE	APPROVED
0	ORIGINAL FEMUR BONE COMPONENT DOWNLOADED FROM OPEN SOURCE WEBSITE.	-	N/A
1	TRIMMED SIDES AND ADDED HOLES FOR ATTACHING TO 80/20.	4/28/2015	JPB

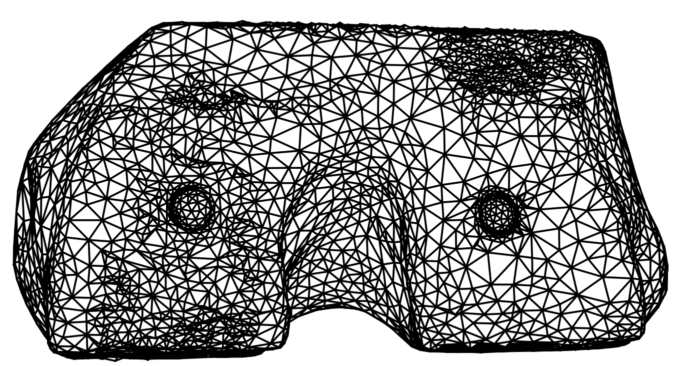






VOLUME: 8.73 CUBIC INCHES





NOTES:
THE PURPOSE OF THIS DRAWING IS TO GIVE THE SIZE OF FEMUR BONE COMPONENT. USE THIS FOR REFERENCE ONLY AND RELY ON CAD MODEL.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
HIGH DENSITY ABS

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

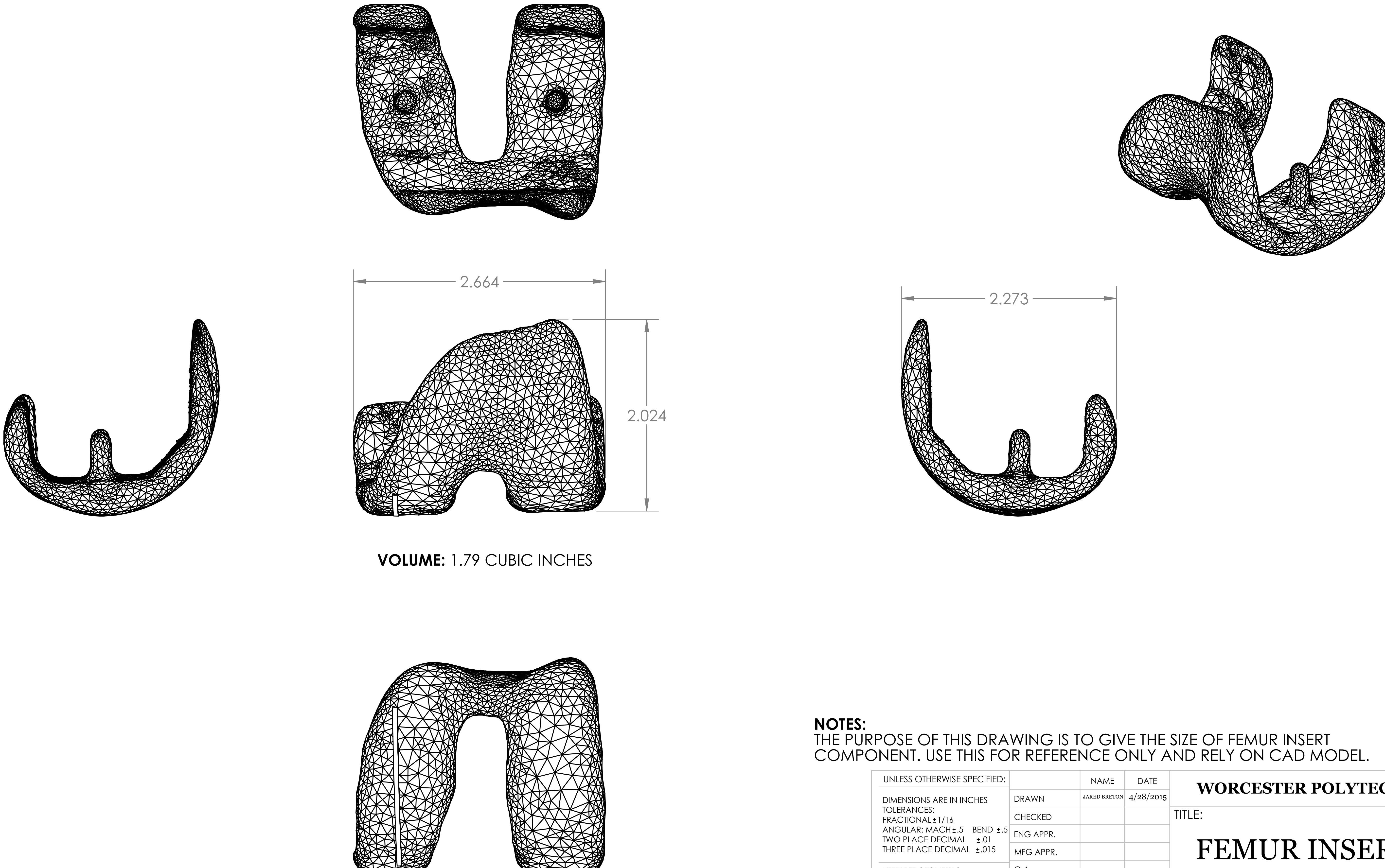
WORCESTER POLYTECH

TITLE:

FEMUR BONE

SIZE	DWG. NO.	REV
B	KTKR-RC-001-A	1

SCALE: 1:1 WEIGHT: 0.32169 SHEET 1 OF 1



VOLUME: 1.79 CUBIC INCHES

NOTES:
THE PURPOSE OF THIS DRAWING IS TO GIVE THE SIZE OF FEMUR INSERT COMPONENT. USE THIS FOR REFERENCE ONLY AND RELY ON CAD MODEL.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±1/16
ANGULAR: MACH±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
HIGH DENSITY ABS

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

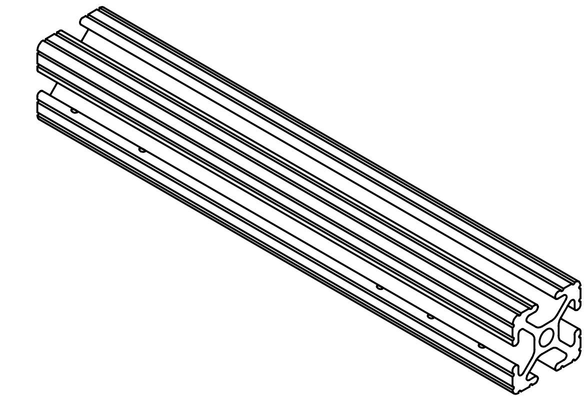
WORCESTER POLYTECH

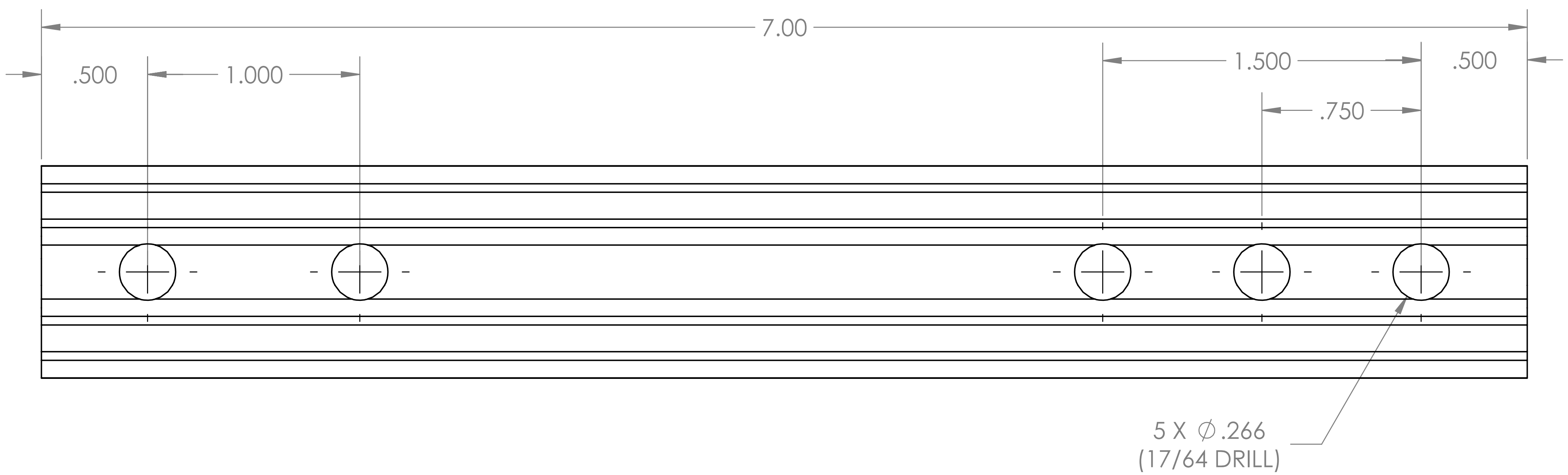
TITLE:

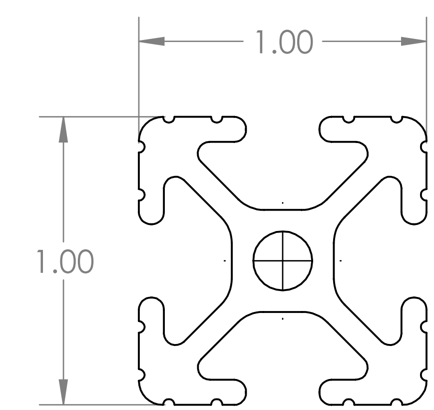
FEMUR INSERT

SIZE	DWG. NO.	REV
B	KTKR-RC-003-A	O

SCALE: 1:1 | WEIGHT: 0.066 | SHEET 1 OF 1







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.

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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

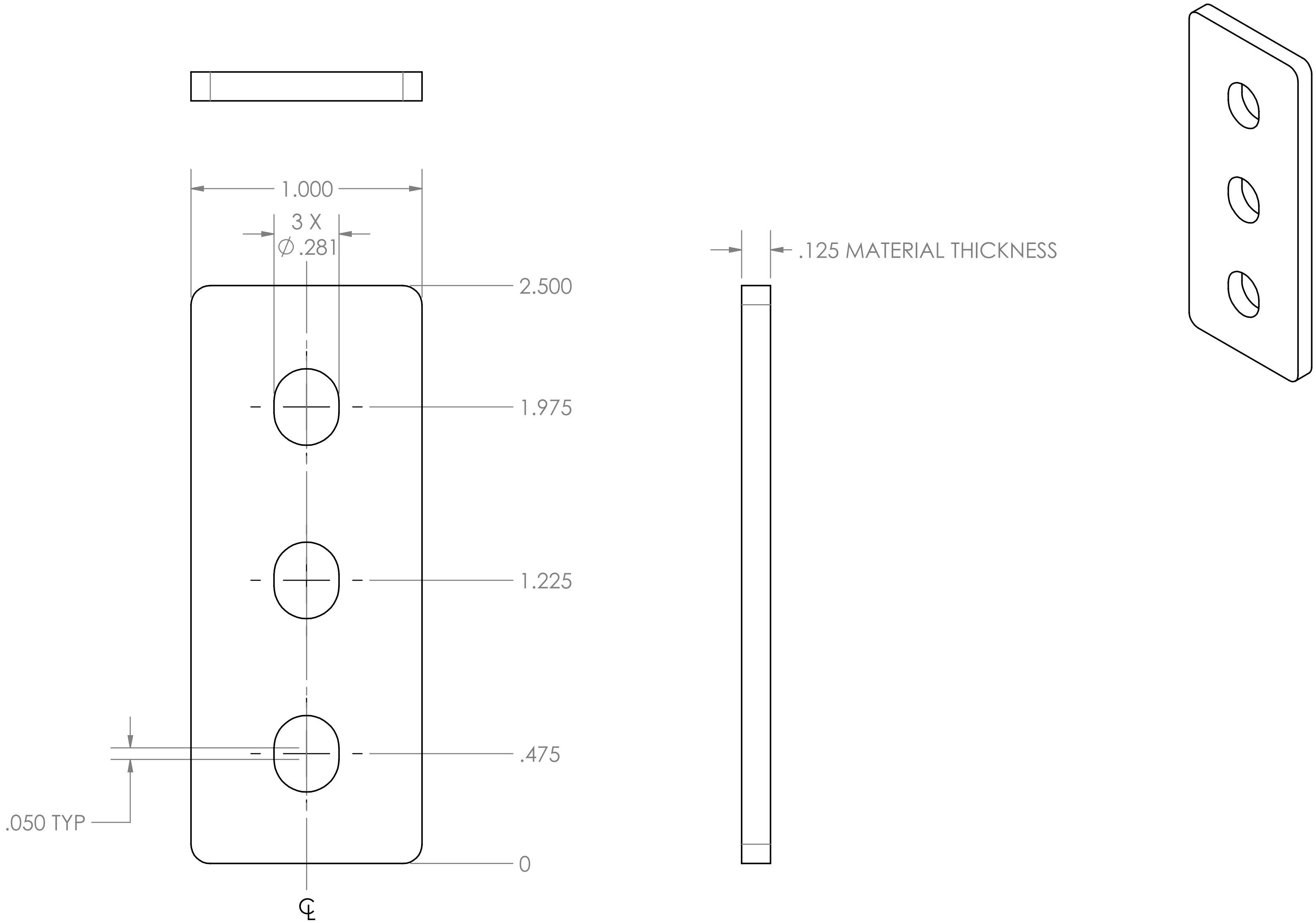
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" EXTRUSION; 7" NOM WITH 17/64 TAPPED HOLES

SIZE	DWG. NO.	REV
B	1010-07-BONE	0

SCALE: 3:2 WEIGHT: 0.289 SHEET 1 OF 1



MATERIAL THICKNESS: 0.125 INCHES
LENGTH OF CUT: 9.8 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

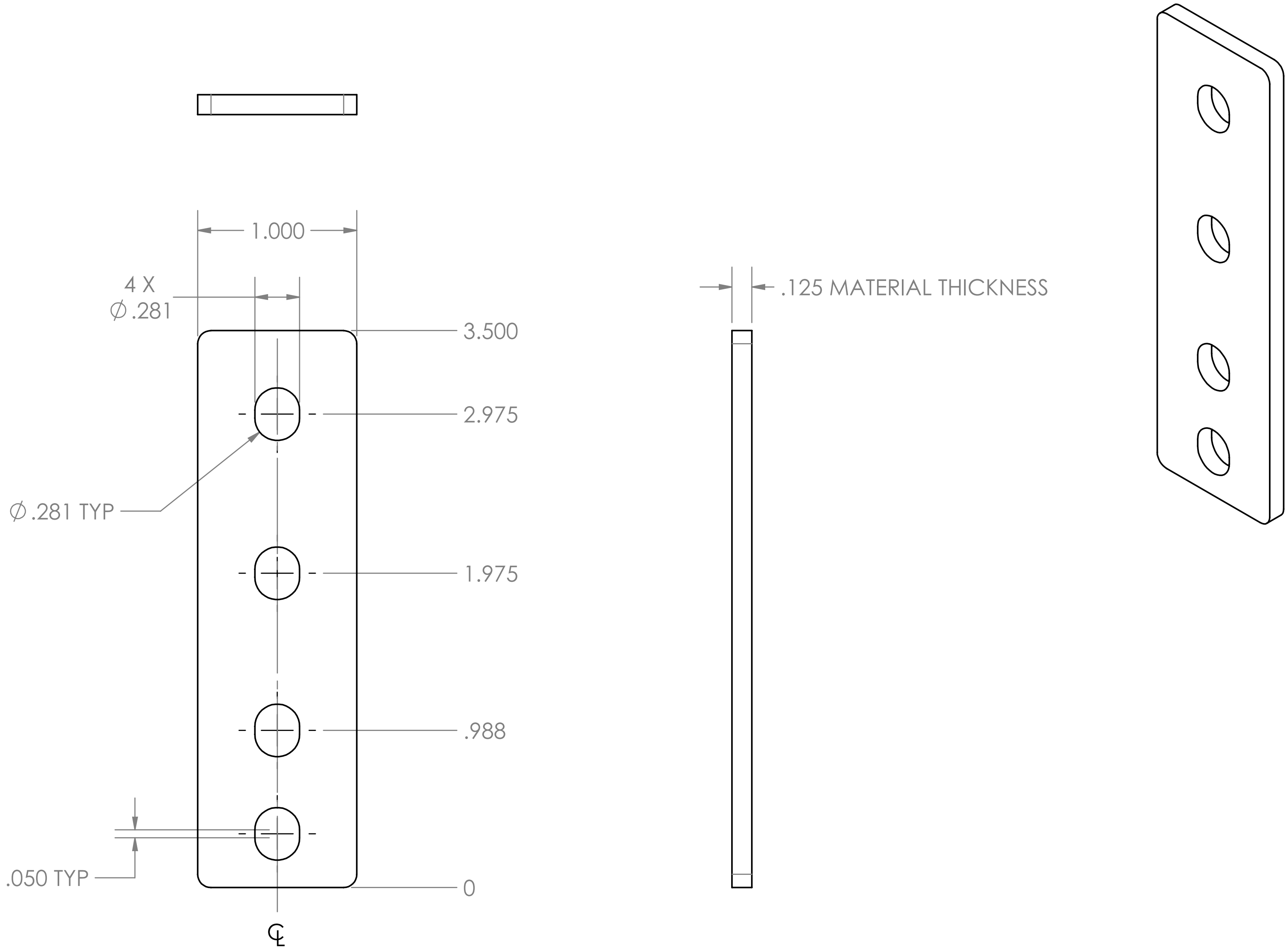
DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT: WORCESTER POLYTECHNIC INSTITUTE
MATERIAL: ALUMINUM
FINISH: NONE

8020 END MTG BRKT

SIZE	DWG. NO.	REV.
A	KTKR-CB-001-A	0

SCALE:3:2 | WEIGHT: | SHEET 1 OF 3



MATERIAL THICKNESS: 0.125 INCHES
LENGTH OF CUT: 12.8 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF SPARTON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF SPARTON IS PROHIBITED.

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

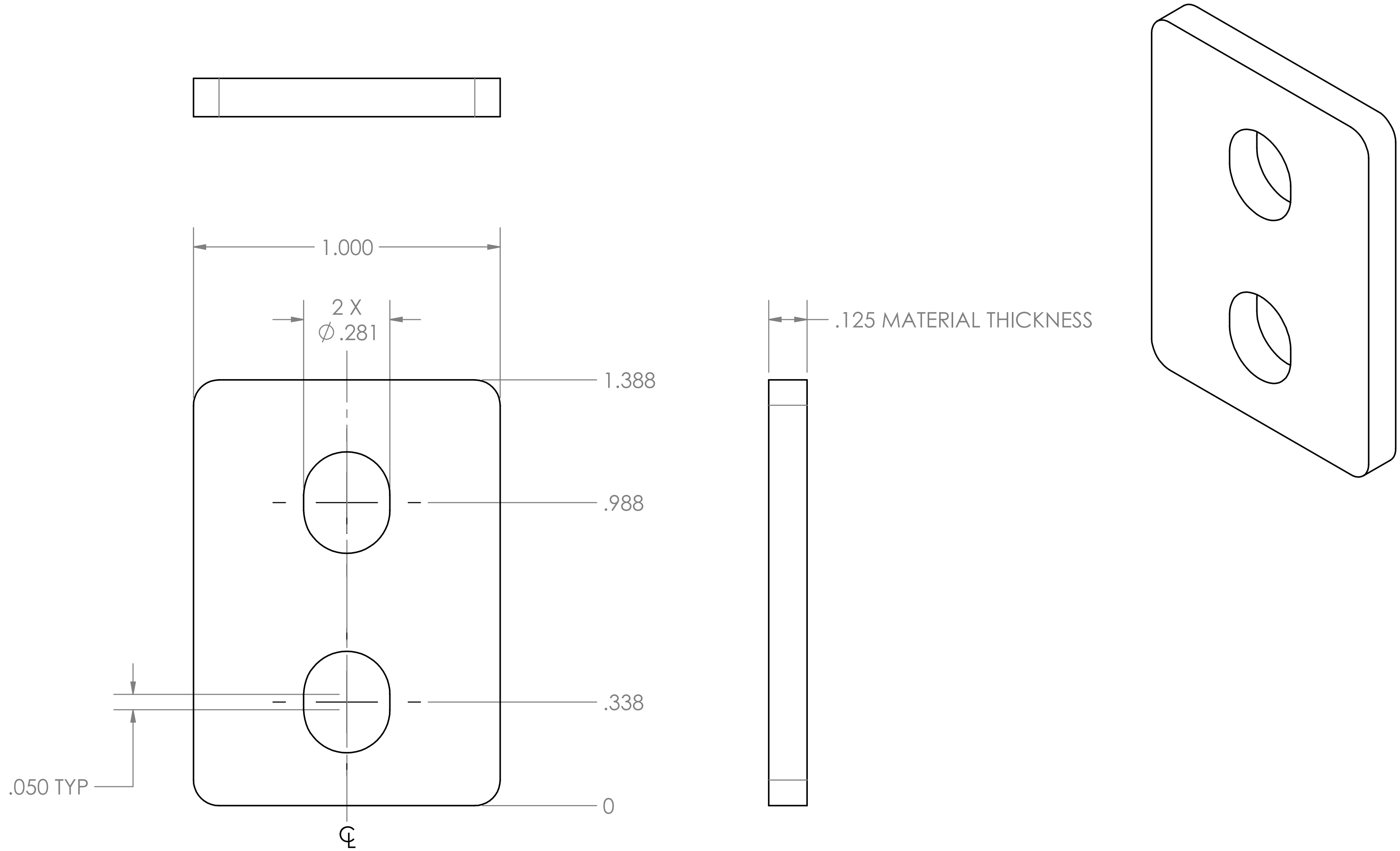
MATERIAL
ALUMINUM

FINISH
NONE

BONE CONNECTING BRKT

SIZE	DWG. NO.	REV.
A	KTKR-CB-002-A	0

SCALE:1:1 | WEIGHT: | SHEET 2 OF 3



MATERIAL THICKNESS: 0.125 INCHES
LENGTH OF CUT: 6.5 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH±.5 BEND ±.5

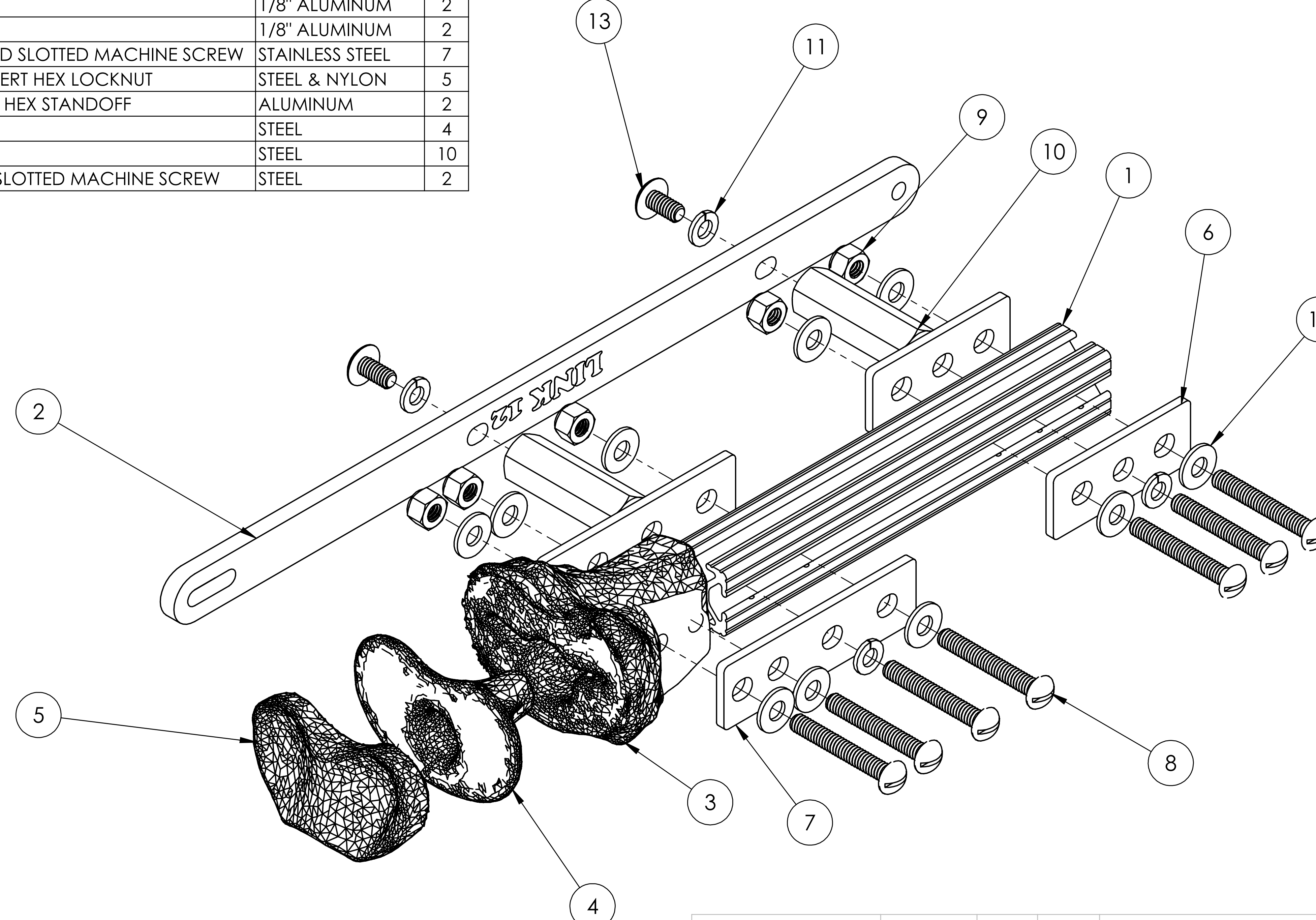
CLIENT: WORCESTER POLYTECHNIC INSTITUTE
MATERIAL: ALUMINUM
FINISH: NONE

FEMUR BONE MTG BRKT SPACER

SIZE	DWG. NO.	REV.
A	KTKR-CB-003-A	0

SCALE:2:1 WEIGHT: SHEET 3 OF 3

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	1010-07-BONE	0	1.0" x 1.0" EXTRUSION; 7" NOM WITH 17/64 TAPPED HOLES	6105-T5 ALUMINUM	1
2	KTKR-LK-12827-0	0	LINK 12: 12.827" LONG	STEEL	1
3	KTKR-RC-002-A	1	TIBIA BONE	HIGH DENSITY ABS	1
4	KTKR-RC-004-A	0	TIBIAL TRAY	HIGH DENSITY ABS	1
5	KTKR-RC-005-A	0	TIBIAL SPACER	HIGH DENSITY ABS	1
6	KTKR-CB-001-A	0	8020 END MTG BRKT	1/8" ALUMINUM	2
7	KTKR-CB-002-A	0	BONE CONNECTING BRKT	1/8" ALUMINUM	2
8	SE-25020-1750-BSS-S0	N/A	1/4"-20 x 1.75" ROUND HEAD SLOTTED MACHINE SCREW	STAINLESS STEEL	7
9	90630A110	N/A	1/4"-20 THREAD NYLON INSERT HEX LOCKNUT	STEEL & NYLON	5
10	91780A979	N/A	FEMALE 1/4"-20 THREAD, 2" HEX STANDOFF	ALUMINUM	2
11	WS-250-STZ-SAE-0	N/A	1/4" LOCK WASHER	STEEL	4
12	WF-250-STZ-SAE-0	N/A	1/4" FLAT WASHER	STEEL	10
13	SE-25020-0500-TSZ-S0	N/A	1/4"-20 x 1/2" TRUSS HEAD SLOTTED MACHINE SCREW	STEEL	2



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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: ALUMINUM, STEEL, ABS

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

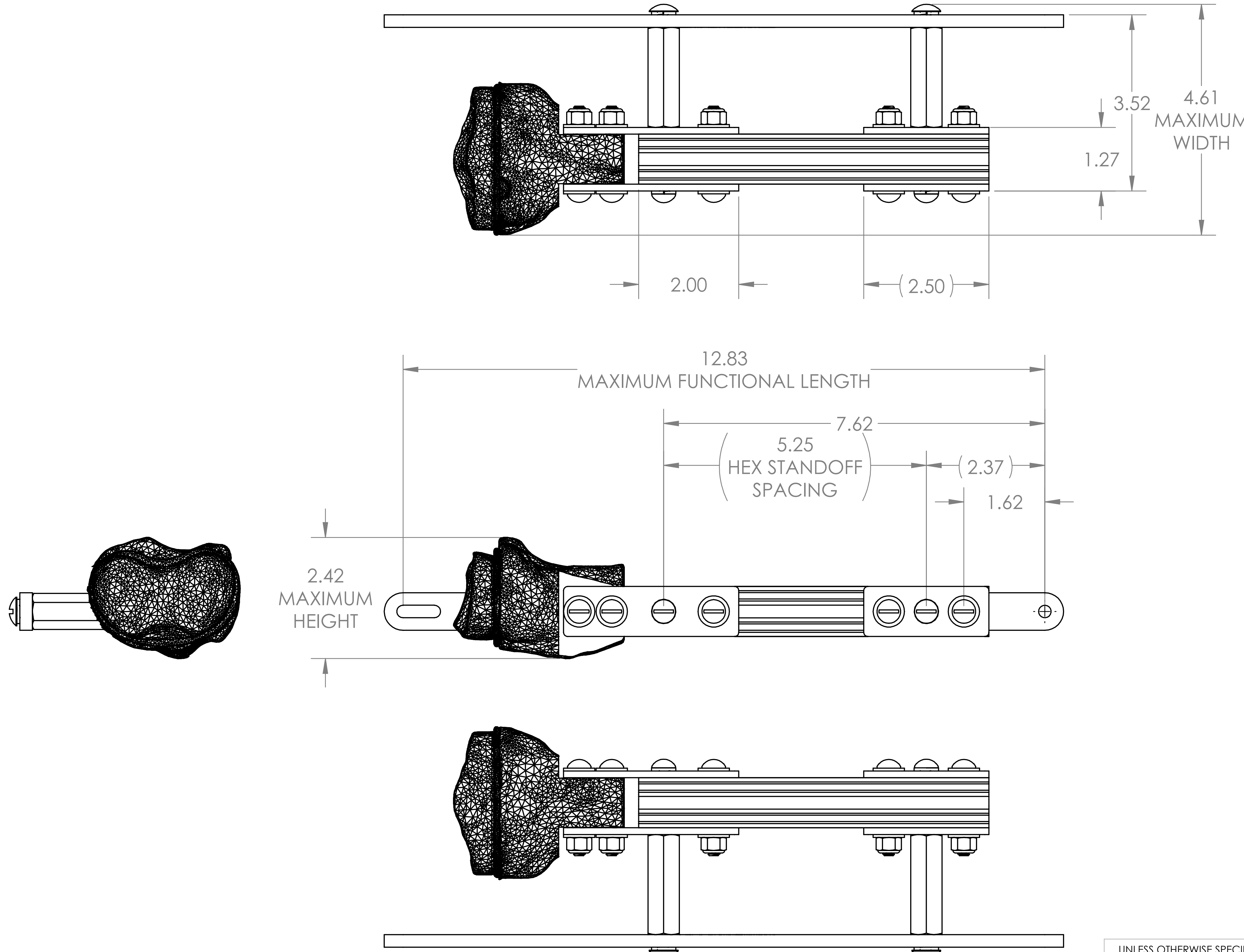
WORCESTER POLYTECHNIC INSTITUTE

TITLE:

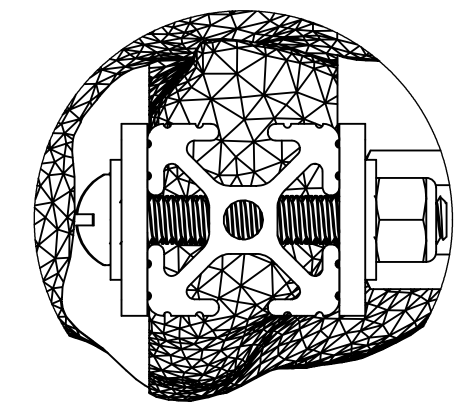
TIBIA SUBASSEMBLY

SIZE: B | DWG. NO.: KTKR-TIBIA | REV: 0

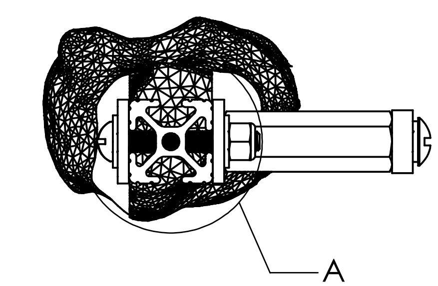
SCALE: 3:5 | WEIGHT: 1.32 | SHEET 1 OF 2



INSTALLATION:
INSTALL ALL HARDWARE AS SHOWN TO ENSURE THE SUBASSEMBLY REMAINS COMPLETELY RIGID WHILE IN OPERATION. APPLY LOCTITE TO HEX STANDOFFS IF NECESSARY.



DETAIL A
SCALE 1 : 1



NOTES:
1. MISSING DIMENSIONS ARE NON-CRITICAL OR CANNOT BE CONTROLLED AT THIS LEVEL.
2. ASSEMBLE COMPONENTS AS SHOWN IN DRAWING VIEWS.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ALUMINUM, STEEL, ABS

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

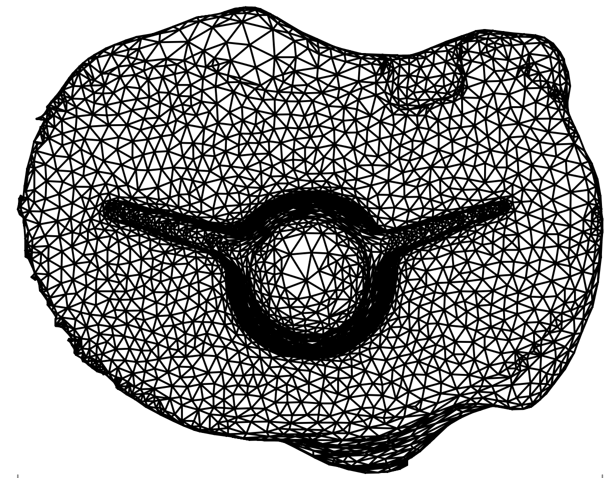
WORCESTER POLYTECHNIC INSTITUTE

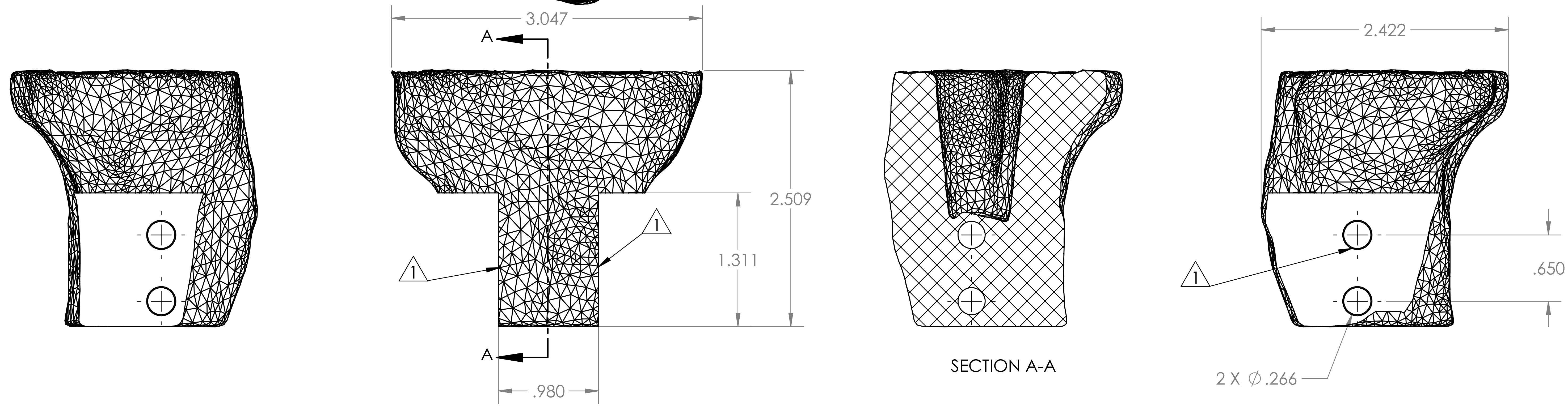
TITLE:

TIBIA SUBASSEMBLY

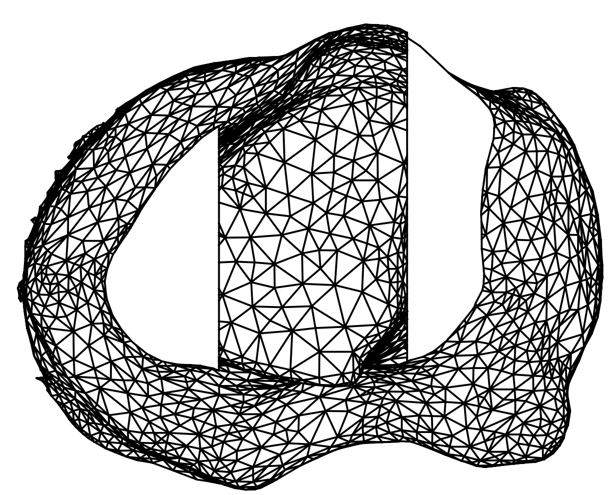
SIZE	DWG. NO.	REV
B	KTKR-TIBIA	0

SCALE: 7:16 WEIGHT: 1.32 SHEET 2 OF 2





VOLUME: 6.11 CUBIC INCHES



REVISIONS

REVISION	DESCRIPTION	DATE	APPROVED
0	ORIGINAL TIBIA BONE COMPONENT DOWNLOADED FROM OPEN SOURCE WEBSITE.	-	N/A
1	TRIMMED SIDES AND ADDED HOLES FOR ATTACHING TO 80/20.	4/28/2015	JPB

NOTES:
THE PURPOSE OF THIS DRAWING IS TO GIVE THE SIZE OF TIBIA BONE COMPONENT. USE THIS FOR REFERENCE ONLY AND RELY ON CAD MODEL.

