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Image Guided Failure Assessment of Whole Bones under Multiple Loading Conditions in a Micro-Computed Tomography Patient Scanner

Diploma Thesis

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Supervision

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Abstract

Osteoporosis (OP) is a debilitating disease characterized by low bone mass and the deterioration of bone tissue micro-architecture. The disease is predominantly found in elder women. Research focuses on fracture prevention which requires a fundamental understanding of bone mechanics.

Image guided failure assessment (IGFA) provides experimental data for micro-computed tomography (μ CT)-based finite element analysis to characterize bone strength. Loading devices are used to perform mechanical tests with bone samples. Existing devices compress or tension the specimens while they are being scanned in a μ CT scanner.

A new mechanical testing device that combines thrust and torsion is developed for a specific μ CT patient scanner (XtremeCT, Scanco Medical AG, Bassersdorf, Switzerland) in the scope of this diploma thesis. The XtremeCT is a high resolution peripheral computer tomograph for human in vivo measurements of both bone density and micro-architecture. Worm & wheel reduction gearboxes create axial and torsional loads of up to 8,000 N and 25 Nm, respectively. Advantages over existing devices are the application of torsion to various bone sizes (e.g., murine femurs and human radii) and the combination of loads (i.e., axial and torsional). None of the other known devices are able to implement torsional tests on larger bones.

Due to time limitations, no experiments or calibrations could be performed in the scope of this thesis. However, experiments are presented here that describe different biomechanical tests that could be achieved with the mechanical testing device in the XtremeCT. The device could thus be used for image guided failure assessment of whole bones under multiple loading conditions.

Contents

Abstract	i
Contents	iv
List of Figures	v
List of Tables	vii
Symbols and Abbreviations	ix
1 Introduction	1
1.1 Motivation	1
1.2 Aim of the diploma thesis and project tasks	2
1.3 Image guided failure assessment	2
2 Materials and Methods	5
2.1 Scanco Medical XtremeCT	5
2.1.1 Mounting the jig inside the scanner	6
2.2 Existing testing devices for XtremeCT	8
2.3 Loading conditions	9
2.4 List of requirements	13
2.4.1 Modifications	14
2.5 Design	15
2.5.1 Load creation	15
2.5.2 Data acquisition	19
2.5.3 Solutions for scannable area where tests are performed	21
2.5.4 Purchased parts	23
2.5.5 Computer aided design (CAD) - SolidWorks	24
2.5.6 Calculations	30
2.6 Sensor calibration	35
2.6.1 Linear displacement	35
2.6.2 Angular displacement	35
2.6.3 Load cell	36
2.7 Testing of the device	37
2.7.1 Leak tightness	37
2.7.2 Experiments with and without saline	37
2.7.3 Influence of the tube	38
3 Results	39
3.1 Mechanical testing device	39
3.1.1 Modifications to original design	40
3.2 Calibration and experimental testing	42

4	Discussion	43
4.1	Comparison of existing devices with new design	43
4.2	Effects of modifications	44
4.2.1	Thread used to create axial load	44
4.2.2	Change of material	44
4.2.3	Fixation ring for LVDT	44
4.2.4	Shaft fixation	44
4.2.5	Adjustable support	44
4.2.6	Signal conditioner	45
4.3	Delays in production	45
4.3.1	Data acquisition (WinDaq)	45
4.4	User recommendations	46
5	Prospect	47
6	Acknowledgments	49
A	Views of testing device	51
B	Schedule	54
	Bibliography	55

List of Figures

1.1	Bending and buckling due to micro-compression	3
2.1	Scanco Medical XtremeCT scanner	5
2.2	XtremeCT opening	6
2.3	Specimen holder for XtremeCT	6
2.4	3309 Phantom KP 70 for calibrations	7
2.5	Steel plate with dimensions of phantom mount	7
2.6	Paul Hulme's loading device	8
2.7	Bone crusher built by Thomas Müller et al.	9
2.8	Worm & wheel reduction gearbox PF30-120	16
2.9	Acme screw thread	16
2.10	Worm & wheel reduction gearbox P60-120	17
2.11	Split hub GN 150	17
2.12	MTS 642.001 Low Force Bend Fixtures	18
2.13	Three-point bending test using MTS 642.001 Bend Fixtures	19
2.14	Data acquisition equipment diagram	20
2.15	Final assembly of mechanical testing device (SolidWorks 2007)	24
2.16	Axial load module	25
2.17	Torque module	26
2.18	Attachments	27
2.19	Testing zone module	28
2.20	Mechanical testing device with cover plates (old design)	28
2.21	Dimensions of mechanical testing device	29
2.22	Increasing stress due to static torsion	34
2.23	Angular displacement calibration	35
3.1	Final mechanical testing device	39
3.2	Mounted mechanical testing device in XtremeCT	40
3.3	Potentiometer fixation	41
3.4	Redesigned adjustable support	41
A.1	Assembly of mechanical testing device (SolidWorks 2006)	51
A.2	Top view of mechanical testing device	51
A.3	Backside view of mechanical testing device	52
A.4	Mechanical testing device's bottom view	52
A.5	Front of mechanical testing device	53
A.6	Back of mechanical testing device	53
B.1	Schedule	54

List of Tables

2.1	Different loading conditions to be applied to bone specimens	11
2.2	Maximum loads for different loading conditions	12
2.3	Requirements for mechanical testing device	13
2.4	Requirements, continued	14
2.5	Force creation and control	15
2.6	Bone compression and tension	15
2.7	Three-point bending variations	18
2.8	Data acquisition components	21
2.9	X-ray translucent testing zone	22
2.10	Suppliers and prices	23
2.11	Maximal shear stresses for groove grounds and ends	34
2.12	Load sensor calibration	36
2.13	Tests to be implemented using the mechanical testing device	37

Symbols and Abbreviations

Symbols

F_x	axial load applied to the specimen	[N]
$F_{x,max}$	maximal compressive load	[N]
T	torque applied to the specimen	[Nmm]
T_{max}	maximal torque or torque at failure	[Nmm]
J	polar moment of inertia	[mm ⁴]
σ_x	normal stress in axial direction	[MPa]
$\sigma_{x,max}$	maximal normal stress	[MPa]
σ_B	tensile strength for brittle materials	[MPa]
σ_F	tensile strength for ductile materials	[MPa]
σ_v	maximal stress for comparison	[MPa]
τ	shear stress	[MPa]
τ_{max}	maximal shear stress	[MPa]
τ_{zul}	maximal tolerated shear stress	[MPa]
p_{zul}	maximal allowed force per area	[N/mm ²]
M_T	required torque to create thrust	[Nmm]
$M_{t,zul}$	maximal torque tolerated to transmit	[Nmm]
A	cross-sectional area of tube or shaft	[mm ²]
D	outer tube or shaft diameter	[mm]
d	inner tube diameter	[mm]
d_e	external diameter	[mm]
d_{est}	estimated shaft diameter	[mm]
d_2	pitch diameter	[mm]
s	wall thickness of tube	[mm]
b	key width	[mm]
h	key height	[mm]
l_k	key length	[mm]
l_{tr}	supporting key length	[mm]
r_k	radius of round-ended feather key	[mm]
t	supporting key height	[mm]
l	handle length	[mm]
P	thread pitch	[mm]
S_B	safety factor for brittle material behavior	[-]
S_F	safety factor for ductile material behavior	[-]
S	safety factor	[-]

α	pitch angle	[°]
α_τ	form factor for groove	[-]

Abbreviations

ASTM	American Society for Testing and Material
IGFA	image guided failure assessment
LVDT	linear variable differential transformer
MCD	micro-compression device
OP	osteoporosis
μ CT	micro-computed tomography

$$1 \text{ MPa} = 1 \text{ N/mm}^2 = 145.04 \text{ psi}$$

Chapter 1

Introduction

1.1 Motivation

Osteoporosis (OP) is a debilitating disease characterized by low bone mass and the deterioration of bone tissue micro-architecture. The disease is most prevalent in women over the age of 50 where, due to a reduction in architectural integrity, osteoporotic bone is prone to spontaneous fracture. Osteoporotic fractures have a devastating effect on morbidity and mortality, and there is a large body of research that focuses on understanding the etiology of the disease. A fundamental goal of this research is to determine methods of fracture prevention, and this can be achieved by a number of means including:

- (i) Early detection of fracture risk.
- (ii) The development of interventions (i.e., pharmaceutical or exercise).
- (iii) The development of preventative measures (i.e., supplemental exercise and diet early in life).

Central to all of these OP studies is the evaluation of bone quality, and this necessitates not only monitoring the apparent density of bone (which is closely related to bone strength), but also the bone micro-architecture. Micro-computed tomography (μ CT) is a relatively new technology that plays a central role in quantifying 3D bone micro-architecture, thus allowing a non-destructive, quantitative assessment that has become a crucial component of OP research. Although until recently μ CT has been limited to in vitro analysis, new in vivo systems are now emerging for animal and patient studies. To fully exploit the use of μ CT to characterize bone strength, finite element modeling is commonly employed to assess patient-specific mechanics.

The main limitation of μ CT-based finite element analysis is the lack of detailed experimental data providing accurate tissue properties and appropriate failure criteria. An experimental method that has demonstrated significant potential for providing these experimental data is called image guided failure assessment (IGFA). This approach loads a bone sample inside a μ CT scanner within a specifically designed loading jig. Sequential 3D images are acquired against which finite element models can be tuned to simulate the experimental load-deformation characterization. However, to date the IGFA has been limited to small bones (i.e., mouse) or extracted bone cores due to the small scanner gantry, and the high resolution scans are long per loading step (>1 hr).

New μ CT equipment has recently been developed that is intended for patient measurements, and has a larger gantry and is designed for rapid scanning speeds (albeit at lower resolution). Although detailed micro-architecture may be difficult to discern in this new scanner, it has the advantage that whole intact bones can be scanned, and the gantry size provides the possibility of designing a jig to perform loading under several complex conditions (3-point bending, cantilever bending, torsion). There is a need to establish a methodology for performing IGFA in the new μ CT scanner.

1.2 Aim of the diploma thesis and project tasks

The outcome of this study will provide an experimental basis on which patient-specific finite element modeling with improved tissue property and failure characteristics can be developed and validated.

Loading devices for the new μ CT scanner have been developed at the University of Bern (Switzerland) and the Swiss Federal Institute of Technology (ETH) in Zurich (Switzerland) in the last year (see section 2.2). However, these devices are only able to perform compression and tension testing. Therefore, the aim of this diploma thesis is to design a new mechanical testing jig that unites the features of the existing devices with more complex loading conditions (i.e., torsion testing). A modular system should allow the mounting of small bones (i.e., rat) as well as human bones (i.e., radius), respectively.

The following project tasks are stated in accordance with the supervisor to develop a mechanical testing device for multiple loading conditions:

- Set up a detailed time-table for the duration of the project.
- Investigate the IGFA methodology, and determine appropriate loading conditions to provide experimental data used for finite element modeling.
- Investigate appropriate materials that can be used inside a μ CT scanner, and associated load and displacement sensing devices.
- Design a versatile loading jig for IGFA inside the μ CT scanner; build and test the jig with whole bones.
- Determine methodology to extract load-deformation information, and failure characteristics; align sequential images for animations of whole bone failure.
- Prepare final report and conclusions.

1.3 Image guided failure assessment

IGFA was first introduced by Ralph Müller et al. at Harvard University in 1998 [1]. Prior, morphologic measurements of trabecular bone were limited to two-dimensional (2D) destructive techniques. IGFA uses μ CT scanners to conduct dynamic measurements of microstructural bone and create three-dimensional (3D) images. An increasing load causes the bone to buckle and bend until a fracture is initiated. The fracture propagates and therefore the damage accumulates in the 3D bone matrix.

In the beginning, micro-compression devices (MCD) were used to apply and maintain strain to the bones while the μ CT imaged the specimen for the given strain configuration. The load, which was measured by an on-board load cell, was increased step-wise and manually locked within the MCD. The size of the specimen was limited to 22 mm in length and to a maximal diameter of 9 mm. Figure 1.1 visualizes the micro-compression of a bone sample in a MCD.

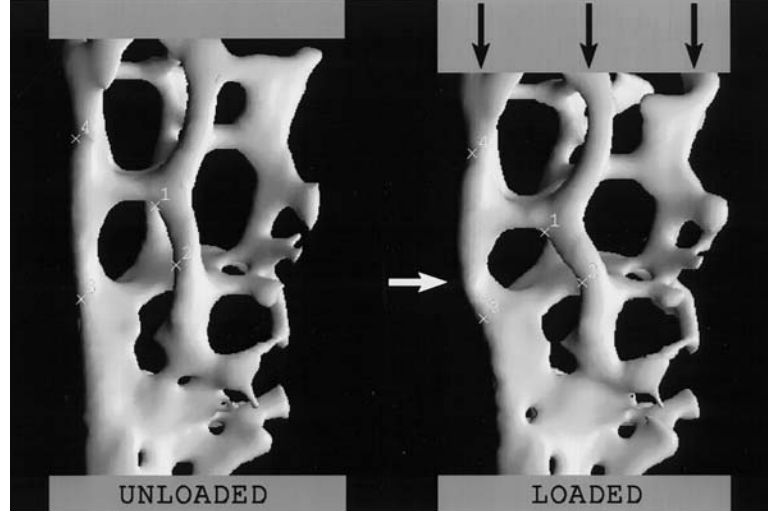


Figure 1.1: Bending and buckling due to micro-compression. The unloaded original structure is on the left and the same sample with applied load on the right [1].

In 2003 the MCD-II was introduced by Nazarian et al. [2] to reduce the errors in measurements due to the first generation MCD. The same study showed that stepwise micro-compression is comparable to classical continuous testing, that is considered as the gold standard, and thus can be used for the dynamic assessment of structural failure mechanism.

IGFA is not only limited to compression and nowadays used for various loading conditions (i.e., bending, tension, torsion, etc.). Multi-functional mechanical testing platforms for different scanners are currently developed.

Chapter 2

Materials and Methods

2.1 Scanco Medical XtremeCT

This chapter describes the mechanical testing device developed specifically for the XtremeCT (figure 2.1 [3], Scanco Medical AG, Bassersdorf, Switzerland). The XtremeCT is a high resolution peripheral computer tomograph for human in vivo measurements of both bone density and micro-architecture. The system is designed for monitoring osteoporosis and its treatment. Typically, structural (e.g., trabecular thickness) or density measurements of the trabecular and cortical regions are performed on the tibia or the radius. In vivo scans on animals such as rats can be accomplished as well as in vitro scans on extracted bones.



Figure 2.1: Scanco Medical XtremeCT scanner (WxDxH: 1380 x 930 x 1460 mm).

A maximal scan length of 150 mm with a 125 mm diameter can be achieved with a nominal resolution of $42\text{ }\mu\text{m}$ at an effective x-ray dose of less than $5\text{ }\mu\text{Sv}$ (ICRP91) per measurement. The scannable field starts at approximately 115 mm from the opening which has a width of 176 mm and height of 185 mm, respectively (figure 2.2). The acquired data allows three-dimensional visualization of the bones and enables image guided failure assessment.

