DESIGN OF A KNEE SIMULATOR FOR THE TESTING OF TOTAL KNEE PROSTHESES

A thesis submitted to the Faculty of Health Sciences, University of Cape Town, in fulfilment of the requirements for the degree of Master of Science in Medicine in Biomedical Engineering

By

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2008

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To all of the above, and to anybody else who has contributed to this dissertation,

THANK YOU.

SYNOPSIS

Introduction

This dissertation describes the design of a knee simulator for the testing and wear analysis of fixed- or rotating-hinge total knee prostheses. The simulator is designed to meet the requirements of ISO 14243-3, which specifies the loading and displacement parameters necessary to replicate in-vivo functioning of the prostheses. The required profiles are based on human gait analysis as well as analyses of recovered total knee prostheses. The simulator was not required to be built or commissioned.

The minimising of wear is a pivotal design criteria in any new total knee prosthesis. Knee simulators are required to simulate the wear in total knee replacement designs and to enable measurement of the amount of wear. This data is used to validate new designs or new materials used in the prostheses.

The knee simulator also tests the biomechanical functioning of the prosthesis for failures bought about by mechanical weakness or fatigue. The simulator is required to run for 5 million cycles, equating to approximately 10 years of normal use by the patient.

Simulator Design

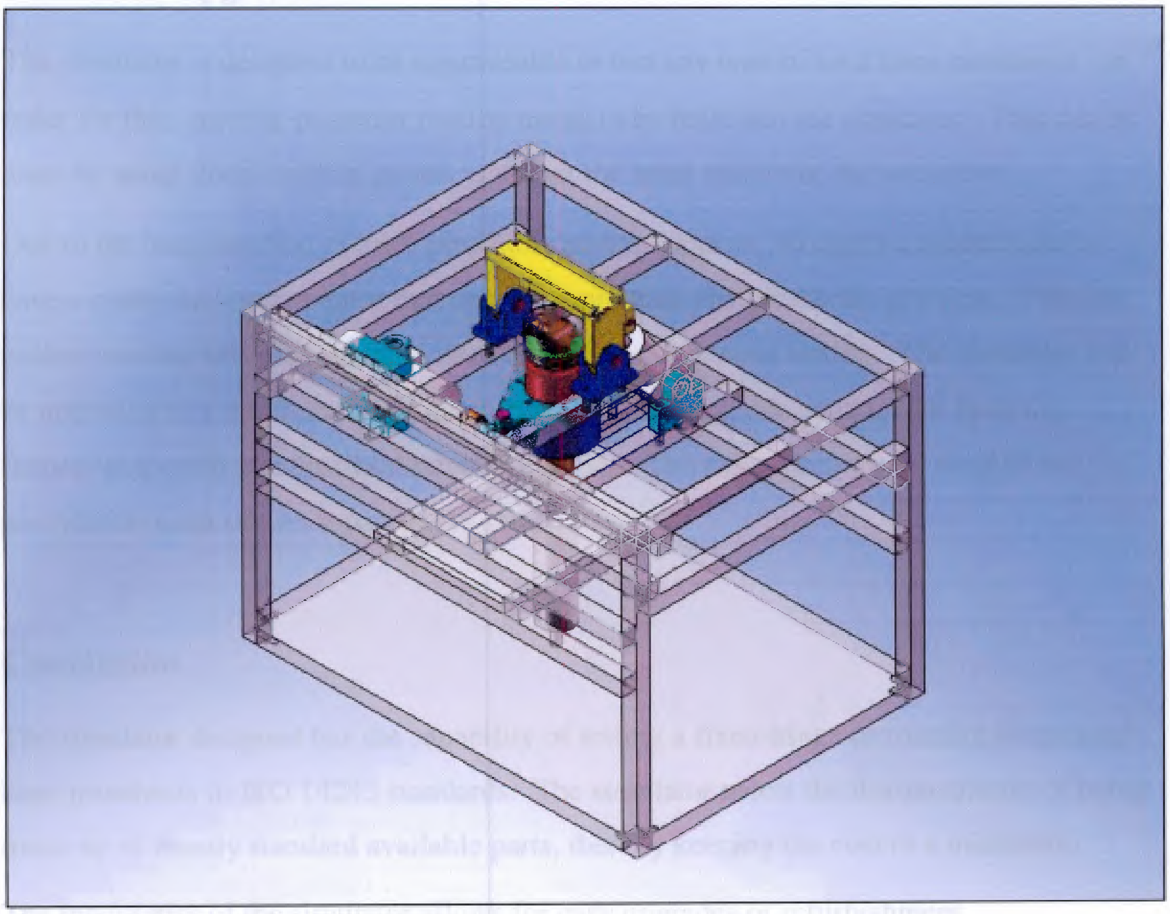
The design consists of a single station, multi-axis simulator capable of testing fixed- and rotating- hinge total knee prostheses that do not have any motion in the anterior-posterior direction. Therefore, the simulator is able to provide flexion-extension, tibial rotation, and axial force motions to the knee prosthesis.

All three motions are provided by linear hydraulic actuators, one for each motion. Linear hydraulics was chosen due to its fast response times and its relative inexpensiveness compared to rotary hydraulics. The linear motion of the actuators is converted to rotary motion by the use of trunnion bearings and spherical rod ends. All actuators are controlled in position control mode by a central desktop computer based interface that integrates the three motions. The axial force is controlled by compressing a die spring and measuring the force generated using a load cell.

Standard, locally available components were chosen where possible for the simulator in order to keep costs as low as possible.

Frame Design

The frame to mount the simulator is constructed from cold-rolled steel using 35mm square bar. The frame is bolted together using M10 socket head screws. The bolting of the frame ensures accurate alignment and also the ability to upgrade the simulator in future.



Synovial Fluid Lubrication System

In order to get test results from the simulator that are indicative of in-vivo conditions, it is necessary to replicate the synovial fluid of the human knee joint and all its lubrication properties.

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1 INTRODUCTION

This dissertation describes the design of a knee simulator for the testing and wear analysis of total knee prostheses. The simulator is designed to meet the requirements of ISO 14243-3, which specifies the loading and displacement parameters necessary to replicate in-vivo functioning of the prostheses. The required profiles are based on human gait analysis as well as analyses of recovered total knee prostheses. The simulator was not required to be built or commissioned.

Ultra high molecular weight polyethylene (UHMWPE) has been the standard bearing material used in total knee prostheses for years. However, UHMWPE wear is a common problem of implanted total knee prostheses and has been linked to adverse biological conditions, bone resorption, and even bone death. The minimising of this wear is a pivotal design criteria in any new total knee prosthesis. Knee simulators are required to simulate the wear in total knee replacement designs and to enable measurement of the amount of wear. This data can be used to validate new designs or new materials used in the prosthesis. The knee simulator also tests the biomechanical functioning of the prosthesis for failures bought about by mechanical weakness or fatigue. The simulator is required to run for 5 million cycles, equating to approximately 10 years of normal use by the patient.

For the purpose of this dissertation, the simulator is designed to test knee replacement prostheses, which are of a fixed-hinge or rotating-hinge configuration, but not including anterior-posterior (AP) motion. The simulator is designed to be upgradeable with minimal design modification to test any knee implant.

1.1 OBJECTIVES

The objectives of this dissertation are to:

- Design a one-station knee simulator capable of testing a fixed-hinge or rotating-hinge total knee prosthesis without AP motion to ISO standards
- Ensure that the simulator is upgradeable to test any total knee prosthesis

- Ensure that the simulator is upgradeable to a multi-station simulator
- Keep the cost of the simulator to a minimum by using standard, locally available parts

1.2 SOURCES OF INFORMATION

Information for this thesis was gained from the following sources:

- Current knee simulator documentation
- General anatomy books
- Specialist knee texts
- Orthopaedic journals
- Various suppliers
- Isiqu Orthopaedics (Cape Town, South Africa)

1.3 PLAN OF DEVELOPMENT

This thesis begins with a literature review concerning the anatomy and biomechanics of the knee, both of which are integral in defining the requirements and operation of the simulator. The literature review then leads on to an overview of the ISO 14243 testing standard, and a comparison of some of the knee simulators that have already been developed. There is also a brief description of the Isiqu proprietary knee that is used as an example of a rotating hinge total knee prosthesis throughout the dissertation. This helps to clarify the design rationale.

This leads into the specification of the simulator and an analysis of the method of actuation and control for the simulator. From this point, the actual design of the simulator components and the frame are discussed before an overview of the total simulator design is given.

The next section looks at a synovial fluid lubrication system for the simulator.

Finally, upgrades to the design are discussed and expanded upon.

2 LITERATURE REVIEW

The evaluation of the performance of total knee replacements is an important requirement both at the design stage, and after production of the finished components. The evaluation of wear, especially, can take many months of testing to simulate ten years or more of usage. A knee simulating machine is essential for this evaluation.

In designing a knee simulating machine it is necessary to have an understanding of the anatomy and biomechanics of the knee, before looking at the requirements of the simulator. This is because the simulator should be able to replicate the anatomical alignment and biomechanics of the knee to as great an extent as possible.

2.1 ANATOMY OF THE KNEE

2.1.1 Introduction

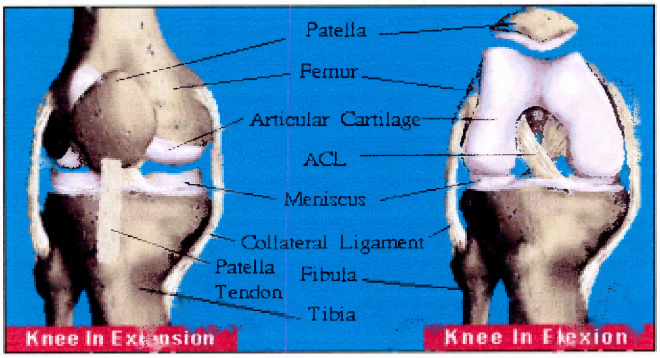

Figure 1: Right Knee in Extension and Flexion[1]

The knee is essentially a hinge joint made up of four bones (*Figure 1*). The femur, which is the largest bone in the thigh, attaches by ligaments and a capsule to the tibia. Just below and next to the tibia is the fibula, which runs parallel to the tibia. The patella rides on the femoral part of the knee joint as the knee bends.

The knee joint also has a structure made of cartilage, which is called the meniscus or meniscal cartilage. The meniscus is a C-shaped piece of tissue that fits into the joint between the tibia and the femur. It helps to protect the joint and allows the bones to slide freely on each other (*Figure 2*).

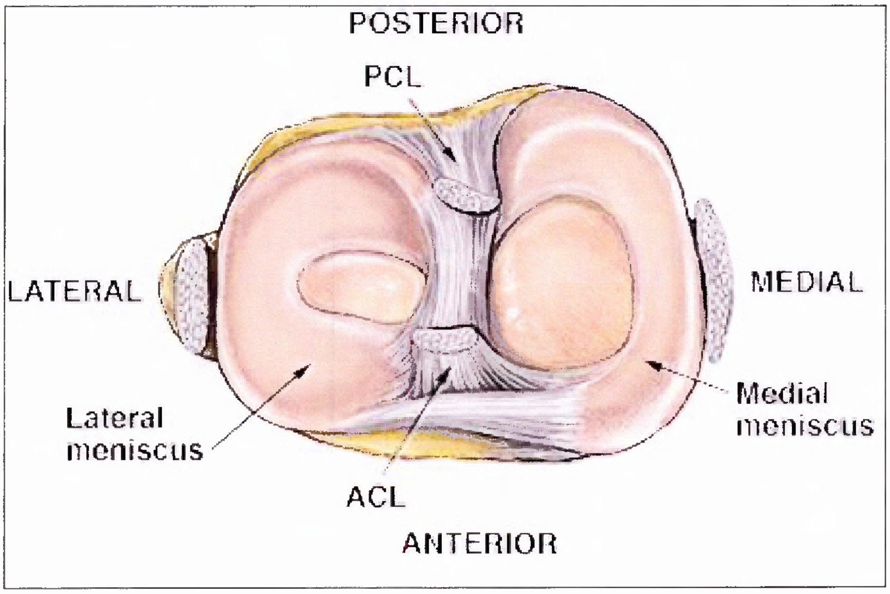

Figure 2: Cross Sectional View of Right Knee[1]

There are two cruciate ligaments located in the centre of the knee joint (*Figure 3*). The anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL) are the major stabilising ligaments of the knee. In *Figure 3*, on the lateral view, the posterior cruciate ligament prevents the femur from sliding forward on the tibia (or the tibia from sliding backwards on the femur). In the medial view, the anterior cruciate ligament prevents the femur from sliding backwards on the tibia (or the tibia from sliding forwards on the femur). Most importantly, both of these ligaments stabilise the knee in a rotational fashion. Thus, if one of these ligaments is significantly damaged, the knee will be unstable when planting the foot of the injured extremity and pivoting, causing the knee to buckle and give way.

The knee can be classified as three separate joints provided by the osseous structures: the patella, the femoral condyles and the tibial plateaus.

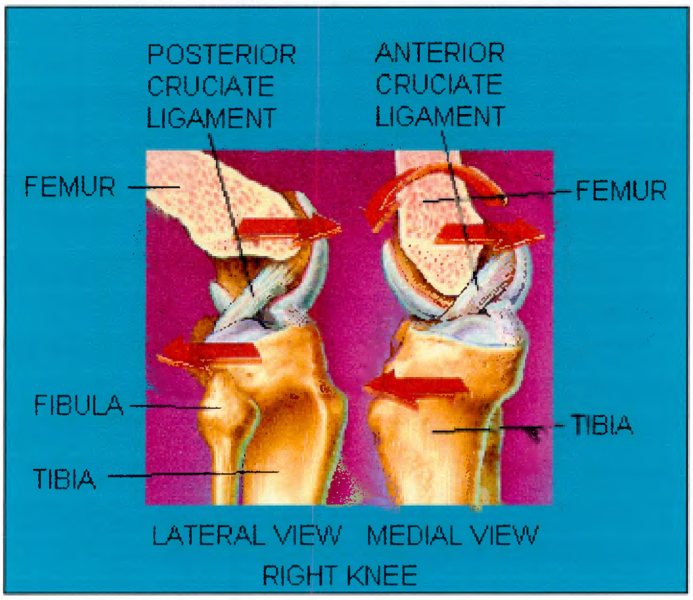

Figure 3: Ligaments of the Knee[1]

2.1.2 Femoral Condyles

The distal end of the femur, which comprises the femoral condyles, is covered with articular cartilage, which is divided into the portion beneath the patella and its articulation and the portion above the tibial plateaus and their articulations by two superficial grooves that run obliquely across the anterior part of the articular surface of each femoral condyle. These grooves are known as the sulci terminales. The articular surface toward the patella – the patellofemoral groove - spreads over the anterior part of the distal femur. The bulk of this surface is situated on the lateral condyle, which reaches to a higher level than does the medial condyle. The portion of the femoral condyles that articulates with the tibia is divided by the intercondylar fossa into the medial and lateral femoral condyles (*Figure 4*).

The femoral condyles are eccentrically curved, the anterior portion being part of an oval and the posterior portion part of a sphere. As the knee flexes, the spherical condylar portions articulate with the tibia, which is deepened by the medial and lateral menisci and in essence becomes a modified ball-and-socket joint with limited rotary motion.

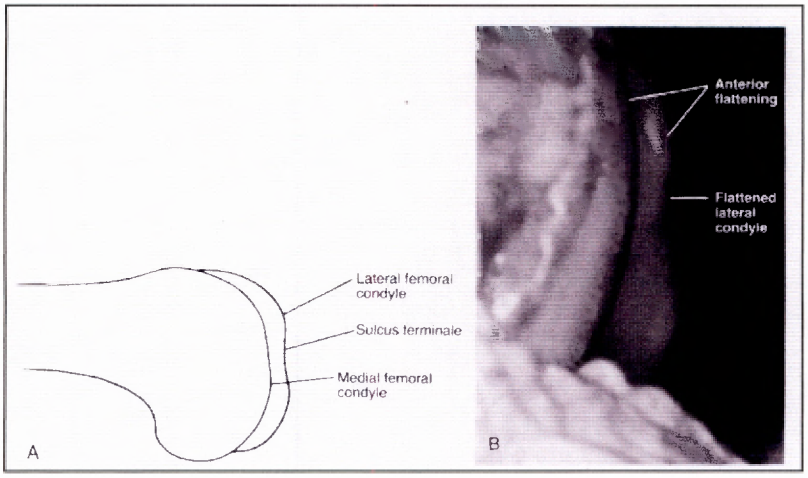

Figure 4: Flattening of the femoral condyle[2]

Anteriorly, the condyles are somewhat flattened, the lateral slightly more so than the medial, and this flattening provides a larger surface area for contact and weight transmission. The articular surface of the lateral condyle is longer and wider than that of the medial condyle. The long axis of the lateral condyle is oriented essentially along the sagittal plane, whereas that of the medial condyle is usually at about a 22° angle to the sagittal plane. This asymmetry of construction is essential for the mechanics of knee motion (*Section 2.3*) (*Figure 5*).

2.1.3 Tibial Plateau

Parsons et al[3] examined tibial plateau topography to study its contribution toward knee stability. The medial tibial plateau shows no significant concavity when viewed in the coronal plane, whereas the lateral tibial plateau shows a slight concavity. In the sagittal plane, the lateral tibial plateau appears convex, whereas the medial condyle is concave. Neither side of the tibial plateau, according to these topographic studies, provides much assistance in stabilising the knee.

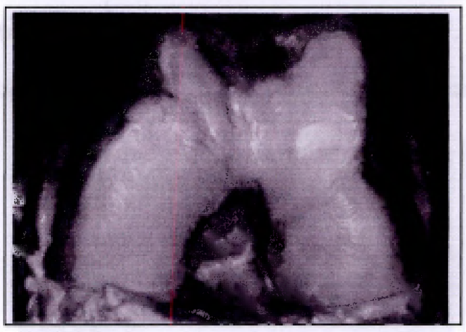

Figure 5: Asymmetry of the femoral condyle[2]

Other studies, however, have shown that the convexity may help protect the ligaments and the capsule. As the knee is flexed, the lateral femoral condyle is displaced slightly more anteriorly to ride upward on the convexity of the lateral tibial condyle. This upward motion absorbs energy and reduces the requirement of the ligamentous capsule to stabilise the knee. The intercondylar eminence of the tibia aids in this stabilisation. The eminence is roughly conical in shape, when viewed from the front, which helps control the amount of rotation possible within the joint. As rotation of the knee occurs, the femur necessarily rides upward on the intercondylar eminence if the supporting structures of the capsule and ligament are intact. With this elevation of the femur, energy is absorbed so as to minimise the load on the capsule and ligaments as rotation occurs.[4]

Parsons et al[3] suggested that the lateral femoral condyle slides slightly laterally, pulling the medial femoral condyle against the medial tibial spine in order to help maintain stability.

2.1.4 The Patella and the Patellofemoral Groove

The patella is a triangular sesamoid bone situated in the extensor mechanism between the quadriceps tendon and the patellar tendon. The proximal wider portion is the base of the patellar, and the narrower distal pole is the apex. Articular facets on the articular surface of the patella articulate with the medial and lateral condyles of the femur (*Figure 6*). Through movement of the knee from 0° to 90° of flexion, a band of contact occurs between the patella and the patellofemoral groove of the femur, from the inferior

2.2.1 Synovial Fluid

Synovial fluid is found surrounding the natural, healthy knee joint and contributes greatly to lowering the friction between the cartilage of the femur and the cartilage of the tibia. It also provides nourishment for the avascular cartilage.[6]

SURFACES IN CONTACT	COEFFICIENT OF FRICTION (μ)
Rubber Tyre/Dry Road	1.0
Metal/Metal	1.0
Glass/Glass	1.0
Perspex/Perspex	0.8
Perspex/Steel	0.3
Wood/Wood	0.25
Ice/Ice	0.05
Synovial Joints	0.02
Articular Cartilage with Saline	0.01
Articular Cartilage with Sinovial Fluid	0.004
Articular Cartilage/Articular Cartilage	0.02 – 0.001

Table 1: Comparative co-efficients of friction between various surfaces[5]

Synovial fluid is produced by the synovial membrane which surrounds the knee (*figure 8*). The synovial membrane is a thin sheet of areolar tissue rich in blood vessels and lymphatics. It has the ability to change plasma into synovial fluid. Thereby it can monitor the level and concentration of the synovial fluid.

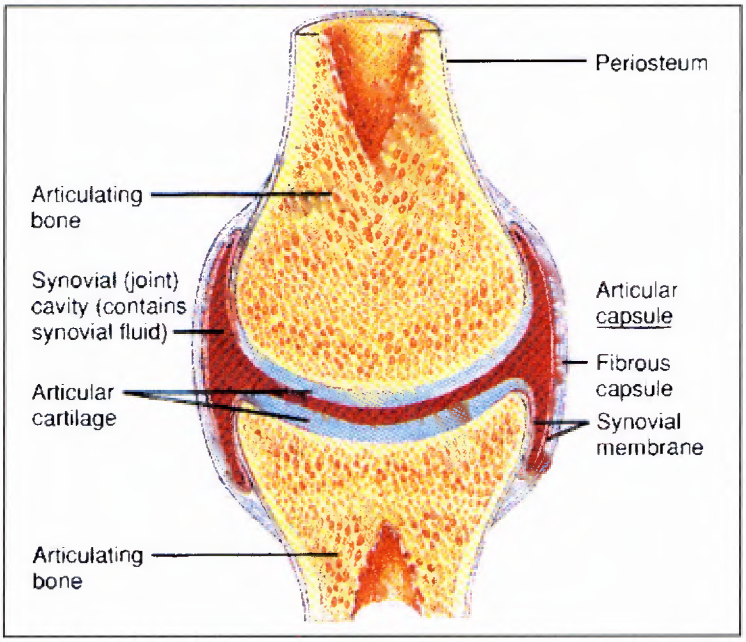

Figure 8: Frontal Section of a generalized diarthrotic (synovial) joint[7]

The main components of synovial fluid are hyaluronic acid and proteins. It is these components that give the synovial fluid its lubrication properties that need to be recreated in a knee testing machine.

2.2.2 Synovial Fluid and Knee Prostheses

Almost all knee prostheses consist of a Cobalt-Chrome (CoCr) Femoral component rotating on an Ultra-High Molecular Weight Polyethylene (UHMWPE) tibial tray. The co-efficient of friction of these components (in-vivo) was found to be approximately 0.07.[8] This represents a value three or four times higher than the natural knee.

In testing the knee prosthesis on a simulator it is necessary to try and recreate this lubrication and friction co-efficient. This is done using bovine serum with a certain protein content.

2.3 BIOMECHANICS OF THE KNEE

2.3.1 Knee Joint Alignment

Proper component and correct limb alignment are essential to achieve durable results after total knee arthroplasty, and are therefore essential in designing a knee prosthesis. Furthermore, this alignment needs to be replicated during the wear testing of the prosthesis.

The mechanical axis of the leg is a line projected from the centre of the ankle to the centre of the femoral head (*Figure 9*).

The mechanical axis of the femur is a line from the centre of the femoral head to the centre of the knee. The mechanical axis of the tibia is a line from the centre of the knee to the centre of the ankle. For a 0° mechanical axis of the leg, the mechanical axis of the tibia and femur would be coincident. The tibiofemoral angle or axial alignment of the limb is formed by the intersection of lines along the centre of the femoral shaft (anatomic axis) and centre of the tibial shaft (anatomic axis) (*Figure 10*).

Different studies have found varying values for the "normal" angle between the mechanical axis and the anatomical axis of the femur. Some investigations have used clinical radiographs whereas others have used anatomical specimens:

- An anatomical study of femoral anatomy in 32 specimens found the angle to be *5.4 ° of valgus.*[9]
- A study of 100 radiographs found the angle to range from *4 ° to 8 ° of valgus.*[10]
- Another radiographic study found the angle to be *5.8 ° ± 0.7 ° of valgus.*[11]

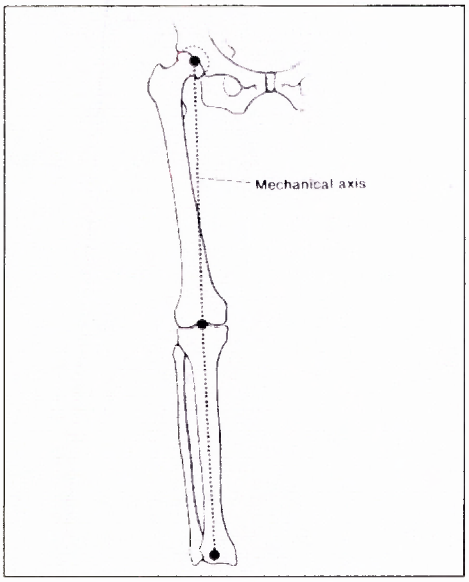

Figure 9: Mechanical axis of the leg[12]

This alignment is built into the TKA prosthesis by having the femoral stem at a set or adjustable valgus angle. The knee simulator needs to be able to accommodate this angled stem for both a left and right knee prosthesis.

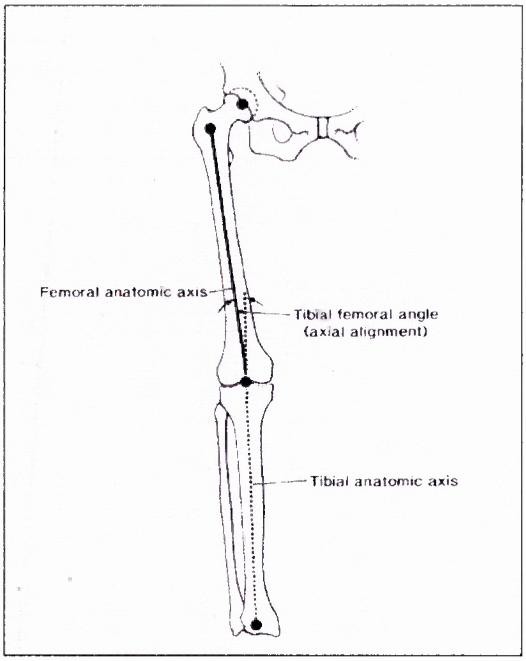

Figure 10: Femoral and Tibial anatomic axes[12]

2.3.2 Ranges of Motion of the Knee Joint

The limits of knee joint motion in the extension/flexion plane are controlled by the cruciate ligaments. The cruciate ligaments act to limit extension and prevent hyperextension. Flexion is controlled by muscles and the natural structure of the leg.

The normal mobility of the knee in the *extension/flexion plane is 5 ° - 0 - 145 °.* A loss of cruciate ligament function leads to pathologic hyperextensibility.[12]

When viewed from above, the knee joint can rotate approximately *20 ° in both the lateral and medial directions.*[12] This degree of motion is controlled by the ligaments of the knee and the muscles of the leg, which cause the knee to return to its neutral position when the force is removed.

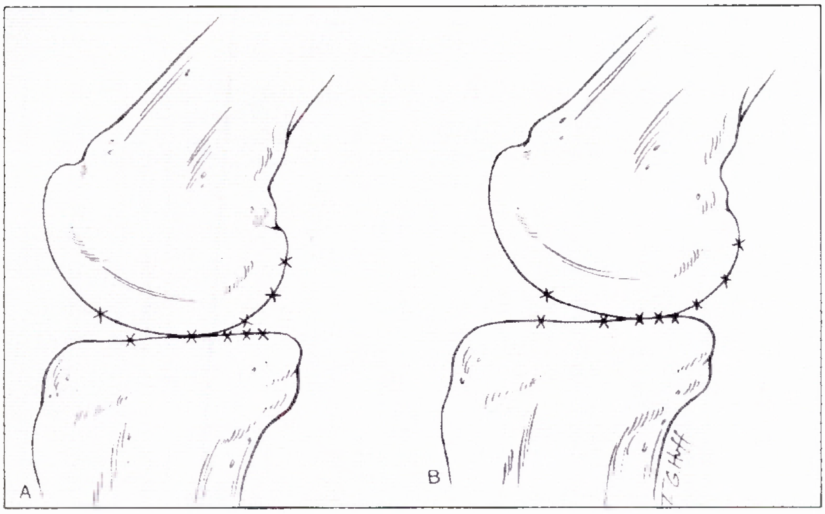

Figure 11: Rolling and gliding motion of the knee. (A) Normal knee. (B) ACL insufficiency[2]

2.3.3 Rolling-Gliding Principle

The motion between the tibia and the femur is not just pure rotation (rolling), but also consists of a gliding motion. This rolling-gliding motion is governed by the anterior and posterior cruciate ligaments (*Figure 11*).

Müller[13] has shown that the basic kinematic principle of motion in the knee joint can be represented by the mechanism of the crossed four-bar linkage (*Figure 12*).

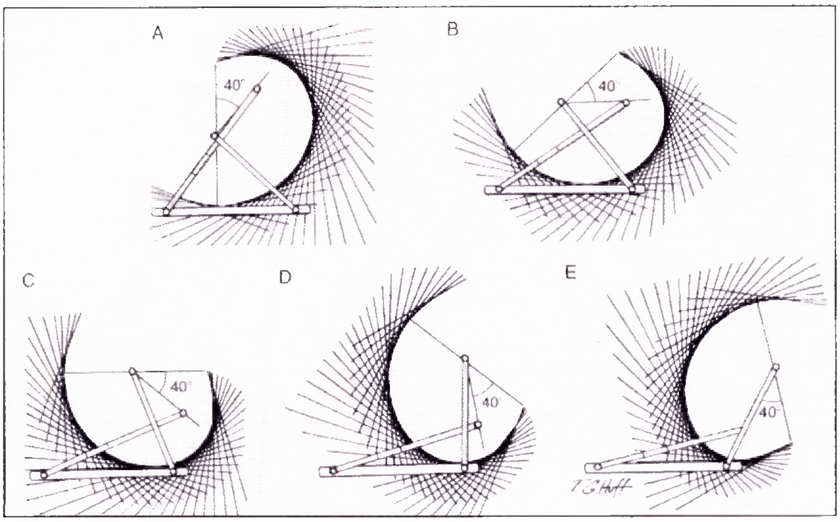

Figure 12: Crossed four-bar linkage[2]

The crossed rods represent the anterior and posterior cruciate ligaments. The rod joining the two crossed rods represents the tibial plateau.

2.4 TOTAL KNEE JOINT PROSTHESIS MOTION DEFINITIONS AND NOMENCLATURE

Below are defined the motions and forces required to be replicated by the simulator and the nomenclature of these motions.

- **Anterior Posterior (AP) Displacement** – Offset between the femoral component and the tibial component, measured in a direction which is perpendicular to both the axial force and flexion/extension axes. It is positive when the tibial component is anterior to its normal position (0° flexion).
- **Axial Force** – Force applied by the tibial component of the knee-joint prosthesis on the femoral component in a direction parallel to the tibial axis. It is considered to be positive when it acts in an inferior-to-superior direction.
- **Tibial Rotation** – Rotation of the tibial component of the knee-joint prosthesis about an axis parallel to the tibial axis. For a right-sided total knee-joint prosthesis, the tibial rotation is positive when a view from a superior position onto

the tibial component shows the tibial component rotated anti-clockwise from its reference position.

- **Flexion/Extension** – Rotation of the femoral component of the knee-joint prosthesis about an axis perpendicular to the tibial axis. It is considered positive when the knee is in flexion.

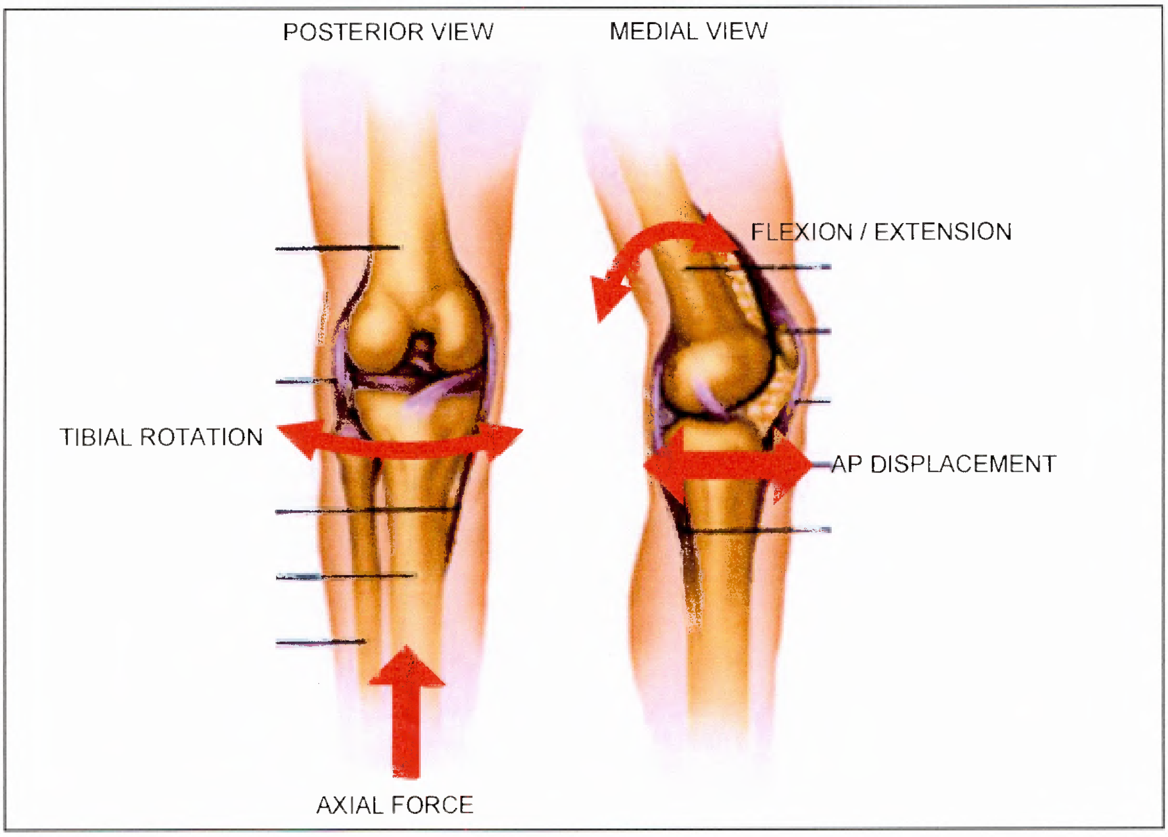

Figure 13: Schematic showing motions and forces to be replicated by knee simulator

2.5 ISO TESTING STANDARDS

The Testing Machine is designed to adhere to ISO Standard 14243-3:

Implants for Surgery – Wear of total knee-joint prostheses – Loading and displacement parameters for wear-testing machines with displacement control and corresponding environmental conditions for test.

ISO 14243-3 specifies relative motion 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 having axial load control, flexion/extension angular motion control, AP displacement control and tibial rotation control.

2.5.1 Principle of Testing[14]

The total knee-joint prosthesis is mounted in an apparatus that applies cyclic variations of flexion/extension angle, tibial rotation angle, AP displacement and axial force to the interface between the tibial and femoral components, simulating normal human walking. The tibial component moves relative to the femoral component under the influence of the applied flexion/extension rotation, tibial rotation, AP displacement, and axial forces. The applied contact force/displacement actions follow a specified cyclic variation, with a fixed relationship between the phases of the actions.

The contacting surfaces of the femoral and tibial components are immersed in a fluid test medium simulating human synovial fluid. A control specimen is subjected to the axial force for reference purposes. This is so as to be able to account for any increase in the mass of the UHMWPE due to absorption of fluid. The test takes place in a controlled environment simulating physiological conditions.

2.5.2 ISO 14243-3 Load / Displacement Curves

Figures 14-17 show the load / displacements as a function of percentage time cycle. These curves are based on a normal walking cycle on flat ground for an average weight person.

The gait data was collected and collated by J.B Morrison[15,16] and adapted to knee wear testing by P.S. Walker et al.[17]

These motion profiles are required to be produced at a frequency of 1 Hz with a tolerance of ± 5% of the maximum value and ± 3% of the full cycle time for phasing.

A lubrication system is required to ensure that the contact surfaces are immersed in the fluid test medium (bovine serum), and that this fluid is maintained at 37°C ± 2°C.

The knee prosthesis is to be tested for 5 million cycles, with regular inspection and wear measurement intervals.

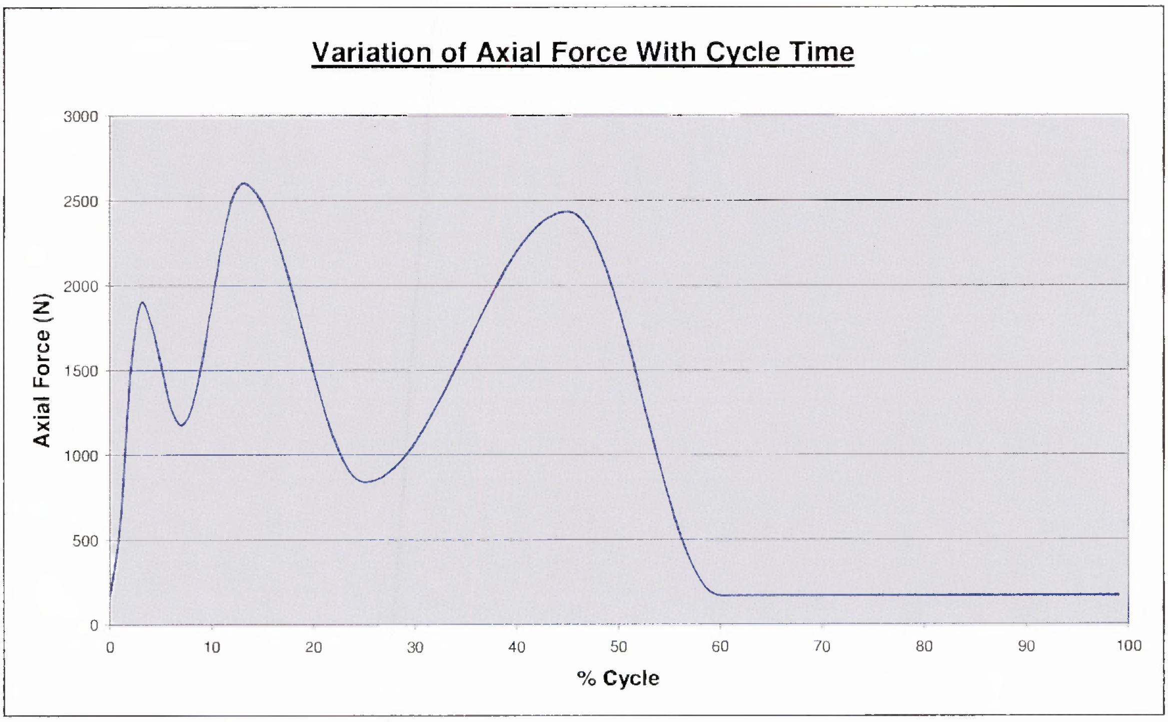

Figure 14: Variation of Axial Force with Cycle Time according to ISO 14243-3

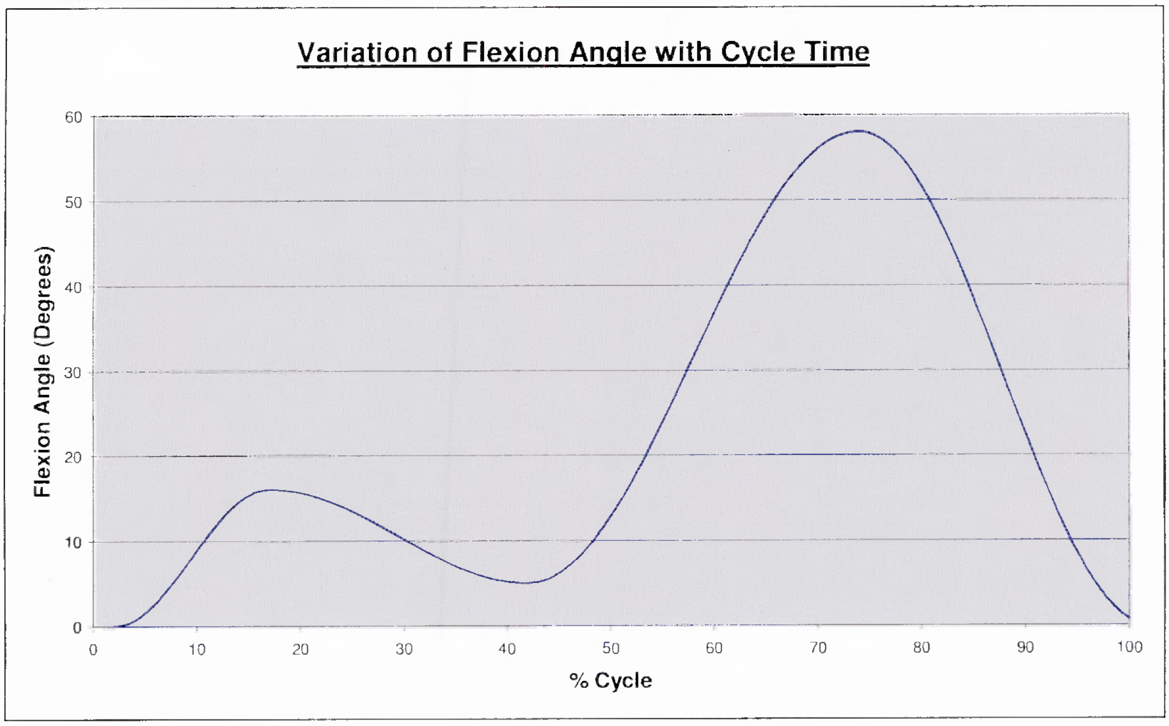

Figure 15: Variation of Flexion Angle with Cycle Time according to ISO 14243-3

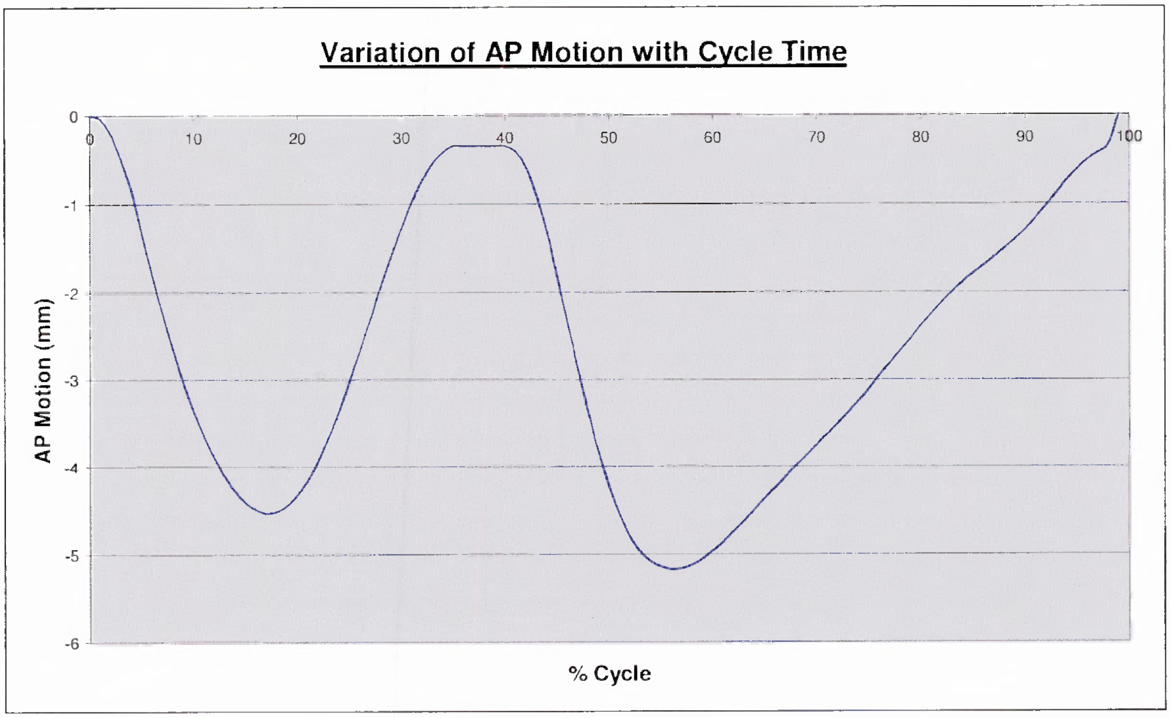

Figure 16: Variation of Anterior-Posterior Motion with Cycle Time according to ISO 14243-3

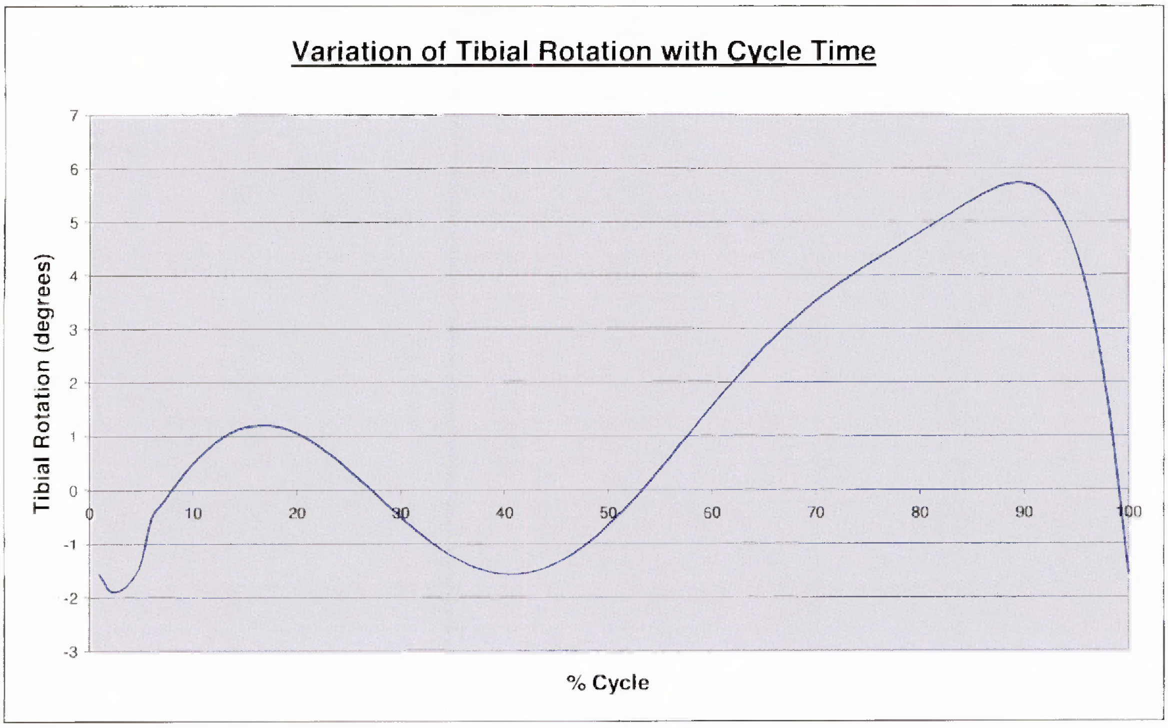

Figure 17: Variation of Tibial Rotation with Cycle Time according to ISO 14243-3

2.6 KNEE PROSTHESIS USED IN SIMULATOR DESIGN

The knee wear simulator is designed to test any knee replacement prostheses which are of a fixed-hinge or rotating-hinge configuration, but not including AP motion. The simulator can be upgraded with minimal design modification to test any knee implant (*Section 7.1*). For the purpose of this report, it will be assumed that the simulator is set-up for one particular knee prosthesis. This prosthesis is a propietary ISIQU Orthopaedics knee, shown in *Figures 18* and *19*.