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.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16
ANGULAR: MACH ± .5 BEND ± .5
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
HIGH DENSITY ABS

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

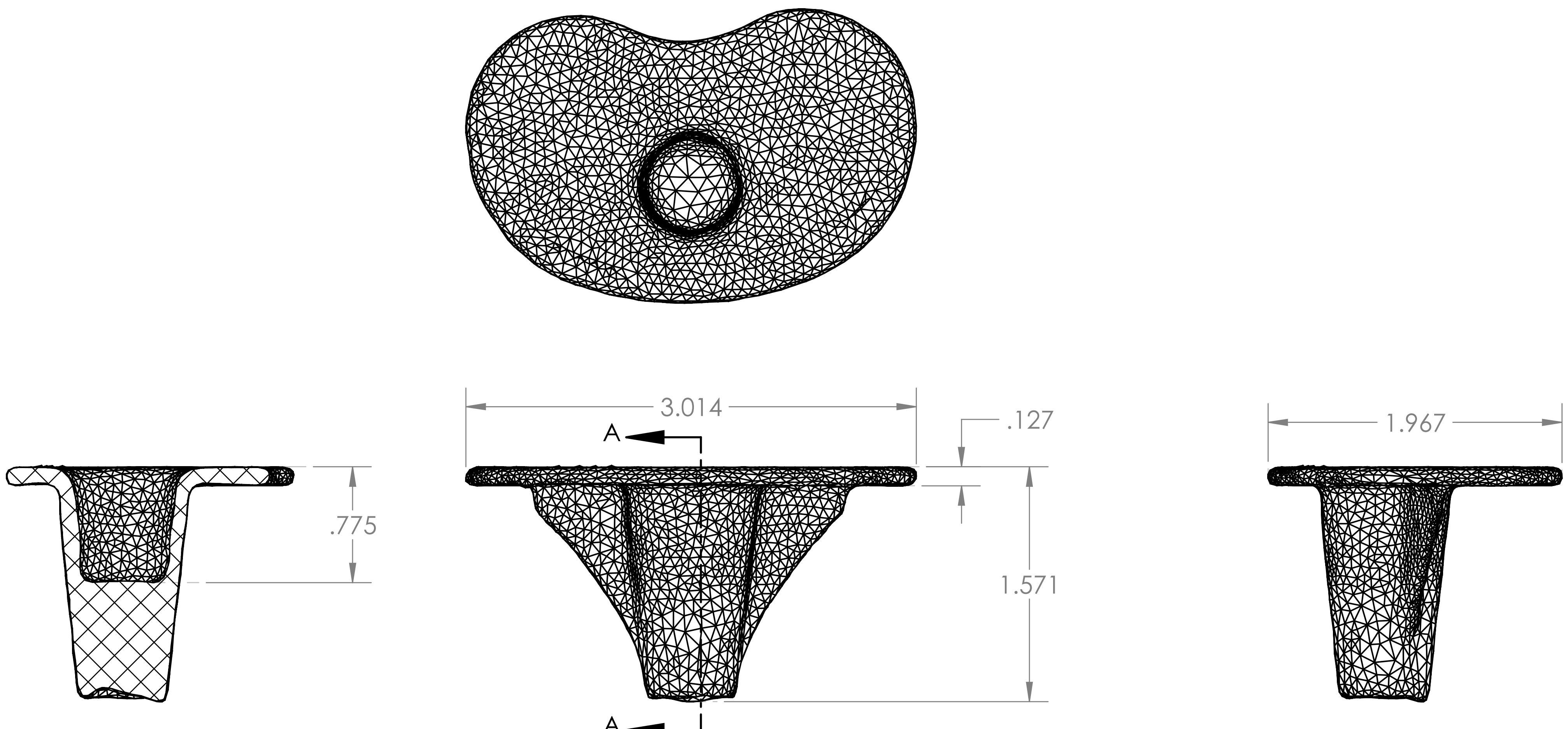
WORCESTER POLYTECH

TITLE:

TIBIA BONE

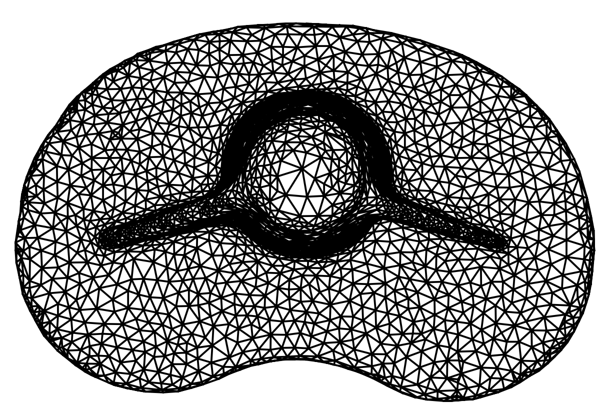
SIZE	DWG. NO.	REV
B	KTKR-RC-002-A	1

SCALE: 1:1 | WEIGHT: 0.225 | SHEET 1 OF 1



SECTION A-A

VOLUME: 0.99 CUBIC INCHES



NOTES:
THE PURPOSE OF THIS DRAWING IS TO GIVE THE SIZE OF TIBIAL TRAY COMPONENT.
USE THIS FOR REFERENCE ONLY AND RELY ON CAD MODEL.

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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HIGH DENSITY ABS

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

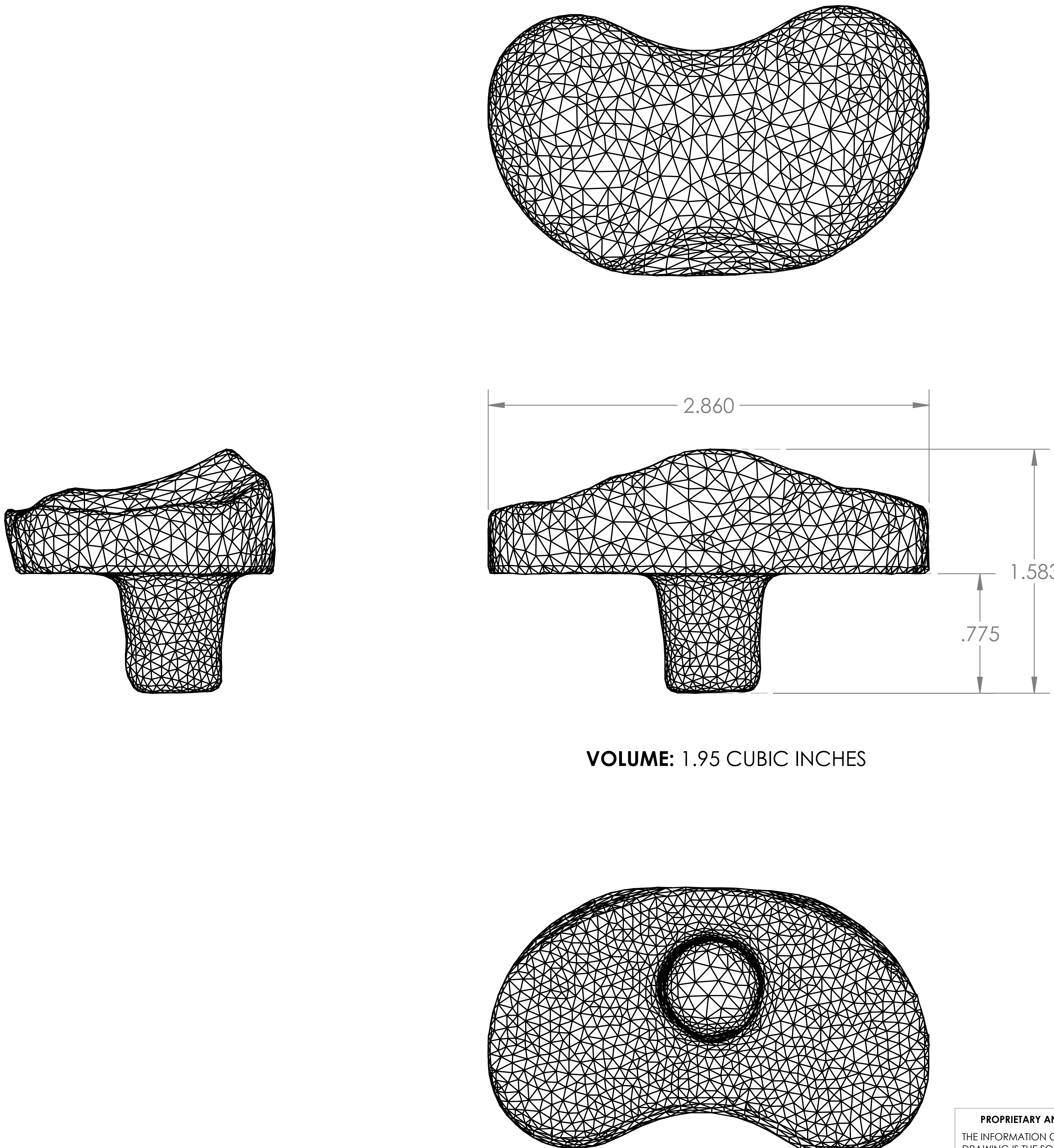
WORCESTER POLYTECH

TITLE:

TIBIAL TRAY

SIZE	DWG. NO.	REV
B	KTKR-RC-004-A	0

SCALE: 1:1 | WEIGHT: 0.036 | SHEET 1 OF 1



NOTES:
THE PURPOSE OF THIS DRAWING IS TO GIVE THE SIZE OF TIBIAL SPACER COMPONENT. USE THIS FOR REFERENCE ONLY AND RELY ON CAD MODEL.

PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/16
ANGULAR: MACH ± .5 BEND ± .5
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HIGH DENSITY ABS

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECH

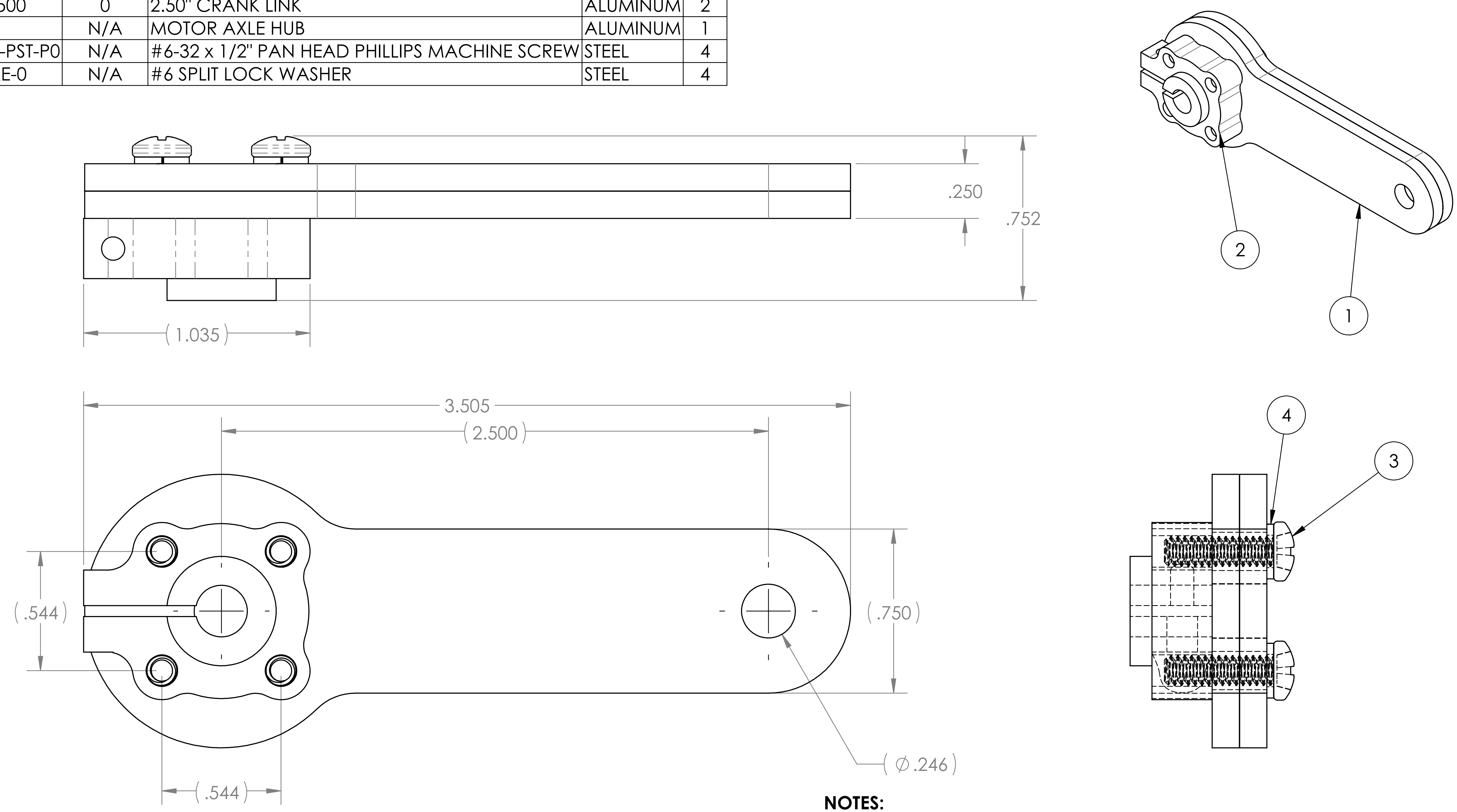
TITLE:

TIBIAL SPACER

SIZE	DWG. NO.	REV
B	KTKR-RC-005-A	0

SCALE: 5:4 | WEIGHT: 0.072 | SHEET 1 OF 1

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	KTKR-LK-02-02500	0	2.50" CRANK LINK	ALUMINUM	2
2	545616	N/A	MOTOR AXLE HUB	ALUMINUM	1
3	SE-00632-0500-PST-P0	N/A	#6-32 x 1/2" PAN HEAD PHILLIPS MACHINE SCREW	STEEL	4
4	WS-006-STZ-SAE-0	N/A	#6 SPLIT LOCK WASHER	STEEL	4



NOTES:
1. ASSEMBLE AS SHOWN USING COMPONENTS INDICATED IN THIS DRAWING.
2. ALL MISSING DIMENSIONS ARE NON CRITICAL.
3. ALL REFERENCE DIMENSIONS CANNOT BE CONTROLLED AT THIS LEVEL.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL ALUMINUM
FINISH NONE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/28/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

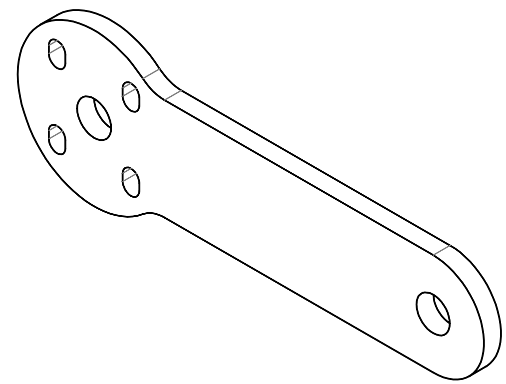
WORCESTER POLYTECH

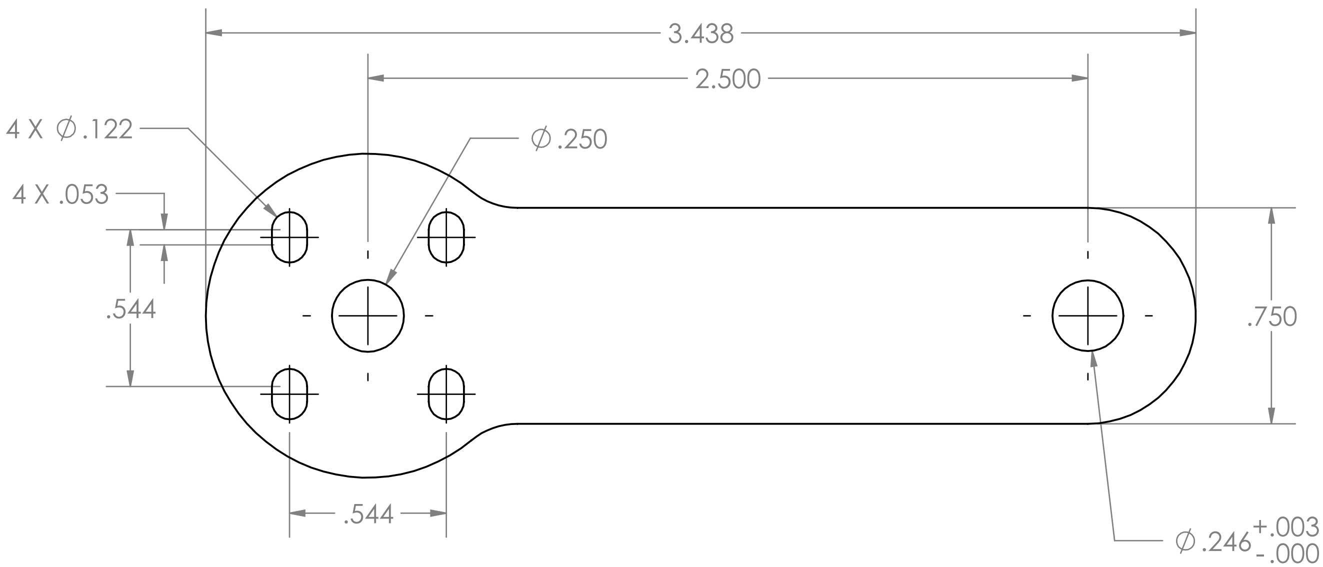
TITLE: 2.50" CRANK LINK

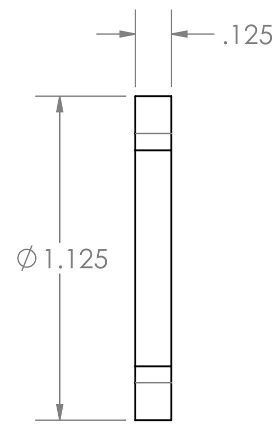
SIZE B | DWG. NO. KTKR-LK-02-02500 | REV 0

SCALE: 2:1 | WEIGHT: 0.03 | SHEET 1 OF 1

NOTES:
ALL MISSING DIMENSIONS ARE NON-CRITICAL. RELY ON CAD DATA FOR ADDITIONAL INFORMATION.







MATERIAL THICKNESS: .125 INCHES
LENGTH OF CUT: 12 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/14/2015

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF SPARTON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF SPARTON IS PROHIBITED.

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

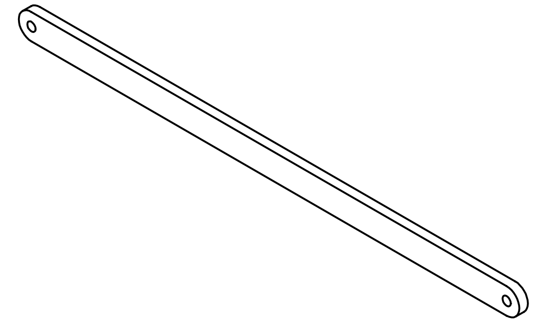
MATERIAL
ALUMINUM

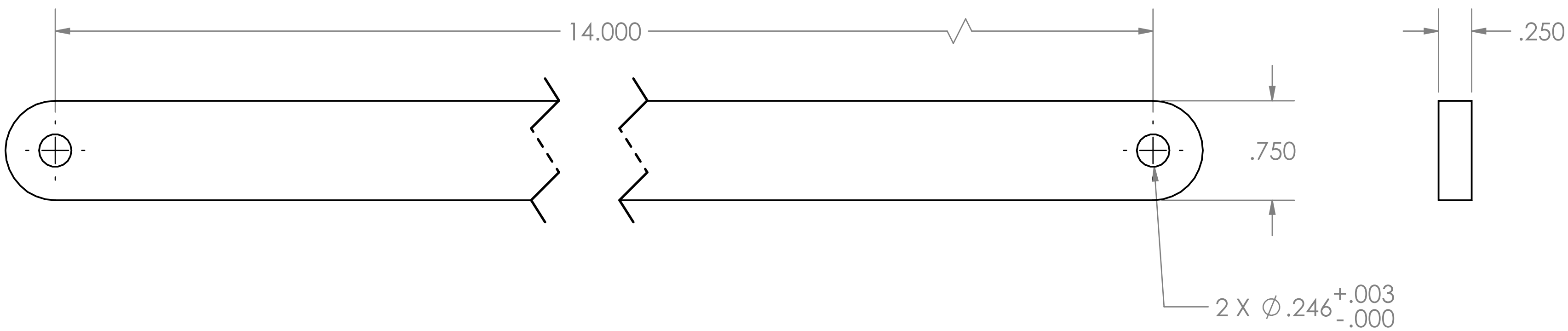
FINISH
NONE

2.50" CRANK LINK

SIZE	DWG. NO.	REV.
A	KTKR-LK-02-02500	0

SCALE:3:2 WEIGHT: SHEET 1 OF 1





MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 32 INCHES

SPARTON TECHNOLOGY

COMMENTS:	DRAWN BY	DATE
DO NOT SCALE DRAWING	JARED BRETON	3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

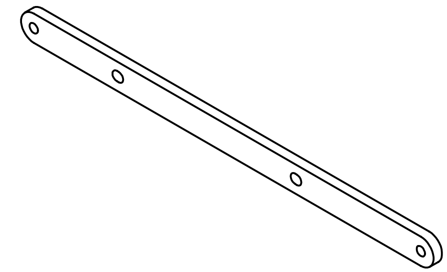
MATERIAL
ALUMINUM

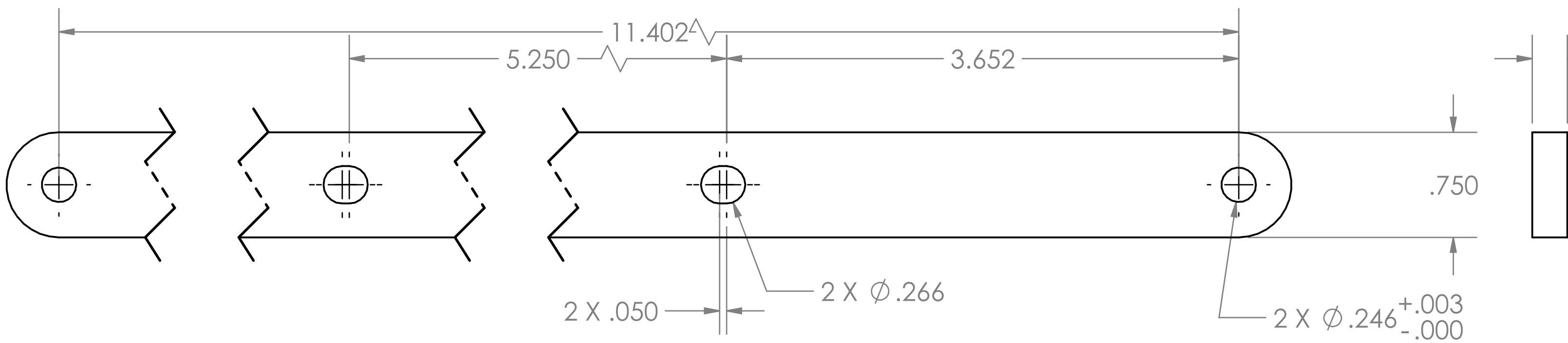
FINISH
NONE

LINK 3: 14.00" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK03-14000	0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1





MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 29 INCHES

SPARTON TECHNOLOGY

COMMENTS:
DO NOT SCALE DRAWING

DRAWN BY: JARED BRETON

DATE: 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT: WORCESTER POLYTECHNIC INSTITUTE

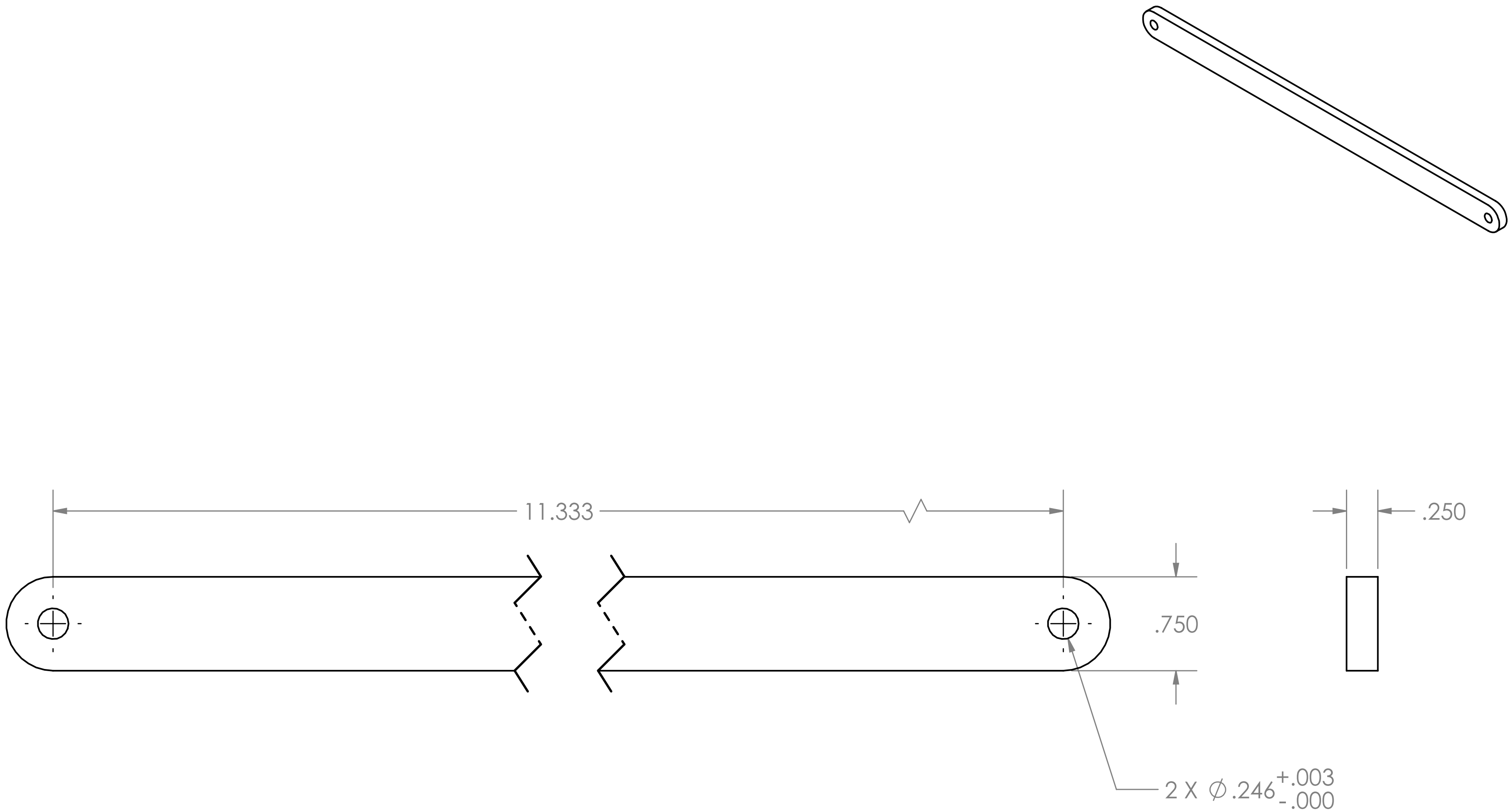
MATERIAL: ALUMINUM

FINISH: NONE

LINK 4: 11.402" LONG

SIZE: A | DWG. NO. KTKR-LK-04-11402 | REV. 0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 27 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

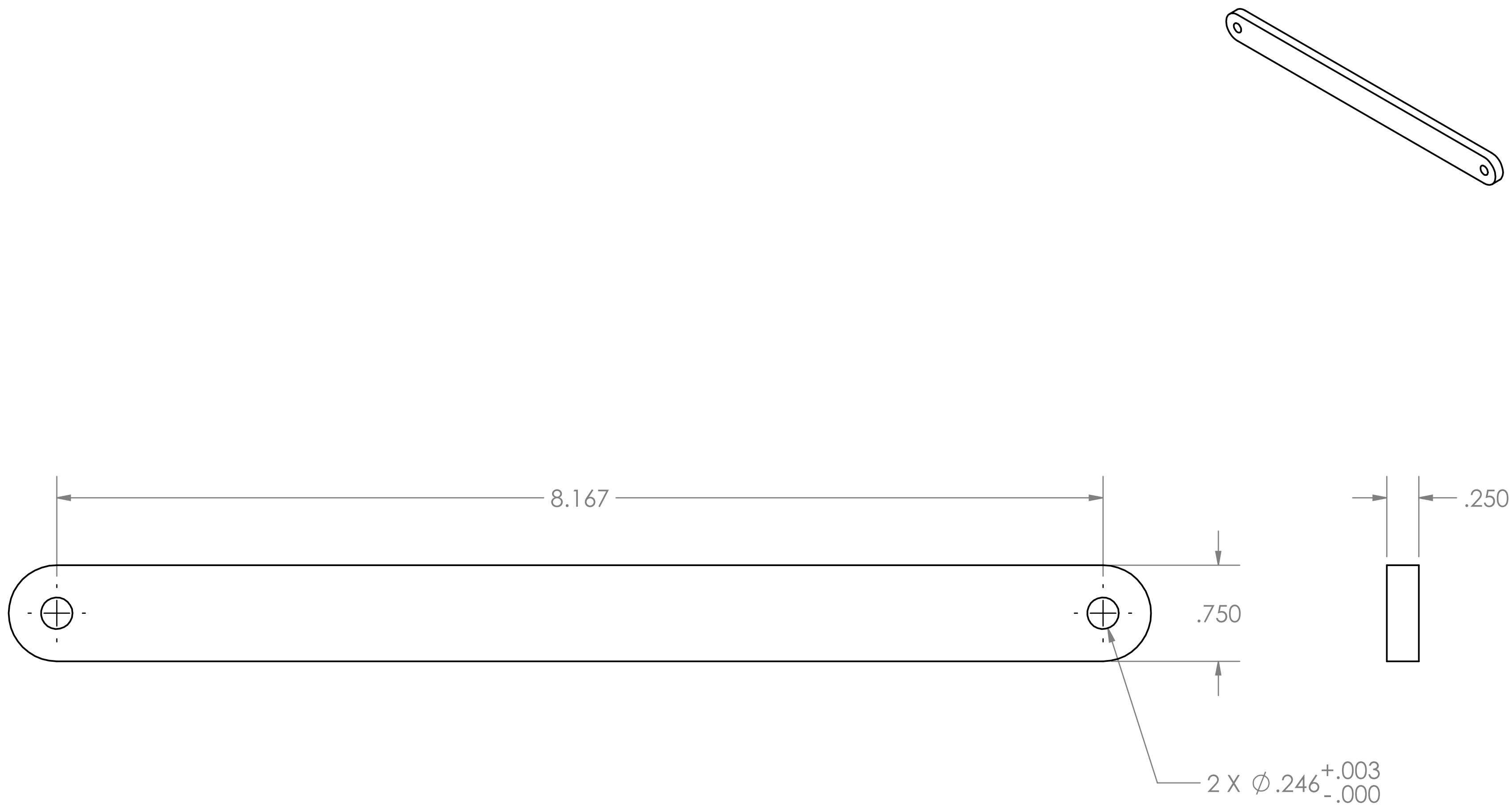
MATERIAL
ALUMINUM

FINISH
NONE

LINK 5: 11.33" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-05-11333	0

SCALE:3:4 WEIGHT: SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 21 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015
PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF SPARTON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF SPARTON IS PROHIBITED.		

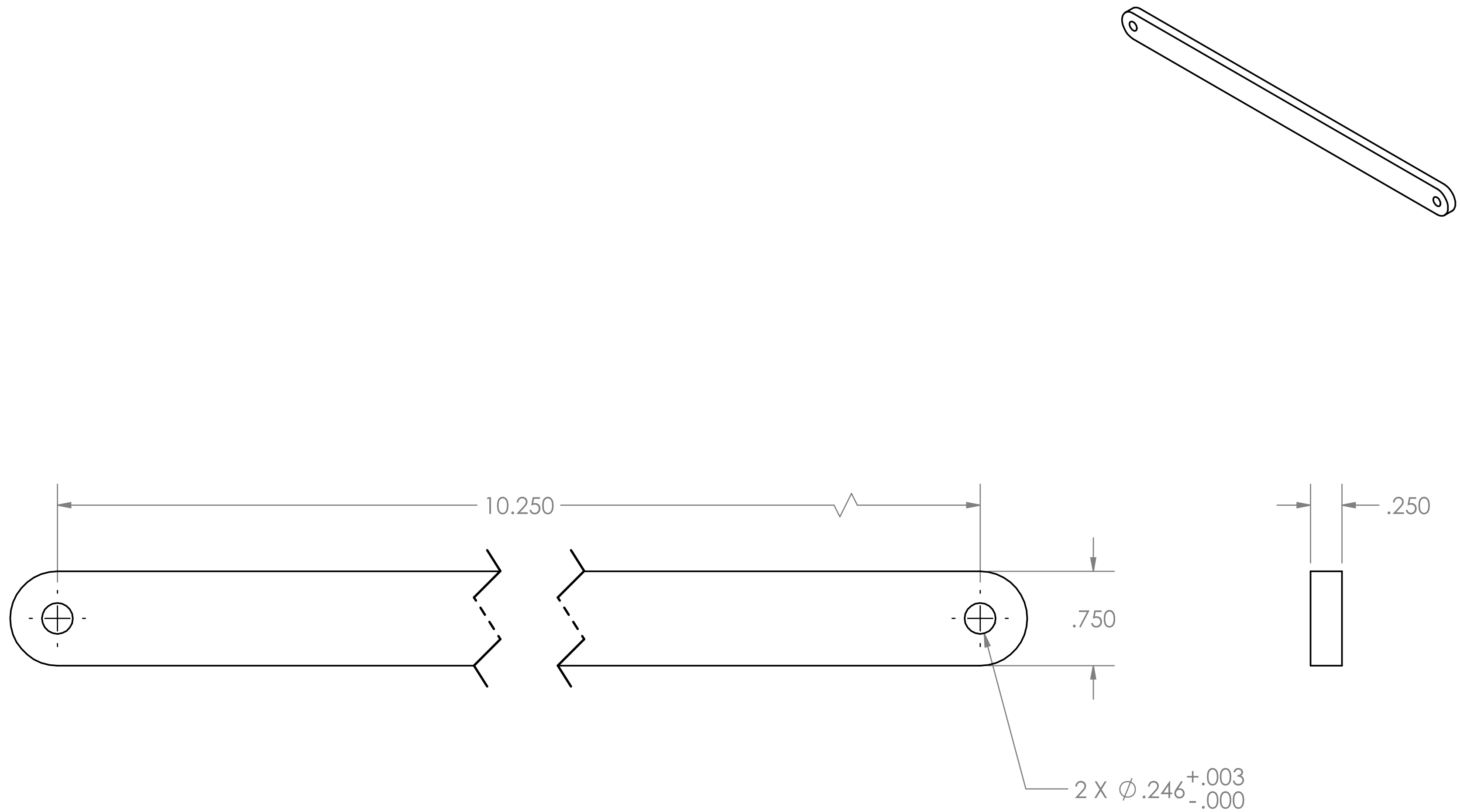
DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT: WORCESTER POLYTECHNIC INSTITUTE
MATERIAL: ALUMINUM
FINISH: NONE

LINK 6: 8.167" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-06-08167	0
SCALE:3:4	WEIGHT:	SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 25 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF SPARTON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF SPARTON IS PROHIBITED.