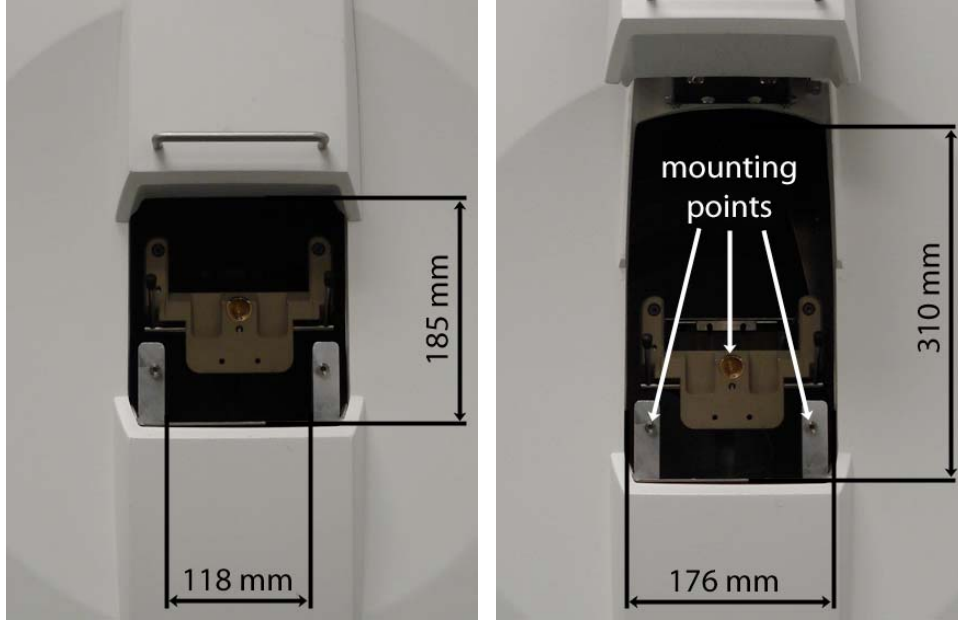


Figure 2.2: Opening to access the scanner with closed (left) and raised cover (right image). The mechanical testing device is designed to fit into the opening which is 176 mm wide and 185 mm high. Two support bars used for mounting limit the width additionally to 118 mm. The height can be extended up to 310 mm by raising the cover.

2.1.1 Mounting the jig inside the scanner

The XtremeCT has three points used for the fixation of any jig. Two mounting points are located on either side of the opening (figure 2.2), with a third located in the centre on a movable plate. This plate can be pushed inside the scanner up to a distance of 300 mm.

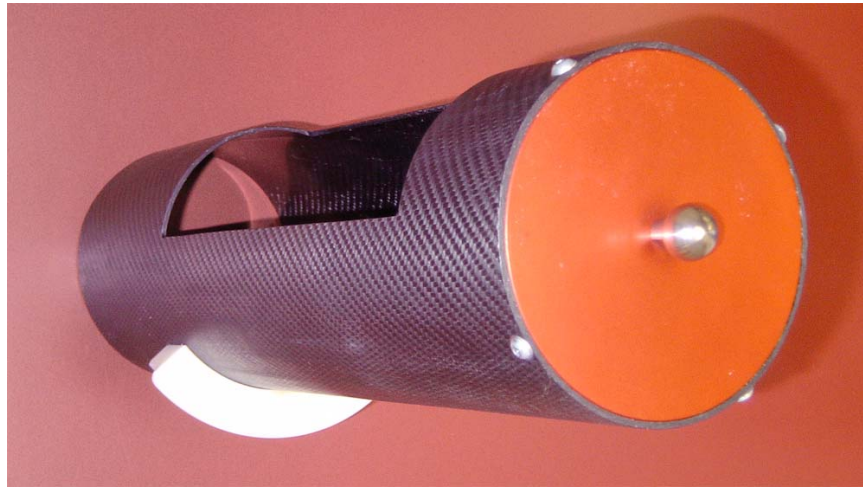


Figure 2.3: Specimen holder for XtremeCT. The white circular plastic plate is placed on two screws and the round knob is fixed inside the scanner.

A specimen holder provided by Scanco Medical AG (figure 2.3) has a circular plastic plate that can be placed on the screws attached to the bars and a ball that fits into the movable point. On the other hand, a calibration phantom (figure 2.4) uses a 4 mm steel plate (see figure 2.5 for dimensions) and a screw with a washer. The latter system will be adapted to the mechanical testing device.

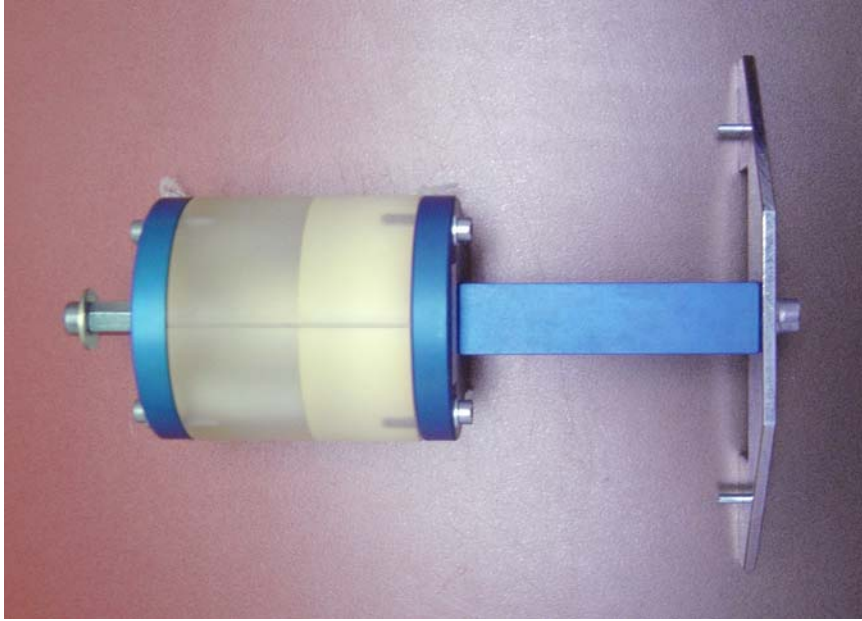


Figure 2.4: XtremeCT 3309 Phantom KP 70 for calibrations. Fixation inside the scanner with screw and tab washer shown on the left side.

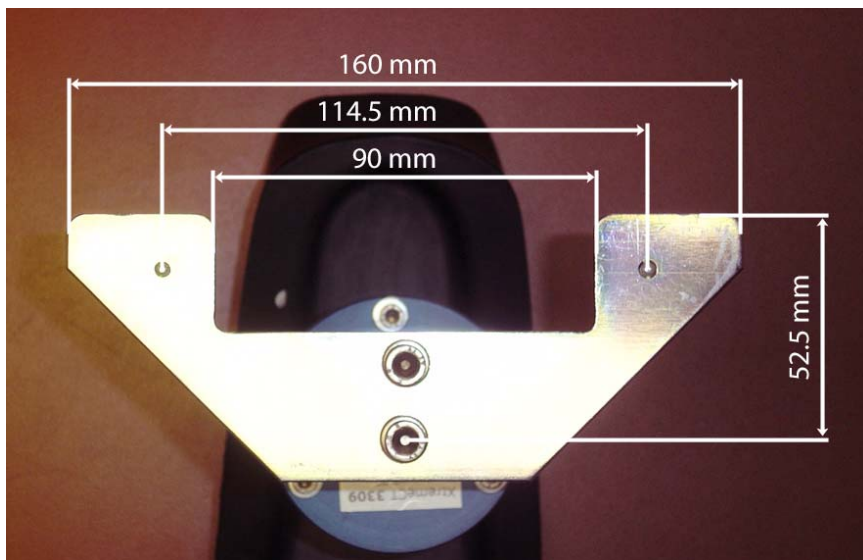


Figure 2.5: Steel plate with dimensions of phantom mount. Two screws at the opening of the XtremeCT (see figure 2.2) provide a rest for the mounting plate.

2.2 Existing testing devices for XtremeCT

Several devices for in vitro tests in smaller scanners (e.g., Scanco Medical μ CT 40) have been built previously (compare work done by Romain Voide at the ETH). Skyscan, a competitor of Scanco, offers a material testing stage for thrust and torsion. The compression and tension is limited to 10 mm and the forces do not exceed 50 N (www.skyscan.be, Kontich, Belgium). All of the existing devices cannot combine any loading conditions (e.g., compression and torsion).

Two different loading devices for the XtremCT are currently known, one of which was developed at the University of Bern (Switzerland) in research collaboration with the University of Calgary by Paul Hulme as part of his PhD study (figure 2.6). It is designed for compressive and tensile loads of up to 5,000 N. A fine M10 screw (0.5 mm pitch) is manually twisted to create the desired load as measured by a Sensotec precision miniature load cell (model 31, 0 - 1,000 lbs, Honeywell International Inc., Columbus, USA). The screw is connected to a bearing for torque relief. The testing chamber can be filled with liquid to prevent the specimen (connected to the loading plates with double sided tape) from drying out.

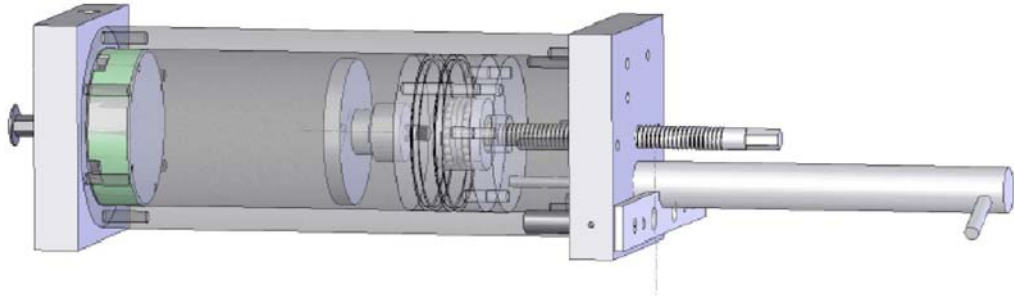


Figure 2.6: Loading device for compression and tension testing designed by Paul Hulme, University of Bern, Switzerland.

Another testing device, built at the ETH in Zurich (Thomas Müller et al.), was developed for compression only within the scope of a bachelor thesis by Andreas Wirth. A sealed chamber was envisioned but the sliding resistance of the shaft was too high and therefore the hub was milled out.

Martin Walz then designed an extension to this device for tensile testing in his bachelor thesis. Compressive loads up to 10,000 N and tensile loads up to 3,000 N can be achieved. The specimen is embedded in a holder using bone cement and can be secured with a pin for tensile testing. A piezo-crystal load cell (Kistler Instrumente AG, Winterthur, Switzerland) is used to measure the loads.

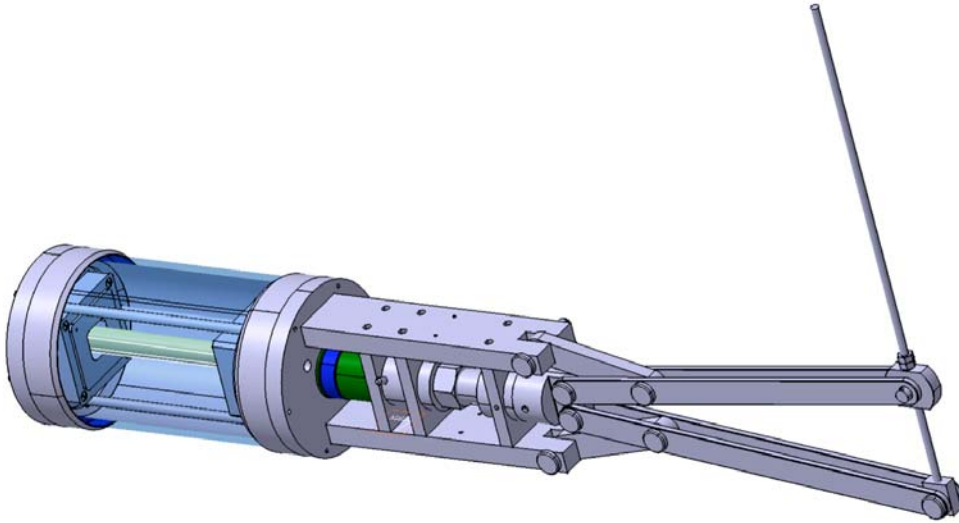


Figure 2.7: Compression device with extension for tension as built by Müller et al., ETH Zurich, Switzerland.

The loading devices for the XtremeCT are limited to compressive and tensile loading. The wall thickness of the tubes where the specimens are placed is 10 mm. The effects of wall thickness on image quality are unknown. Displacement is measured in both cases with a linear variable differential transformer (LVDT). Please refer to Hulme and Th. Müller's work for further information.

2.3 Loading conditions

Bone can be loaded in many different ways. C. M. Langton et al. describes the mechanical testing of bones in *The physical measurement of bone* [4]. Basic concepts in bone mechanics and definition of terms (e.g., stress-strain curve) as well as specimen handling are published. The following methods to measure the mechanical properties of bone tissues are presented:

- Uniaxial compressive test
- Uniaxial tensile test
- Bending test
- Torsion test
- Fatigue
- Indentation/hardness tests
- Ultrasound

Stephen C. Cowin also introduces in *Bone Mechanics Handbook* [5] pure shear and site-specific tests (e.g., fall configuration). Compressive testing is the most common method used to determine characteristics of bone tissue. Standards for carrying out these measurements have been developed by the American Society for Testing and Material (ASTM). They will not be discussed further in this thesis as most people using this mechanical testing device should be familiar with the methods prior to use [4].

Three- or four-point bending configurations are used for the bending tests. Unwanted shear stresses arise near the mid-section in three-point bending, especially on short specimens. This can be avoided with the four-point configuration. However, four-point bending can be difficult to implement due to the non-uniform shape of the bones which leads to a non-equally distributed force at each loading point. Therefore, the three-point bending is the most widely used method. Cantilever bending distorts the bone over a longer distance and thus applies a larger torque.

Fatigue tests require the use of a power unit due to the high number of repetitions and are more time-consuming than other methods.

Table 2.1 summarizes and illustrates the different loading conditions. They are applied either alone or in combination (e.g., tension and torsion). Hardness and ultrasound tests are not within the scope of this thesis.

One of the aims of this thesis is to test various bone sizes. Therefore, loading conditions of murine, rat, and human bones were collected from literature and studies made at the Swiss federal institute of technology in Zurich. The human radius is of particular interest as the XtremeCT scans for diagnosis are performed there. No values for torque applied to the human radius could be found in literature. Kasra et al. [6] tested tibiae of cynomolgus monkeys under torsional load and found a maximum shear stress (τ_{max}) of 46 ± 8.7 MPa. It was calculated using the following equation:

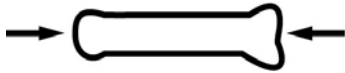
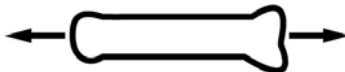
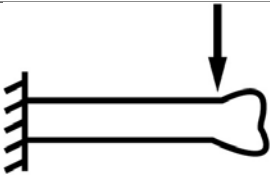
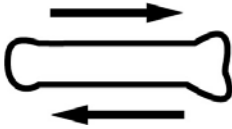
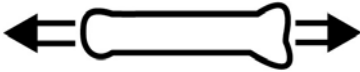
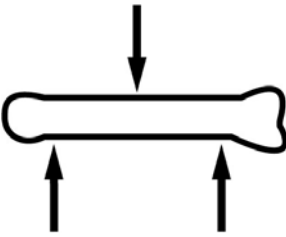
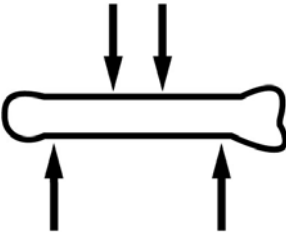
$$\tau_{max} = \frac{T_{max} \cdot d_e}{2 \cdot J}, \quad (2.1)$$

where T_{max} is the torque at failure, $d_e = 7.89 \pm 0.71$ mm the external diameter, and $J = 379.1 \pm 129.8$ mm⁴ the polar moment of inertia of the cross-section fractured. Using the upper limits for τ_{max} and J and the lower for d_e gives a maximum torque at failure of 7,754 Nmm.