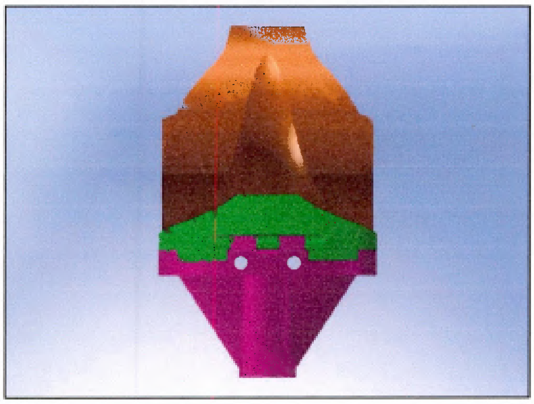

Figure 18: Schematic of the Anterior View of Isiqu Propietary Knee Replacement

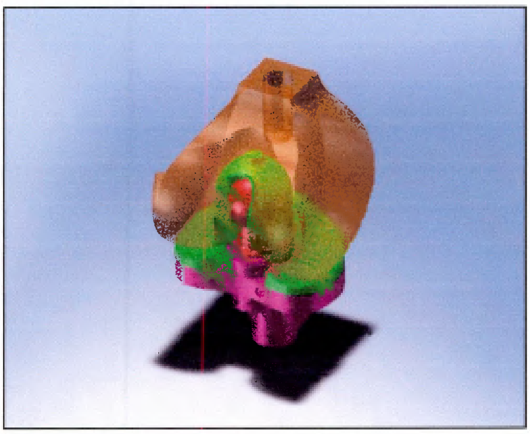

Figure 19: Schematic and Transparent View of Isiqu Proprietary Knee Replacement showing the bearing mechanism

It is a modular knee prosthesis for use in cases of gross ligament instability and bone loss, where the cruciate and collateral ligaments are absent or do not stabilise the joint. The clinical indications for the prosthesis are as follows:

- Significant bone loss
- Bone tumours – primary or metastatic
- Multiple Revision Arthroplasties
- Ligamentous deficiencies

- Trauma
- Connective tissue disorders

2.6.1 Prosthesis Function

The ISIQU knee is constrained by a "ball and stem" connecting the femoral condyle component and the tibial plateau component. It makes use of the "screw home" mechanism of the natural knee to return the knee to its neutral position during lateral and medial rotation. This mechanism relies on the rotating component lifting as it rotates, causing a lessening of surface area and an increase in stress concentration. The knee returns to its natural position due to the weight of the body pushing down on it. It is this mechanism that leads to increased wear on the polyethylene and thereby reduces the polyethylene lifespan.

The prosthesis is fully constrained in the anterior-posterior and medio-lateral directions meaning that there is no gliding motion, but rather pure rotation.

2.7 EXISTING KNEE SIMULATOR DESIGNS

Simulator	# Stations	Control System	Axial Force	Tibial Rotation	Anterior-Posterior	Flexion-Extension
AMTI Force 5	1	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
AMTI-Boston Six Station	6	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
Endolab	6	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
Instron Biopuls Dual-Station	2	Hybrid Electric Servo-Motor and Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
MTS Bionix	6	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
Prosim	6	Hybrid Servo-Hydraulics and Pneumatics	Controlled	Controlled	Controlled	Controlled
Purdue Knee Simulator	1	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
Shore Western	6	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
Stanmore	4	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
University College London	1	Servo-Hydraulics	Controlled	Controlled	Controlled	Controlled
University of Durham	6	Servo-Hydraulics	Controlled	No	Controlled	Controlled

Table 2: Comparative overview of existing simulators

There are a number of existing knee simulators that are either available to be bought commercially or have been designed by the institutions that are using them (*Table 2*). They have been designed to simulate the loading and multi-axis motion of the knee in a physiologic environment. *LaBerge et al*[18] have shown that knee simulators produce similar wear rates and patterns as seen with explanted total knee replacements. Simulators vary, to some extent, in the range of motions achievable as well as in the degrees of freedom. *Table 2* provides a comparative overview of some of these simulators, before a more detailed description of selected simulators is given.

2.7.1 AMTI-Boston Six Station[19]

Figure 20: AMTI-Boston Six Station Simulator

The AMTI-Boston Six Station Knee Simulator has 5-degress of freedom. The femoral component is mounted directly onto a rotating shaft. This mounting arrangement is suitable for simple resurfaced knee femoral components, but the mounting of solid femoral components of the sort used in limb salvage operations, would be difficult and require modification of the component. It also does not allow for testing of any femoral stem components attached to the condyle component. The simulator has the following features and limitations:

- Six testing stations
- Up to 134° of flexion / extension
- Up to 25 mm of AP sliding
- Up to 20° of tibial rotation
- Unconstrained abduction / adduction and medial sliding
- Physiologic loading up to 4500 N

- Operating speeds up to 2 Hz

- Temperature Control

2.7.2 Endolab Simulator[20]

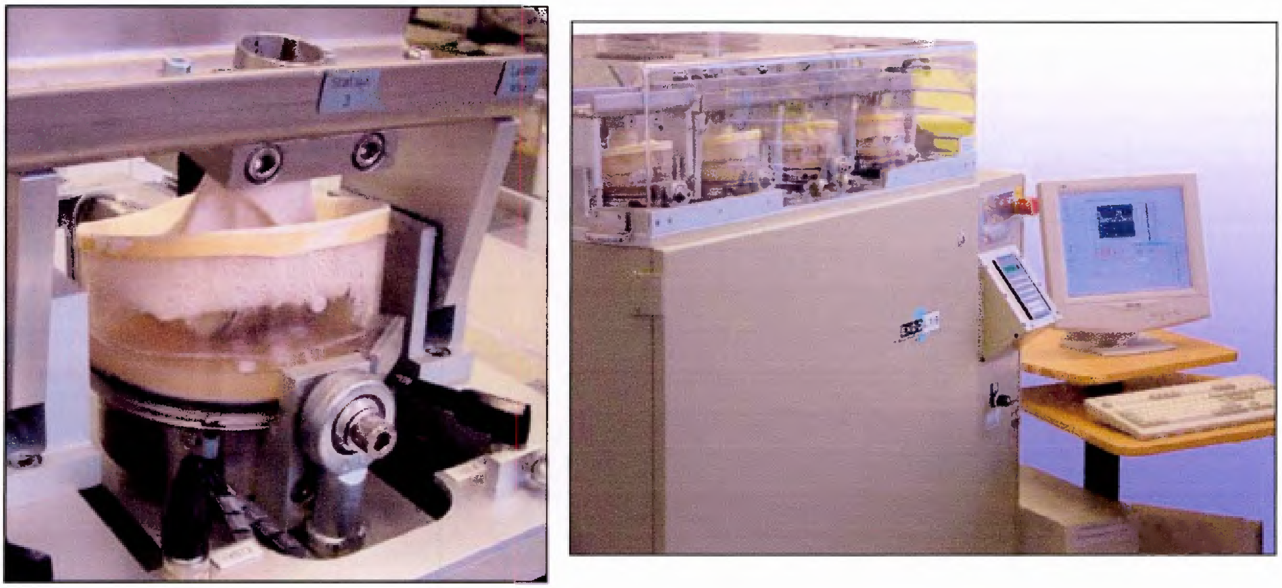

Figure 21 (a and b): Endolab Knee Simulator

The Endolab Simulator is commercially available with four test stations. Its design is based on the requirements of ISO 14243. It makes use of a rocking arm, somewhat like a crankshaft to produce the flexion-extension motion. This rocking arm allows easy mounting of both resurfaced knee femoral components and solid femoral components. It also allows the femoral stem attachment components to be tested if that is desired. The flexion-extension is achieved using a linear hydraulic actuator. The simulator is controlled in four degrees of freedom: flexion-extension, tibial rotation, anterior-posterior motion, and axial loading. The axial loading in each station is individually controlled.

The specimens are mounted in temperature-controlled chambers and submersed in physiological testing fluid. One of the four stations can be used optionally as a load-soak-station, to control for the weight gain of the components due to axial load with fluid exposure.

2.7.3 University of Durham – 6 Station Simulator[21]

The University of Durham simulator was designed and built for the university and is not commercially available. It consists of six stations commonly driven in flexion-extension by a rotary hydraulic actuator. The rotary actuator provides no limit on the flexion-extension angle achievable. The axial loading in each station is individually controlled. The mounting of the femoral components is achieved using a rocking arm similar to that of the Endolab simulator. This allows easy mounting of the components and the ability to test the femoral stem attachment components if required.

The simulator is controlled in flexion-extension, axial loading, and anterior-posterior motion. However, the tibial rotation is not controlled, but is rather an unconstrained passive rotation due to the other forces and motions. ISO 14243 requires that this tibial rotation be controlled and follow a certain motion profile. Therefore, this simulator would more than likely not meet with ISO Standards.

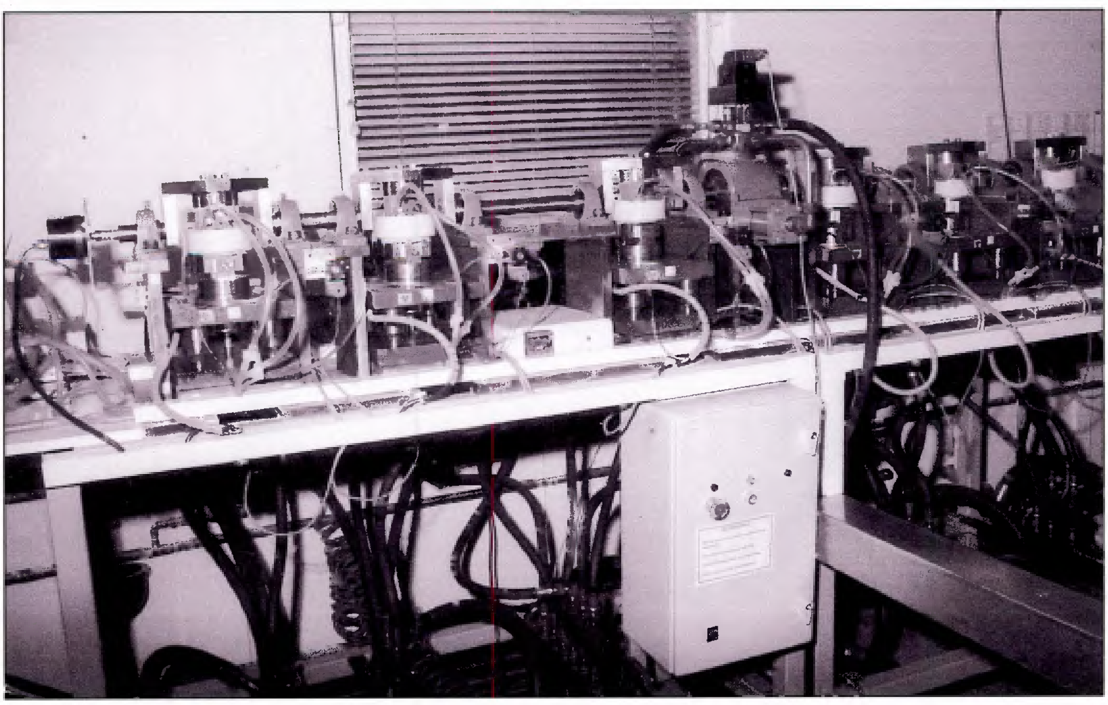

Figure 22: University of Durham 6-Station Knee Simulator

The simulator has the following features and limitations:

- Up to 65° flexion-extension
- Up to 5000 N axial load
- Up to 15.6 mm anterior-posterior translation
- 1.2 - 6.4° unconstrained passive abduction-adduction
- ± 5° unconstrained passive tibial rotation

2.7.4 Instron – Stanmore 4 Station Knee Simulator

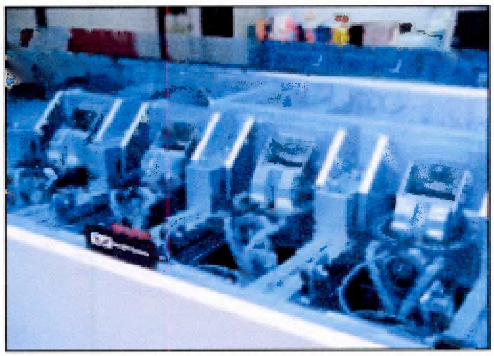

Figure 23: Instron-Stanmore 4 Station Knee Simulator

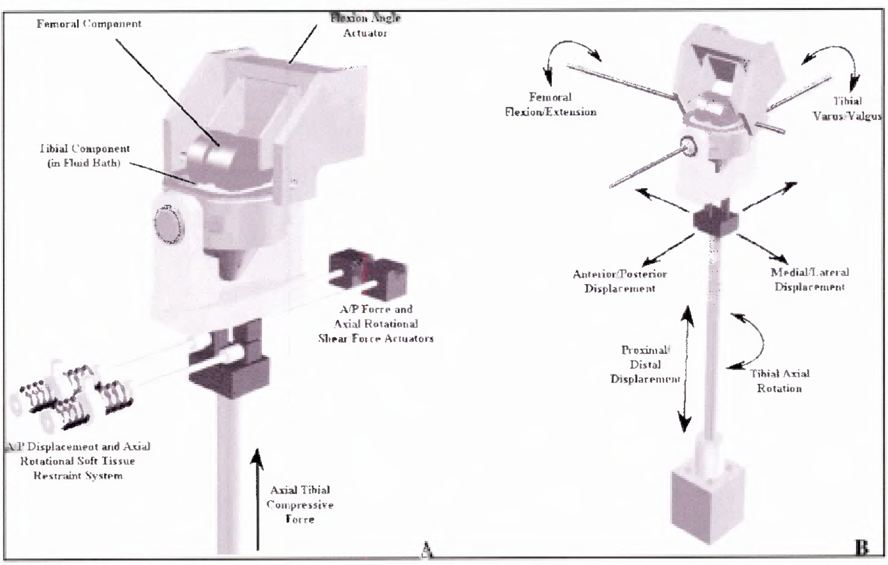

Figure 24: Instron-Stanmore Knee Simulator Schematic

The Instron – Stanmore simulator is a four station simulator with six degrees of freedom. It was designed by the University College of London (UCL) Department of Biomedical Engineering at Stanmore Royal National Orthopaedic Hospital. It was designed specifically to allow development of the ISO 14243 standards.

The simulator accepts most Total Knee Replacement (TKR) designs, including Hinge, Condylar, and Meniscal. It has built in buffers to simulate passive soft tissue restraint. Individual microprocessor-controlled pumping systems for joint lubrication are used for each test station. This critical design feature allows for wear debris collection and measurement without risk of cross-sample contamination.

2.7.5 Instron Biopuls Dual Station Simulator

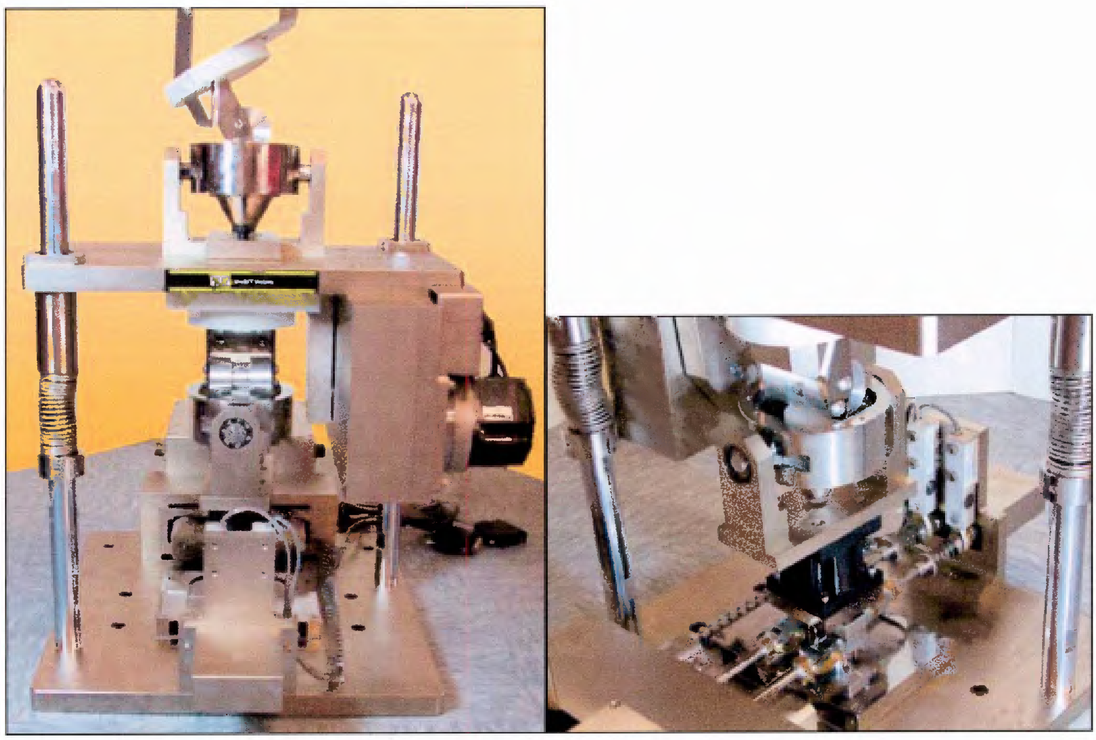

Figure 25: Instron Biopuls Dual Station Simulator

The Instron Biopuls Dual Station Simulator is designed to work on an Instron FastTrack 8870 Series Fatigue Testing Rig. It has two testing stations: one providing all the necessary forces and motions to meet with ISO 14243, the other acting as a soak station.

Also featured is a buffer system to simulate the soft tissue restraint on both the anterior-posterior motion and the tibial rotation.

The simulator has the following features and limitations:

- Axial load up to 4400 N
- ± 20° tibial rotation
- Flexion-extension up to 120°
- ± 25 mm anterior-posterior translation
- ± 15 mm unconstrained medial-lateral translation
- ± 20° unconstrained varus-valgus

3 KNEE SIMULATOR DESIGN SPECIFICATION

3.1 DESIGN SPECIFICATION

The aim of this dissertation is to design a knee simulating machine capable of testing a fixed-hinge total knee replacement according to ISO 14243 standards (*Section 2.5*).

The other design specifications required for the simulator are listed below:

- Due to the fact that it is designed to test a fixed-hinge knee prosthesis, no anterior-posterior motion control needs to be incorporated. *Section 7.1* discusses how the simulator can be upgraded to incorporate anterior-posterior motion control.
- The simulator needs to be able to test one total knee replacement (one station), but have the ability to be easily upgradeable to a multi-station testing rig.
- Continuous force and torsion measurements need to be recorded to verify the testing protocol.
- The cost of the simulator needs to be kept to as low as feasibly possible, while still achieving ISO 14243 standards. In order to achieve this components and vendors should be locally sourced as much as possible, and as many components as possible should be standard components.

3.2 METHODS OF ACTUATION

One of the cornerstones of the design, and the first step in the design, was to find an actuation system that would be capable of producing the required ISO 14243 load profiles (*Section 2.5.2*). By choosing the actuation system to be used, the rest of the simulator design can be specified and designed. The three types of actuation systems considered were pneumatic, electric servo-motors, and hydraulics. A hybrid of these actuation methods could also be used. As can be seen from *Table 2* on page 22, simulators have been designed using the various actuation methods but most use a servo-hydraulic system. The sections below look at the three possible methods of actuation and then the rationale behind the final actuation system choice.

3.2.1 Servo-Pneumatic Actuation

A servo-pneumatic system was considered to provide the necessary motion profiles. One of the main advantages of pneumatics is its inexpensiveness in relation to servo-motors and hydraulics. However, for complicated load profiles at a relatively high frequency (1 Hz), the control of pneumatics can be a problem.

After discussion with pneumatic specialists it was deemed that linear pneumatic actuators would be able to produce the flexion-extension profile as well as the tibial rotation profile. The flexion-extension angle would be limited to approximately 70°. This is due to the fact that the line of action of the linear actuator will move past the centre of rotation of the knee during flexion and therefore not allow it to move in an extensile direction again (see *Figure 52*).

However, the axial force would be extremely difficult to reproduce with pneumatics. The axial force profile is the most robust with very sharp changes of force on the profile. The response time of the pneumatics was seen to be a problem in reproducing this profile.

3.2.2 Electric Servo-Motor Actuation

Electric servo-motors are more expensive than pneumatics but have a much faster response time to motion profile changes. Therefore servo-motors would easily be able to reproduce both the flexion-extension profile and the tibial rotation. An added bonus of servo motors is the ability to be able to extend the flexion angle to any value due to the rotational axis of the actuator being the same as that of the knee. This means that the simulator would be able to test total replacement knees as if they were being used for stair climbing and other gait cycles more robust than normal walking.

Again, the axial force proved to be the problem. In order to produce the axial force profile a high-tech servo-motor would be required with substantial gearing. On investigation these servo-motors proved to not be available locally and to be highly expensive.

3.2.3 Servo-Hydraulic Actuation

Almost all of the existing knee simulators use servo-hydraulics as their actuation method (*Table 2*). This is due to the fast response time of servo-hydraulics and the force generating ability of hydraulic systems.

Both linear and rotary hydraulic actuators are available and could be used in the simulator design. The advantage with rotary actuators for the flexion-extension motion profile is that they can flex the knee up to any angle so as to be able to simulate stair climbing and other such activities. However, rotary actuators are far more expensive than linear actuators.

Linear actuators can be used for the flexion-extension profile (up to approximately 70°) and the tibial rotation profile. Most importantly, servo-hydraulics has no problem in reproducing the axial force profile using a linear actuator.

Hydraulics is more expensive than pneumatics and approximately the same cost as servo-motors.

3.2.4 Comparative Analysis of Actuation Methods

Table 3 summarises the comparative analysis of the three actuation methods.

Hybrid systems were considered to combine the benefits of the various actuation methods, but these would have been substantially more expensive due to the integrated control systems and software required.

	PNEUMATICS	SERVO-MOTORS	HYDRAULICS
Cost	Lowest Cost	Expensive	Expensive
Availability	Locally available	Not fully locally available	Locally Available
Flexion-Extension	Up to 70° with linear actuator.	Up to 135°	Up to 135° with rotary actuator. Up to 70° with linear actuator.
Tibial Rotation	Suitable	Suitable	Suitable
Axial Force	Not Suitable	Not Suitable	Suitable

Table 3: Comparative Analysis of Actuation Systems

Ultimately, it was decided to design the simulator using a servo-hydraulic system with all three motion profiles being created using linear actuators. Linear actuators were chosen due to them being so much cheaper than rotary actuators, and still being able to reproduce the ISO 14243 motion profiles. This choice is in some way vindicated by the fact that most of the existing simulators use linear servo-hydraulics for their actuation systems. This choice forms one of the bases of the simulator design, as the entire design needs to incorporate the linear actuators and the assemblies that ensure that the motion profiles are correctly created.

4 SERVO-HYDRAULIC SYSTEM

Moog South Africa was approached with regards to supplying the hydraulic system for the simulator. Together with Moog, a hydraulic system was designed capable of producing the required load profiles, and recording all the force and displacement data.

Each required motion profile is to be provided by linear actuators provided by Hanchen Hydraulik-Zylinder from Germany (*Appendix 4*). They are a preferred supplier of Moog's and were able to offer highly competitive prices on the actuators. Each motion profile and the relevant simulator design will be dealt with in *Section 5*. Those parts of the hydraulic system common to all motion profiles, such as the control system and valves will be discussed now. All relevant Moog catalogues can be obtained through Moog South Africa.

4.1.1 Servo Valves

Three servo valves are required: one for each axis. Moog Direct Drive servo-proportional valves were proposed for the system. The valves were sized according to the actuators and the motion profiles required and calculations were done to ensure that the valves would be able to function correctly (*Appendix 3*). The selected valves have the following features:

- **Axis cut spool and bushing**, with 0% overlap, resulting in the maximum possible hydraulic stiffness.
- **Direct drive valve**. The valves are robust high performance servo valves.
- **Integrated valve electronics**. The valve electronics are robust surface mounted component card sets that are mounted in an IP 65 housing on the side of the valve.
- **Good dynamic and static performance.** The valves have high resolution allowing them to respond to small control errors, improving the position control accuracy.
- **Robust Spool Drive System.** The valve spool is actuated by a linear force motor, reducing the valve's sensitivity to contamination.

- **Local Service.** The valves can be fully serviced and / or rebuilt in Moog South Africa.

4.1.2 Controller

The motion control will be done using a Moog MSC digital controller and an analog extension unit.

The motion profiles are downloaded to the controller in an Excel file. These files are then loaded into an array that will be used to sequence the three axes and generate the motion profile for the PID closed loop controller.

The interface to the controller is via a desktop PC, communicating with Ethernet. Using Lab View, a user specific interface is created that allows trending of actual performance and saving of results to file.

4.1.3 Control Enclosure

The controller will be installed in a 19" Desktop enclosure. This enclosure will contain the following equipment:

- Moog MSC controller
- Moog analog extension module
- Moog signal conditioner for the load cell
- Moog 24Vdc, 10A power supply
- Terminals, relays and fuses required for the system
- Cooling fan
- Front panel D-sub connectors to sensors and servo valves
- Data acquisition module.

All connections to the field devices will be with 9 and 15 way mil spec D-sub connectors on the controller front panel. This will allow simplified set up of the system cabling.

The hydraulic power pack will also be interfaced with the controller, allowing the operator to Stop/Start the unit from the PC. This will also allow an automatic stop when the test ends, or there is a failure.

4.1.4 Hydraulic Power Unit (HPU)

The HPU is designed for continuous operation and will have an integrated Air Blast cooler. The unit will have the following specifications:

- Moog radial piston pump (32cc, de-stroked to 26cc) with through drive gear pump (11cc).
- 15kW electric motor, 380Vac, 3 phase
- Air blast oil cooler
- 3 micron high pressure filter
- 3 micron off line filtration filter
- Level switch
- Temperature sensor
- 10 litre accumulator and safety block
- Stainless steel oil tank (200 litres)

5 SIMULATOR DESIGN

This section outlines the final design of the simulator. Each motion profile will be treated separately and then the combined design will be discussed. All component drawings can be found in *Appendix 1*.

5.1 AXIAL FORCE ASSEMBLY

As discussed in *Section 3.2.4* the axial force motion profile will be provided by a linear servo-hydraulic actuator.

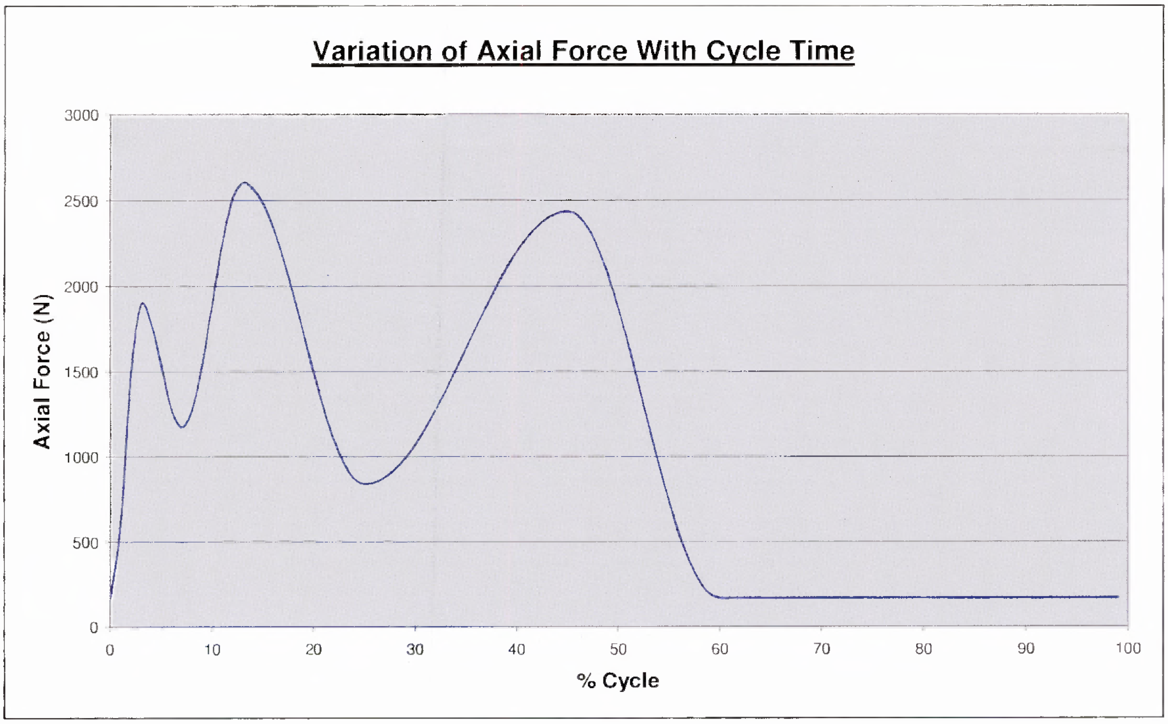

Figure 26: Variation of Axial Force with Cycle Time

Due to the rapid increase in load for the axial force axis, it is necessary for the actuator to be controlled in position rather than force control mode. This will result in a more dynamic solution. This can best be achieved by combining the actuator with a spring system, which increases the load as the spring is compressed. *Figure 27* is a schematic representation of this concept.

This use of a spring system forms the foundation of the axial force assembly design, which is described below and shown in *Figure 28*.

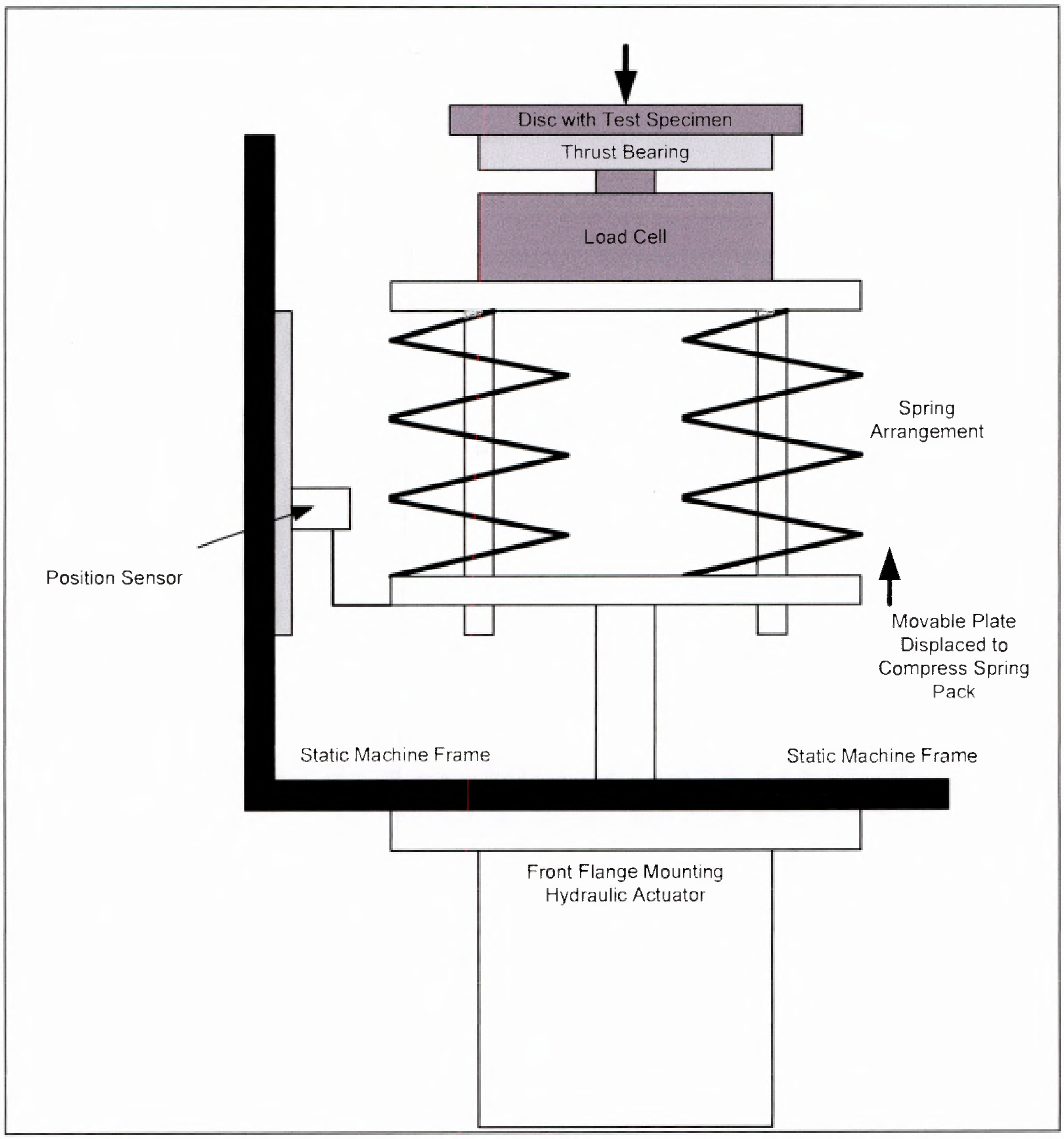

Figure 27: Conceptual representation of a linear actuator and spring system being used to control the actuator in position control.

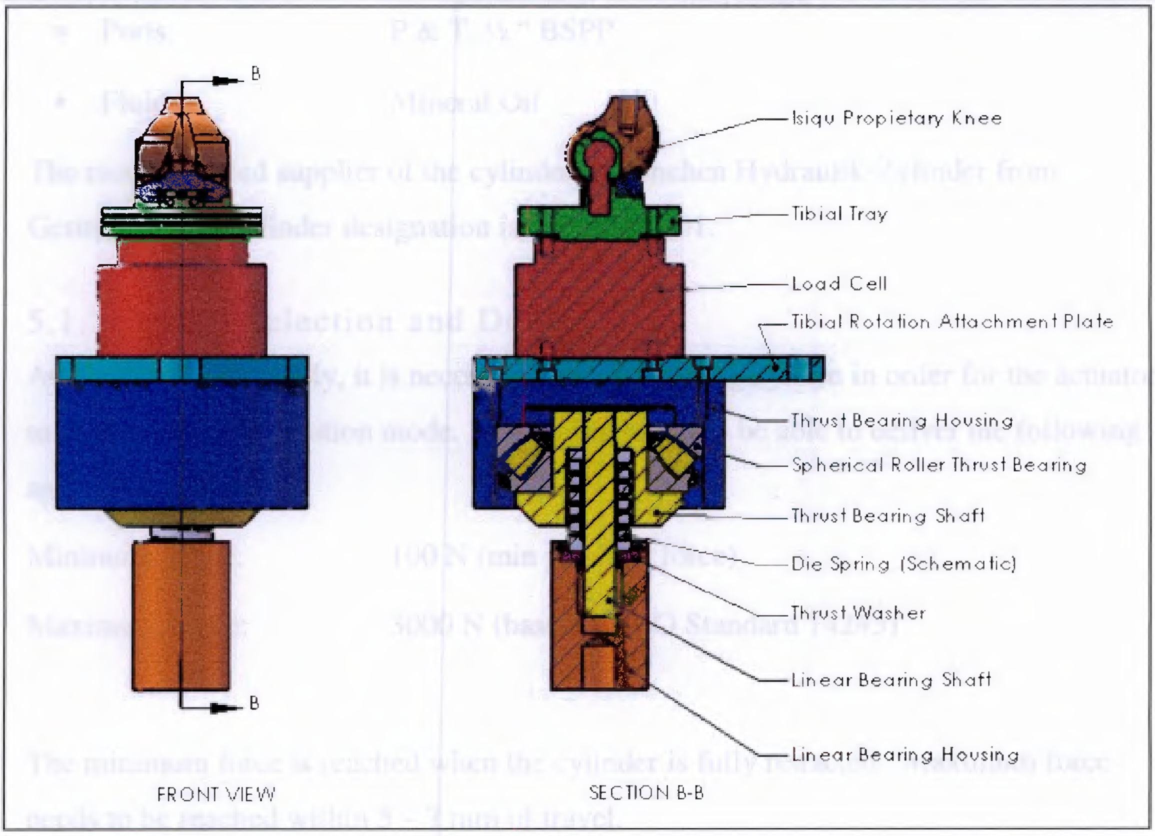

Figure 28: Axial Force Assembly (Sectioned)

5.1.1 Hydraulic Actuator

The system uses an actuator with a front flange mounting. The specifications of the actuator are given below:

- Bore: 40 mm
- Rod: 25 mm (double rod cylinder)
- Stroke: 40 mm
- Working Pressure: 300 Bar
- Mounting: Front flange
- Rod End: M20 male thread
- Valve Mounting: NG6

present in the system), and its suitability for the application. The chosen bearing is an SKF LBBR 20-2LS (*Figure 30*). It is a closed linear bearing with double lip seals on both ends and requires no lubrication during operation.

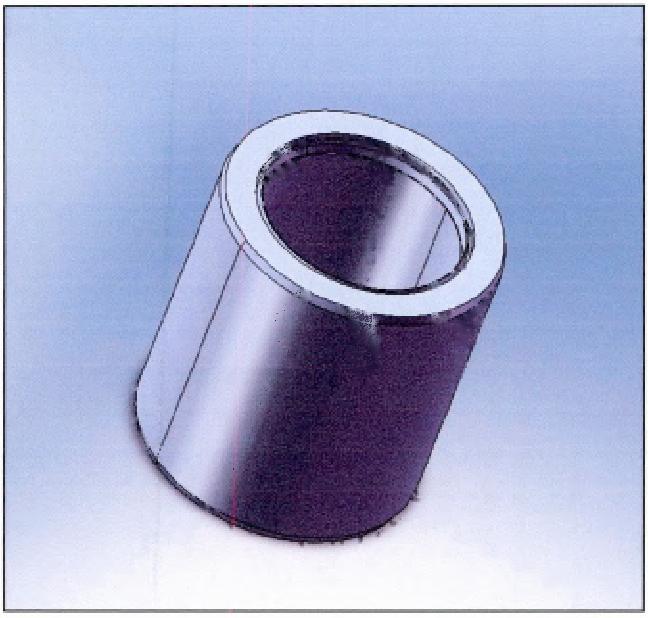

Figure 30: SKF LBBR 20-2LS Linear Bearing

The housing for the linear bearing (*Figure* 31) was designed using the specified tolerances for the bearing and also to provide a connection to the hydraulic piston rod end which has a M20 male thread. The top of the housing has a shoulder where a thrust washer is seated and secured by means of a cir-clip and on which the spring is seated.

Figure 31: Linear Bearing Housing

5.1.4 Thrust Bearing Shaft

The thrust bearing shaft transmits the axial force from the spring through the spherical roller thrust bearing, and therefore allows rotation of the tibial components at the same time (*Figure 32*).

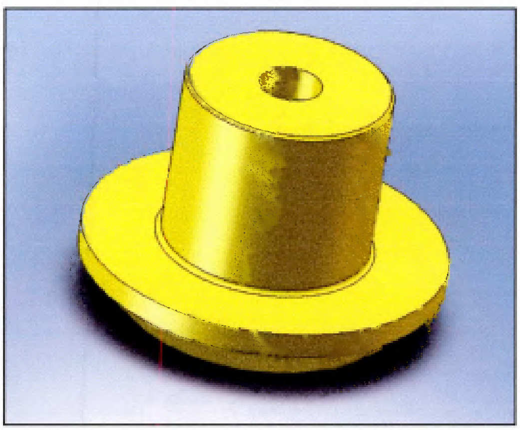

Figure 32: Thrust Bearing Shaft

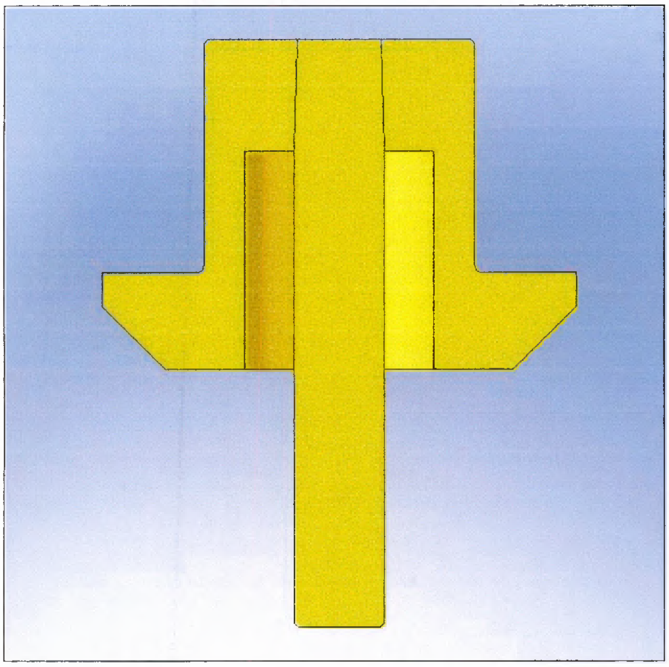

Figure 33: Section View of Assembled Thrust Bearing Shaft

The shaft is made up of two parts: the shaft passing through the linear bearing and the die spring, and the part housing the outside of the spring and acting as the shaft of the thrust bearing. The two are connected by means of a 1.5 degree taper lock to ensure machinability and alignment (*Figure 33*).

The shaft passing through the spring and linear bearing has its diameter governed by the spring and the forces present in the system. The diameter of the shaft is therefore 20mm. The finish and tolerance of the shaft is governed by the linear bearing.

The spring is encased in the thrust bearing part of the shaft in order to minimise space and vertical dimensions, thereby minimising moments in the assembly (*Section 5.1.11*).

The thrust bearing shaft is designed based on the dimensions of the cylindrical roller thrust bearing chosen. Finite Element Analysis using COSMOS has been carried out on the thrust bearing shaft to ensure that localised stresses will not be an issue. These stresses were found to be minimal with the highest stress approximately 7 MPa (*Figures 34 and 35*). Isometry was assumed in the FEA model.

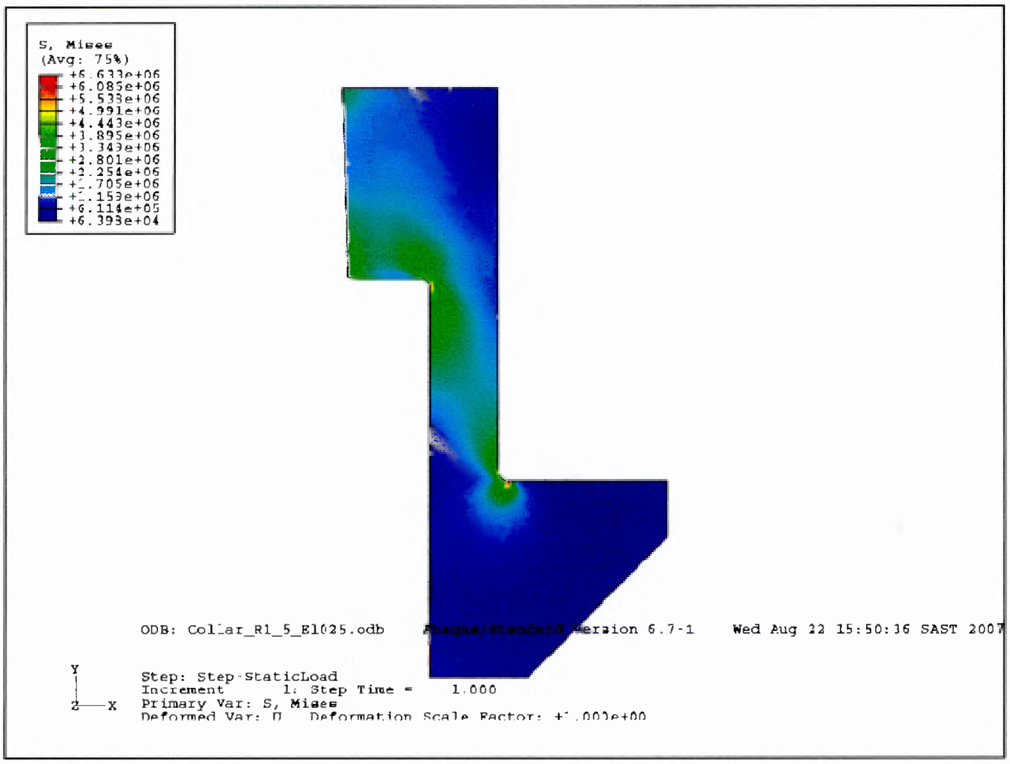

Figure 34: Finite Element Analysis of Thrust Bearing Shaft

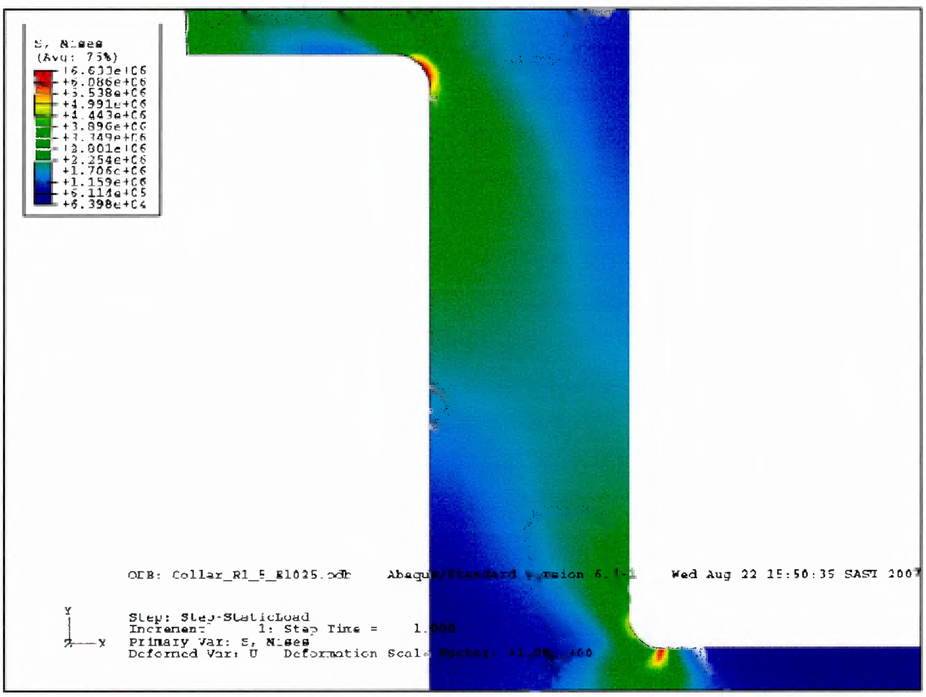

Figure 35: Finite Element Analysis of Thrust Bearing Shaft (Magnified View)

5.1.5 Spherical Roller Thrust Bearing

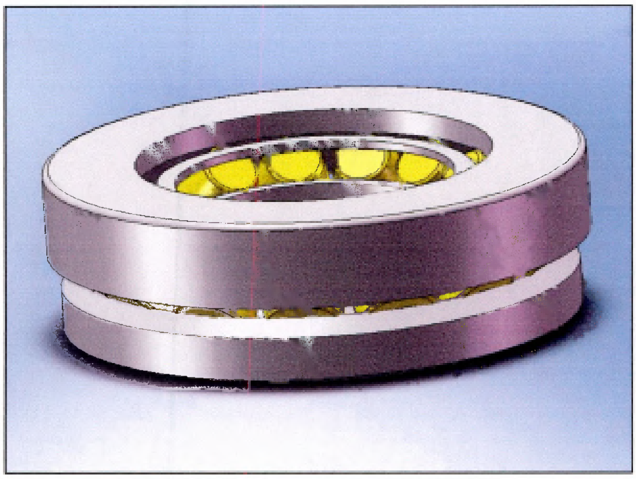

Figure 36: SKF 29412 E Spherical Roller Thrust Bearing

A spherical roller thrust bearing is chosen due to the fact that both axial and radial loads need to be transmitted. The bearing also allows easy assembly as the shaft washer and housing washer can be mounted separately. Bearing calculations show that the bearing far exceeds the required load and life ratings (*Appendix 6*). The bearing is also capable of carrying slight misalignments between the shaft and the housing.

The chosen bearing is SKF 29412 E (*Figure 36*).

5.1.6 Thrust Bearing Housing

The thrust bearing housing (*Figure* 37) is designed to house the bearing as well as provide a mounting for the tibial rotation attachment block. Its dimensions and tolerances are governed by the thrust bearing as well as the mounting requirements of the tibial rotation attachment block.