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

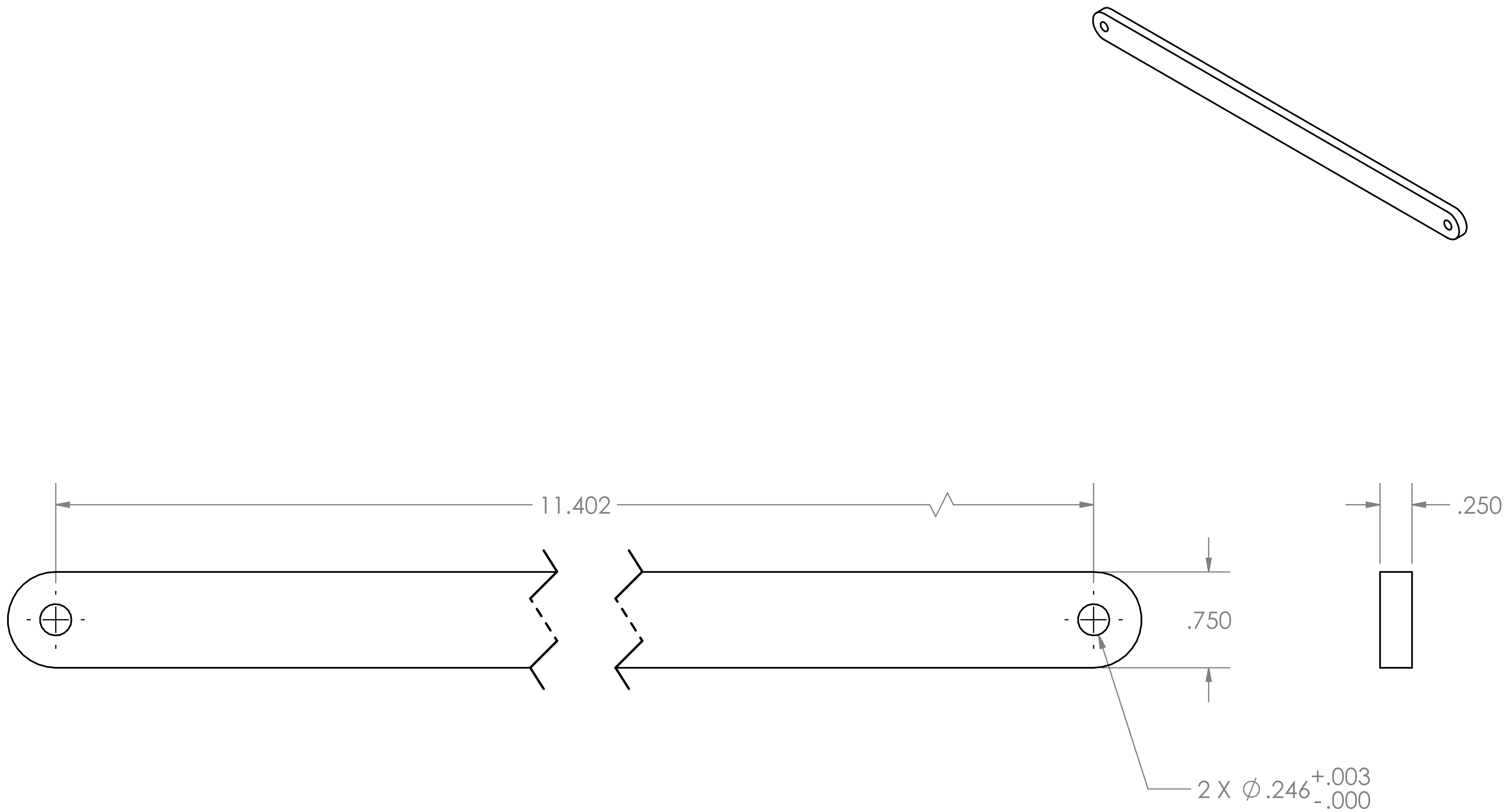
MATERIAL
ALUMINUM

FINISH
NONE

LINK 7: 10.25" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-07-10250	0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 27 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

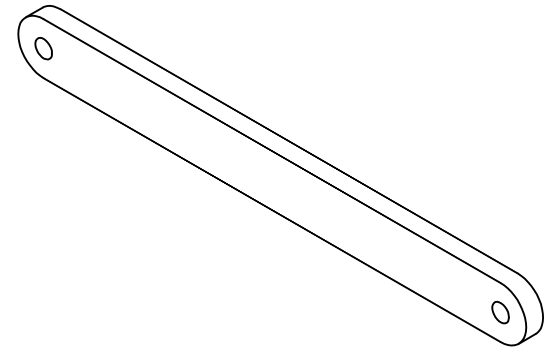
MATERIAL
ALUMINUM

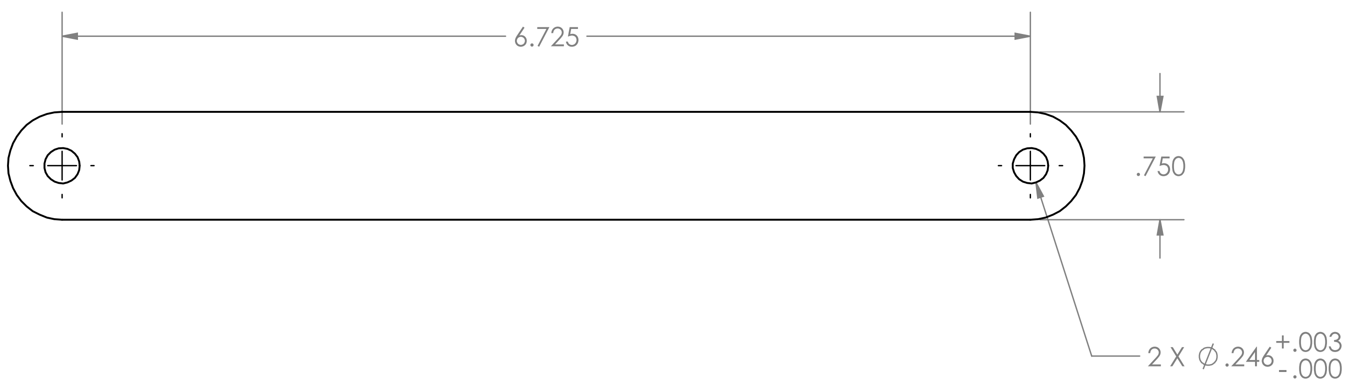
FINISH
NONE

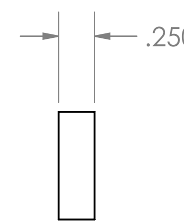
LINK 8: 11.402" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-08-11402	0

SCALE:3:4 WEIGHT: SHEET 1 OF 1







MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 18 INCHES

SPARTON TECHNOLOGY

COMMENTS:
DO NOT SCALE DRAWING

DRAWN BY
JARED BRETON

DATE
3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

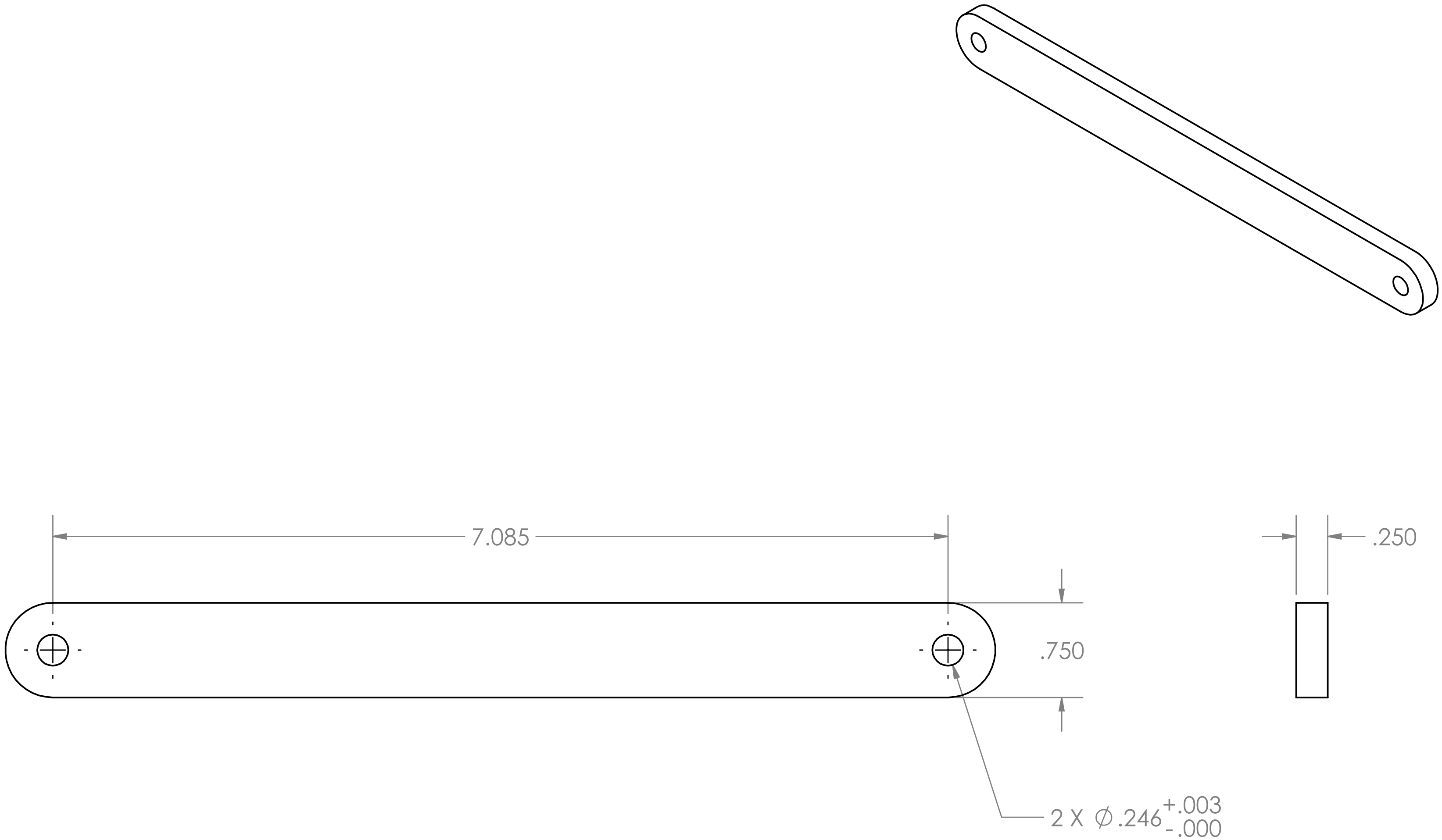
MATERIAL
ALUMINUM

FINISH
NONE

LINK 9: 6.725" LONG

SIZE A | DWG. NO. KTKR-LK-09-06725 | REV. 0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 19 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING	DRAWN BY JARED BRETON	DATE 3/11/2015		
PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF SPARTON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF SPARTON IS PROHIBITED.				

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

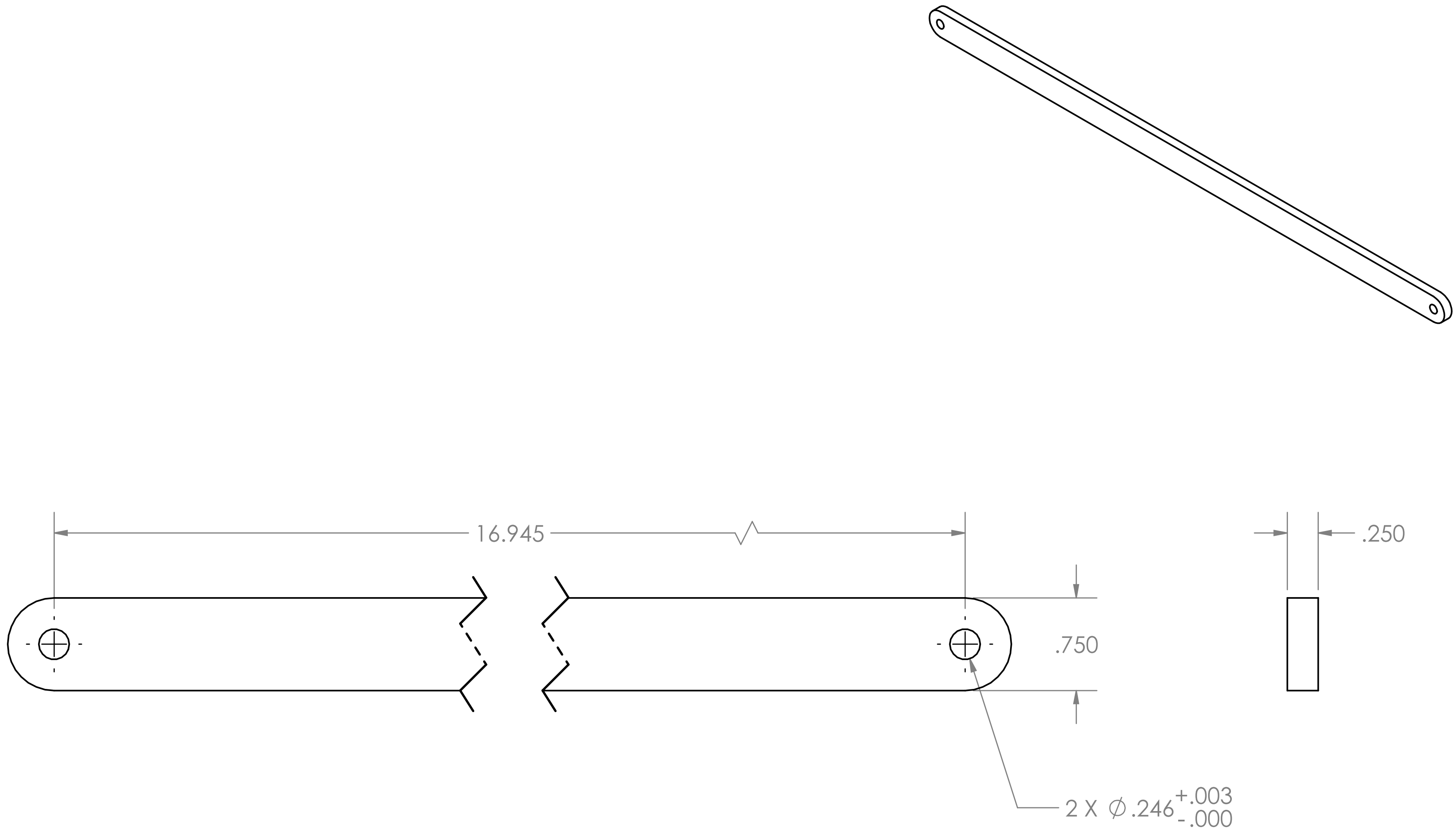
DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT: WORCESTER POLYTECHNIC INSTITUTE
MATERIAL: ALUMINUM
FINISH: NONE

LINK 10: 7.085" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-10-07085	0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1



MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 38 INCHES

SPARTON TECHNOLOGY

COMMENTS:	DRAWN BY	DATE
DO NOT SCALE DRAWING	JARED BRETON	3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT
WORCESTER POLYTECHNIC INSTITUTE

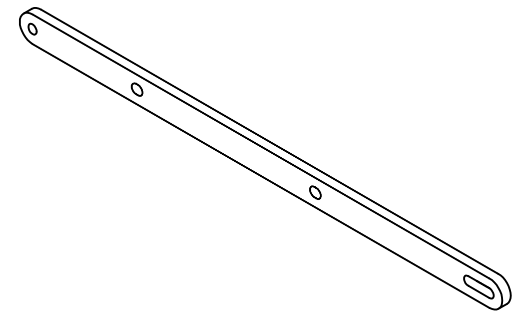
MATERIAL
ALUMINUM

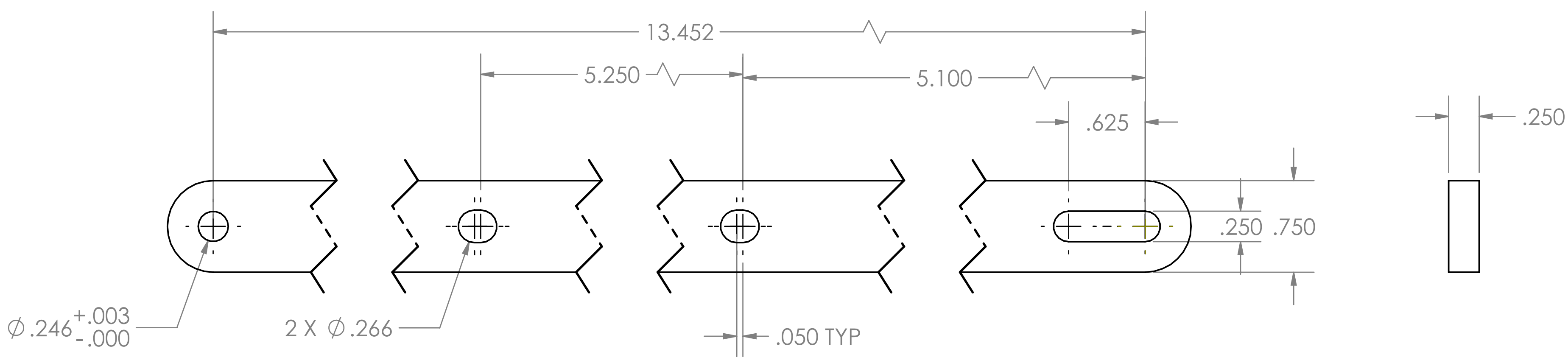
FINISH
NONE

LINK 11: 16.945" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-11-16945	0

SCALE:3:4 | WEIGHT: | SHEET 1 OF 1





MATERIAL THICKNESS: .250 INCHES
LENGTH OF CUT: 34 INCHES

SPARTON TECHNOLOGY

COMMENTS: DO NOT SCALE DRAWING

DRAWN BY: JARED BRETON

DATE: 3/11/2015

PROPRIETARY AND CONFIDENTIAL

DIMENSIONS ARE IN INCHES
TOLERANCES FOR SHEET METAL:
HOLES & FEATURES: ± .005
EDGE TO EDGE: ± .005
EDGE TO BEND: ± .010
BEND TO BEND: ±.015
WELDED FEATURES: ±.015
ANGULAR: MACH ±.5 BEND ±.5

DIMENSIONS ARE IN INCHES
TOLERANCES FOR MACHINING:
.X: ± .030
.XX: ± .010
.XXX: ± .005
ANGULAR: MACH ±.5 BEND ±.5

CLIENT: WORCESTER POLYTECHNIC INSTITUTE

MATERIAL: ALUMINUM

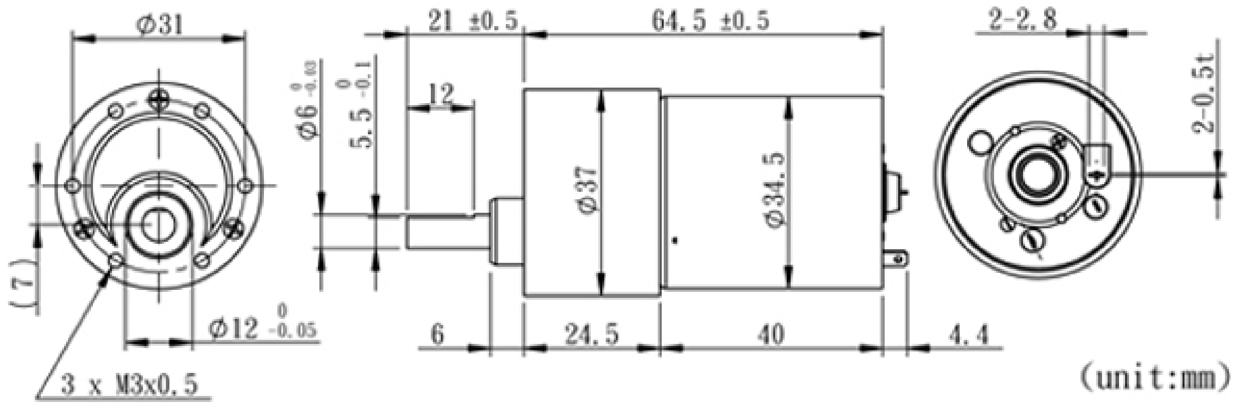
FINISH: NONE

LINK 12: 13.452" LONG

SIZE	DWG. NO.	REV.
A	KTKR-LK-12-13452	0

SCALE: 3:4 | WEIGHT: | SHEET 1 OF 1

Appendix C: Dimension Drawing of the Precision Gear Motor



Appendix D: Specifications of the Precision Gear Motor

Precision Gear Motor Specifications	
Operating Range	6-12 V (Direct Current)
Stall Torque (at 12V)	166.6 oz-in.
Stall Current (at 12V)	1.0 A
No-Load Current	120 mA
No-Load Speed	75 RPM
Gear Ratio	60:1
Motor Size	1.355 in. Dia x 1.70 in. L
Gear Size	1.45 in. Dia x 1.30 in. L
Shaft Size	6mm (0.236 in.) Dia x 0.715 in. L
Weight	0.504 lbs
Insulation Resistance	20 MΩ
Dielectric Strength	250 V (Direct Current)

Appendix E: Results of the SolidWorks Simulation for Torque

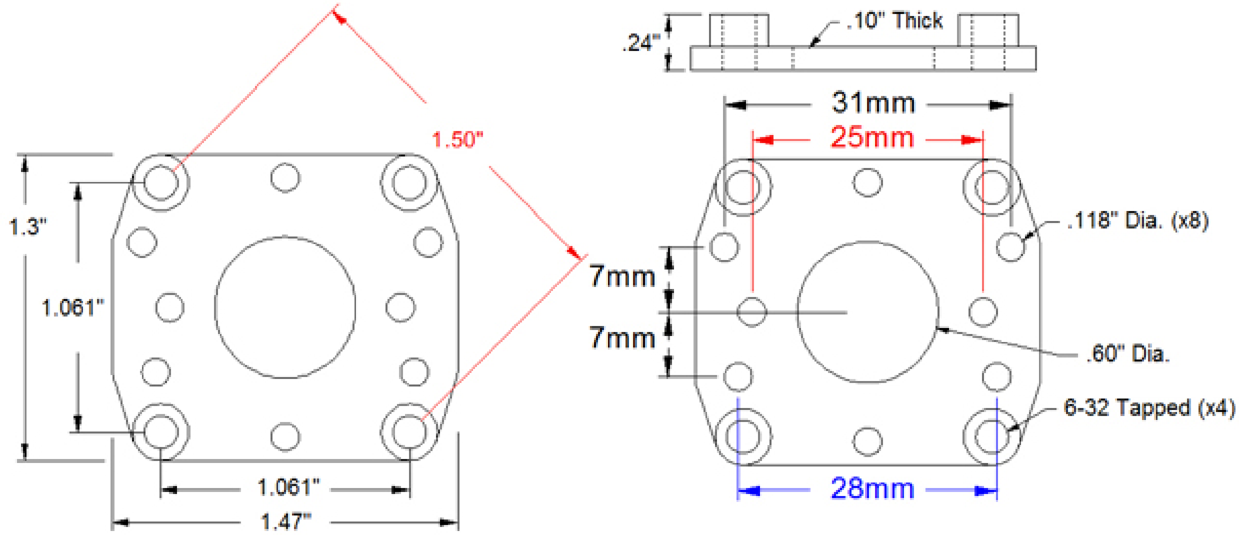
Position	Link #	X - Direction						Y-Direction						Z-Direction						Magnitudes				Properties		
		F	T	v	ω	a	α	F	T	v	ω	a	α	F	T	v	ω	a	α	v	ω	a	α	m	I	
1 0 sec	2	0	0	-0.005567	0	0.639513	0	0	0	-0.14357	0	-0.28808	0	0		0	4.525321	0	8.28628	0.143679	4.525321	0.701405	8.28628	0.03804	0.00014	Current
	3	0	0	-0.336287	0	2.07656	0	0	0	-0.01277	0	0.082881	0	0	0	0	-2.39283	0	1.037739	0.336529	2.39283	2.078214	1.037739	0.11906	0.00134	
	4	0	0	-0.33072	0	1.437047	0	0	0	0.130798	0	0.370964	0	0	0	0	-2.45603	0	8.28628	0.355646	2.45603	1.484156	8.28628	0.48606	0.00589	
	5	0	0	0.1885722	0	3.11928	0	0	0	-0.03057	0	0.592378	0	0	0	0	-2.25891	0	-14.2598	0.191034	2.25891	3.17503	14.2598	0.0971	0.00073	
	6	0	0	0.1941388	0	2.479767	0	0	0	0.113001	0	0.880461	0	0	0	0	-2.16581	0	-24.934	0.224631	2.16581	2.631436	24.934	0.07102	0.00029	
	7	0	0	0.1112479	0	1.883634	0	0	0	0.278366	0	2.963754	0	0	0	0	-2.16581	0	-24.934	0.299773	2.16581	3.511683	24.934	0.08818	0.00055	
	8	0	0	-0.496502	0	0.244782	0	0	0	0.461528	0	4.53755	0	0	0	0	-2.45603	0	8.28628	0.677881	2.45603	4.544148	8.28628	0.09766	0.00074	
	9	0	0	-0.744331	0	2.277962	0	0	0	0.426961	0	2.825221	0	0	0	0	-2.16581	0	-24.934	0.858094	2.16581	3.629185	24.934	0.05915	0.00017	
	10	0	0	-0.082891	0	-0.59613	0	0	0	0.165365	0	2.083293	0	0	0	0	-2.16581	0	-24.934	0.184977	2.16581	2.166907	24.934	0.05915	0.00017	
	11	0	0	-0.955358	0	-0.7639	0	0	0	0.144199	0	0.026957	0	0	0	0	-2.16581	0	-24.934	0.966179	2.16581	0.764371	24.934	0.14331	0.00234	
	12	0	0	-0.872467	0	-0.16776	0	0	0	-0.02117	0	-2.05634	0	0	0	0	-2.16581	0	-24.934	0.872724	2.16581	2.063168	24.934	0.4953	0.00541	
2 0.075 sec	2	0	0	0.0593476	0	1.210851	0	0	0	-0.16974	0	-0.35417	0	0		0	5.663478	0	23.23022	0.179815	5.663478	1.261586	23.23022	0.097944	0.00006	Steel
	3	0	0	-0.10578	0	4.243605	0	0	0	-0.07407	0	-1.82514	0	0	0	0	-1.95502	0	11.42161	0.129137	1.95502	4.619449	11.42161	0.468722	0.005379	
	4	0	0	-0.165127	0	3.032754	0	0	0	0.095665	0	-1.47096	0	0	0	0	-1.31787	0	23.23022	0.190837	1.31787	3.370657	23.23022	0.537514	0.003014	
	5	0	0	0.4619365	0	3.818599	0	0	0	-0.04848	0	-1.35413	0	0	0	0	-3.12645	0	-4.53459	0.464473	3.12645	4.051588	4.53459	0.382745	0.002943	
	6	0	0	0.4025889	0	2.607748	0	0	0	0.121261	0	-0.99996	0	0	0	0	-4.05393	0	-21.3858	0.420455	4.05393	2.792895	21.3858	0.280646	0.001175	
	7	0	0	0.3236263	0	3.56364	0	0	0	0.458368	0	1.091847	0	0	0	0	-4.05393	0	-21.3858	0.561102	4.05393	3.727152	21.3858	0.347816	0.002216	
	8	0	0	-0.323052	0	4.944539	0	0	0	0.769879	0	2.712644	0	0	0	0	-1.31787	0	23.23022	0.834911	1.31787	5.639761	23.23022	0.384958	0.002994	
	9	0	0	-0.409217	0	7.021401	0	0	0	0.528438	0	-0.85012	0	0	0	0	-4.05393	0	-21.3858	0.66836	4.05393	7.072678	21.3858	0.234165	0.000691	
	10	0	0	-0.078963	0	0.955892	0	0	0	0.337107	0	2.091803	0	0	0	0	-4.05393	0	-21.3858	0.346231	4.05393	2.299864	21.3858	0.234165	0.000691	
	11	0	0	-0.916402	0	2.63752	0	0	0	0.105474	0	-1.00966	0	0	0	0	-4.05393	0	-21.3858	0.922452	4.05393	2.824166	21.3858	0.563673	0.009327	
	12	0	0	-0.83744	0	1.681627	0	0	0	-0.23163	0	-3.10146	0	0	0	0	-4.05393	0	-21.3858	0.868884	4.05393	3.528019	21.3858	0.621608	0.004212	
3 0.150 sec	2	0	0	0.1893903	0	2.211541	0	0	0	-0.16906	0	0.747621	0	0		0	7.995661	0	36.28635	0.253869	7.995661	2.334492	36.28635	0.03804	0.00014	Aluminum
	3	0	0	0.3151385	0	6.78773	0	0	0	-0.24496	0	-1.83939	0	0	0	0	-0.63453	0	22.98837	0.399146	0.63453	7.03254	22.98837	0.11906	0.00134	
	4	0	0	0.1257482	0	4.576188	0	0	0	-0.0759	0	-2.58701	0	0	0	0	1.014315	0	36.28635	0.14688	1.014315	5.256817	36.28635	0.48606	0.00589	
	5	0	0	0.6578721	0	0.607869	0	0	0	-0.19078	0	-1.29895	0	0	0	0	-2.19265	0	32.50724	0.684977	2.19265	1.434144	32.50724	0.0971	0.00073	
	6	0	0	0.4684818	0	-1.60367	0	0	0	-0.02172	0	-2.04657	0	0	0	0	-4.52191	0	14.5308	0.468985	4.52191	2.60004	14.5308	0.07102	0.00029	
	7	0	0	0.5104214	0	-0.00412	0	0	0	0.362186	0	-3.46978	0	0	0	0	-4.52191	0	14.5308	0.625867	4.52191	3.469785	14.5308	0.08818	0.00055	
	8	0	0	0.2096273	0	7.775295	0	0	0	0.69192	0	-5.43344	0	0	0	0	1.014315	0	36.28635	0.722978	1.014315	9.485646	36.28635	0.09766	0.00074	
	9	0	0	0.293436	0	10.75193	0	0	0	0.232108	0	-6.59724	0	0	0	0	-4.52191	0	14.5308	0.374137	4.52191	12.61458	14.5308	0.05915	0.00017	
	10	0	0	0.0419396	0	1.599554	0	0	0	0.383911	0	-1.42321	0	0	0	0	-4.52191	0	14.5308	0.386195	4.52191	2.141053	14.5308	0.05915	0.00017	
	11	0	0	-0.396957	0	11.81016	0	0	0	-0.02477	0	-2.65286	0	0	0	0	-4.52191	0	14.5308	0.397729	4.52191	12.10445	14.5308	0.14331	0.00234	
	12	0	0	-0.438897	0	10.21061	0	0	0	-0.40868	0	-1.22964	0	0	0	0	-4.52191	0	14.5308	0.599706	4.52191	10.28439	14.5308	0.4953	0.00541	
4 0.225 sec	2	0	0	0.3248665	0	0.682923	0	0	0	-0.0117	0	3.305794	0	0		0	10.23875	0	17.7436	0.325077	10.23875	3.375597	17.7436			
	3	0	0	0.7639732	0	3.635854	0	0	0	-0.18396	0	3.797513	0	0	0	0	1.108325	0	20.29779	0.785809	1.108325	5.257427	20.29779			
	4	0	0	0.4391067	0	2.952931	0	0	0	-0.17226	0	0.491719	0	0	0	0	3.257401	0	17.7436	0.471688	3.257401	2.993591	17.7436			
	5	0	0	0.5325775	0	-3.59297	0	0	0	-0.07774	0	4.184522	0	0	0	0	0.897271	0	38.34967	0.538222	0.897271	5.515401	38.34967			
	6	0	0	0.2077111	0	-4.27589	0	0	0	-0.06605	0	0.878728	0	0	0	0	-2.10147	0	41.85262	0.217958	2.10147	4.36525	41.85262			
	7	0	0	0.2726699	0	-5.21791	0	0	0	0.101269	0	-2.59029	0	0	0	0	-2.10147	0	41.85262	0.290868	2.10147	5.825479	41.85262			
	8	0	0	0.5690245	0	1.068892	0	0	0	0.162366	0	-6.44632	0	0	0	0	3.257401	0	17.7436	0.591736	3.257401	6.534341	17.7436			
	9	0	0	0.9431724	0	4.963842	0	0	0	-0.17721	0	-2.48558	0	0	0	0	-2.10147	0	41.85262	0.959676	2.10147	5.551382	41.85262			
	10	0	0	0.0649589	0	-0.94202	0	0	0	0.167315	0	-3.46902	0	0	0	0	-2.10147	0	41.85262	0.179482	2.10147	3.59465	41.85262			
	11	0	0	0.6023596	0	11.68384	0	0	0	-0.20958	0	-1.1244	0	0	0	0	-2.10147	0	41.85262	0.637777	2.10147	11.73782	41.85262			
	12	0	0	0.5374007	0	12.62586	0	0	0	-0.37689	0	2.344619	0	0	0	0	-2.10147	0	41.85262	0.656389	2.10147	12.84171	41.85262			
5 0.300 sec	2	0	0	0.2427437	0	-2.58278	0	0	0	0.227764	0	2.36336	0	0		0	10.48401	0	-8.3832	0.332868	10.48401	3.500889	8.3832			
	3	0	0	0.7469995	0	-3.59845	0	0	0	0.173143	0	4.261039	0	0	0	0	2.164661	0	7.90997	0.766803	2.164661	5.57721	7.90997			
	4	0	0	0.5042557	0	-1.01567	0	0	0	-0.05462	0	1.897678	0	0	0	0	3.502665	0	-8.3832	0.507205	3.502665	2.152386	8.3832			
	5	0	0	0.1756009	0	-5.47644	0	0	0	0.252626	0	3.382215	0	0	0	0	2.57344	0	6.92176	0.307661	2.57344	6.436672	6.92176			
	6	0	0	-0.067143	0	-2.89366	0	0	0	0.024861	0	1.018854	0	0	0	0	0.690322	0	29.57635	0.071598	0.690322	3.067788	29.57635			
	7	0	0	-0.091027	0	-3.87978	0	0	0	-0.02904	0	-1.30696	0	0	0	0	0.690322	0	29.57635	0.095548	0.690322	4.094	29.57635			
	8	0	0	0.4564872	0	-2.98791	0	0	0	-0.16243	0	-2.75394	0	0	0	0	3.502665	0	-8.3832	0.484524	3.502665	4.063475	8.3832			
	9	0	0	0.9846272	0	-3.01746	0	0	0	-0.16315	0	1.469545	0	0	0	0	0.690322	0	29.57635	0.998052	0.690322	3.356281	29.57635			
	10	0	0	-0.023884	0	-0.98612	0	0	0	-0.0539	0	-2.32581	0	0	0	0	0.690322	0	29.57635	0.058959	0.690322	2.526229	29.57635			
	11	0	0	1.0969563	0	1.791234	0	0	0	-0.15776	0	1.777697	0	0	0	0	0.690322	0	29.57635	1.108242	0.690322	2.523634	29.57635			
	12	0	0	1.1208405	0	2.777357	0	0	0	-0.10386	0	4.103508	0	0	0	0	0.690322	0	29.57635	1.125642	0.690322	4.955047	29.57635			

Kinematic Tester for Knee Replacements

Position	Link #	X - Direction						Y-Direction						Z-Direction						Magnitudes			
		F	T	v	ω	a	α	F	T	v	ω	a	α	F	T	v	ω	a	α	v	ω	a	α
6 0.375 sec	2	0	0	0.0196186	0	-2.87717	0	0	0	0.300158	0	-0.32649	0	0		0	9.473966	0	-16.1716	0.300799	9.473966	2.895638	16.1716
	3	0	0	0.3779484	0	-5.31005	0	0	0	0.34353	0	0.285299	0	0	0	0	2.390584	0	-1.19686	0.510743	2.390584	5.317713	1.19686
	4	0	0	0.3583297	0	-2.43288	0	0	0	0.043372	0	0.611789	0	0	0	0	2.49262	0	-16.1716	0.360945	2.49262	2.508625	16.1716
	5	0	0	-0.211162	0	-4.39936	0	0	0	0.355536	0	-0.51972	0	0	0	0	2.43284	0	-7.37899	0.413516	2.43284	4.429952	7.37899
	6	0	0	-0.23078	0	-1.52219	0	0	0	0.055378	0	-0.19323	0	0	0	0	2.288266	0	13.83654	0.237332	2.288266	1.534402	13.83654
	7	0	0	-0.288158	0	-1.44164	0	0	0	-0.13144	0	-1.45419	0	0	0	0	2.288266	0	13.83654	0.316722	2.288266	2.047679	13.83654
	8	0	0	0.2435745	0	-2.27178	0	0	0	-0.33027	0	-1.91014	0	0	0	0	2.49262	0	-16.1716	0.410377	2.49262	2.968098	16.1716
	9	0	0	0.6592818	0	-4.78521	0	0	0	-0.10008	0	-0.03738	0	0	0	0	2.288266	0	13.83654	0.666835	2.288266	4.785358	13.83654
	10	0	0	-0.057378	0	0.080551	0	0	0	-0.18682	0	-1.26096	0	0	0	0	2.288266	0	13.83654	0.195435	2.288266	1.263533	13.83654
	11	0	0	1.026869	0	-2.70433	0	0	0	-0.0381	0	1.178503	0	0	0	0	2.288266	0	13.83654	1.027576	2.288266	2.949957	13.83654
	12	0	0	1.0842466	0	-2.78488	0	0	0	0.14872	0	2.439466	0	0	0	0	2.288266	0	13.83654	1.094399	2.288266	3.702234	13.83654
7 0.450 sec	2	0	0	-0.147729	0	-1.4982	0	0	0	0.216292	0	-1.63776	0	0		0	8.249668	0	-15.981	0.261927	8.249668	2.219651	15.981
	3	0	0	0.0296946	0	-3.79397	0	0	0	0.263747	0	-2.01071	0	0	0	0	2.060592	0	-7.25928	0.265413	2.060592	4.29385	7.25928
	4	0	0	0.1774233	0	-2.29577	0	0	0	0.047455	0	-0.37295	0	0	0	0	1.268322	0	-15.981	0.18366	1.268322	2.325865	15.981
	5	0	0	-0.447833	0	-1.8516	0	0	0	0.227131	0	-2.49507	0	0	0	0	1.777145	0	-9.09315	0.502139	1.777145	3.107051	9.09315
	6	0	0	-0.300105	0	-0.3534	0	0	0	0.01084	0	-0.85731	0	0	0	0	2.895388	0	3.106595	0.3003	2.895388	0.927291	3.106595
	7	0	0	-0.324442	0	0.333027	0	0	0	-0.23525	0	-1.19183	0	0	0	0	2.895388	0	3.106595	0.400754	2.895388	1.237481	3.106595
	8	0	0	0.1287485	0	-0.92292	0	0	0	-0.44472	0	-1.04199	0	0	0	0	1.268322	0	-15.981	0.462982	1.268322	1.391949	15.981
	9	0	0	0.3305091	0	-3.90511	0	0	0	-0.15118	0	-1.08042	0	0	0	0	2.895388	0	3.106595	0.363443	2.895388	4.051817	3.106595
	10	0	0	-0.024337	0	0.686423	0	0	0	-0.24609	0	-0.33452	0	0	0	0	2.895388	0	3.106595	0.247288	2.895388	0.763596	3.106595
	11	0	0	0.7708745	0	-3.92193	0	0	0	0.01782	0	0.375975	0	0	0	0	2.895388	0	3.106595	0.77108	2.895388	3.939911	3.106595
	12	0	0	0.7952119	0	-4.60835	0	0	0	0.263907	0	0.710493	0	0	0	0	2.895388	0	3.106595	0.83786	2.895388	4.662802	3.106595
8 0.525 sec	2	0	0	-0.207965	0	-0.19005	0	0	0	0.087082	0	-1.65614	0	0		0	7.101122	0	-14.6257	0.225461	7.101122	1.667008	14.6257
	3	0	0	-0.191462	0	-2.20582	0	0	0	0.092418	0	-2.30581	0	0	0	0	1.343582	0	-11.5855	0.2126	1.343582	3.190989	11.5855
	4	0	0	0.0165029	0	-2.01577	0	0	0	0.005337	0	-0.64967	0	0	0	0	0.119776	0	-14.6257	0.017344	0.119776	2.117876	14.6257
	5	0	0	-0.498257	0	0.362744	0	0	0	0.03351	0	-2.40848	0	0	0	0	1.132301	0	-8.0263	0.499383	1.132301	2.435646	8.0263
	6	0	0	-0.290293	0	0.552793	0	0	0	-0.05357	0	-0.75234	0	0	0	0	2.846159	0	-3.9249	0.295194	2.846159	0.933595	3.9249
	7	0	0	-0.261188	0	1.199535	0	0	0	-0.29491	0	-0.3367	0	0	0	0	2.846159	0	-3.9249	0.39394	2.846159	1.245894	3.9249
	8	0	0	0.0747119	0	-0.72228	0	0	0	-0.47733	0	0.181609	0	0	0	0	0.119776	0	-14.6257	0.483145	0.119776	0.744766	14.6257
	9	0	0	0.0621102	0	-3.38479	0	0	0	-0.23066	0	-0.88371	0	0	0	0	2.846159	0	-3.9249	0.238877	2.846159	3.498253	3.9249
	10	0	0	0.0291045	0	0.646742	0	0	0	-0.24133	0	0.415642	0	0	0	0	2.846159	0	-3.9249	0.243083	2.846159	0.768787	3.9249
	11	0	0	0.4486617	0	-4.6466	0	0	0	0.025382	0	-0.13661	0	0	0	0	2.846159	0	-3.9249	0.449379	2.846159	4.648606	3.9249
	12	0	0	0.4195572	0	-5.29334	0	0	0	0.266717	0	-0.55225	0	0	0	0	2.846159	0	-3.9249	0.497158	2.846159	5.322071	3.9249
9 0.600 sec	2	0	0	-0.191564	0	0.522902	0	0	0	-0.0185	0	-1.1215	0	0		0	6.061576	0	-12.9969	0.192455	6.061576	1.237415	12.9969
	3	0	0	-0.31949	0	-1.31886	0	0	0	-0.05557	0	-1.52758	0	0	0	0	0.372825	0	-13.8942	0.324287	0.372825	2.018142	13.8942
	4	0	0	-0.127927	0	-1.84176	0	0	0	-0.03706	0	-0.40608	0	0	0	0	-0.91977	0	-12.9969	0.133188	0.91977	1.885998	12.9969
	5	0	0	-0.419697	0	1.553623	0	0	0	-0.10967	0	-1.33629	0	0	0	0	0.56515	0	-7.21318	0.433789	0.56515	2.049249	7.21318
	6	0	0	-0.228134	0	1.030721	0	0	0	-0.09116	0	-0.21479	0	0	0	0	2.368704	0	-8.45984	0.245674	2.368704	1.052863	8.45984
	7	0	0	-0.164938	0	1.260238	0	0	0	-0.28335	0	0.62128	0	0	0	0	2.368704	0	-8.45984	0.327855	2.368704	1.405058	8.45984
	8	0	0	-0.001535	0	-1.38273	0	0	0	-0.42143	0	1.266062	0	0	0	0	-0.91977	0	-12.9969	0.42143	0.91977	1.874794	12.9969
	9	0	0	-0.192657	0	-3.45401	0	0	0	-0.26631	0	0.023916	0	0	0	0	2.368704	0	-8.45984	0.328691	2.368704	3.454092	8.45984
	10	0	0	0.0631958	0	0.229517	0	0	0	-0.19218	0	0.836069	0	0	0	0	2.369704	0	-8.45984	0.202305	2.369704	0.867	8.45984
	11	0	0	0.0809338	0	-5.07572	0	0	0	0.005812	0	-0.29991	0	0	0	0	2.370704	0	-8.45984	0.081142	2.370704	5.084572	8.45984
	12	0	0	0.017738	0	-5.30524	0	0	0	0.197993	0	-1.13598	0	0	0	0	2.371704	0	-8.45984	0.198786	2.371704	5.425494	8.45984
10 0.675 sec	2	0	0	-0.142919	0	0.706805	0	0	0	-0.08117	0	-0.57707	0	0		0	5.176701	0	-10.3816	0.16436	5.176701	0.912461	10.3816
	3	0	0	-0.400084	0	-0.85638	0	0	0	-0.1276	0	-0.38008	0	0	0	0	-0.6716	0	-13.4814	0.419939	0.6716	0.936937	13.4814
	4	0	0	-0.257165	0	-1.56319	0	0	0	-0.04643	0	0.196992	0	0	0	0	-1.80465	0	-10.3816	0.261323	1.80465	1.575552	10.3816
	5	0	0	-0.287667	0	1.860719	0	0	0	-0.16618	0	-0.21445	0	0	0	0	0.029568	0	-7.2302	0.332217	0.029568	1.873036	7.2302
	6	0	0	-0.144747	0	1.153914	0	0	0	-0.08501	0	0.362625	0	0	0	0	1.6185	0	-11.3641	0.167866	1.6185	1.209551	11.3641
	7	0	0	-0.082321	0	0.915209	0	0	0	-0.20835	0	1.329627	0	0	0	0	1.6185	0	-11.3641	0.224019	1.6185	1.614161	11.3641
	8	0	0	-0.132311	0	-2.0406	0	0	0	-0.2931	0	2.130996	0	0	0	0	-1.80465	0	-10.3816	0.321577	1.80465	2.950456	10.3816
	9	0	0	-0.451903	0	-3.36508	0	0	0	-0.21619	0	1.360987	0	0	0	0	1.6185	0	-11.3641	0.500955	1.6185	3.629884	11.3641
	10	0	0	0.0624267	0	-0.23871	0	0	0	-0.12333	0	0.967002	0	0	0	0	1.6185	0	-11.3641	0.138232	1.6185	0.996028	11.3641
	11	0	0	-0.295032	0	-4.80952	0	0	0	-0.00427	0	0.126905	0	0	0	0	1.6185	0	-11.3641	0.295063	1.6185	4.811198	11.3641
	12	0	0	-0.357458	0	-4.57082	0	0	0	0.119062	0	-0.8401	0	0	0	0	1.6185	0	-11.3641	0.376766	1.6185	4.647381	11.3641