Martens et al. [7] tested non-pathological human tibial and femoral bones in torsional loading. The mean maximum torque for the tibiae $T_{max,tibiae}$ and for the femora $T_{max,femora}$ was 101 Nm and 183 Nm, respectively. Scaling the torque to a human radius in regards to the polar moment of inertia and assuming the diameters $d_{e,radius} = 15$ mm and $d_{e,tibia} = 25$ mm returns:

$$T_{max, radius} = T_{max, tibia} \cdot \frac{d_{e,radius}^3}{d_{e,tibia}^3} = 101 \cdot \frac{15^3}{25^3} \approx 22 \text{ Nm}. \quad (2.2)$$

Table 2.1: Different loading conditions to be applied to bone specimens.

1	axial compression	
2	axial tension	
3	cantilever bending	
4	shear	
5	torsion	
6	three-point bending	
7	four-point bending	

Maximum values for compressive tests with human radii were found by Hoyer et al. [8]. Radius segments of a certain length were tested and the mean fracture load determined to be 7,371 N.

Tensile tests (pulling out screws) up to 3,000 N were accomplished by Thomas Müller et al. at the ETH in Zurich.

Boeree et al. [9] measured the compressive and tensile strengths of fresh human bones from different anatomical sites. The compressive strength for radii was found to be 1.3 times higher than the tensile (149 vs. 114 N/mm²). Using this ratio with the value determined by Hoyer et al. gives a maximum tensile fracture load of 5,640 N for the human radius.

Lochmüller et al. [10] determined the failure moment for human radii in three-point bending as 31.3 Nm at 33% proximal to the wrist joint. This corresponds to about 400 N assuming that 80 mm is 33% of the radius length.

Romain Voide (ETHZ, Switzerland) performed several tests with mouse and rat bones. Maximal forces for compression of mouse femurs were 10 times lower than the ones of human trabecular vertebrae (cylinder with a diameter of 7 – 8 mm: 200 – 500 N).

Three-point bending experiments with mouse femurs resulted in maximum loads of 20 – 40 N and dental implants were pulled out of rat tibiae with 20 – 100 N. Dental implants in bovine trabecular femoral bone resisted a maximum torque of 50 Ncm.

Lind et al. [11] measured maximum torques for rat humeri up to 200 Nmm. The bone ends were embedded in purpose-built aluminum fittings which were filled with plastic padding. A custom jig ensured the proper alignment of the bone axis along the load axis of the testing machine.

Table 2.2 summarizes the maximum loads for the various loading conditions of interest.

Table 2.2: Maximum loads for different loading conditions.

test	bone specimen	max. load	reference
compressive	human radius	7,371 N	Hoyer et al. (1980) [8]
tensile	human radius	5,640 N ¹	Boeree et al. (1993) [9]
torsion	human tibiae	101 Nm	Martens et al. (1981) [7]
three-point bending	human radius	400 N ²	Lochmüller et al. (2002) [10]

¹Value calculated with maximal fracture load of Hoyer et al.:

$F_{tensile} = F_{compressive} \cdot \frac{tensile\ strength}{compressive\ strength} = 7,371\text{ N} \cdot \frac{114\text{ MPa}}{149\text{ MPa}} = 5,640\text{ N}.$

²31.3 Nm at 33% proximal to the wrist joint.

2.4 List of requirements

The following list of requirements (tables 2.3 and 2.4) are a result of both the restrictions of the scanner (section 2.1) and the loading conditions (section 2.3). The requirements are divided into *demands* (i.e., have to be fulfilled) and *wishes* (i.e., nice to have).

Table 2.3: Requirements for mechanical testing device. $d = demand$, $w = wish$.

d/w	requirement	limit	modification	date
d	fits into XtremeCT	-	-	-
d	x-ray translucent in scan field	-	-	-
w	view on specimen	-	-	-
w	allows testing in saline solution to prevent dry out of specimen	-	-	-
w	fluid inlet and outlet port	-	-	-
d	no dropping of liquid into scanner	-	-	-
d	exchangeable sealing rings	-	-	-
d	can be handled by one person	-	-	-
d	easy to change loading condition	-	-	-
w	demountable for cleaning purpose	-	-	-
d	easy to disinfect	-	-	-
d	sterilizable	-	-	-
d	working conditions: room temperature, atmospheric pressure	-	-	-
d	chips and splinters breaking away from the specimen cannot get free (endanger people or machine)	-	-	-
d	protects user from electrical hazards	-	-	-
w	non-corrosive	-	-	-
d	non-reactive with products used inside (PMMA, saline) or parts of μ CT	-	-	-
d	frame withstands loads	-	-	-
d	holds specimen	-	-	-
	specimen:			
d	length	130 mm	-	-
d	diameter	30 mm	-	-
	geometry of part in scanner:			
d	length	300 mm	-	-
d	diameter	125 mm	176 mm	2006/12/20
	geometry at opening:			
d	width	176 mm	-	-
d	height	240 mm	-	-
d	scannable area from 50 – 200 mm	-	-	-
d	scannable diameter	125 mm	-	-

Table 2.4: Requirements for mechanical testing device, continued.

d/w	requirement	limit	modification	date
	applies and keeps the following loading conditions independently:			
d	compression	10,000 N	8,000 N	2007/01/05
d	tension	5,000 N	-	-
d	torsion	25 Nm	-	-
d	three/four-point bending	40 Nm	-	-
w	cantilever bending	100 Nm	-	-
d	applies compressive and tensile force without inducing bending moments	-	-	-
d	measures loads (thrust and torque)	-	-	-
d	measures linear displacement	10 mm	-	-
d	measures angular displacement	360°	-	-
d	weight	20 kg	-	-
d	costs	< \$9,999	-	-

2.4.1 Modifications

The following modifications were made in the course of the project:

- The diameter of the device within the scanner was extended to the size of the opening (i.e., 176 mm). There are no restrictions provided the specimen stays in the scannable area.
- The maximal compressive load was reduced to 8,000 N due to sensor capacity (2,000 lbs).

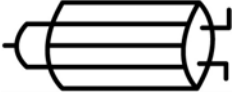
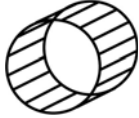
2.5 Design

The design of the mechanical testing device is accomplished in accordance to the specifications stated in section 2.4. Ideas and different solutions are collected and the most appropriate, in the view of the author, chosen. Subsection 2.5.4 lists the purchased parts and 2.5.5 the final mechanical testing device drawn using SolidWorks (Education Editions 2006 and 2007, SolidWorks Corporation, Concord, MA, USA).

2.5.1 Load creation

There are several ways to both create and control a force. Table 2.5 lists a selection of the different possibilities:

Table 2.5: Different possibilities to create and control a force.

load creation			
	manually	motor	hamster
force control	(servo-)hydraulic	screw-driven	pneumatic

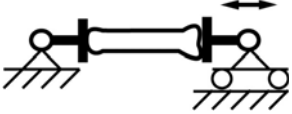
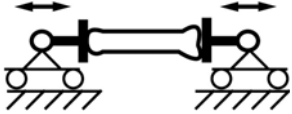
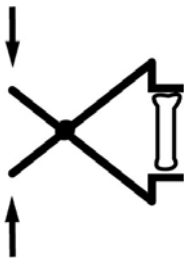
The forces are manually created with the help of two worm & wheel reduction gearboxes (Rino Mechanical Components Inc., Freeport, NY, USA). A ratio of 120:1 allows fine adjustment for both compression and torsion. Motors can be attached to the gearboxes at a later stage. This would also allow fatigue testing.

The specimen can be fixed with a pin, resin, or in bone cement. A special holder has been designed and is presented in subsection 2.5.5 (figure 2.18).

Axial compression and tension

Alternatives to apply compressive and tensile loads to a specimen are shown in table 2.6. The most convenient way in the XtremeCT is to apply the load from one side.

Table 2.6: Different ways to compress and tense a bone.

		
fixed on one side	load on both sides	clamp

The worm & wheel reduction gearbox (PF30-120: left in figure 2.8) is used to create a moment. The moment is transformed into an axial load through a shaft with an acme screw thread (Tr 12 x 2, figure 2.9) which is connected to the $\text{Ø}8$ mm output bore of the gearbox. A commercial crank handle (right in figure 2.8) is used to drive the gearbox.

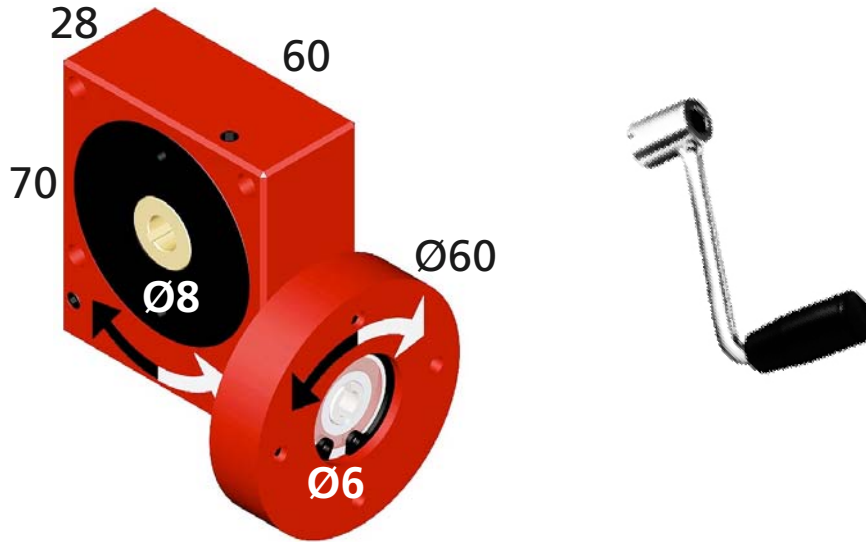


Figure 2.8: Worm & wheel reduction gearbox PF30-120 for thrust applications with dimensions in mm on the left (www.rinomechanical.com). The picture on the right shows the commercial crank handle that is connected to the $\text{Ø}6$ mm input bore with a pinned rod.

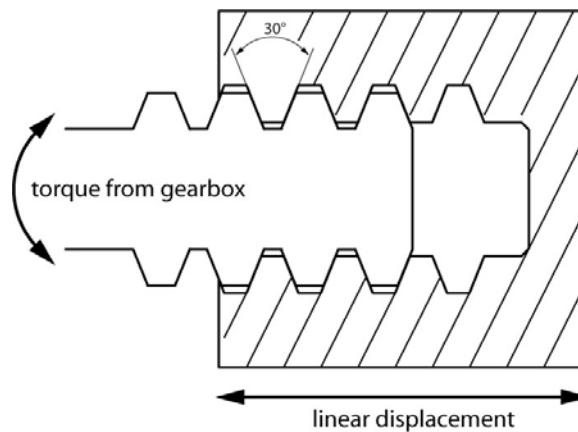


Figure 2.9: Acme screw thread to convert torque to compressive or tensile force.

Non-parallel surfaces at the ends of the bone can induce bending moments. Pivoting plates with a ball joint at one end can be used to reduce the effect of irregularities and to prevent misalignment [4]. They will not be built as a part of this project and can be supplied later when needed for specific tests.

Torsion

Torsional loads are created directly with a P60-120 worm & wheel reduction gearbox (figure 2.10). A shaft transferring the axial loads slides in the Ø20 mm output bore and transmits the torque over a 6 mm wide key in accordance to DIN 6885.

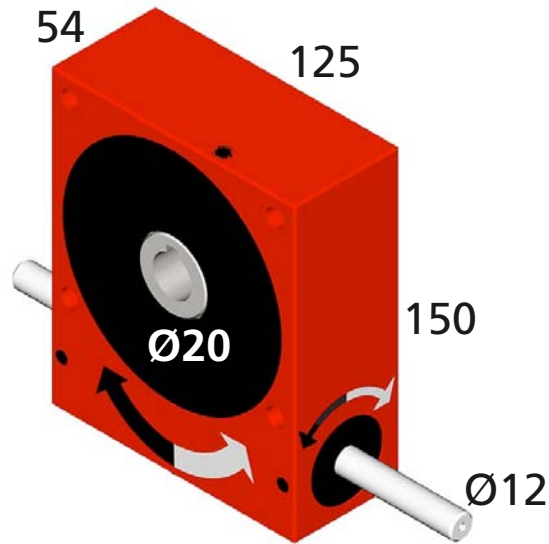


Figure 2.10: Worm & wheel reduction gearbox P60-120 to create torque with dimensions in mm (www.rinomechanical.com).

A split hub GN 150 with a bore diameter of 12 mm (figure 2.11) is clamped to one side of the input shaft. The force is created manually with the help of a gear lever handle GN 310 that is connected with a metric thread (M8 x 1.25) to the split hub (J.W. Winco Inc., New Berlin, WI, USA).



Figure 2.11: Split hub GN 150 to connect lever handle to input shaft of gearbox P60-120.

Three- and four-point bending

Table 2.7: Three-point bending variations that allow different arrangements of the bone along the axis.

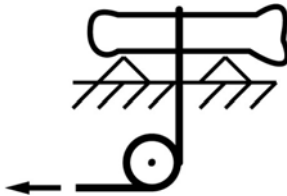
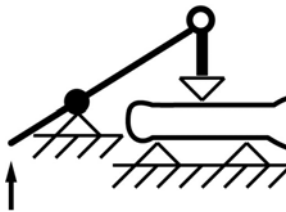
 vertical beam	 deflection pulley	 lever
--	--	---

Table 2.7 shows some options to bend a bone. The bone can be aligned differently. The Bone Imaging Laboratory [12] at the University of Calgary uses the MTS 642.001 Low Force Bend Fixtures for mechanical testing of bones (figure 2.12). The same device can be used for three-point and four-point bending tests within the XtremeCT. Therefore, the attachments for the holder inside the testing tube of the jig are designed accordingly. Five different rollers (1 – 5 mm diameter) are provided by MTS and have static force capacities from 0.57 kN to 2.89 kN. Assuming a bone length of 40 mm gives a maximum bending moment of 115.6 Nm ($= 2,890 \text{ N} \cdot 40 \text{ mm}$) that meets the requirement of 40 Nm. Figure 2.13 shows a three-point bending test with a rat femur performed at the Bone Imaging Laboratory using the MTS device [12].



Figure 2.12: MTS 642.001 Low Force Bend Fixtures (MTS Systems Corporation, Eden Prairie, MN, USA).