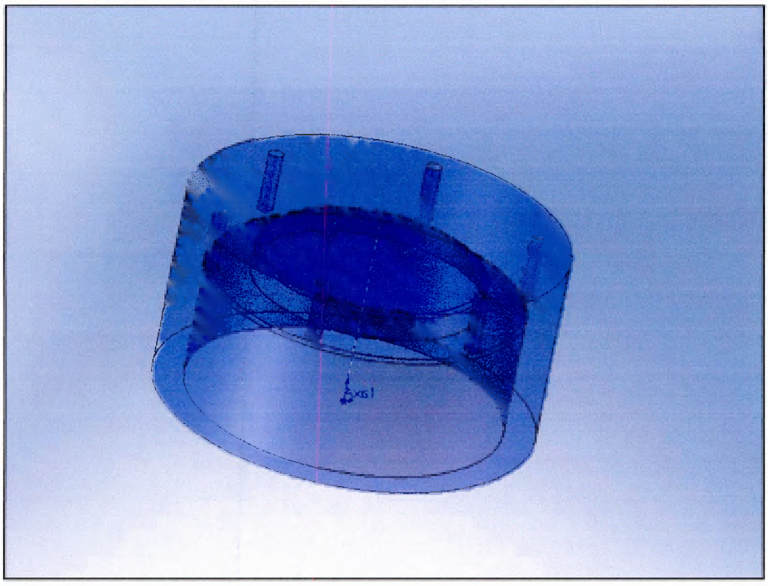

Figure 37: Thrust Bearing Housing (transparent)

5.1.7 Tibial Rotation Attachment Block

The tibial rotation attachment block (*Figure 38)* works to combine the axial force assembly with the tibial rotation assembly. It achieves this by attaching to both the thrust bearing housing and the spherical bearing of the tibial rotation assembly.

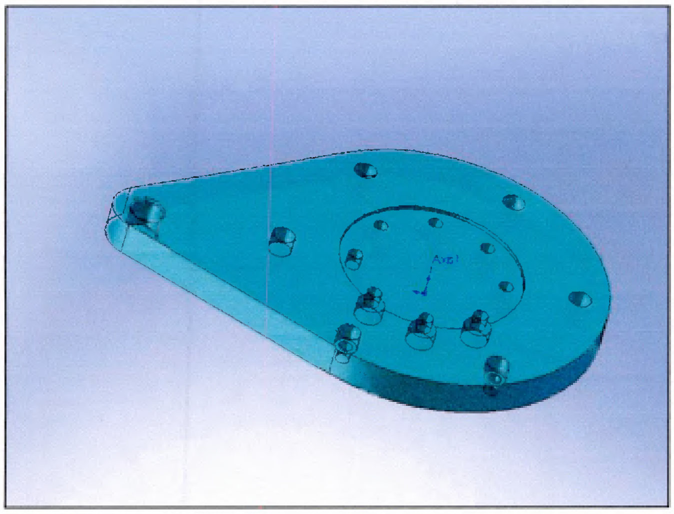

Figure 38: Tibial Rotation Attachment Block (transparent)

It has a series of counter-bored threaded holes to attach to the thrust bearing housing, and to allow for mounting of the load cell.

5.1.8 Combined Axial Torsion Load Cell

The load cell chosen for the application is a combined Axial Torsion Load Cell (Model 1216) manufactured by Interface (*Figure 39*).

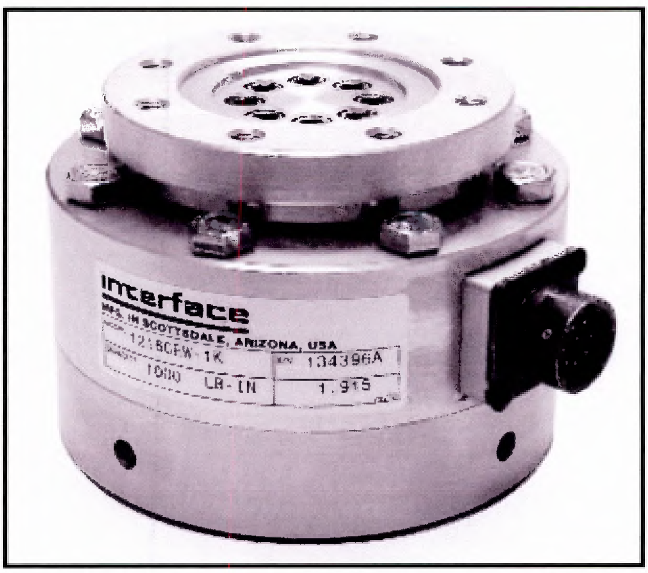

Figure 39: Model 1216 Interface combined axial torsion load cell

It is fatigue rated to 100 million fully reversed cycles. It has a capacity of 1000lbf (4450N). The load cell will be able to read both the axial force transmitted to the tibial component, as well as the torsion created by the tibial rotation motion profile. It is mounted onto the tibial rotation attachment block. The output is fully compatible with the Moog control software. The load cell data sheet is shown in *Appendix 7*.

5.1.9 Tibial Tray

The tibial tray (*Figure* 40) used as an example in this design is based on a proprietary ISIQU Orthopaedics knee design. It must be manufactured from the same material as the actual tray in order to test the fatigue properties.

If other knees are to be tested, suitable trays for holding the tibial component will need to be machined. The tibial tray connects directly to the load cell using six socket head screws.

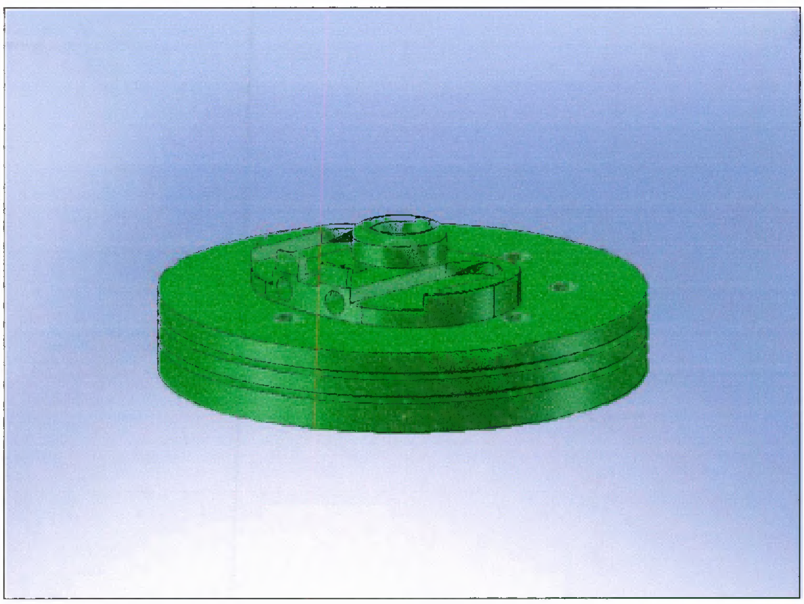

Figure 40: Tibial Tray for Isiqu Proprietary Knee

The tray also has two o-ring grooves surrounding its circumference. This is to provide a seal for the bovine serum containment vessel, which will also be secured by the six allen screws used for the mounting of the tray (*Section 6.3*).

5.1.10 Knee Components

The knee components used as an example in this design are all part of an ISIQU Orthopaedics proprietary knee (*Section 2.6*). The design of these components will not be discussed in this document, apart from where applicable to the design.

5.1.11 Bending Moment Acting on Hydraulic Actuator

One of the main concerns with using a design with only one spring, as above, was that a bending moment would be created on the piston of the hydraulic actuator providing the axial force. This could lead to leaking of the actuator seals or failure of the piston itself. This bending force could be negated using a die system if required.

When the knee is at 0° of flexion, there is no bending moment, as the force is transmitted straight up through the tibial component and into the femoral component. However, as the knee starts to flex, a bending moment is created. The maximum bending moment will occur at the piston of the hydraulic actuator. One way to minimise this moment is to minimise the vertical height of the axial assembly. This has been done in the above design.

Even though the vertical height has been minimised, a bending moment still exists. The magnitude of this moment is due to both the angle of flexion and the axial force value. *Figure 41* shows the axial force and the angle of flexion overlayed on one graph.

The maximum bending moment occurs at 14% of cycle time and has a value of 210 Nm. See *Appendix 8* for a diagram showing why the bending moment occurs. This value was discussed with the manufacturers of the hydraulic actuator, Hanchen Hydraulik-Zylinder and it was deemed that it would not be a problem due to the short stroke of the cylinder and the small force.

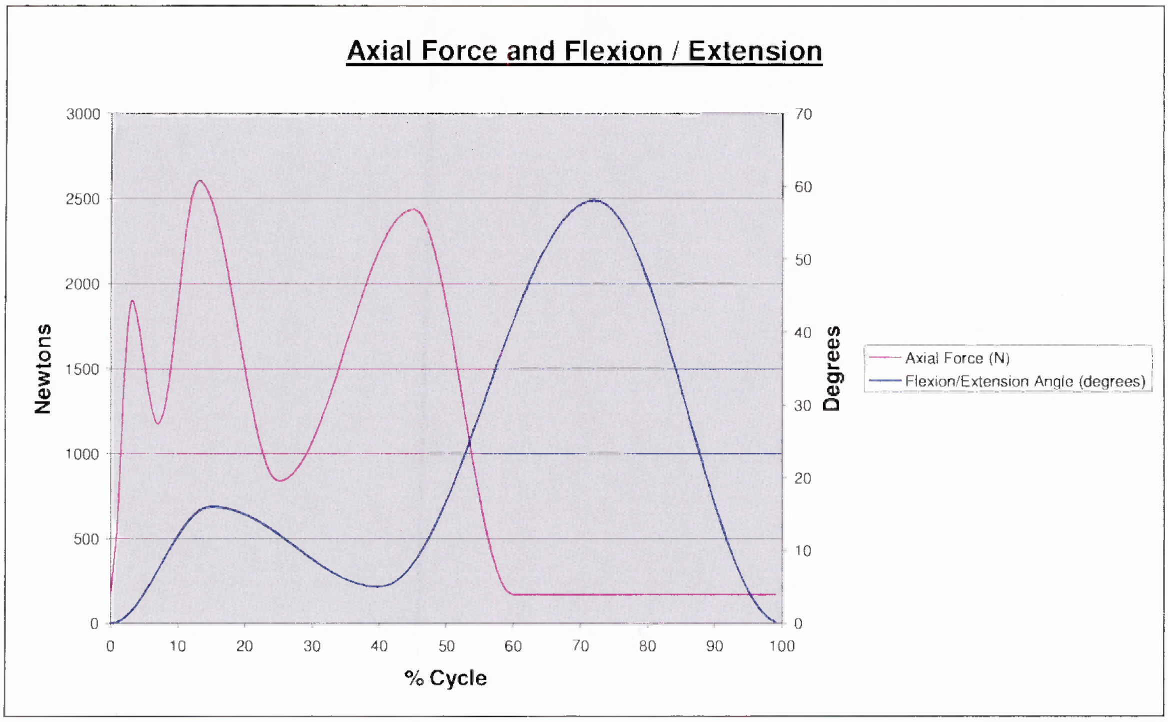

Figure 41: Axial Force and Flexion/Extension Overlay Plot

5.2 TIBIAL ROTATION ASSEMBLY

As discussed in *Section 3.2.4,* the tibial rotation motion profile will be provided by a linear servo-hydraulic actuator. The actuator will be controlled in pure position control using a temposonics magnetostrictive position sensor (*Appendix 5*). *Figure 42* shows the tibial rotation motion profile that needs to be replicated.

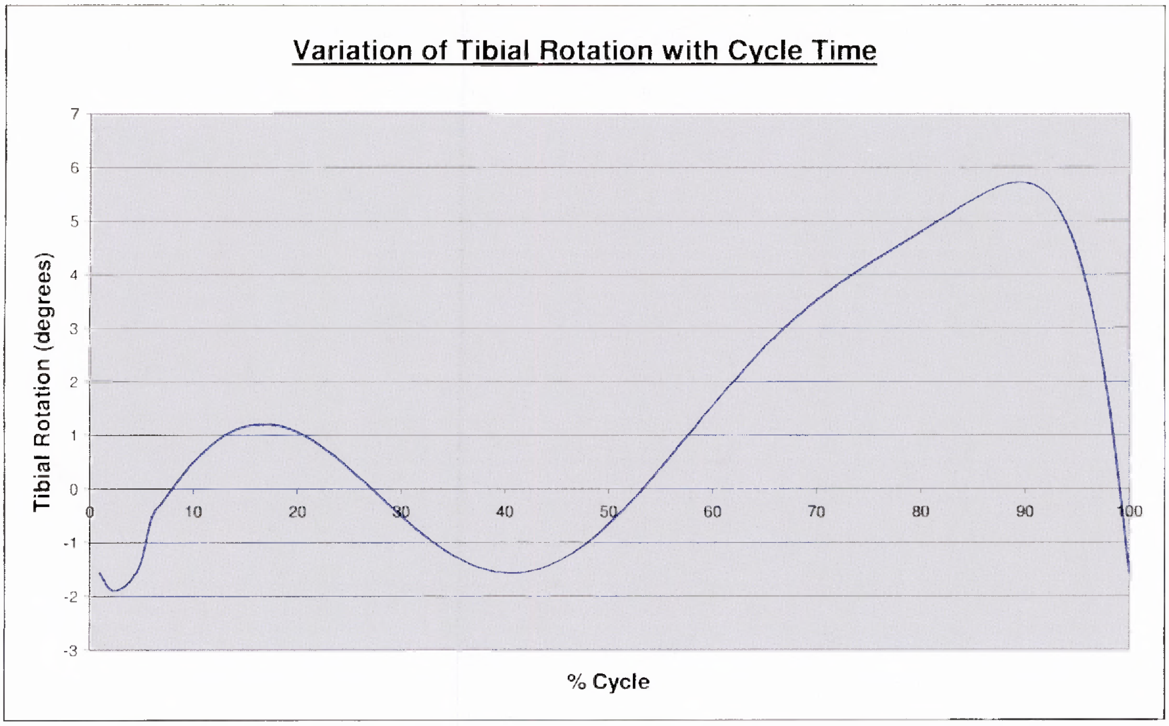

Figure 42: Variation of Tibial Rotation with Cycle Time

The hydraulic actuator is connected to the tibial rotation attachment block by means of a M20-M14 Crossover and a spherical rod-end. The spherical rod-end used is a THK NHS-14T (*Appendix 7*).

The hydraulic actuator has the following specifications:

- Bore: 40 mm
- Rod: 25 mm (double rod cylinder)
- Stroke: 60 mm
- Working Pressure: 300 Bar
- Mounting: Mid-Trunnion
- Rod End: M20 male thread
- Valve Mounting: NG6

- Ports: P & T, ½ " BSPP
- Fluid: Mineral Oil

The spherical rod end and the mid-trunnion mounting of the actuator allow the linear motion of the actuator to be converted into the rotational motion required for the tibial rotation.

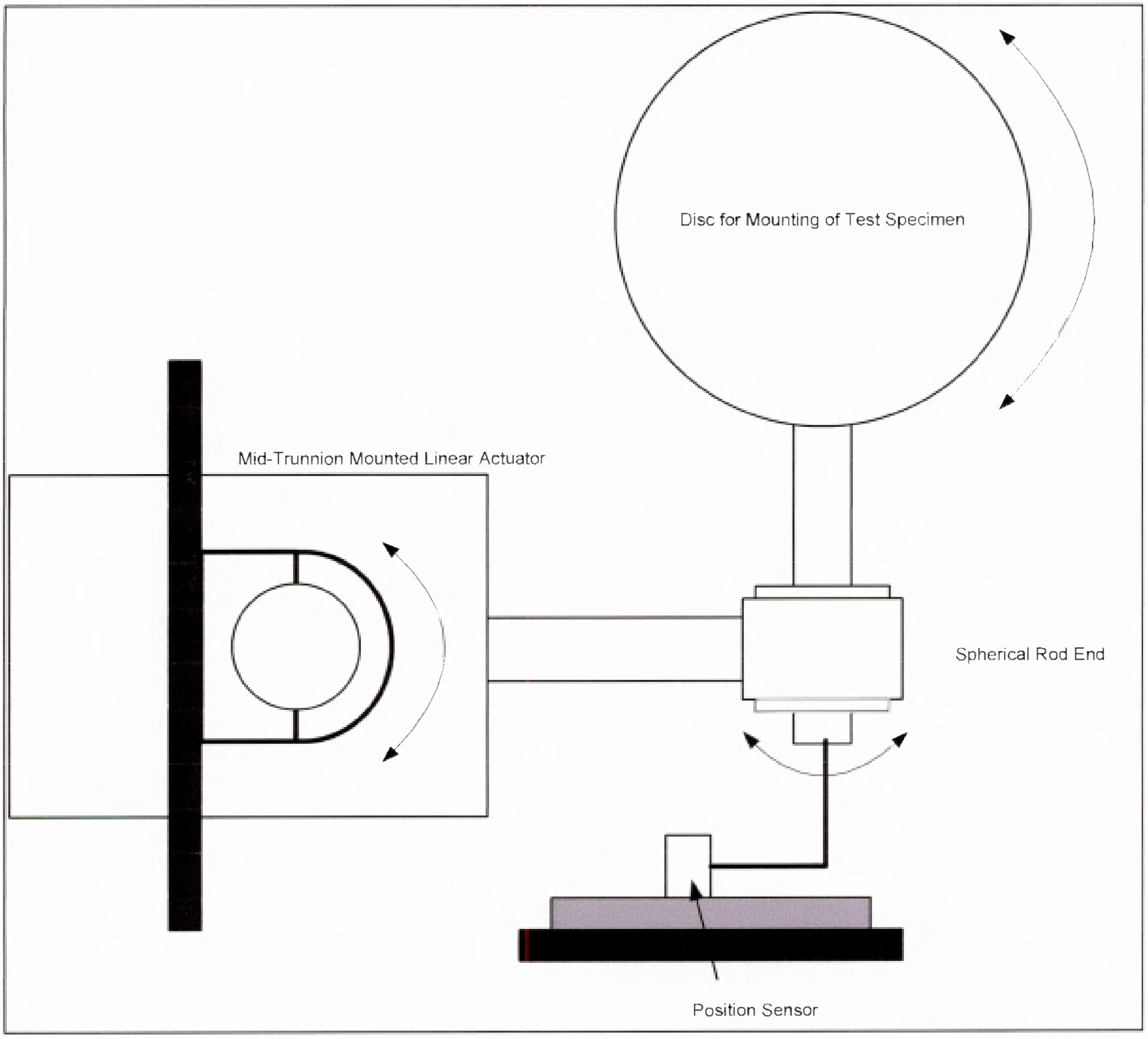

Figure 43: Conceptual representation of a linear actuator system being used to generate the required tibial rotational profile.

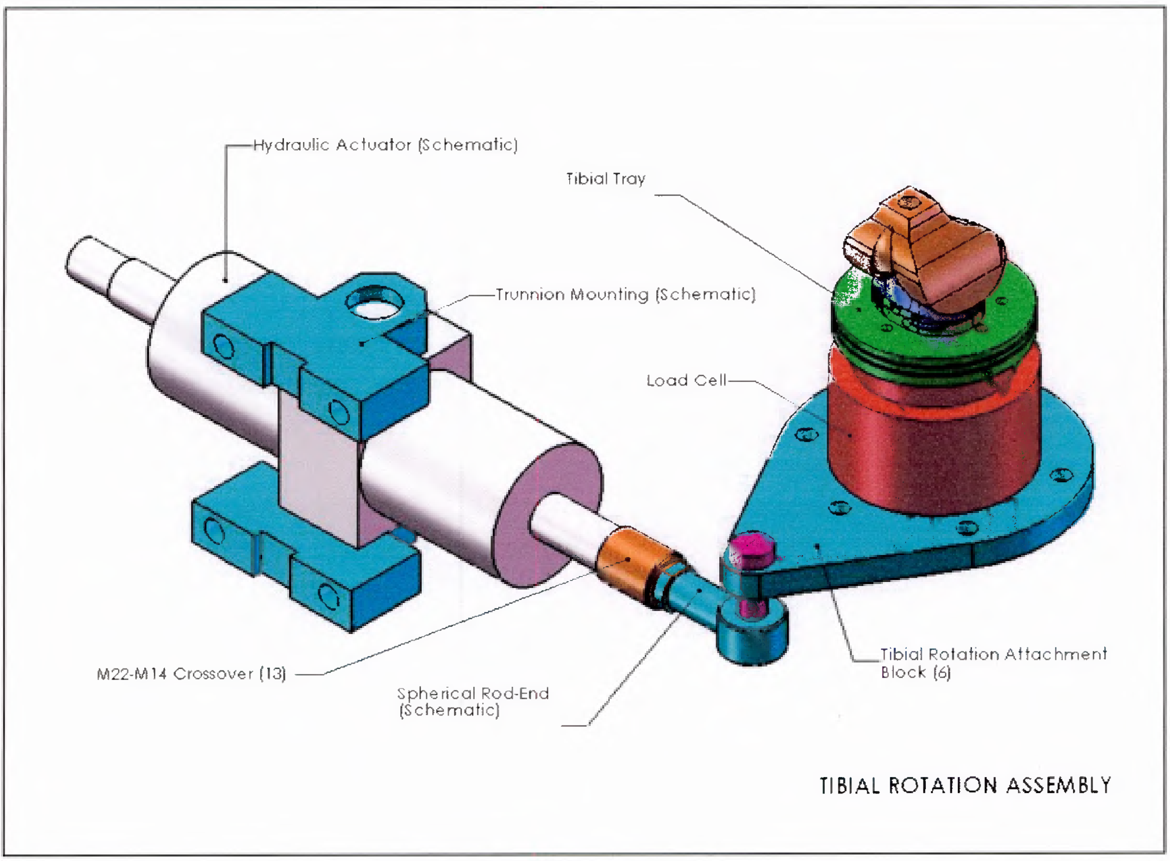

Figure 44: Tibial Rotation Assembly

Figure 44 shows the tibial rotation assembly used in the simulator. It can be seen how the mid-trunnion mounting and spherical bearing will convert the linear motion to rotary motion in the attachment block.

5.3 FLEXION / EXTENSION ASSEMBLY

As discussed in *Section 3.2.4*, the flexion-extension motion profile will be provided by a linear servo-hydraulic actuator. The actuator will be controlled in pure position control using a temposonics magnetostrictive position sensor. *Figure 45* shows the flexion / extension motion profile that needs to be replicated.

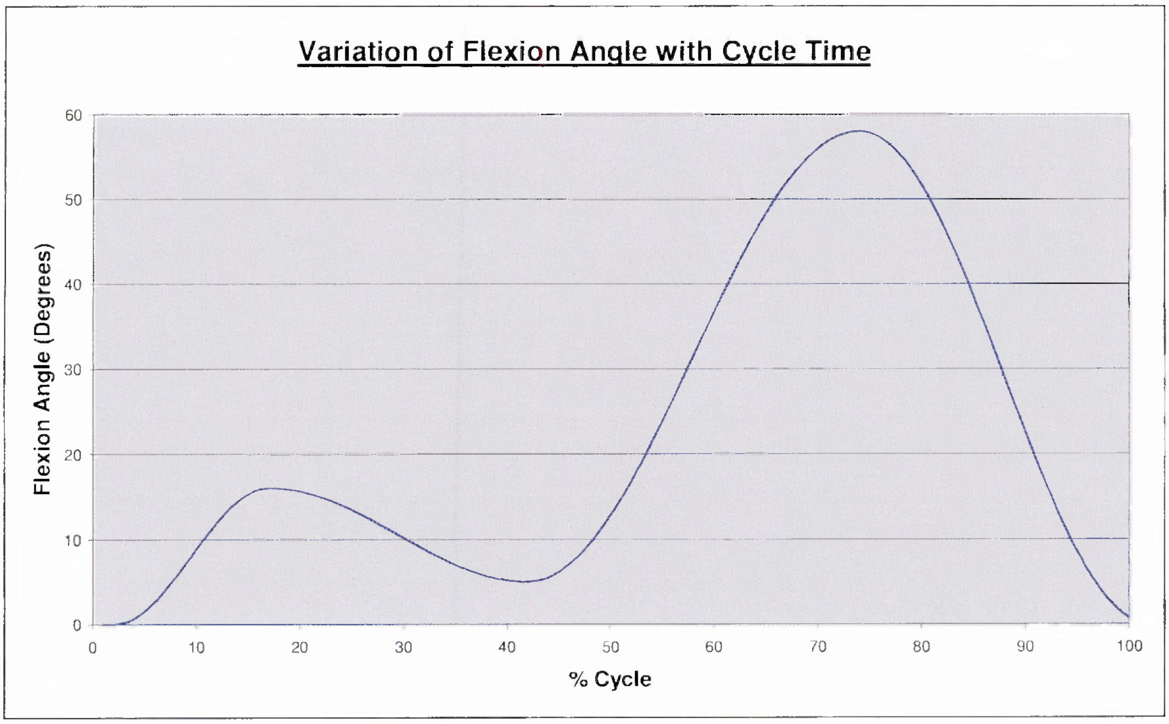

Figure 45: Variation of Flexion Angle with Cycle Time

Two possible set-ups were considered for the flexion / extension assembly. The one set up involved mounting the femoral condyle component directly onto a perpendicular shaft and then rotating the shaft. This is similar to the ASTM Boston Six Station Simulator, shown in *Section 2.7.1*. The main disadvantage with this configuration is the difficulty of mounting the various femoral condyle components. For instance, a knee such as the Isiqu knee described in *Section 2.6* would be very difficult to mount. The other disadvantage is that it does not test the connection between the femoral condyle component and the femoral stem components.

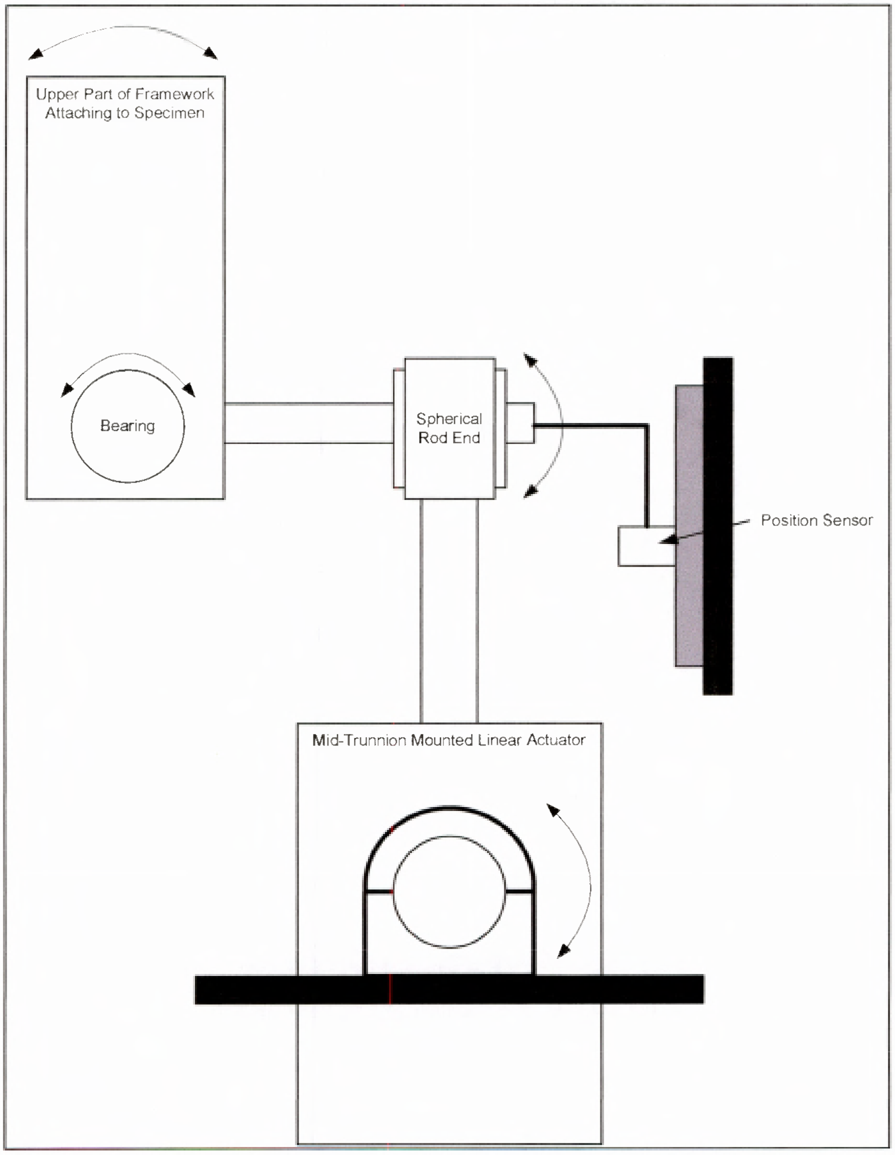

Figure 46: Conceptual representation of a linear actuator system being used to generate the required flexion-extension rotational profile.

The other possible set-up is one that resembles a crankshaft. This is similar to the Endolab Simulator shown in *Section 2.7.2*. In this configuration the femoral condyle component is mounted using either its femoral stem components or a specially designed femoral component. This allows the connection between the femoral condyle component and the femoral stem components to be tested. This is shown in *Figure 46*. It is also relatively simple to convert this set-up into a multi-station rig (*Section 7.2)*.

Therefore, this type of set-up was used as the basis for this design (*Figure 47*). The connection between the femoral component and the rocking arm is not shown in this document due to the fact that it would be different for each individual knee prosthesis tested.

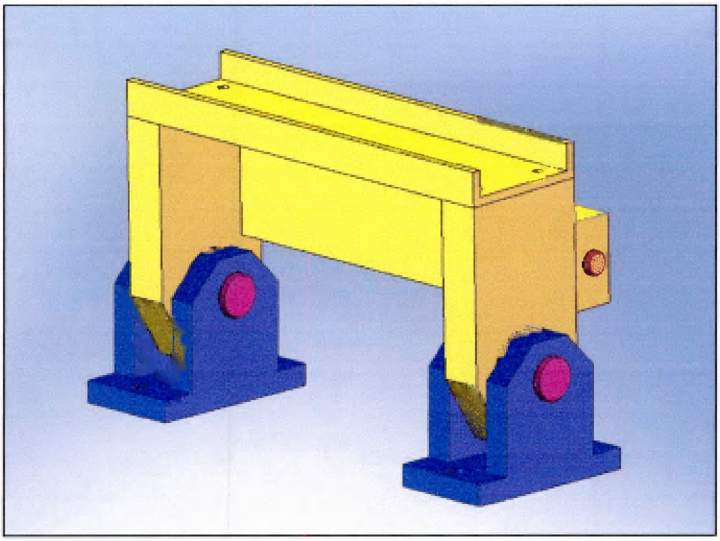

Figure 47: Rocking Arm Assembly

5.3.1 Rocking Arm Mounting Blocks

The rocking arm mounting blocks secure the flexion / extension arm to the frame and house the shafts that allow the arm to rotate. Each housing is secured to the frame by means of two socket head screws.

Each shaft is 25mm in diameter. The shafts will experience a radial force due to the axial force being applied to the knee. They will experience minimal axial force. Therefore they are stopped from moving axially by two external circlips. The fit between the mounting and the shafts is H7-k5.

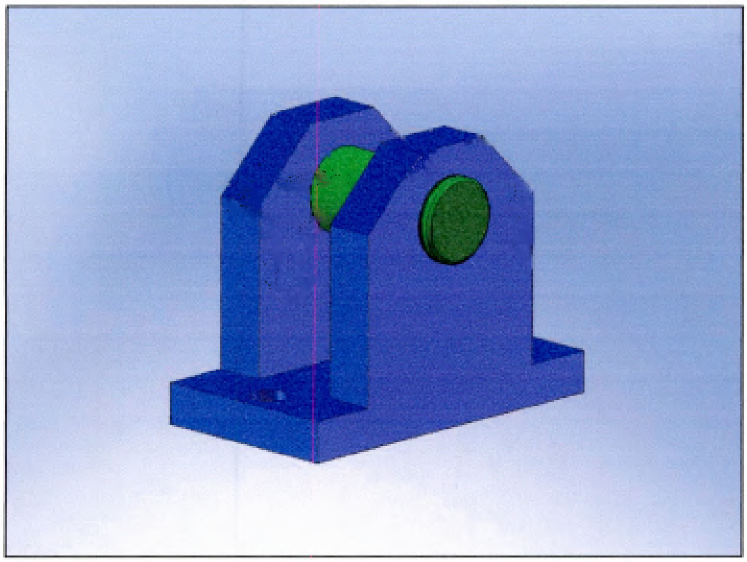

Figure 48: Rocking Arm Mounting Block and Shaft

5.3.2 Rocking Arm

The rocking arm is made up of 3 parts: the two upright bearing housings and the cross beam that joins them and acts as the mounting point for the knee prosthesis (*Figure 49*). The three parts are connected by means of socket-head screws.

The bearings to be used in the housings are SKF self-aligning ball bearings with integral seals (Designation SKF 2205 E2RS1TN9). The bearings are lubricated for life and are maintenance free. Self aligning ball bearings were chosen due to the fact that the two bearings sit in separate housings on separate shafts, but need to be aligned. The self-alignment allows for a 1.5° angular misalignment in the mounting of the housings. The bearings will experience a radial force but very little axial force. Therefore, they are secured in place by internal circlips.

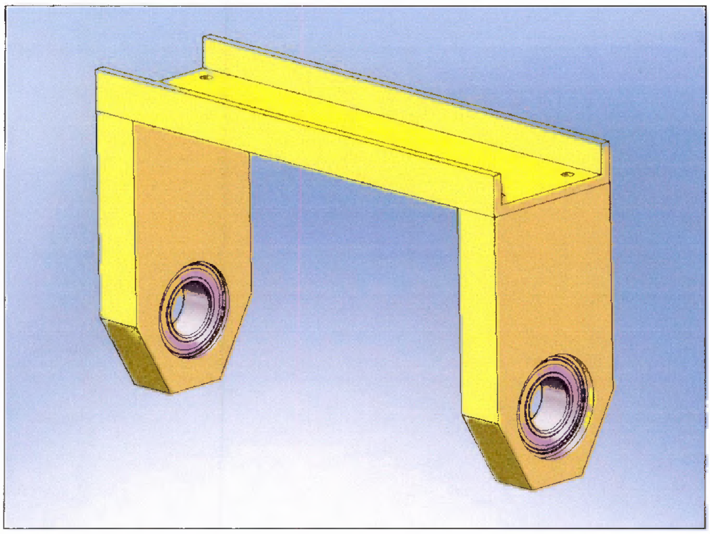

Figure 49: Rocking Arm with Self-Aligning Bearings

It is essential when testing a total knee replacement, to ensure that the centre of rotation of the femoral component aligns with the centre of the two bearings. This is to ensure the correct kinematic loading and behaviour of the knee components. This alignment can be achieved by adjusting the height of the knee using the axial force actuator, and by ensuring that the tibial base plate is designed correctly.

5.3.3 Hydraulic Actuator Connection

The connection between the hydraulic actuator and the rocking arm is made mid-span of the rocking arm. This is to ensure that both bearings see the same force and there is therefore an even torque distribution.

The plate housing the connecting rod is secured to the two bearing housings using four socket-head screws. It acts as both the connecting rod housing and also helps with the alignment of the two bearing housings (*Figure 50*). The connecting rod does not experience any axial force and is therefore held in place by two external circlips.

The actuator is connected to the connecting rod by means of a spherical rod-end. The chosen rod-end is a THK NHS 14T (*Appendix 7*). The rod-end is lubrication free. This rod-end ensures that the linear motion of the actuator can be converted into a rotational motion of the rocking arm. Between the rod-end and the actuator is a M20-M14 crossover.

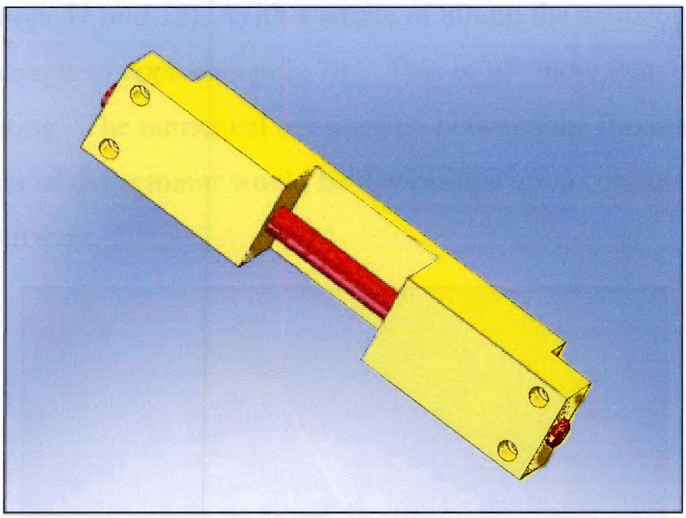

Figure 50: Hydraulic Actuator Connection

5.3.4 Flexion / Extension Hydraulic Actuator

The linear hydraulic actuator chosen to generate the flexion / extension profile has the following specifications:

- Bore: 40 mm
- Rod: 25 mm (double rod cylinder)
- Stroke: 80 mm
- Working Pressure: 300 Bar
- Mounting: Mid-Trunnion
- Rod End: M20 male thread
- Valve Mounting: NG6
- Ports: P & T, ½ " BSPP
- Fluid: Mineral Oil

5.4 FRAME DESIGN

The frame structure, *Figure 53*, is designed to accommodate the mountings and motions of all the hydraulic cylinders and associated components. It needs to be designed in such a way as to avoid static and dynamic frame failure, whilst also ensuring that it does not vibrate to an extent that will effect the operation of the simulator. All frame machine and assembly drawings are shown in *Appendix 2*.

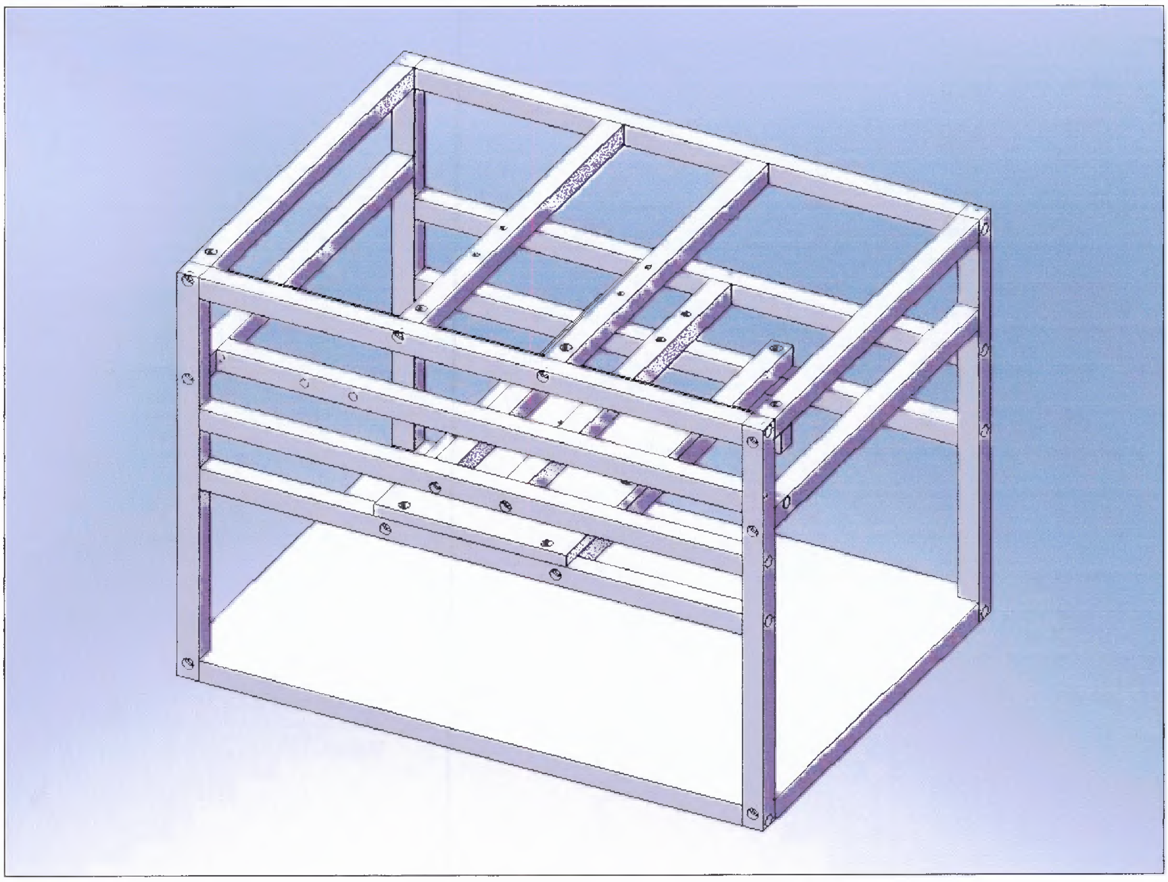

Figure 53: Frame Assembly for Knee Simulator

5.4.1 Structural Components

The bar and plate components of the frame are to be manufactured using cold-rolled steel, for its high strength and relatively low material cost. All bars are designed to be square 35mm x 35mm sections and the base plate to be 35mm thick.

5.4.2 Frame Analysis

Finite Element Analysis (FEA) was conducted on the proposed frame design in order to establish whether it will be stable during operation. The FEA was done using COSMOS software. For simplicity, the frame was considered as one solid piece of steel as opposed to a bolted together structure. Even though this assumption would eliminate stress concentrations at the bolt sites, it was anticipated that a tightly bolted frame would respond similarly to a solid frame. For this study, FEA was used only to estimate the stresses and displacements in the frame. Additionally, if the FEA resulted in a large enough factor of safety, it could be concluded that the frame would be structurally stable even with bolted components.

For the FEA analysis, a vertical load of 2600N was applied at the site of the flexion-extension mountings, as they would transmit the axial force to the frame. The resultant maximum von Mises stress, as calculated by COSMOS, was 38.1 MPa (*Figure 54*). Cold-rolled steel has a yield strength of approximately 200 MPa. This means that there is a factor of safety of 5 against yielding of the steel during loading. The maximum displacement of the frame under loading was found to be 0.32mm, which is negligible. This can be seen in *Figure 55* which is an exaggerated displacement model of the frame.

The bar thickness could be significantly reduced, without compromising an appropriate factor of safety, but since the material costs are almost negligible compared to the machining costs, the bars were left at 35mm x 35mm to ensure superior stability and minimal frame displacement. In addition, the larger bars will yield a heavier frame, reducing frame vibration during operation.

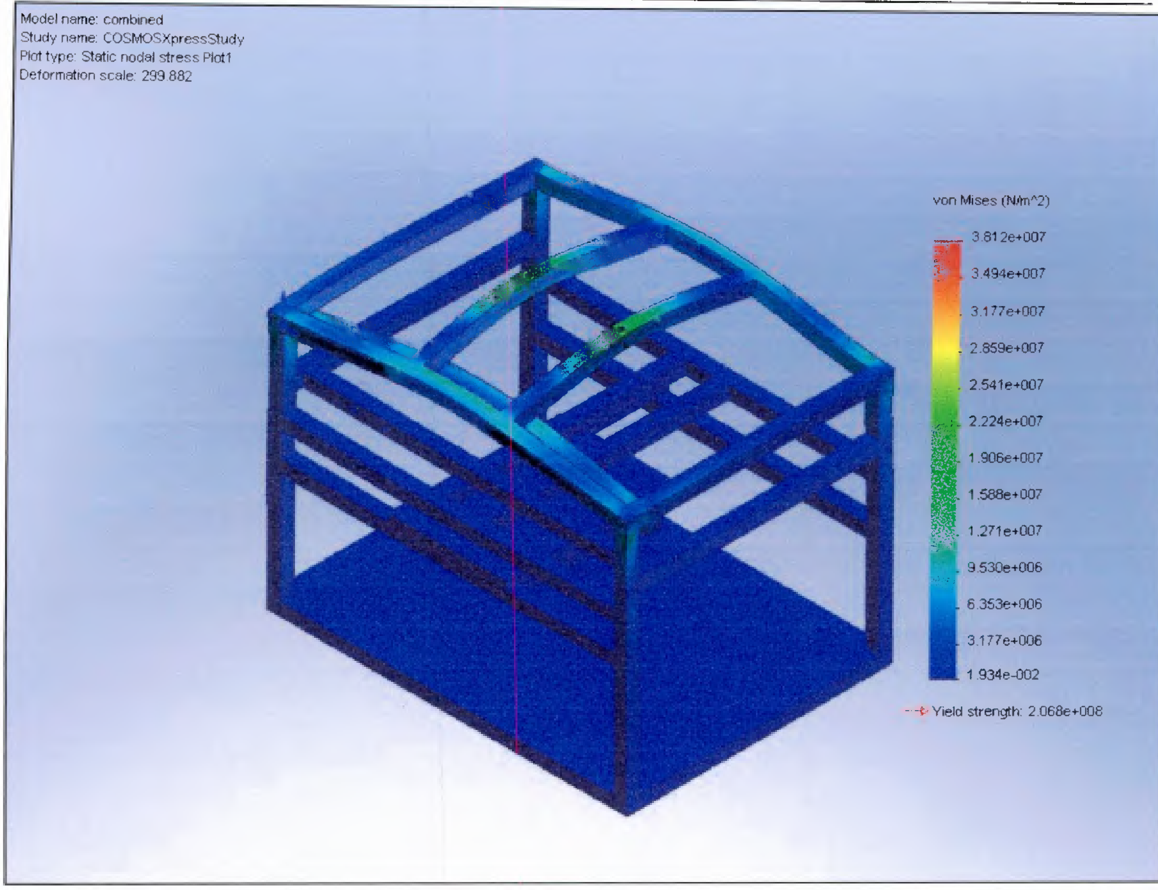

Figure 54: FEA Stress Analysis of Frame

5.4.3 Frame Assembly

Two possible methods were considered for assembly of the frame: welding and bolting. Welding would be a far cheaper option due to the lack of machining required. However, due to the thickness of the bars, and the nature of the assembly, the distortion that would be caused by welding was considered to be too great.

Therefore, it was decided that the frame should be bolted together using M10 Socket Head Screws. The screws for each bar would be offset so as to not allow the bar to rotate. Using screws increases the machining cost and time of manufacture, but should provide a more accurate frame alignment than welding. It also has the added bonus of being disassembled and reassembled if the simulator were to be upgraded (*Section 7*).

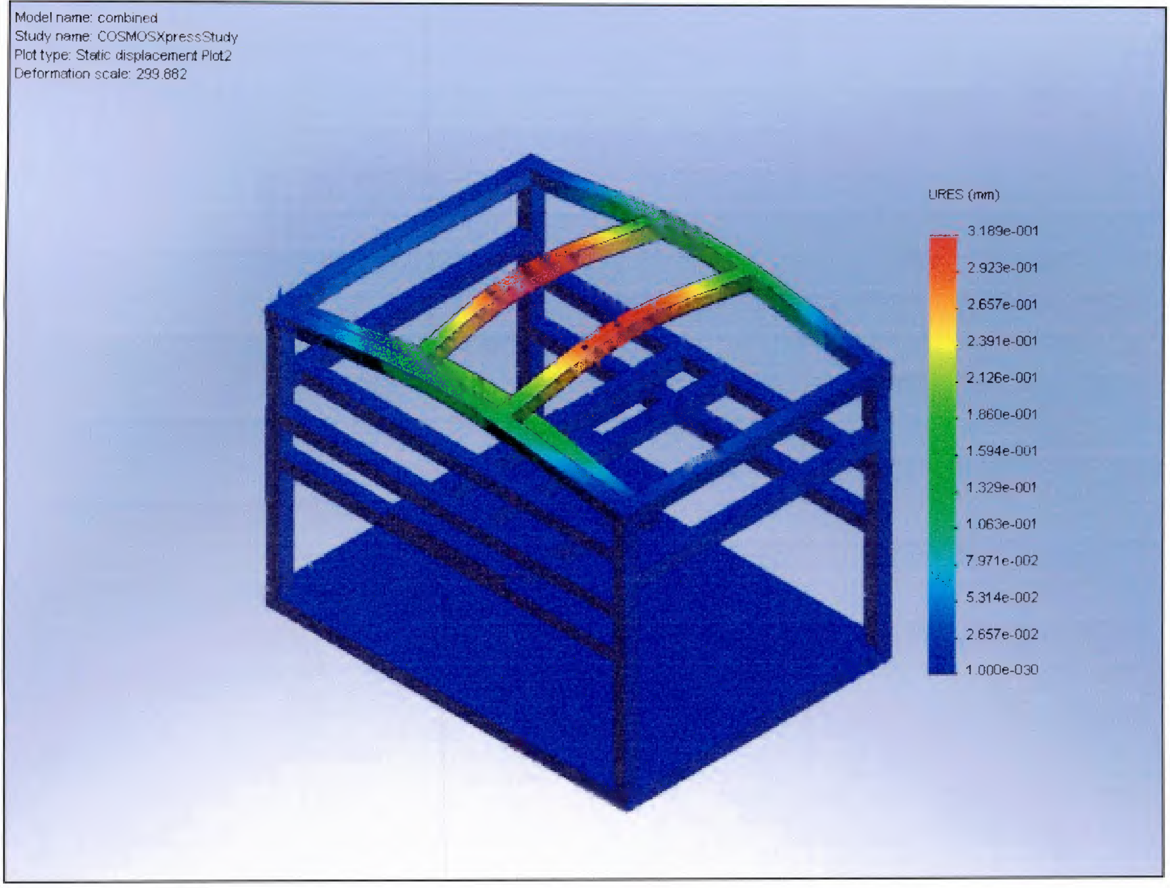

Figure 55: FEA Displacement Analysis of Frame (Exaggerated)

5.5 ASSEMBLED DESIGN

Figure 56 shows the axial assembly, tibial rotation assembly, and flexion-extension assembly combined together. *Figure 57* shows these assemblies mounted on the frame. As can be seen, each actuation system is mounted separately and therefore operates individually of the other actuators. The Moog control system integrates the actuators to ensure that each actuator is providing the correct motion / force at the correct cycle time.