Position	Link #	X - Direction						Y-Direction						Z-Direction						Magnitudes			
		F	T	v	ω	a	α	F	T	v	ω	a	α	F	T	v	ω	a	α	v	ω	a	α
11 0.750 sec	2	0	0	-0.091953	0	0.632578	0	0	0	-0.11101	0	-0.2622	0	0		0	4.539981	0	-6.35008	0.144145	4.539981	0.684767	6.35008
	3	0	0	-0.445422	0	-0.30192	0	0	0	-0.11719	0	0.584646	0	0	0	0	-1.58458	0	-10.5016	0.460582	1.58458	0.658001	10.5016
	4	0	0	-0.353469	0	-0.9345	0	0	0	-0.00619	0	0.84685	0	0	0	0	-2.44136	0	-6.35008	0.353523	2.44136	1.261125	6.35008
	5	0	0	-0.148615	0	1.846887	0	0	0	-0.1513	0	0.544056	0	0	0	0	-0.54909	0	-8.44687	0.212078	0.54909	1.925354	8.44687
	6	0	0	-0.056662	0	1.214308	0	0	0	-0.04029	0	0.806259	0	0	0	0	0.670346	0	-14.0465	0.069526	0.670346	1.4576	14.0465
	7	0	0	-0.026462	0	0.614102	0	0	0	-0.08893	0	1.845704	0	0	0	0	0.670346	0	-14.0465	0.092783	0.670346	1.945185	14.0465
	8	0	0	-0.293069	0	-2.13491	0	0	0	-0.10347	0	2.92574	0	0	0	0	-2.44136	0	-6.35008	0.310798	2.44136	3.621849	6.35008
	9	0	0	-0.676738	0	-2.4692	0	0	0	-0.06102	0	2.733145	0	0	0	0	0.670346	0	-14.0465	0.679483	0.670346	3.683343	14.0465
	10	0	0	0.0301999	0	-0.60021	0	0	0	-0.04864	0	1.039445	0	0	0	0	0.670346	0	-14.1465	0.057253	0.670346	1.200289	14.1465
	11	0	0	-0.619645	0	-3.72794	0	0	0	0.032073	0	0.820785	0	0	0	0	0.670346	0	-14.1465	0.620474	0.670346	3.817226	14.1465
	12	0	0	-0.649844	0	-3.12773	0	0	0	0.080713	0	-0.21866	0	0	0	0	0.670346	0	-14.1465	0.654838	0.670346	3.135366	14.1465
12 0.825 sec	2	0	0	-0.048252	0	0.546782	0	0	0	-0.12655	0	-0.1877	0	0		0	4.265871	0	-0.61132	0.135442	4.265871	0.578102	0.61132
	3	0	0	-0.435217	0	0.64931	0	0	0	-0.05672	0	0.878813	0	0	0	0	-2.20208	0	-5.69989	0.438897	2.20208	1.092664	5.69989
	4	0	0	-0.386964	0	0.102528	0	0	0	0.069838	0	1.066515	0	0	0	0	-2.71548	0	-0.61132	0.393216	2.71548	1.071432	0.61132
	5	0	0	-0.003315	0	2.122381	0	0	0	-0.09411	0	0.913262	0	0	0	0	-1.28041	0	-11.3386	0.094171	1.28041	2.31053	11.3386
	6	0	0	0.0449374	0	1.575599	0	0	0	0.032442	0	1.100964	0	0	0	0	-0.53438	0	-18.5304	0.055424	0.53438	1.922143	18.5304
	7	0	0	0.0205845	0	0.751759	0	0	0	0.071043	0	2.452492	0	0	0	0	-0.53438	0	-18.5304	0.073965	0.53438	2.565124	18.5304
	8	0	0	-0.43567	0	-1.54515	0	0	0	0.147038	0	3.76957	0	0	0	0	-2.71548	0	-0.61132	0.459814	2.71548	4.07396	0.61132
	9	0	0	-0.798281	0	-0.61878	0	0	0	0.178276	0	3.484558	0	0	0	0	-0.53438	0	-18.5304	0.817946	0.53438	3.539073	18.5304
	10	0	0	-0.024353	0	-0.82384	0	0	0	0.0386	0	1.351528	0	0	0	0	-0.53438	0	-18.5304	0.04564	0.53438	1.582826	18.5304
	11	0	0	-0.84326	0	-2.2183	0	0	0	0.103741	0	0.923993	0	0	0	0	-0.53438	0	-18.5304	0.849617	0.53438	2.403047	18.5304
	12	0	0	-0.818907	0	-1.39446	0	0	0	0.065141	0	-0.42753	0	0	0	0	-0.53438	0	-18.5304	0.821494	0.53438	1.458532	18.5304

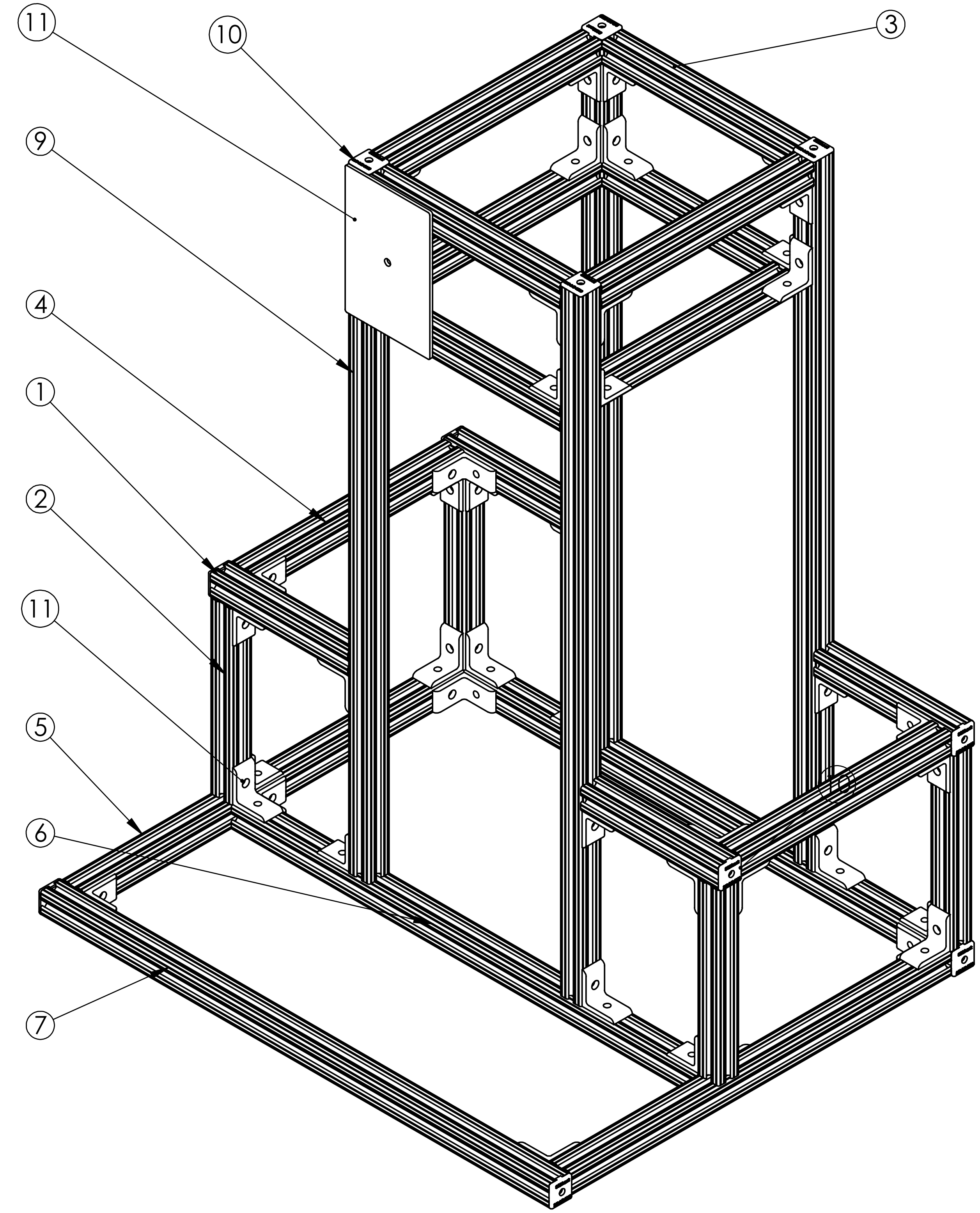
Appendix F: Dimension Drawing of the Motor Mount



Appendix G: Frame Design Alternatives

The following pages depict detailed drawings of each design alternative of the frame, including all necessary dimensions.

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	1010-06	N/A	1.0" 1.0" 8020 COMP; 6.5" NOM	6105-T5 ALUMINUM	4
2	1010-08	N/A	1.0" 1.0" 8020 COMP; 8" NOM	6105-T5 ALUMINUM	4
3	1010-09	N/A	1.0" 1.0" 8020 COMP; 9" NOM	6105-T5 ALUMINUM	4
4	1010-10	N/A	1.0" 1.0" 8020 COMP; 10" NOM	6105-T5 ALUMINUM	6
5	1010-18	N/A	1.0" 1.0" 8020 COMP; 18" NOM	6105-T5 ALUMINUM	2
6	1010-22	N/A	1.0" 1.0" 8020 COMP; 22" NOM	6105-T5 ALUMINUM	1
7	1010-24	N/A	1.0" 1.0" 8020 COMP; 24" NOM	6105-T5 ALUMINUM	2
11	N/A	0	LINKAGE GROUND PLATE	WOOD	1
9	1010-29	N/A	1.0" 1.0" 8020 COMP; 29" NOM	6105-T5 ALUMINUM	4
10	2015	N/A	80/20 1010 SERIES BLACK END CAP	PLASTIC	12
11	4503	N/A	10 S TO 15 S 2 HOLE TRANS INSIDE CRN BRKT	ALUMINUM	49



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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

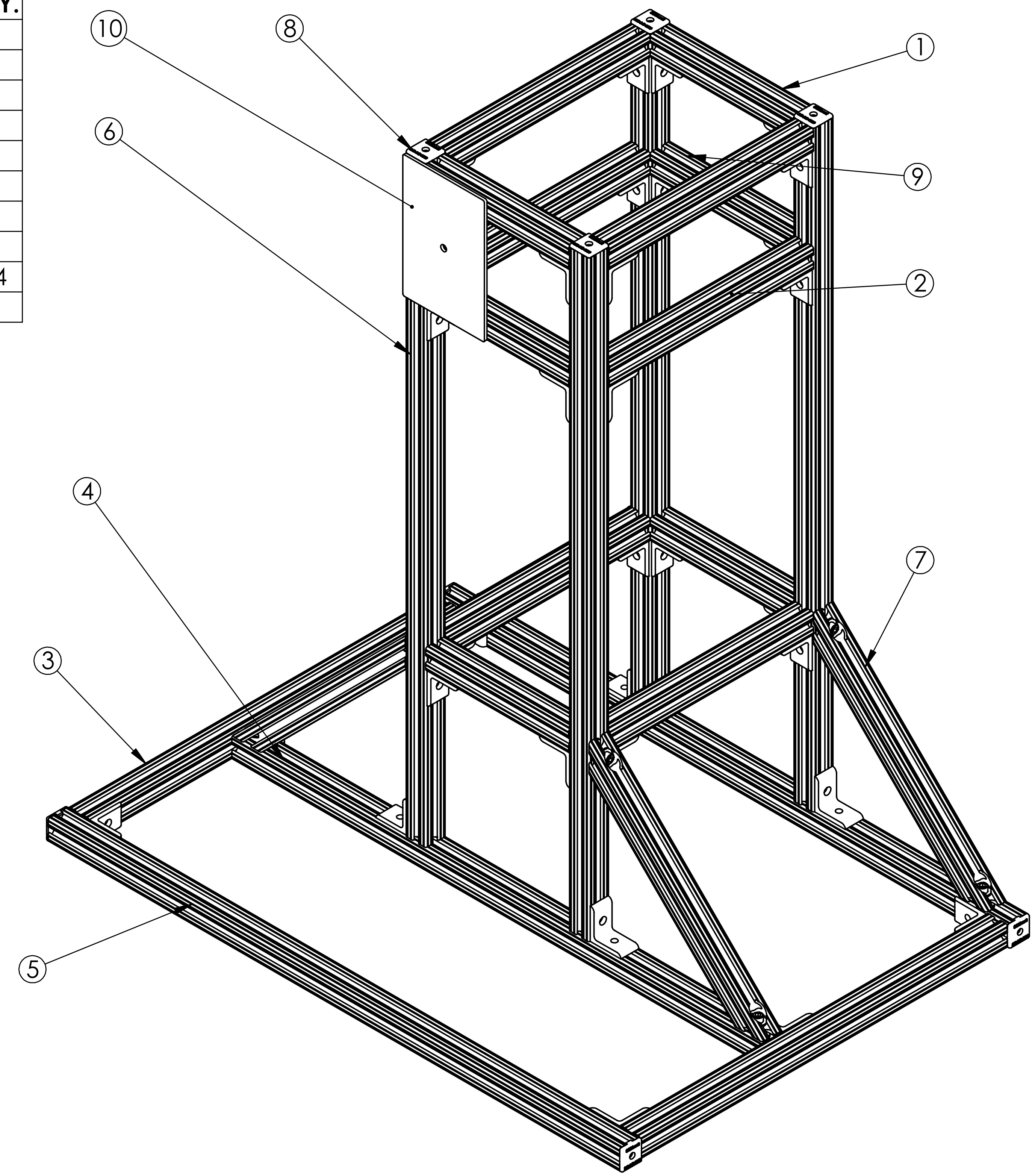
TITLE:

1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE B | DWG. NO. | REV 0

SCALE: 1:5 | WEIGHT: 15.54 | SHEET 1 OF 2

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	1010-07	N/A	1.0" 1.0" 8020 COMP; 7" NOM	6105-T5 ALUMINUM	6
2	1010-10	N/A	1.0" 1.0" 8020 COMP; 10" NOM	6105-T5 ALUMINUM	6
3	1010-18	N/A	1.0" 1.0" 8020 COMP; 18" NOM	6105-T5 ALUMINUM	2
4	1010-26	N/A	1.0" 1.0" 8020 COMP; 26" NOM	6105-T5 ALUMINUM	1
5	1010-28	N/A	1.0" 1.0" 8020 COMP; 28" NOM	6105-T5 ALUMINUM	2
6	1010-29	N/A	1.0" 1.0" 8020 COMP; 29" NOM	6105-T5 ALUMINUM	4
7	2570	N/A	1020 X 12" 45 DEGREE SUPPORT	6105-T5	4
8	2015	N/A	80/20 1010 SERIES BLACK END CAP	PLASTIC	8
9	4503	N/A	10 S TO 15 S 2 HOLE TRANS INSIDE CRN BRKT	ALUMINUM	34
10	N/A	0	LINKAGE GROUND PLATE	WOOD	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

TITLE:

1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE B | DWG. NO. | REV 0

SCALE: 1:5 | WEIGHT: 15.54 | SHEET 2 OF 2

Appendix H: Quote for Anchor-Fastened Frame Option

The following pages depict detailed drawings of each component of the anchor-fastened frame design. These were sent to 80/20 to get a price quote, which would help choose the final design.

QUOTATION

AIR INCORPORATED
8 FORGE PARK
FRANKLIN, MA 02038
USA

Tel 508-528-3020
Fax 508-528-7050
sales@airinc.net

www.airinc.net

Quote Number	
1103725	
Quote Date	Page
2/12/2015 14:26:04	1 of 2

Quote Expires On: 4/13/2015

Bill To:

AIR INC (HOUSE ACCOUNT)
8 FORGE PARK
FRANKLIN, MA 02038

508-528-3020

Ship To:

WPI
100 INSTITUTE DRIVE
ATTN: ALEX MAAG
WORCESTER, MA 01609

Requested By: . Jared Breton

Customer ID: 40146

RFQ	*Carrier*	*Taker*
KTKR-FR-1010-0-ANK	UPS GROUND	PTRAINOR

Quantities Ordered	Allocated	Remaining	UOM / Unit Size	Disp.	Item ID / Item Description	Pricing UOM / Unit Size	Unit Price	Extended Price
6.0	0.0	6.0	EA / 1.0		1010 X 6 IN 80/20 EXTRUSION With 7042 In A Both Ends	EA / 1.0	1.38	8.28
6.0	0.0	6.0	EA / 1.0		1010 X 10 IN 80/20 EXTRUSION With 7042 In A Both Ends	EA / 1.0	2.30	13.80
2.0	0.0	2.0	EA / 1.0		1010 X 14 IN 80/20 EXTRUSION With 7042 in A Both Ends	EA / 1.0	3.22	6.44
1.0	0.0	1.0	EA / 1.0		1010 X 29 IN 80/20 EXTRUSION With 7042 In A Both Ends	EA / 1.0	6.67	6.67
4.0	0.0	4.0	EA / 1.0		1010 X 29 IN 80/20 EXTRUSION With 7042 In A One End Only	EA / 1.0	6.67	26.68
2.0	0.0	2.0	EA / 1.0		1010 X 31 IN 80/20 EXTRUSION	EA / 1.0	7.13	14.26
21.0	0.0	21.0	EA / 1.0		7005 80/20 1010-CUT-CHARGE	EA / 1.0	1.95	40.95
34.0	0.0	34.0	EA / 1.0		7042 80 MACHINE COUNTERBORE#10	EA / 1.0	2.25	76.50
8.0	0.0	8.0	EA / 1.0 *Ordered As:*		2015-BLACK 80 1010 END CAP 2015	EA / 1.0	1.05	8.40
4.0	0.0	4.0	EA / 1.0		2128 80 1X2 BSE PLATE 1/4-20	EA / 1.0	9.75	39.00
4.0	0.0	4.0	EA / 1.0		2193 80 1/4-20 ECONO LVL FOOT	EA / 1.0	1.00	4.00

QUOTATION

AIR INCORPORATED
8 FORGE PARK
FRANKLIN, MA 02038
USA

Tel 508-528-3020
Fax 508-528-7050
sales@airinc.net

www.airinc.net

Quote Number	
1103725	
Quote Date	Page
2/12/2015 14:26:04	2 of 2

Quote Expires On: 4/13/2015

Quantities					*Item ID*	*Pricing UOM*	*Unit Price*	*Extended Price*
Ordered	*Allocated*	*Remaining*	*UOM Unit Size*	*Disp.*	*Item Description*	*Unit Size*		
4.0	0.0	4.0	EA		2570	EA	15.35	61.40
			1.0		80 45 DEG SUPP 1010X12	1.0		
8.0	0.0	8.0	EA		3266	EA	0.21	1.68
			1.0		SELF TAPPING SCREW	1.0		
34.0	0.0	34.0	EA		3395	EA	2.90	98.60
			1.0		80 ANCH FAST10-32BLT&TNUT	1.0		
8.0	0.0	8.0	EA		3491	EA	0.37	2.96
			1.0		80 1/4-20X1/2 SHCS T-NUT	1.0		

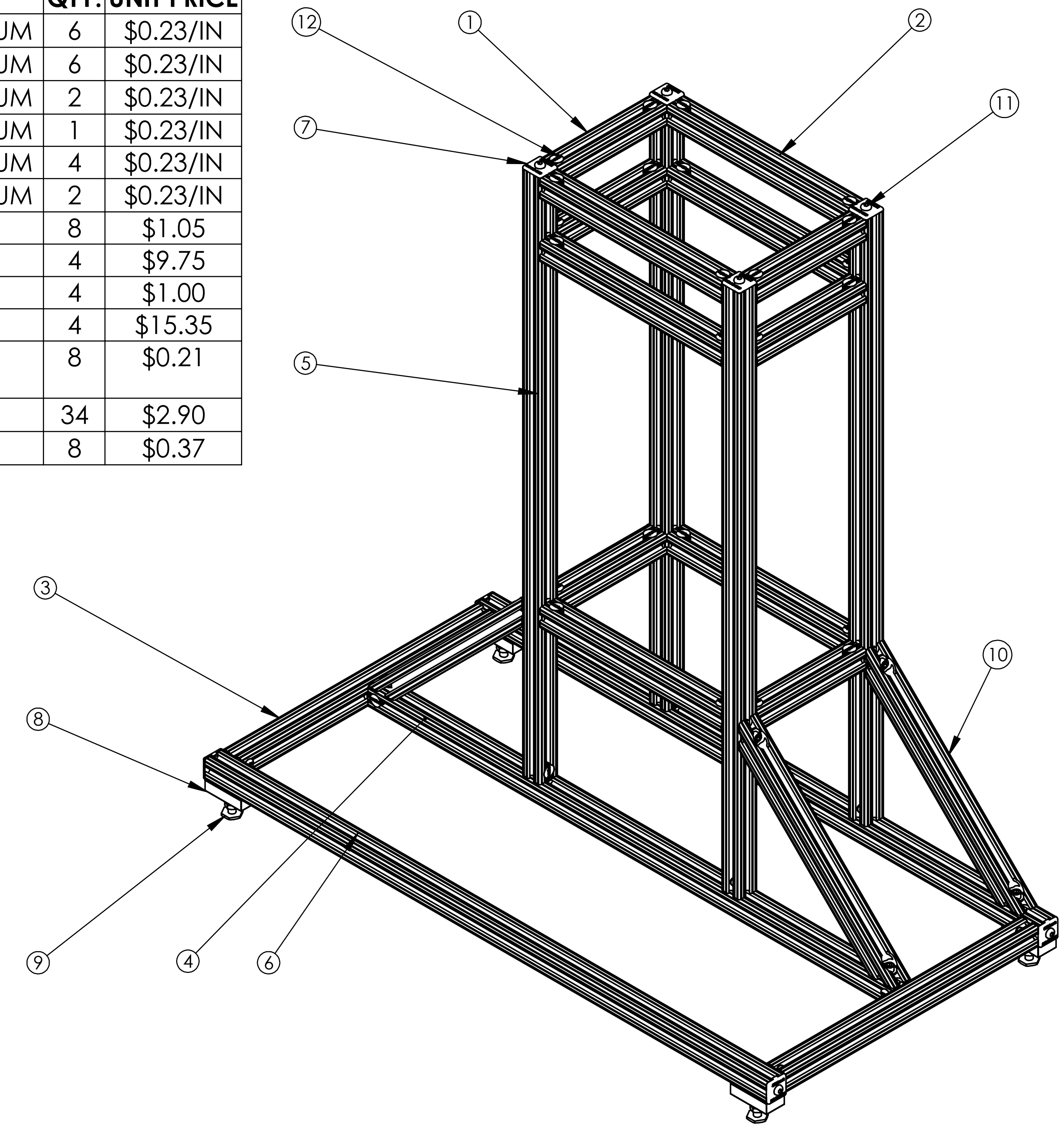
Total Lines: 15

Pricing based on quantity ordered
All lead times are factory estimates

SUB-TOTAL:	409.62
TAX:	0.00
AMOUNT DUE:	**409.62**

U.S. Dollars

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.	UNIT PRICE
1	1010-06	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 6" NOM	6105-T5 ALUMINUM	6	$0.23/IN
2	1010-10	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 10" NOM	6105-T5 ALUMINUM	6	$0.23/IN
3	1010-14	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 14" NOM	6105-T5 ALUMINUM	2	$0.23/IN
4	1010-29A	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM, 2 C-BORE	6105-T5 ALUMINUM	1	$0.23/IN
5	1010-29B	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM, 1 C-BORE	6105-T5 ALUMINUM	4	$0.23/IN
6	1010-31	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM	6105-T5 ALUMINUM	2	$0.23/IN
7	2015	N/A	80/20 1010 SERIES BLACK END CAP	PLASTIC	8	$1.05
8	2128	N/A	10 S 1" X 2" BASE PLATE W/ 1/4-20 TAP IN CENTER	ALUMINUM	4	$9.75
9	2193	N/A	1/4-20 ECONOMY LEVELING FOOT	ALUMINUM	4	$1.00
10	2570	N/A	1020 X 12" 45 DEGREE SUPPORT	6105-T5	4	$15.35
11	3266	N/A	12-24 X .375" SOCKET BUTTON HEAD THREAD BLK ZINC SELF TAP	N/A	8	$0.21
12	3395	N/A	10 S ANCHOR FASTENER ASSEMBLY	ALUMINUM	34	$2.90
13	3491	N/A	1/4"-20 X 1/2" SHCS, ECON T-NUT	ALUMINUM	8	$0.37



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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

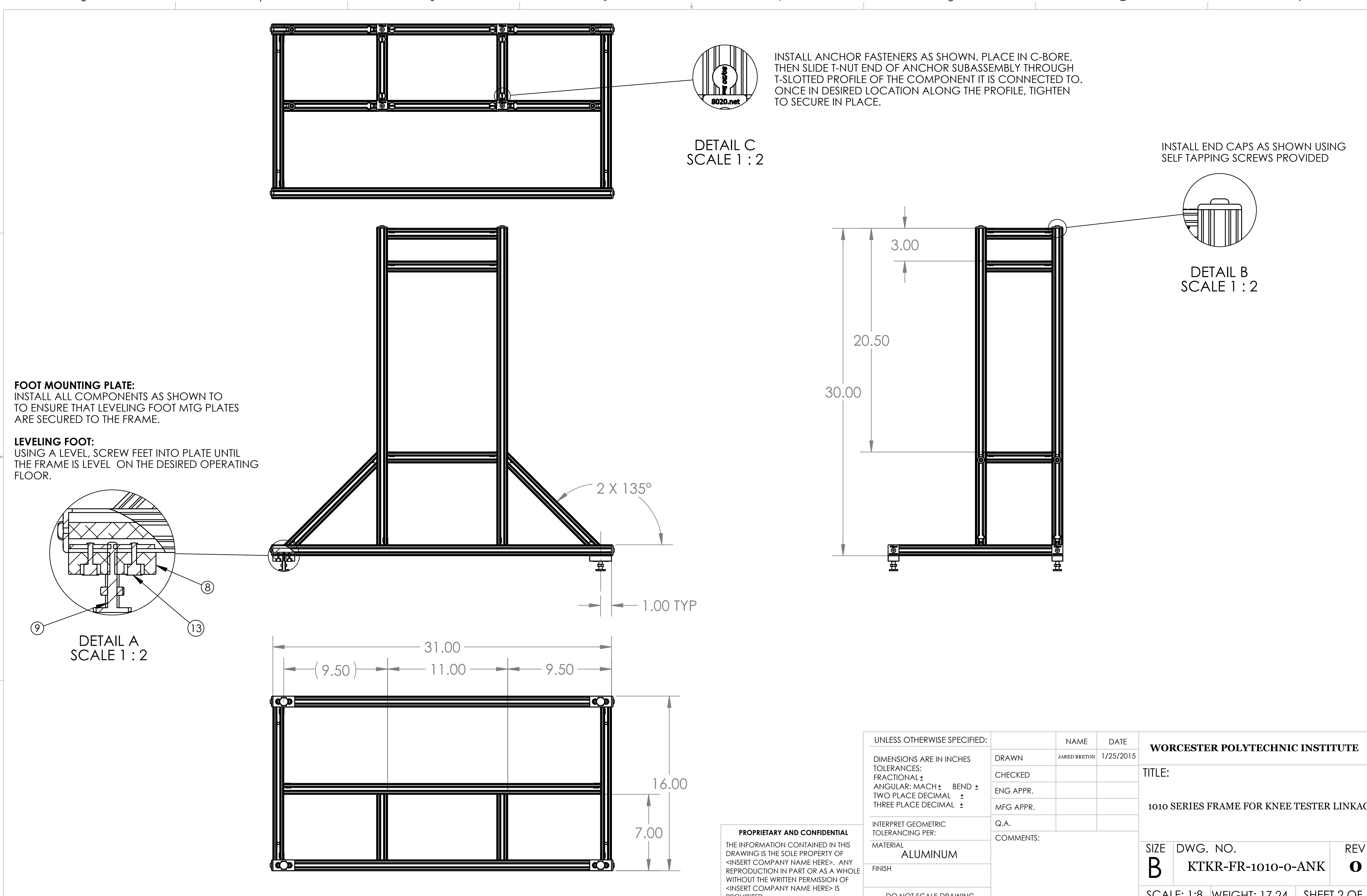
WORCESTER POLYTECHNIC INSTITUTE

TITLE:

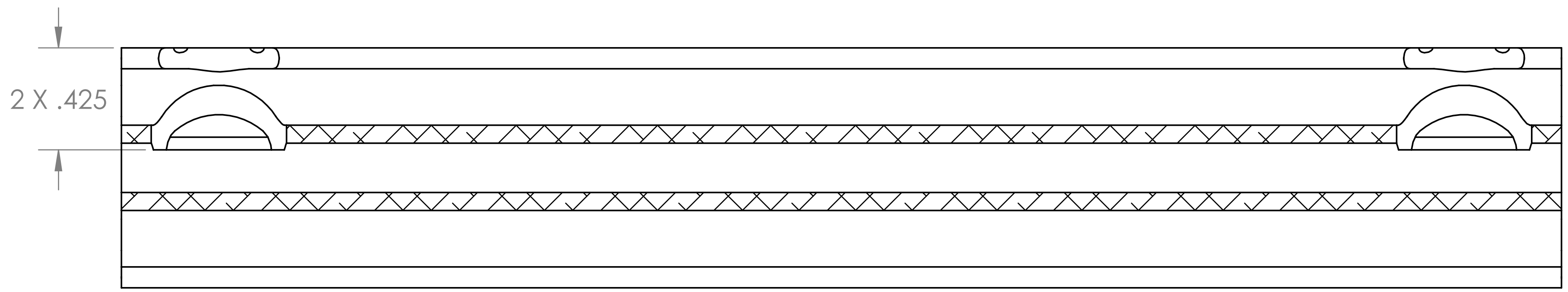
1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE: B | DWG. NO.: KTKR-FR-1010-0-ANK | REV: 0

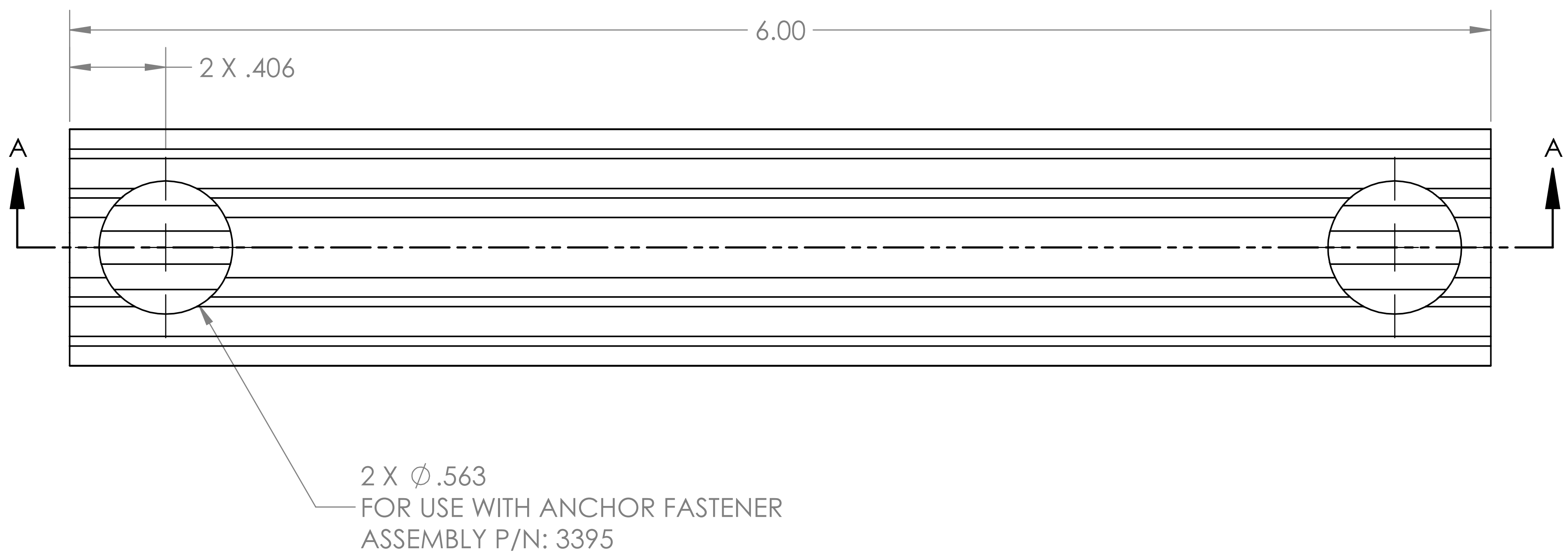
SCALE: 1:6 | WEIGHT: 17.24 | SHEET 1 OF 4

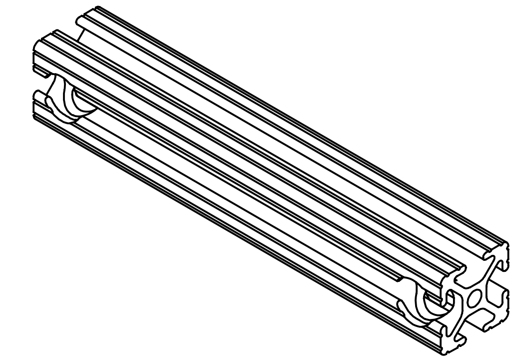


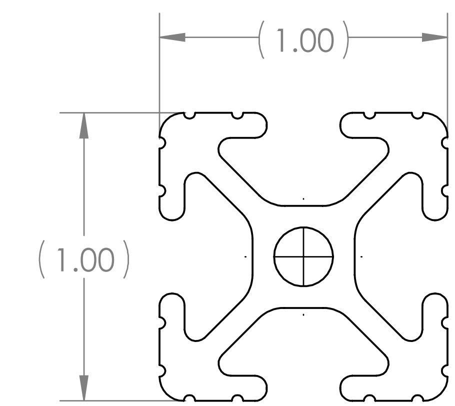
INSTALL ANCHOR FASTENERS AS SHOWN. PLACE IN C-BORE, THEN SLIDE T-NUT END OF ANCHOR SUBASSEMBLY THROUGH T-SLOTTED PROFILE OF THE COMPONENT IT IS CONNECTED TO. ONCE IN DESIRED LOCATION ALONG THE PROFILE, TIGHTEN TO SECURE IN PLACE.
8020.net
DETAIL C
SCALE 1 : 2
INSTALL END CAPS AS SHOWN USING SELF TAPPING SCREWS PROVIDED
DETAIL B
SCALE 1 : 2
3.00
20.50
30.00
FOOT MOUNTING PLATE:
INSTALL ALL COMPONENTS AS SHOWN TO TO ENSURE THAT LEVELING FOOT MTG PLATES ARE SECURED TO THE FRAME.
LEVELING FOOT:
USING A LEVEL, SCREW FEET INTO PLATE UNTIL THE FRAME IS LEVEL ON THE DESIRED OPERATING FLOOR.
2 X 135°
8
9
13
1.00 TYP
DETAIL A
SCALE 1 : 2
31.00
(9.50)
11.00
9.50
16.00
7.00
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.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
JARED BRETON
1/25/2015
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
WORCESTER POLYTECHNIC INSTITUTE
TITLE:
1010 SERIES FRAME FOR KNEE TESTER LINKAGE
SIZE
B
DWG. NO.
KTKR-FR-1010-0-ANK
REV
0
SCALE: 1:8
WEIGHT: 17.24
SHEET 2 OF 4



SECTION A-A







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

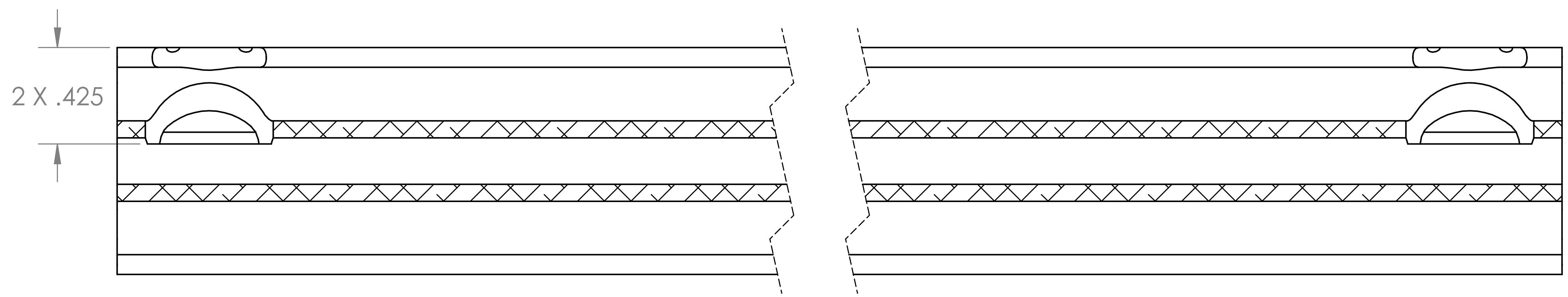
WORCESTER POLYTECH

TITLE:

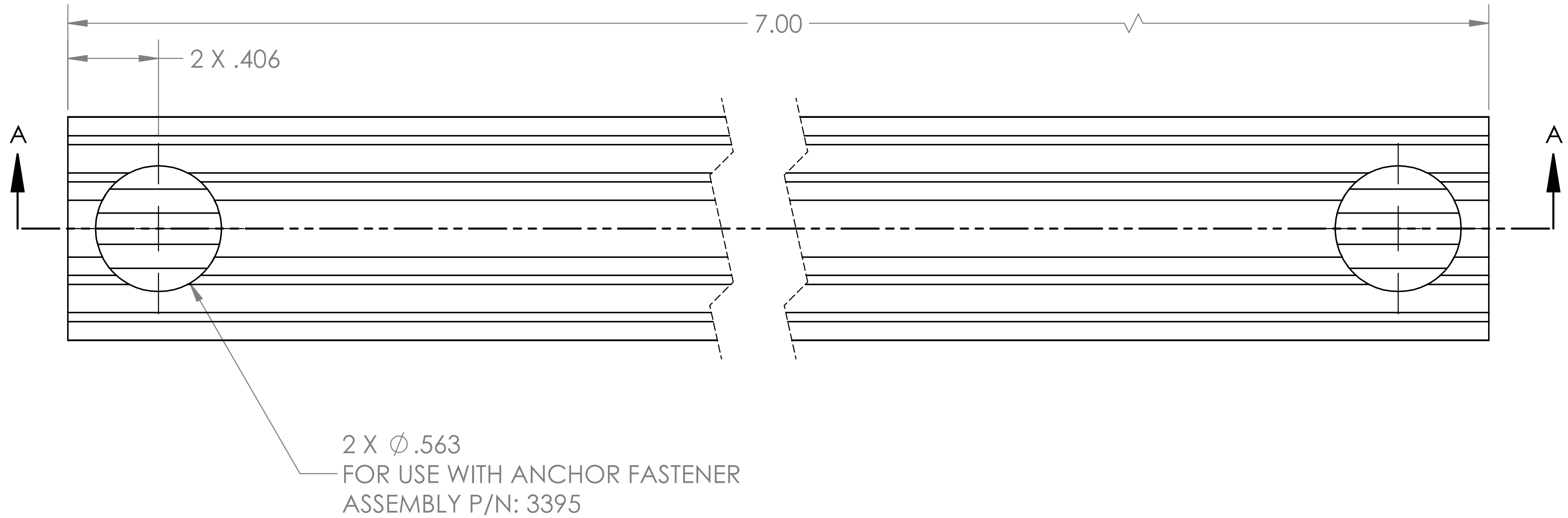
1.0" x 1.0" T-SLOTTED EXTRUSION; 6" NOM

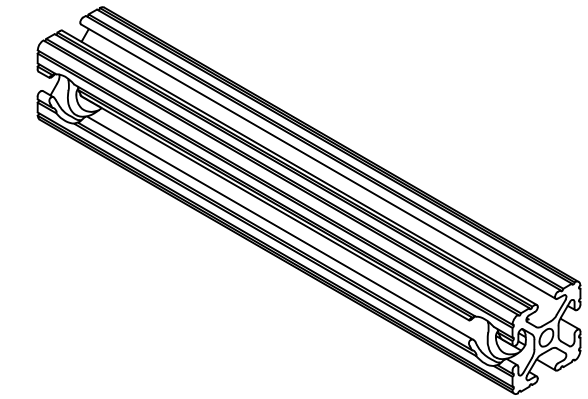
SIZE	DWG. NO.	REV
B	1010-06	0

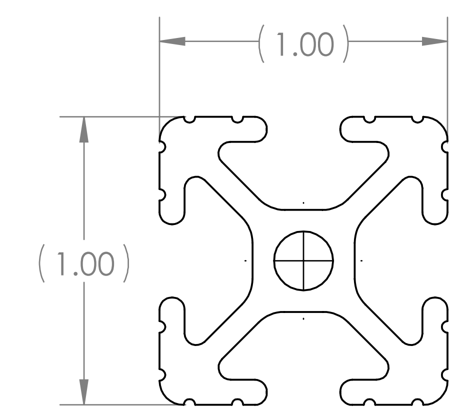
SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



SECTION A-A







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 6105-T5 ALUMINUM

FINISH: CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

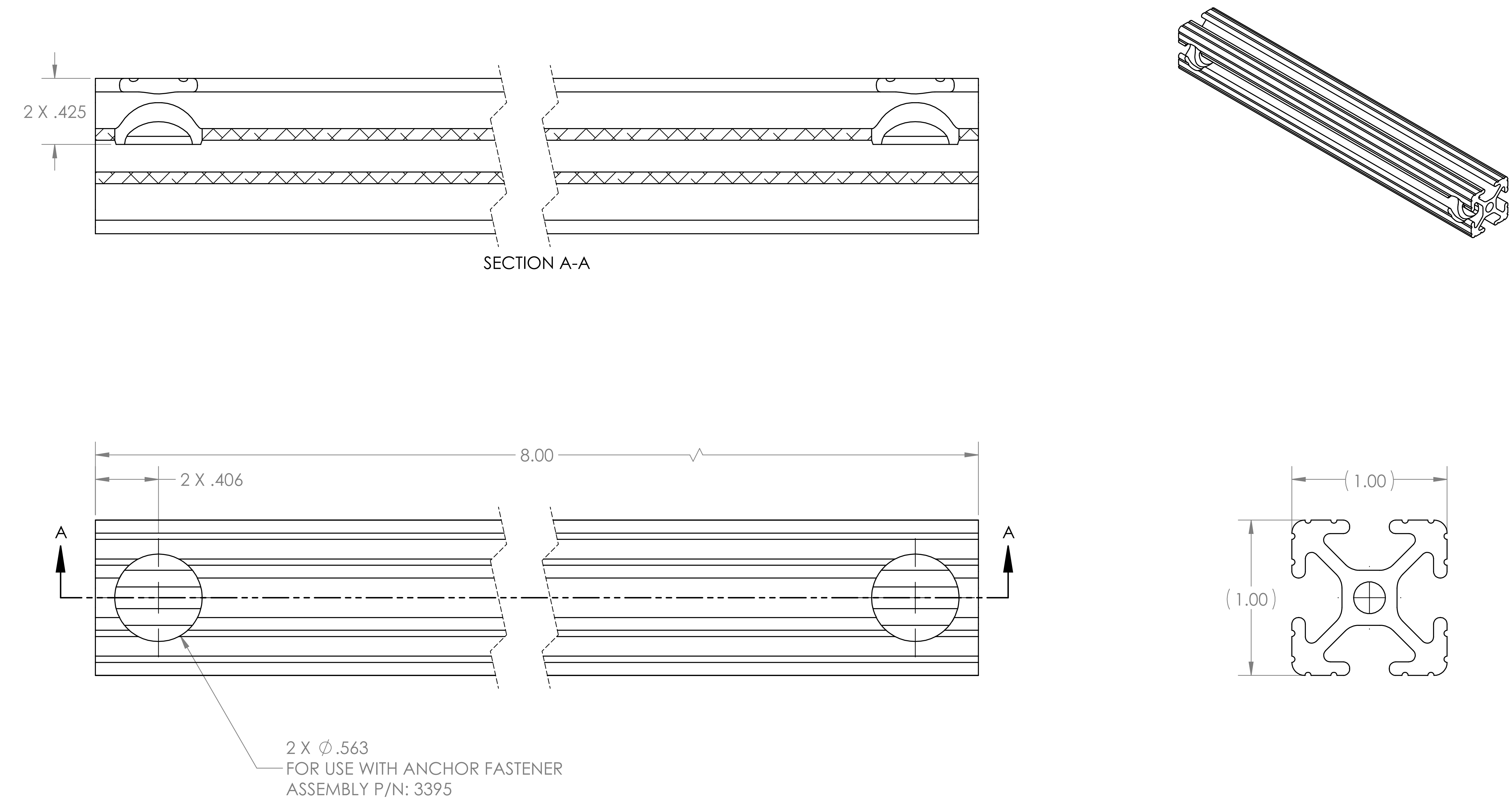
COMMENTS:

WORCESTER POLYTECH

TITLE: 1.0" x 1.0" T-SLOTTED EXTRUSION; 7" NOM

SIZE	DWG. NO.	REV
B	1010-07	0

SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

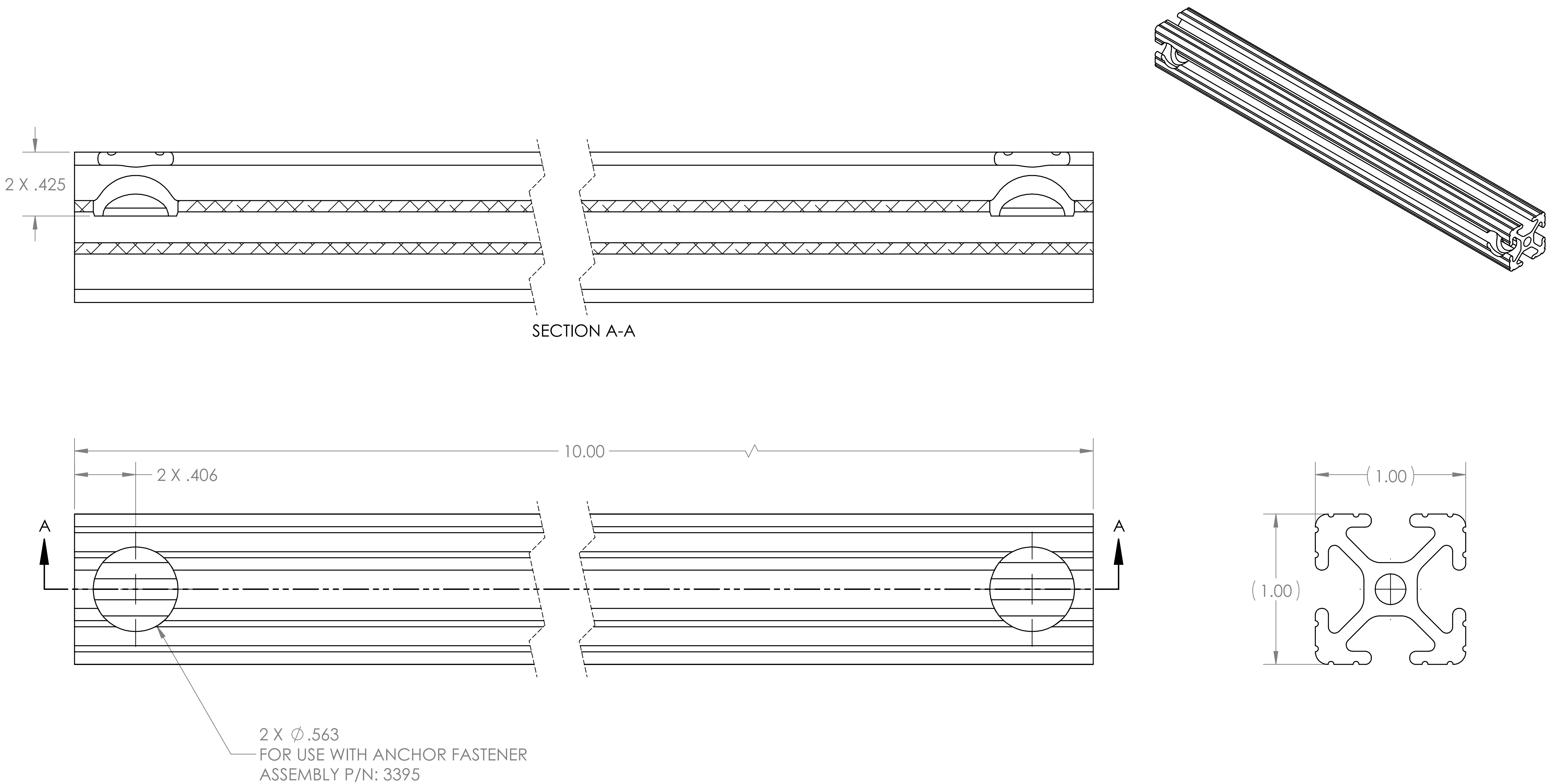
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 8" NOM

SIZE	DWG. NO.	REV
B	1010-08	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

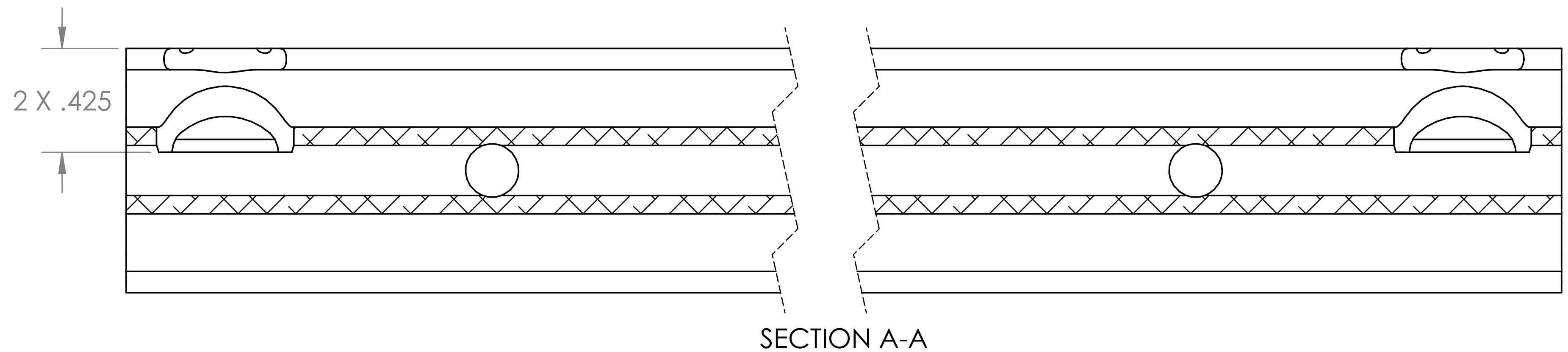
WORCESTER POLYTECH

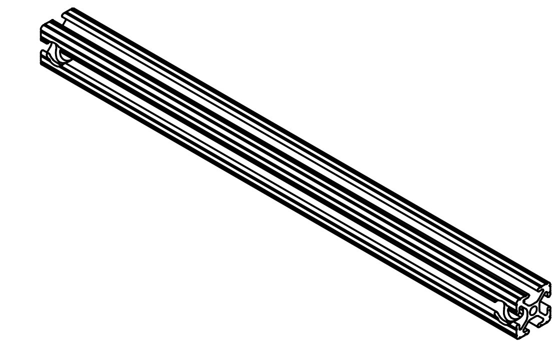
TITLE:

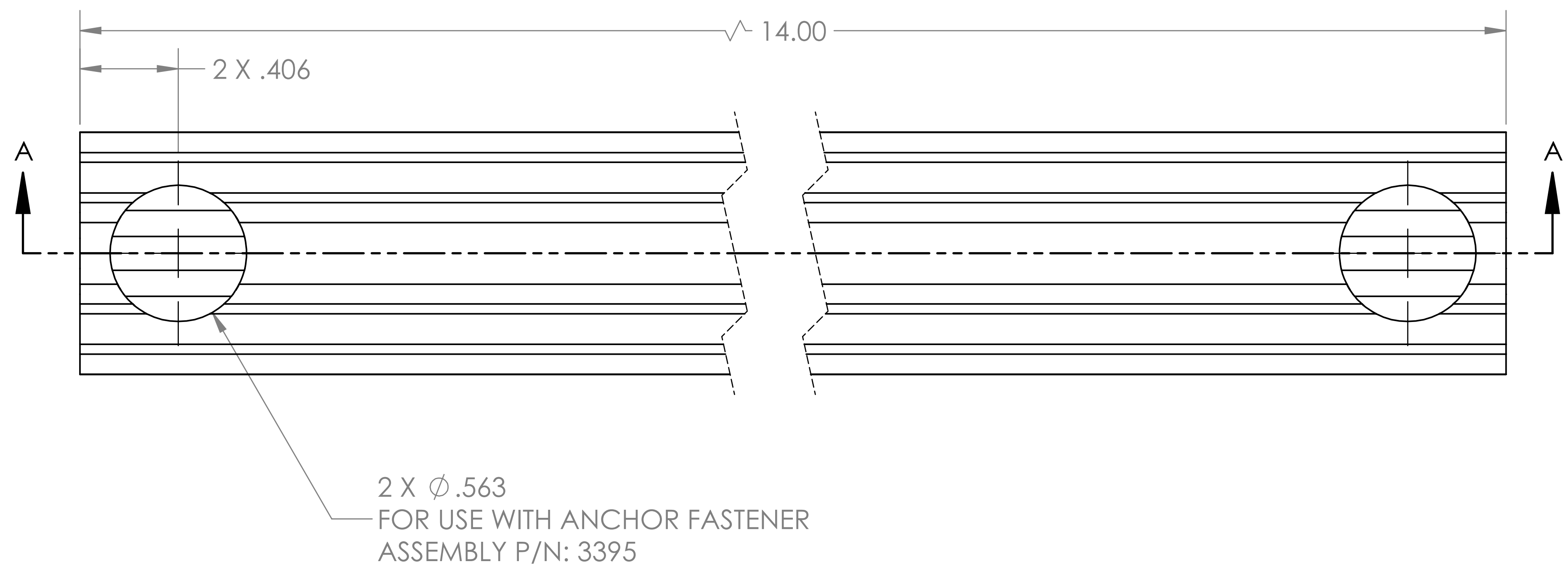
1.0" x 1.0" T-SLOTTED EXTRUSION; 10" NOM

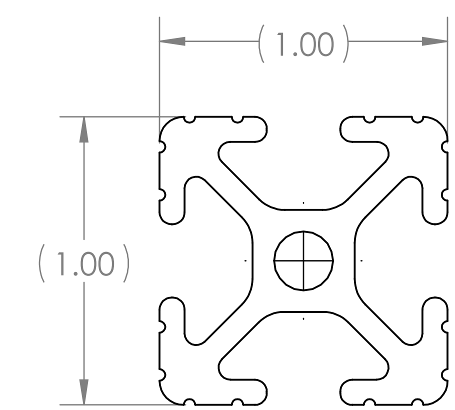
SIZE	DWG. NO.	REV
B	1010-10	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1









NOTE:
1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

PROPRIETARY AND CONFIDENTIAL

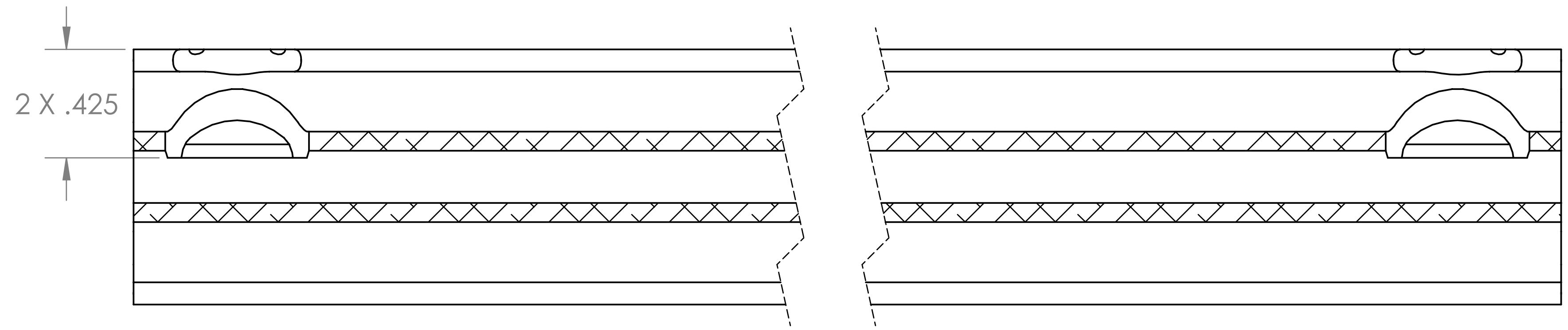
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	JARED BRETON	1/20/2015
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 6105-T5 ALUMINUM	COMMENTS:		
FINISH CLEAR ANODIZED			
DO NOT SCALE DRAWING			

WORCESTER POLYTECH

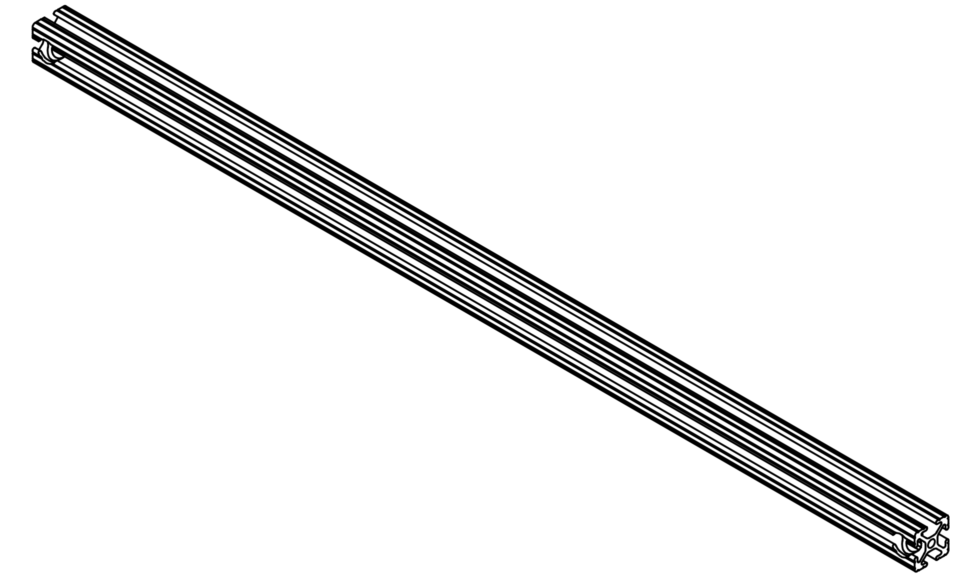
TITLE:

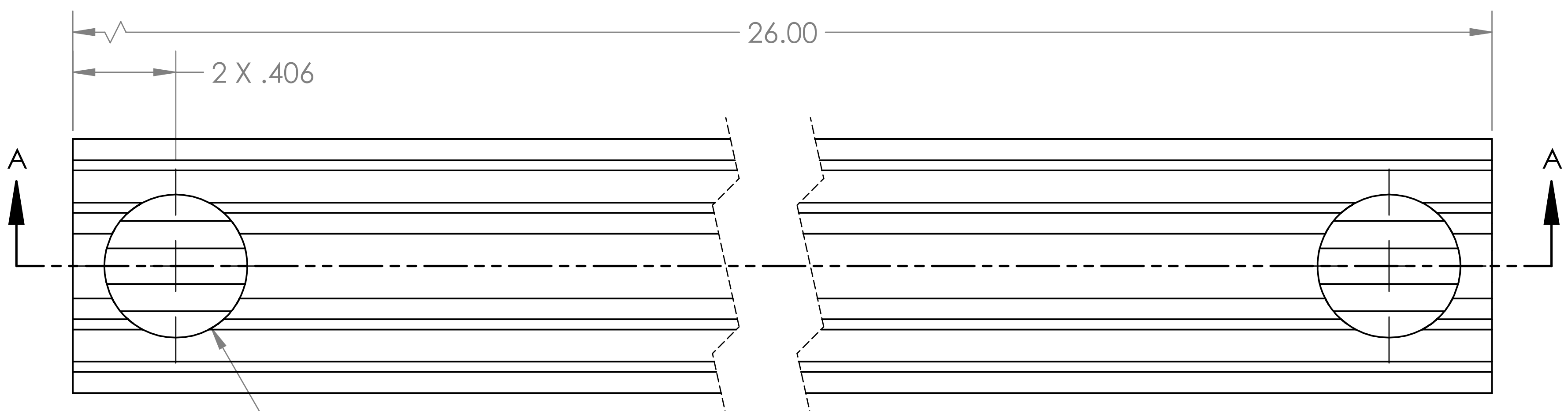
1.0" x 1.0" T-SLOTTED EXTRUSION; 14" NOM

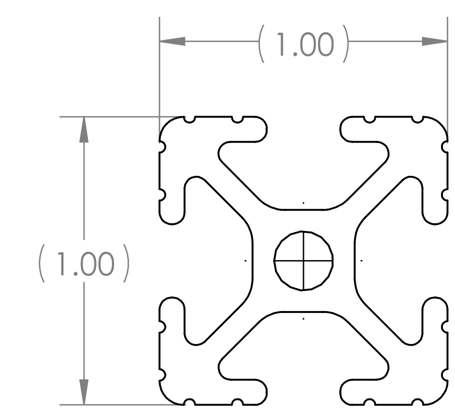
SIZE	DWG. NO.	REV
B	1010-14	0
SCALE: 3:2	WEIGHT: 1.301	SHEET 1 OF 1



SECTION A-A







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

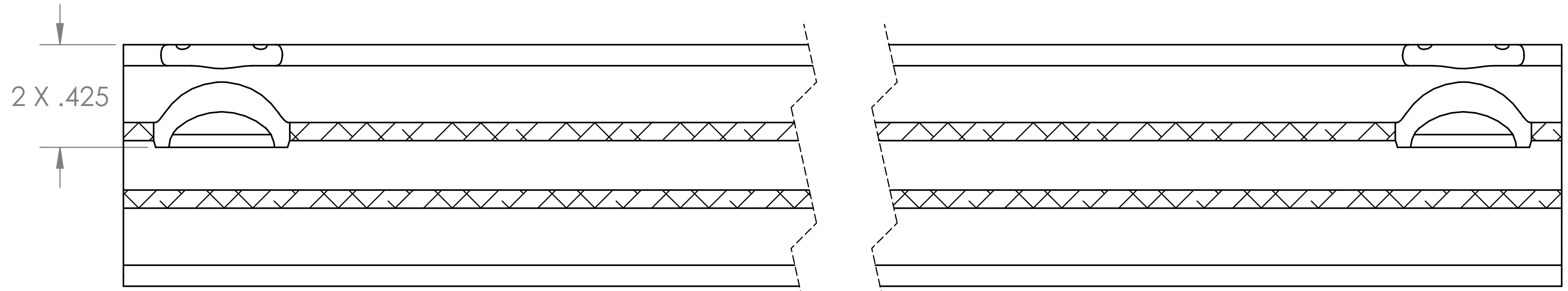
WORCESTER POLYTECH

TITLE:

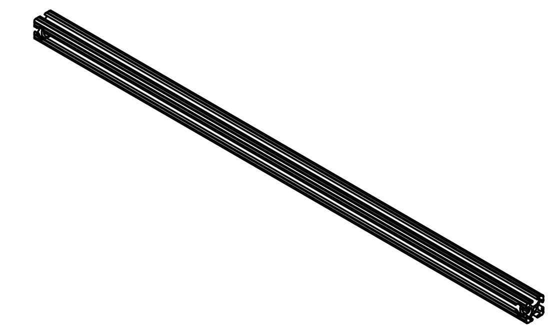
1.0" x 1.0" T-SLOTTED EXTRUSION; 26" NOM

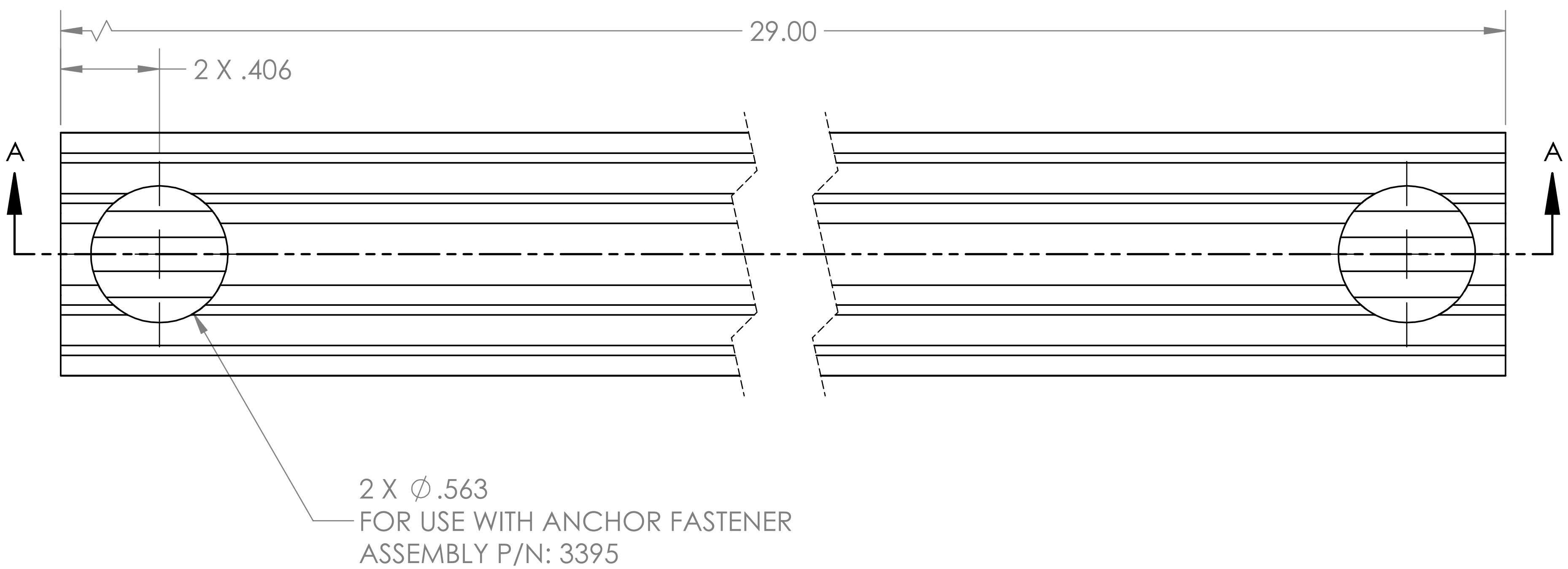
SIZE	DWG. NO.	REV
B	1010-26	0

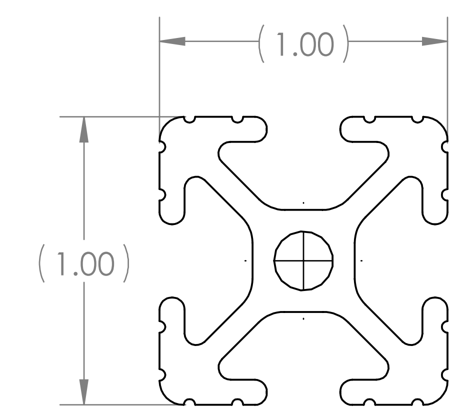
SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1



SECTION A-A







NOTE:
1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6105-T5 ALUMINUM
FINISH
CLEAR ANODIZED
DO NOT SCALE DRAWING

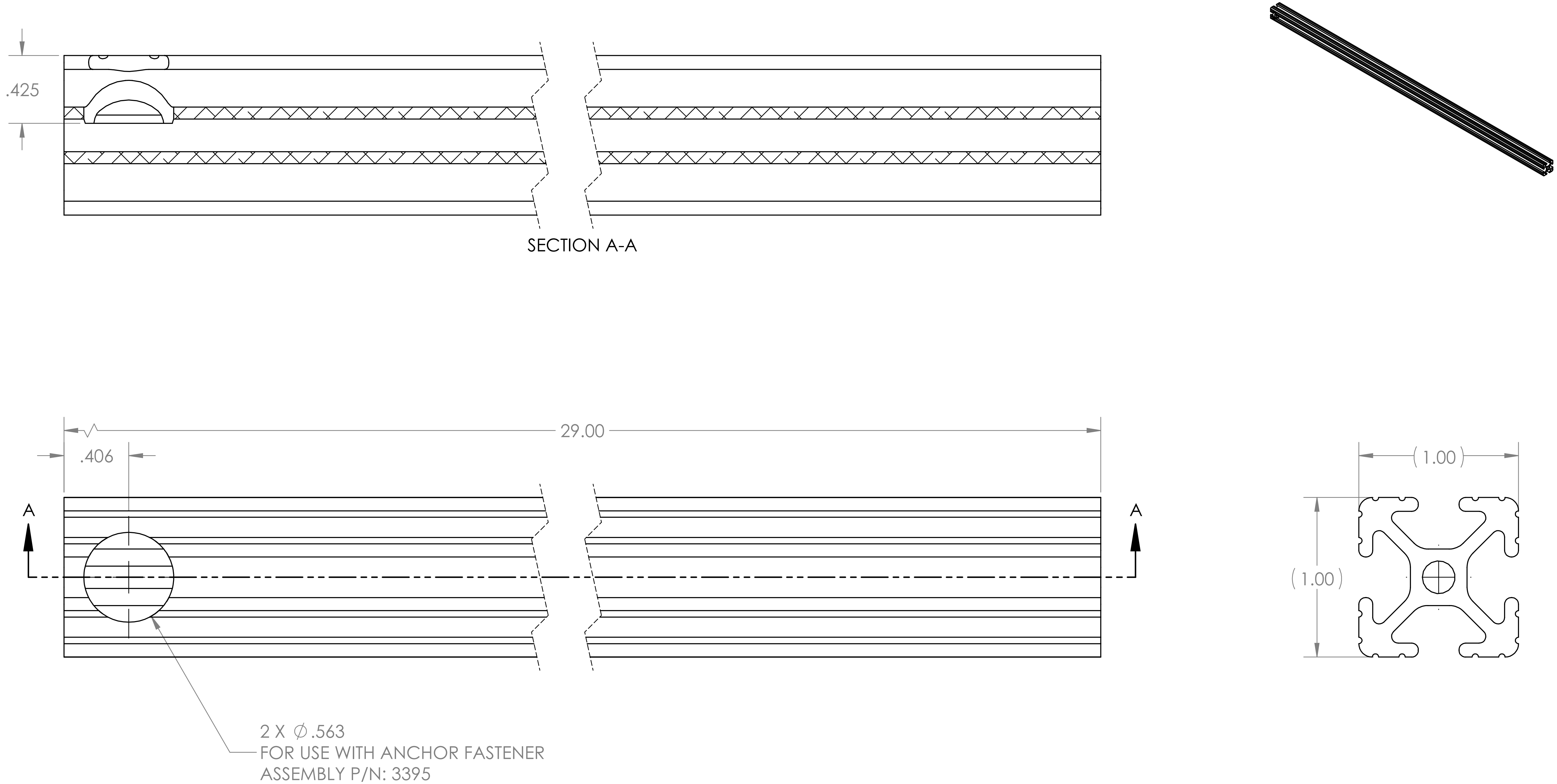
	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

WORCESTER POLYTECH

TITLE:
1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM, 2 C-BORE

SIZE	DWG. NO.	REV
B	1010-29A	0

SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1



NOTE:
1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW ANCHOR FASTENER GUIDELINES GIVEN ON PAGE 568 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6105-T5 ALUMINUM
FINISH
CLEAR ANODIZED
DO NOT SCALE DRAWING

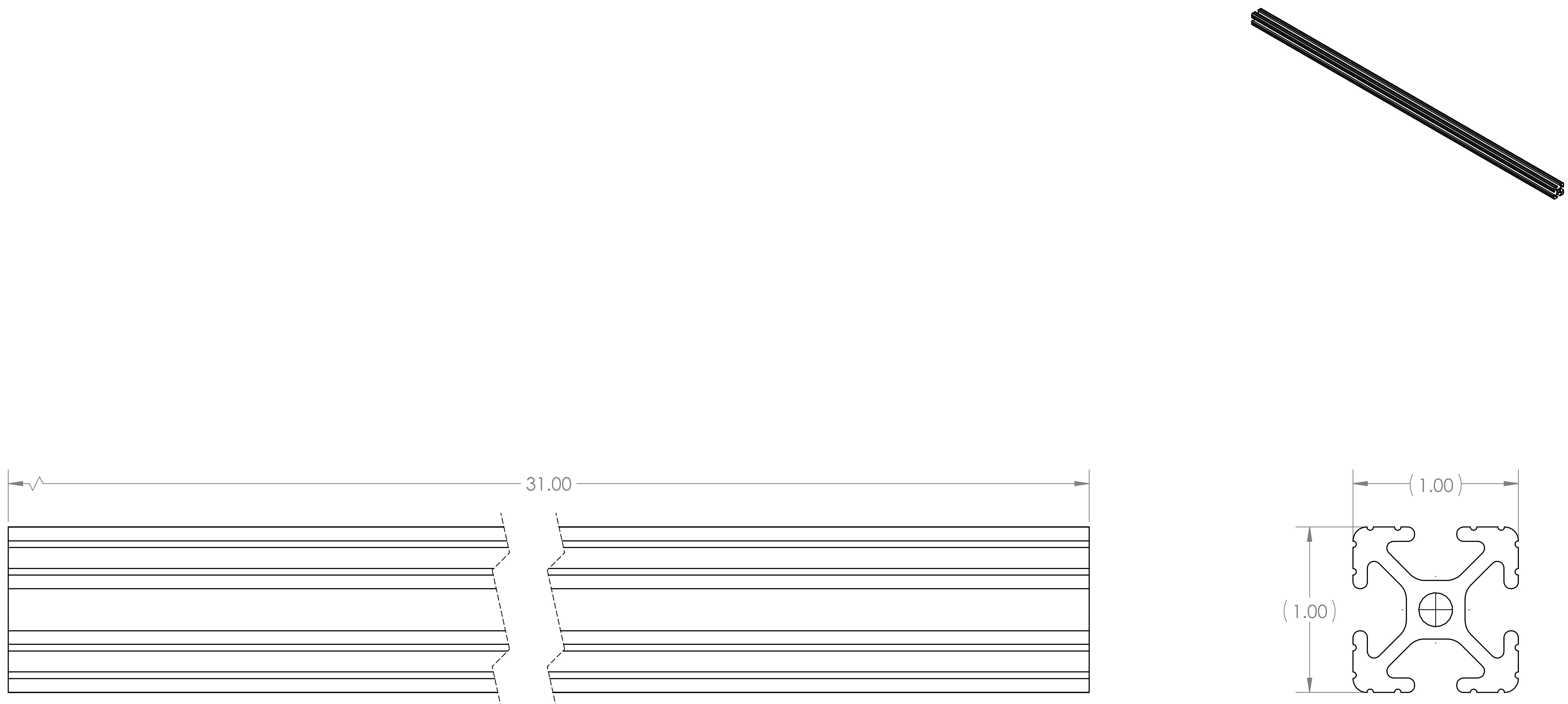
	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

WORCESTER POLYTECH

TITLE:
1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM, 1 C-BORE

SIZE	DWG. NO.	REV
B	1010-29B	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



NOTE:
1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM

SIZE B | DWG. NO. 1010-31 | REV 0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1

Appendix I: Quote for Standard End-Fastened Frame Option

The following pages depict detailed drawings of each component of the standard end-fastened frame design. These were sent to 80/20 to get a price quote, which would help choose the final design.