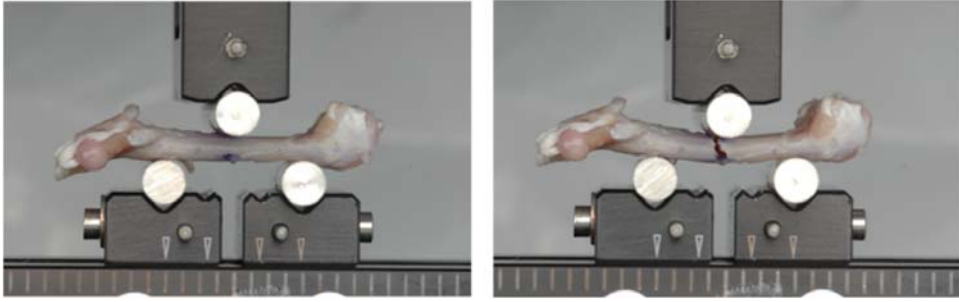


Figure 2.13: Three-point bending test with rat femur using the MTS 642.001 Bend Fixtures (Bone Imaging Laboratory, University of Calgary [12]).

Combined loads

The axial load is transmitted via two SKF angular contact ball bearings (2x 7202 BECBP DB, Kinacor, Calgary, Canada). The bearings are mounted on a $\varnothing 15$ mm shaft and secured with a M14 internal tab washer (DIN 462) and a M14 slotted round nut (DIN 1804). This configuration allows the application of combined loads (e.g., compressive and torsional) to the specimen.

2.5.2 Data acquisition

The load sensors need to be able to measure loads in a wide range. Piezo-crystal sensors or strain gauges can be used. Piezo-crystals start to drift under static loads and therefore a sensor with strain gauges is used. It is difficult to find a sensor that combines such high axial loads (10,000 N) with torque measurements. Two different sensors could be used but a combined one is preferable due to limited space. A-Tech Instruments Ltd. (Scarborough, Canada) supplies a flange mount reaction torque sensor ($\pm 2,000$ in lbs = ± 226 Nm, Transducer Techniques Inc., Temecula, CA, USA) with a thrust bridge option ($\pm 2,000$ lbs = $\pm 8,896$ N) and the other components needed to acquire the data (see table 2.8 for a complete list). The sensor is connected to a Dataforth data acquisition system (isoLynx SLX718B-U with 8B38 strain gage input modules, Dataforth Corporation, Tucson, AZ, USA) that plugs into any computer with USB. The data is recorded with the included WINDAQ recording software.

The angular displacement is measured using a 100 turn geared potentiometer (ML100-1K 125MB, Novotechnik U.S. Inc., Southborough, MA, USA) that is connected to the worm gearbox with spur gears (see table 2.10, Stock Drive Products/Sterling Instrument, New Hyde Park, NY, USA). A MUP100-1 signal conditioning module provides the potentiometer with a highly stable, constant voltage. A DC/DC displacement transducer (8740-5025, burster präzisionsmesstechnik gmbh & co kg, Gernsbach, Germany) measures the linear displacement up to 25 mm. Both signals are conditioned with a Dataforth voltage input module (8B31) placed in the isoLynx box.

All components used for data acquisition are shown in figure 2.14 and listed in table 2.8.

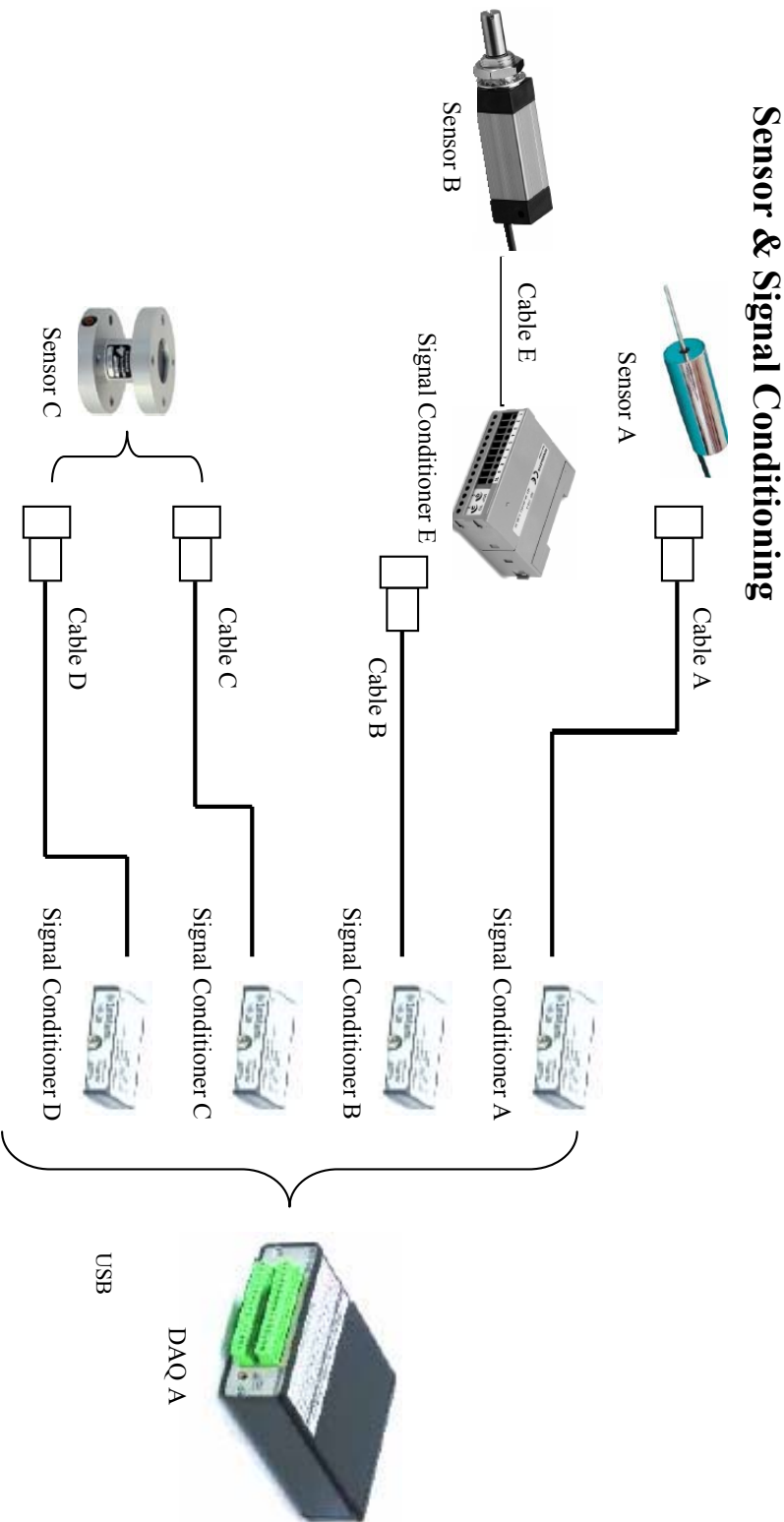


Figure 2.14: Equipment diagram showing components used for data acquisition (A-Tech Instruments Ltd., Scarborough, Ontario, Canada).

Table 2.8: List of components for data acquisition supplied by A-Tech Instruments Ltd., Scarborough, Canada.

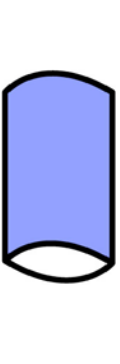
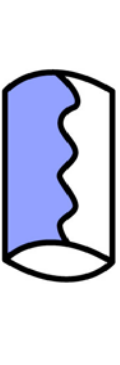
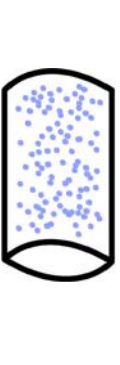
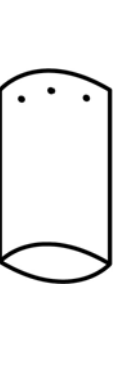
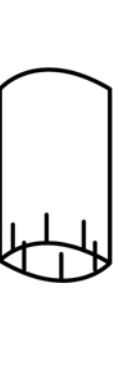
title	model #	description
sensor A	8740-5025	DC/DC disp. transducer; 0-25 mm range; 0-5 Vdc o/p; 9-25 Vdc pwr required; 2 m integral cable
cable A	integral cable	sensor excitation cable
signal cond. A	8B31-02	analog voltage input module; ± 5 Vdc input; ± 5 Vdc o/p; 3Hz (-3dB); +5 Vdc@30 mA pwr required; 1500 Vrms isolation; 8B PCB mount
sensor B	ML100-1K 125MB	100 turn geared potentiometer, 1 k Ω
signal cond. E	MUP-100-1	signal conditioning module; potentiometer i/p; 0-10 Vdc o/p; 10 VDC reference voltage; 10-36 VDC supply
cable B	ZAXXX-ZAXXX-010-03(11288E)	10 ft. jumper cable
signal cond. B	8B31-03	analog voltage input module; ± 10 Vdc input; ± 5 Vdc o/p
sensor C	TRS-2K w/ TH-option	flange mount reaction torque sensor; ± 2000 in lbs ; ± 2 mV/V nom. o/p; 10 Vdc i/p; 10 ft int. cable with 4-pin Microtech conn. TH-thrust bridge option for TRS series torque sensors
cable C	integral cable	sensor excitation cable
signal cond. C	8B38-35	strain gage input module; ± 2 mV/V input; ± 5 Vdc o/p
cable D	integral cable	sensor excitation cable
signal cond. D	8B38-35	strain gage input module; ± 2 mV/V input; ± 5 Vdc o/p
DAQ A	SLX718B-U	IsoLynx benchtop enclosure; 8-channel; USB PC-connected operation; 9-36 Vdc pwr req.; 1000 VDC/peakAC ip-out iso, 500 VDC/peakAC ch-ch iso; 2 removable 16-position screw term. connectors

2.5.3 Solutions for scannable area where tests are performed

Due to its symmetry, a tube is the most obvious solution as a testing chamber. The specimen can be positioned in various orientations inside the tube. Filling the tube completely, or partially, with saline prevents the specimen from drying out. Misty and dry environments are other possibilities.

Different x-ray translucent materials are currently available on the market. Table 2.9 lists some of them as well as additional ideas presented in this subsection. A clear material is preferred to allow a view of the specimen during testing and therefore Plexiglas is chosen. Different kinds of Plexiglas exist. Cast acrylic has better machining properties and higher tensile strength than extruded and is thus used for the mechanical testing device. A tube with an outside diameter of $4\frac{1}{2}$ inches and wall thickness of $\frac{1}{4}$ inches was available at the University's machine shop. Calculations for a thinner wall show that a thickness of $\frac{1}{8}$ inches should withstand the required loads (see subsection 2.5.6). The tube can be fixed with glue, pins, screws, or a thread. Glue was chosen because of the brittle behavior of Plexiglas.

Table 2.9: Possibilities to design a x-ray translucent testing zone for bone specimen.

positioning				
environment	 in saline	 partly filled with saline	 mist	 dry
tube fixation	 glue	 pins	 screws	 thread
tube material	composite (PEEK)	Plexiglas (PMMA)	POM	Torlon
bone fixation	acrylic cement	glue	double-sided tape	pin

2.5.4 Purchased parts

The size within the scanner is given by the XtremeCT (see section 2.1). However, as much space as necessary can be used outside of the scanner. The chosen sensors for data acquisition and other acquired parts confine the design additionally. Table 2.10 lists all obtained parts with their prices and suppliers. The components for data acquisition (see subsection 2.5.2) are taken together as one position and listed under the supplier's name (A-Tech).

Table 2.10: Suppliers and prices of purchased parts.

part #	description	size [mm]	supplier	price
data acquisition		-	A-Tech	\$5,600
PF30-120	worm gearbox	70 x 28 x 60	Rino	\$450
P60-120	worm gearbox	125 x 54 x 150	Rino	\$900
7202 BECBP	SKF bearing	$O.D. = 35$	Kinecor	\$88
12MC47	split hub GN150	bore $\varnothing 12$	J.W.Winco	\$15
10W80B68/A	gear lever	$l = 80$	J.W.Winco	\$5
10MC22/N	crank handle	$l = 63$	J.W.Winco	\$15
140FSNB	slotted round nut	M14 x 1.5	J.W.Winco	\$12
S1VS10M025	fairloc gear	bore $\varnothing 6$	SDP/SI	\$25
A1B2MY10050	spur gear	bore $\varnothing 10$	SDP/SI	\$23
total cost				\$7,134

2.5.5 Computer aided design (CAD) - SolidWorks

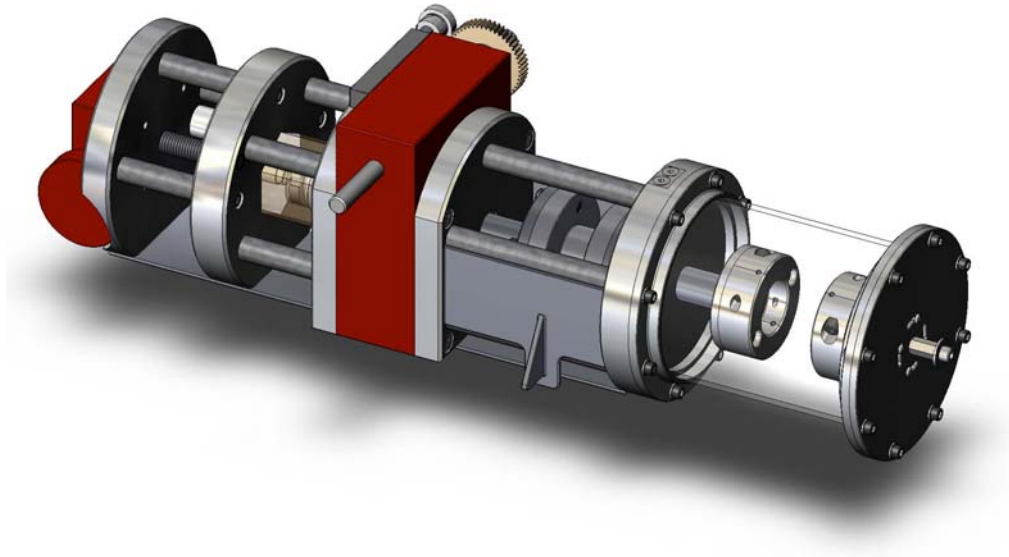


Figure 2.15: Final assembly of mechanical testing device. Overworked appearance with SolidWorks 2007. The previous version can be found in Appendix A.

The mechanical testing device has been split up into three functional modules:

- axial load
- torque
- testing zone

Each module is designed on SolidWorks (Education Editions 2006 SP4.1 and 2007, SolidWorks Corporation, Concord, MA, USA) and then added together in an assembly (figure 2.15). The interfaces have to be considered carefully so that no module is interfering with another (e.g., axial load module prevents shaft from rotating). The principles of the modules were described previously in subsection 2.5.1. Only the arrangements of the final parts are presented here. The CAD data are available at the Bone Imaging Laboratory (University of Calgary).

Steel spacing rods with a diameter of $5/8$ inch and of varying lengths are used to hold plates at certain distances and give the whole device its rigid structure. They allow a section-wise disassembly. The rods are fixed to the plates with $1/4$ -20 x 1 socket head cap screws.