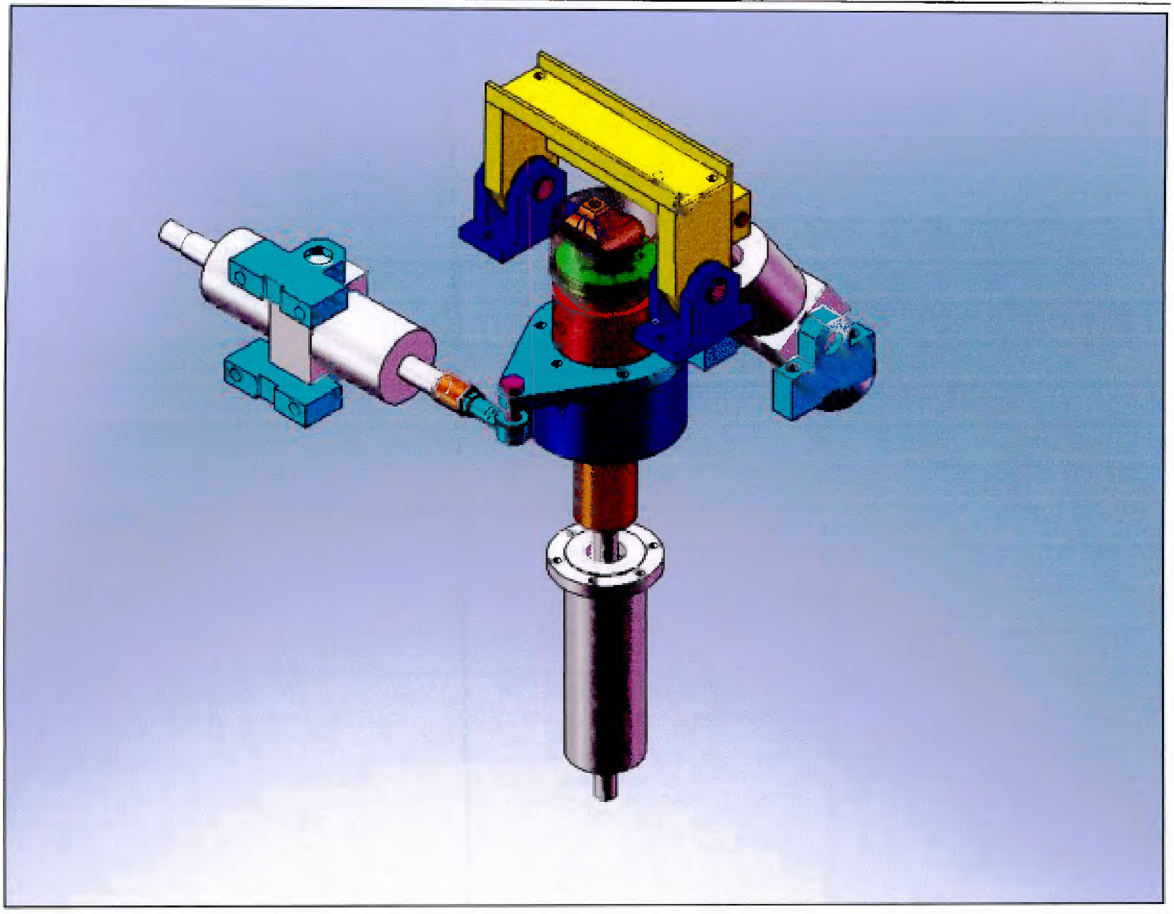

Figure 56: Combined Component Assembly

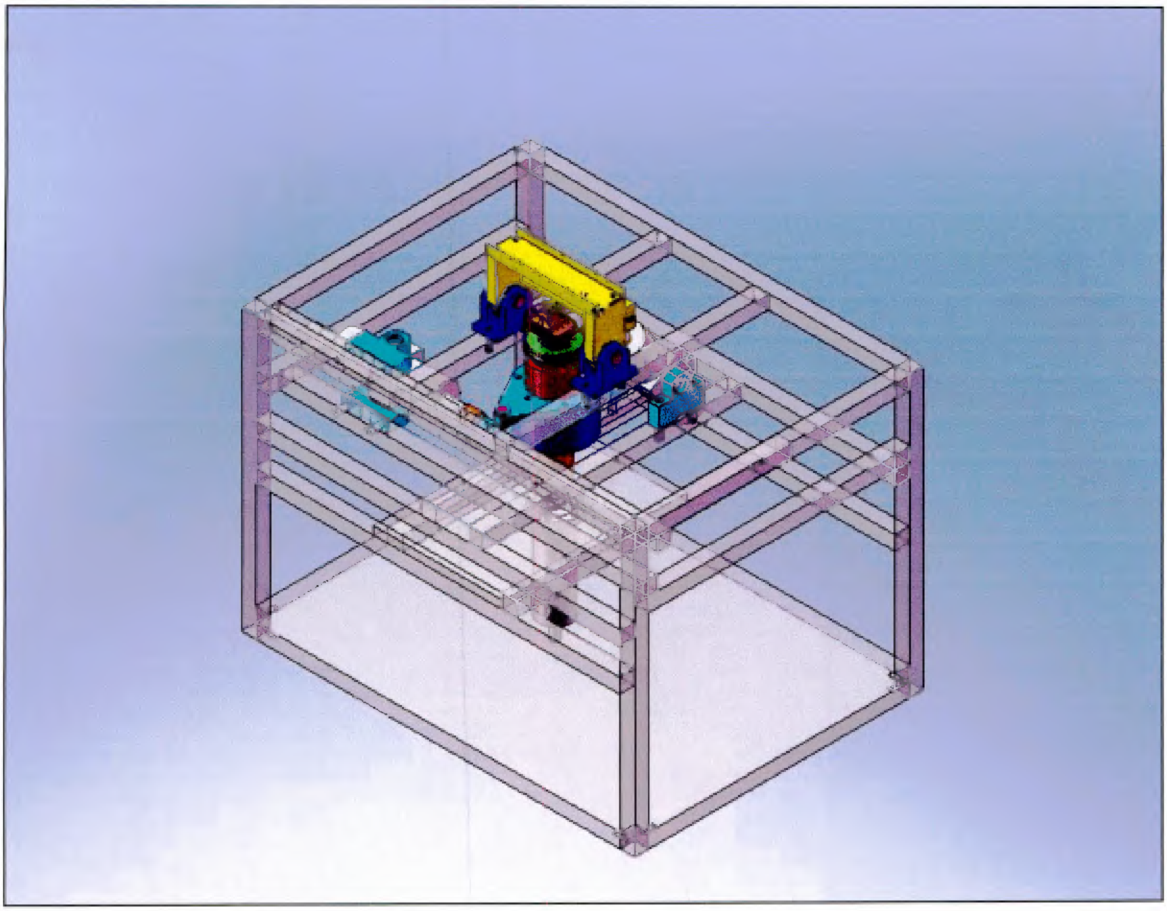

Figure 57: Total Assembly Mounted on Frame (Transparent)

6 SYNOVIAL FLUID LUBRICATION SYSTEM

In order to get test results from the simulator that are indicative of in-vivo conditions, it is necessary to replicate the synovial fluid of the human knee joint and all its lubrication properties (*Section 2.2*).

6.1 BOVINE SERUM PREPARATION

The ISO 14243 standard outlines the use of bovine serum (25% ± 2%) diluted with deionised water. The fluid should be filtered through a 2μm filter after dilution and should have a protein content of not less than 17g/l.

However, this protein content value appears to not be in the measured in-vivo range. Dumbleton[22] found that the in-vivo protein content ranges between 20 and 40 g/l. Noordin et al[23] determined the protein content of synovial fluid taken from patients with prosthetic joint arthroplasty to be 27.9 g/l (mean) within a range of 21 to 43 g/l.

Wang[24] and Clark[25] have measured the impact of protein concentration on the wear of total joint replacements. The testing of metal hip balls against polyethylene cups resulted in low wear rates at low and high protein concentrations. The wear maximum was found to be within the physiological range of the synovial fluid.

From this data the following can be concluded:

- The physiological protein level is about 30 g/l
- The maximum wear will be measured at about 30 g/l

Therefore, it is recommended that all testing be conducted using a protein level of 30 g/l. This is contrary to the ISO 14243 and would need to be clarified before testing.

6.2 BOVINE SERUM DURING SIMULATOR OPERATION

During the testing of a knee prosthesis on the simulator, all wear surfaces of the knee need to be submerged in bovine serum. The bovine serum needs to be maintained at a temperature of 37°C ± 2°C to simulate in-vivo conditions. This necessitates the incorporation of both a heating and cooling system into the bovine serum system. It also means that the bovine serum needs to be circulated during simulation.

Fluid lost due to evaporation can be replaced with deionised water, and the entire fluid needs to be replaced every 5 x 10^5 cycles (*ISO 14243*).

6.3 BOVINE SERUM SYSTEM

The bovine serum that surrounds the knee prosthesis is contained in a cylindrical plastic container. The container is stopped from leaking by two o-rings present on the tibial mounting plate, and is held in place by the bolts passing through it from the tibial mounting plate to the load cell.

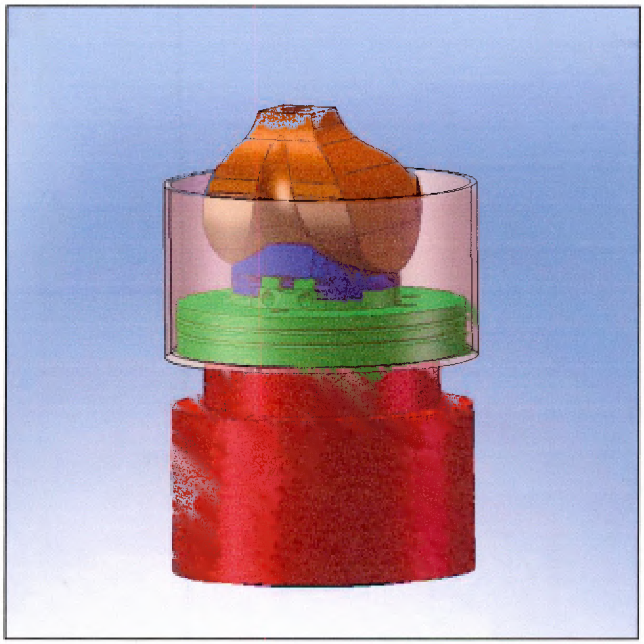

Figure 58: Bovine Serum Container

Furthermore, the fluid can be contained by installing a bag (much like a bellows) that seals off the top of the container and seals on the stem used to mount the knee prosthesis to the rocking arm.

6.3.1 Temperature Control and Circulation System

Due to the fact that the bovine serum needs to be maintained at a constant temperature of 37°C ± 2°C, the fluid needs to be circulated. Due to the movement of the femoral component, and the resultant friction, the fluid in the container surrounding the knee prosthesis will heat up very quickly beyond 37°C.

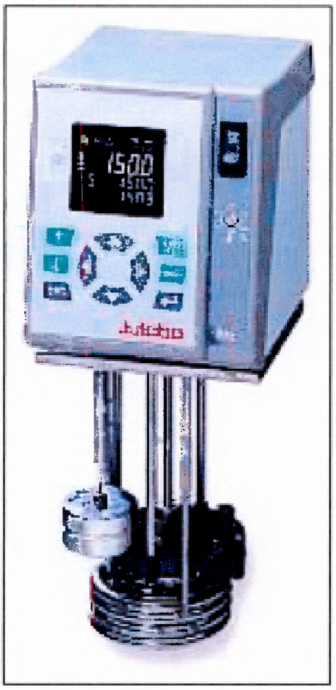

Figure 59: Julabo ME Heating Immersion Circulator

The proposed solution is to use a heating immersion circulator and fluid bath. The proposed model is a Julabo ME Heating Immersion Circulator (*Figure 59*). This model would be mounted in a fluid bath that would heat / cool the bovine serum, which would be in a closed system, to the correct temperature. The unit has the capability of measuring the temperature of the bovine serum at the site of the knee prosthesis, thereby giving an accurate representation of the bovine serum temperature. The unit also has the abiliy to interface with the desktop being used to run the hydraulic control system. This will allow full control of the simulator system from the desktop. The cooling and external pumping units are available as accessories to the unit. The product specification sheet is shown in *Appendix 7*.

A filter can be installed in the fluid circulation system in order to collect wear debris for analysis.

7 SIMULATOR UPGRADE

The simulator described in this document is capable of testing one fixed- or rotating-hinge knee prosthesis, where there is no anterior-posterior motion present. In order to test any type of knee prosthesis it is necessary to be able to produce the anterior-posterior motion described in *Section 2.5.2*. This is an upgrade that can be designed into the knee simulator.

Another upgrade to the simulator would be to increase the number of stations available, so as to test multiple knees or to have a soak station for comparative wear studies. Due to the long nature of testing (approximately 60 days), it is highly beneficial to have a multi-station testing rig.

7.1 ANTERIOR-POSTERIOR MOTION UPGRADE

In order to upgrade the simulator to contain anterior-posterior motion control it is necessary to either make the whole axial assembly movable, or to make the whole flexion-extension assembly mobile. As the axial assembly involves less motion than the flexion-extension it would be easier to make it the movable assembly.

One way of making the axial assembly movable would be to mount the axial assembly on linear motion guides (*Figure* 60) and drive the mounting using a hydraulic actuator acting in position control mode (*Figure 61*).

One of the issues with using this setup would be the effect that the anterior-posterior movement would have on the tibial rotation assembly. The anterior-posterior motion would be taken up by the trunnion bearings and the spherical rod end of the tibial rotation assembly.

The linear movements of the tibial rotation actuator will be different to the present set-up and therefore the position control will need to be re-programmed to ensure that the correct tibial rotation profile is achieved.

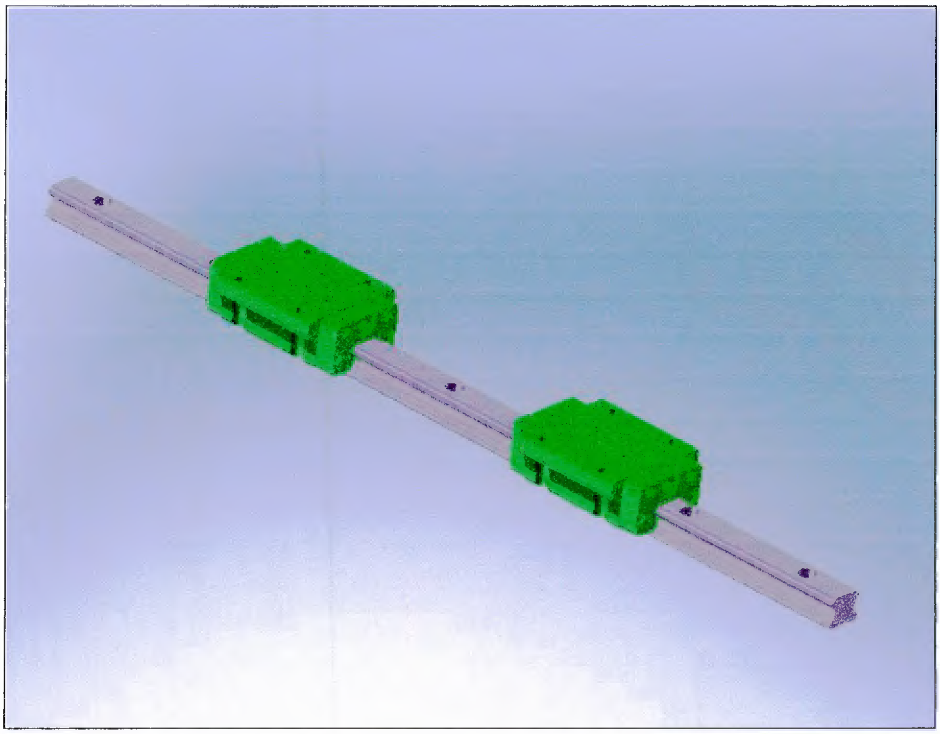

Figure 60: Possible Linear Motion Guide to be used to Provide Anterior-Posterior Motion

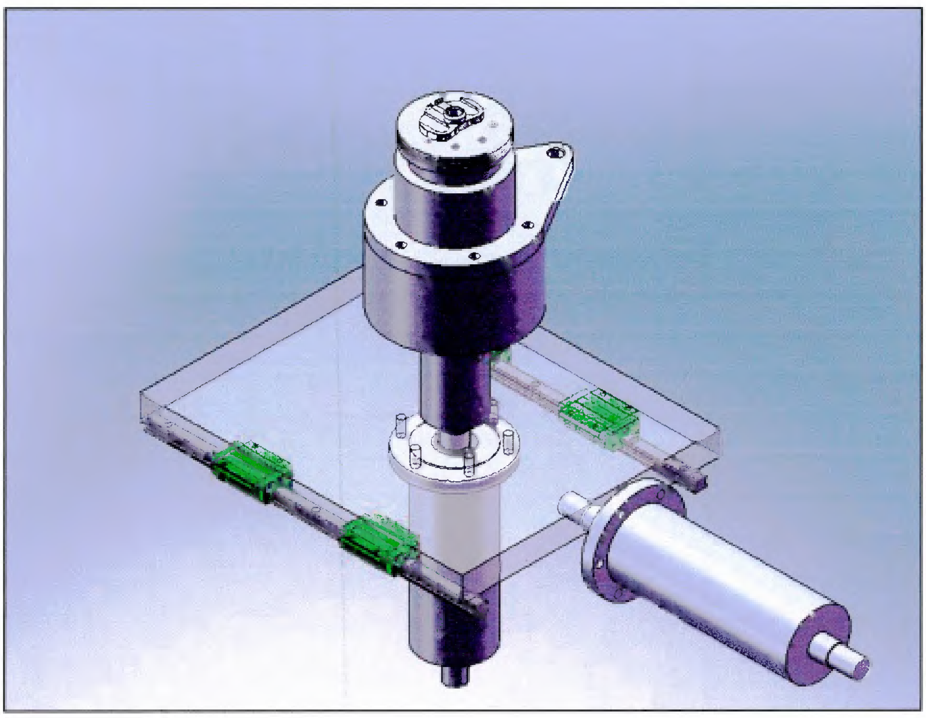

Figure 61: Possible Assembly to provide Anterior-Posterior Motion

7.2 MULTIPLE STATION UPGRADE

If the simulator were to be upgraded to a multi-station simulator, then each station would have to have a separate axial force actuator. This would be due to the fact that, depending on the knee prosthesis being tested, a different amount of force will need to be transmitted from the actuator to get the correct force measurement at the knee prosthesis. However, it would be possible to provide both the flexion/extension and the tibial rotation using one actuator for all the stations. The number of actuators required to provide the anterior-posterior motion would be dependent on the number of stations.

The tibial rotation attachment plates of each station would be connected to the adjacent attachment plate by means of a steel connecting rod with a spherical rod-end on each end. This would transfer the tibial rotation motion generated by the actuator to all of the stations.

In order to create the flexion-extension motion in a multiple-station simulator with one actuator it is necessary to have one rocking arm that is common to all the stations. It can be designed in such a way that one of the station's rocking arms can be disengaged, so as to not allow flexion-extension. This would allow this station to be used as a soak station for comparative wear analysis.

Figure 62 shows a possible three-station simulator without soak station capability.

9 REFERENCES

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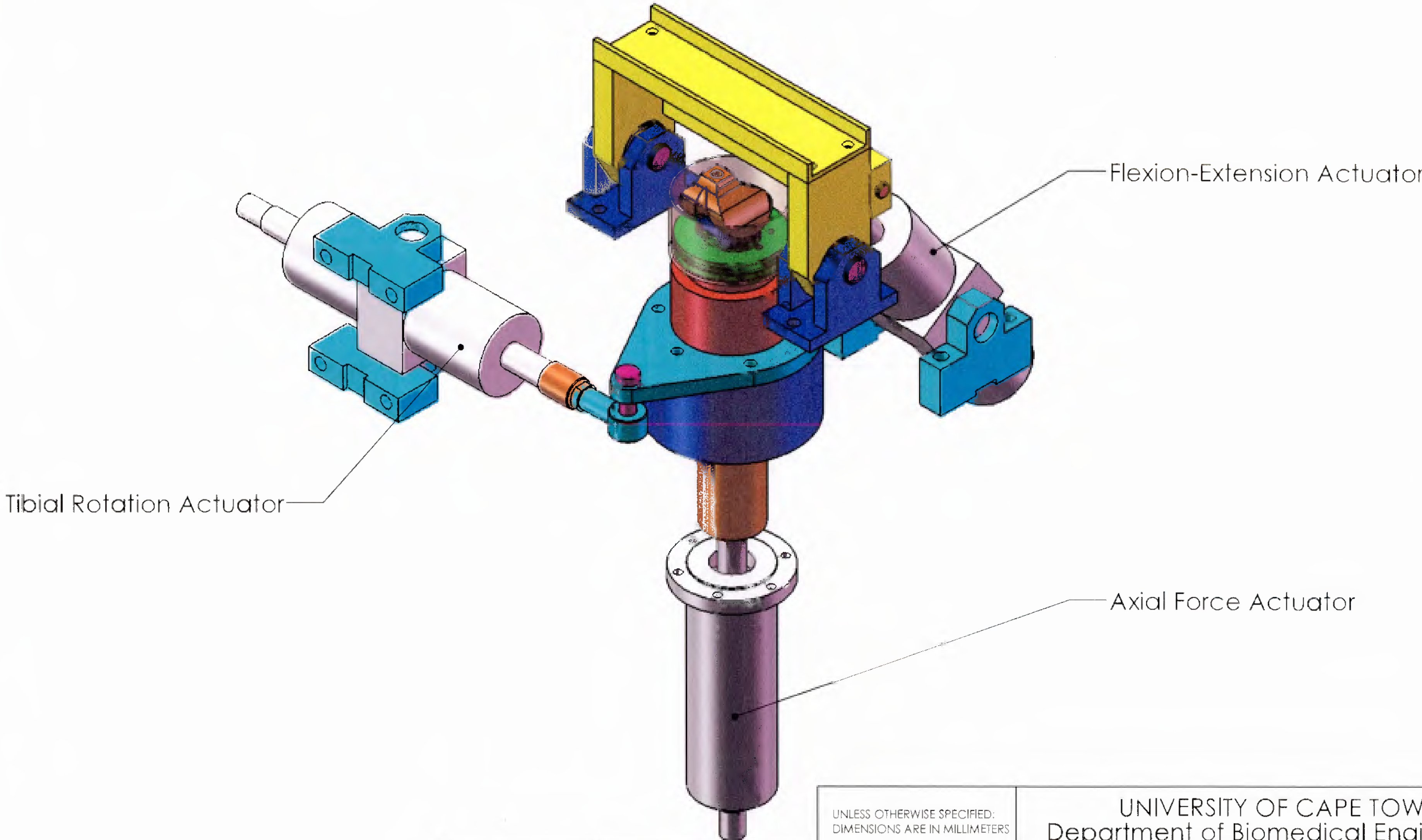
10.1 APPENDIX 1 –COMPONENT DRAWINGS



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CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

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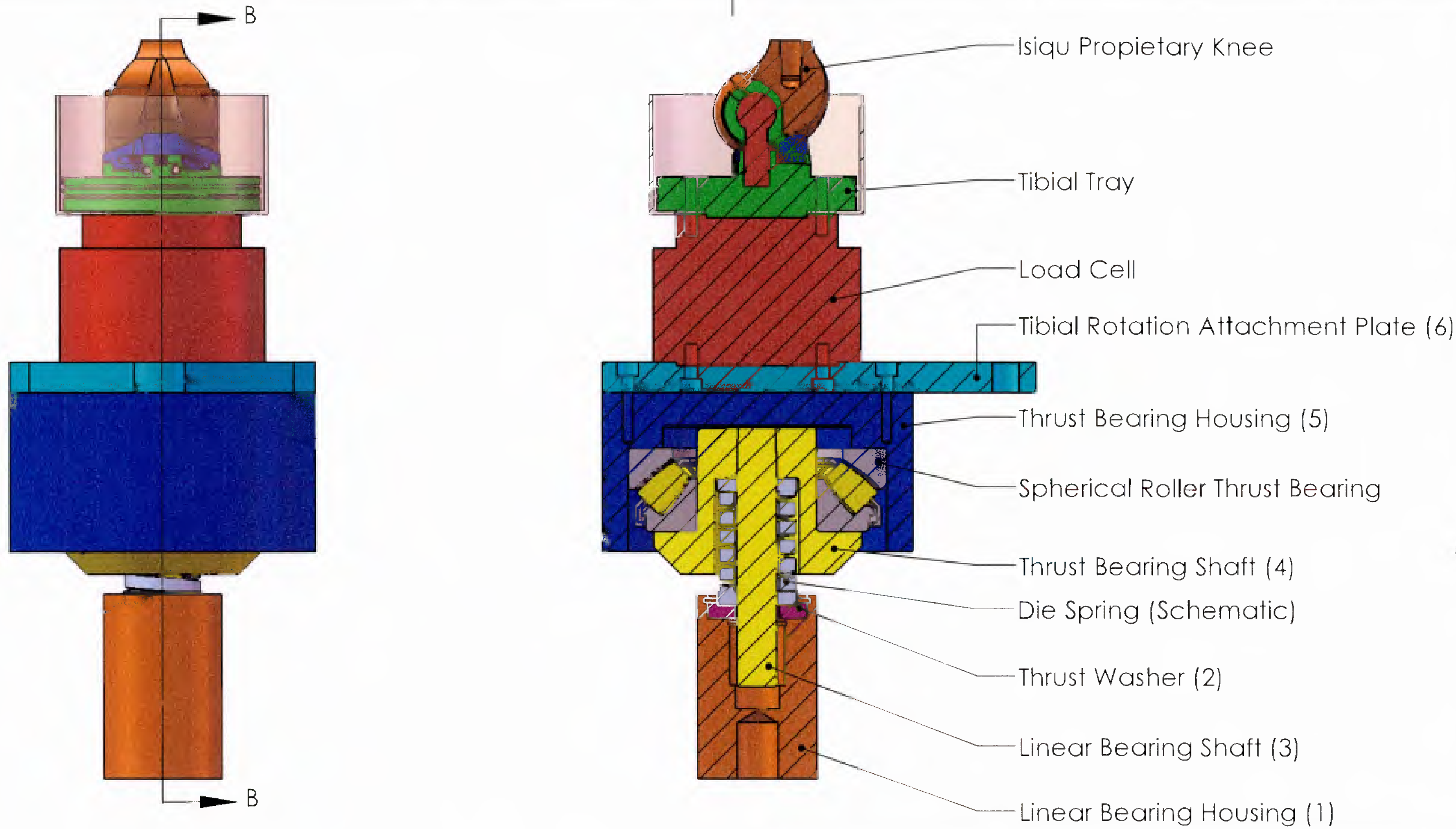

FRONT VIEW

SECTION B-B

(Numbers) refer to drawing numbers of individual components.

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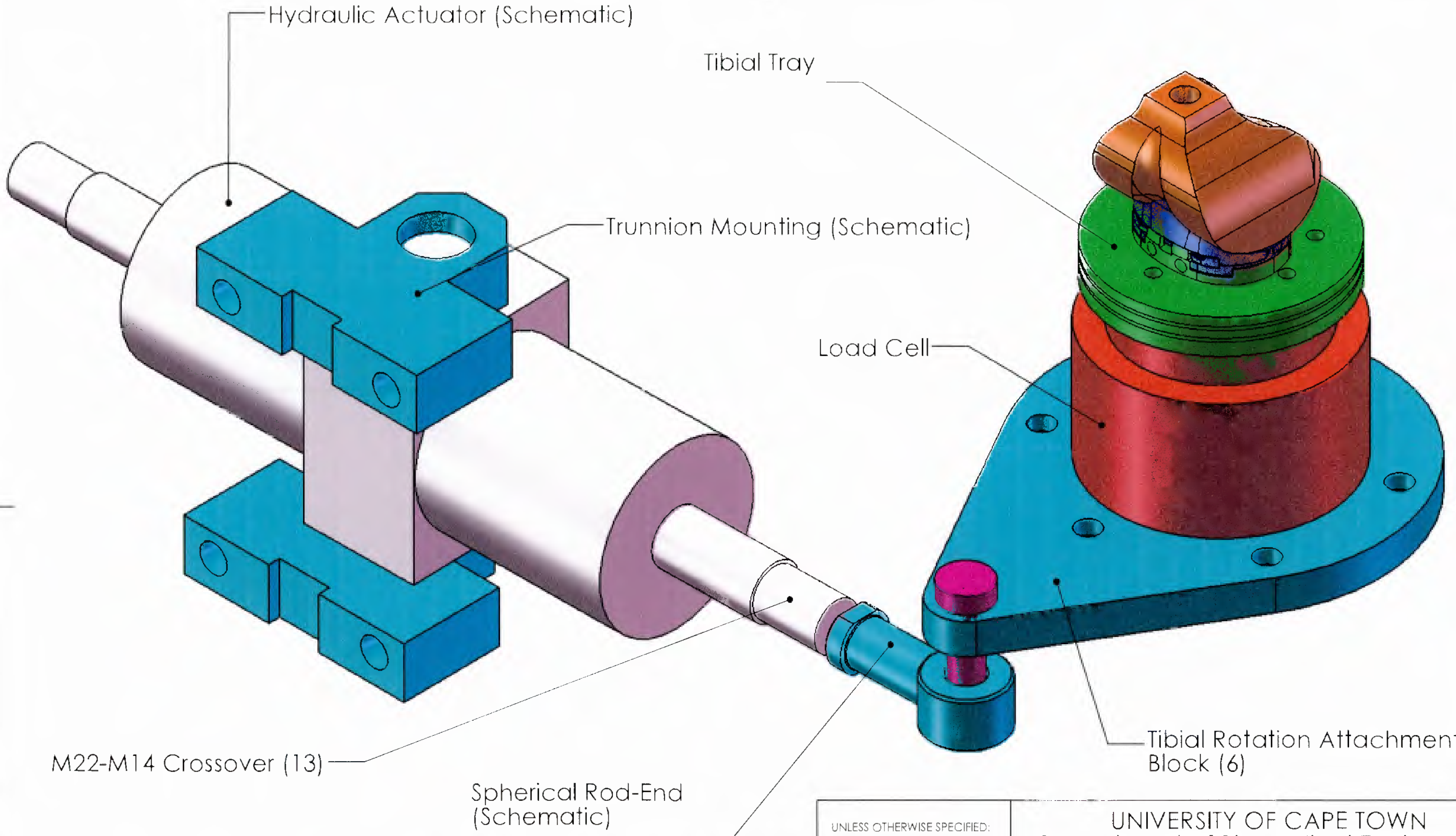

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MATERIAL:

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

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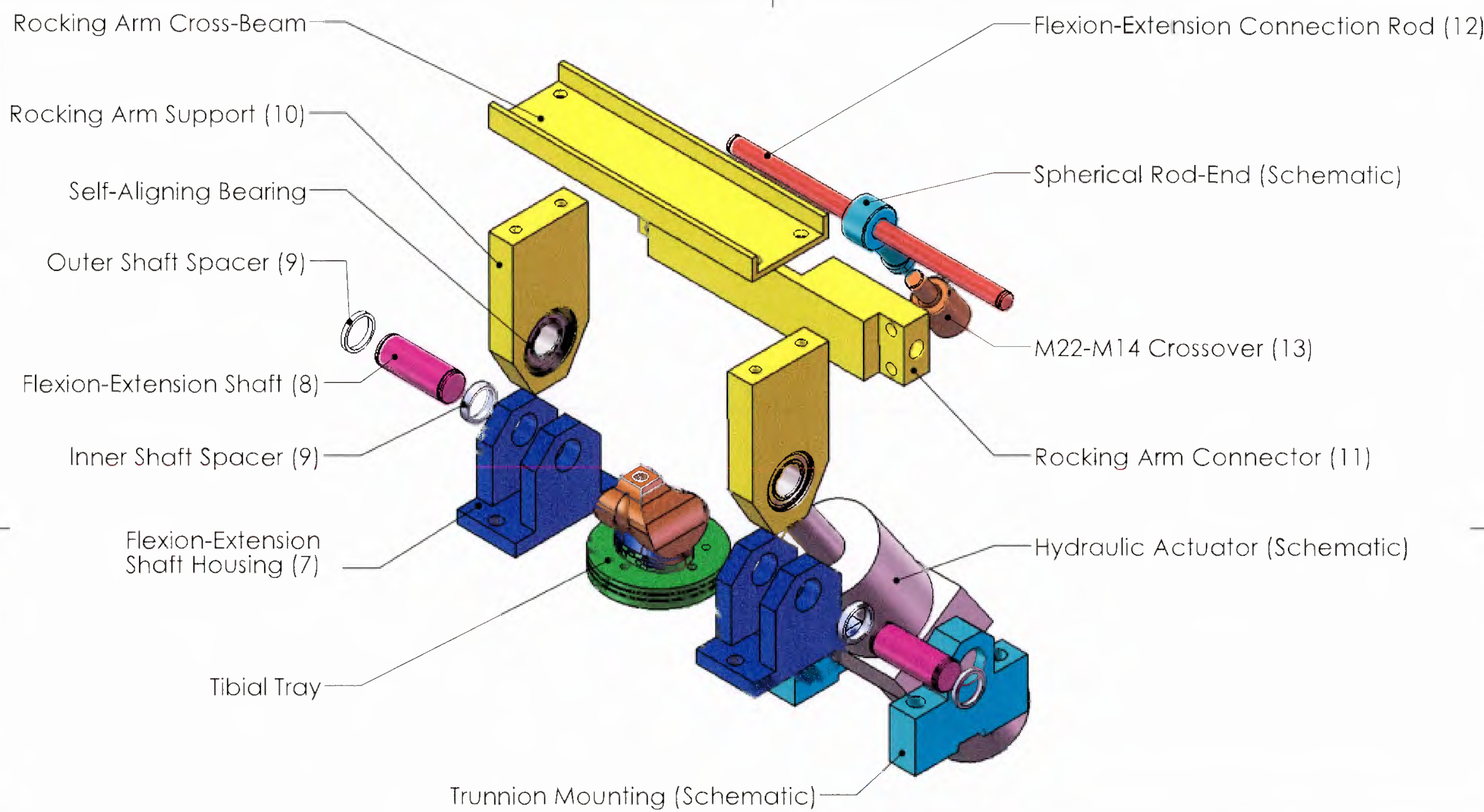

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UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

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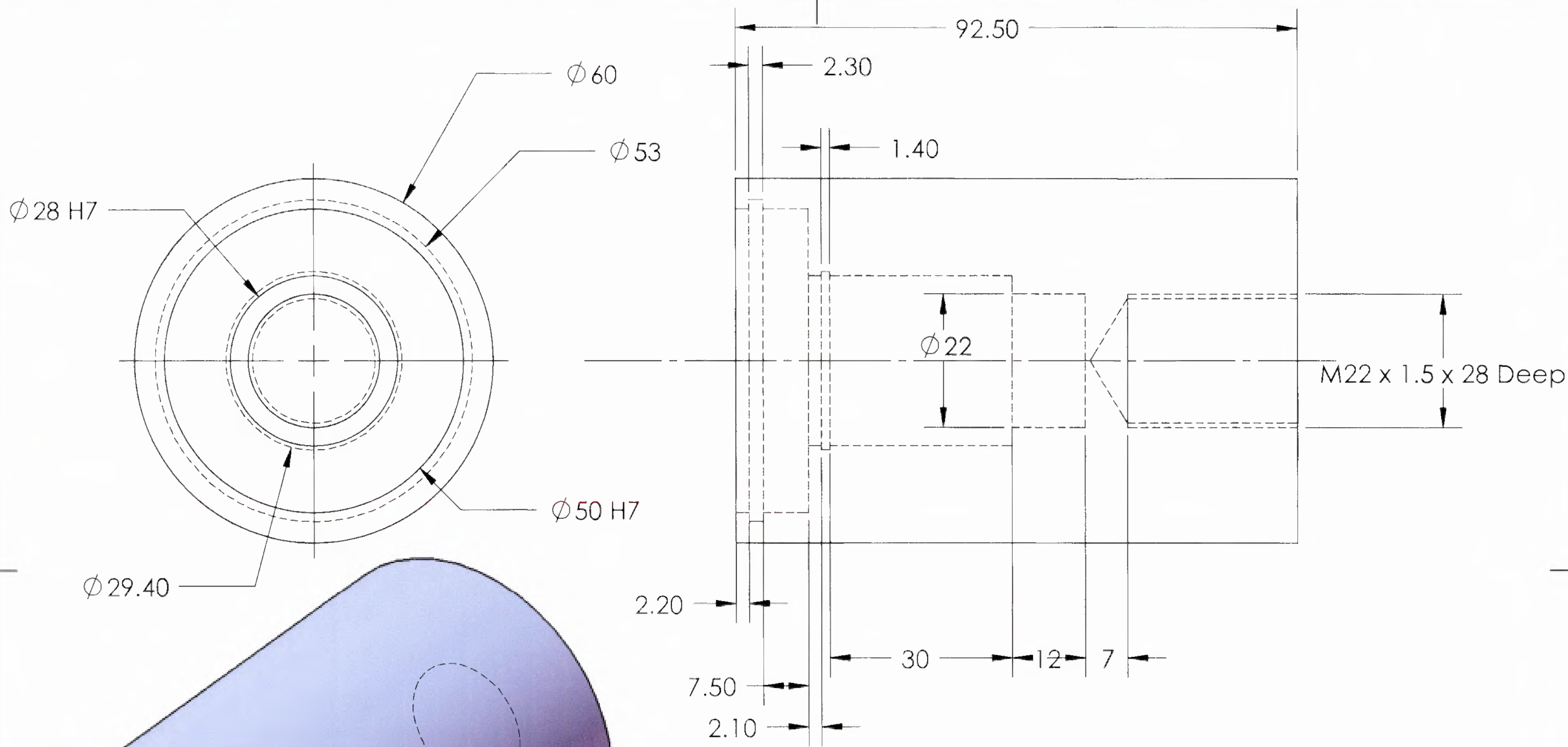

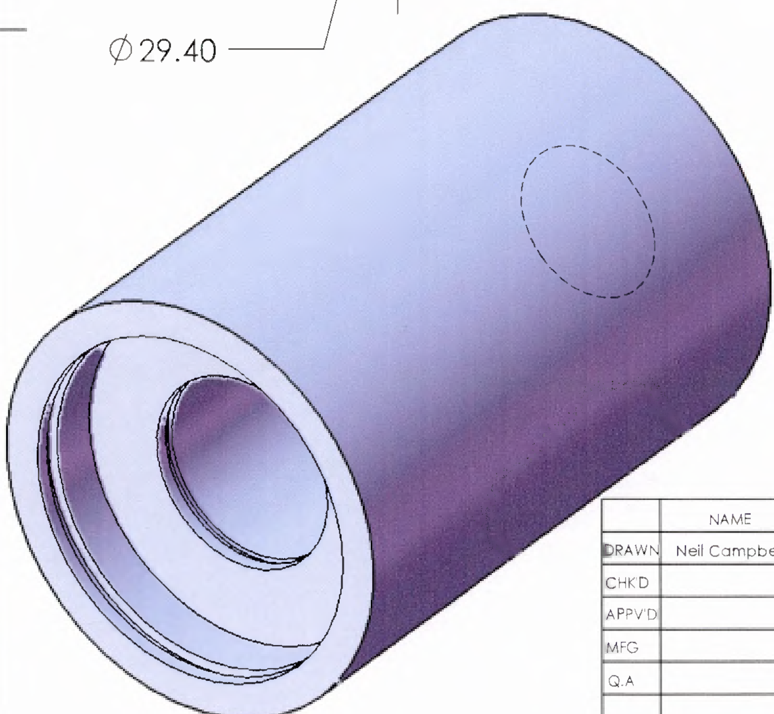

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Department of Biomedical Engineering

TITLE:

LINEAR BEARING HOUSING

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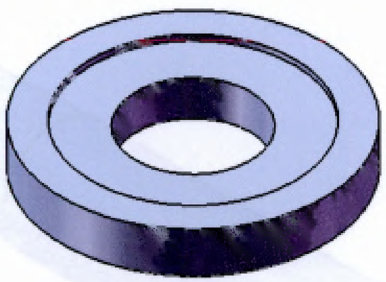

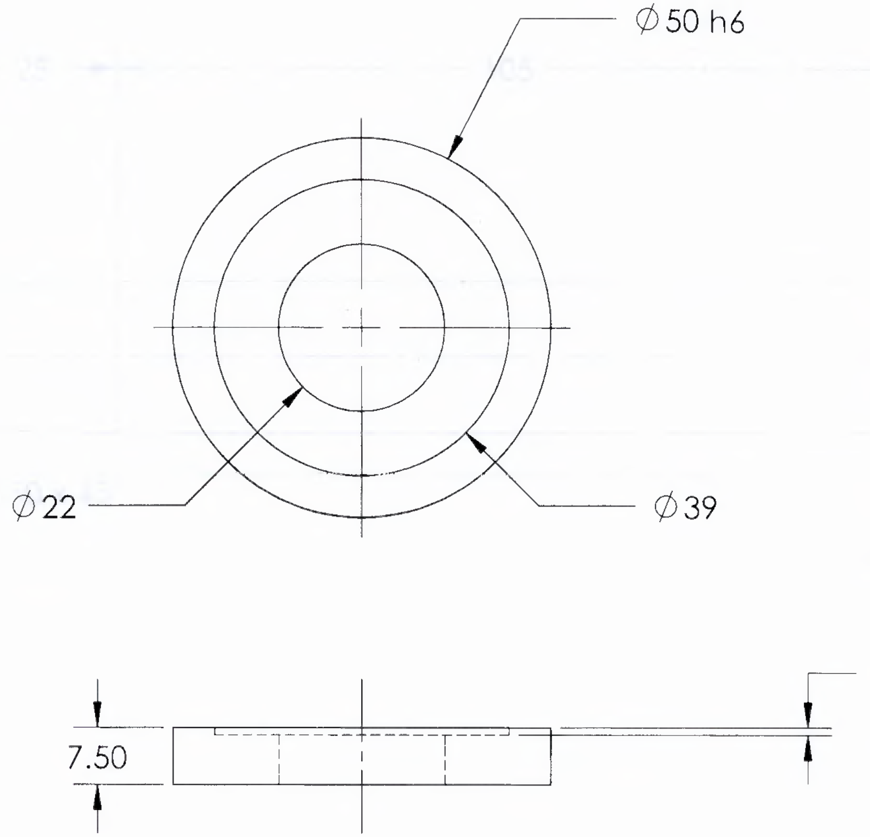

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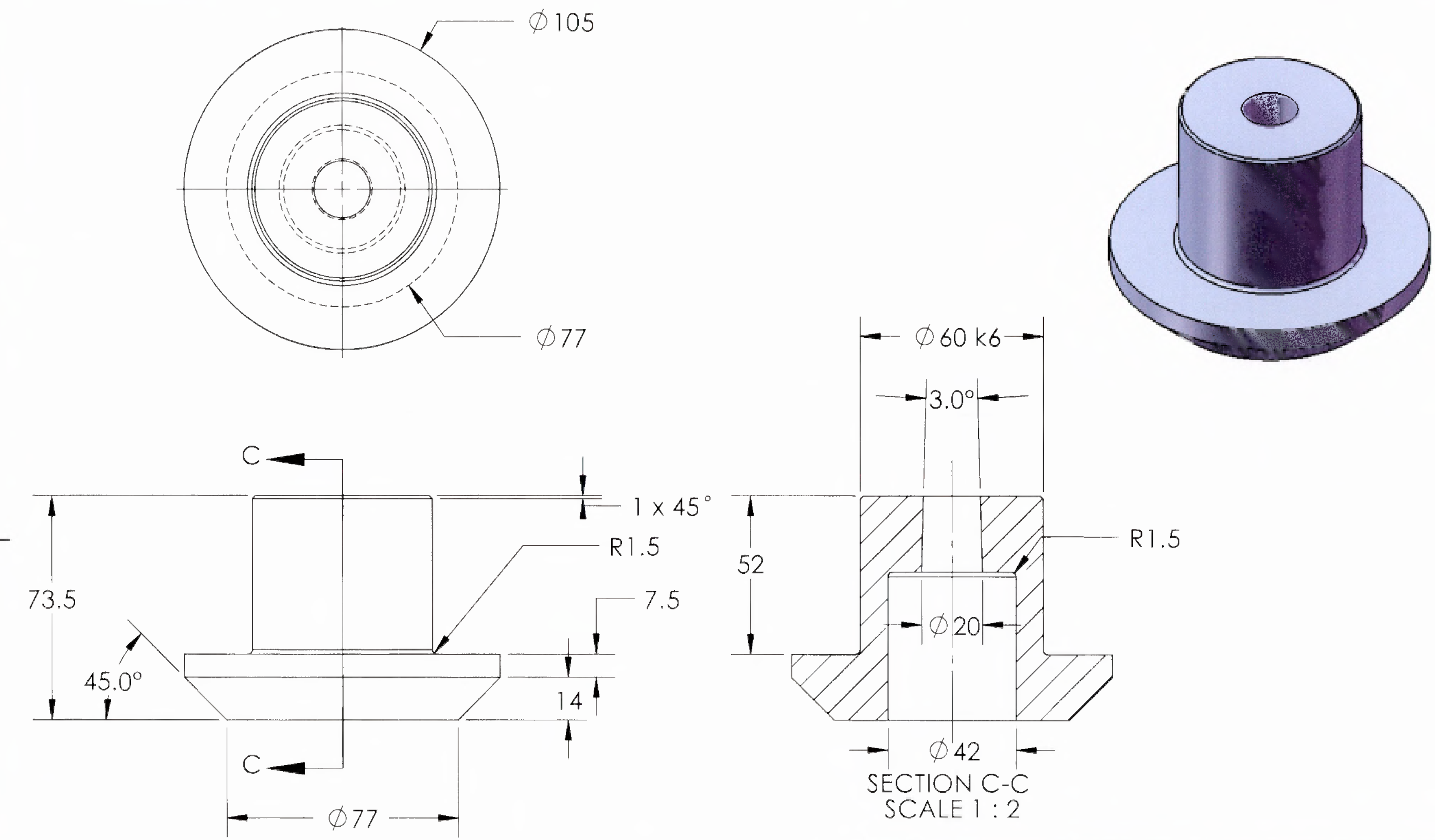

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Department of Biomedical Engineering