ORDER ACKNOWLEDGEMENT

AIR INCORPORATED
8 FORGE PARK
FRANKLIN, MA 02038
USA

Tel 508-528-3020
Fax 508-528-7050
sales@airinc.net

www.airinc.net

Order Number	
1104006	
Order Date	Page
2/17/2015 10:24:17	1 of 2

Bill To:

WPI-ME DEPARTMENT
100 INSTITUTE RD
HIGGINS LABS -130 /BARBARA FURHMAN
WORCESTER, MA 01609

508-831-6046

Ship To:

WPI- ME DEPT
100 INSTITUTE ROAD
HIGGINS LABS - 130 ATTN:COBB/PEREZ
WORCESTER, MA 01609

Ordered By: . Jared P. Breton

Customer ID: 53629

PO Number	*Carrier*	*Taker*
ME 15-449	UPS GROUND	PTRAINOR

Quantities					*Item ID*	*Pricing UOM*		
Ordered	*Allocated*	*Remaining*	*UOM* / *Unit Size*	*Disp.*	*Item Description*	*Unit Size*	*Unit Price*	*Extended Price*
6.0	0.0	6.0	EA	D	1010 X 6 IN	EA	1.38	8.28
			1.0		80/20 EXTRUSION With 7061 Both Ends	1.0		
6.0	0.0	6.0	EA	D	1010 X 10 IN	EA	2.30	13.80
			1.0		80/20 EXTRUSION With 7061 Both Ends	1.0		
2.0	0.0	2.0	EA	D	1010 X 14 IN	EA	3.22	6.44
			1.0		80/20 EXTRUSION With 7051 In Slot R @ 6.50 From Left End. With 7061 Both Ends.	1.0		
1.0	0.0	1.0	EA	D	1010 X 29 IN	EA	6.67	6.67
			1.0		80/20 EXTRUSION With 7051 In Slot R @ 9.00 & 20.00 From Left End. With 7061 Both Ends.(1010-29A EF)	1.0		
4.0	0.0	4.0	EA	D	1010 X 29 IN	EA	6.67	26.68
			1.0		80/20 EXTRUSION With 7051 In Slot R & S @ .50, 3.50, 20.00 From Left End. With 7061 Right End Only. (1010-29B EF)	1.0		
1.0	0.0	1.0	EA	D	1010 X 31 IN	EA	7.13	7.13
			1.0		80/20 EXTRUSION With 7051 In Slot R @ .50 & 30.50 From Left End.(1010-31A EF)	1.0		
23.0	0.0	23.0	EA	D	7005	EA	1.95	44.85
			1.0		80/20 1010-CUT-CHARGE	1.0		
8.0	0.0	8.0	EA	D	2015-BLACK	EA	1.05	8.40
			1.0		80 1010 END CAP	1.0		
			Ordered As:		2015			
4.0	0.0	4.0	EA	D	2128	EA	9.75	39.00

ORDER ACKNOWLEDGEMENT

AIR INCORPORATED
8 FORGE PARK
FRANKLIN, MA 02038
USA

Tel 508-528-3020
Fax 508-528-7050
sales@airinc.net

www.airinc.net

Order Number	
1104006	
Order Date	Page
2/17/2015 10:24:17	2 of 2

Quantities					*Item ID*	*Pricing UOM*		
Ordered	*Allocated*	*Remaining*	*UOM Unit Size*	*Disp.*	*Item Description*	*Unit Size*	*Unit Price*	*Extended Price*
			1.0		80 1X2 BSE PLATE 1/4-20	1.0		
4.0	0.0	4.0	EA	D	2193	EA	1.00	4.00
			1.0		80 1/4-20 ECONO LVL FOOT	1.0		
4.0	0.0	4.0	EA	D	2570	EA	15.35	61.40
			1.0		80 45 DEG SUPP 1010X12	1.0		
8.0	0.0	8.0	EA	D	3266	EA	0.21	1.68
			1.0		SELF TAPPING SCREW	1.0		
8.0	0.0	8.0	EA	D	3491	EA	0.37	2.96
			1.0		80 1/4-20X1/2 SHCS T-NUT	1.0		
34.0	0.0	34.0	EA	D	3381	EA	1.50	51.00
			1.0		80 END FAST. 1/4-20	1.0		
1.0	0.0	1.0	EA	D	1010 X 31 IN	EA	7.13	7.13
			1.0		80/20 EXTRUSION With 7051 In Slot R @ .50 & 30.50 With 7051 In Slot S @ 10.00 & 21.00 From Left End. (1010-31B-EF)	1.0		
1.0	0.0	1.0	EA	D	1010 X 9 IN	EA	2.07	2.07
			1.0		80/20 EXTRUSION	1.0		
1.0	0.0	1.0	EA	D	1010 X 10 IN	EA	2.30	2.30
			1.0		80/20 EXTRUSION	1.0		
10.0	0.0	10.0	EA	D	3321	EA	0.50	5.00
			1.0		80 10S 1/4-20X1/2 W/ECON.	1.0		
34.0	0.0	34.0	EA	D	7061	EA	1.95	66.30
			1.0		80 1/4-20 TAP 1010,1012	1.0		
34.0	0.0	34.0	EA	D	7051	EA	1.95	66.30
			1.0		80 #10 ACCESS HOLE	1.0		

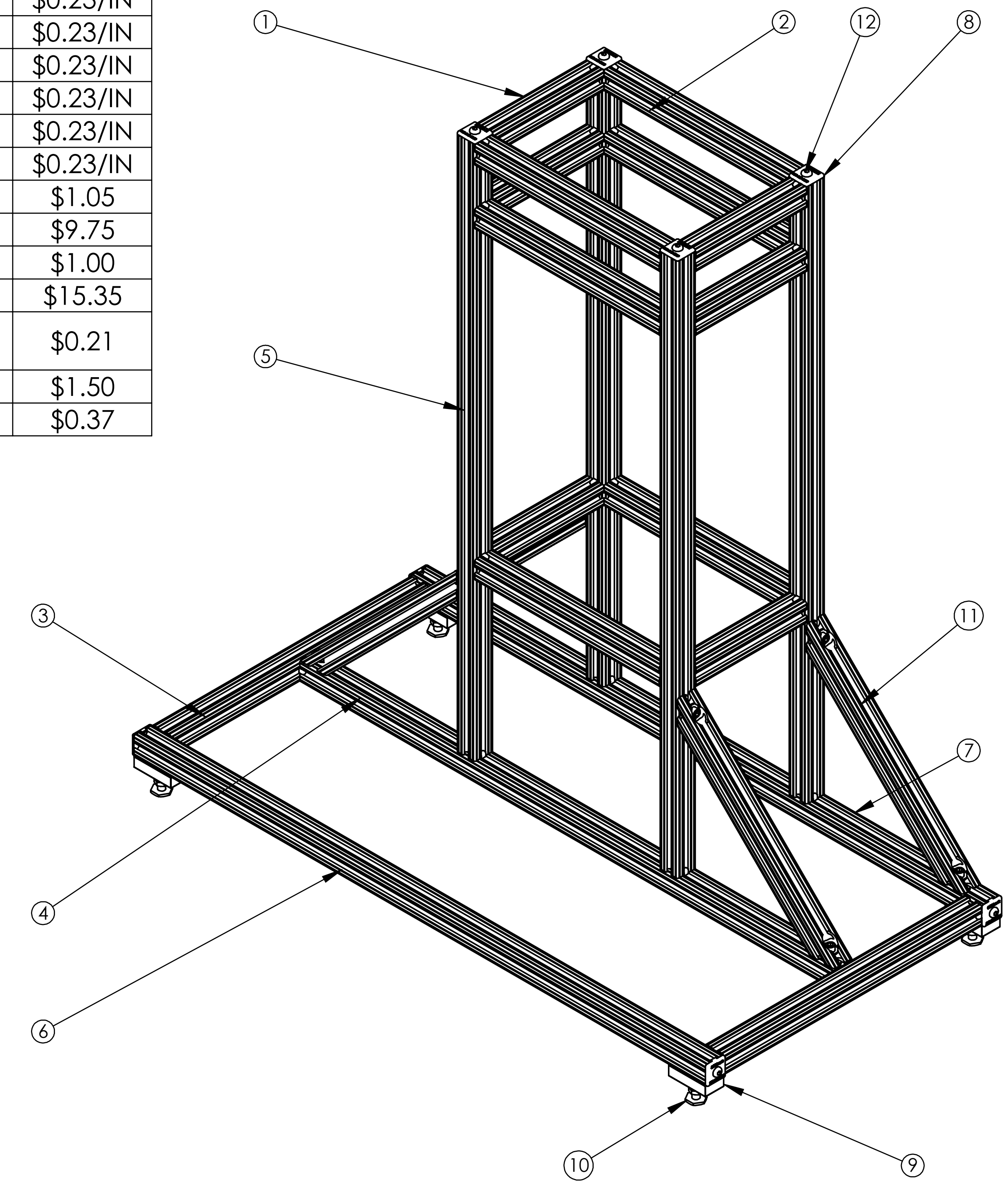
Total Lines: 20

Pricing based on quantity ordered
All lead times are factory estimates

SUB-TOTAL:	431.39
TAX:	0.00
AMOUNT TENDERED :	0.00
AMOUNT DUE:	**431.39**

U.S. Dollars

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.	UNIT PRICE
1	1010-06 EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 6" NOM	6105-T5 ALUMINUM	6	$0.23/IN
2	1010-10 EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 10" NOM	6105-T5 ALUMINUM	6	$0.23/IN
3	1010-14 EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 14" NOM	6105-T5 ALUMINUM	2	$0.23/IN
4	1010-29A EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM	6105-T5 ALUMINUM	1	$0.23/IN
5	1010-29B EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM	6105-T5 ALUMINUM	4	$0.23/IN
6	1010-31A EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM	6105-T5 ALUMINUM	1	$0.23/IN
7	1010-31B EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM	6105-T5 ALUMINUM	1	$0.23/IN
8	2015	N/A	80/20 1010 SERIES BLACK END CAP	PLASTIC	8	$1.05
9	2128	N/A	10 S 1" X 2" BASE PLATE W/ 1/4-20 TAP IN CENTER	ALUMINUM	4	$9.75
10	2193	N/A	1/4-20 ECONOMY LEVELING FOOT	ALUMINUM	4	$1.00
11	2570	N/A	1020 X 12" 45 DEGREE SUPPORT	6105-T5	4	$15.35
12	3266	N/A	12-24 X .375" SOCKET BUTTON HEAD THREAD BLK ZINC SELF TAP	N/A	8	$0.21
13	3381	N/A	10 S END FASTENER W/ 1/4-20 SCR	N/A	34	$1.50
14	3491	N/A	1/4"-20 X 1/2" SHCS, ECON T-NUT	ALUMINUM	8	$0.37



PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

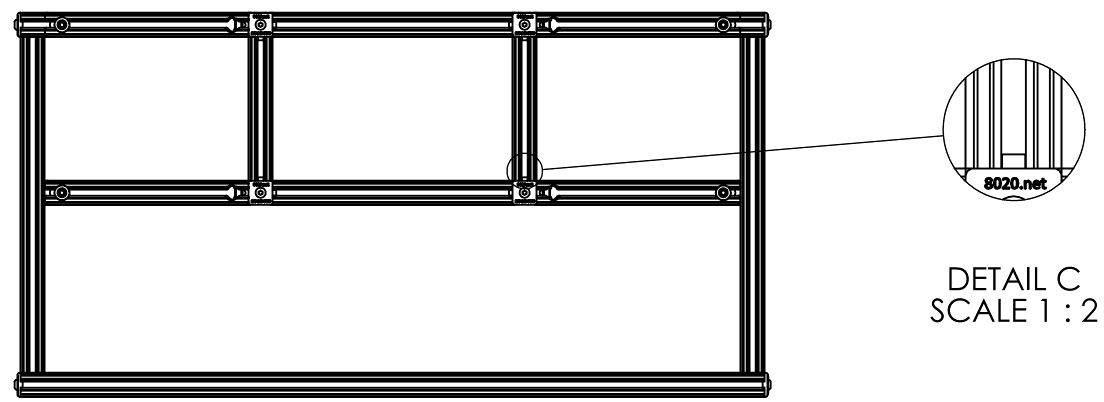
WORCESTER POLYTECHNIC INSTITUTE

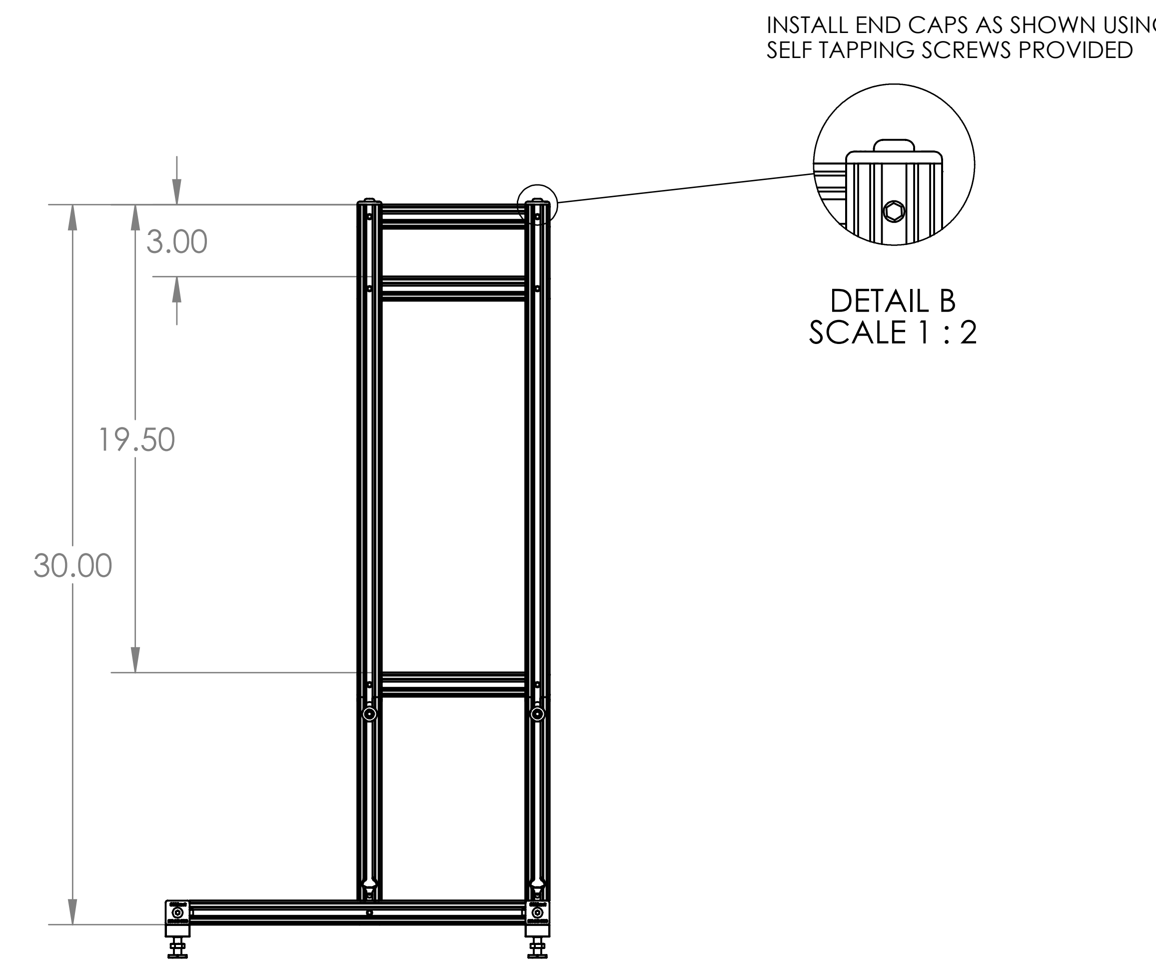
TITLE:

1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE	DWG. NO.	REV
B	KTKR-FR-1010-0-EF	0

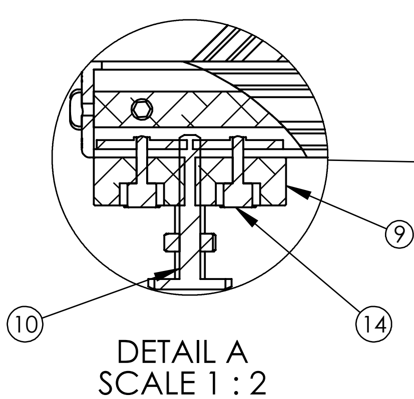
SCALE: 1:6 | WEIGHT: 17.24 | SHEET 3 OF 4

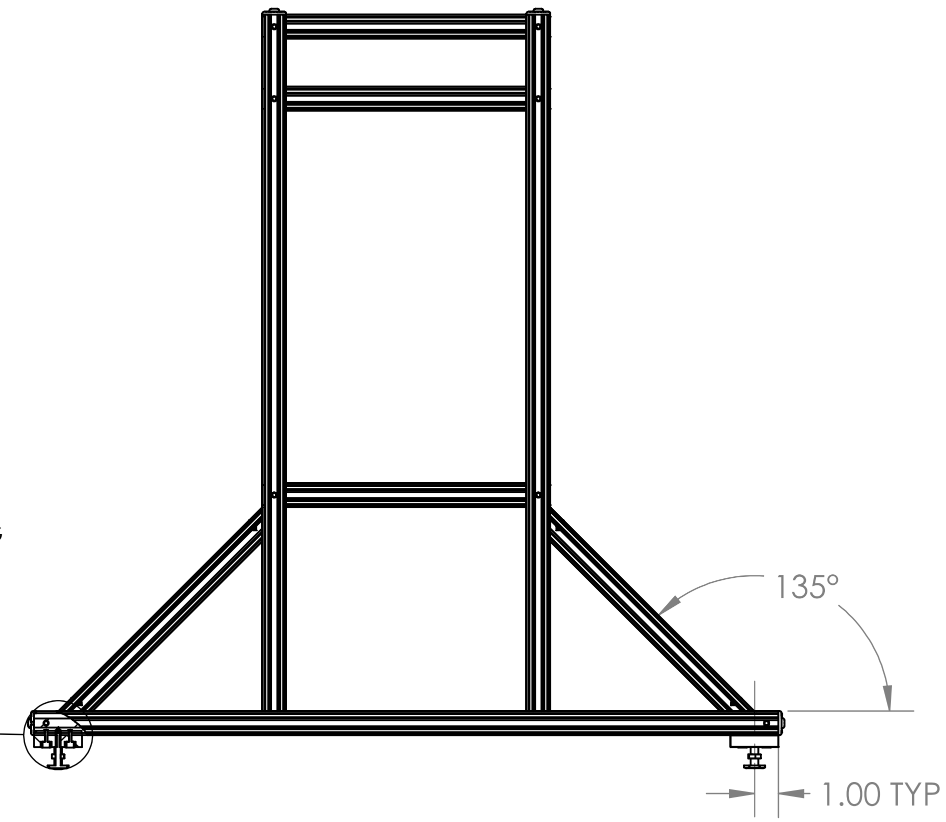


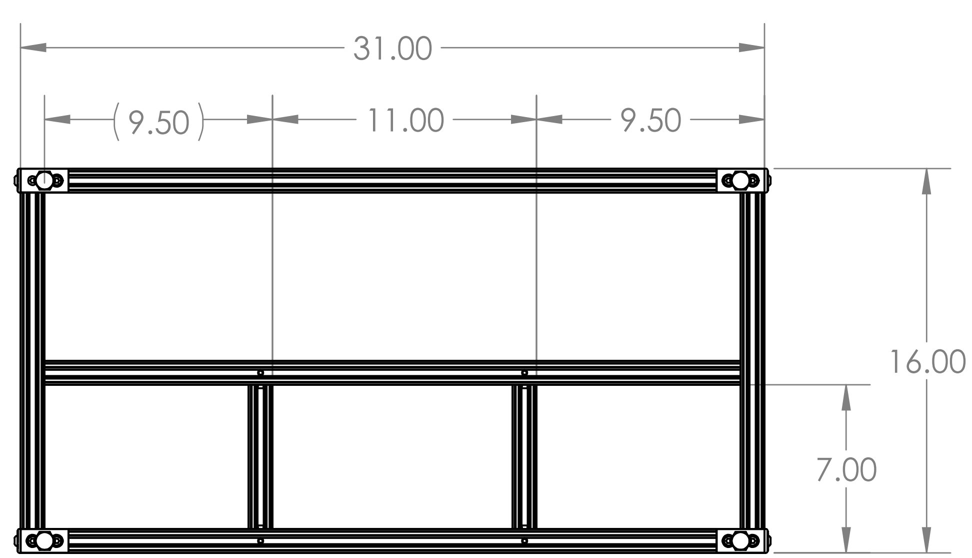


FOOT MOUNTING PLATE:
INSTALL ALL COMPONENTS AS SHOWN TO TO ENSURE THAT LEVELING FOOT MTG PLATES ARE SECURED TO THE FRAME.

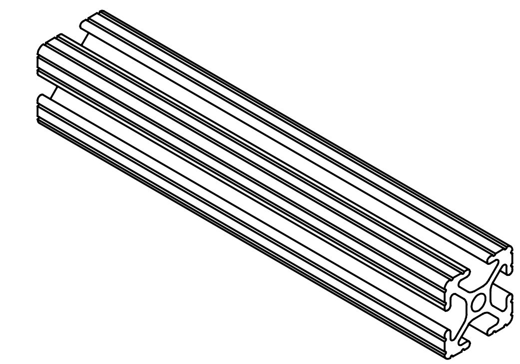
LEVELING FOOT:
USING A LEVEL, SCREW FEET INTO PLATE UNTIL THE FRAME IS LEVEL ON THE DESIRED OPERATING FLOOR.

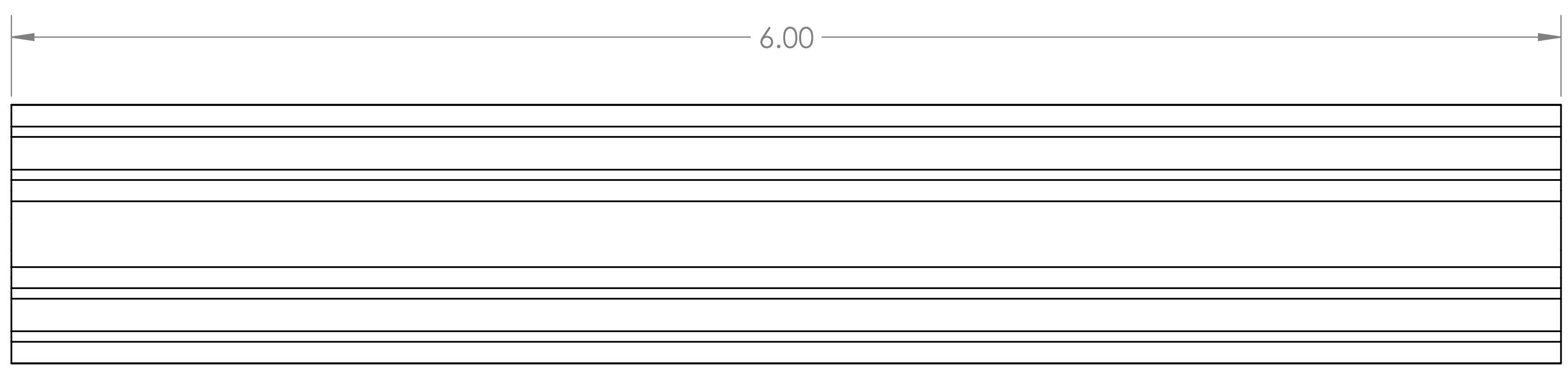


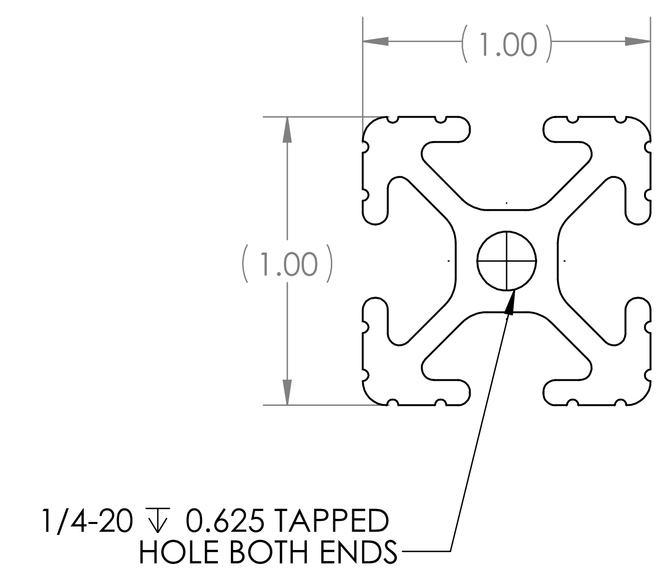




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	WORCESTER POLYTECHNIC INSTITUTE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	JARED BRETON	1/25/2015	TITLE:
	CHECKED			1010 SERIES FRAME FOR KNEE TESTER LINKAGE
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL ALUMINUM	COMMENTS:			SIZE B DWG. NO. KTKR-FR-1010-0-EF REV 0
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:8 WEIGHT: 17.24 SHEET 4 OF 4







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.

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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

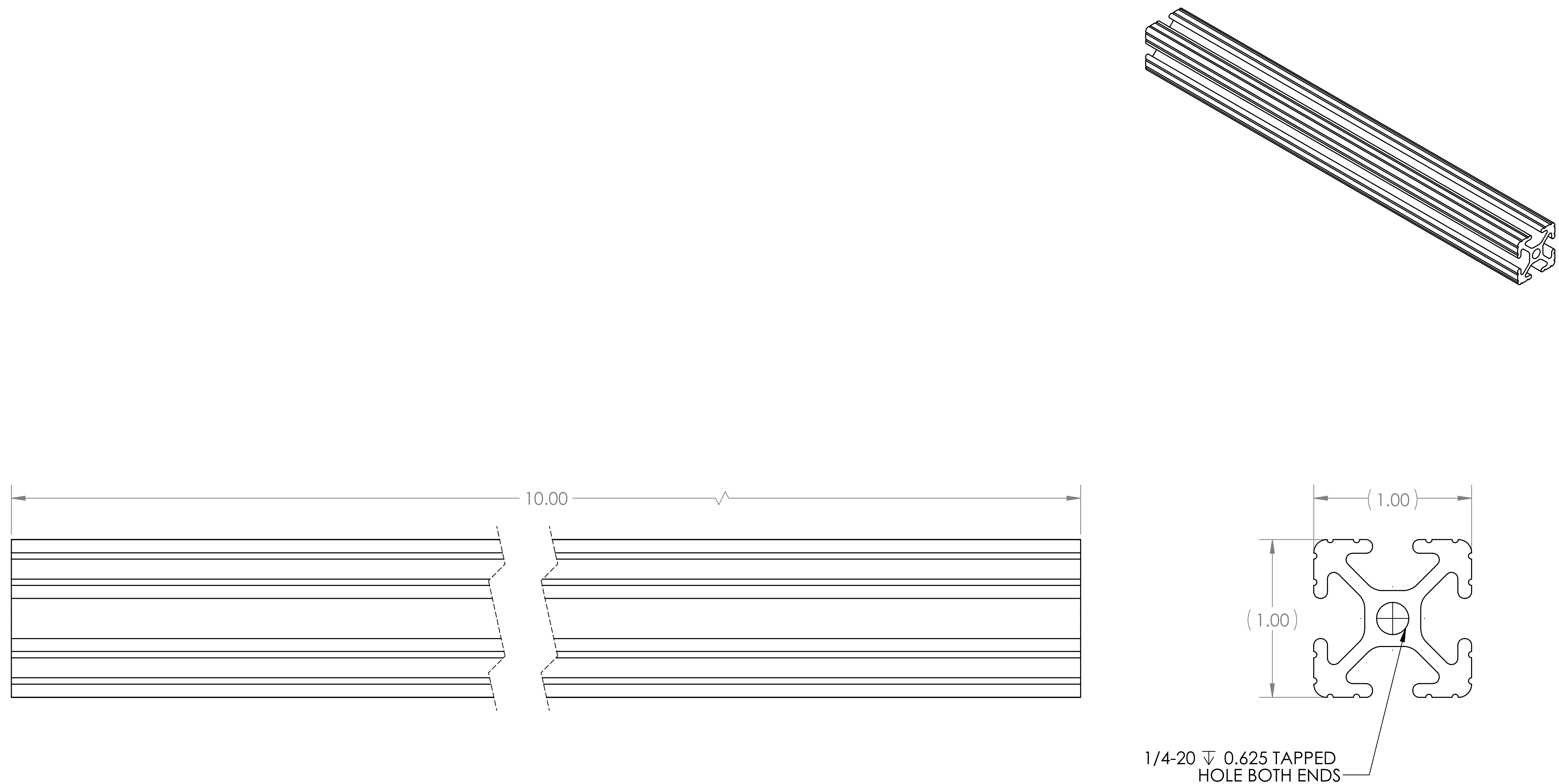
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 6" NOM

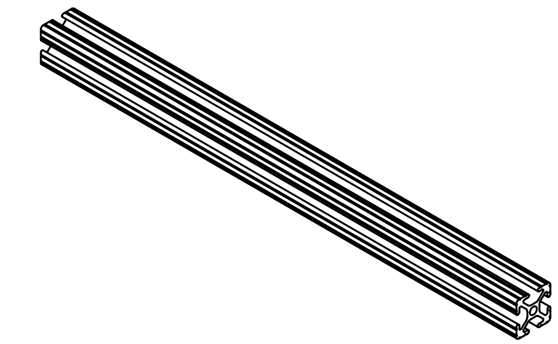
SIZE	DWG. NO.	REV
B	1010-06 EF	0

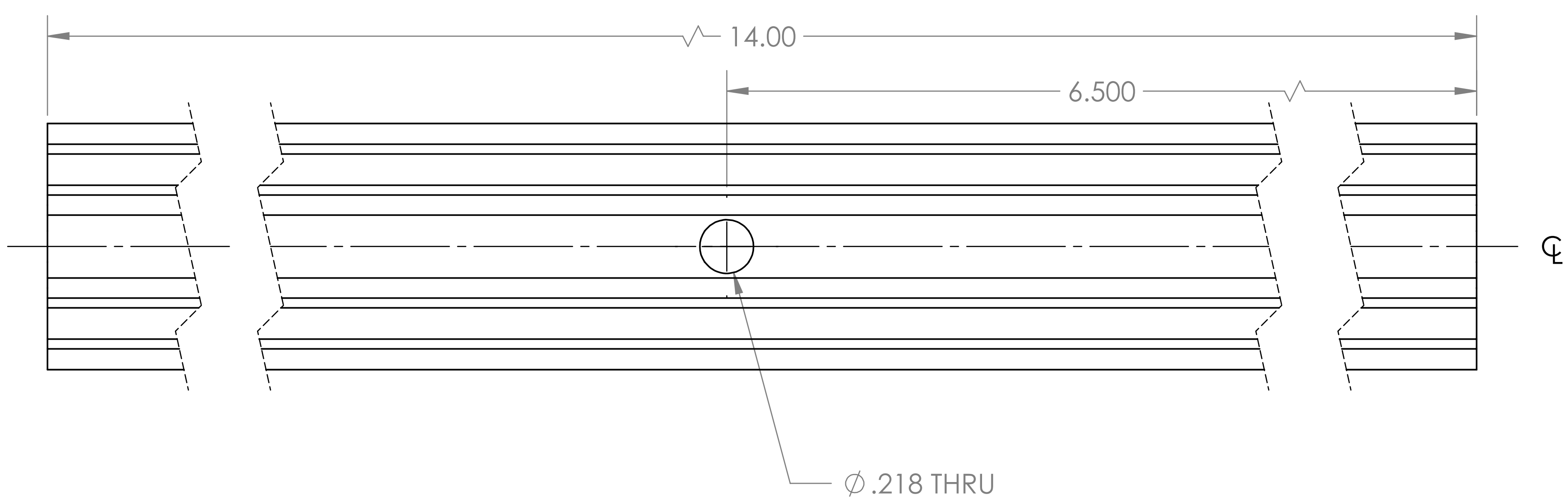
SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1

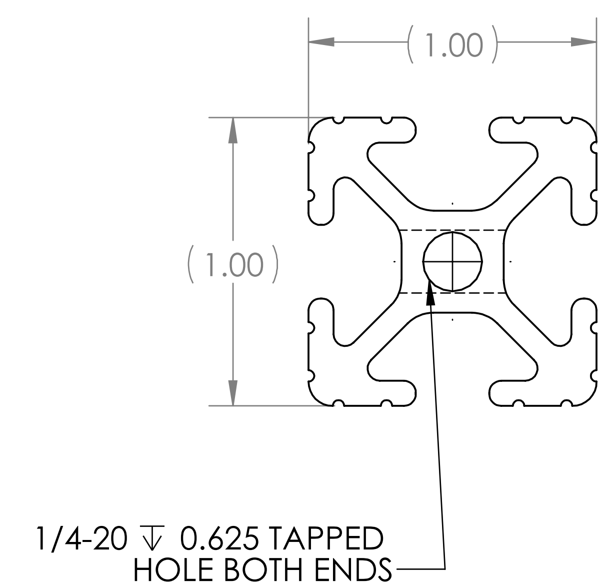


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	WORCESTER POLYTECH
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	JARED BRETON	1/20/2015	TITLE:
	CHECKED			1.0" x 1.0" T-SLOTTED EXTRUSION; 10" NOM
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 6105-T5 ALUMINUM	COMMENTS:			SIZE B · DWG. NO. 1010-10A EF · REV 0
FINISH CLEAR ANODIZED				
DO NOT SCALE DRAWING				SCALE: 3:2 · WEIGHT: 1.301 · SHEET 1 OF 1

NOTE:
1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.







NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW END FASTENER GUIDELINES GIVEN ON PAGE 566 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

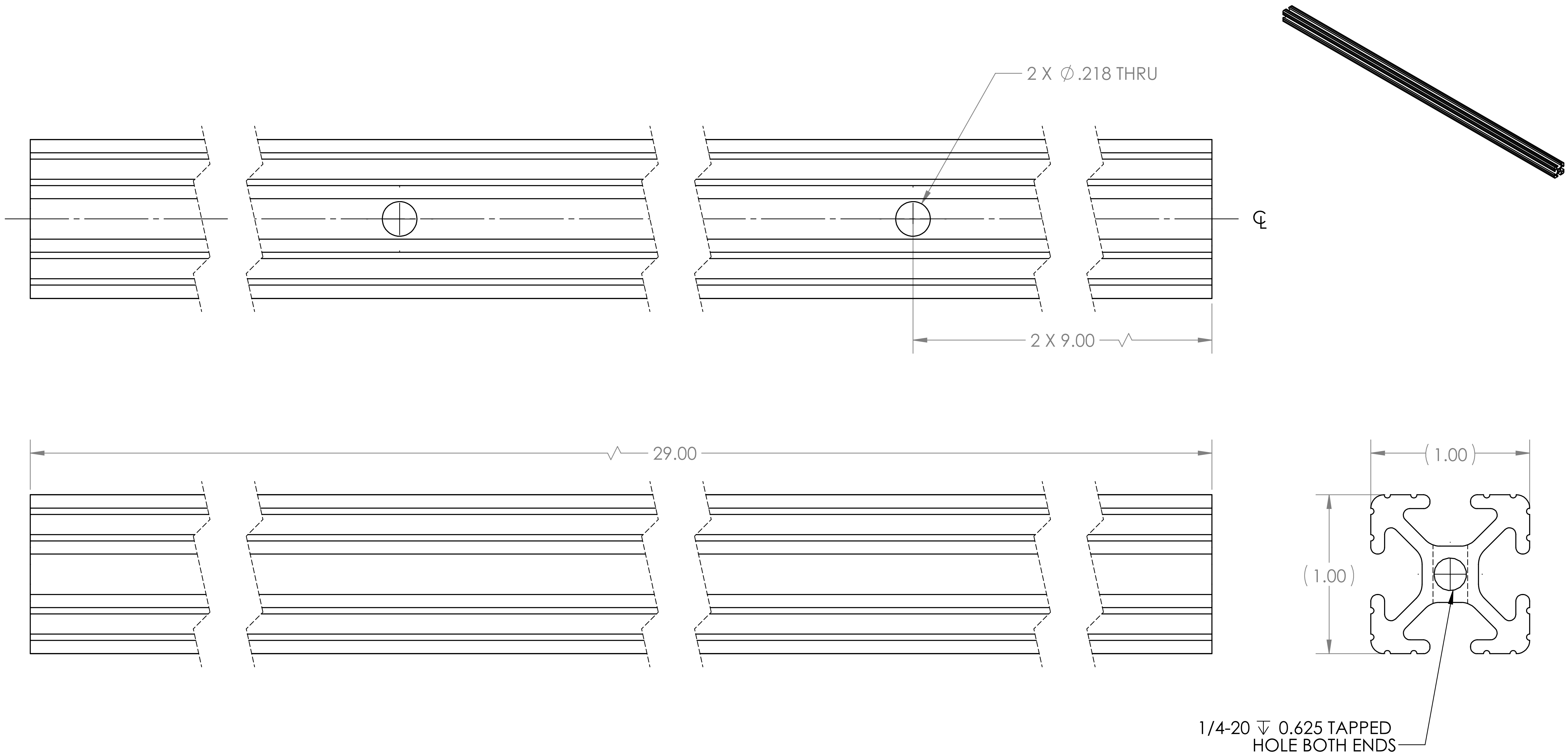
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 14" NOM

SIZE	DWG. NO.	REV
B	1010-14 EF	0

SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW END FASTENER GUIDELINES GIVEN ON PAGE 566 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

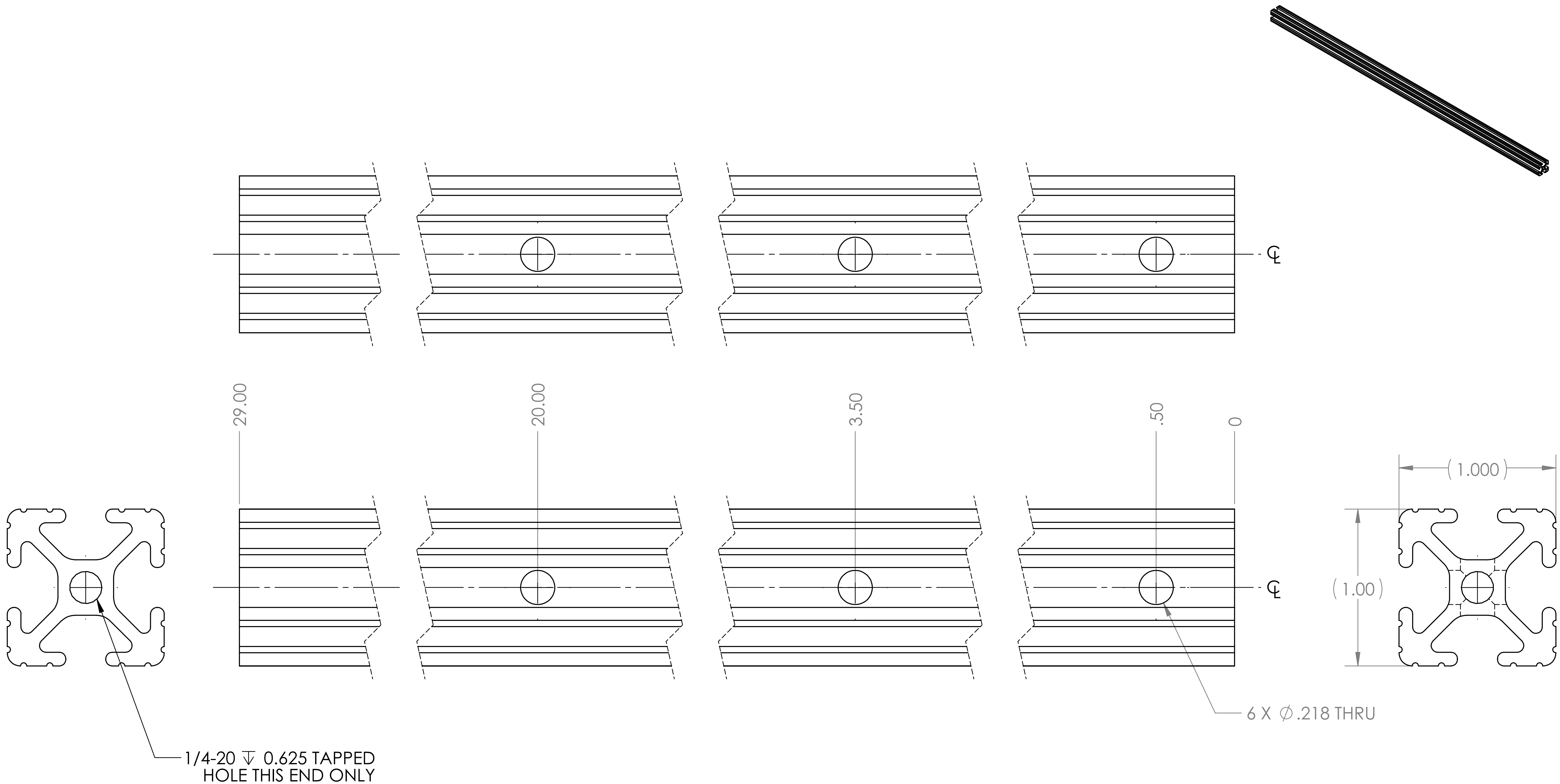
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM

SIZE	DWG. NO.	REV
B	1010-29A EF	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW END FASTENER GUIDELINES GIVEN ON PAGE 566 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

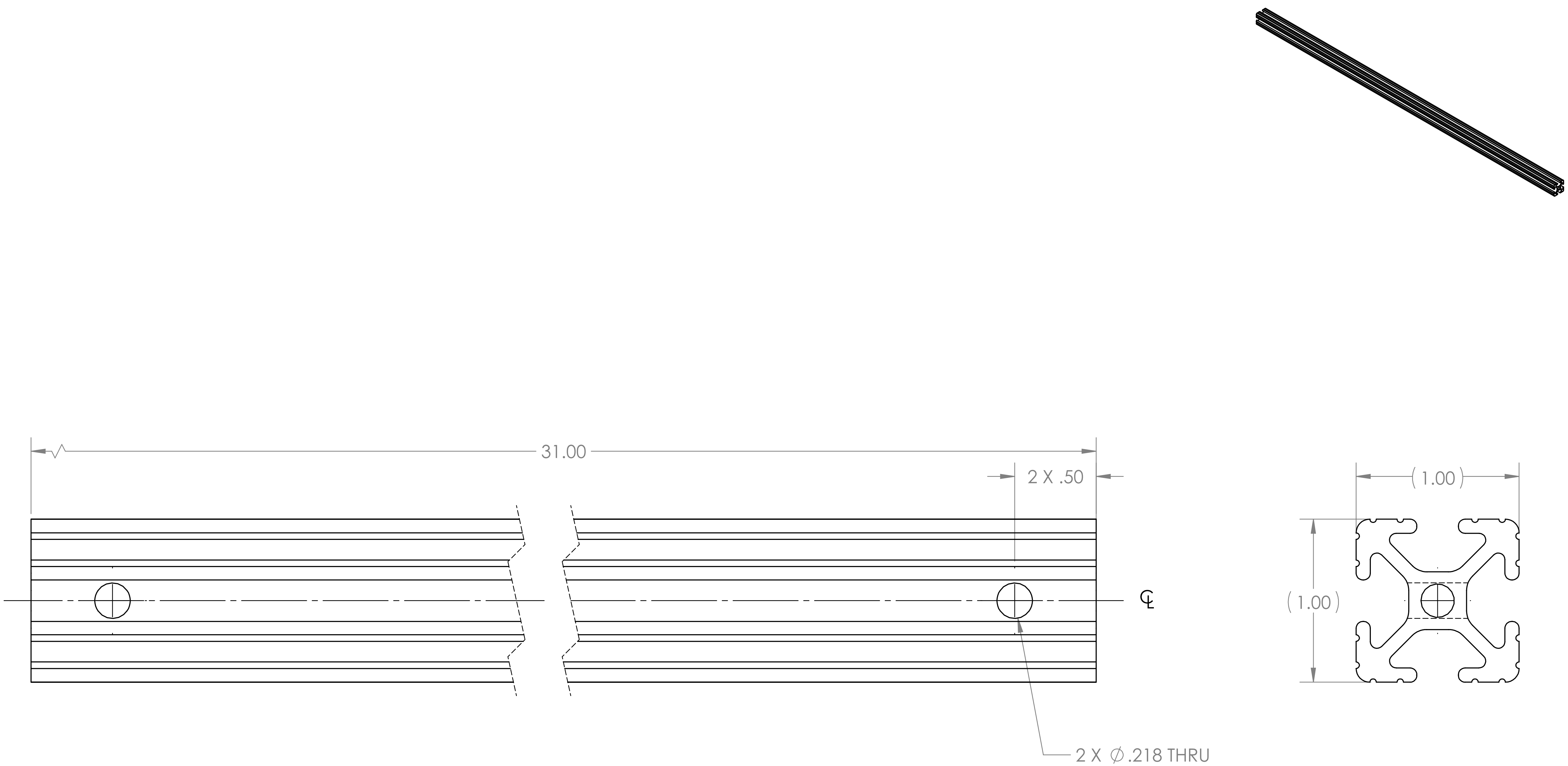
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM

SIZE	DWG. NO.	REV
B	1010-29B EF	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW END FASTENER GUIDELINES GIVEN ON PAGE 566 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

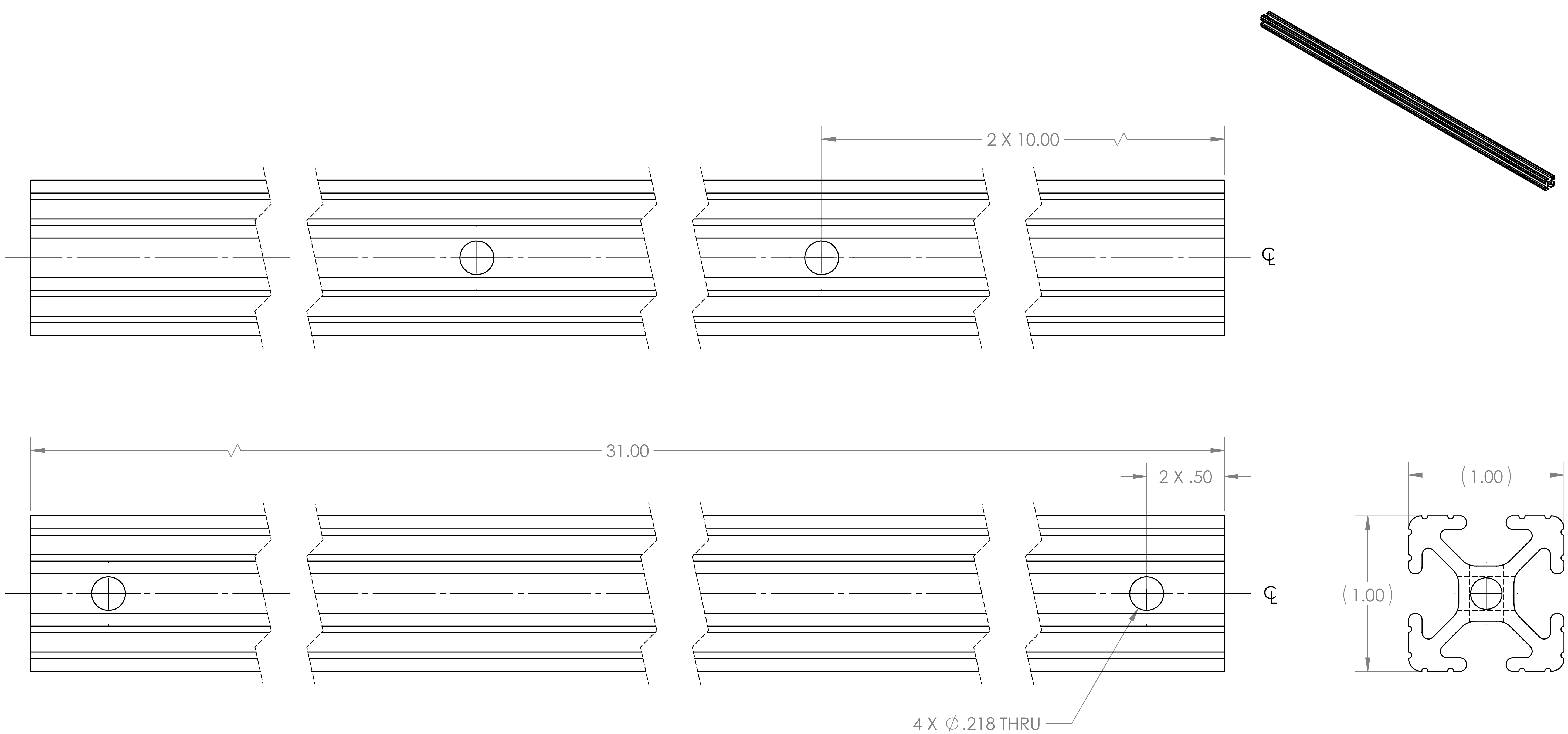
WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM

SIZE	DWG. NO.	REV
B	1010-31A EF	0

SCALE: 3:2 | WEIGHT: 1.301 | SHEET 1 OF 1



NOTE:

1. MISSING DIMENSIONS ARE NOT CRITICAL.
2. THE PURPOSE OF THIS DRAWING IS TO INDICATE THE NOMINAL LENGTH OF A 1010 80/20 ALUMINUM EXTRUSION.
3. HOLES ARE LOCATED ON THE CENTERLINE OF THE EXTRUSION AND FOLLOW END FASTENER GUIDELINES GIVEN ON PAGE 566 OF THE 80/20 CATALOG.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6105-T5 ALUMINUM

FINISH
CLEAR ANODIZED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECH

TITLE:

1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM

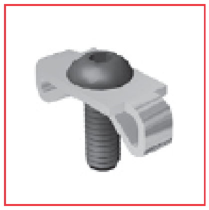
SIZE	DWG. NO.	REV
B	1010-31B EF	0

SCALE: 3:2 WEIGHT: 1.301 SHEET 1 OF 1

Appendix J: Steps to Implement 80/20 End Fasteners

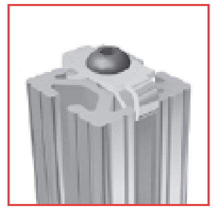
Step #1

End fasteners are composed of a button head socket cap screw (BHSCS) and a wing clip.



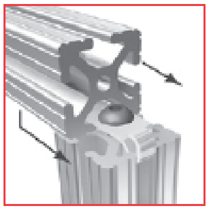
Step #2

Pre-assemble by placing the BHSCS through the hole in the wing clip as shown in the photo at left.



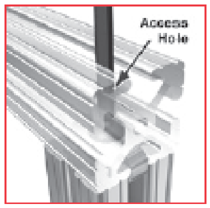
Step #3

Orient the wing clip in the direction of the mating profile's T-slot. Begin to screw the BHSCS into the tapped hole of the mounting profile. (Do NOT fully tighten)



Step #4

Slide the mating profile into place. When aligned, the access hole on the mating profile should align with the BHSCS.



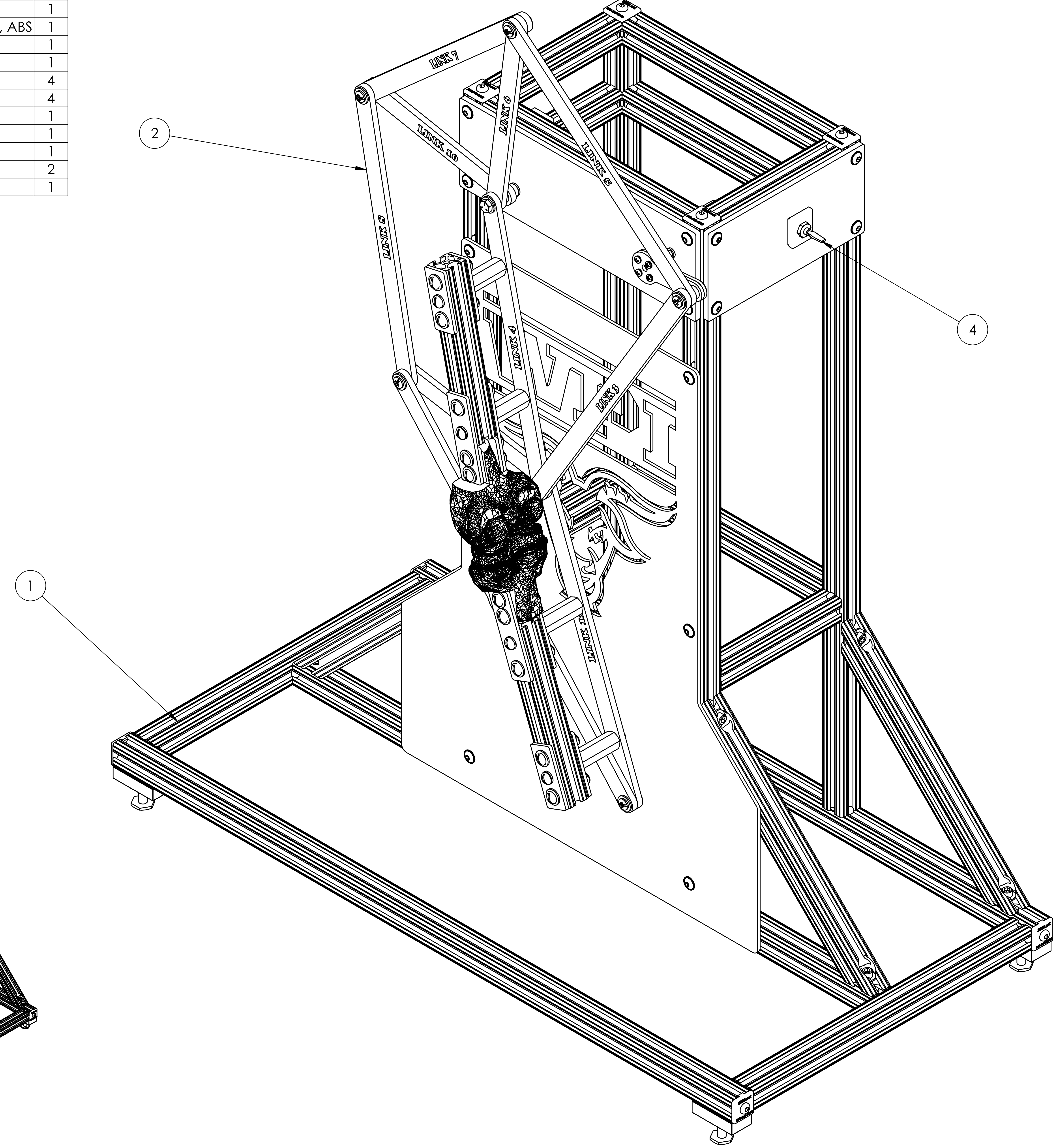
Step #5

Place a T-handle hex wrench into the access hole until the wrench head inserts into the BHSCS. Tighten clockwise until secure.

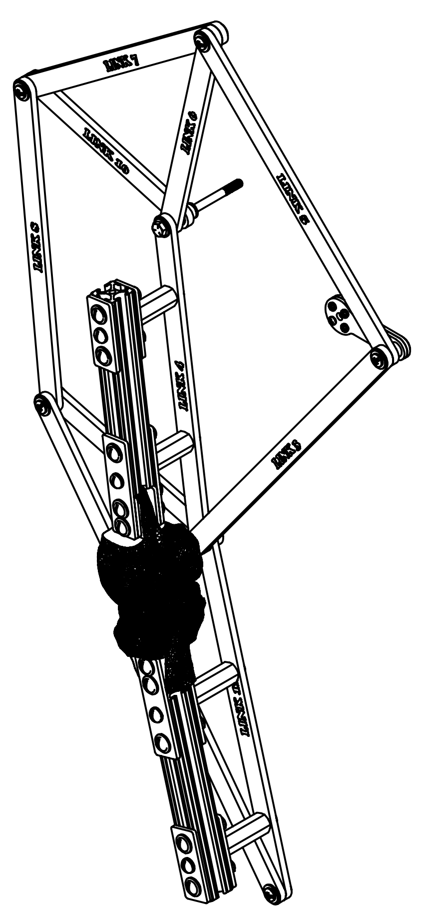
Appendix K: Detailed Drawings of Final Top-Level Assembly

The following pages depict detailed drawings of the top-level assembly, the drawings for each acrylic plate (KTKR-PT-001, KTKR-PT-002, KTKR-PT-003, KTKR-PT-004), and the frame with the four plates attached.

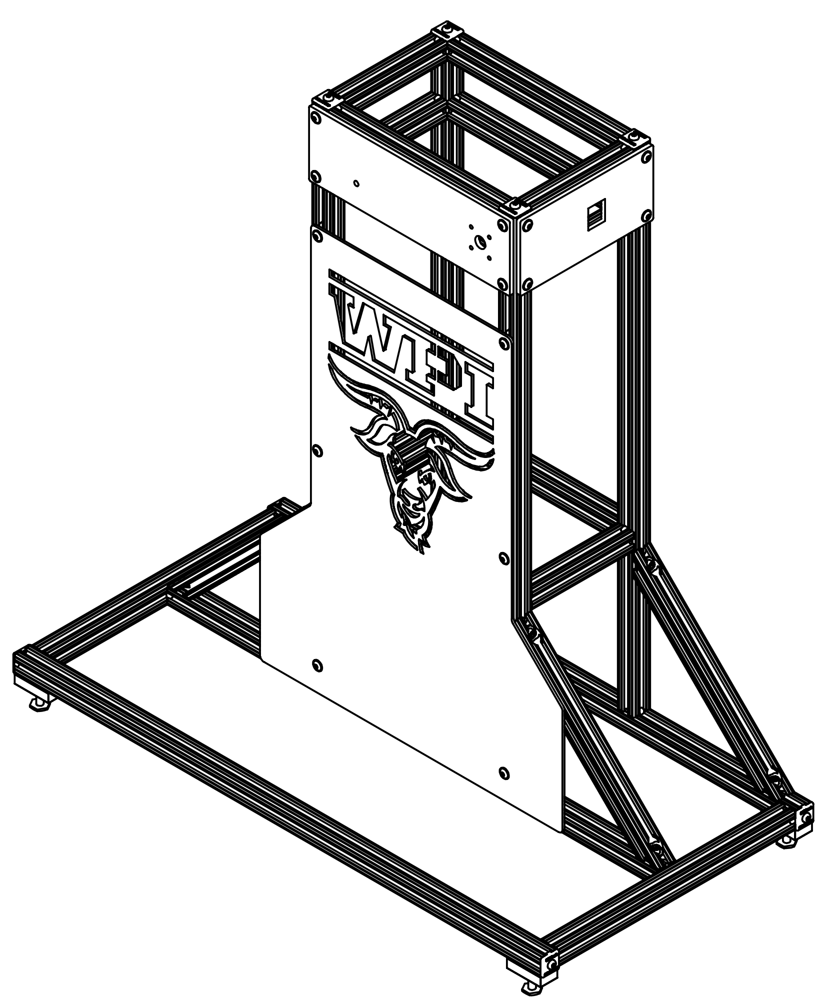
ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	KTKR-FR-1010-EF	0	1010 SERIES FRAME FOR KNEE TESTER LINKAGE	ALUMINUM	1
2	KTKR-12-BAR	0	12 BAR KNEE TESTER LINKAGE	ALUMINUM, STEEL, ABS	1
3	638234	N/A	SERVO CITY MOTOR W/ MOUNT	N/A	1
4	275-0710	N/A	DC MOTOR SWITCH	PLASTIC	1
5	90272A146	N/A	#6-32 x 3/8" PAN HEAD PHILLIPS MACHINE SCREW	STEEL	4
6	90126A509.16	N/A	#6 FLAT WASHER, 3/8" OD	STEEL	4
7	N/A	N/A	FIBER WASHER FOR 1/4" DIA.	FIBER	1
8	KTKR-PT-004	0	AXLE MOMENT NEUTRALIZING PLATE	0.22" ACRYLIC	1
9	N/A	N/A	1/4"-20 SERRATED FLANGE LOCKNUT	STEEL	1
10	3321	N/A	1/4"-20 FBHSCS W/ ECON T-NUT	STEEL	2
11	N/A	N/A	1/4" ID, 1/2" OD x 1" LG NYLON SPACER	NYLON	1



12-BAR KNEE TESTER LINKAGE



FRAME SUBASSEMBLY



NOTES:
1. DIMENSIONS SHOWN IN PARENTHESES CANNOT BE CONTROLLED AT THIS ASSEMBLY LEVEL.
2. ALL MISSING DIMENSIONS ARE NON-CRITICAL AT THIS LEVEL.
3. ASSEMBLE COMPONENTS AS SHOWN.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: ALUMINUM, STEEL, ABS
FINISH: NONE
DO NOT SCALE DRAWING

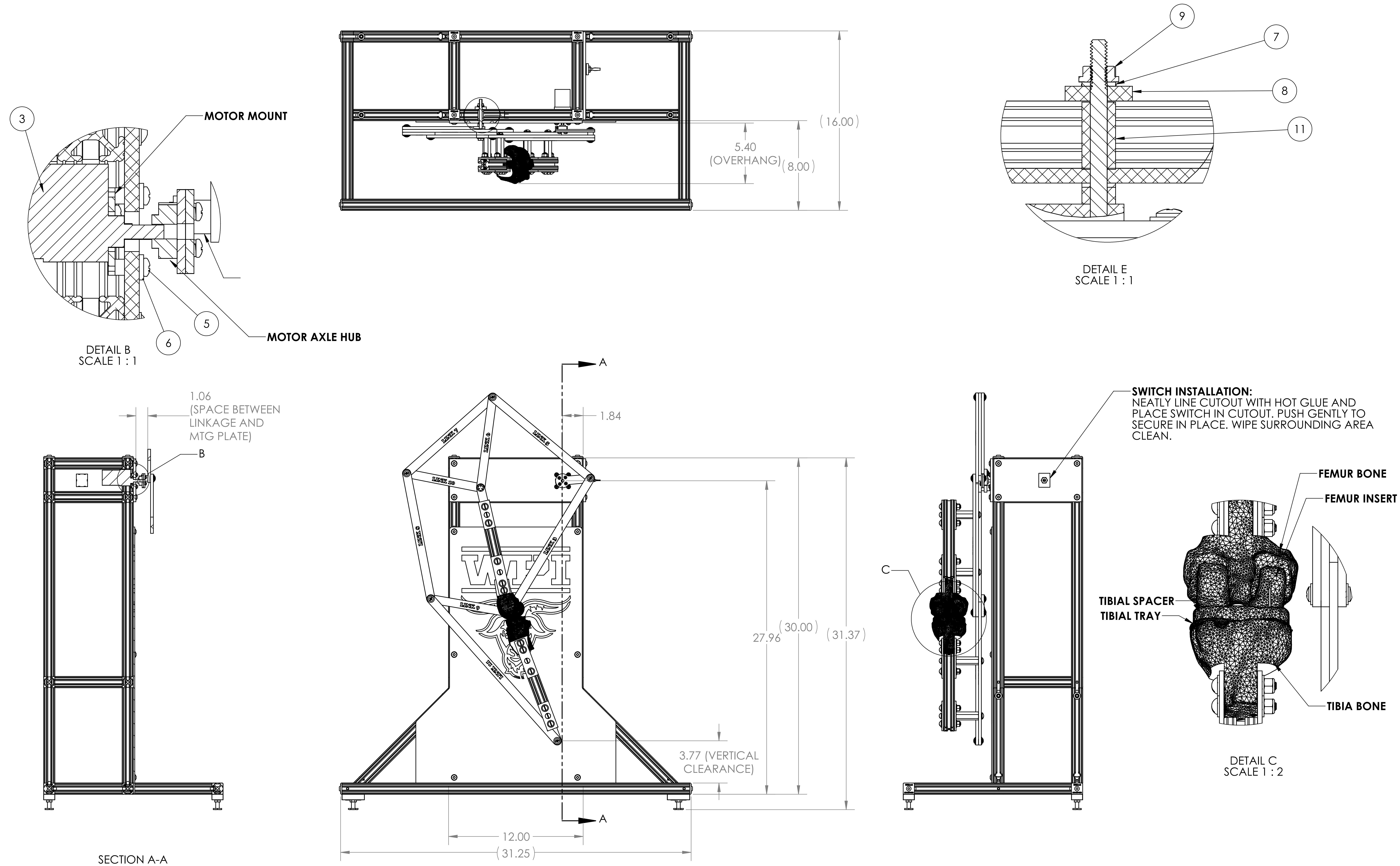
	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

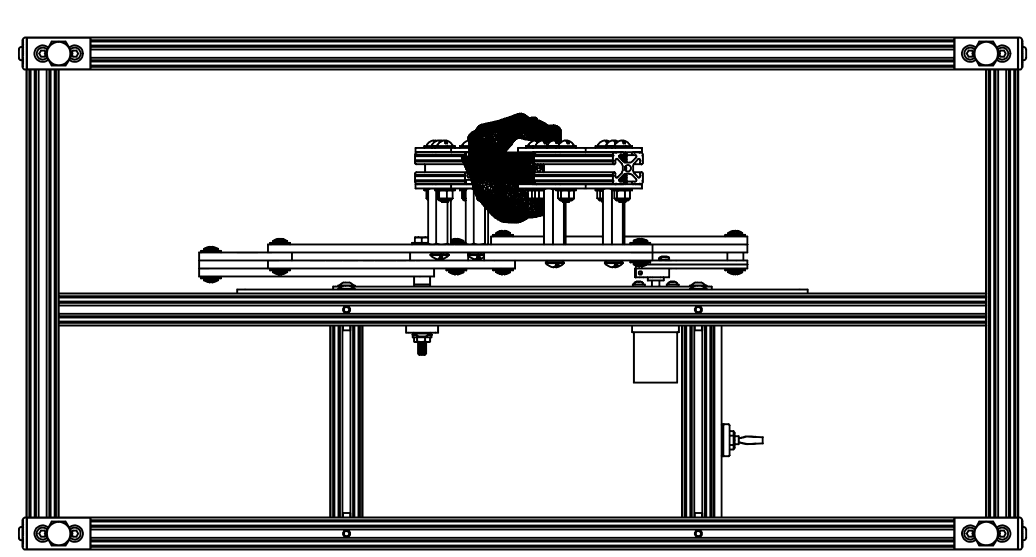
WORCESTER POLYTECHNIC INSTITUTE

TITLE: KNEE TESTER MECHANISM

SIZE: C | DWG. NO.: KTKR-1200 | REV: 0

SCALE: 1:3 | WEIGHT: 24.12 | SHEET 1 OF 2





NOTES:

1. DIMENSIONS SHOWN IN PARENTHESES CANNOT BE CONTROLLED AT THIS ASSEMBLY LEVEL.
2. ALL MISSING DIMENSIONS ARE NON-CRITICAL AT THIS LEVEL.
3. INSTALL ALL COMPONENTS AS SHOWN AND USE HARDWARE INDICATED IN 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, STEEL, ABS

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	3/22/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECHNIC INSTITUTE

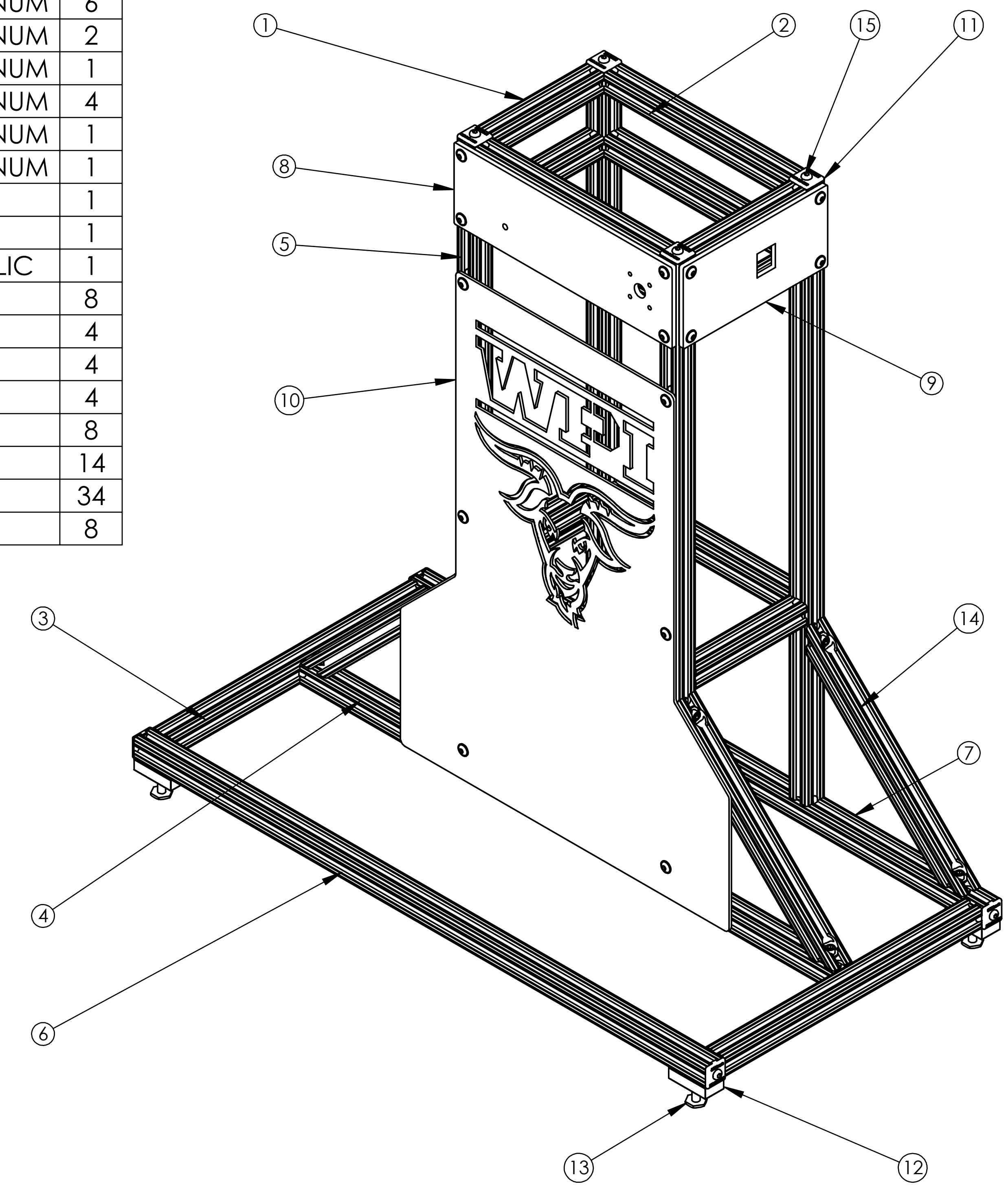
TITLE:

KNEE TESTER MECHANISM

SIZE	DWG. NO.	REV
C	KTKR-1200	0

SCALE: 1:6 | WEIGHT: 24.12 | SHEET 2 OF 2

ITEM NO.	PART NUMBER	REVISION	DESCRIPTION	MATERIAL	QTY.
1	1010-06 EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 6" NOM	6105-T5 ALUMINUM	6
2	1010-10A EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 10" NOM	6105-T5 ALUMINUM	6
3	1010-14 EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 14" NOM	6105-T5 ALUMINUM	2
4	1010-29A EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM	6105-T5 ALUMINUM	1
5	1010-29B EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 29" NOM	6105-T5 ALUMINUM	4
6	1010-31A EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM	6105-T5 ALUMINUM	1
7	1010-31B EF	0	1.0" x 1.0" T-SLOTTED EXTRUSION; 31" NOM	6105-T5 ALUMINUM	1
8	KTKR-PT-001	0	LINKAGE GROUND PLATE	0.22" ACRYLIC	1
9	KTKR-PT-002	0	SWITCH MTG PLATE	0.22" ACRYLIC	1
10	KTKR-PT-003	0	COLLISION PLATE	1/8" RED ACRYLIC	1
11	2015	N/A	80/20 1010 SERIES BLACK END CAP	PLASTIC	8
12	2128	N/A	10 S 1" X 2" BASE PLATE W/ 1/4-20 TAP IN CENTER	ALUMINUM	4
13	2193	N/A	1/4-20 ECONOMY LEVELING FOOT	ALUMINUM	4
14	2570	N/A	1020 X 12" 45 DEGREE SUPPORT	6105-T5	4
15	3266	N/A	12-24 X .375" SOCKET BUTTON HEAD THREAD BLK ZINC SELF TAP	N/A	8
16	3321	N/A	1/4"-20 FBHSCS W/ ECON T-NUT	STEEL	14
17	3381	N/A	10 S END FASTENER W/ 1/4-20 SCR	N/A	34
18	3491	N/A	1/4"-20 X 1/2" SHCS, ECON T-NUT	ALUMINUM	8



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF WORCESTER POLYTECHNIC INSTITUTE. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF WORCESTER POLYTECHNIC INSTITUTE IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL ALUMINUM

FINISH NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

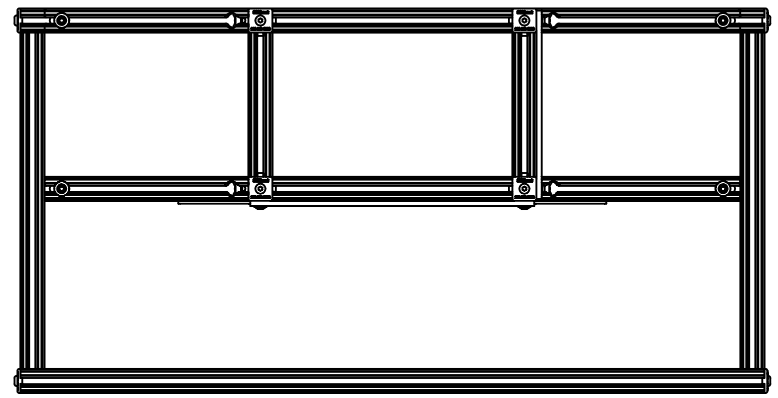
WORCESTER POLYTECHNIC INSTITUTE

TITLE:

1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE B | DWG. NO. KTKR-FR-1010-EF | REV 0

SCALE: 1:6 | WEIGHT: 19.39 | SHEET 1 OF 2

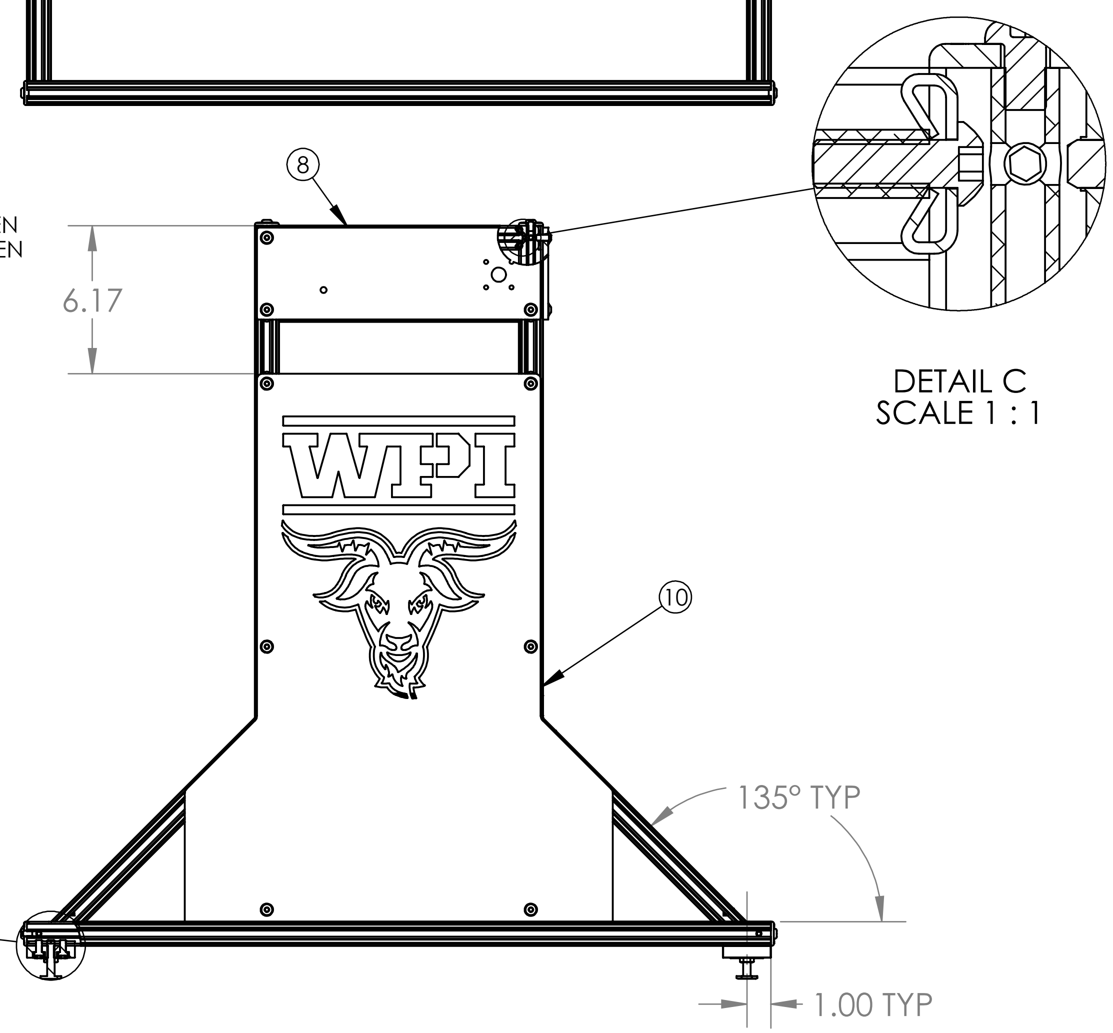


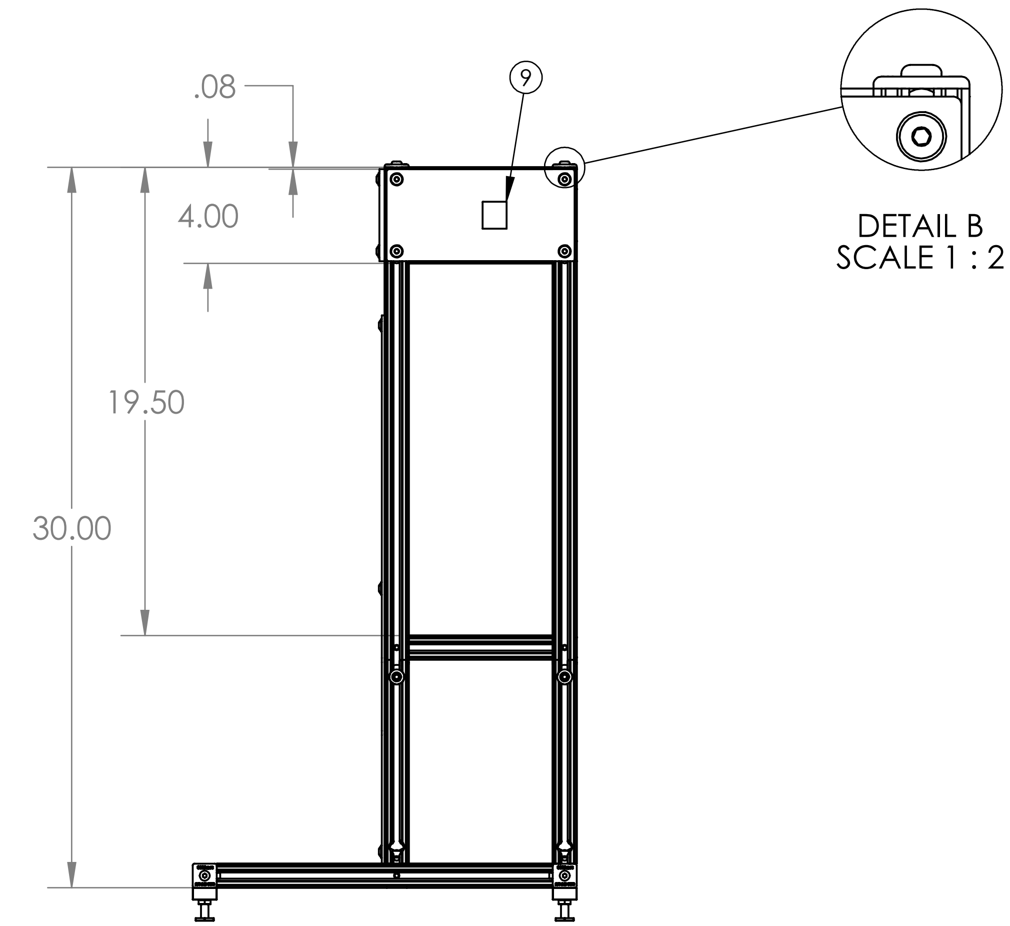
END FASTENERS:
INSTALL END FASTENERS AS SHOWN. BEGIN BY SCREWING THE BUTTON HEAD CAP SCREW (BHSCS) INTO THE 1/4-20 TAPPED HOLE ON THE END OF THE DESIRED COMPONENT. LEAVE ROOM FOR ADDITIONAL TIGHENING.