Figure 2.21 at the end of this subsection shows the dimensions of the final mechanical testing device. The device has a total length of about 650 mm. Other views (e.g., front) can be found in Appendix A.

A variation with cover plates (figure 2.20) was designed first but then abandoned due to longer production time. The large shaft ($D = 58$ mm) used to create axial load was replaced with a 2 inch hexagonal rod that was easily available at the machine shop.

Module - axial load

A round 20 mm thick aluminum plate (part (1) in Figure 2.16) holds the LVDT (2) and the worm gearbox (3) that creates the axial load. Threaded holes are provided to fasten the bottom plate with two #6 - 32 x 3/4 button head cap screws. An additional 1/4 - 20 tap drill on the bottom allows the use of a standard tripod for weight support. The LVDT is fixed with a threaded cap (4).

The 1/8 inch aluminum bottom plate and three 5/8 inch steel rods (10) keep the aluminum plate 60 mm away from a 25 mm steel plate (5). The plate serves as a hub for the 2 inch brass hex-shaft (6) that transforms the torsion into an axial load. The LVDT is connected with a connector (7) and a flange (8) that retains the bearings (see next paragraph). Six #10 - 24 x 0.625 button head cap screws secure the flange on the hex-shaft.

A threaded shaft (9) goes into the axial moving hex-rod and is fixed to the gearbox with an external retaining ring ((11) DIN 471). The load from the gearbox is transferred with a 22 mm long standard key (12) to the shaft whose diameter belongs to tolerance class h7. A 1/8 inch pin (13) in the hex-shaft serves as a guide so that the shaft is not moved too far.

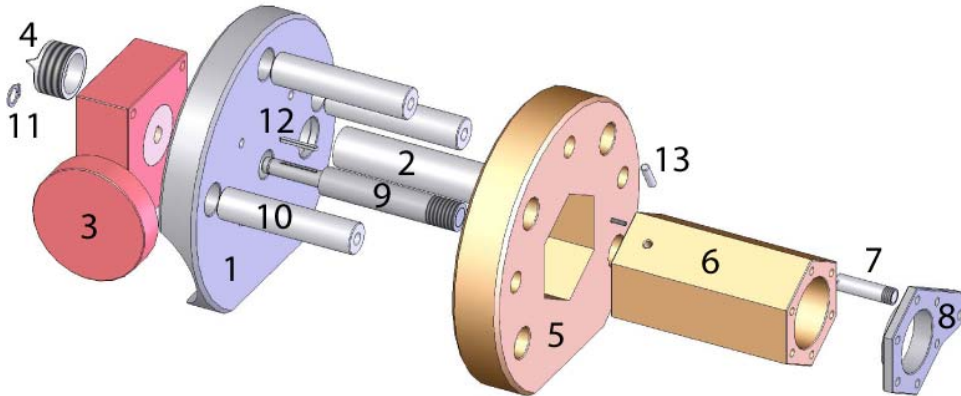


Figure 2.16: Parts to create axial load and to measure linear displacement. The numbers represent the following parts: (1) 20 mm aluminum plate, (2) LVDT, (3) worm gearbox PF30-120, (4) cap to fix LVDT, (5) 25 mm steel plate, (6) hex-shaft, (7) connector, (8) flange, (9) threaded shaft, (10) 71 mm spacing rods, (11) external retaining ring, (12) round-ended key, and (13) pin.

Module - torque

The larger worm gearbox P60-120 (part (1) in figure 2.17) is held between two aluminum plates by four 5/16 - 24 x 3.25 socket head cap screws. Both plates are 18 mm wide and the left one (2) holds a potentiometer (3) that measures the angular displacement. The potentiometer is connected to the input shaft of the gearbox with two gears (4) and (5) that have a ratio of 2:1.

The torque created with the gearbox is transferred to a 20 mm shaft (6) with a 26 mm long sliding key (7). The shaft also transmits the axial load and thus slides in the gearbox. Tolerances for the shaft and the hub are g6 and H8, respectively. Two bearings (8) allow the rotations while the axial load is applied. The bearings are fixed to the shaft with a DIN 462 washer (9) and a M14 nut ((10), DIN 1804). A flange (11) in-between ensures the proper fixation.

The load sensor (12) is connected to the right side of the shaft with four 1/4 - 20 x 1 socket head cap screws. Rings (13) are used to align the sensor and the connecting shafts. 69 mm (14) and 135 mm rods (15) represent the link to the other modules. The 125 mm rod (16) has only a decorative purpose. Two steel plates (17) that carry the weight of the device are welded on the 135 mm rods.

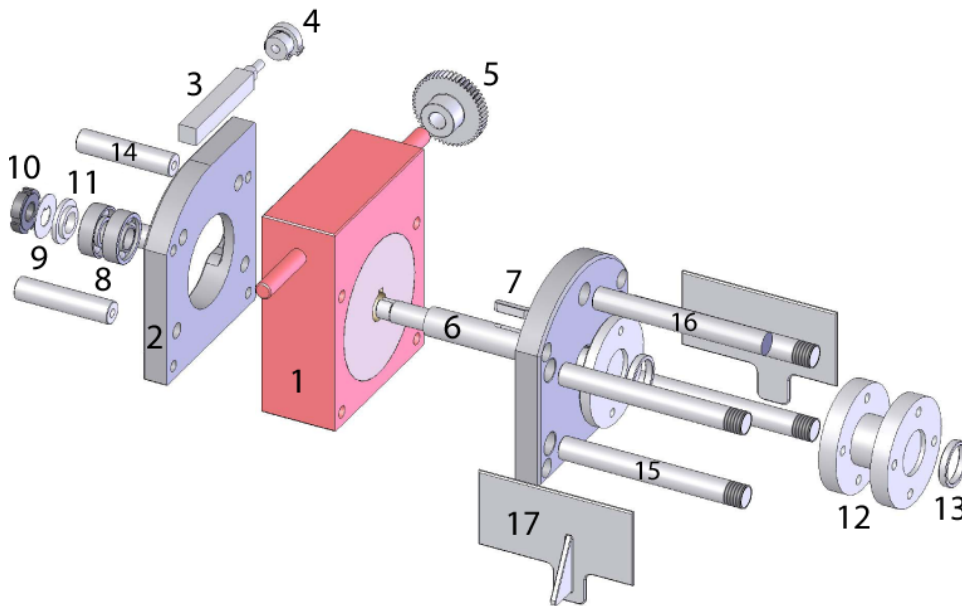


Figure 2.17: Parts to create torque and to measure angular displacement. The parts are represented by the following numbers: (1) worm gearbox P60-120, (2) aluminum plate, (3) potentiometer, (4) simplified fairloc gear, (5) spur gear, (6) shaft, (7) key, (8) bearings, (9) washer, (10) M14 nut, (11) flange, (12) load sensor, (13) centering rings, (14) 69 mm rods, (15) 135 mm threaded rods, (16) 125 mm decorative rod, and (17) supporting side plates.

Module - testing zone

A acrylic cast tube (part (1) in figure 2.19) defines the testing zone. It comes in two different lengths (i.e., 140 and 195 mm). Two flanges (2) are glued to the tube and allow fixation on the end plates with #10 - 24 x 0.625 socket head cap screws. End plate (3) has a hole where the shaft (4) that is connected to the force sensor enters. A round joint plate (5) is attached to the shaft with a 1/4 - 20 x 0.625 screw. One of the following attachments fits on the joint plate and can be chosen according to the test setup:

- holders (6) where the specimen can be embedded with bone cement,
- flat plates,
- or a 45° rod for cantilever bending.

Figure 2.18 shows the three different attachments. A 1/8 steel rod can be placed inside the holders for tensile testing. The reusable holders consist of two pieces that allow extracting of the bone cement after the experiments.

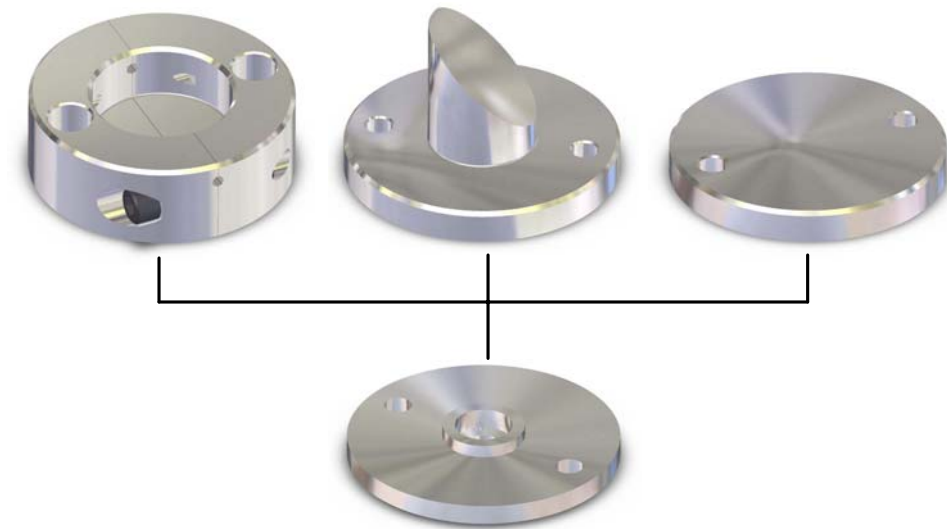


Figure 2.18: Alternatives that can be attached to the joint plate inside the tube and used for different test setups. From left to right: cement holder, 45° rod, and flat plate.

Another round joint plate (7) is attached to a joint rod (8) that is fixed with four #5 - 44 x 0.375 screws to the right end plate (9). The joint comes in three lengths (i.e., 20, 40, and 60 mm). These and the two tubes ensure a modular system for various specimens. Two holes are tapped to the left plate (5) while the right one (7) has two clearance holes. This ensures that the attachments can be fixed from one side of the tube. Two aluminum rods are placed in the same holes to guarantee proper alignment while the bones are cemented in the holders. They are removed for the scanning. Two sets of rods exist, one for each tube length. They are marked to see which joint rod (8) has to be used.

A screw and a tab washer (10) support the device inside the scanner much like the phantom (figure 2.4). The testing zone is sealed off with 5 O-rings of the sizes 129 (11), 211 (12), and 247 (13).

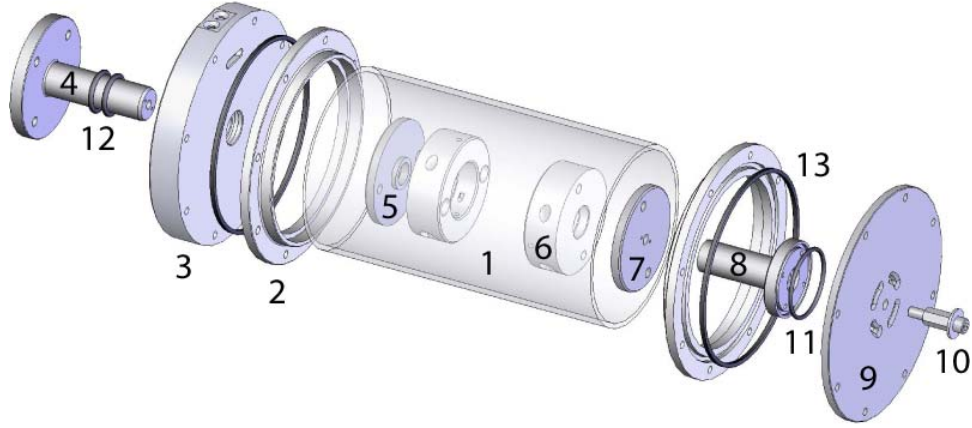


Figure 2.19: Parts representing the testing zone: (1) acrylic cast tube, (2) flanges, (3) left end plate, (4) shaft, (5) joint plate with threaded holes, (6) holders, (7) joint plate with clearance holes, (8) joint rod, (9) right end plate, (10) support screw, (11) 129 O-ring, (12) 211 O-rings, and (13) 247 O-rings.

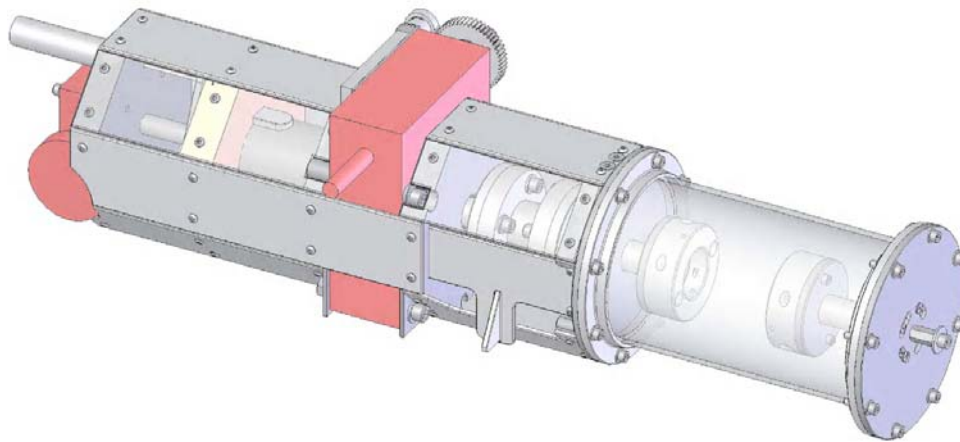


Figure 2.20: Mechanical testing device with cover plates (old design).