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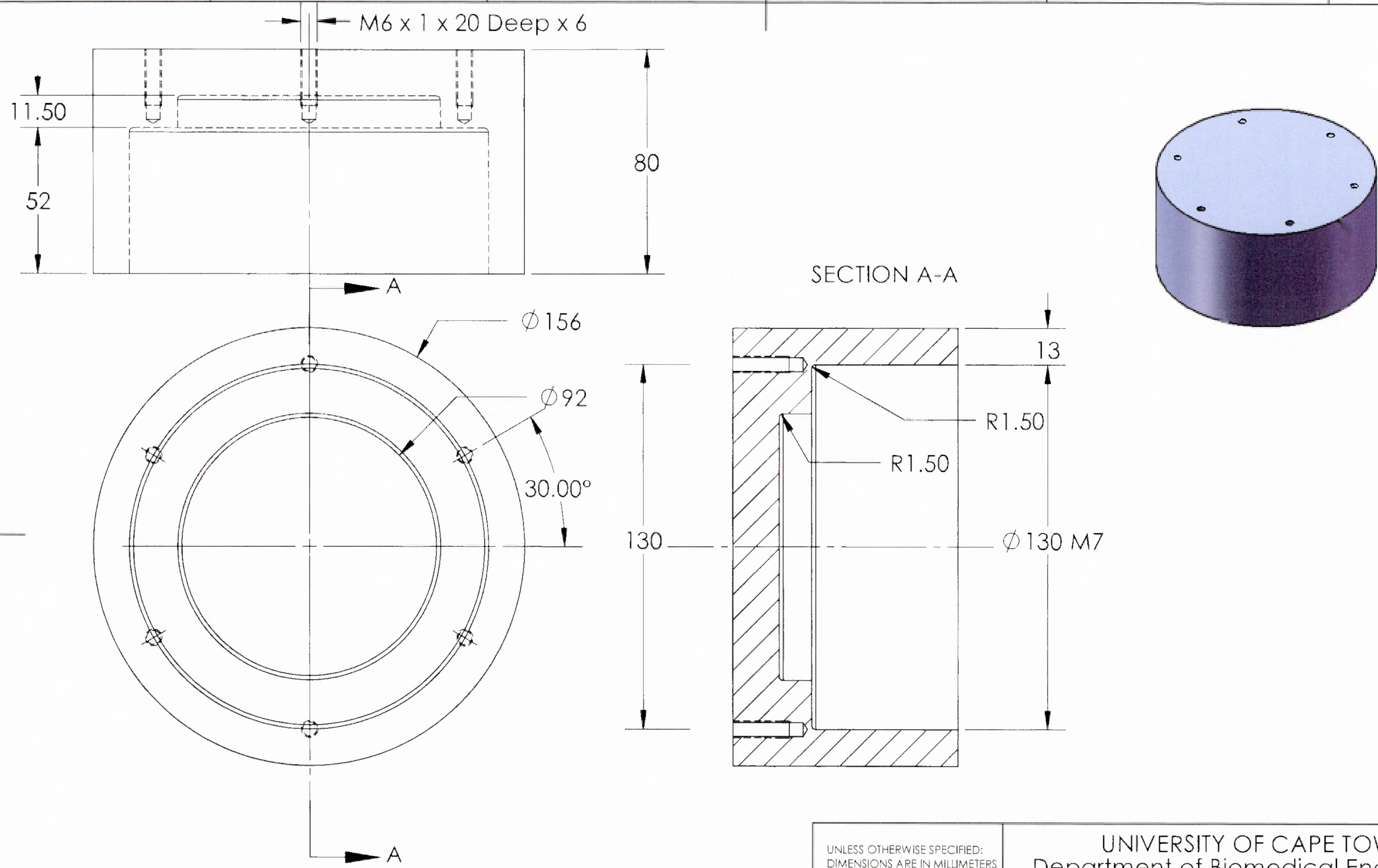

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Department of Biomedical Engineering

TITLE:

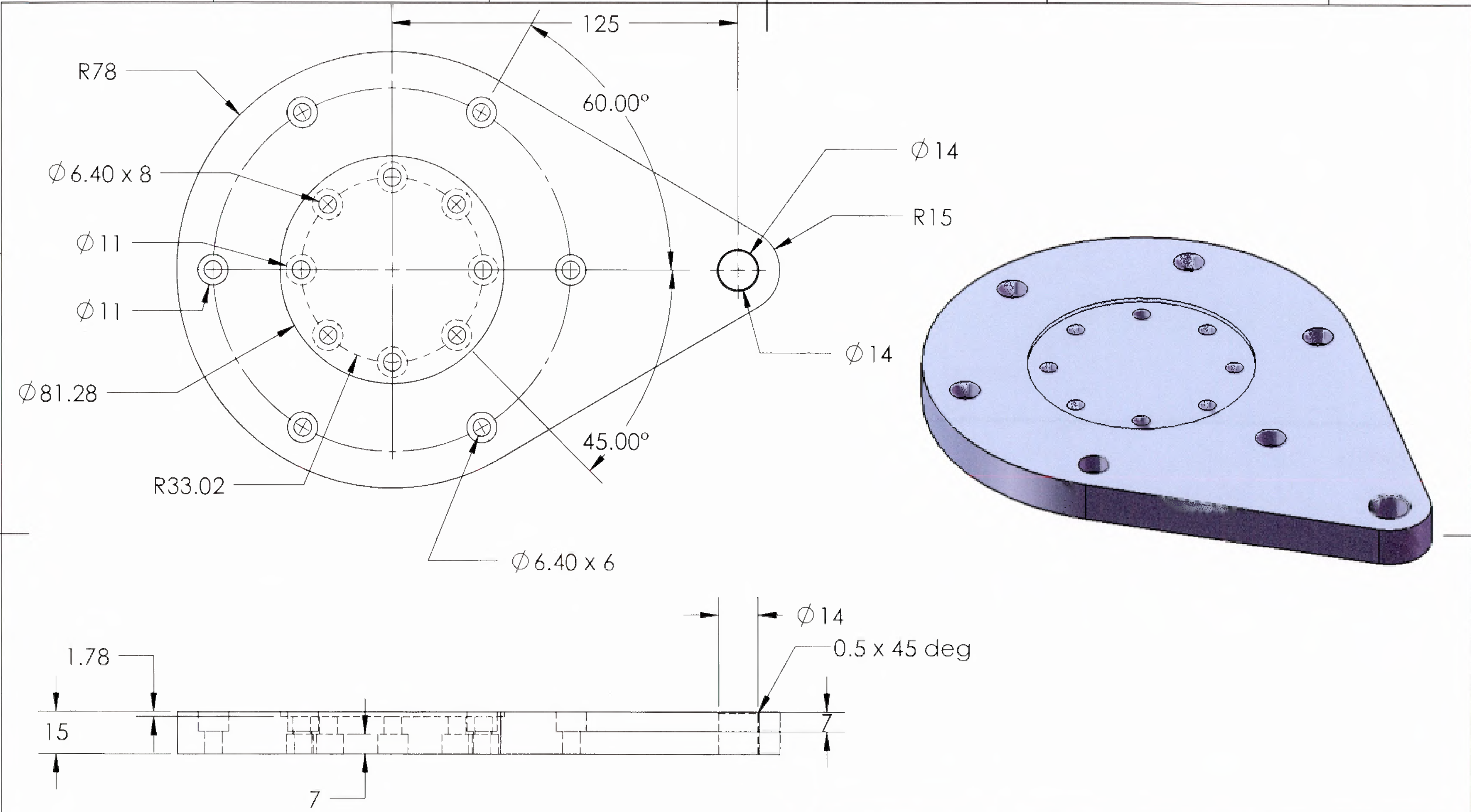
THRUST BEARING HOUSING

DWG NO. 5

A4

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

TIBIAL ROTATION ATTACHMENT PLATE

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHKD			
APPVD			
MFG			
Q.A			

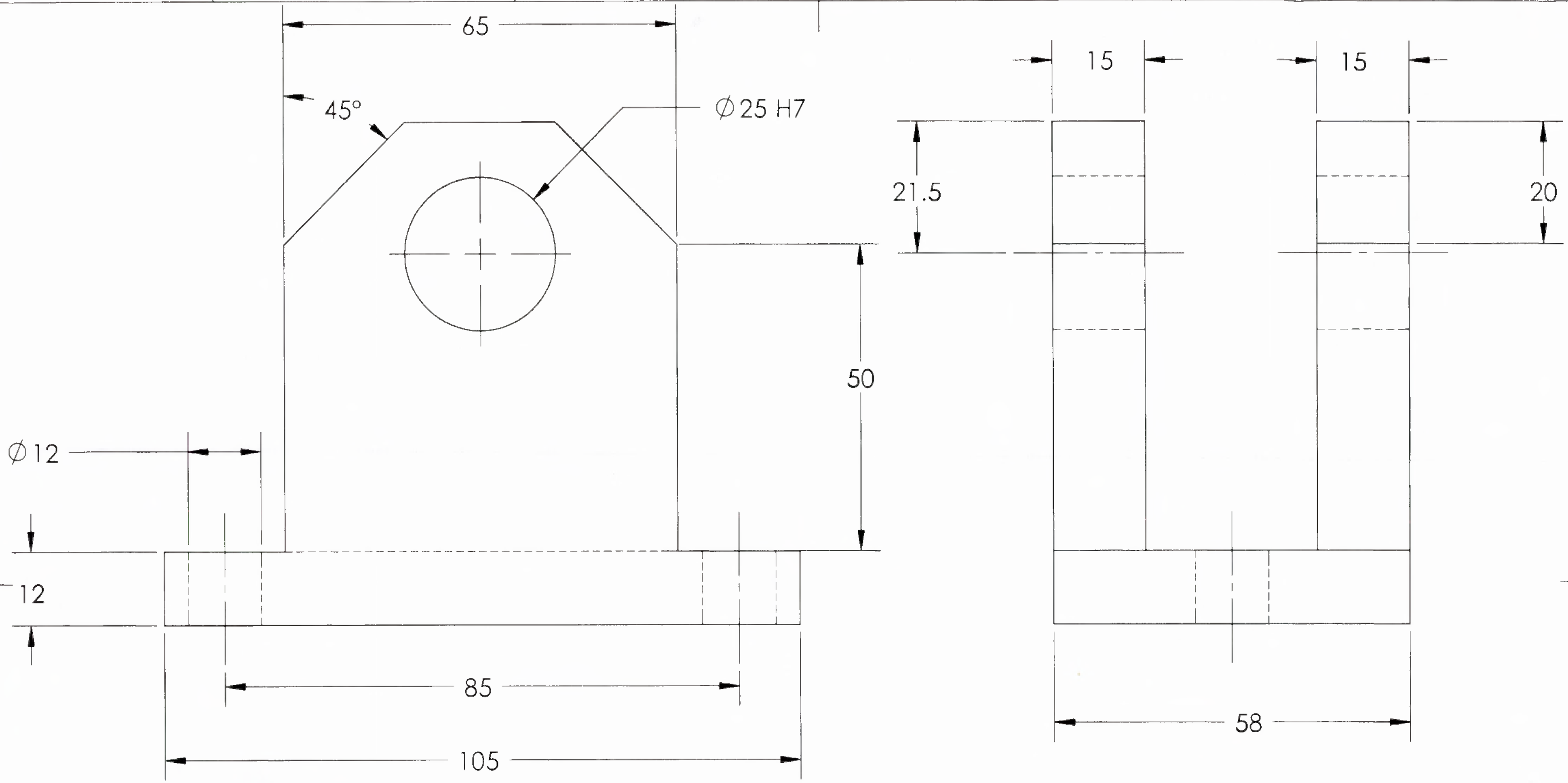
MATERIAL: STAINLESS STEEL 316L

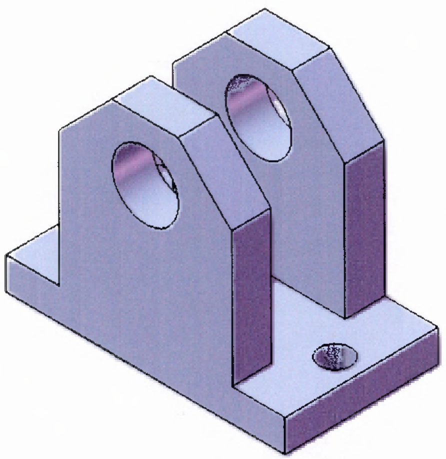
DWG NO. 6

A4

SCALE:1:2

SHEET 1 OF 1





	NAME	SIGNATURE	DATE	
DRAWN	Neil Campbell		12/01/08	
CHK'D				
APPV'D				
MFG				
Q.A				

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

MATERIAL:
STAINLESS STEEL 316L

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

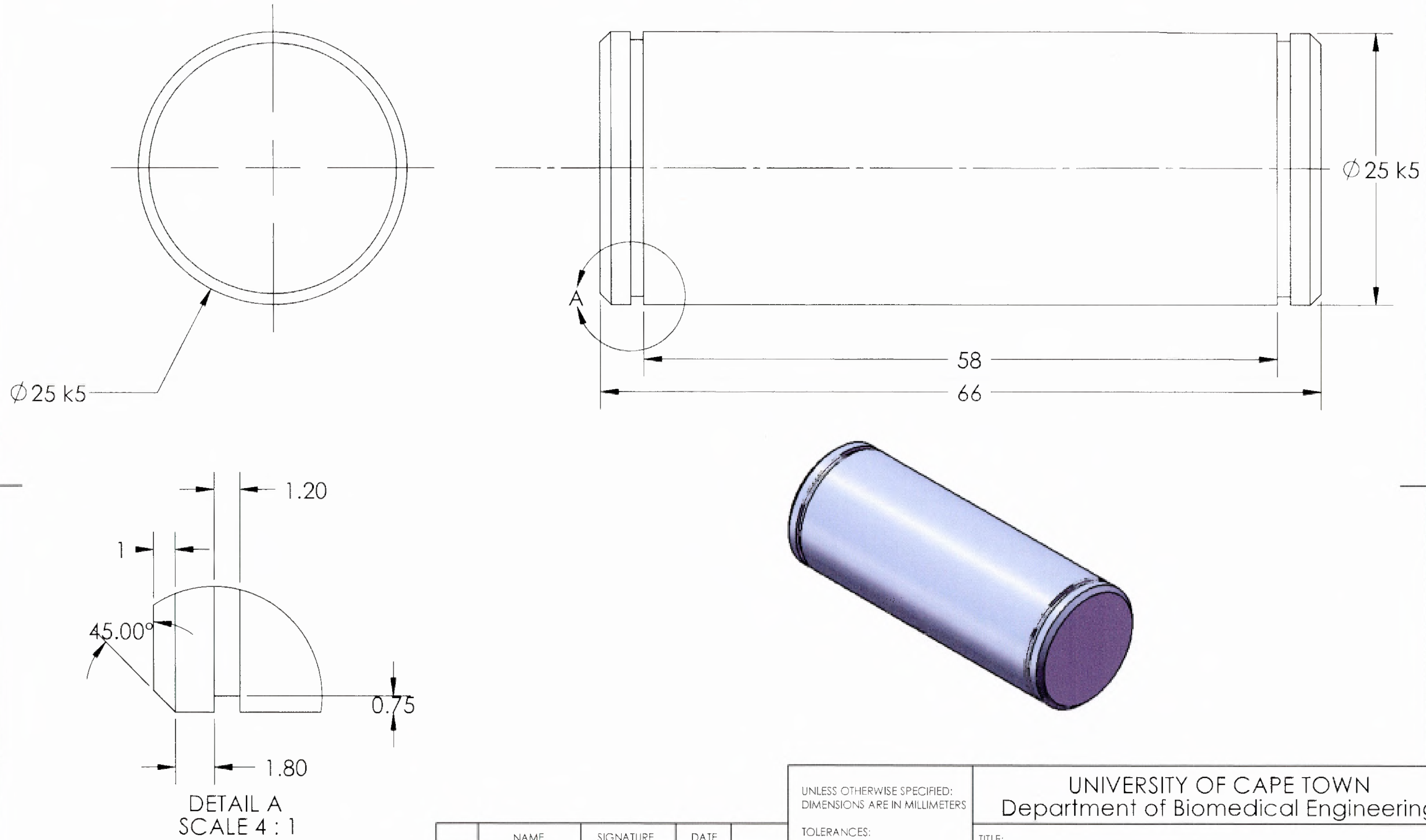
FLEXION-EXTENSION SHAFT HOUSING

DWG NO. 7

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

FLEXION-EXTENSION SHAFT

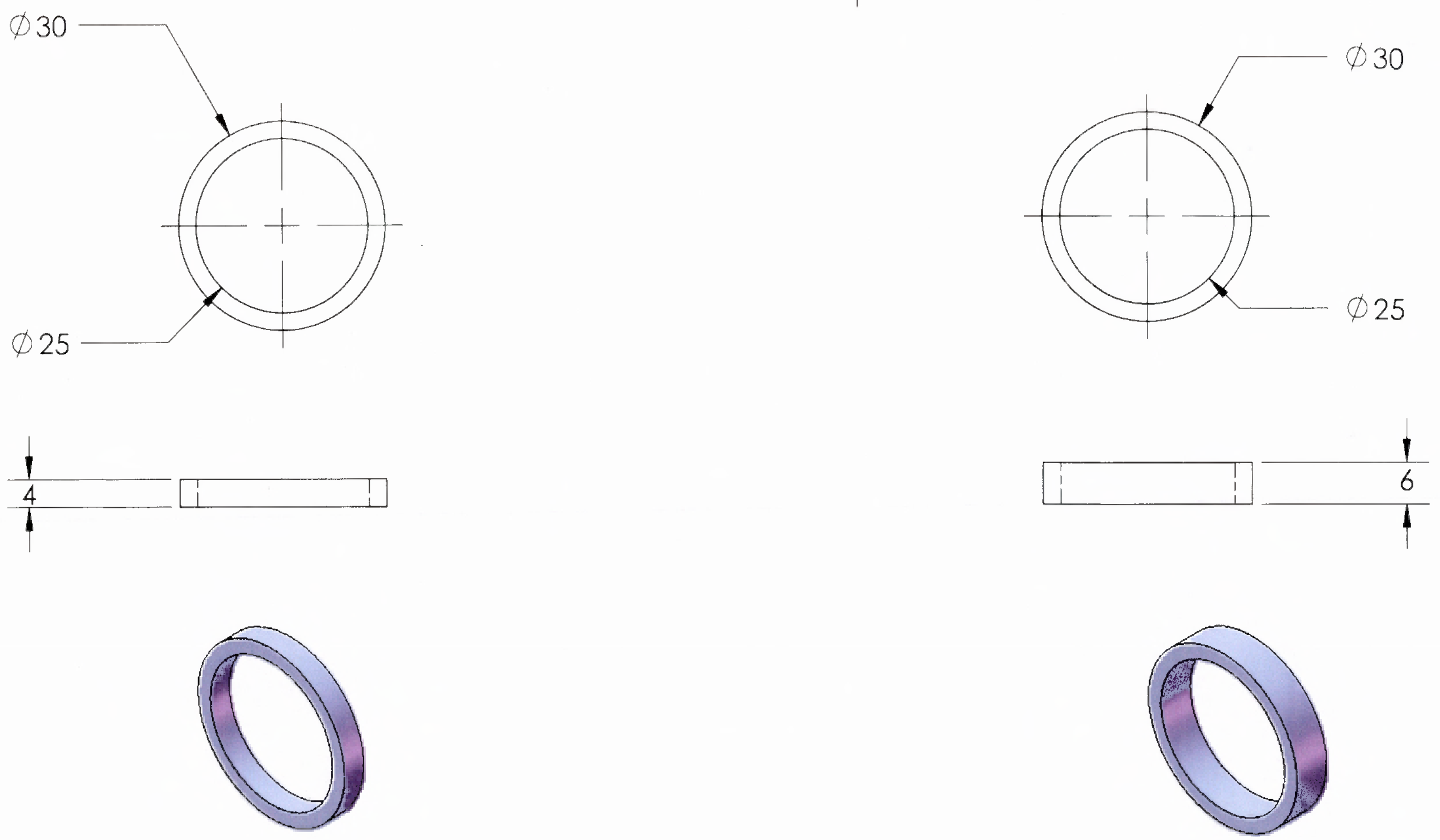
MATERIAL:
STAINLESS STEEL 316L

DWG NO. 8

A4

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

FLEXION-EXTENSION SHAFT SPACERS

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

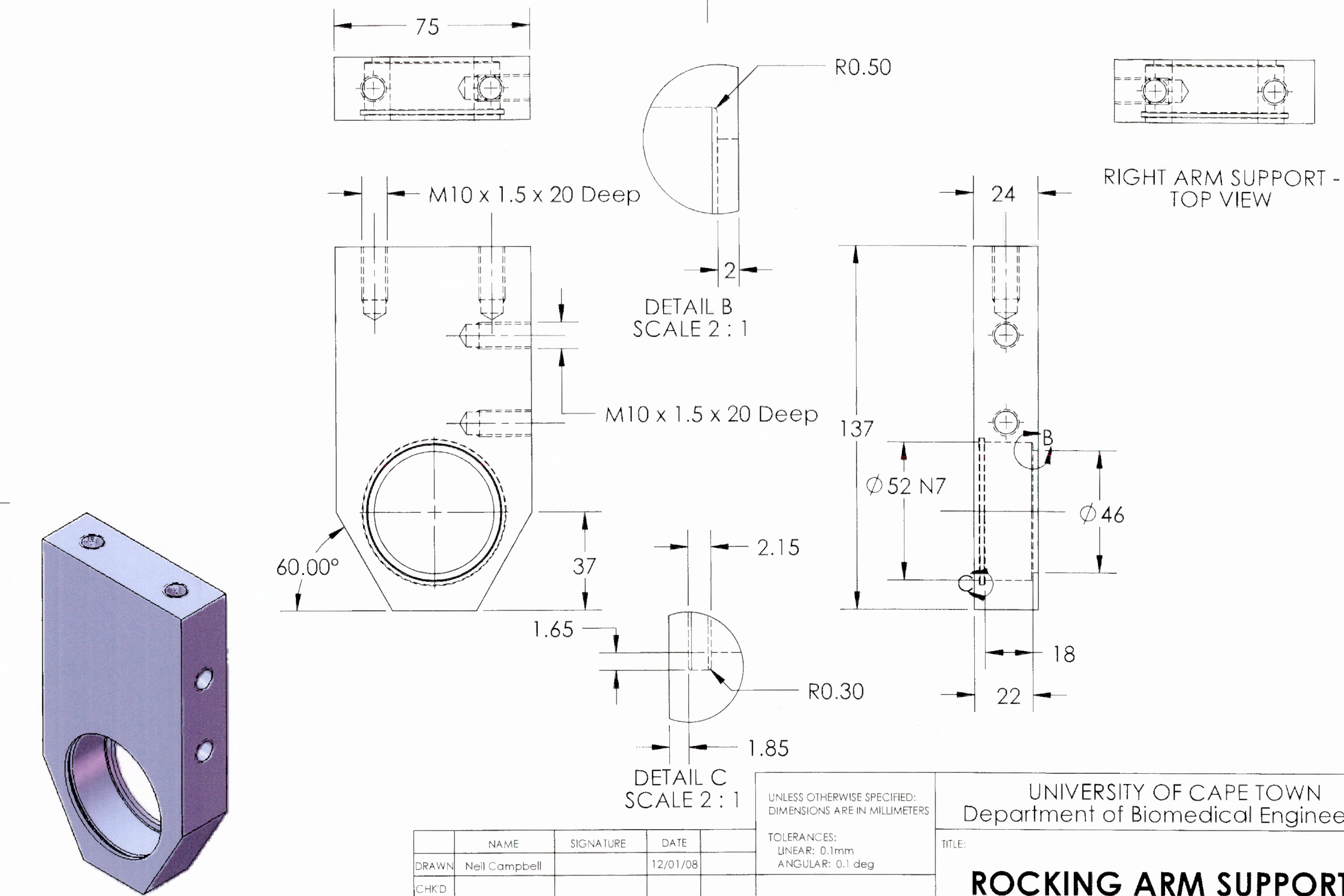
MATERIAL: STAINLESS STEEL 316L

DWG NO. 9

A4

SCALE:1:1

SHEET 1 OF 1



	NAME	SIGNATURE	DATE	
DRAWN	Neil Campbell		12/01/08	
CHK'D				
APPV'D				
MFG				
Q.A				

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

ROCKING ARM SUPPORTS

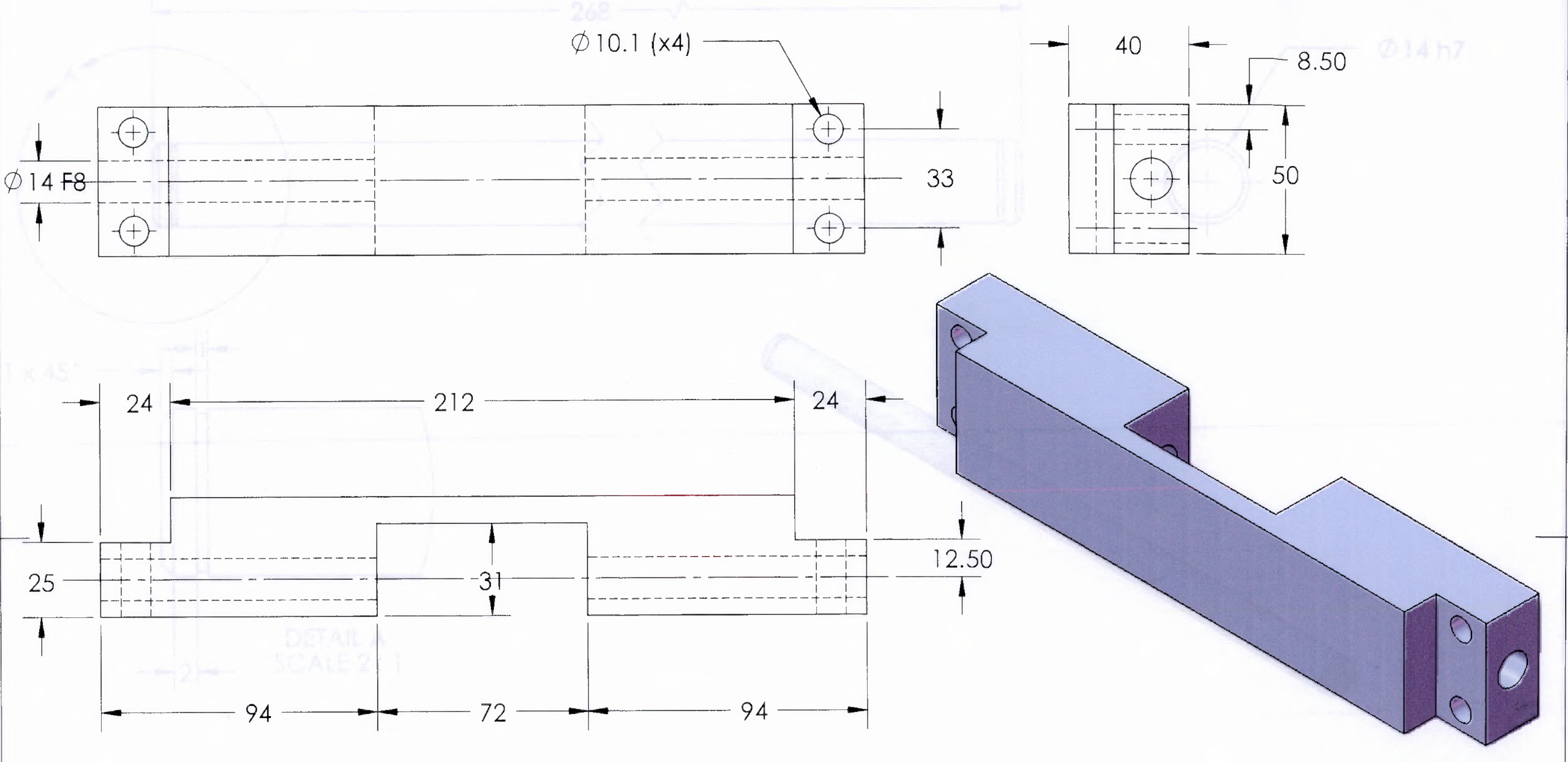
MATERIAL:
STAINLESS STEEL 316L

DWG NO.
10

A4

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

ROCKING ARM CONNECTOR

MATERIAL:
STAINLESS STEEL 316L

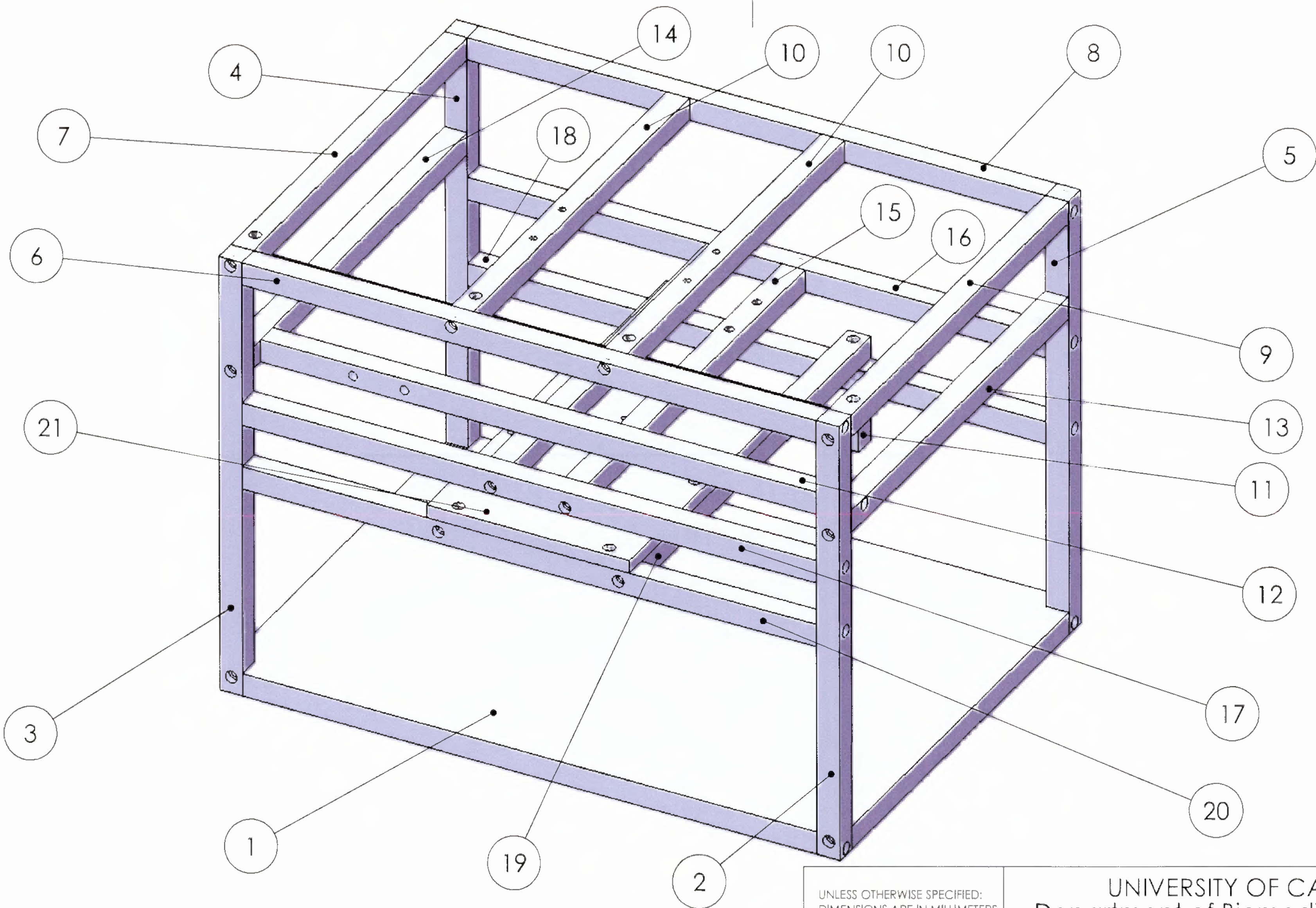
DWG NO. 11

A4

SCALE:1:2

SHEET 1 OF 1

10.2 APPENDIX 2 – FRAME DRAWINGS



ALL NUMBERS REFER TO DRAWING NUMBERS FOR EACH COMPONENT

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

ASSEMBLED FRAME

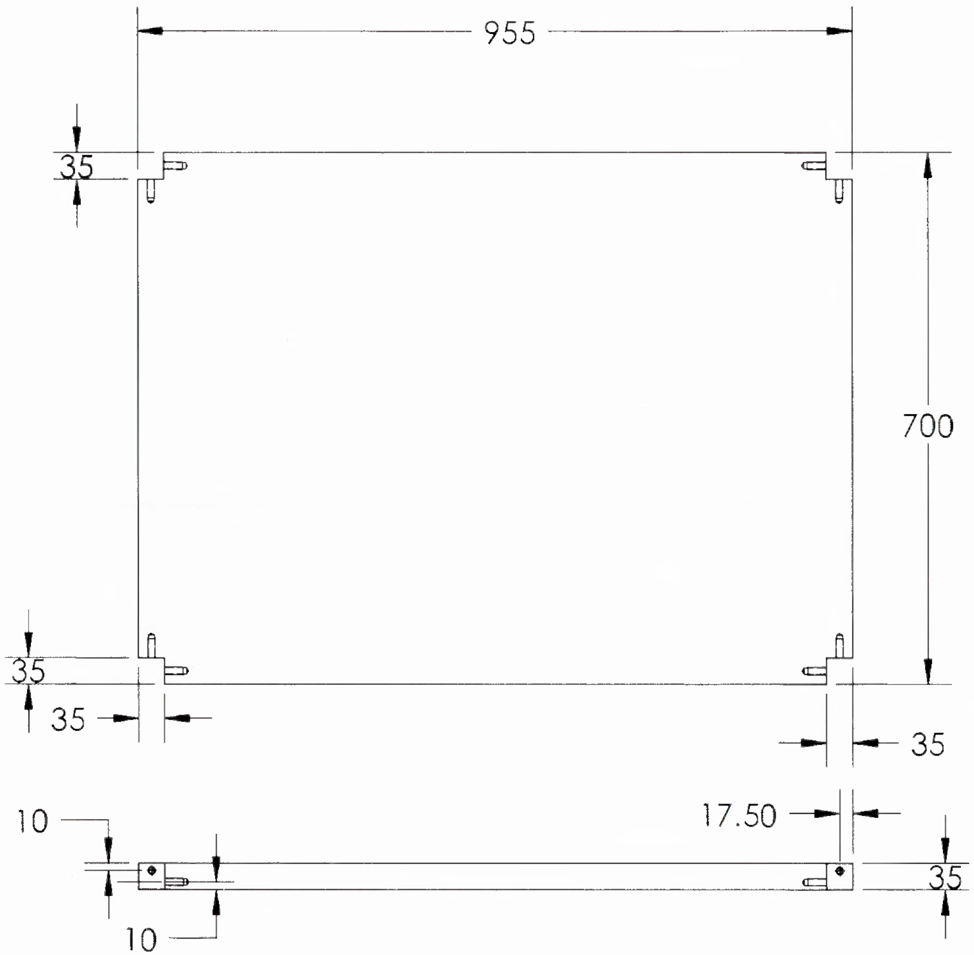
MATERIAL:
COLD ROLLED STEEL

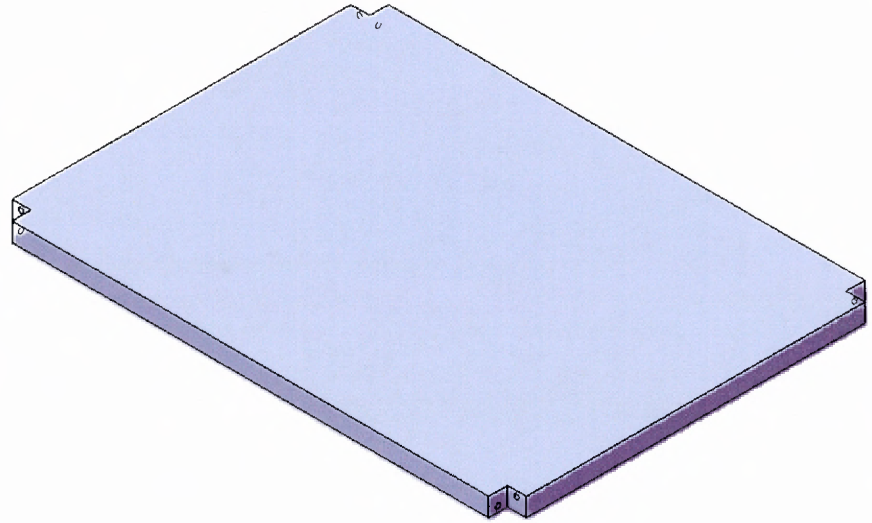
DWG NO.

A4

SCALE:1:8

SHEET 1 OF 1





All Threads: M10 x 1.5 x 25 Deep

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BASE PLATE

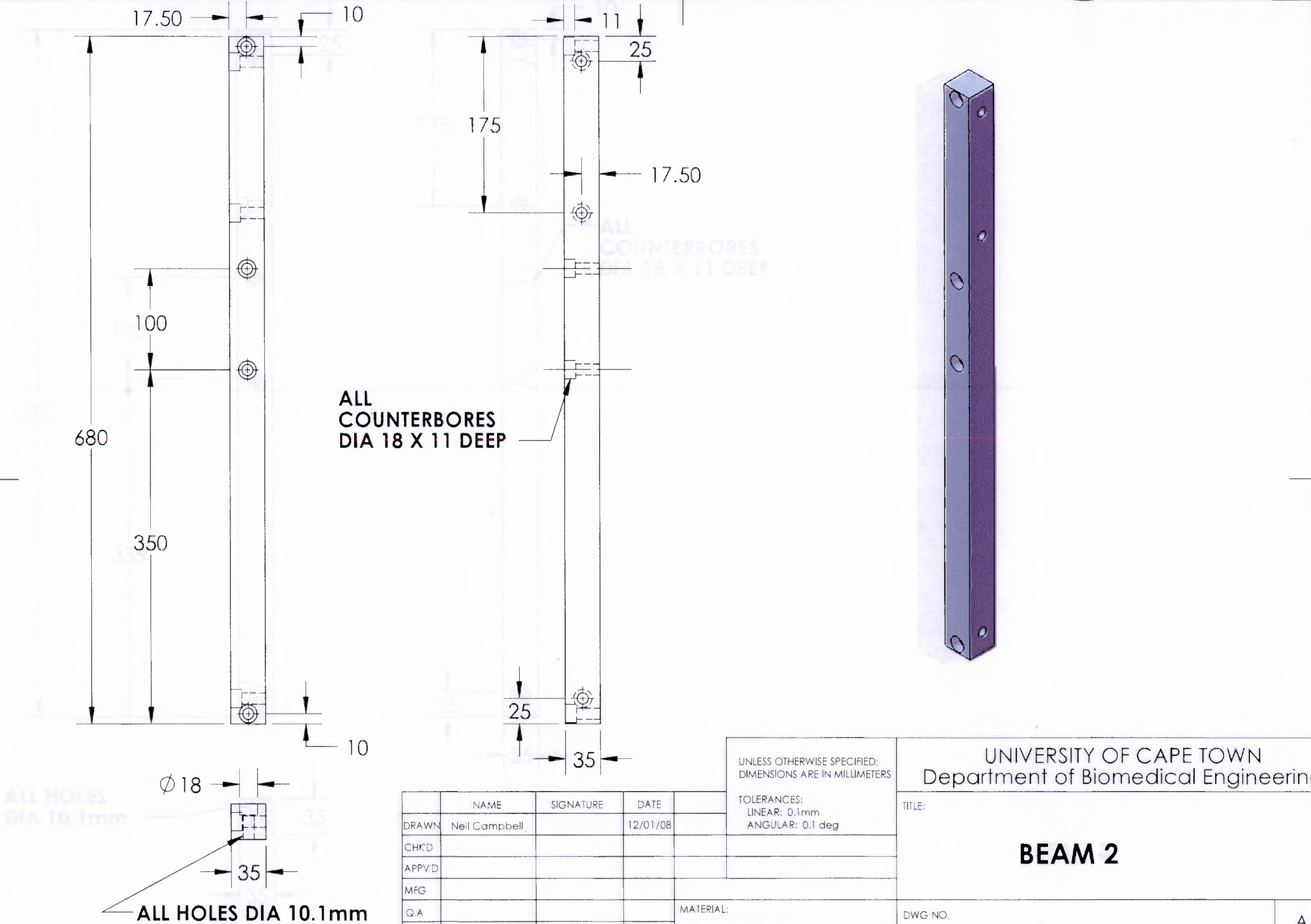
MATERIAL:
COLD ROLLED STEEL

DWG NO.
1

A4

SCALE:1:10

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 2

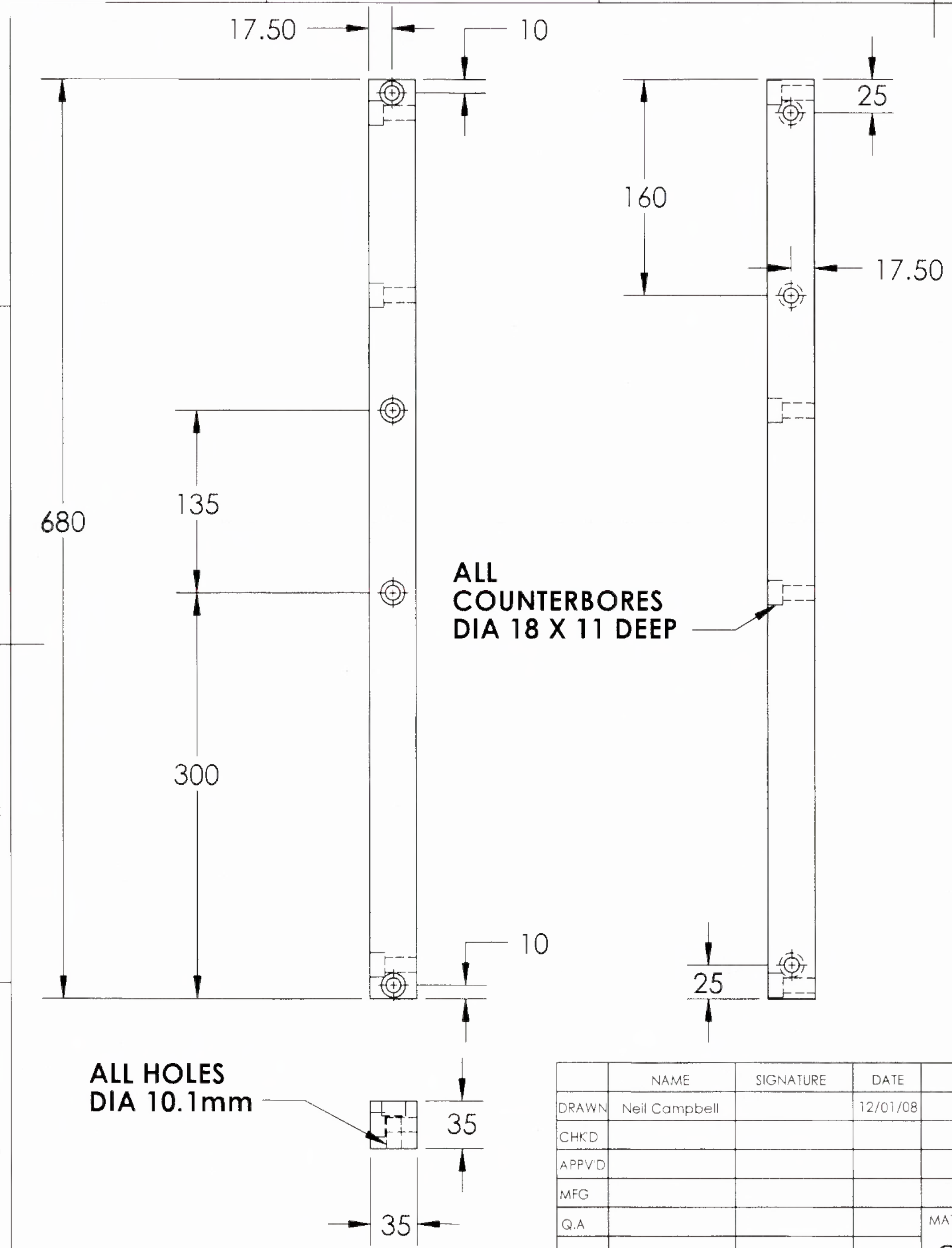
MATERIAL:
COLD ROLLED STEEL

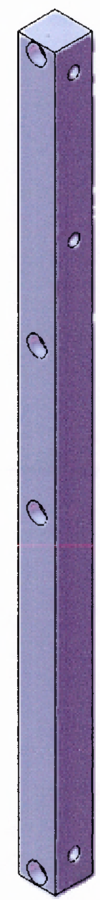
DWG NO. 2

A4

SCALE:1:5

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHKD			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