THEN SLIDE COMPONENT DOWN CHANNEL OF ADJOINING COMPONENT UNTIL AT THE DESIRED LOCATION. INSERT TOOL THROUGH TOOLING HOLE IN ADJOINING COMPONENT AND TIGHTEN BHSCS UNTIL TIGHT AND FULLY SECURE.

END CAPS:
INSTALL END CAPS AS SHOWN USING SELF TAPPING SCREWS PROVIDED

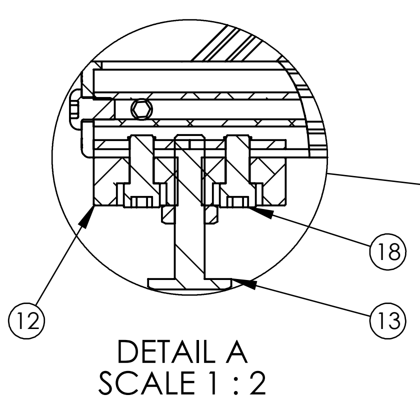
ACRYLIC PLATE INSTALLATION:
INSERT BHSCS THROUGH HOLES IN PLATES, THEN PARTIALLY THREAD T-NUTS. ALIGN T-NUTS IN 80/20 EXTRUSION CHANNELS, SLIDE INTO LOCATION INDICATED ON DRAWING, AND TIGHTEN USING APPROPRIATE TOOLS. DO NOT OVER TIGHTEN OR THE PLATES WILL CRACK.

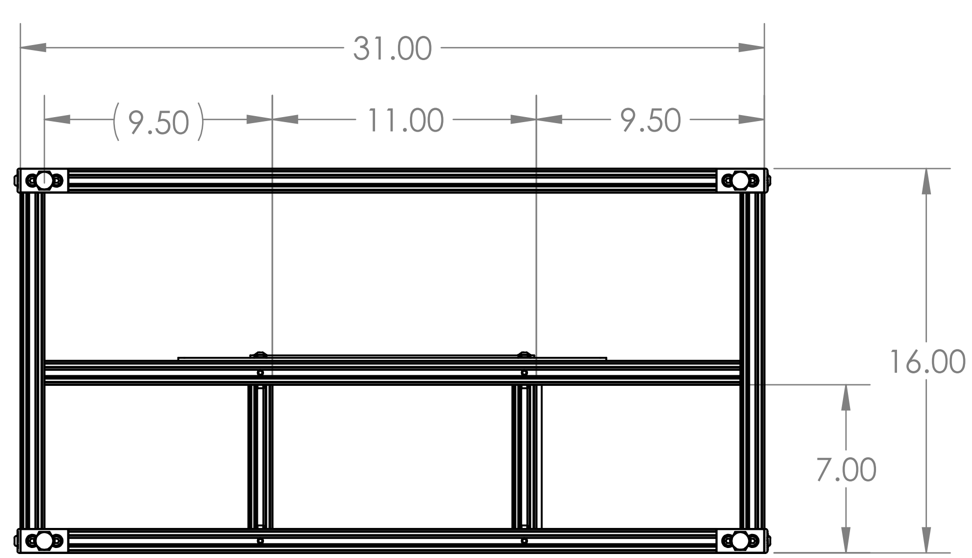




FOOT MOUNTING PLATES:
INSTALL ALL COMPONENTS AS SHOWN TO TO ENSURE THAT LEVELING FOOT MTG PLATES ARE SECURED TO THE FRAME.

LEVELING FEET:
USING A LEVEL, SCREW FEET INTO PLATE UNTIL THE FRAME IS LEVEL ON THE DESIRED OPERATING FLOOR.





PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: ALUMINUM

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/25/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

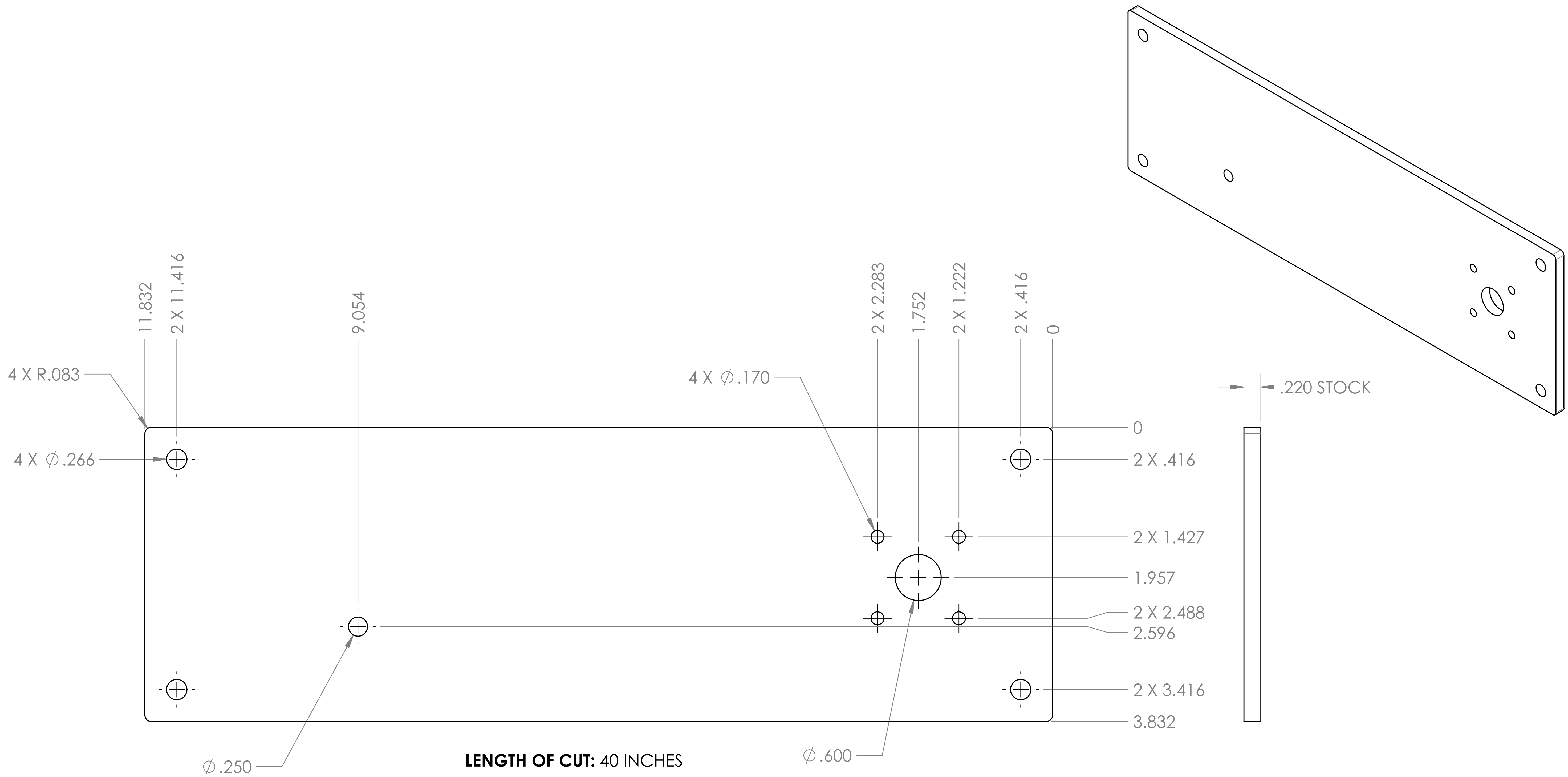
WORCESTER POLYTECHNIC INSTITUTE

TITLE:

1010 SERIES FRAME FOR KNEE TESTER LINKAGE

SIZE	DWG. NO.	REV
B	KTKR-FR-1010-EF	0

SCALE: 1:8 | WEIGHT: 19.39 | SHEET 2 OF 2



LENGTH OF CUT: 40 INCHES

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL 0.22" ACRYLIC

FINISH NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	1/20/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

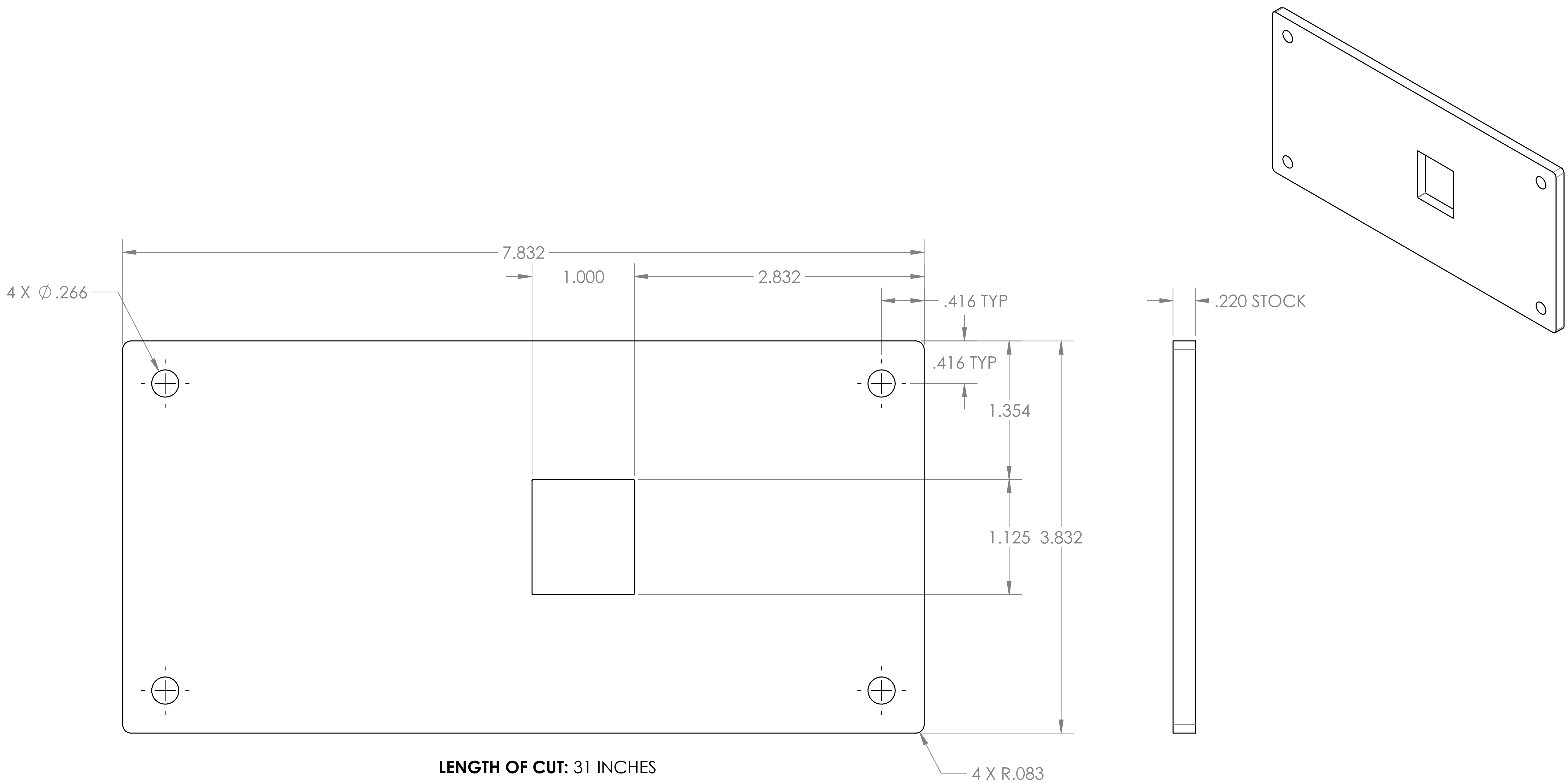
COMMENTS:

WORCESTER POLYTECH

TITLE: LINKAGE GROUND PLATE

SIZE B | DWG. NO. KTKR-PT-001 | REV 0

SCALE: 3:4 | WEIGHT: 0.43 | SHEET 1 OF 1



LENGTH OF CUT: 31 INCHES

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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 0.22" ACRYLIC

FINISH: NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED RBETON	4/21/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

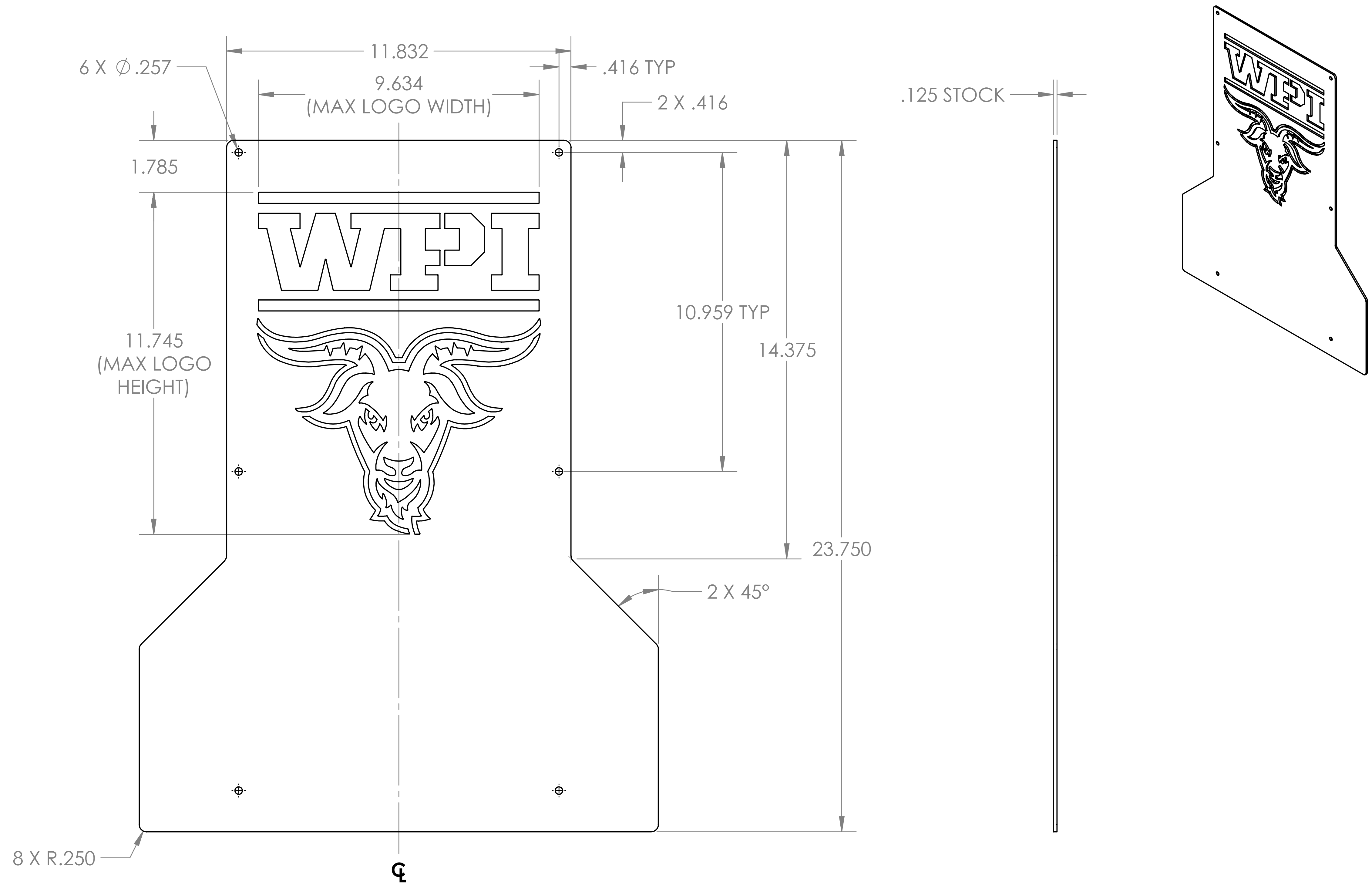
COMMENTS:

WORCESTER POLYTECH

TITLE: SWITCH MTG PLATE

SIZE	DWG. NO.	REV
B	KTKR-PT-002	0

SCALE: 1:1 | WEIGHT: 0.27 | SHEET 1 OF 1



LENGTH OF CUT: 306 INCHES

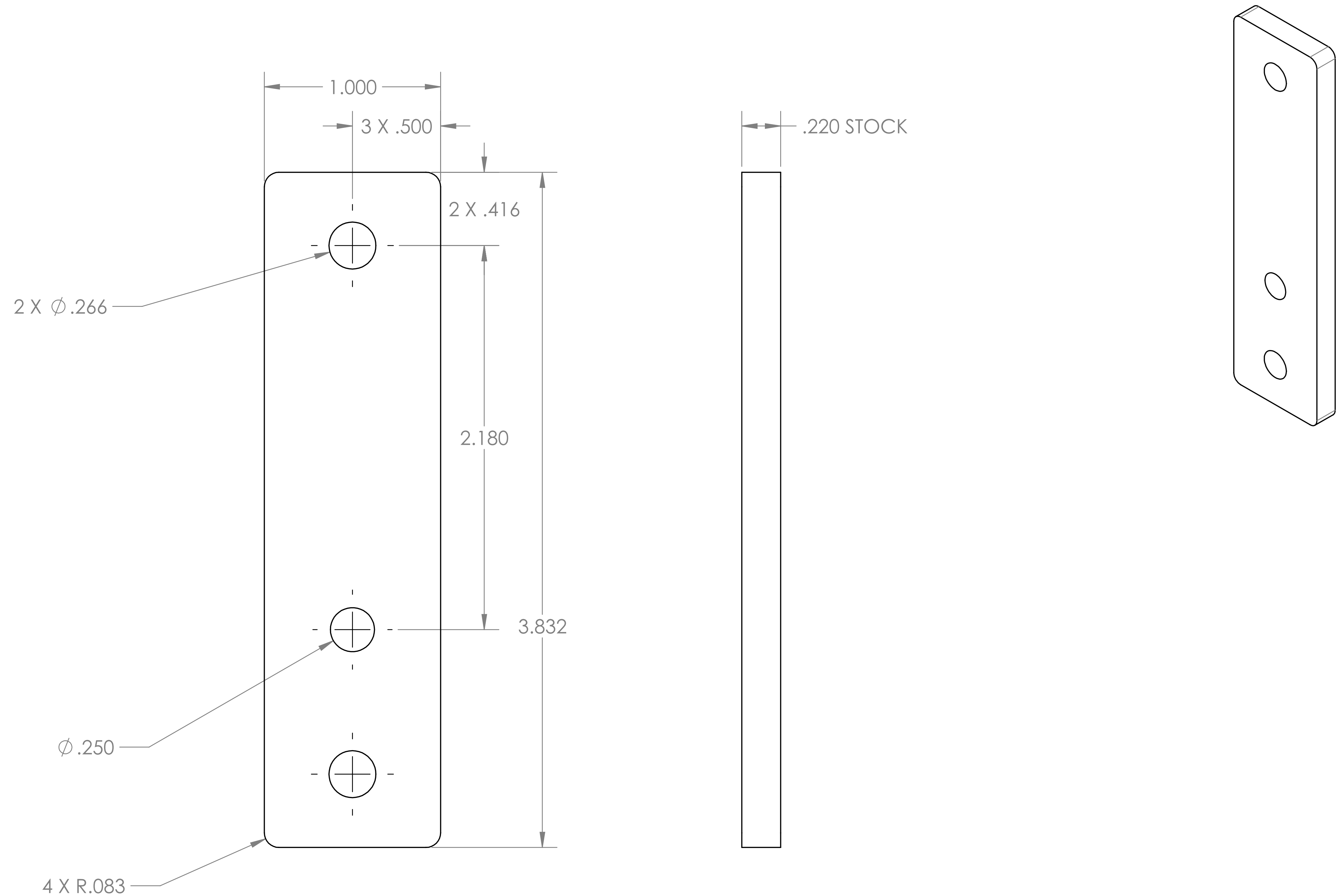
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/16 ANGULAR: MACH ±.5 BEND ±.5 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.015	DRAWN	JARED BRETON	4/21/2015
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 1/8" RED ACRYLIC	COMMENTS:		
FINISH NONE			
DO NOT SCALE DRAWING			

WORCESTER POLYTECH

TITLE: COLLISION PLATE

SIZE	DWG. NO.	REV
B	KTKR-PT-003	0

SCALE: 1:4 | WEIGHT: 1.39 | SHEET 1 OF 1



LENGTH OF CUT: 12 INCHES

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.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: MACH ±.5 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.015

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
0.22" ACRYLIC

FINISH
NONE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JARED BRETON	4/21/2015
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

WORCESTER POLYTECH

TITLE:

AXLE MOMENT NEUTRALIZING PLATE

SIZE	DWG. NO.	REV
B	KTKR-PT-004	0

SCALE: 3:2 WEIGHT: 0.03 SHEET 1 OF 1

Appendix L: Position Data and Calculations from the Tracker Program

Step #	Knee Position		Ankle Position		Femur Vector			Tibia Vector			Dot Product	Magnitude Product	Cos(θ)	θ (rad)	θ (deg)	Actual θ (deg)
	X	Y	X	Y	X-Component	Y-Component	Magnitude	X-Component	Y-Component	Magnitude						
1	-89.19	-361.58	-43.39	-725.57	89.19	361.58	372.42	45.80	-363.99	366.86	-127528.15	136626.84	-0.93	2.77	158.97	**158.97**
2	-80.08	-363.47	-36.41	-726.51	80.08	363.47	372.19	43.66	-363.04	365.65	-128457.85	136092.65	-0.94	2.81	160.72	**160.72**
3	-69.50	-365.40	-29.34	-726.62	69.50	365.40	371.95	40.16	-361.21	363.44	-129197.20	135182.54	-0.96	2.84	162.89	**162.89**
4	-60.14	-366.47	-22.29	-726.80	60.14	366.47	371.37	37.85	-360.33	362.31	-129773.58	134552.33	-0.96	2.87	164.68	**164.68**
5	-49.48	-367.90	-14.65	-727.63	49.48	367.90	371.22	34.84	-359.73	361.41	-130620.75	134161.05	-0.97	2.91	166.81	**166.81**
6	-40.70	-368.52	-6.23	-727.95	40.70	368.52	370.76	34.47	-359.43	361.08	-131053.17	133873.31	-0.98	2.94	168.22	**168.22**
7	-31.08	-369.33	2.30	-728.60	31.08	369.33	370.64	33.38	-359.26	360.81	-131649.85	133730.26	-0.98	2.96	169.88	**169.88**
8	-21.45	-369.72	10.96	-729.42	21.45	369.72	370.34	32.41	-359.71	361.16	-132294.51	133753.15	-0.99	2.99	171.53	**171.53**
9	-12.82	-369.85	20.38	-729.18	12.82	369.85	370.07	33.19	-359.33	360.86	-132473.22	133544.59	-0.99	3.01	172.74	**172.74**
10	-4.46	-370.01	30.40	-729.56	4.46	370.01	370.04	34.86	-359.55	361.23	-132880.98	133669.81	-0.99	3.03	173.77	**173.77**
11	4.97	-369.69	40.42	-729.46	-4.97	369.69	369.72	35.45	-359.78	361.52	-133180.30	133660.42	-1.00	3.06	175.14	**175.14**
12	12.72	-369.42	50.54	-729.53	-12.72	369.42	369.64	37.82	-360.11	362.09	-133513.38	133843.08	-1.00	3.07	175.98	**175.98**
13	20.99	-368.75	61.28	-728.84	-20.99	368.75	369.34	40.30	-360.09	362.34	-133627.36	133826.70	-1.00	3.09	176.87	**176.87**
14	29.52	-367.83	71.98	-728.46	-29.52	367.83	369.01	42.46	-360.63	363.12	-133902.40	133994.61	-1.00	3.10	177.87	**177.87**
15	37.63	-366.84	82.81	-727.47	-37.63	366.84	368.76	45.18	-360.63	363.45	-133993.22	134026.89	-1.00	3.12	178.72	**178.72**
16	44.61	-365.68	94.41	-725.87	-44.61	365.68	368.39	49.80	-360.19	363.62	-133935.91	133953.05	-1.00	3.13	179.08	**179.08**
17	53.36	-364.40	106.10	-724.99	-53.36	364.40	368.28	52.75	-360.59	364.43	-134212.29	134212.29	-1.00	3.14	179.99	**179.99**
18	59.77	-363.30	117.57	-723.29	-59.77	363.30	368.18	57.81	-359.99	364.61	-134239.86	134240.84	-1.00	3.14	179.78	**180.22**
19	67.37	-361.74	129.59	-722.12	-67.37	361.74	367.96	62.22	-360.38	365.71	-134556.87	134568.54	-1.00	3.13	179.25	**180.75**
20	74.24	-360.69	142.05	-720.71	-74.24	360.69	368.25	67.81	-360.02	366.35	-134891.53	134910.64	-1.00	3.12	179.04	**180.96**
21	79.99	-359.42	154.13	-717.71	-79.99	359.42	368.21	74.14	-358.29	365.88	-134705.61	134720.67	-1.00	3.13	179.14	**180.86**
22	86.63	-357.68	167.17	-715.37	-86.63	357.68	368.02	80.54	-357.69	366.65	-134915.57	134933.14	-1.00	3.13	179.08	**180.92**
23	92.48	-356.38	181.55	-712.65	-92.48	356.38	368.18	89.08	-356.28	367.24	-135205.44	135210.77	-1.00	3.13	179.49	**180.51**
24	99.45	-354.38	194.44	-709.37	-99.45	354.38	368.07	94.98	-354.99	367.48	-135247.20	135257.19	-1.00	3.13	179.30	**180.70**
25	104.24	-353.00	208.82	-705.80	-104.24	353.00	368.07	104.58	-352.80	367.97	-135439.42	135439.49	-1.00	3.14	179.94	**180.06**
26	109.48	-351.25	221.67	-702.48	-109.48	351.25	367.92	112.19	-351.23	368.71	-135651.99	135655.36	-1.00	3.13	179.60	**180.40**
27	114.70	-349.36	235.27	-698.69	-114.70	349.36	367.70	120.57	-349.33	369.55	-135871.39	135886.94	-1.00	3.13	179.13	**179.13**
28	119.24	-348.03	248.34	-694.60	-119.24	348.03	367.89	129.10	-346.57	369.84	-136011.39	136059.21	-1.00	3.12	178.48	**178.48**
29	124.05	-345.97	261.48	-690.54	-124.05	345.97	367.54	137.43	-344.57	370.96	-136257.71	136342.31	-1.00	3.11	177.98	**177.98**
30	127.92	-344.45	275.11	-685.91	-127.92	344.45	367.44	147.19	-341.46	371.83	-136444.36	136624.84	-1.00	3.09	177.05	**177.05**
31	131.91	-342.85	287.92	-680.68	-131.91	342.85	367.35	156.02	-337.82	372.11	-136403.48	136695.41	-1.00	3.08	176.25	**176.25**
32	134.85	-341.50	298.78	-676.44	-134.85	341.50	367.16	163.94	-334.94	372.91	-136490.05	136918.27	-1.00	3.06	175.47	**175.47**
33	137.70	-340.40	309.97	-671.61	-137.70	340.40	367.20	172.26	-331.21	373.33	-136464.13	137084.75	-1.00	3.05	174.55	**174.55**
34	139.99	-339.35	320.87	-666.49	-139.99	339.35	367.10	180.88	-327.13	373.81	-136335.17	137223.05	-0.99	3.03	173.48	**173.48**
35	141.79	-338.52	332.74	-660.84	-141.79	338.52	367.01	190.95	-322.32	374.64	-136186.42	137496.93	-0.99	3.00	172.08	**172.08**
36	144.10	-337.61	343.09	-655.84	-144.10	337.61	367.08	198.99	-318.23	375.32	-136112.93	137773.44	-0.99	2.99	171.10	**171.10**
37	144.21	-337.31	352.26	-650.50	-144.21	337.31	366.84	208.05	-313.19	375.99	-135643.67	137930.37	-0.98	2.96	169.55	**169.55**
38	145.44	-336.68	361.31	-644.48	-145.44	336.68	366.75	215.88	-307.81	375.96	-135027.89	137883.19	-0.98	2.94	168.32	**168.32**
39	145.22	-336.77	371.80	-637.45	-145.22	336.77	366.74	226.58	-300.68	376.49	-134163.28	138076.30	-0.97	2.90	166.33	**166.33**
40	144.66	-336.79	381.87	-629.85	-144.66	336.79	366.54	237.21	-293.06	377.04	-133014.69	138198.53	-0.96	2.87	164.26	**164.26**
41	143.23	-337.44	390.36	-623.30	-143.23	337.44	366.58	247.13	-285.86	377.87	-131857.54	138521.30	-0.95	2.83	162.16	**162.16**
42	141.10	-338.42	398.54	-614.79	-141.10	338.42	366.66	257.44	-276.37	377.70	-129855.80	138486.59	-0.94	2.79	159.67	**159.67**
43	138.41	-339.39	406.50	-607.54	-138.41	339.39	366.53	268.09	-268.14	379.18	-128112.99	138980.22	-0.92	2.74	157.19	**157.19**
44	134.95	-340.66	412.84	-599.69	-134.95	340.66	366.42	277.89	-259.03	379.89	-125743.13	139199.24	-0.90	2.70	154.60	**154.60**
45	129.88	-342.58	418.31	-593.34	-129.88	342.58	366.37	288.43	-250.77	382.20	-123367.69	140026.71	-0.88	2.65	151.77	**151.77**

46	123.89	-344.45	421.72	-586.33	-123.89	344.45	366.06	297.83	-241.88	383.68	-120213.82	140446.51	-0.86	2.60	148.86	**148.86**
47	117.99	-346.49	423.52	-580.39	-117.99	346.49	366.03	305.53	-233.90	384.79	-117092.10	140841.36	-0.83	2.55	146.24	**146.24**
48	111.16	-348.64	424.09	-574.96	-111.16	348.64	365.93	312.93	-226.32	386.19	-113689.28	141320.70	-0.80	2.51	143.56	**143.56**
49	103.02	-351.39	423.14	-570.11	-103.02	351.39	366.18	320.12	-218.72	387.71	-109836.53	141971.82	-0.77	2.46	140.68	**140.68**
50	93.79	-354.29	421.22	-566.24	-93.79	354.29	366.50	327.43	-211.95	390.04	-105800.54	142946.50	-0.74	2.40	137.74	**137.74**
51	84.60	-356.62	417.26	-563.05	-84.60	356.62	366.52	332.66	-206.43	391.51	-101760.66	143494.91	-0.71	2.36	135.17	**135.17**
52	74.50	-359.39	412.36	-560.32	-74.50	359.39	367.03	337.85	-200.93	393.09	-97384.42	144276.33	-0.67	2.31	132.45	**132.45**
53	63.87	-361.48	405.49	-558.63	-63.87	361.48	367.08	341.62	-197.15	394.43	-93086.79	144787.30	-0.64	2.27	130.01	**130.01**
54	53.37	-363.56	398.47	-557.96	-53.37	363.56	367.46	345.10	-194.40	396.09	-89091.72	145545.03	-0.61	2.23	127.74	**127.74**
55	42.06	-365.44	390.41	-557.66	-42.06	365.44	367.86	348.36	-192.22	397.87	-84894.79	146358.49	-0.58	2.19	125.45	**125.45**
56	30.94	-367.10	382.43	-558.21	-30.94	367.10	368.40	351.48	-191.11	400.08	-81031.52	147390.16	-0.55	2.15	123.35	**123.35**
57	18.60	-368.10	372.83	-558.75	-18.60	368.10	368.57	354.23	-190.65	402.27	-76767.99	148265.59	-0.52	2.12	121.18	**121.18**
58	7.11	-368.99	363.49	-560.13	-7.11	368.99	369.06	356.38	-191.14	404.40	-73062.47	149248.32	-0.49	2.08	119.31	**119.31**
59	-4.31	-369.03	352.66	-560.89	4.31	369.03	369.06	356.98	-191.86	405.27	-69261.70	149566.40	-0.46	2.05	117.59	**117.59**
60	-17.01	-368.93	342.59	-562.32	17.01	368.93	369.32	359.60	-193.39	408.31	-65229.36	150794.72	-0.43	2.02	115.63	**115.63**
61	-28.14	-368.62	331.25	-562.49	28.14	368.62	369.70	359.39	-193.86	408.34	-61351.38	150963.05	-0.41	1.99	113.98	**113.98**
62	-40.34	-367.71	318.69	-562.91	40.34	367.71	369.92	359.04	-195.20	408.67	-57293.57	151173.40	-0.38	1.96	112.27	**112.27**
63	-51.64	-366.74	307.81	-564.59	51.64	366.74	370.36	359.45	-197.85	410.30	-53996.40	151957.57	-0.36	1.93	110.81	**110.81**
64	-63.18	-364.85	295.71	-566.48	63.18	364.85	370.28	358.89	-201.63	411.65	-50889.14	152426.85	-0.33	1.91	109.50	**109.50**
65	-74.50	-362.89	283.98	-568.53	74.50	362.89	370.46	358.49	-205.64	413.28	-47915.81	153104.56	-0.31	1.89	108.24	**108.24**
66	-82.28	-361.32	271.58	-571.49	82.28	361.32	370.57	353.86	-210.17	411.57	-46823.91	152515.52	-0.31	1.88	107.88	**107.88**
67	-94.56	-358.68	258.78	-574.61	94.56	358.68	370.93	353.35	-215.93	414.10	-44035.97	153603.85	-0.29	1.86	106.66	**106.66**
68	-102.96	-356.38	245.64	-578.66	102.96	356.38	370.95	348.60	-222.28	413.44	-43322.56	153366.39	-0.28	1.86	106.41	**106.41**
69	-113.81	-353.57	231.92	-582.74	113.81	353.57	371.43	345.73	-229.17	414.79	-41683.38	154065.41	-0.27	1.84	105.70	**105.70**
70	-123.37	-350.86	217.93	-588.28	123.37	350.86	371.92	341.31	-237.42	415.76	-41192.73	154629.23	-0.27	1.84	105.45	**105.45**
71	-129.90	-348.57	203.60	-594.02	129.90	348.57	371.99	333.50	-245.45	414.09	-42237.20	154035.58	-0.27	1.85	105.91	**105.91**
72	-138.12	-345.53	188.84	-600.27	138.12	345.53	372.11	326.96	-254.73	414.48	-42857.76	154234.95	-0.28	1.85	106.13	**106.13**
73	-143.99	-343.41	173.89	-606.89	143.99	343.41	372.37	317.89	-263.48	412.89	-44708.53	153747.99	-0.29	1.87	106.91	**106.91**
74	-151.30	-340.68	158.13	-613.73	151.30	340.68	372.76	309.42	-273.05	412.68	-46208.73	153830.38	-0.30	1.88	107.48	**107.48**
75	-156.59	-338.66	141.59	-621.38	156.59	338.66	373.11	298.18	-282.73	410.91	-49055.86	153312.71	-0.32	1.90	108.66	**108.66**
76	-161.48	-336.62	124.87	-629.60	161.48	336.62	373.35	286.35	-292.98	409.67	-52383.50	152951.07	-0.34	1.92	110.03	**110.03**
77	-166.12	-334.64	108.14	-637.26	166.12	334.64	373.61	274.27	-302.62	408.41	-55705.66	152584.62	-0.37	1.94	111.41	**111.41**
78	-170.45	-332.81	90.56	-646.55	170.45	332.81	373.92	261.01	-313.74	408.11	-59927.94	152600.57	-0.39	1.97	113.12	**113.12**
79	-170.81	-332.42	73.02	-655.87	170.81	332.42	373.74	243.83	-323.45	405.06	-65874.93	151385.71	-0.44	2.02	115.79	**115.79**
80	-172.92	-331.65	53.48	-664.27	172.92	331.65	374.02	226.40	-332.62	402.36	-71164.63	150492.25	-0.47	2.06	118.22	**118.22**
81	-171.91	-332.49	36.83	-672.81	171.91	332.49	374.31	208.74	-340.31	399.23	-77267.76	149436.35	-0.52	2.11	121.14	**121.14**
82	-170.54	-333.53	19.02	-681.86	170.54	333.53	374.60	189.56	-348.33	396.57	-83849.18	148554.39	-0.56	2.17	124.36	**124.36**
83	-167.81	-334.47	0.52	-690.38	167.81	334.47	374.21	168.34	-355.91	393.72	-90792.02	147330.75	-0.62	2.23	128.04	**128.04**
84	-163.48	-336.53	-16.90	-698.85	163.48	336.53	374.14	146.57	-362.31	390.84	-97969.80	146227.40	-0.67	2.30	132.07	**132.07**
85	-158.96	-338.54	-31.93	-705.82	158.96	338.54	374.00	127.03	-367.28	388.62	-104148.62	145347.57	-0.72	2.37	135.77	**135.77**
86	-153.60	-340.75	-44.04	-712.02	153.60	340.75	373.77	109.56	-371.27	387.10	-109682.17	144686.39	-0.76	2.43	139.29	**139.29**
87	-146.43	-343.46	-59.68	-720.19	146.43	343.46	373.37	86.75	-376.73	386.59	-116688.72	144340.77	-0.81	2.51	143.94	**143.94**
88	-139.20	-346.46	-61.78	-723.51	139.20	346.46	373.38	77.42	-377.05	384.92	-119857.00	143720.81	-0.83	2.56	146.51	**146.51**