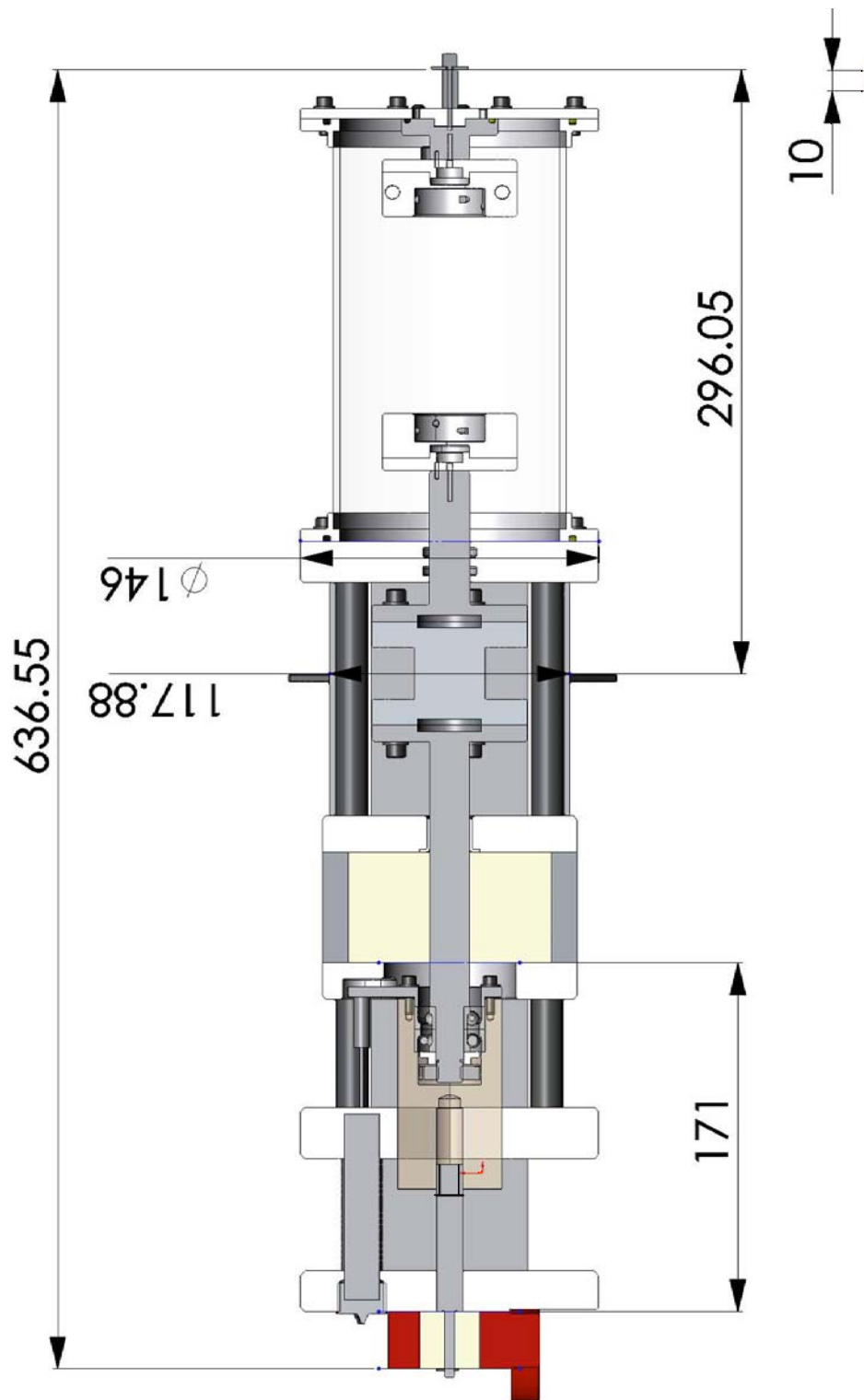


Figure 2.21: Dimensions of mechanical testing device in mm. The figure shows a sectional view from the top in the middle. The device fits between the two bars at the opening of the scanner (117.88 mm width). The maximal length inside the scanner is 296.05 mm.

2.5.6 Calculations

Different components of the mechanical testing device are verified with calculations according to *Grundlagen der Produkt-Entwicklung* and *Dimensionieren I & II* by Prof. Dr. Markus Meier (lecture scripts SS 2005, WS 2005-06, ETH Zurich, Switzerland). Designing loads are $F_{x,max} = 8,000$ N for the axial force and $T_{max} = 25$ Nm for torsion.

Tube

The tube with an outside diameter of $D = 4\frac{1}{2}$ inches = 114.3 mm and a wall thickness of $s = \frac{1}{8}$ inches = 3.175 mm has a polar moment of inertia given by:

$$J = \frac{\pi}{32} \cdot (D^4 - d^4) = \frac{\pi}{32} \cdot (114.3^4 - (114.3 - 2 \cdot 3.175)^4) = 3,424,706.2 \text{ mm}^4. \quad (2.3)$$

The shear stress is maximal at the outside of the tube. Using equation 2.1 gives $\tau_{max} = 0.42$ N/mm².

A tensile load acting upon the tube when the specimen is compressed will result in a tensile stress of:

$$\sigma_{x,max} = \frac{F_{x,max}}{A} = \frac{8,000}{1,108.42} = 7.21 \text{ N/mm}^2, \quad (2.4)$$

where

$$A = \frac{\pi}{4} \cdot (D^2 - d^2) = \frac{\pi}{4} \cdot (114.3^2 - 107.95^2) = 1,108.42 \text{ mm}^2 \quad (2.5)$$

is the cross sectional area of the tube. The maximal stress for comparison σ_v can be calculated using the normal stress hypothesis that combines shear with normal stress:

$$\begin{aligned} \sigma_v &= \frac{\sigma_{x,max}}{2} + \frac{1}{2} \cdot \sqrt{\sigma_{x,max}^2 + 4 \cdot \tau_{max}^2} \\ &= \frac{7.21}{2} + \frac{1}{2} \cdot \sqrt{7.21^2 + 4 \cdot 0.42^2} = 7.23 \text{ N/mm}^2. \end{aligned} \quad (2.6)$$

Adding a safety factor $S_B = 2$ and comparing to the tensile strength of acrylic PMMA ($\sigma_B = 55$ MPa, www.boedeker.com) shows that the tube should withstand the applied loads:

$$\sigma_v \cdot S_B = 7.23 \cdot 2 = 14.46 \text{ N/mm}^2 \leq \sigma_B = 55 \text{ N/mm}^2. \quad (2.7)$$

Required torque to create thrust

The thrust is created with an acme screw thread (Tr 12 x 2) which requires a certain torque M_T given by:

$$M_T = \frac{d_2}{2} \cdot F_x \cdot \tan(\alpha), \quad (2.8)$$

where d_2 is the pitch diameter, and α the pitch angle. Pitch angle can be calculated from the thread pitch P :

$$\tan(\alpha) = \frac{P}{\pi \cdot d_2}. \quad (2.9)$$

Thus the torque needed to compress a specimen with $F_{x,max}$ is:

$$M_T = \frac{F_{x,max}}{2} \cdot \frac{P}{\pi} = \frac{8,000 \cdot 0.002}{2\pi} = 2.55 \text{ Nm}. \quad (2.10)$$

The gearbox PF30-120 has a maximal output torque of 6.70 Nm which is high enough to create M_T .

Shaft-to-hub connections

Keys are the most common shaft-to-hub connections for torque transmission. Critical components next to the key are the hub and shaft. Surface pressure on the hub is typically most critical. The maximal allowed torque to transmit is:

$$M_{t,zul} = \frac{p_{zul} \cdot D \cdot l_{tr} \cdot (h - t)}{2}, \quad (2.11)$$

where D is the shaft diameter, $l_{tr} = (l_k - 2 \cdot r_k)$ the supporting key length (l_k : length of key, r_k : radius of round-ended feather key), h the key height, t the supporting key height, and p_{zul} the maximal tolerated stress:

$$p_{zul} = \frac{\sigma_F}{S_F}, \quad (2.12)$$

where σ_F is the tensile strength for ductile materials and S_F a safety factor:

- $S_F = 1.3 - 2.5$ for tightly keys
- $S_F = 3.0 - 4.0$ for loosely fitted keys

Three shaft-to-hub connections are used in the mechanical testing device. A tightly fitted round-ended feather key connects the PF30-120 gearbox with the threaded shaft ($\varnothing 8$ mm) that creates the thrust. The parameters used to calculate $M_{t,zul}$ are: $\sigma_F = \text{N/mm}^2$, $S_F = 2.5$, $D = 8$ mm, $l_{tr} = 18$ mm, $h = 2$ mm, and $t = 1.2$ mm. Therefore,

$$M_{t,zul} = \frac{\frac{\sigma_F}{S_F} \cdot D \cdot l_{tr} \cdot (h - t)}{2} = \frac{\frac{800}{2.5} \cdot 8 \cdot 18 \cdot (2 - 1.2)}{2} = 18,432 \text{ Nmm.} \quad (2.13)$$

Using torque M_T previously calculated in equation 2.10 for comparison shows that the required torque can be transmitted using this shaft-to-hub connection:

$$M_{t,zul} \approx 18 \text{ Nm} \geq M_T \approx 3 \text{ Nm.} \quad (2.14)$$

A loosely fitted round-ended feather key is needed additionally for the thrust module. It prevents rotation while allowing angular displacement. This part is only used in the first version (figure 2.20) and then replaced by a 2 inch hex-rod.

$$M_{t,zul} = \frac{\frac{800}{4} \cdot 58 \cdot 40 \cdot (10 - 6)}{2} = 928 \text{ Nm,} \quad (2.15)$$

where $\sigma_F = 800 \text{ N/mm}^2$, $S_F = 4$, $D = 58$ mm, $l_{tr} = 40$ mm, $h = 10$ mm, and $t = 6$ mm. The maximal tolerated torque is again compared with M_T :

$$M_{t,zul} \approx 928 \text{ Nm} \geq M_T \approx 3 \text{ Nm.} \quad (2.16)$$

Thus, the thrust module should withstand the loads.

Another loosely fitted key is used to create the torque T with the P60-120 gearbox. A rough estimation of the shaft diameter d_{est} (equation 2.17) shows, that $D = 20$ mm is sufficient. Equation 2.17 results out of equations 2.1 and 2.3.

$$d_{est} = \sqrt[3]{\frac{16 \cdot T_{max}}{\pi \cdot \tau_{zul}}} = \sqrt[3]{\frac{16 \cdot 25,000}{\pi \cdot 100}} = 10.8 \text{ mm} \leq D, \quad (2.17)$$

where

$$\tau_{zul} = \frac{\sigma_F}{S} = \frac{800}{8} = 100 \text{ N/mm}^2 \quad (2.18)$$

is the maximal tolerated shear stress for the shaft and $S = 8$ a safety factor.

Using $\sigma_F = 800 \text{ N/mm}^2$, $S_F = 4$, $D = 20 \text{ mm}$, $l_{tr} = 20 \text{ mm}$, $h = 6 \text{ mm}$, and $t = 3.5 \text{ mm}$ will result in a maximal tolerated torque $M_{t,zul} = 100 \text{ Nm}$ which is larger than T_{max} .

The feather key itself has to withstand shear stress and surface pressure. The key for the torque module experiences the following maximal shear stress τ at the linking layer between the shaft and the hub:

$$\tau = \frac{2 \cdot T_{max}}{D \cdot b \cdot l_{tr}} = \frac{2 \cdot 25,000}{58 \cdot 16 \cdot 40} = 1.35 \text{ N/mm}^2, \quad (2.19)$$

where $b = 16$ is the width of the key. The surface pressure for the shaft is

$$\sigma_x = \frac{F_{x,max}}{A} = \frac{8,000}{314.16} = 25.46 \text{ N/mm}^2, \quad (2.20)$$

where $A = \frac{\pi}{4} \cdot D^2$ is the cross-sectional area of the shaft with diameter $D = 20 \text{ mm}$. Using this value and the changing shape hypothesis (equation 2.21) gives the stress for comparison σ_v which is smaller than the key's maximal tolerated stress $p_{zul} = \frac{\sigma_F}{S_F} = \frac{400}{2} = 200 \text{ N/mm}^2$.

$$\sigma_v = \sqrt{\sigma_x^2 + 3 \cdot \tau^2} = \sqrt{25.46^2 + 3 \cdot 1.35^2} \approx 26 \text{ N/mm}^2 \leq p_{zul}. \quad (2.21)$$

The highest stress of the shaft appears in the ground radius of the groove (Nutgrun-dradius) and in the groove ends (Nutrand). The shear stress resulting from torsion is:

$$\tau_{max} = \alpha_\tau \frac{T_{max} \cdot D}{2 \cdot J}, \quad (2.22)$$

where α_τ is a form factor and determined with figure 2.22. Since the shaft is a full circle equation 2.3 changes to:

$$J = \frac{\pi}{32} \cdot D^4. \quad (2.23)$$

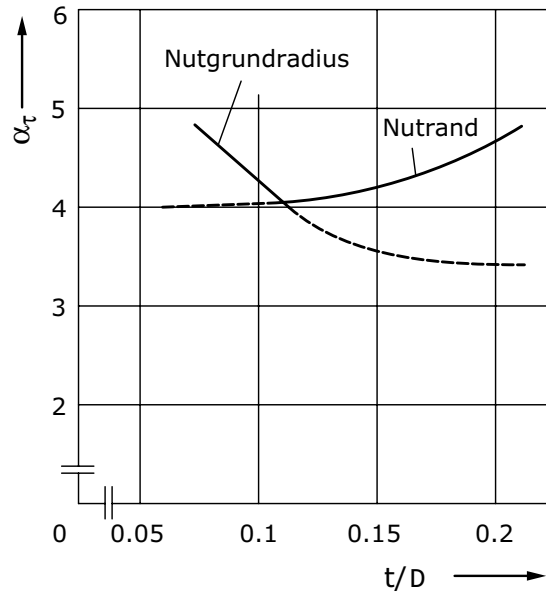


Figure 2.22: Increasing stress due to static torsion where t is the supporting key height (lecture script *Dimensionieren II*, Prof. Dr. M. Meier, ETHZ, Switzerland).

The strain stress hypothesis can be used to calculate the maximal stress:

$$\sigma_v = 2 \cdot \tau_{max} \quad (2.24)$$

Different values for the three shaft-to-hub connections are listed in Table 2.11. All σ_v are smaller than $p_{zul} = 400 \text{ N/mm}^2$ and thus the connections should withstand the torsional load.

Table 2.11: Maximal shear stresses for groove grounds and ends. Values for the form factor are extracted from figure 2.22 using the shaft diameter D and the groove depth t . The maximal stress for comparison σ_v is calculated according to the strain stress hypothesis (equation 2.24). Stresses for the big shaft ($D = 58 \text{ mm}$) are fairly small due to its high polar moment.

D [mm]	t [mm]	α_τ [-]		T_{max} [Nm]	τ_{max} [N/mm ²]		σ_v [N/mm ²]	
		ground	ends		ground	ends	ground	ends
8	1.2	3.65	4.25	3	108.9	126.8	217.8	253.6
58	6.0	4.20	4.05	3	0.33	0.32	0.66	0.64
20	3.5	3.50	4.45	25	55.7	70.8	111.4	141.6

2.6 Sensor calibration

This section describes how to relate the LVDT and potentiometer to the rotations of the worm & wheel reduction gearboxes. Both sensors were previously calibrated by the supplier. It is recommended to recalibrate the LVDT in 24 month intervals. Subsection 2.6.3 discusses the calibration of the load sensor, which should be recalibrated every 12 months.

2.6.1 Linear displacement

The chosen acme screw thread has a pitch of 2 mm. A single rotation of the input shaft on the small gearbox corresponds to a $1/120$ rotation of the threaded shaft resulting in a linear displacement of $16.6 \mu\text{m}$. A resolution of approximately $85 \mu\text{m}$ can be achieved using the XtremeCT's scout-view feature. The mechanical testing device is placed with the flat plates inside the scanner and the distance between the two plates measured in the scout-view while the LVDT value recorded. After ten rotations of the input shaft a second distance measurement is recorded and the actual displacement calculated as the difference between the two measurements. The input shaft is again rotated ten times and another distance recorded. This process is repeated several times until the plates have moved considerably. The recorded data from the LVDT can now be compared to the physically measured ones. The LVDT does not have to resolve linear displacement beyond the resolution of the scanner. Therefore, the detection of the displacement of five input shaft rotations is sufficient.

2.6.2 Angular displacement

fiber

The procedure to measure angular displacement is similar to that of linear displacement. A single rotation of the input shaft of the large gearbox results in a 3° shaft rotation. The potentiometer achieves 100 revolutions and therefore a specimen can be twisted 150° as the gears that connect the sensor to the input shaft have a 2:1 ratio. Four steel or carbon fiber rods are fixed on the outside of the right holder. Two rods are taped to half of the holder mounted on the left side such that the rods overlap each other. This is illustrated in figure 2.23.