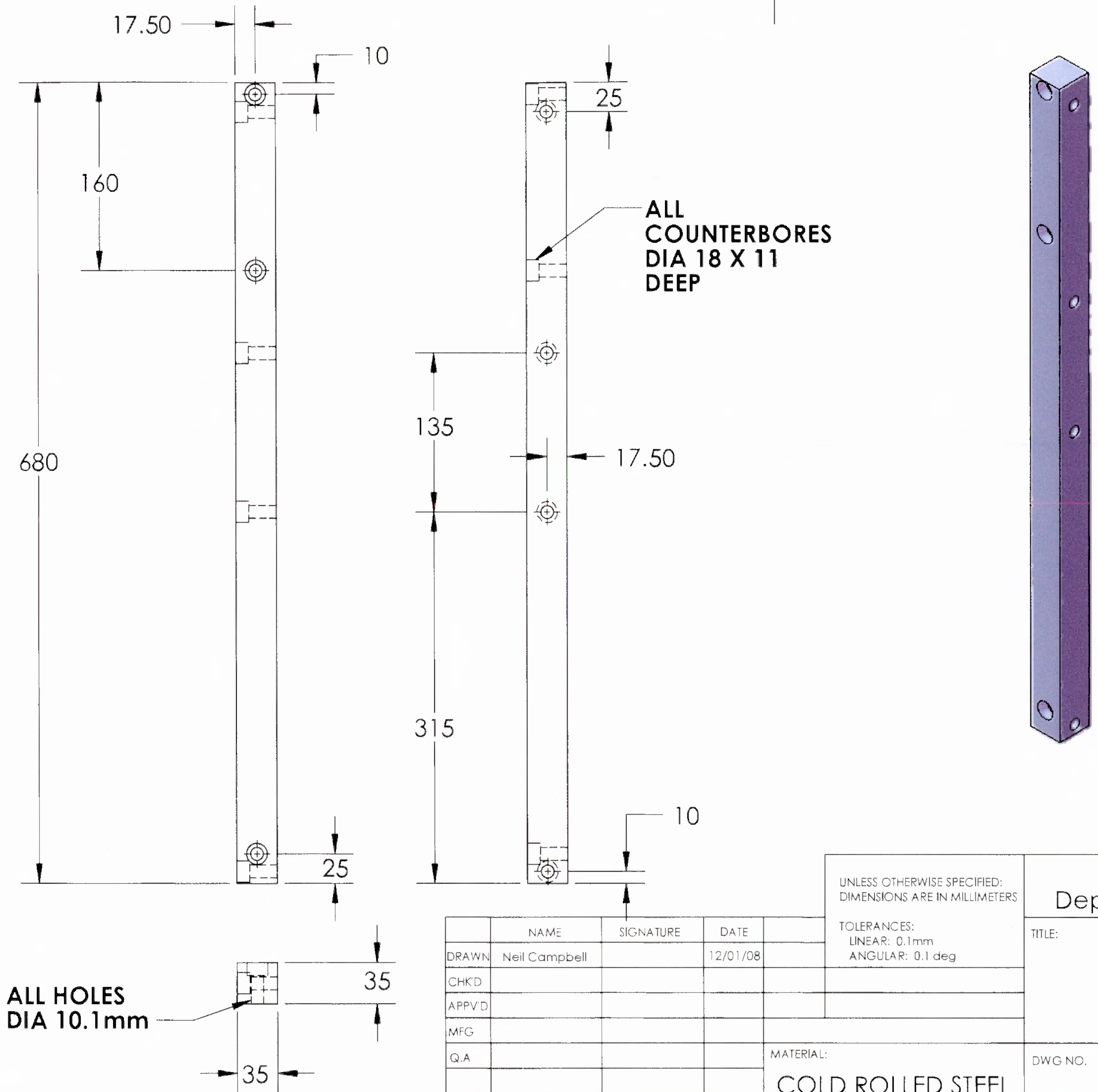
TITLE: **BEAM 4**

DWG NO. 4

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

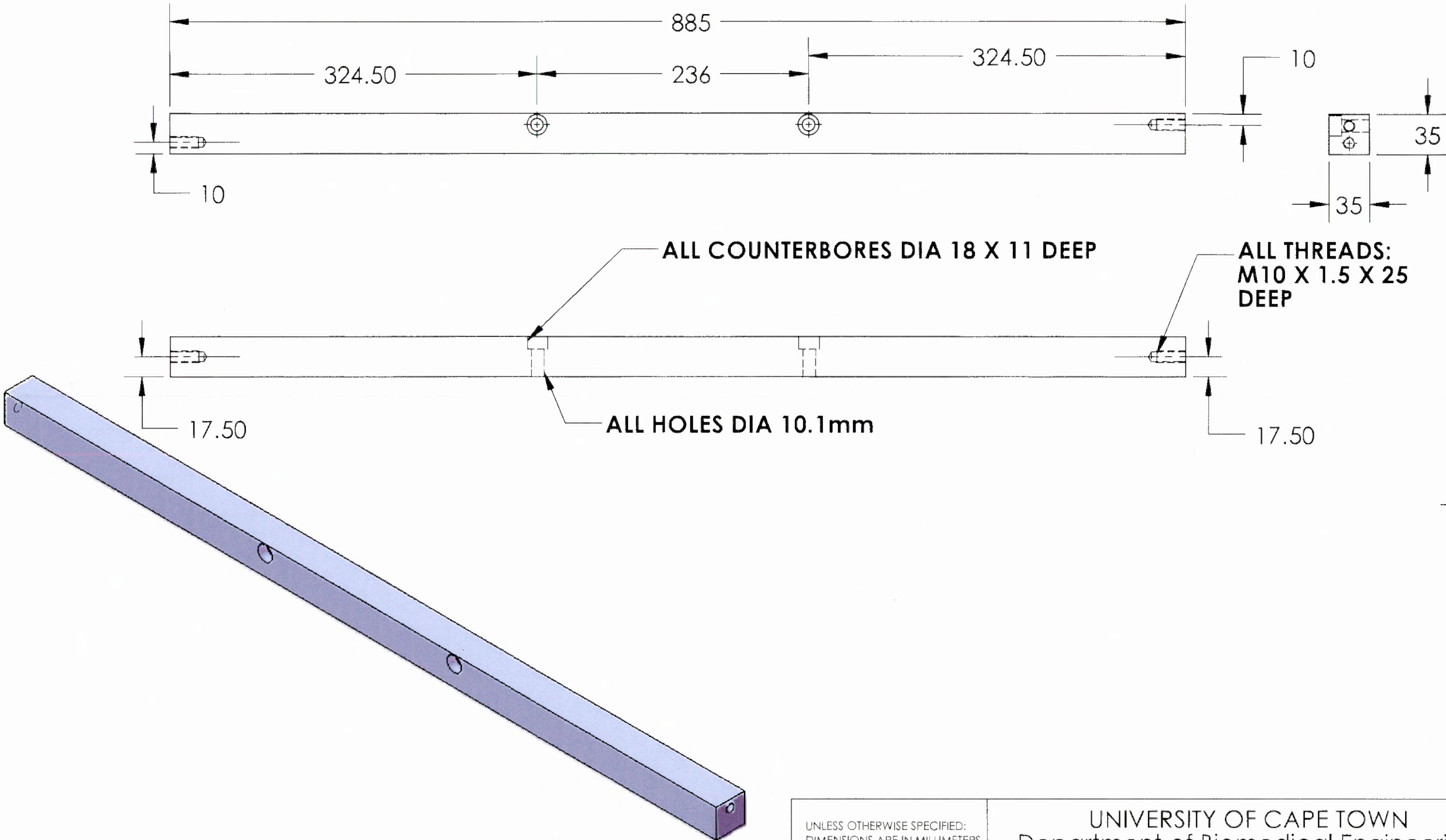
TITLE: **BEAM 5**

DWG NO. **5**

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 6

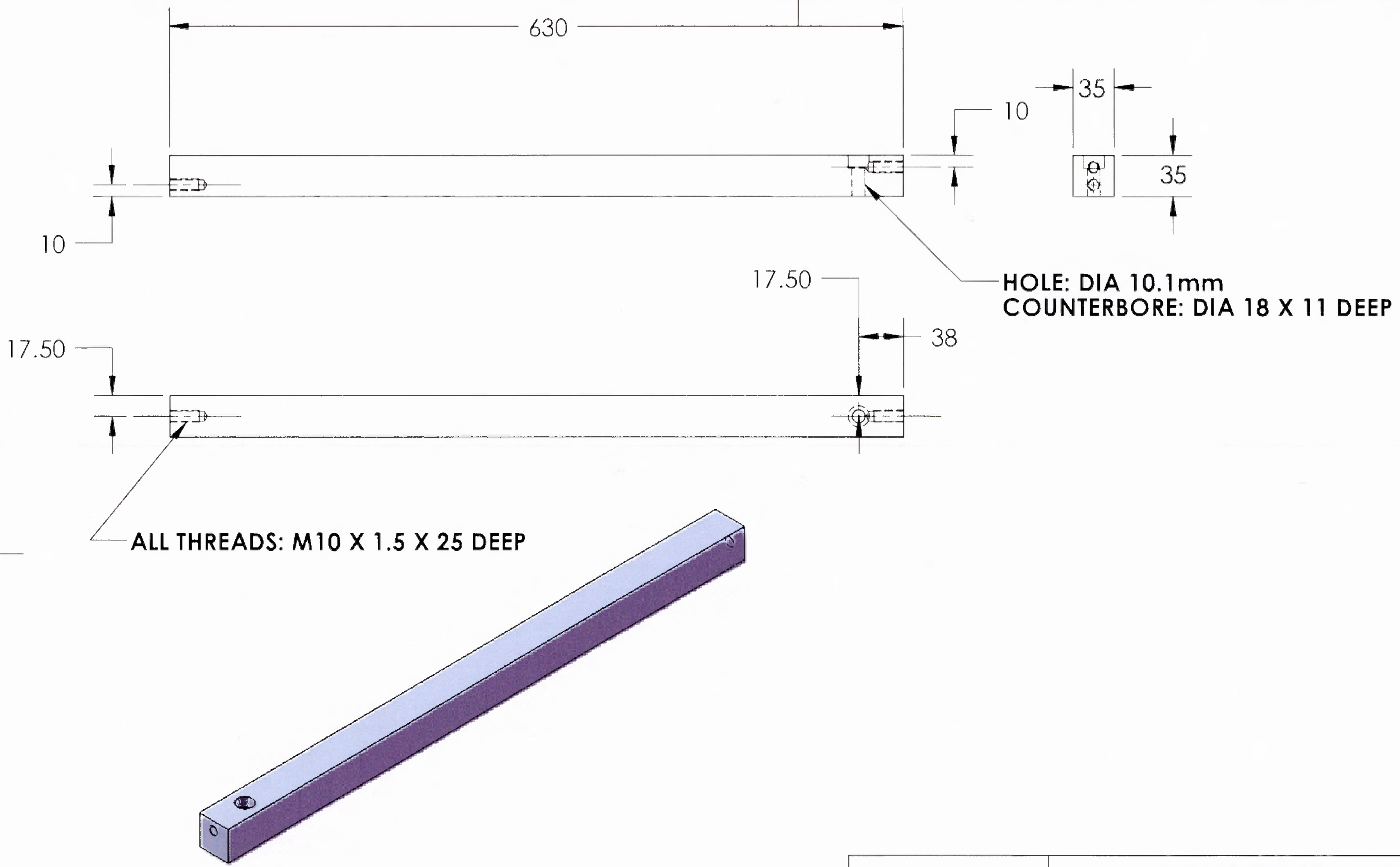
MATERIAL:
COLD ROLLED STEEL

DWG NO.
6

A4

SCALE:1:5

SHEET 1 OF 1



	NAME	SIGNATURE	DATE	
DRAWN	Neil Campbell		12/01/08	
CHK'D				
APPV'D				
MFG				
Q.A				

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

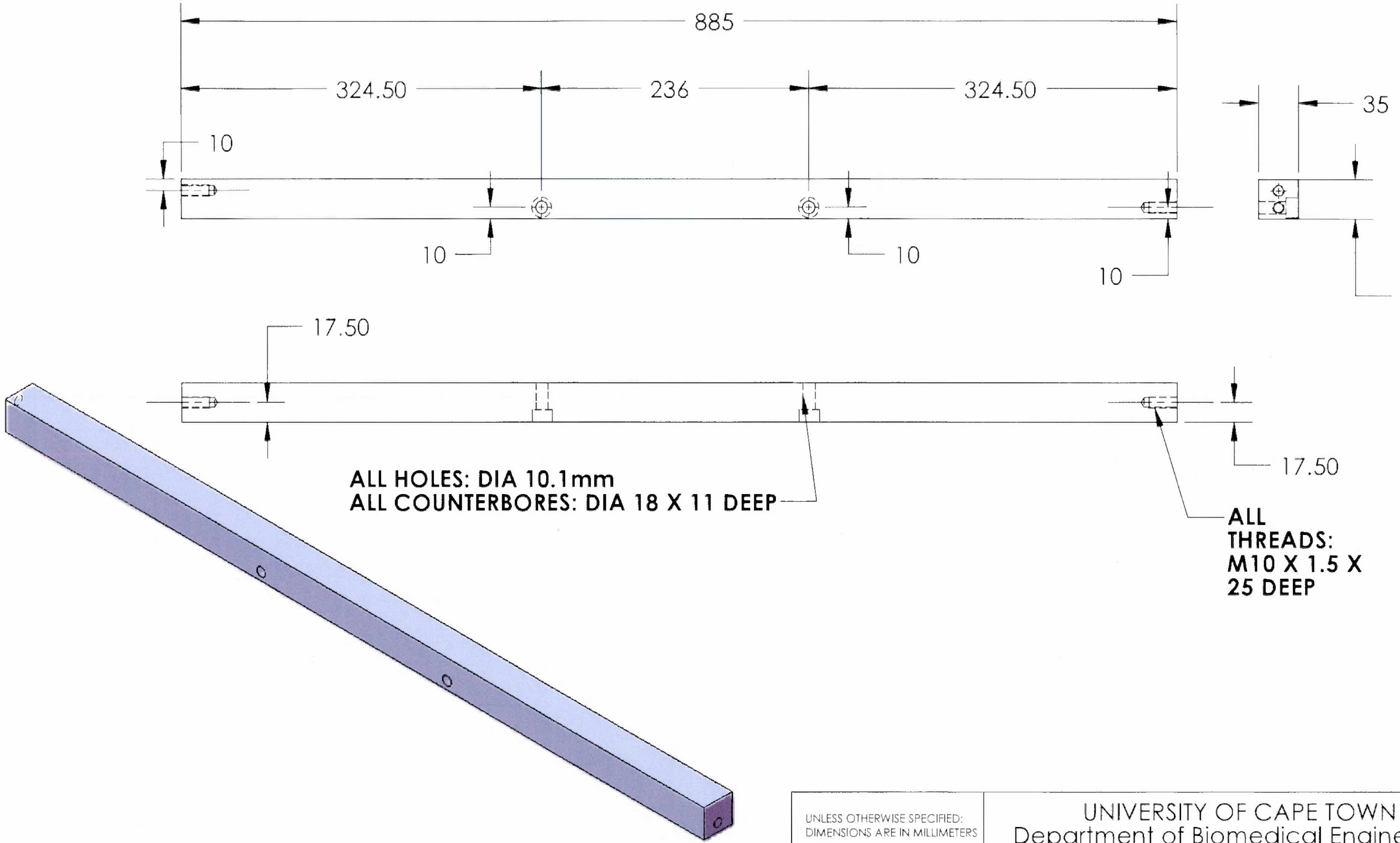
UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

BEAM 7

MATERIAL:
COLD ROLLED STEEL

DWG NO.		
7		A4
SCALE:1:5		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

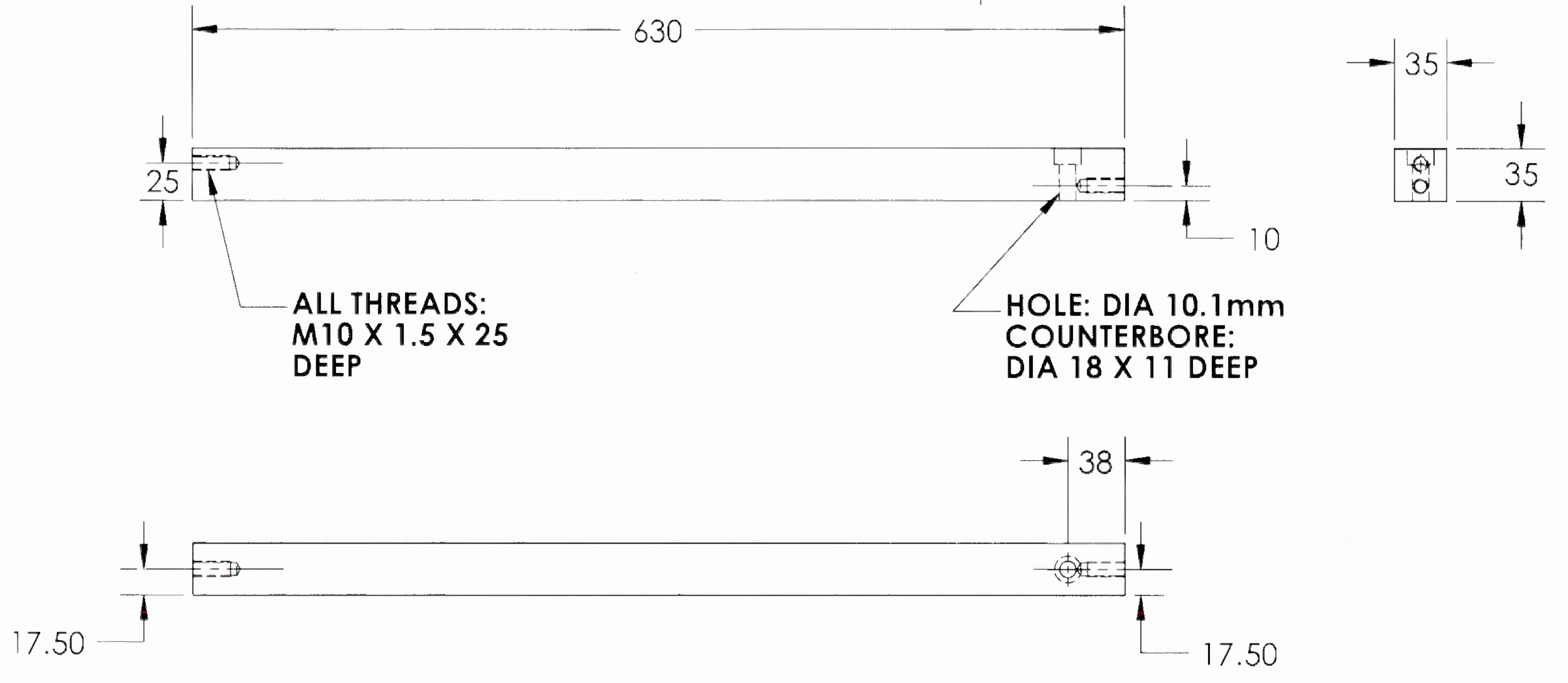
TITLE: **BEAM 8**

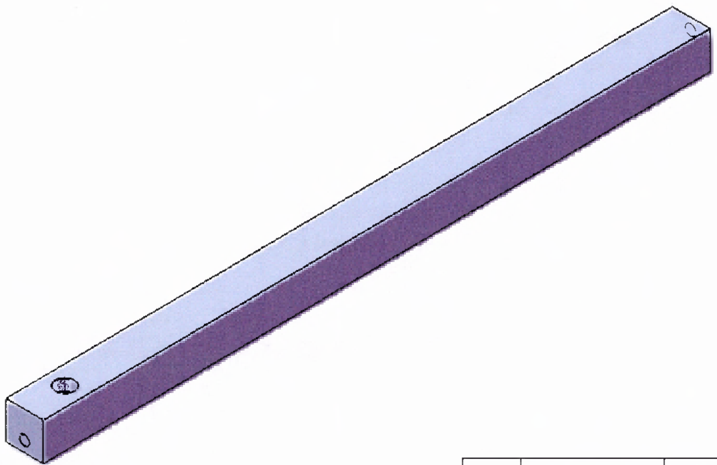
DWG NO. **8**

A4

SCALE:1:5

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:
COLD ROLLED STEEL

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

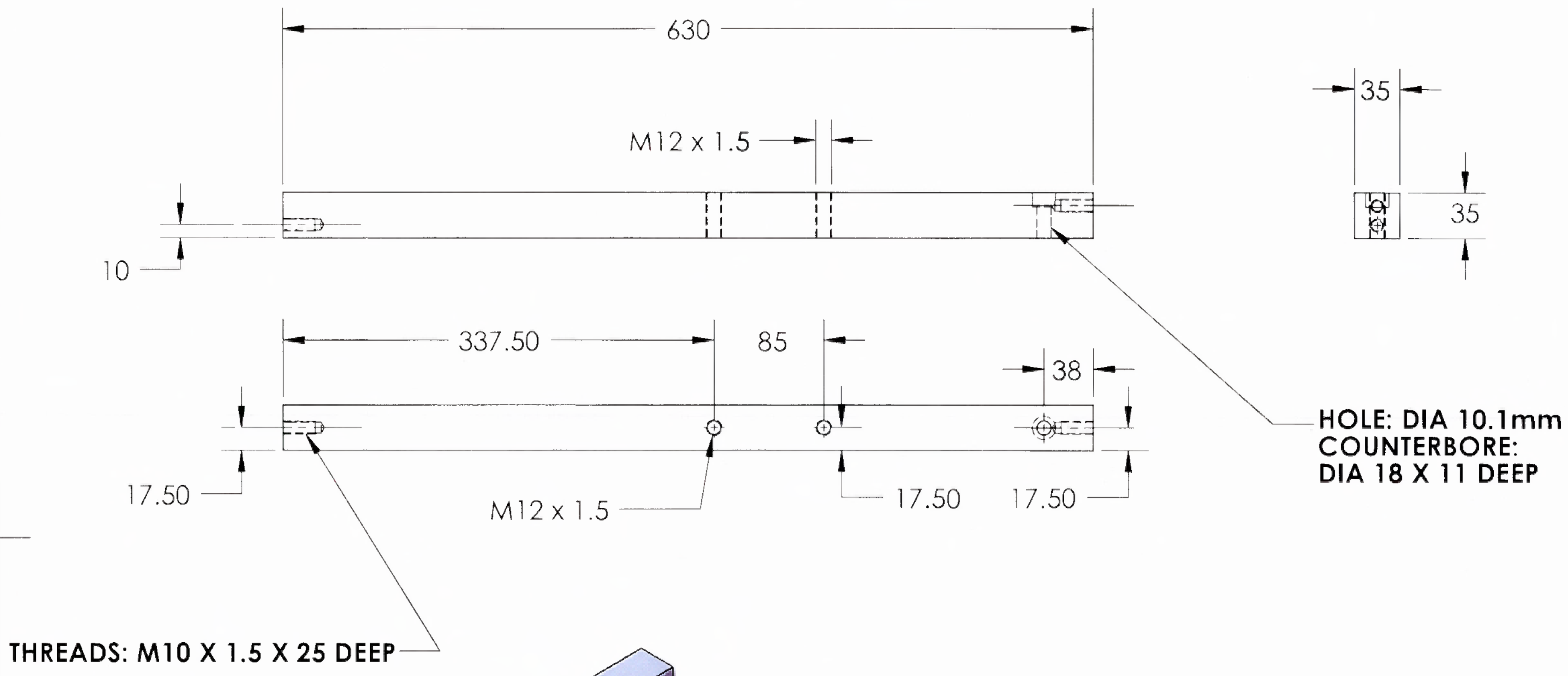
BEAM 9

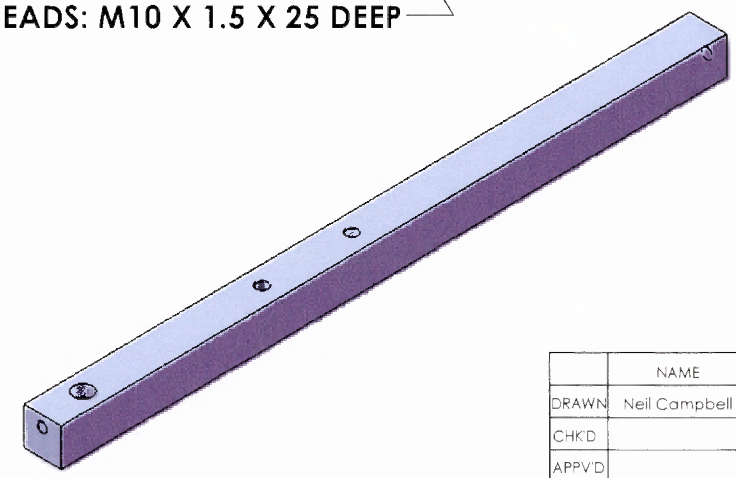
DWG NO.
9

A4

SCALE:1:5

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:
COLD ROLLED STEEL

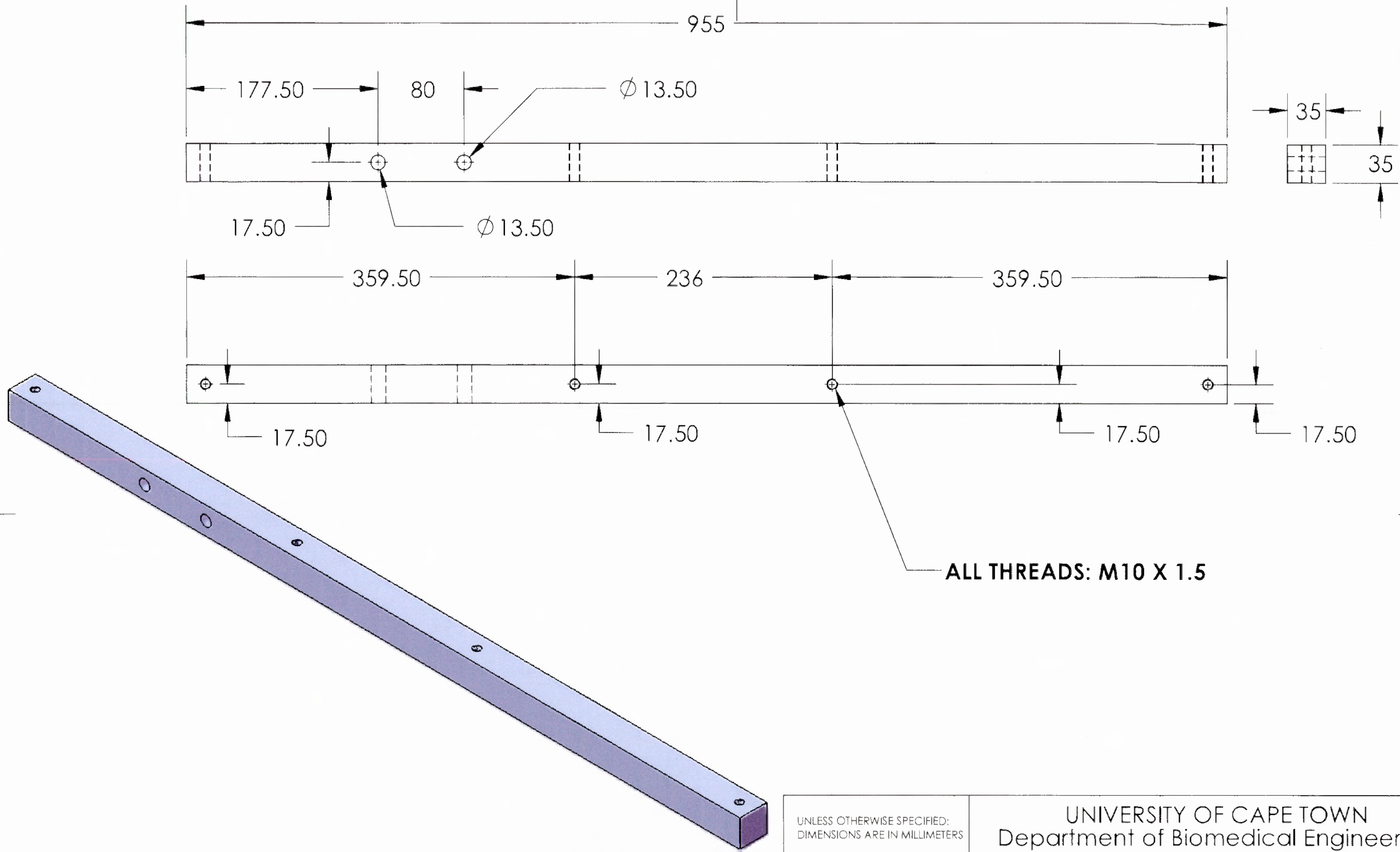
TITLE:
BEAM 10

DWG NO.
10

A4

SCALE:1:5

SHEET 1 OF 1



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ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 11

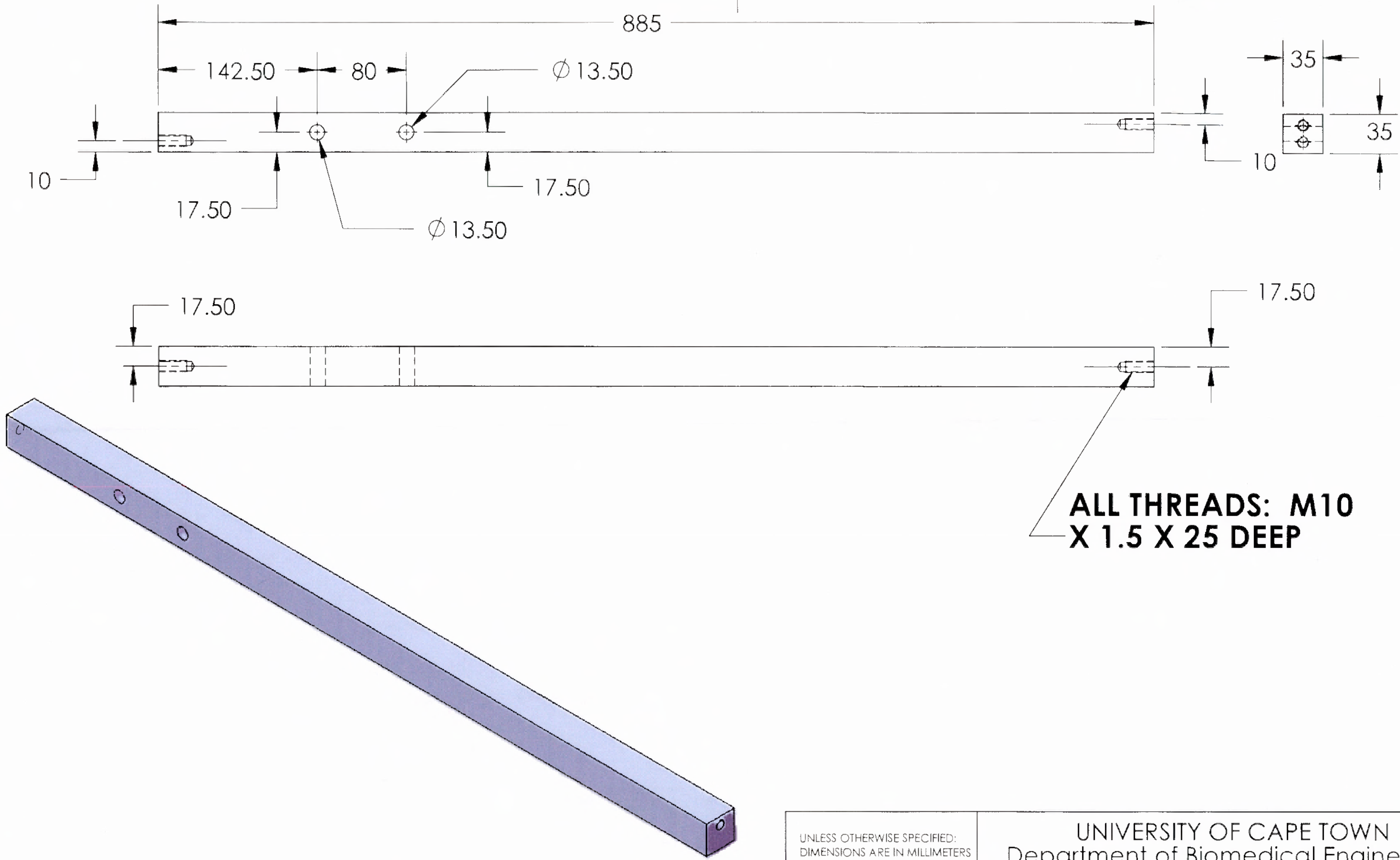
MATERIAL:
COLD ROLLED STEEL

DWG NO.
11

A4

SCALE:1:5

SHEET 1 OF 1



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TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 12

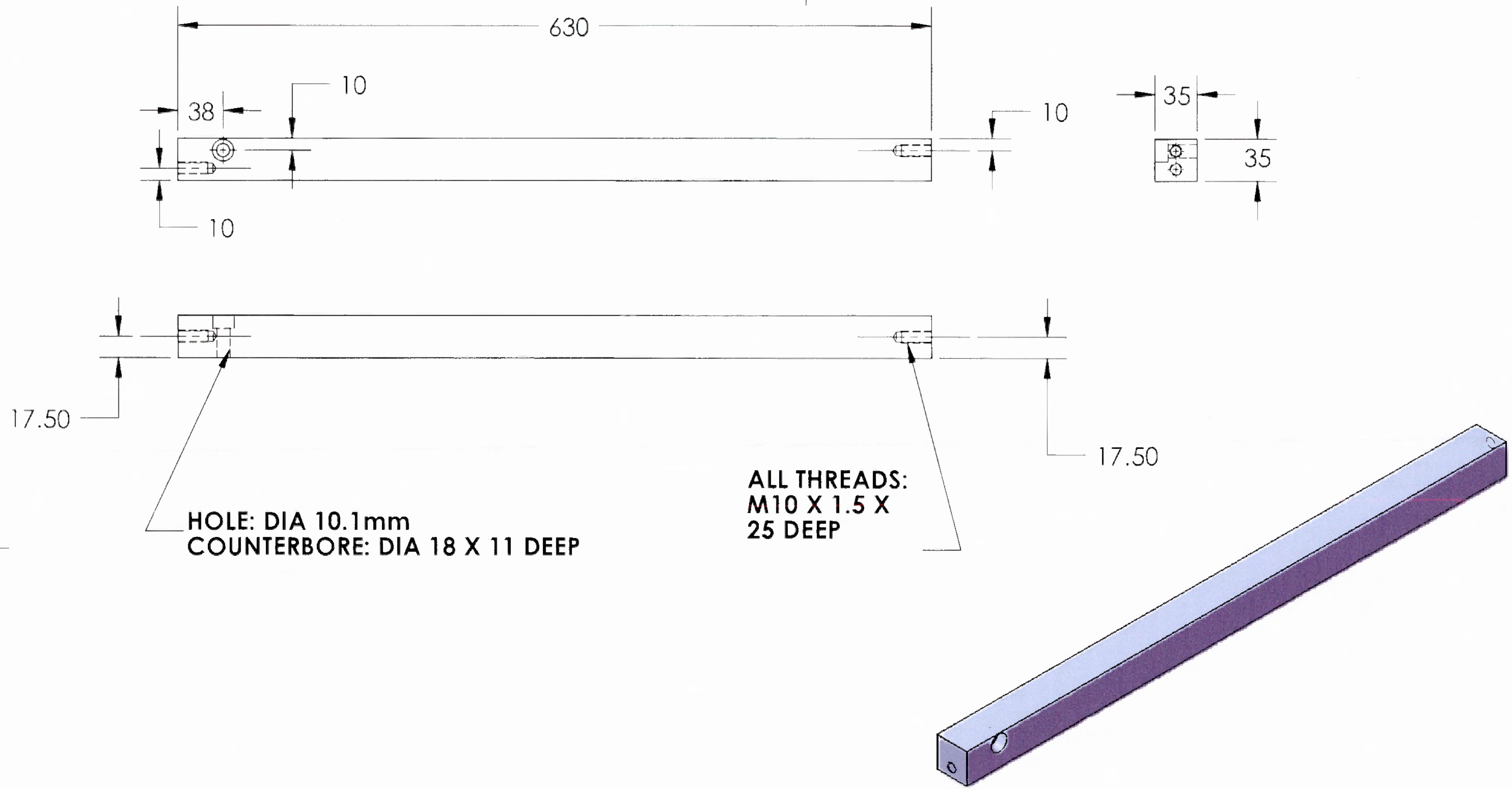
MATERIAL:
COLD ROLLED STEEL

DWG NO.
12

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 13

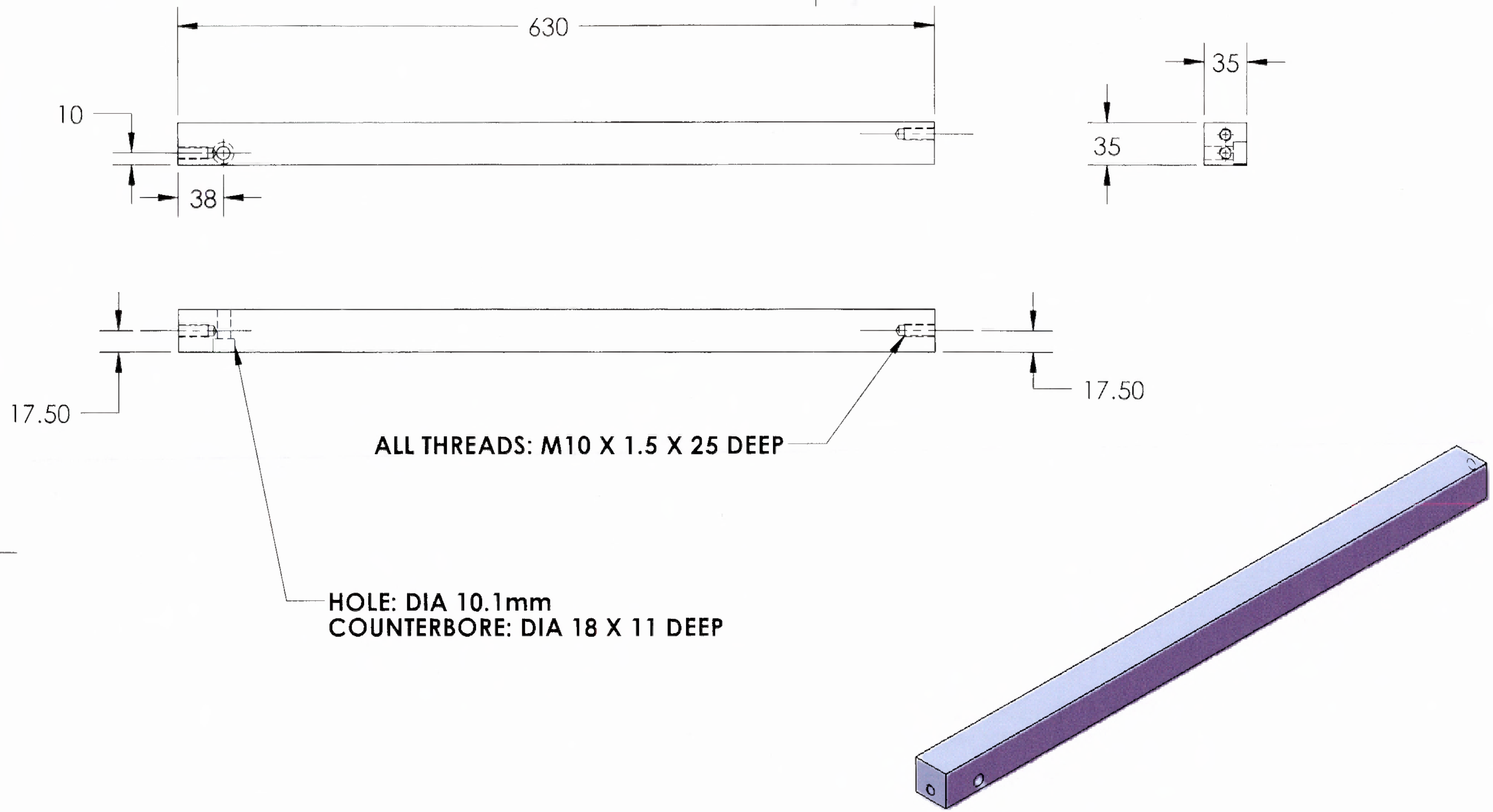
MATERIAL:
COLD ROLLED STEEL

DWG NO.
13

A4

SCALE:1:5

SHEET 1 OF 1



	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

TITLE:

BEAM 14

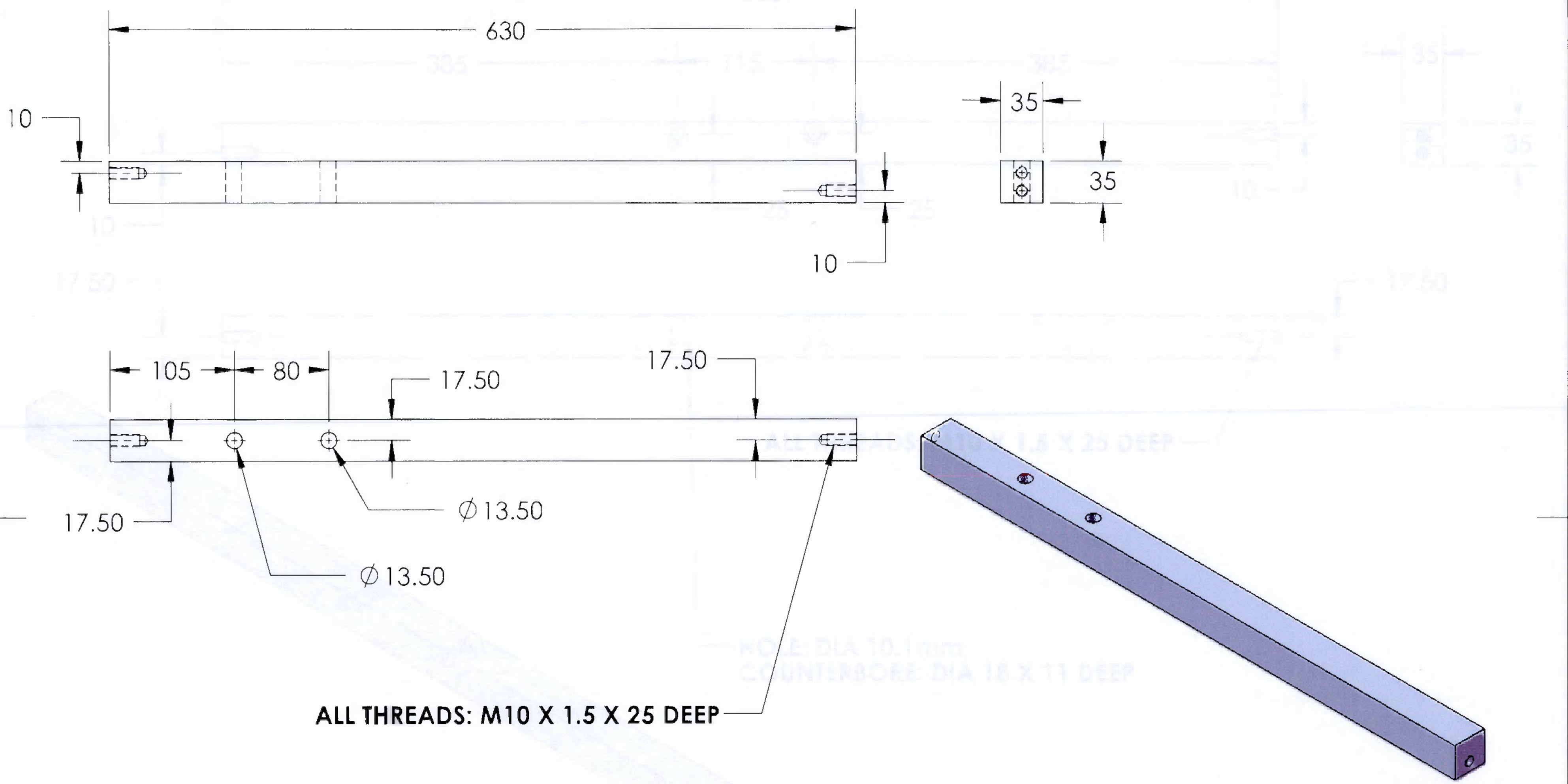
MATERIAL:
COLD ROLLED STEEL

DWG NO. **14**

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

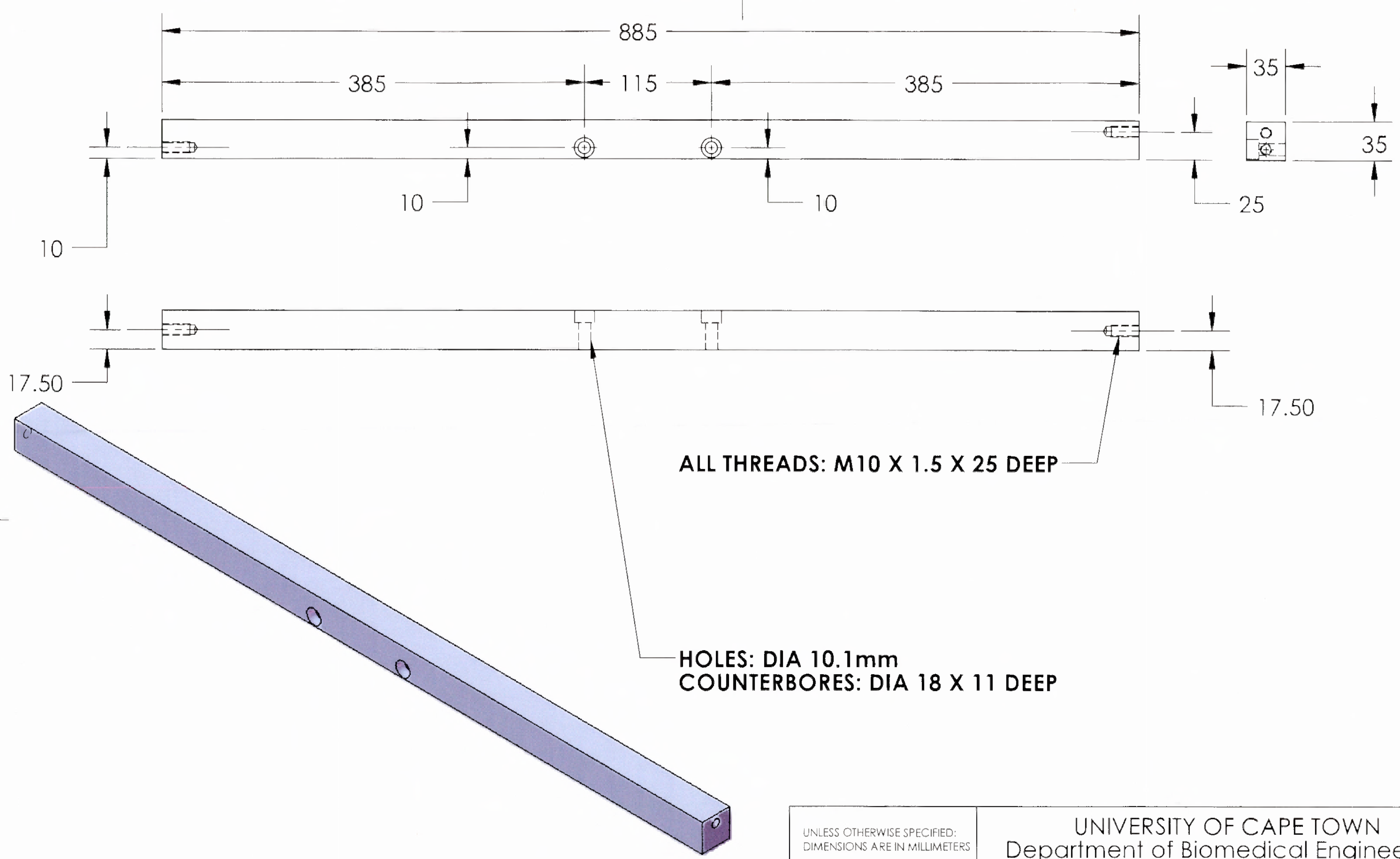
TITLE: **BEAM 15**

DWG NO. **15**

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:
COLD ROLLED STEEL

TITLE:

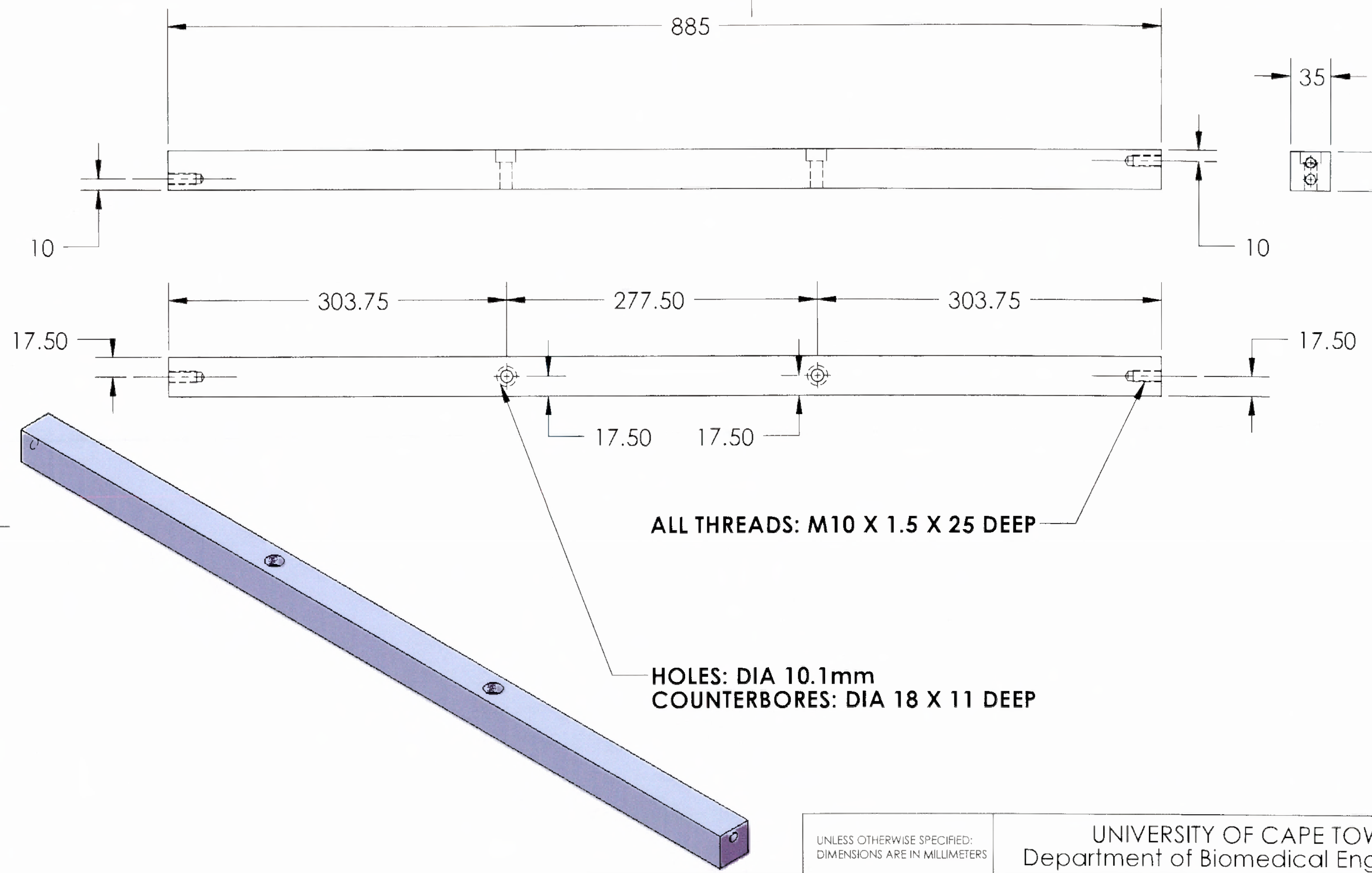
BEAM 17

DWG NO.
17

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

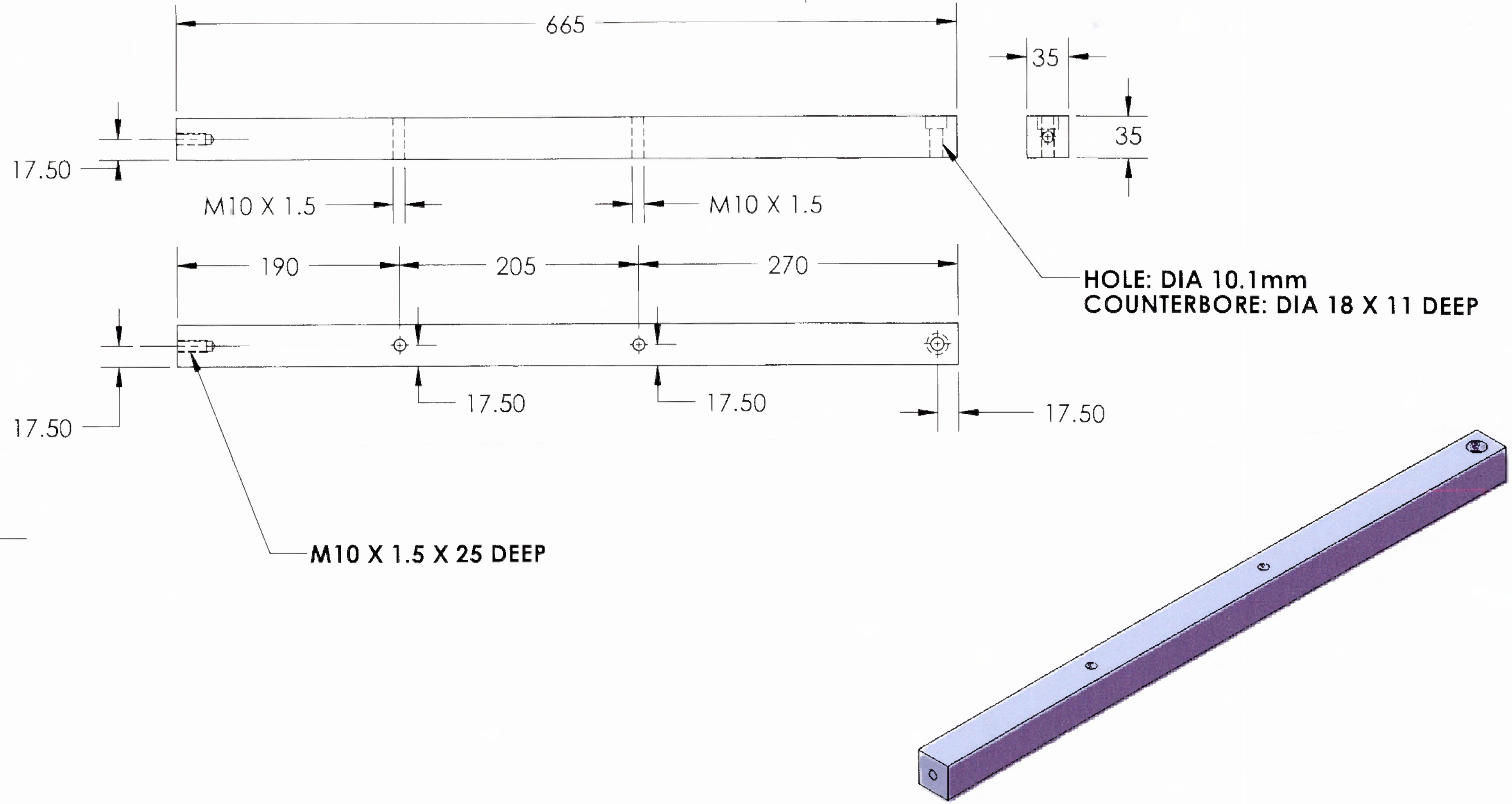
TITLE: **BEAM 18**

DWG NO. **18**

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BEAM 19

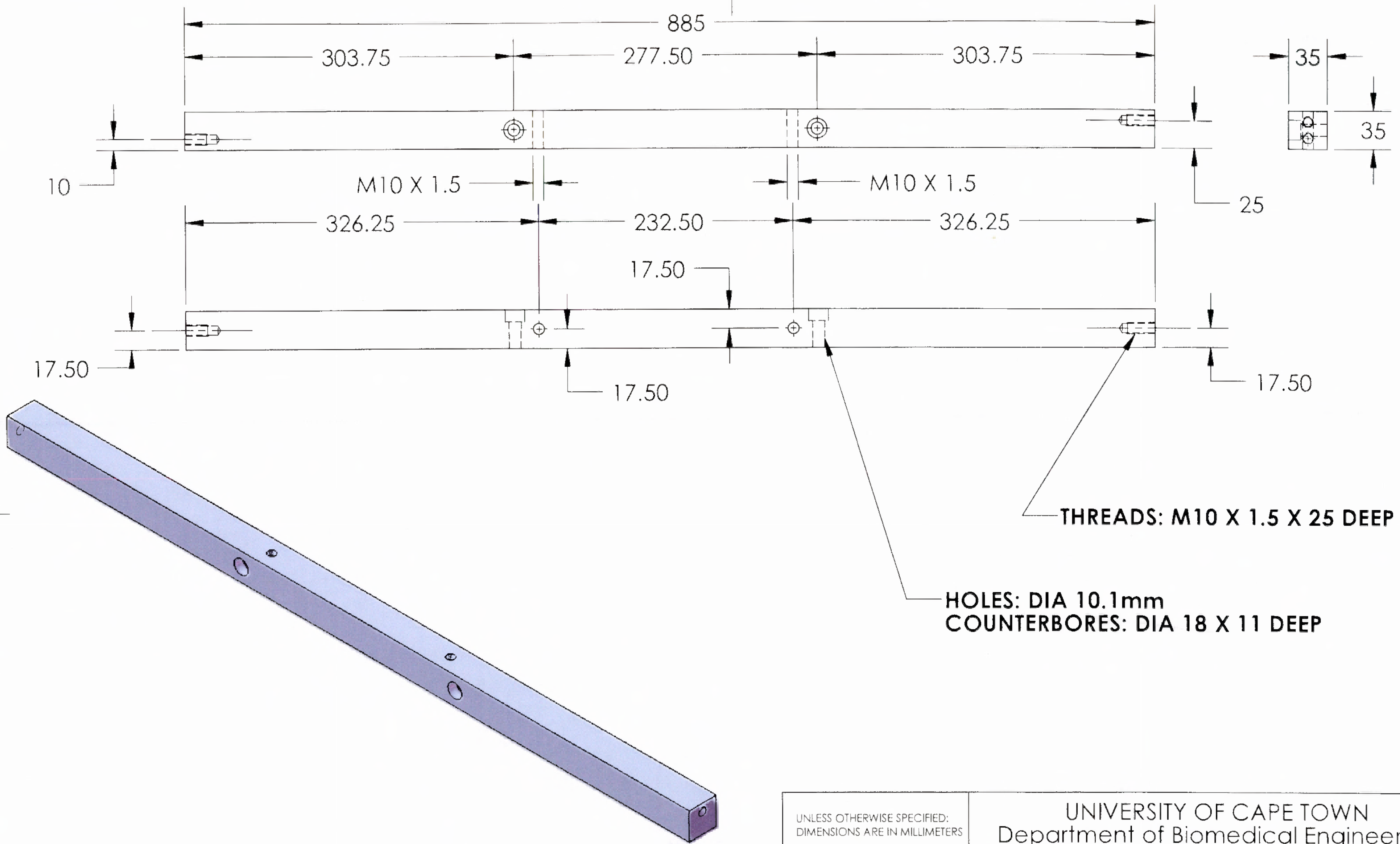
MATERIAL:
COLD ROLLED STEEL

DWG NO.
19

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		12/01/08
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: COLD ROLLED STEEL

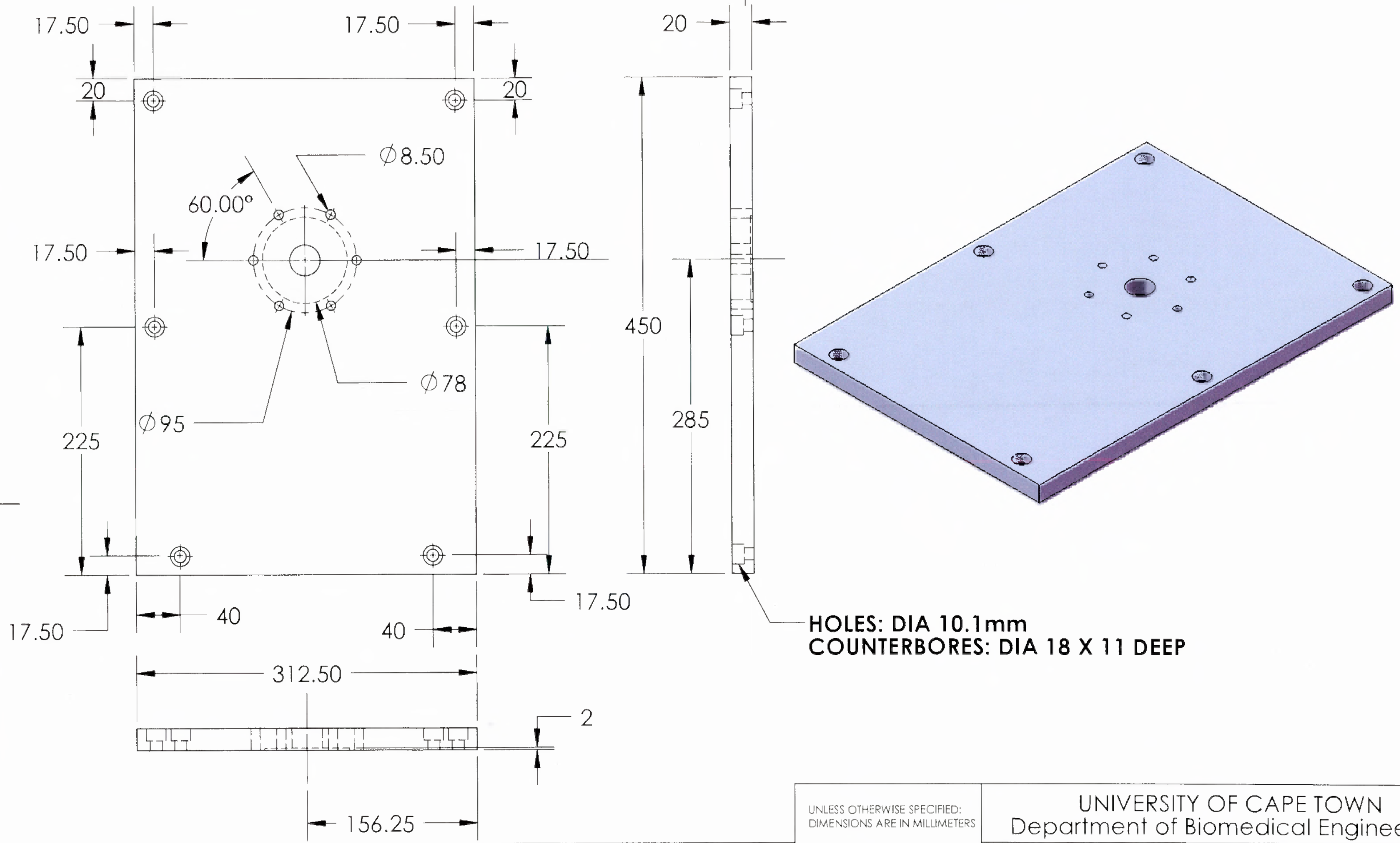
TITLE: **BEAM 20**

DWG NO. **20**

A4

SCALE:1:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
LINEAR: 0.1mm
ANGULAR: 0.1 deg

UNIVERSITY OF CAPE TOWN
Department of Biomedical Engineering

	NAME	SIGNATURE	DATE
DRAWN	Neil Campbell		11/02/08
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

AXIAL MOUNTING PLATE

MATERIAL:

COLD ROLLED STEEL

DWG NO.

21

A4

SCALE:1:5

SHEET 1 OF 1

10.3 APPENDIX 3 – MOOG HYDRAULIC SYSTEM DATA

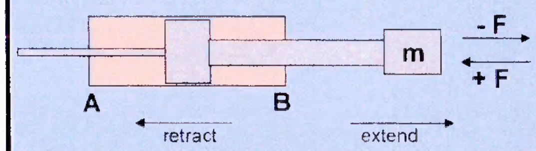
10.3.1 Flexion-Extension Actuator Valve Selection

MOOG: Sizing of 4/3 servo/proportional valves for position and velocity control

Input of drive data

specified extend velocity	0.325	m/s
specified retract velocity	0.325	m/s
piston diameter	40	mm
rod diameter A-side	25	mm
rod diameter B-side	25	mm
+/- max. external force extend *	5,000	N
+/- max. external force retract *	-5,000	N
moving mass (inertia)	10	kg
specified extend acceleration time	10	ms
specified retract acceleration time	10	ms

* sign of the force + / - see drawing



calculation

piston area =	12.57	cm²
working area A-side =	7.66	cm²
working area B-side =	7.66	cm²
cylinder area ratio =	1.00	

	extend	retract	
flow QA max =	14.9	14.9	l/min
flow QB max =	14.9	14.9	l/min
load pressure pA =	65	0	bar
load pressure pB =	0	65	bar
specified acceleration =	33	33	m/s²
mass acceleration force =	325	325	N
acceleration pressure =	4	4	bar
deceleration pressure =	4	4	bar
max. deceleration force =	4,675	-4,675	N

Select a suitable valve and go to the next working sheet

language, Sprache, langue, idioma, lingua, linguagem >> en

Customer:	UCT
Project:	Knee simulator, Flexion
Date:	22/ June 2007

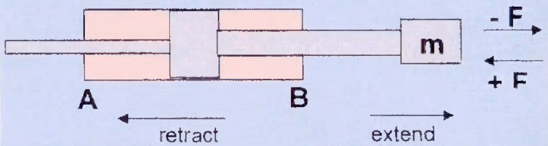
Moog GmbH

work sheet 1 of 4

MOOG: 2. Pressure Calculation for Cylinders with 4/3 Servo/Proportional Valves

Input of drive data

rated flow metering edge P-A	20.0	l/min
rated flow metering edge P-B	20.0	l/min
rated flow metering edge A-T	20.0	l/min
rated flow metering edge B-T	20.0	l/min
rated pressure drop/land ΔpN	70	bar
pressure at P-port	210	bar
pressure drop in blocks, pipes etc.	5	bar
valve size	6	
piston diameter	40	mm
rod diameter A-side	25	mm
rod diameter B-side	25	mm
+/- max. external force extend *	5,000	N
+/- max. external force retract *	-5,000	N



ZEB

calculation

spool area ratio BT/PA =	1.00	
spool area ratio PB/AT =	1.00	
working area A-side =	7.66	cm^2
working area B-side =	7.66	cm^2
cylinder area ratio =	1.00	

pressures in cylinder	v = constant		dynamic		
	extend	retract	extend	retract	
Δp_{PA} =	70		72		bar
Δp_{BT} =	70		72		bar
Δp_{PB} =		70		72	bar
Δp_{AT} =		70		72	bar
p_A =	135	70	133	72	bar
p_B =	70	135	72	133	bar

at fully open valve vmax =	0.435	0.435	m/s
valve opening for v =	75%	75%	
at fully open valve QA =	20.0	20.0	l/min
at fully open valve QB =	20.0	20.0	l/min
Result :			

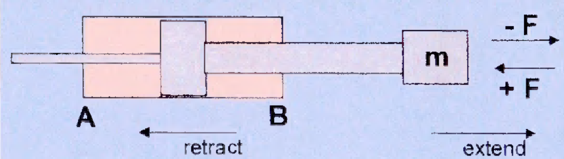
Customer: UCT
Project: Knee simulator, Flexion
Date: 22/ June 2007

Moog GmbH

work sheet 2 of 4

MOOG: 3. Calculation of Cylinder Dynamics

Input of drive data		
cylinder stroke	80	mm
pipe length side A	40	mm
pipe length side B	40	mm
hose length side A	0	mm
hose length side B	0	mm
fluid velocity in pipe A and B	10	m/s
internal diameter of pipe/hose side A	8	mm
internal diameter of pipe/hose side B	8	mm
equivalent fluid bulk modulus	9,000	bar



calculation		
piston area =	12.57	cm^2
working area A-side =	7.66	cm^2
working area B-side =	7.66	cm^2
calculated internal diameter of pipe side A =	4	mm
calculated internal diameter of pipe side B =	4	mm
equivalent trapped volume in pipe A-side =	2.01	cm^3
equivalent trapped volume in pipe B-side =	2.01	cm^3
position of minimum stiffness =	40.0	mm
minimum stiffness =	3.23E+07	N/m
natural frequency of pipe A =	4094.2	Hz
natural frequency of pipe B =	4094.2	Hz
min. hydraulic natural frequency of system =	1764	sec^{-1}
min. hydraulic natural frequency of system in Hz =	280.7	Hz

Result:

The drive is well controllable !

Customer:	**UCT**
Project:	**Knee simulator, Flexion**
Date:	**22/ June 2007**

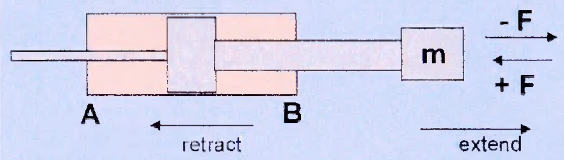
Moog GmbH

work sheet 3 of 4

MOOG: 4. Closed Loop Position Control System with simple P-Controller

Input of drive data

natural frequency of the valve	100 Hz
rated pilot pressure of the valve	0 bar
pilot pressure of pilot operated valve	210 bar
temperature drift of the valve	1.0 %
pressure gain of valve	3.0 %
load/actuator damping ratio	0.20
natural frequency of the cylinder	280.7 Hz
piston diameter	40 mm
rod diameter A-side	25 mm
rod diameter B-side	25 mm
moving mass (inertia)	10 kg



calculation

natural frequency of the valve at given pilot pressure =	100 Hz
position control system -3dB bandwidth =	26.19 Hz
possible loop gain =	165 sec^{-1}
time constant of the drive system =	6 ms
optimum acceleration and deceleration time =	18 ms
extend velocity error at 100% valve opening =	2.64 mm
retract velocity error at 100% valve opening =	2.64 mm
extend velocity error at selected speed =	1.98 mm
retract velocity error at selected speed =	1.98 mm
static error caused by external force =	0.031 mm
static error caused by valve drift =	0.026 mm
total static error =	0.057 mm
P gain of controller =	30.3 V/V

Note :

Improved control results can be achieved with more complex control algorithms. The physical limits of the drive cannot be exceeded even with the best possible controller!

Customer: UCT
Project: Knee simulator, Flexion
Date: 22/ June 2007

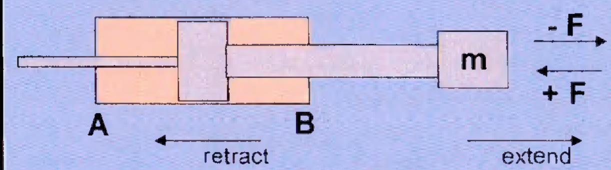
Moog GmbH

work sheet 4 of 4

MOOG: 3. Calculation of Cylinder Dynamics

Input of drive data

cylinder stroke	50	mm
pipe length side A	40	mm
pipe length side B	40	mm
hose length side A	0	mm
hose length side B	0	mm
fluid velocity in pipe A and B	10	m/s
internal diameter of pipe/hose side A	10	mm
internal diameter of pipe/hose side B	10	mm
equivalent fluid bulk modulus	9,000	bar



calculation

piston area =	12.57 cm²
working area A-side =	7.66 cm²
working area B-side =	7.66 cm²
calculated internal diameter of pipe side A =	4 mm
calculated internal diameter of pipe side B =	4 mm
equivalent trapped volume in pipe A-side =	3.14 cm³
equivalent trapped volume in pipe B-side =	3.14 cm³
position of minimum stiffness =	25.0 mm
minimum stiffness =	4.74E+07 N/m
natural frequency of pipe A =	4094.2 Hz
natural frequency of pipe B =	4094.2 Hz
min. hydraulic natural frequency of system =	2149 sec^{-1}
min. hydraulic natural frequency of system in Hz =	342.1 Hz

Result:

The drive is well controllable !

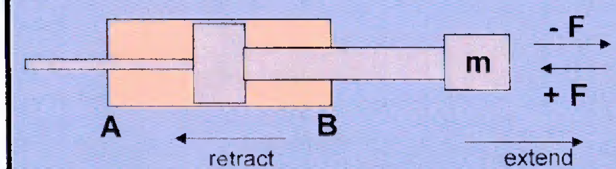
Customer:	UCT
Project:	**Knee simulator, Axial force**
Date:	**16/ April 2007**

Moog GmbH

work sheet 3 of 4

MOOG: 4. Closed Loop Position Control System with simple P-Controller

Input of drive data		calculation	
natural frequency of the valve	100 Hz	natural frequency of the valve at given pilot pressure =	100 Hz
rated pilot pressure of the valve	0 bar	position control system -3dB bandwidth =	27.96 Hz
pilot pressure of pilot operated valve	210 bar	possible loop gain =	176 sec^{-1}
temperature drift of the valve	2.0 %	time constant of the drive system =	6 ms
pressure gain of valve	3.0 %	optimum acceleration and deceleration time =	17 ms
load/actuator damping ratio	0.20	extend velocity error at 100% valve opening =	1.37 mm
natural frequency of the cylinder	342.1 Hz	retract velocity error at 100% valve opening =	1.37 mm
piston diameter	40 mm	extend velocity error at selected speed =	1.25 mm
rod diameter A-side	25 mm	retract velocity error at selected speed =	1.25 mm
rod diameter B-side	25 mm	static error caused by external force =	0.008 mm
moving mass (inertia)	10 kg	static error caused by valve drift =	0.027 mm
		total static error =	0.036 mm
		P gain of controller =	36.5 V/V



Note :

Improved control results can be achieved with more complex control algorithms. The physical limits of the drive cannot be exceeded even with the best possible controller!

Customer:	UCT
Project:	Knee simulator, Axial force
Date:	16/ April 2007

Moog GmbH

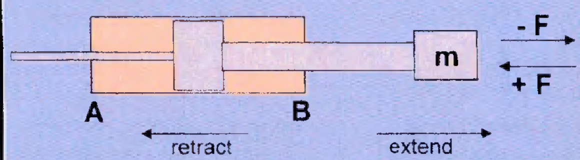
work sheet 4 of 4

MOOG: Sizing of 4/3 servo/proportional valves for position and velocity control

Input of drive data

specified extend velocity	0.325	m/s
specified retract velocity	0.325	m/s
piston diameter	40	mm
rod diameter A-side	25	mm
rod diameter B-side	25	mm
+/- max. external force extend *	5,000	N
+/- max. external force retract *	5,000	N
moving mass (inertia)	10	kg
specified extend acceleration time	10	ms
specified retract acceleration time	10	ms

* sign of the force + / - see drawing



calculation

piston area =	12.57	cm²
working area A-side =	7.66	cm²
working area B-side =	7.66	cm²
cylinder area ratio =	1.00	

	extend	retract	
flow QA max =	14.9	14.9	l/min
flow QB max =	14.9	14.9	l/min
load pressure pA =	65	65	bar
load pressure pB =	0	0	bar
specified acceleration =	33	33	m/s²
mass acceleration force =	325	325	N
acceleration pressure =	4	4	bar
deceleration pressure =	4	4	bar
max. deceleration force =	4,675	5,325	N

Select a suitable valve and go to the next working sheet

language, Sprache, langue, idioma, lingua, linguagem >> en

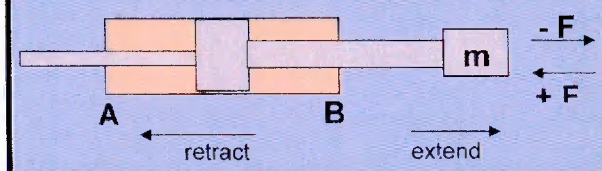
Customer:	**UCT**
Project:	**Knee simulator, Flexion**
Date:	**7/ March 2007**

Moog GmbH work sheet 1 of 4

MOOG: 2. Pressure Calculation for Cylinders with 4/3 Servo/Proportional Valves

Input of drive data

rated flow metering edge P-A	20.0 l/min
rated flow metering edge P-B	20.0 l/min
rated flow metering edge A-T	20.0 l/min
rated flow metering edge B-T	20.0 l/min
rated pressure drop/land ΔpN	70 bar
pressure at P-port	210 bar
pressure drop in blocks, pipes etc.	5 bar
valve size	6
piston diameter	40 mm
rod diameter A-side	25 mm
rod diameter B-side	25 mm
+/- max. external force extend *	5,000 N
+/- max. external force retract *	5,000 N



ZEB

calculation

spool area ratio BT/PA =	1.00
spool area ratio PB/AT =	1.00
working area A-side =	7.66 cm²
working area B-side =	7.66 cm²
cylinder area ratio =	1.00

pressures in cylinder	v = constant		dynamic		
	extend	retract	extend	retract	
Δp_{PA} =	70		72		bar
Δp_{BT} =	70		72		bar
Δp_{PB} =		135		137	bar
Δp_{AT} =		135		137	bar
p_A =	135	135	133	137	bar
p_B =	70	70	72	68	bar
at fully open valve vmax =	0.435	0.605	m/s		
valve opening for v =	75%	54%			
at fully open valve QA =	20.0	27.8	l/min		
at fully open valve QB =	20.0	27.8	l/min		

Result :

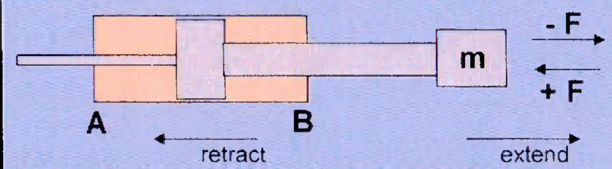
Customer: UCT
Project: Knee simulator, Flexion
Date: 7/ March 2007

Moog GmbH

MOOG: 3. Calculation of Cylinder Dynamics

Input of drive data

cylinder stroke	60	mm
pipe length side A	40	mm
pipe length side B	40	mm
hose length side A	0	mm
hose length side B	0	mm
fluid velocity in pipe A and B	10	m/s
internal diameter of pipe/hose side A	8	mm
internal diameter of pipe/hose side B	8	mm
equivalent fluid bulk modulus	9,000	bar



calculation

piston area =	12.57 cm²
working area A-side =	7.66 cm²
working area B-side =	7.66 cm²
calculated internal diameter of pipe side A =	4 mm
calculated internal diameter of pipe side B =	4 mm
equivalent trapped volume in pipe A-side =	2.01 cm³
equivalent trapped volume in pipe B-side =	2.01 cm³
position of minimum stiffness =	30.0 mm
minimum stiffness =	4.22E+07 N/m
natural frequency of pipe A =	4094.2 Hz
natural frequency of pipe B =	4094.2 Hz
min. hydraulic natural frequency of system =	2016 sec^{-1}
min. hydraulic natural frequency of system in Hz =	320.8 Hz

Result:

The drive is well controllable !

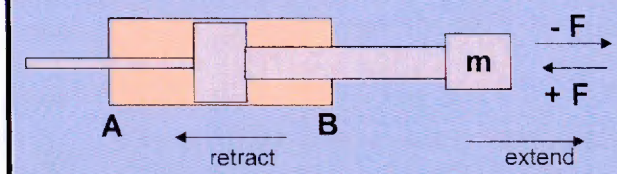
Customer:	**UCT**
Project:	**Knee simulator, Flexion**
Date:	**7/ March 2007**

Moog GmbH

work sheet 3 of 4

MOOG: 4. Closed Loop Position Control System with simple P-Controller

Input of drive data		calculation	
natural frequency of the valve	100 Hz	natural frequency of the valve at given pilot pressure =	100 Hz
rated pilot pressure of the valve	0 bar	position control system -3dB bandwidth =	27.43 Hz
pilot pressure of pilot operated valve	210 bar	possible loop gain =	172 sec^{-1}
temperature drift of the valve	1.0 %	time constant of the drive system =	6 ms
pressure gain of valve	3.0 %	optimum acceleration and deceleration time =	17 ms
load/actuator damping ratio	0.20	extend velocity error at 100% valve opening =	2.52 mm
natural frequency of the cylinder	320.8 Hz	retract velocity error at 100% valve opening =	3.51 mm
piston diameter	40 mm	extend velocity error at selected speed =	1.89 mm
rod diameter A-side	25 mm	retract velocity error at selected speed =	1.89 mm
rod diameter B-side	25 mm	static error caused by external force =	0.041 mm
moving mass (inertia)	10 kg	static error caused by valve drift =	0.035 mm
		total static error =	0.076 mm
		P gain of controller =	23.8 V/V



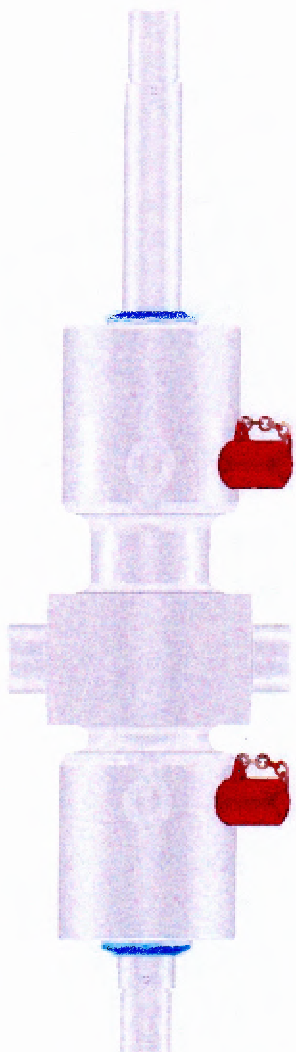
Note :

Improved control results can be achieved with more complex control algorithms. The physical limits of the drive cannot be exceeded even with the best possible controller!

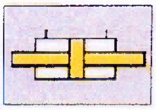
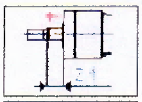
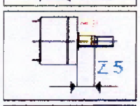
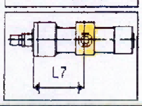
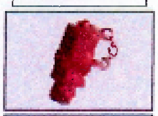
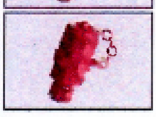
Customer: UCT
Project: Knee simulator, Flexion
Date: 7/ March 2007

10.4 APPENDIX 4 – HANCHEN HYDRAULIC CYLINDERS

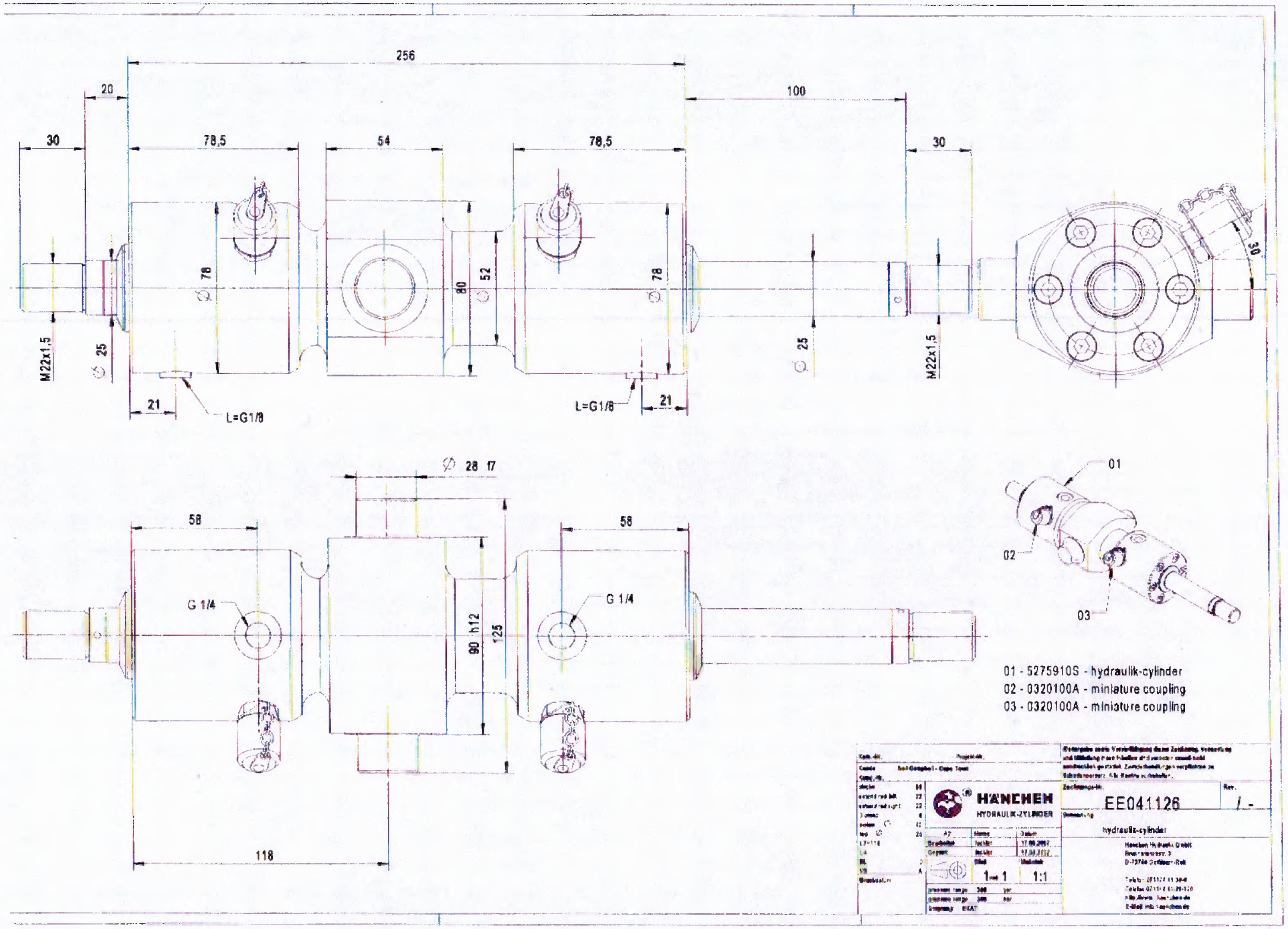
10.4.1 Hanchen 80mm Stroke Hydraulic Actuator



Field service personnel
Herbert Hänchen GmbH & Co.KG
Hydraulik-Zylinder
(07 11) 4 41 39-0

Position		***Description***	***Technical Data***	***Order data***
1		Hydraulic cylinder range 300 double rod cylinder without cushioning Type 300 15008-01	Ø piston = 40 mm Ø rod = 25 mm * Weight = 8,47 kg quality = Servocop® pressure range (bar) = 300 test pressure (bar) = 450	**5275910S** Stroke = 80 mm
			Extend rod left Z1 = 20 mm	= 22 mm
			Extend rod right Z5 = 100 mm	= 22 mm
				L7 = 118 mm
2		"Minimess" miniature coupling	venting system = M 8x1	**0320100A**
3		"Minimess" miniature coupling	venting system = M 8x1	**0320100A**

*** Weight:** 8,60 kg


256
20
100
30
78,5
54
78,5
30
78
80
52
78
M22x1,5
∅ 25
∅ 25
M22x1,5
21
L=G1/8
L=G1/8
21
∅ 28 f7
58
58
G 1/4
G 1/4
90 h12
125
118
01
02
03
01 - 5275910S - hydraulik-cylinder
02 - 0320100A - miniature coupling
03 - 0320100A - miniature coupling
HÄNCHEN
HYDRAULIK-ZYLINDER
EE041126
hydraulik-cylinder
1:1

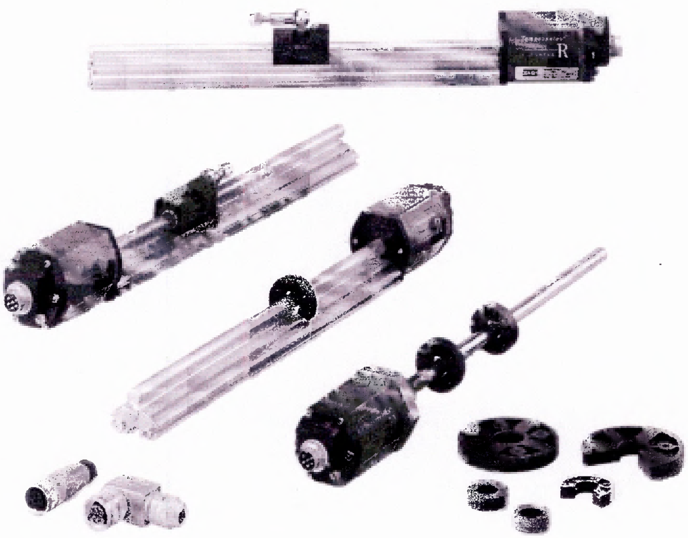
10.5 APPENDIX 5 – MAGNETOSTRICTIVE POSITION SENSORS

MTS SENSORS GROUP

Magnetostrictive Position Sensors

Temposonics® R-Series

Analog



Profile + Rod Models RP/RH

- Linear, Absolute Measurement
- Contactless Sensing with Highest Durability
- Rugged Industrial Sensor, EMC shielded and CE certified
- Superior Accuracy: Linearity Tolerance: better 0,02 %, Repeatability: 0,001 %
- Direct Analog Output (V/mA) for Displacement and Velocity
- Measuring Range: 50 - 7600 mm

Temposonics R-Series, *Analog*

Sensor Style, Dimensions

Measuring Principle

Temposonics are highly repeatable position sensors for measuring linear movements. Their absolute nature provides instant recognition of machine position after power loss recovery. Using the unique **magnetostrictive principle**, which MTS pioneered, the sensor precisely senses the position of an external magnet through the housing wall to measure displacements with a high degree of resolution. This time-based method with up to 10'000 measurements/second provides sensors of highest accuracy. The non-contact sensing eliminates the wear, noise and erroneous signal problems and guarantees the best durability.

Temposonics-RP

- Stable Profile
- Active Stroke 50 - 5000 mm

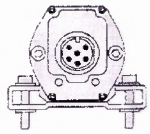
Temposonics-RP. A robust aluminum profile is designed for the machine building industry in harshest industrial environments. Position measurement is contactless via different versions of permanent magnets.

1. A captive sliding magnet running in profile housing rails. Connection with the mobile machine part is via a ball jointed arm.

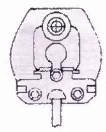
2. The removable floating magnet, mounted directly on the moving machine part, travels over the profile at a low distance.

Profile mounting

1. Sliding mounting feet



2. T-slot nut M5 in base channel

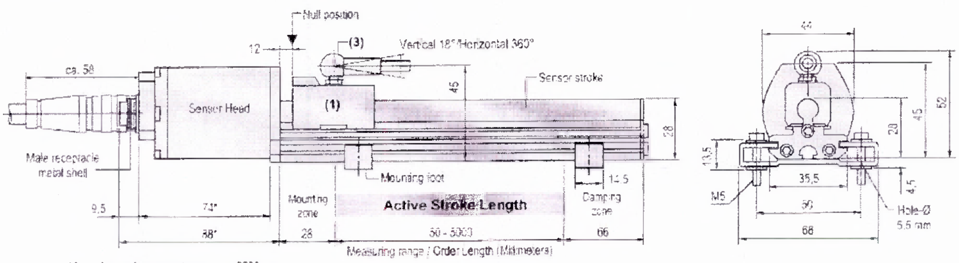


Temposonics-RH

- High Pressure Rod
- Active Stroke 50 - 7600 mm

Temposonics-RH. The pressure proof stainless steel sensor is designed for direct mounting in hydraulic cylinders. This version is easy to mount and highly insensitive to contamination. Position measurement is contactless via a permanent magnet (closed or open ring). It can also be mounted externally in many other industrial automation devices.

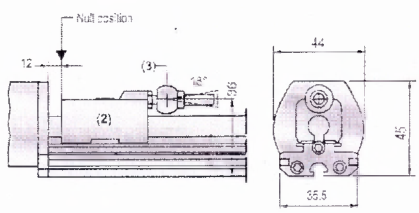
1) Temposonics Style RP-S..



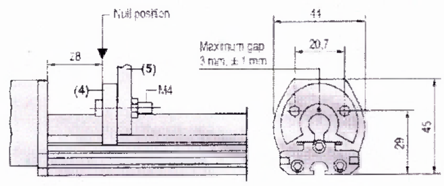
* 10 mm longer for measuring range > 3500 mm

(1) Captive sliding magnet style S
(2) Captive sliding magnet style V
(3) Ball jointed arm (M5 thread)
(4) Floating magnet style M (open ring)
(5) Nonferrous support, screws

2) Temposonics Style RP-V..



3) Temposonics Style RP-M..



Technical alterations reserved

2

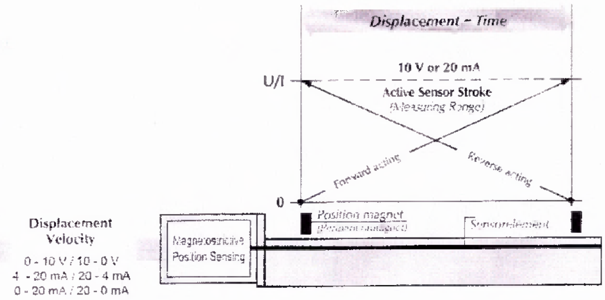
R-Series, *Analog*

MTS
SENSORS GROUP

Function

Output

Analog R-Series sensors feature 16 bit resolution via a D/A converter and its output is updated at high speed. The sensing system provides direct analog outputs including voltage and current. Dual outputs of a common type (i.e. displacement or velocity) are standard with each sensor. Voltage and current outputs allow **100 % adjustments** of zero and span setpoints. Since the outputs are direct, no signal conditioning electronics are needed when interfacing with controllers or meters.



Smart Analog Sensor

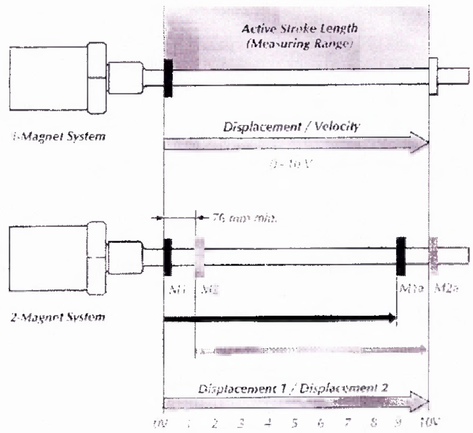
Analog R-Series sensors will support one or two position magnets.

1-Magnet System
provides one displacement output over the entire active range of the sensor's stroke length and one velocity output.

2-Magnet System
provides two identical displacement outputs; a separate output is provided for each of two magnets positioned along the sensor length.
Note: A gap of at least 76 mm must be maintained between the magnets. Therefore, the output range of each magnet equals the active stroke length of the sensor less 76 mm. Minimum measuring range for dual magnet system is 150 mm.

Programming
Using two pushbuttons inside the sensorhead, the operation modes and the start and end positions of the ordered output, can be programmed at any setpoints inside the active measuring range.

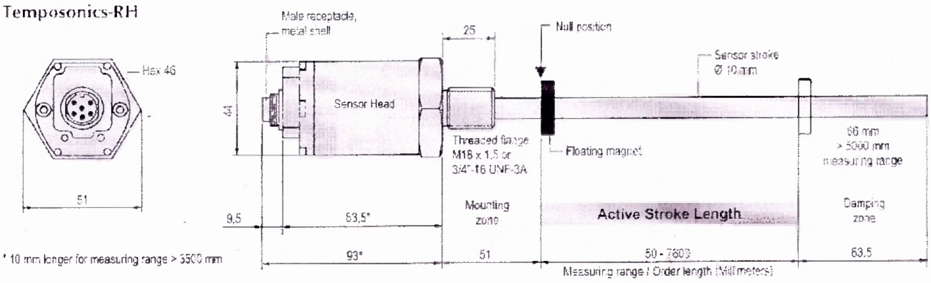
Note:
Temposonics R-Series sensors are supplied with either Vdc or mA output from the factory and cannot be reprogrammed in the field.