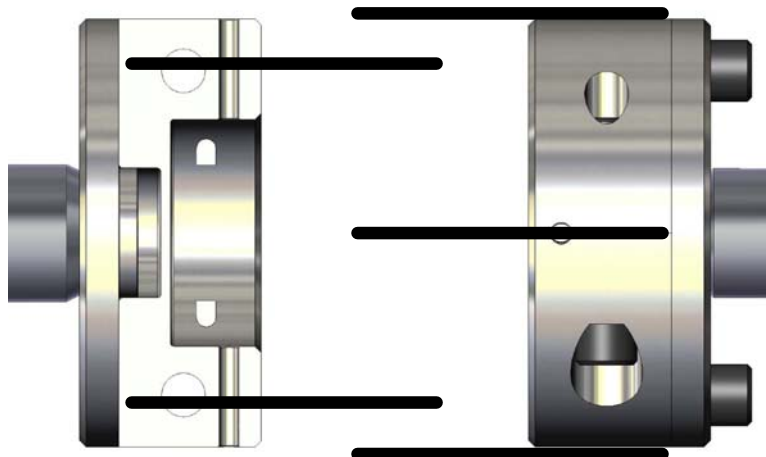


Figure 2.23: Sketch of setup used for calibrating the angular displacement.

An initial image is taken with the XtremeCT while the output of the potentiometer is recorded. The input shaft is rotated once again and another scan performed. This procedure is repeated 20 times in the one direction and the whole process repeated again for the shaft rotating in the opposite direction. The angle of rotation can be determined using either the XtremeCT's evaluation software or an external program (e.g., ImageJ, <http://rsb.info.nih.gov/ij/download.html>) and then related to the recorded values of the potentiometer.

2.6.3 Load cell

The load sensor was calibrated by the manufacturer. Table 2.12 gives the values for compression and torque (clockwise and counter clockwise). These results can be controlled with an universal testing machine (e.g., MTS 858 MiniBionix II) by applying certain loads. A custom holder is required if the torque cannot be tested on the machine. Weights can be used to perform a calibration for lower loads.

Table 2.12: Calibration of the load sensor by the manufacturer (1 lbs = 4.448 N).

calibration	thrust		torque	
	load [lbs]	signal [mV/V]	load [in.lbs.]	signal [mV/V]
compression	1,512.6	0.5060	580.9	0.5071
	3,025.3	1.0120	1,161.7	1.0142
clockwise torque	1,507.3	0.5060	1,161.2	1.0137
	3,014.6	1.0120	2,322.3	2.0274
counter clockwise	1,577.1	0.5060	1,148.1	1.0137
	3,154.1	1.0120	2,296.3	2.0274

2.7 Testing of the device

Experiments to test the capabilities of the mechanical testing device are presented in this section. Table 2.13 lists different tests to be implemented. They cannot be accomplished within the scope of this thesis due to time limitations. The specimens are undefined as it is not known what will be available at the time of testing. Some tests can also be performed with artificial materials (e.g., aluminum foams) instead of bone samples and then compared to their known tissue properties. A preload should be applied prior to all tests to eliminate any play inside the device. No definitive amounts can currently be given and have to be determined at the time of testing.

One of the main tasks of this thesis was to build a device that allows the testing of torsional loads applied to a specimen. A specimen is therefore fixed on both ends in the specially designed aluminum holders. The holders and the specimen are placed inside the loading device and preloaded. The lever on the large worm gearbox is half-turned which corresponds to a shaft rotation of 1.5° . After 5 minutes the device is placed inside the XtremeCT and scanned. During this time the load sensor continually records to determine relaxation. The shaft is rotated in 1.5° increments, and scanned after each, until failure of the specimen occurs.

Compressive and tensile tests are done in different steps according to the specimen size and expected failure loads. They can be combined with torsional loads. Other specimens are tested in the cantilever bending setup. In this case, the specimen is cemented into one holder and the bending adapter moved at 1 mm steps. After each step, the specimen is scanned in the XtremeCT.

Table 2.13: Tests to be implemented using the mechanical testing device. The specimens are just examples and can be replaced as desired.

test	specimen	iteration
cantilever bending	e.g. rat femur	2 mm
compression	e.g. human vertebra	0.5 mm
tension	e.g. screw in trabecular bone	0.5 mm
torsion	e.g. rat femur	1.5°
torsion & compression	e.g. human radius	1.5° and 4 mm
three-point bending	e.g. mouse femur	0.2 mm

2.7.1 Leak tightness

The tube is filled with water to test for handling and leaks. This test is performed outside the scanner. The shaft is axially moved and rotated several times while the testing zone is filled with liquid.

2.7.2 Experiments with and without saline

A bone sample (e.g., section of human radius) is scanned twice, once in saline and then a second time without. The resolution of the trabecular bone is then compared to determine any deviations.

2.7.3 Influence of the tube

The effects of the tube, which defines the testing zone, on the mechanical testing is investigated using the following tests:

Tube material and wall thickness

Different x-ray translucent materials for making the tube are available (see table 2.9 in subsection 2.5.3). Plexiglas was chosen due to its transparency which is an advantage while testing. Although a wall thickness of $\frac{1}{8}$ inches would be sufficient (equation 2.7), a tube with a $\frac{1}{4}$ inches wall was used as it was readily available at the machine shop. A second tube can be put over the testing device to determine the influence of wall thickness while a specimen (i.e., bone sample or aluminum foam) is being scanned. The same specimen is also scanned in a carbon fiber tube (figure 2.3) to see whether the tube material has any influence on scan quality.

Compliance in torsional and axial loading

The setup with the longest joint rod and the shorter tube is used to test the compliance of tube in torsional and axial loading. Both fixation plates are screwed together and a compressive load (i.e., 1,000 N) applied. An additional torque of 10 Nm is exerted and held for 20 min. The tube (or some other part of the device) has deformed if a force can be measured when the levers on the input shafts are returned to their original positions. The same loads are applied again after a 30 min duration and the force curves of the load sensor compared to those measured previously.

Chapter 3

Results

The final mechanical testing device and modifications made during production are presented in this chapter.

3.1 Mechanical testing device

Figure 3.1 shows the final testing device which was produced at the University of Calgary's machine shop according to the SolidWorks drawings presented in subsection 2.5.5. Some changes were made during production and are presented in subsection 3.1.1. The device mounted in the XtremeCT can be seen in Figure 3.2. A tripod is used to support the weight. Production was one month delayed to the original plan as the machine shop had too much work to do (see Appendix B).

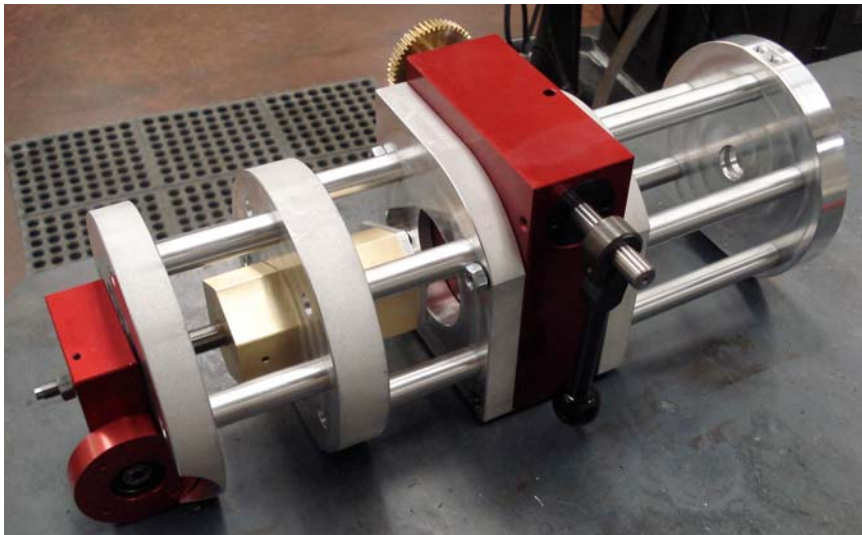


Figure 3.1: Mechanical testing device.



Figure 3.2: Mounted mechanical testing device in XtremeCT. The device is supported by a standard tripod (not shown in image).

3.1.1 Modifications to original design

Several adjustments were made during the course of production, and are listed in this subsection. The influences will be discussed later in section 4.2.

No acme thread

A $1/2 - 20$ UNF thread was tapped in the 2 inch hex-shaft in place of an acme Tr 12 x 2 as the machine shop is equipped with imperial rather than metric tools.

Plate and rod material

To minimize cost, the 25 mm steel plate was replaced with one made of aluminum reducing weight and production time. Additionally, aluminum rods were used instead of steel ones. All aluminum parts were anodized for a hard finish.

LVDT fixation

As the cable exiting the LVDT is not centered, the threaded cap cannot be used. Instead, a split aluminum ring is placed between the LVDT and the end plate, and a locking screw is used to compress the ring, thus fixing the LVDT.

Potentiometer fixation

Figure 3.3 shows a steel plate used to fix the potentiometer to the left plate holding the P60-120. There is some play in the screw clearance holes such that the potentiometer's fairloc gear can easily be fit to the spur gear.



Figure 3.3: Steel plate designed on SolidWorks 2007 for potentiometer fixation. Extra clearance in the screw holes allows a good fit between the gears.

External retaining ring

A washer with a 5/16 inch nut was used instead of the external retaining ring (part (11) in figure 2.16) to fix the threaded shaft to the PF30-120 worm gearbox.

Supports

The support plates were replaced with two aluminum parts that can slide onto the rods. They are fixed by two #10 - 24 x 3/4 screws and can easily be adjusted. Figure 3.4 shows the new design drawn with SolidWorks 2007.



Figure 3.4: Redesigned adjustable support.

Liquid inlets

Two 1/16 NPT holes were tapped into the left plate that connects to the tube, allowing the testing zone to be filled with liquid. One releases the air while the liquid is filled through the other. A vacuum can also be applied to one and the liquid drawn through the second. Plugs or hose connectors can be attached.

Signal conditioner

A-tech Instruments Ltd. discovered during testing of the entire data acquisition system that the MUP-100-1 amplifier (signal conditioner E in figure 2.14) and the 8B31-03 module (signal conditioner B) can be replaced with a 8B36 potentiometer input module (i.e., 8B36-03: 0-1 k Ω input range, 0-5 Vdc o/p). The 10 ft. jumper cable (cable B) becomes redundant as well.

3.2 Calibration and experimental testing

The calibrations and tests presented in sections 2.6 and 2.7 were not accomplished as the device was not assembled on time. This should be the first step performed in future work. In doing so, the fact that the thread used for linear displacement has a 1.27 mm instead of a 2 mm pitch must be considered. One input shaft rotation on the smaller gearbox thus results in 10.6 μ m linear displacement.

Chapter 4

Discussion

In this chapter the mechanical testing device designed in this project is discussed and compared to existing devices. The modifications made during production are listed in section 4.2. No experiments or calibrations were performed due to time limitations. However, they can be done at a later date according to sections 2.6 and 2.7.

4.1 Comparison of existing devices with new design

A comparison of existing mechanical testing devices with the new multi-purpose one is difficult due to limited access to information. The major difference and advantage over existing ones is that this project's device can test multiple loading conditions. Not only can compression and tension tests be performed with the new device, torsional loads can also be applied to specimens separately or in combination with axial loads. As a result, torque and axial loads, as well as linear and angular displacements, can be measured.

The use of worm & wheel reduction gearboxes ensures an exact load application. High loads can be achieved with less force than with Paul Hulme's device. The weight could be kept low by machining parts out of aluminum. If they do not withstand the load, they have to be replaced with steel ones.

The distance of the sensors from the specimen was a point of consideration. Once a load is applied, the structure is quite rigid and the location of the axial displacement measured is not critical. The gearboxes do not have any backlash and the ratio of 120:1 minimizes any error made while measuring the angular displacement of the large gearbox's input shaft.

Any effects of the sealing rings on the measured loads as happened with Thomas Müller's device can be tested by removing the rings while loading a standardized spring. The standardized spring can also be used to test the reproducibility and resolution of the load sensor.

4.2 Effects of modifications

This section discusses the effects of any modifications made during production to improve and simplify the mechanical testing device. The CAD drawings are updated accordingly and the old ones are archived.

4.2.1 Thread used to create axial load

The 1/2 - 20 UNF thread has a pitch of 1.27 mm which is less than the designed 2 mm of the Tr 12 x 2 acme thread. This allows for finer adjustments of the axial load. However, the flank angle is twice that of the acme thread (i.e., 60° instead of 30°). An UNF thread is not intended for high axial loads as the apex of the threads may shear off. Therefore, the UNF thread may wear faster than the acme thread. The hex-shaft provides enough space to tap a different thread should the other wear out.

This results in only slight changes to the calculations:

The torque needed to compress a specimen with $F_{x,max}$ decreases due to the reduced thread pitch (see equation 2.10), and less force has to be transmitted with the gearbox.

4.2.2 Change of material

Aluminum was used instead of steel for the 25 mm plate that serves as a hub for the 2 inch brass hex-shaft. Reduced sliding ability could be observed during testing. The material of the hex-shaft itself may be too soft for the power transmission. A steel piece can be inserted if the thread in the hex-shaft wears off too easily and a change in the thread (i.e., acme thread) does not improve the situation. The aluminum rods should be able to withstand the expected loading conditions.

4.2.3 Fixation ring for LVDT

The aluminum ring that fixes the LVDT does not effect the performance of the mechanical testing device. The LVDT can still be removed without disassembling any other parts and there is no longer a cable attached.

4.2.4 Shaft fixation

Fixing the threaded shaft with a washer and nut substitutes the external retaining ring. This provides less play, a more rigid connection and easier assembly.

4.2.5 Adjustable support

The adjustable support allows the device to slide further inside the scanner when the shorter tube is in use. Nylon screws may have to be used to avoid scratching the aluminum rods if the parts are often adjusted. Replacing the aluminum rods with steel ones is another option.

4.2.6 Signal conditioner

The use of a 8B36 potentiometer input module simplified the system and made it cleaner. The cost was also reduced by \$344 as the MUP-100-1 amplifier and the ZAXXX-ZAXXX-010-03(11288E) jumper cable are not required anymore.

4.3 Delays in production

Production was delayed over a month (see Appendix B). The University's machine shop ensured in December that they would be able to start production by the middle of January. It actually commenced in the second week of February on a part-time basis. The device was completed at the end of March with no time remaining for testing.

4.3.1 Data acquisition (WinDaq)

It proved difficult to find an appropriate sensor, but this had no effect on the timing of the rest of the project. The program for the data collection (i.e., WinDaq) and the acquisition system arrived in the final week. It is installed on the lab computer and ready to use. Occupied channels are:

- Channel 1: thrust
- Channel 2: torque
- Channel 7: LVDT
- Channel 8: potentiometer

The limits can be adjusted under scaling and data recorded by pressing F4. A quick start guide can be found in the program folder. The channels have to be calibrated according to section 2.6 and page 15 of the user guide. A power supply between 9 and 28 VDC is needed for the LVDT and therefore a rechargeable 12 V battery is connected.

4.4 User recommendations

A few user recommendations to prevent damages and injuries are listed in this section:

- Never change loads while device is in scanner, especially when testing chamber is filled with liquid.
- Do not compress further than position indicated with pin.
- Make sure prior to testing that plates can move far enough.
- Always leave enough relaxation time.
- Do not overturn potentiometer (you can detach gear and rewind potentiometer manually)
- Do not use if leakage occurs.
- Do not drop.
- Support weight with tripod or other stand.
- Do not pull on cables.

Chapter 5

Prospect

Different bone samples and other specimens can now be mechanically tested and compared to finite element calculations. Results from such tests help to validate analysis methods. The best failure criterion for both compression and torsion can be found. However, sensors should first be calibrated according to the methods presented in section 2.6.

Defined movements of objects inside the scanner (i.e., rotation and axial displacement) can also provide an improved understanding of motion artifacts during patient scans (current study at the University of Calgary by Yves Pauchard).

Additional attachments like the bone cement holder and 45° rod can be produced and easily attached to the joint plate. The steel rods of the MTS bending device and the 45° rod may have to be replaced with a x-ray translucent material if image quality is affected. An acrylic plate can be glued to the top of the 45° rod if the contact area is of interest. Another device that helps with aligning bones while cementing may be needed. The effectiveness of the alignment rods needs to be determined first. The reproducibility of the device can be tested using a standardized spring or materials with known tissue properties (e.g., aluminum foams).

A stand may be needed for putting the specimens in the device. It can be made out of wood and should be able to hold the device in an upright position while the specimen is put in from the top. Another wood stand instead of the tripod can be used to support the weight.

Furthermore, the testing device could be equipped with motors which would allow for fully automated testing routines including fatigue testing. Safety switches should not be left out to prevent the device from being damaged.

The effects of the 211 O-rings upon the sensor could be tested by removing the sealing rings.

All CAD data are available at the Bone Imaging Laboratory (University of Calgary, Canada). Later changes can be performed on the same CAD models.

Chapter 6

Acknowledgments

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- Shannon Boucousis - Bone Imaging Laboratory, University of Calgary
- Bone Imaging Laboratory, University of Calgary
- Machine Shop, University of Calgary

Appendix A

Views of testing device

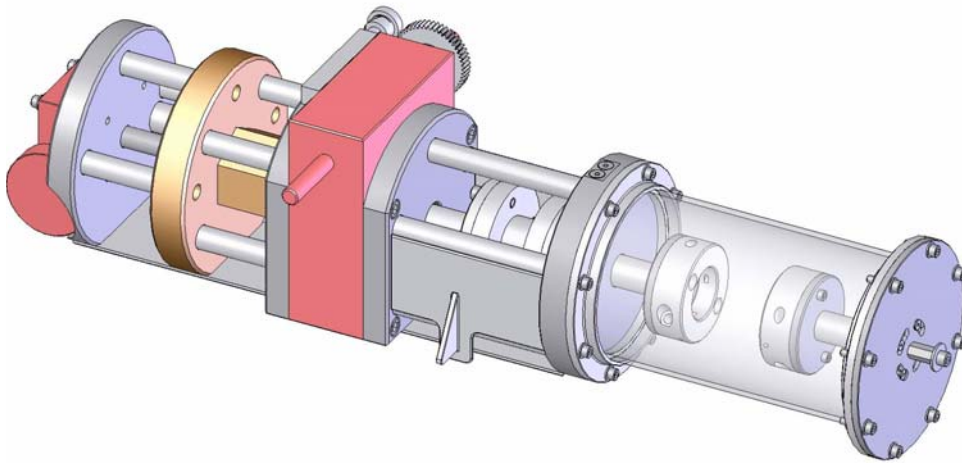


Figure A.1: Assembly of mechanical testing device (designed with SolidWorks 2006).

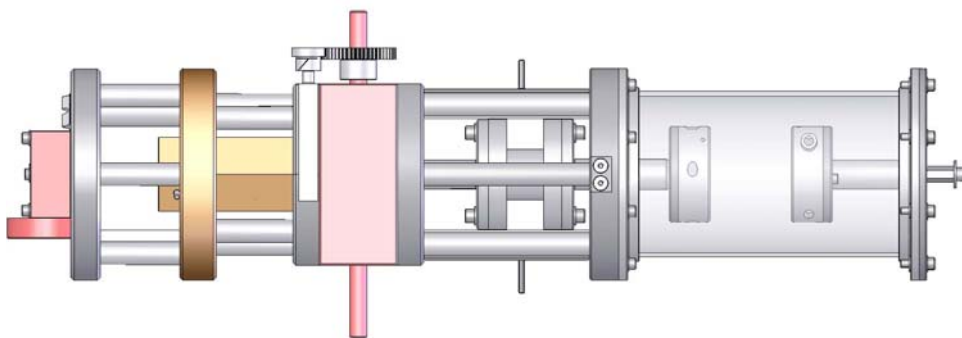


Figure A.2: Top view of mechanical testing device.

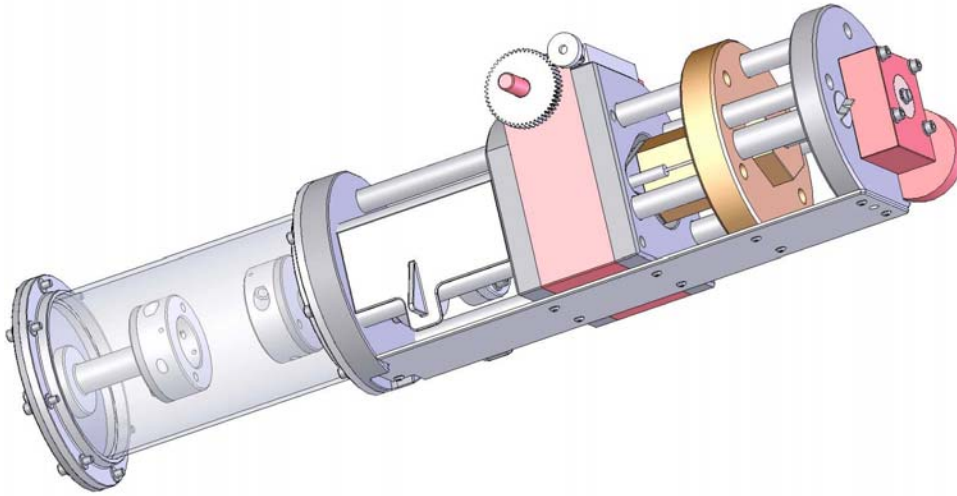


Figure A.3: Backside view of mechanical testing device.

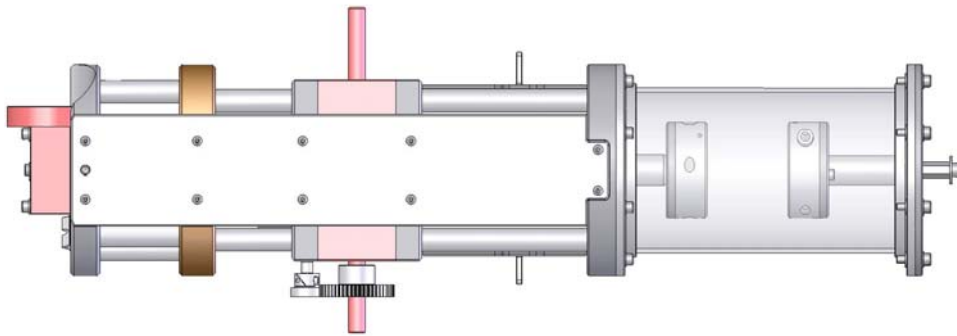


Figure A.4: Mechanical testing device's bottom view.

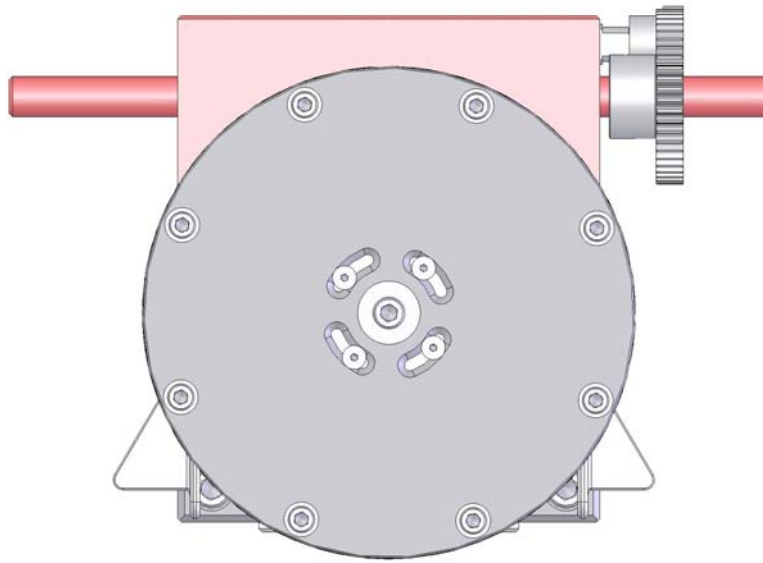


Figure A.5: Front of mechanical testing device.

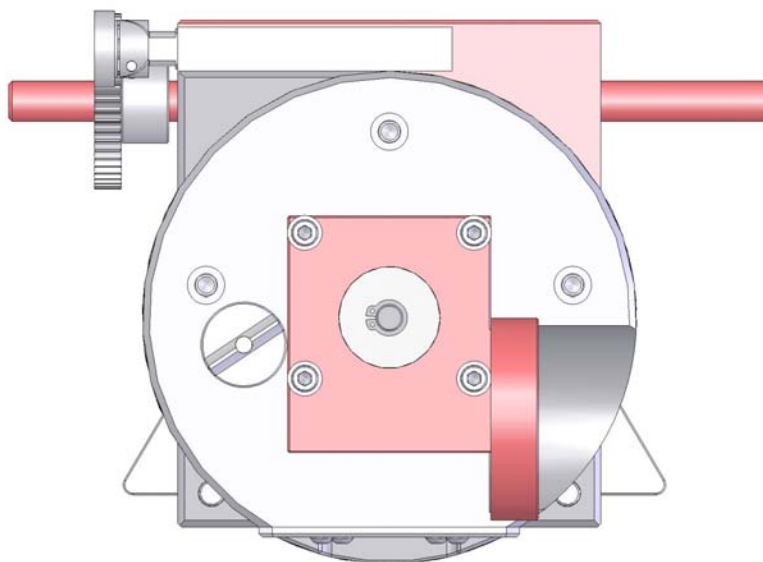


Figure A.6: Back of mechanical testing device.

Appendix B

Schedule

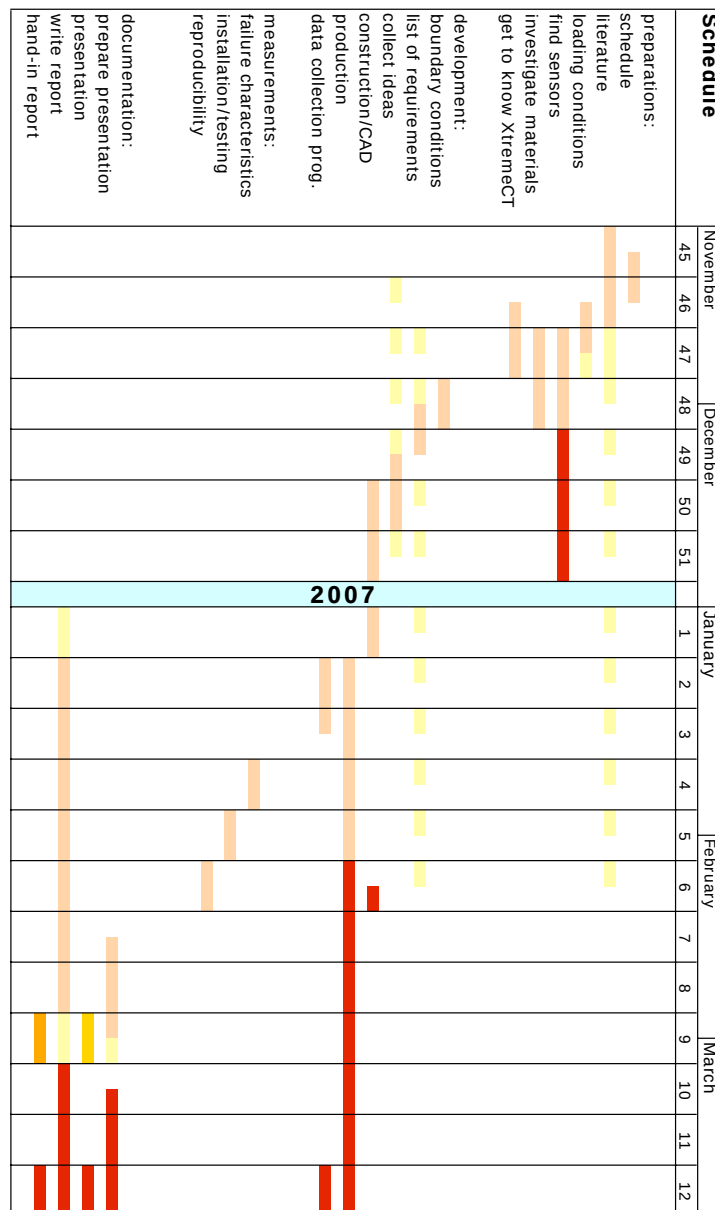


Figure B.1: The schedule had to be modified (red bars) due to production delays.

Bibliography

- [1] MÜLLER R, GERBER SC, HAYES WC (1998) *Micro-compression: a novel technique for the nondestructive assessment of local bone failure*. Technol Health Care **6** 433-444
- [2] NAZARIAN A, STAUBE M, MÜLLER R (2005) *Design and Implementation of a Novel Mechanical Testing System for Cellular Solids*. J Biomed Mater Res B Appl Biomater **73** 400-411
- [3] www.scanco.ch
- [4] LANGTON CM, NJEH CF (2004) *The physical measurement of bone*. Series in Medical Physics and Biomedical Engineering, IOP Publishing Ltd., London, UK
- [5] COWIN SC (2001) *Bone Mechanics Handbook*. CRC Press, Boca Raton, FL, USA
- [6] KASRA M, GRYMÜS D (1995) *The Effects of Androgens on the Mechanical Properties of Primate Bone*. Bone **17** 265-270
- [7] MARTENS M, VAN AUDEKERCKE R, DE MEESTER P, MULIER JC (1981) *The Geometrical Properties of Human Femur and Tibia and Their Importance for the Mechanical Behaviour of These Bone Structures*. Arch Orthop Traumat Surg **98** 113-120
- [8] HOYER HE, KOKEMOHR M, LIPPERT H (1980) *Compression strength of human radii*. Z Orthop Ihre Grenzgeb. **5** 816-821
- [9] BOEREE NR, DOVE J, COPPER JJ, KNOWLES J, HASTINGS GW (1993) *Development of a degradable composite for orthopaedic use: mechanical evaluation of an hydroxyapatite-polyhydroxybutyrate composite material*. Biomaterials **14** 793- 796
- [10] LOCHMÜLLER EM, LILL CA, KUHN V, SCHNEIDER E, ECKSTEIN F (2002) *Radius Bone Strength in Bending, Compression, and Falling and Its Correlation With Clinical Densitometry at Multiple Sites*. J Bone Miner Res **17** 1629-1638
- [11] LIND PM, LIND L, LARSSON S, ÖRBERG J (2001) *Torsional Testing and Peripheral Quantitative Computed Tomography in Rat Humerus*. Bone **29** 265-270
- [12] www.ucalgary.ca/eng/bonelab/