Example: Output 0 - 10V

- *M1 = Magnet 1 / Start point (0 V)*
- *M1a = Magnet 1 / End point*
- *M2 = Magnet 2 / Start point*
- *M2a = Magnet 2 / End point (10 V)*

Temposonics-RH



* 10 mm longer for measuring range > 3500 mm

3

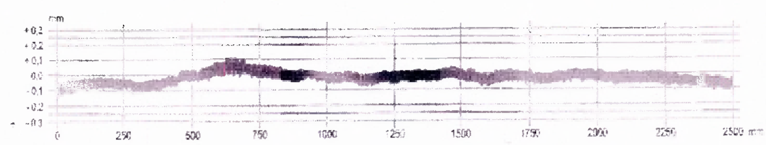
Temposonics R-Series, *Analog*

Product Specifications

General	Measured Variables	Displacement, Velocity
	Measuring Range	**Profile:** 50 - 5000 mm / **Rod:** 50 - 7600 mm
	Output	**Voltage:** 0 - 10 Vdc or 10 - 0 Vdc - Minimum load: ≥ 5 kΩ **Current:** 4(0) - 20 mA or 20 - 4(0) mA - Minimum load: 0 Ω / Maximum load: 500 Ω
	Position Measurement	
	- Adjustment of NULL and SPAN	100 % of measuring range (min. range 25 mm)
	- Resolution	16 bit; 0,0015 % (minimum 10 um)
	- Linearity Tolerance, uncorrected	< ± 0,02 % F.S. (minimum ± 50 µm)
	- Repeatability	< ± 0,001 % F.S. (minimum ± 2,5 µm)
	- Hysteresis	< 4 µm
	- Update Frequency	1000 Hz typical at output (10 kHz internal)
	Velocity Measurement	
	- Range	0,1 - 10 m/s
	- Velocity Deviation	< 2 %
	- Output Delay	2 - 10 ms
	Input Voltage	24 Vdc (+20 % / -15 %)
	Current Drain	100 mA typical
	Ripple	< 1 % s-s
	Electric Strength	500 V (DC ground to machine ground)
	Operating Temperature	-40° C ... +75° C
	Temperature Coefficient	< 40 ppm/° C
	Dew Point, Humidity	90% rel. humidity, no condensation
	Mounting Position, Sensor	Any orientation
	Magnet Speed	Any
	Connection Type	6 pin connector or integral cable output
	EMC-Test	DIN IEC 801-4 / Type 4 / CE qualified
	Shock Rating	100 g (Single hit) / IEC-Standard 68-2-27
	Vibration Rating	5 g / 10 - 150 Hz / IEC-Standard 68-2-6
Profile Model	Electronic Head	Aluminum diecasting housing
	Sensor Stroke	Aluminum profile
	Sealing	IP 65*
	Installation	Adjustable mounting feet or T-slot nut M5 in base channel
	Magnet Type	Captive sliding magnet, Floating magnet
Rod Model	Electronic Head	Aluminum diecasting housing
	Sensor Rod with Flange	Stainless steel
	Pressure Rating	350 bar, 530 bar peak pressure
	Sealing	IP 67*
	Installation	Threaded flange M18 x 1,5 or 3/4"-16 UNF-3A
	Magnet Type	GF plastic with permanent magnets (Ring)

**In the case of sensors with receptacle connection type, the IP rating is valid only if the mating cable connector is correctly fitted.*

Linearity Protocol



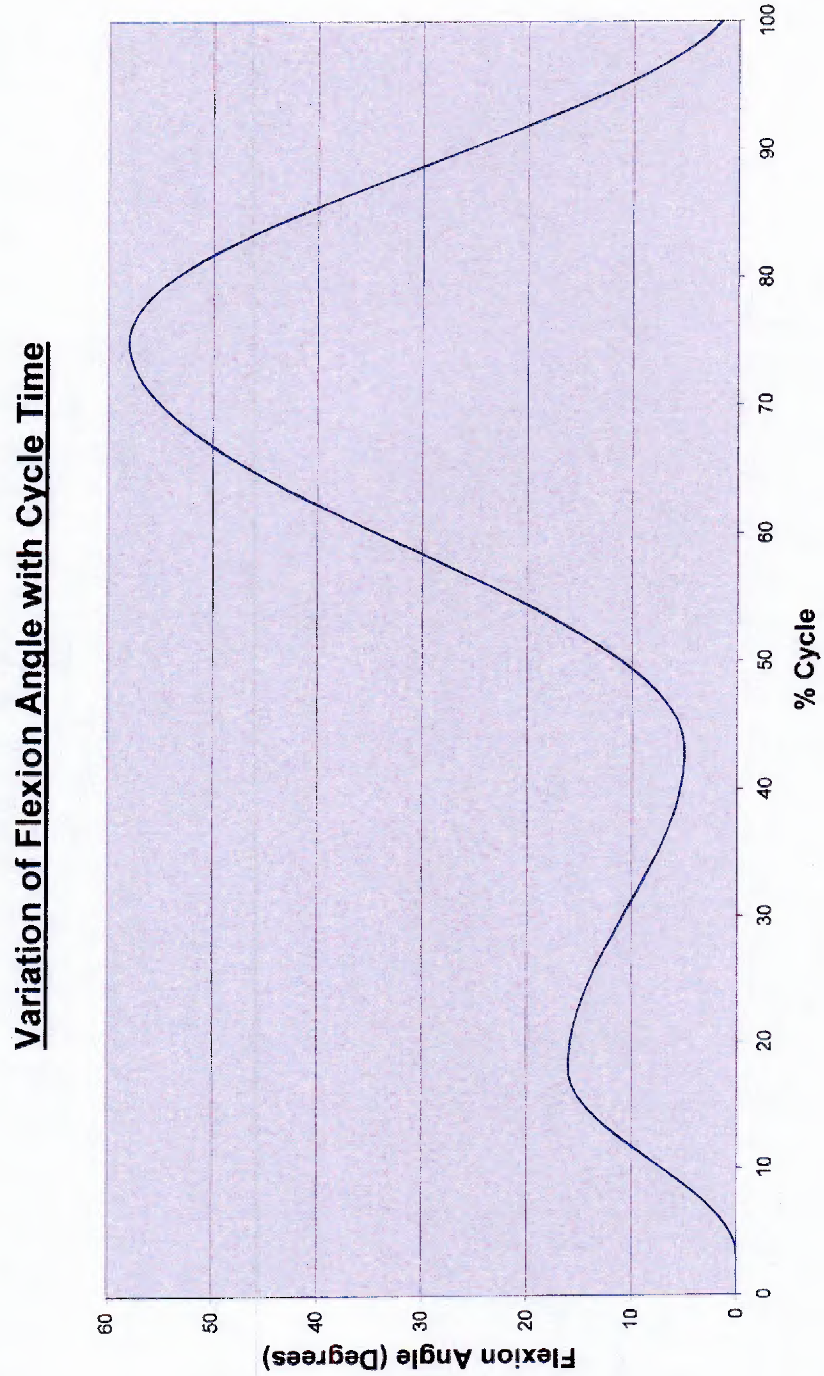
Example:
Sensortype RP, Stroke Length 2500 mm
Tolerance, allowed: ± 0,25 mm
Tolerance, measured: ± 0,116 mm, uncorrected

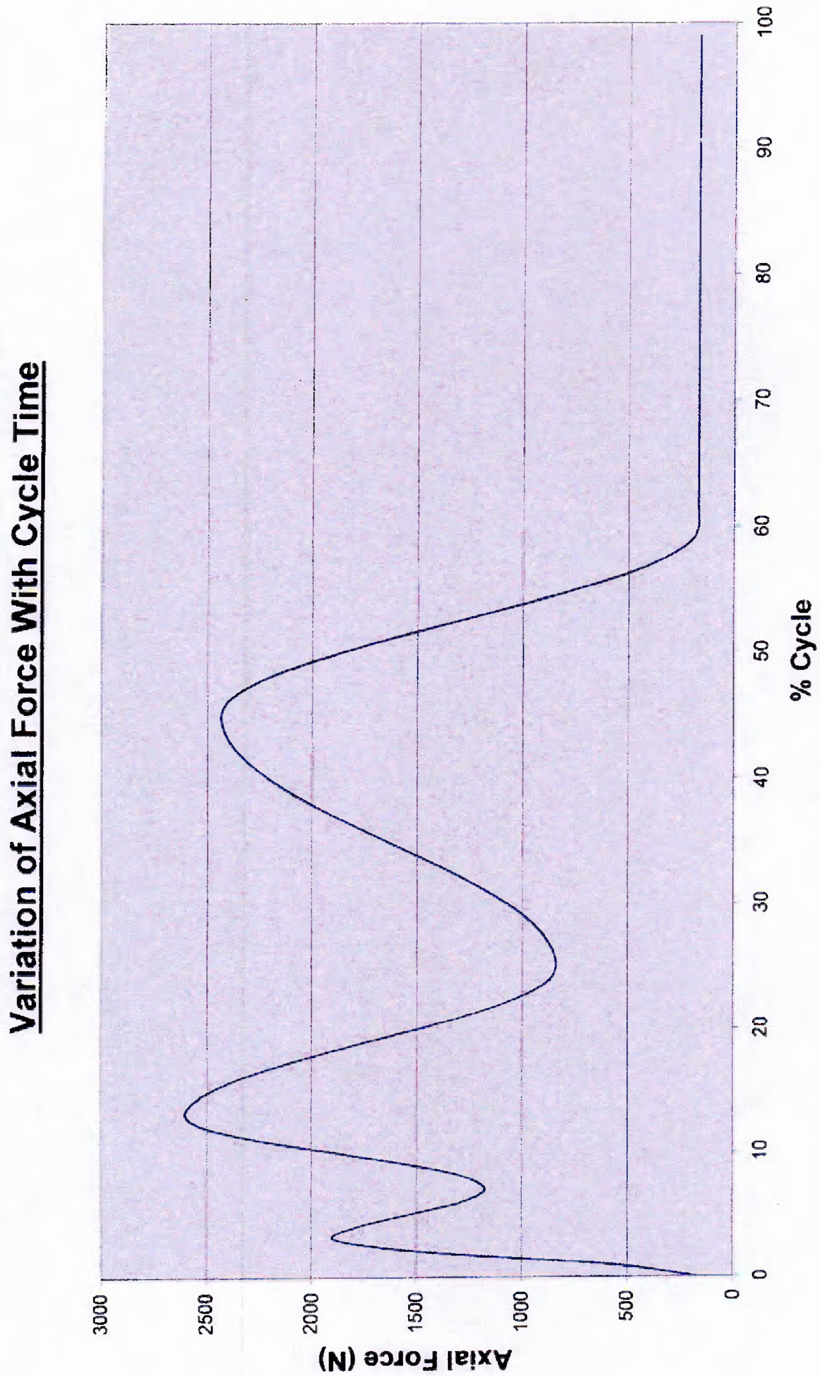
10.6 APPENDIX 6 - ISO 14243-3 MOTION PROFILE DATA

ISO 14243-3 MOTION PROFILE DATA

Percentage of Time Cycle %	Flexion/Extension Angle Degrees	Axial Force N	AP Motion mm	Tibial Int/ext Rotation Degrees
0	0.00	167.60	0.00	-1.57
1	0.17	597.50	-0.04	-1.87
2	0.69	1457.40	-0.21	-1.87
3	1.53	1887.30	-0.49	-1.70
4	2.65	1782.90	-0.84	-1.36
5	4.00	1530.90	-1.32	-0.54
6	5.53	1278.80	-1.79	-0.26
7	7.16	1174.60	-2.24	0.01
8	8.84	1270.10	-2.65	0.26
9	10.47	1530.90	-3.03	0.49
10	12.00	1887.30	-3.36	0.68
11	13.35	2243.60	-3.65	0.85
12	14.47	2504.50	-3.90	0.99
13	15.31	2600.00	-4.11	1.09
14	15.83	2570.00	-4.28	1.16
15	16.00	2482.00	-4.41	1.19
16	15.96	2342.00	-4.49	1.20
17	15.83	2159.50	-4.53	1.18
18	15.61	1947.10	-4.51	1.13
19	15.32	1719.10	-4.44	1.05
20	14.95	1491.10	-4.32	0.95
21	14.51	1278.60	-4.15	0.83
22	14.01	1096.20	-3.93	0.69
23	13.45	956.20	-3.66	0.54
24	12.84	868.20	-3.36	0.37
25	12.20	838.20	-3.02	0.20
26	11.53	848.00	-2.67	0.03
27	10.85	877.20	-2.31	-0.15
28	10.16	925.10	-1.94	-0.33
29	9.47	990.50	-1.60	-0.51
30	8.80	1071.80	-1.28	-0.67
31	8.16	1167.00	-0.99	-0.83
32	7.55	1273.70	-0.74	-0.98
33	6.99	1389.30	-0.55	-1.12
34	6.49	1511.10	-0.42	-1.24
35	6.05	1635.80	-0.35	-1.34
36	5.68	1760.60	-0.35	-1.43
37	5.39	1882.30	-0.35	-1.49
38	5.17	1998.00	-0.35	-1.54
39	5.04	2104.70	-0.35	-1.56
40	5.00	2199.90	-0.35	-1.57
41	5.13	2281.20	-0.41	-1.55
42	5.50	2346.60	-0.58	-1.51
43	6.14	2394.50	-0.89	-1.45
44	7.02	2423.70	-1.29	-1.36
45	8.13	2433.50	-1.81	-1.26
46	9.47	2408.80	-2.34	-1.14
47	11.02	2335.60	-2.87	-1.00
48	12.76	2217.10	-3.37	-0.84
49	14.69	2058.70	-3.83	-0.66
50	16.78	1867.00	-4.22	-0.48

Percentage of Time Cycle %	Flexion/Extension Angle Degrees	Axial Force N	AP Motion mm	Tibial int/ext Rotation Degrees
51	19.01	1650.70	-4.54	-0.28
52	21.36	1419.00	-4.80	-0.07
53	23.80	1182.20	-4.97	0.15
54	26.33	950.50	-5.08	0.38
55	28.90	734.10	-5.14	0.61
56	31.50	542.50	-5.17	0.85
57	34.10	384.00	-5.16	1.08
58	36.67	265.60	-5.12	1.32
59	39.19	192.40	-5.05	1.55
60	41.64	167.60	-4.96	1.78
61	44.00	167.60	-4.86	2.00
62	46.22	167.60	-4.74	2.22
63	48.31	167.60	-4.62	2.43
64	50.24	167.60	-4.49	2.64
65	51.98	167.60	-4.36	2.83
66	53.53	167.60	-4.24	3.02
67	54.87	167.60	-4.11	3.19
68	55.98	167.60	-3.99	3.36
69	56.86	167.60	-3.87	3.52
70	57.49	167.60	-3.75	3.67
71	57.87	167.60	-3.63	3.81
72	58.00	167.60	-3.51	3.94
73	57.82	167.60	-3.38	4.07
74	57.27	167.60	-3.25	4.20
75	56.37	167.60	-3.11	4.32
76	55.13	167.60	-2.96	4.44
77	53.56	167.60	-2.82	4.56
78	51.67	167.60	-2.67	4.68
79	49.51	167.60	-2.53	4.80
80	47.08	167.60	-2.38	4.92
81	44.42	167.60	-2.25	5.04
82	41.58	167.60	-2.12	5.16
83	38.58	167.60	-2.00	5.29
84	35.45	167.60	-1.89	5.40
85	32.25	167.60	-1.79	5.51
86	29.00	167.60	-1.70	5.60
87	25.75	167.60	-1.61	5.68
88	22.55	167.60	-1.51	5.72
89	19.42	167.60	-1.41	5.72
90	16.42	167.60	-1.30	5.66
91	13.57	167.60	-1.17	5.53
92	10.92	167.60	-1.03	5.30
93	8.49	167.60	-0.89	4.94
94	6.33	167.60	-0.74	4.44
95	4.44	167.60	-0.62	3.75
96	2.87	167.60	-0.51	2.83
97	1.63	167.60	-0.43	1.64
98	0.73	167.60	-0.34	0.13
99	0.18	167.60	0.00	-1.57


Variation of Flexion Angle with Cycle Time
Flexion Angle (Degrees)
0
10
20
30
40
50
60
% Cycle
0
10
20
30
40
50
60
70
80
90
100



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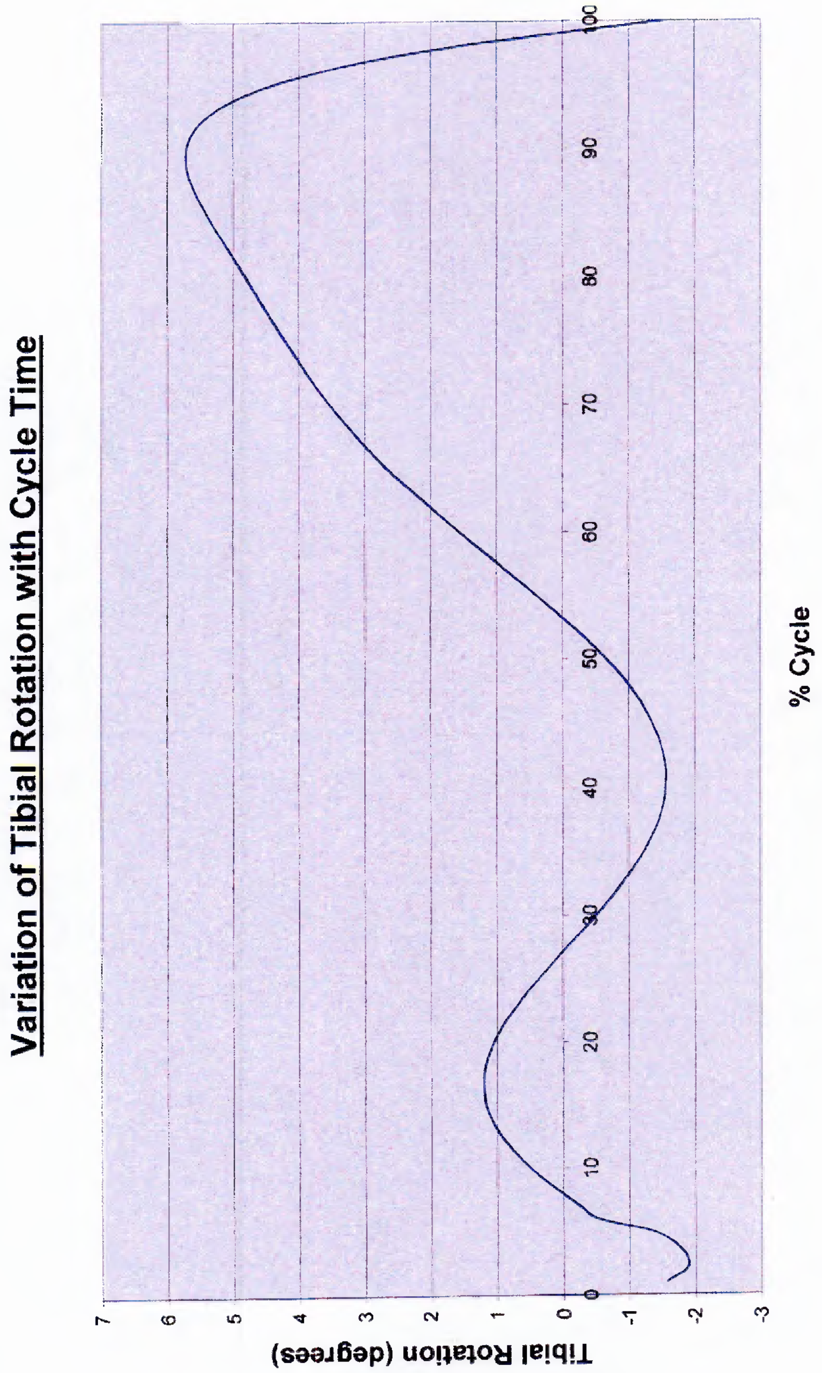

Department of Biomedical Engineering
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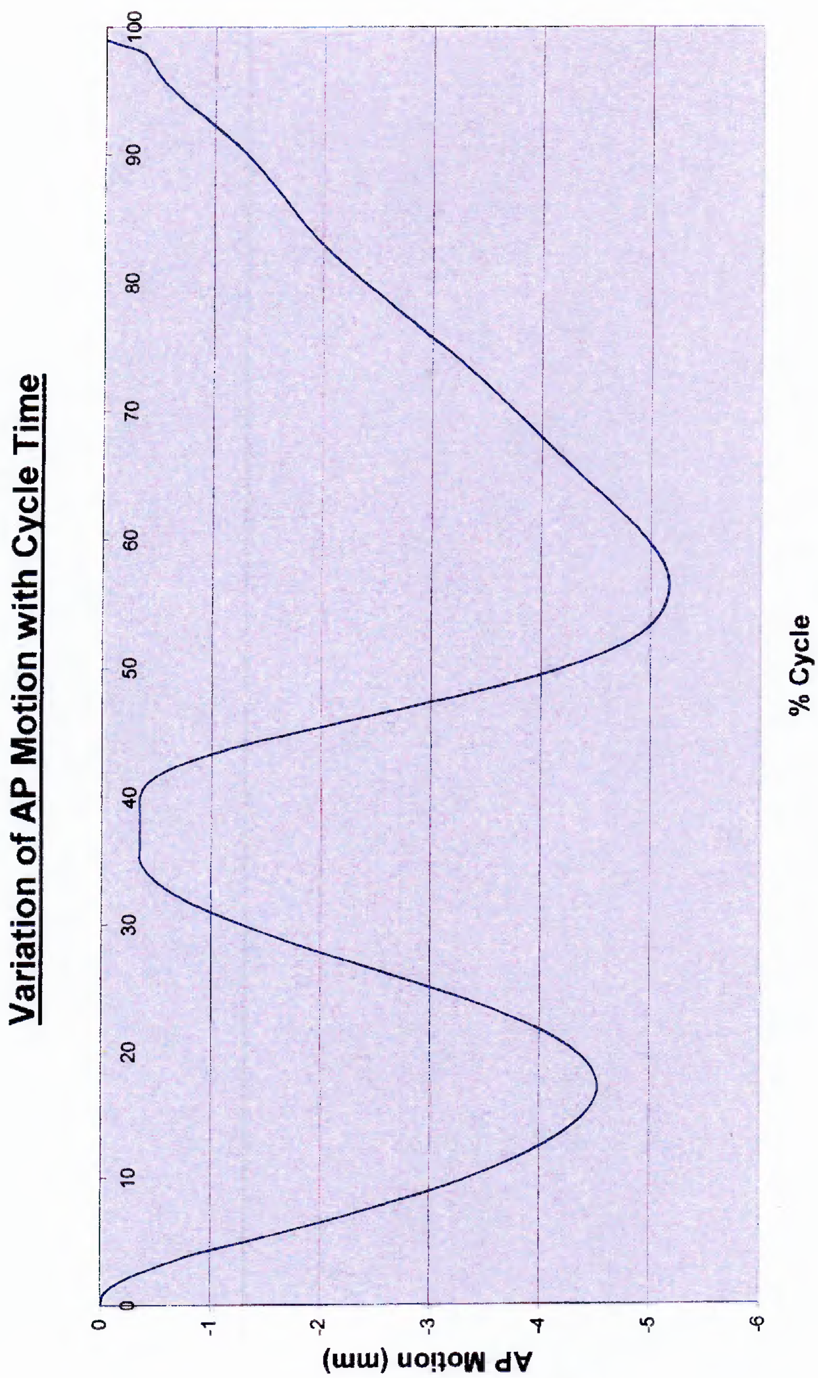

Variation of AP Motion with Cycle Time
AP Motion (mm)
0
-1
-2
-3
-4
-5
-6
0
10
20
30
40
50
60
70
80
90
100
% Cycle

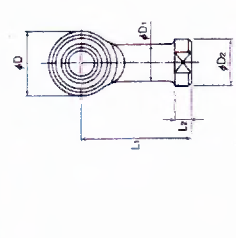
10.7 APPENDIX 7 – COMPONENT DATA SHEETS

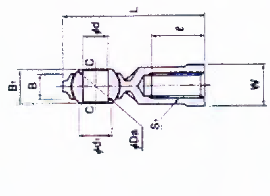
10.7.1 Spherical Rod End

s. Rod End

Model NHS-T

Lubrication-free Type





Unit: mm

Model No.	Outer dimensions Length L	Diameter D	Width B_1 $^{0}_{-0.1}$	Screw S JIS Class 2	Holder dimensions W $^{0}_{-0.2}$	D_1	D_2	B $^{+0.1}_{-0.4}$	L_1	L_2	ℓ	Spherical inner ring dimensions d H7	Ball diameter Da mm (inch)	d_1	C	Permissible tilt angle α_1°	α_2°	α_3°	Static applied load Radial C_0 N	Mass g
NHS 3T	27	12	6	M3X0.5	7	6.5	8	4.5	21	3	10	3	9.525 (3/8)	7.4	0.3	8	10	42	1570	8.5
NHS 4T	31	14	7	M4X0.7	8	8	9.5	5.3	24	4	12	4	10.319 (13/32)	7.6	0.3	9	11	35	2250	10
NHS 5T	35	18	8	M5X0.8	9	9	11	8	27	4	14	5	11.112 (7/16)	7.7	0.3	8	13	30	3920	16.5
NHS 6T	39	18	9	M6X1	11	18	13	6.75	30	5	14	6	12.7 (1/2)	9	0.3	9	13	30	5000	25
NHS 8T	47	22	12	M8X1.25	14	12.5	16	9	38	5	17	8	15.875 (5/8)	10.4	0.5	9	14	25	7450	43
NHS 10T	56	26	14	M10X1.5	17	15	19	10.5	43	8.5	21	10	19.05 (3/4)	12.9	0.5	8	14	25	9410	72
NHS 12T	65	30	16	M12X1.75	19	17.5	22	12	50	8.5	24	12	22.225 (7/8)	15.4	0.5	8	13	25	11000	107
NHS 14T	74	34	19	M14X2	22	20	25	13.5	57	8	27	14	25.4 (1)	16.9	0.7	10	16	24	15200	160
NHS 16T	83	38	21	M16X2	22	22	27	15	64	8	33	16	28.575 (1 1/8)	19.4	0.7	9	15	24	20200	210
NHS 18T	92	42	23	M18X1.5	27	25	31	16.5	71	10	36	18	31.75 (1 1/4)	21.9	0.7	9	15	24	25200	295
NHS 20T	100	46	25	M20X1.5	30	27.5	34	18	77	10	40	20	34.925 (1 3/8)	24.4	0.7	9	15	24	27800	380
NHS 22T	109	50	29	M22X1.5	32	30	37	20	84	12	43	22	38.1 (1 1/2)	26.8	0.7	10	15	23	35900	490

■Material

Holder: S35C (color chromate finish)
Spherical inner ring: SUJ2, 58 HRC or higher (hard chrome plated)
Bush: Self-lubricating synthetic resin

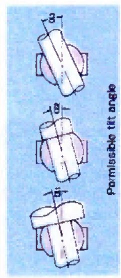
■Fitting with the Shaft

Service conditions	Dimensional tolerance of the shaft
Normal load	h7
Indeterminate load	p6

■Clearance

Unit: mm

Radial clearance	0.035 or less
Axial clearance	0.1 or less



Permissible tilt angle

■Initial Lubrication

This model can be used without lubrication. However, if desiring to provide initial lubrication, apply oil or grease to the spherical area.

■Identification of Left-hand Thread

If the female thread is left-hand, symbol "L" is added.

The actual product is marked with symbol "L" on the holder.

Model number coding

NHS10T L
1 2

1 Model number 2 Left-hand thread

Rod End S 13

s-12 THK

THK s-13

10.7.2 Axial Torsion Load Cell

The Leader in Force Measurement **interface**

Model 1216 Axial Torsion Load Cell

Why the Interface model 1216 Axial Torsion Load Cell is the best in class:

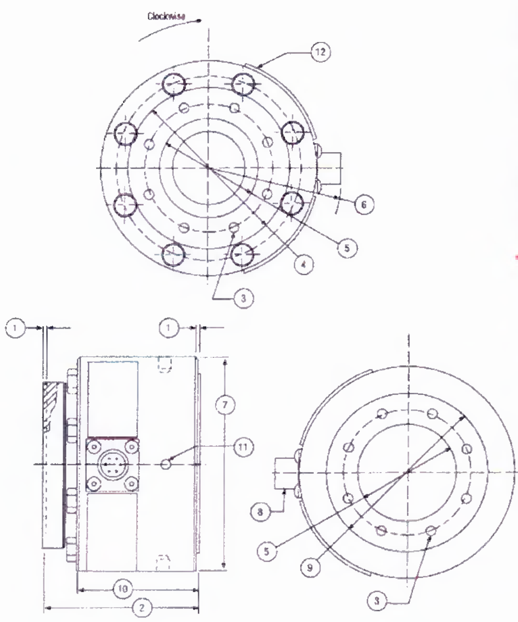
- Measures load and torque
- Minimal crosstalk
- Extraneous load resistance
- Fatigue rated

OPTIONS

Integral Cable
Compression Overload Protection
Connector Protector

SPECIFICATIONS

ACCURACY – (MAX ERROR)	Axial Bridge A	Torsion Bridge B
Nonlinearity–% FS	±0.04	±0.07
Hysteresis–% FS	±0.04	±0.05
Nonrepeatability–% RO	±0.02	±0.05
Creep, in 20 min–%	±0.025	±0.025
TEMPERATURE		
Compensated Range–°F	15 to 115	15 to 115
Compensated Range–°C	-10 to 45	-10 to 45
Operating Range–°F	-65 to 200	-65 to 200
Operating Range–°C	-55 to 90	-55 to 90
Effect on Output–%/100°F – MAX	±0.08	±0.08
Effect on Zero–% RO/100°F – MAX	±0.08	±0.08
ELECTRICAL		
Rated Output–mV/V (Nominal)	1.50	1.80
Zero Balance–% RO	±2.0	±2.0
Input Resistance–Ohms	700±7	700±7
Output Resistance–Ohms	700±7	700±7
Excitation Voltage – MAX	20 VDC	20 VDC
MECHANICAL		
Calibration	T&C	CW & CCW
Safe Overload–% CAP	±200	±200
Ultimate Overload–% CAP	±400	±400



DIMENSIONS

See Drawing	MODEL 1216	
	CAPACITY (lbf)/(inch-lb)	
	250/125, 500/250, 1K/500, 2K/1000	
	inch	mm
1	0.070	1.78
2	3.00	76.2
3	0.250-28 x 0.43 deep on a 2.600 B.C.	
4	3.20	81.3
5	2.000 + 0.002 / -0.000	
6	2.77	70.3
7	4.13	104.3
8	PT02E-12-8P	
9	3.200	81.28
10	2.33	59.2
11	0.25 0.25 deep	6.4 6.4 deep
12	Label	

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www.interfaceforce.com • Email: gen@interfaceforce.com • **ORDER TOLL-FREE 1-800-947-5598**

1216Axial_6E
12/06

10.7.3 Heating Immersion Circulator

Julabo

Product Data Sheet

ME Heating Immersion Circulator **Print Data Sheet**

Product Image

Order Information

Model: ME

Order no.: 9160000

Available mains power:
230V / 50-60Hz
100-115V / 50-60Hz

Similar Models

These models could also be interesting for you:

MC
MB
ED

Sales & Support:

+49 7823 51-190

Monday to Friday
7:30 am - 17:00 pm

JULABO Labortechnik GmbH
Eisenbahnstrasse 45
77960 Seelbach/Germany
Phone +49 7823 51-0
Fax +49 7823 2491
info@julabo.de
www.julabo.de

Description

Heating Immersion Circulator for any bath tanks up to 50 liters

JULABO Heating Immersion Circulators are available for various bath tanks up to a capacity of 50 litres and come equipped with a bath clamp that fits onto all tanks with a wall thickness up to 26 mm. This clamp allows fast and problem-free assembling for existing as well as new bath tanks. The immersion depth is 16.5 cm (adjustable down to 14.5 cm). The immersed parts are made of high-quality stainless steel or plastic. The pump set, which is available as an accessory, provides pumping to external systems for provision of external temperature tasks. An integrated cooling coil for cooling-water connection is also available as an accessory.

Advantages

- o VFD COMFORT DISPLAY, resolution 0.1 °C
- o Keypad for setpoints, warning/safety values and menu functions
- o PID3 cascade temperature control
- o ATC3 3-Point-Calibration
- o Pt100 External sensor connection for measurement and control
- o SMART PUMP, electronically adjustable pump stages
- o Early warning system for low liquid level (DBGM 203 06 059.8)
- o Adjustable high temperature cut-out, visible via display
- o RS232 interface for online communication
- o Integrated programmer for 10 program steps

Technical Specifications

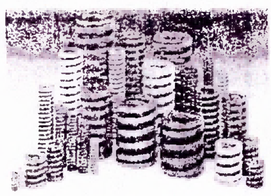
Working temperature range	20 ... 200 °C
Temperature control	PID, cascade
Temperature stability	±0.01 °C
Display	VFD
Display resolution	0.1 °C
Integrated programmer	available
Heater capacity	2000 W
Pump capacity	Pressure: 450 mbar Flow rate: 11-16 l/min
Digital interfaces	RS232
External Pt100 sensor connection	available
Dimensions (W x L x H)	13 x 15 x 33 cm
Weight	4 kg
Ambient temperature	5...40 °C
Classification according to DIN 12876-1	3 (FL)

Miscellaneous

Installation cooling coil and pump set for external applications available as accessory.

10.7.4 Rectangular Section Die Spring

RECTANGULAR SECTION DIE SPRINGS TO ISO 10243



These are rectangular wire section compression springs with rounded edges. For the same dimensions, each spring has four different load and stroke values, according to the series it belongs to. The four series are distinguished by an identifying colour. In order to identify a spring using the tables, all that is necessary is to specify the following three parameters: Load Series + External Diameter + Free Length.

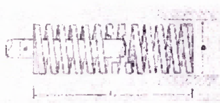
The code indicates the values of all three parameters in sequence:

Series:	1S	Green Colour	Light Load
	2S	Blue Colour	Medium Load
	3S	Red Colour	Heavy Load
	4S	Yellow Colour	Extra heavy Load

External Diameter: Diameter of the hole or housing that the spring will fit into.

Free length: Length of the spring at rest.

Spring rate: Load - in Newton - necessary to deflect the spring by 1 mm (1 Newton = 0.102 kg).



When selecting and using die springs, the following points are recommended:

- Select the lightest and longest springs that working conditions allow
- Operating travel must never exceed the maximum deflection indicated. Ensure this is so each time the die is sharpened.
- Pre-load each spring in the tool by at least 5% of the free length, with a minimum of 2mm
- Provide for an even base for each spring
- Provide proper guidance to avoid buckling

SERIES 1S • LIGHT LOAD - COLOUR GREEN

Hole Ø D - 10mm. Rod Ø d - 5mm
Wire section - 1.7mm x 1mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 30% N	mm	Max deflection 40% N	mm	Deflection to solid approx N	mm
1S10025	25	10.0	75.0	7.5	100	10.0	130	13
1S10032	32	8.5	81.6	9.6	109	12.8	136	16
1S10038	38	6.8	77.5	11.4	103	15.2	136	20
1S10045	44	6.0	79.2	13.2	106	17.6	144	24
1S10050	51	5.0	76.5	15.3	102	20.4	135	27
1S10065	64	4.3	82.6	19.2	110	25.6	151	35
1S10075	76	3.2	73.0	22.8	97.3	30.4	125	39
1S10303	305	1.1	101	91.5	134	122	169	154

Continued...

Continued

Hole Ø D - 12.5mm. Rod Ø d - 6.3mm
Wire section - 2.4mm x 1.25mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 30% N	mm	Max deflection 40% N	mm	Deflection to solid approx N	mm
1S13025	25	17.9	134	7.5	179	10.0	233	13
1S13032	32	16.4	157	9.6	210	12.8	279	17
1S13038	38	13.6	155	11.4	207	15.2	286	21
1S13045	44	12.1	160	13.2	213	17.6	315	26
1S13050	51	11.4	174	15.3	233	20.4	331	29
1S13065	64	9.3	179	19.2	238	25.6	344	37
1S13075	76	7.1	162	22.8	216	30.4	298	42
1S13090	89	5.4	144	26.7	192	35.6	270	50
1S13303	305	1.4	128	91.5	171	122	227	162

Hole Ø D - 16mm. Rod Ø d - 8mm
Wire section - 3.2mm x 1.5mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 30% N	mm	Max deflection 40% N	mm	Deflection to solid approx N	mm
1S16025	25	23.4	176	7.5	234	10.0	304	13
1S16032	32	22.9	202	9.6	293	12.8	389	17
1S16038	38	19.3	202	11.4	293	15.2	386	20
1S16045	44	17.1	226	13.2	301	17.6	428	25
1S16050	51	15.7	240	15.3	320	20.4	424	27
1S16065	64	10.7	205	19.2	274	25.6	385	36
1S16075	76	10.0	228	22.8	304	30.4	430	43
1S16090	89	8.6	230	26.7	306	35.6	447	52
1S16101	102	7.8	239	30.6	318	40.8	452	58
1S16303	305	2.5	229	91.5	305	122	415	166

Hole Ø D - 20mm. Rod Ø d - 10mm
Wire section - 4mm x 2mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 30% N	mm	Max deflection 40% N	mm	Deflection to solid approx N	mm
1S19025	25	55.8	419	7.5	558	10.0	725	13
1S19032	32	45.0	432	9.6	576	12.8	465	17
1S19038	38	33.3	380	11.4	506	15.2	666	20
1S19045	44	30.0	396	13.2	528	17.6	720	24
1S19050	51	24.5	375	15.3	500	20.4	662	27
1S19065	64	20.0	384	19.2	512	25.6	700	35
1S19075	76	16.0	365	22.8	486	30.4	640	40
1S19090	89	14.0	374	26.7	498	35.6	686	49
1S19101	102	12.0	367	30.6	490	40.8	660	55
1S19115	115	10.9	375	34.5	501	46.0	676	62
1S19126	127	9.5	362	38.1	483	50.8	675	71
1S19140	139	8.4	350	41.7	467	55.6	638	76
1S19151	152	7.5	342	45.6	456	60.8	608	81
1S19303	305	4.0	356	91.5	488	122	672	165

Hole Ø D - 25mm. Rod Ø d - 12.5mm
Wire section - 5.4mm x 2.7mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 30% N	mm	Max deflection 40% N	mm	Deflection to solid approx N	mm
1S26025	25	100	750	7.5	1000	10.0	1200	12
1S26032	32	80.3	771	9.6	1028	12.8	1285	16
1S26038	38	62.0	707	11.4	942	15.2	1178	19
1S26045	44	52.9	698	13.2	931	17.6	1164	22
1S26050	51	44.0	673	15.3	898	20.4	1100	25
1S26065	64	35.2	676	19.2	901	25.6	1197	34
1S26075	76	28.0	638	22.8	851	30.4	1064	38
1S26090	89	24.0	641	26.7	854	35.6	1152	48
1S26101	102	21.1	646	30.6	861	40.8	1139	54
1S26115	115	18.7	645	34.5	860	46.0	1141	61
1S26126	127	16.7	636	38.1	848	50.8	1152	69
1S26140	139	15.3	638	41.7	851	55.6	1148	75
1S26151	152	14.0	638	45.6	851	60.8	1134	[illegible]
1S26176	178	12.5	668	53.4	890	71.2	1200	96
1S26202	203	10.4	633	60.9	844	81.2	1144	110
1S26303	305	7.0	641	91.5	854	122	1176	168

Continued...

Hole Ø D - 25mm. Rod Ø d - 12.5mm
Wire section - 5.6mm x 4.6mm

Stock code	Free length mm	Spring rate N/mm	Recommended deflection 17% N	mm	Max deflection 25% N	mm	Deflection to solid approx N	mm
4S26032	32	374	2037	5.4	2995	8.0	4118	11
4S26038	38	346	2235	6.5	3287	9.5	4498	13
4S26045	44	244	1825	7.5	2684	11.0	3904	16
4S26050	51	208	1799	8.7	2646	12.8	3725	18
4S26065	64	161	1752	10.9	2576	16.0	3703	23
4S26075	76	131	1590	12.9	2485	19.0	3401	26
4S26090	89	111	1672	15.1	2459	22.3	3426	31
4S26101	102	96.3	1670	17.3	2456	25.5	3467	36
4S26115	115	85.7	1675	19.6	2464	28.8	3514	41
4S26126	127	76.3	1647	21.6	2423	31.8	3586	47
4S26151	152	63.5	1641	25.8	2410	38.0	3429	54
4S26176	178	53.9	1631	30.3	2399	44.5	3396	63
4S26202	203	47.0	1622	34.5	2385	50.8	3384	72
4S26303	305	30.9	1602	51.9	2356	76.3	3492	113

Hole Ø D - 32mm. Rod Ø d - 16mm
Wire section - 7.15mm x 5.7mm

4S32038	38	528	3412	6.5	5018	9.5	6328	12
4S32045	44	424	3175	7.5	4668	11.0	6366	15
4S32050	51	353	3061	8.7	4501	12.3	6001	17
4S32065	64	269	2929	10.9	4307	16.0	5922	22
4S32075	76	219	2823	12.9	4152	19.0	5463	25
4S32090	89	160	2728	15.1	4012	22.3	5950	33
4S32101	102	155	2688	17.3	3953	25.5	5580	36
4S32115	115	140	2737	19.6	4025	28.8	5680	42
4S32126	127	124	2677	21.6	3937	31.8	5704	46
4S32151	152	102	2636	25.8	3876	38.0	5712	56
4S32176	178	88.2	2669	30.3	3925	44.5	5645	64
4S32202	203	76.0	2623	34.5	3857	50.8	5396	71
4S32252	254	60.8	2625	43.2	3861	63.5	5472	90
4S32303	305	49.0	2541	51.9	3736	76.3	5047	103

Hole Ø D - 40mm. Rod Ø d - 20mm
Wire section - [illegible]

4S38050	51	628	5445	8.7	8007	12.8	10676	17
4S38065	64	487	5299	10.9	7792	16.0	11201	23
4S38075	76	379	4897	12.9	7201	19.0	10233	27
[illegible]	[illegible]	[illegible]	4857	15.1	7142	22.3	[illegible]	31
4S38101	102	281	4873	17.3	7166	25.5	10116	36
4S38115	115	245	4790	19.6	7044	28.8	9800	40
4S38126	127	221	4771	21.6	7017	31.8	9724	44
4S38126	139	202	4773	23.6	7020	34.8	10504	52
4S38151	152	168	4341	25.8	6384	38.0	9408	56
4S38176	178	148	4478	30.3	6586	44.5	9028	61
4S38202	203	132	4555	34.5	6699	50.8	9636	73
4S38252	254	107	4620	43.2	6785	63.5	9951	93
4S38303	305	87.8	4552	51.9	6695	76.3	9307	106

Hole Ø D - 50mm. Rod Ø d - 25mm
Wire section - 11.5mm x 9.2mm

4S51065	64	709	7714	10.9	11344	16.0	14889	21
4S51075	76	572	7390	12.9	10868	19.0	14300	25
* 4S51090	89	475	7187	15.1	10569	22.3	13300	28 *
4S51101	102	405	7023	17.3	10328	25.5	13365	33
4S51115	115	352	6882	19.6	10120	28.8	13376	38
4S51126	127	316	6822	21.6	10033	31.8	13588	43
4S51126	139	289	6829	23.6	10043	34.8	13583	47
4S51151	152	239	6176	25.8	9082	38.0	12667	53
4S51176	178	216	6536	30.3	9612	44.5	12960	60
4S51202	203	187	6453	34.5	9490	50.8	13277	71
4S51252	254	153	6607	43.2	9716	63.5	13923	91
4S51303	305	127	6585	51.9	9681	76.3	13462	106

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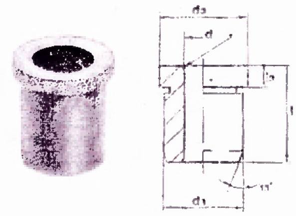
PRESS FIT, THROUGH HARDENED HEADED DRILL BUSHES TO DIN 172A



SHORT

Stock code	Bore d F7	d₁ n6	d₂	L	[illegible]
HDB2.0-HDB2.6	2.0-2.6	5	8	6	[illegible]
HDB2.7-HDB3.3	2.7-3.3	6	10	8	[illegible]
HDB3.4-HDB4	3.4-4	7	11	8	[illegible]
HDB4.1-HDB5	4.1-5	8	12	8	[illegible]
HDB5.1-HDB6	5.1-6	10	14	10	[illegible]
HDB6.1-HDB8	6.1-8	12	16	10	[illegible]
HDB8.1-HDB10	8.1-10	15	19	12	[illegible]
HDB10.1-HDB12	10.1-12	18	22	12	[illegible]
HDB12.1-HDB15	12.1-15	22	26	16	[illegible]
HDB15.1-HDB18	15.1-18	26	30	16	[illegible]
HDB18.1-HDB22	13.1-22	30	35	20	[illegible]
HDB22.1-HDB26	22.1-26	35	40	20	[illegible]
HDB26.1-HDB30	26.1-30	42	47	20	[illegible]
HDB30.1-HDB35	30.1-35	48	55	25	[illegible]
HDB35.1-HDB42	35.1-42	55	62	25	[illegible]
HDB42.1-HDB48	42.1-48	63	69	30	[illegible]
HDB48.1-HDB50	48.1-50	70	77	30	[illegible]

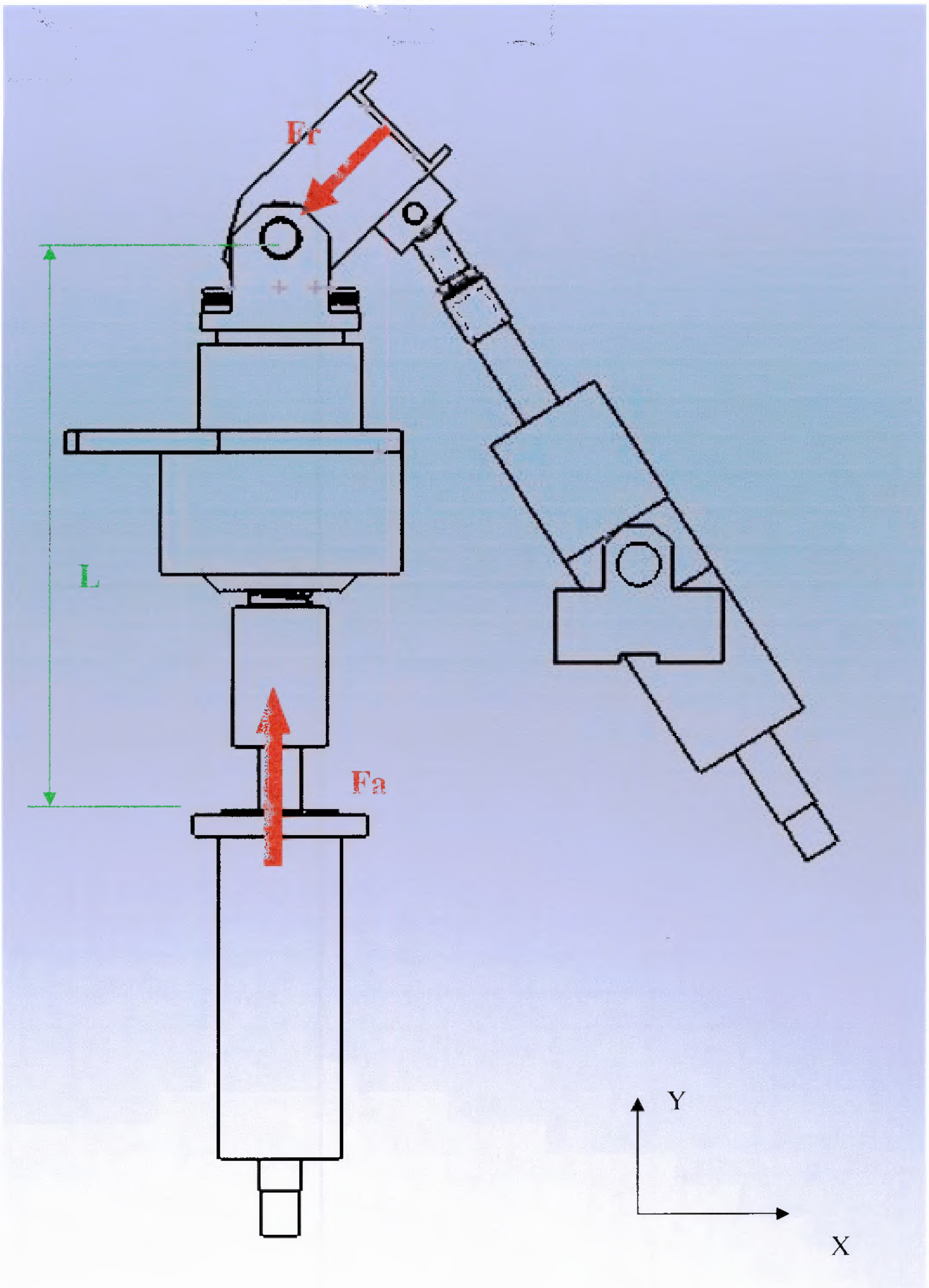
Note: Bushes with Ø range 2mm to 20mm are available in 0.1mm increments and bushes with Ø range 21mm to 50mm are available in 1.0mm increments.

LONG

Stock code	Bore d F7	d₁ n6	d₂	L	L₁
HDBL2.0-HDBL2.6	2.0-2.6	5	8	9	[illegible]
HDBL2.7-HDBL3.3	2.7-3.3	6	10	12	[illegible]
HDBL3.4-HDBL4	3.4-4	7	11	12	[illegible]
HDBL4.1-HDBL5	4.1-5	8	12	12	[illegible]
HDBL5.1-HDBL6	5.1-6	10	14	16	[illegible]
HDBL6.1-HDBL8	6.1-8	12	16	16	[illegible]
HDBL8.1-HDBL10	8.1-10	15	19	20	[illegible]
HDBL10.1-HDBL12	10.1-12	18	22	20	[illegible]
HDBL12.1-HDBL15	12.1-15	22	26	28	[illegible]
HDBL15.1-HDBL18	15.1-18	26	30	28	[illegible]
HDBL18.1-HDBL22	18.1-22	30	35	36	[illegible]
HDBL22.1-HDBL26	22.1-26	35	40	36	[illegible]
HDBL26.1-HDBL30	26.1-30	42	47	36	[illegible]
HDBL30.1-HDBL35	30.1-35	48	55	45	[illegible]
HDBL35.1-HDBL42	35.1-42	55	62	45	[illegible]
HDBL42.1-HDBL48	42.1-48	63	69	56	[illegible]

Note: Bushes with Ø range 2mm to 20mm are available in 0.1mm increments and bushes with Ø range 21mm to 50mm are available in 1.0mm increments.

10.8 BENDING MOMENT ACTING ON AXIAL ACTUATOR



Fa = Axial Force exerted by Piston

Fr = Fa = Reaction force due to Fa

As the flexion angle changes, so does the X and Y force components of Fr. The Y component of Fr will cause a bending moment in the piston. This can be calculated as follows:

$\mathbf{Fr_y = Fr \times cosine(\varphi)}$ φ = angle of flexion

Therefore, the bending moment acting on the piston (M) is given by:

$\mathbf{M = Fr_y \times L}$

Therefore, if L is minimised then M is minimised.