Monash Rehabilitation Technology Research Unit

A Tester For The Decay Of Hydraulic /Pneumatic Prosthetic Knee Control Units

Bill Contoyannis, Ross Stewart

MONASH
AUSTRALIA'S INTERNATIONAL UNIVERSITY

REHAB *Tech*- Monash Rehabilitation Technology Research Unit assume no liability for any claim of adverse effects resulting from misapplication of the information presented here in. While every effort is made to ensure the accuracy of the guide no responsibility or liability will be taken for any inaccuracies.

REHAB*Tech* is finance and supported by

Commonwealth Department of Veterans' Affairs

In collaboration with

MONASH
AUSTRALIA'S INTERNATIONAL UNIVERSITY

© Copyright 1998
All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording or any information storage and retrieval system, without permission in writing from the publisher.
Requests for permission to make copies of any part of the work should be addressed to:

REHAB *Tech*- Monash Rehabilitation Technology Research Unit
C/- C.G.M.C.
260 - 294 Kooyong Road
CAULFIELD VIC 3162
AUSTRALIA
Email rehab.tech@eng.monash.edu.au

TABLE OF CONTENTS

List of Figures

List of Tables

Summary

A test rig has been designed which aims to evaluate the function of hydraulic and pneumatic knee control units that are used as part of the knee joint of a prosthesis for a trans - femoral (above the knee) amputee.

The rig can be used to asses the decay of the units in the clinical; environment without dismantling the prosthesis. It also allows for a passive test of the unit by the clinician in a manner that would be the current practice.

It is assumed that following a number of clinical evaluations, the rig will be modified to provide the most appropriate feedback to the clinician.

Introduction

Levels of amputation

The most common form of artificial limbs (prostheses) are used primarily for the ambulation of people who have lost one or both of their legs at a variety of different levels. These levels are simply categorised as below the knee or above the knee, however international standards terminology describes the position as a function of the anatomy which has been affected ie a below the knee amputee is a trans tibial amputee. The components that are being addressed as part of this design are those for which provide the knee function for a trans - femoral amputee

Components

The general components of a prosthesis are a simple support structure with little mechanical function. The most basic aim is to provide balance and support through a rigid system and some impact absorption and smooth rolling over whilst walking via a prosthetic foot.

The trans femoral (above the knee) amputee presents unique problems due to the absence of the anatomical knee. Mechanical knee mechanisms need to provide support when the amputee is stepping through with all of his/her load on the prosthesis. The artificial knee cannot buckle until the other leg is ready to take the load. When the artificial limb is then swinging through the mechanism must swing as such to allow the toe of the prosthesis to clear the ground and swing through at a rate that will mean the limb is extend ready to take the load at the end of this swing phase in rhythm with the opposite leg. This is achieved by a number of options including friction, spring, pneumatic and/or hydraulic knee control units.

Pneumatics and hydraulics

Pneumatic and hydraulic units are used as the control systems of an otherwise typically simple single axis mechanical joint. The units provide a resistance to the joint being flexed which can be adjusted to suit a particular walking style. The major advantage of using these systems as opposed to simple springs or friction is that they will vary their response with velocity according to the turbulent flow theory of fluids. This means that a number of gait speeds or cadences will be accommodated. This is why they are often termed as cadence responsive units. These units are also often used in conjunction with a spring and have an adjustable porting for the fluid flow such that the general response can be altered.

Problem :

Hydraulic / pneumatic prosthetic knee control units fail with little or no indication. They usually fail in one of two ways either spring failure or more commonly "leakage " failure where the unit cannot sustain fluid pressure. Age is not an indicator and we currently do not have a quantitative method of measuring changes in response.

Need Statement

To know what the decaying response indicators are (partially done in a previous study[1]) and to be able to monitor these in the clinical environment.

Further Need

To be able to assess hydraulic / pneumatic prosthetic knee control units in relation to their decaying response (in order to supplement the study [1])

PROBLEM DEFINITION

Establish a (quick / easy) clinical method of assessing the performance of a variety of the most commonly used hydraulic / pneumatic prosthetic knee control units.

Criteria - Requirements- Objectives

The following criteria have been established as part of the design process through the authors' experience from conducting assessments and education about component servicing and feedback from prosthetists who are the prime clinicians involved in the assessment of these units.

- ***Inexpensive***- A major concern for the use of devices in the clinical environment is the cost. A comparative cost is therefore the only guide that we can use to assess the market acceptance of cost. The relevant associated costs are:
  - $1800[2] per unit (with a 2 year warranty)
  - $600[3] per service due to failure (with a 6- 12 month warranty following service.)
  Interestingly there are almost no assessment tools of this type used in the field. There are however assessment devices for purposes of alignment or manufacture of the prosthesis rather than assessment of the component. These vary in price between $500-3,000. The price of an average trans- femoral prosthesis is $3,000 -5,000.
- ***Small*** - The clinical environment is frequently an area of limited space and assessments may be done in clinical booths in the gymnasium. As such any test rig would need to be easily transportable and useable in this type of environment. Dedicated pieces of equipment in a particular laboratory are unlikely to be used.
- Give an indication of ***time response*** as per study[1].(0-10 seconds = minimum to maximum). The study found that this is the prime indicator of deterioration and effectiveness of the units.
- Cope with a ***variety of prosthetic knees frames***. Table 1 shows the geometric variations of the knee frames into which these hydraulic and pneumatic knee control units are fitted.

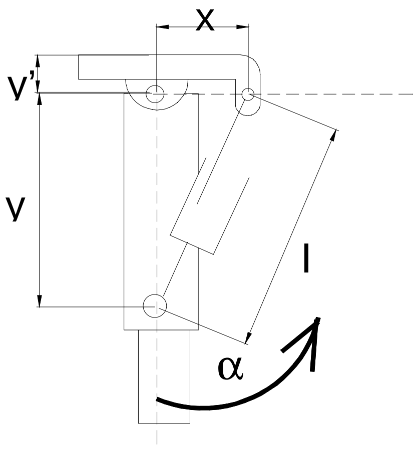


Figure 1, Geometry of Knee and Hydraulic Unit

Knee Unit	x, mm	y, mm	y', mm	l, mm
USMC Mark V[8]	30	190	25	195
Blatchford IP Knee[11]	31	164	48	160
Blatchford Total Knee[13]	27	160	24	164
Otto Bock 3C1*[12]	22	191	22	193
USMC Blackmax[9]	30	190	20	195
Hosmer QSA[10]	30	190	16	195

Table 1

* The hydraulic unit in the Otto Bock 3C1 can not be removed, except by the manufacturer.

- Allows for the ***investigation of knees*** as per the protocol. The establishment of a test rig means that a greater number of tests can be performed thus better defining the characteristic responses.
- Be ***minimally intrusive*** . To obtain acceptance and usage into regular clinical practice for checking hydraulic and pneumatic knee control units, the rig must not only be small but minimally intrusive in terms of function and time. Also it needs to be unintrusive in the areas where it is likely to be used including the clinic and the prosthetic laboratory.
- ***Feeling*** **-**The current form of assessment of these units is to "feel" the response of the unit by manually deflecting it. The hand of the clinician then *feels* the unit performance. Although this practice has

questionable accuracy and repeatability it is acknowledged that the clinical requirement to do this remains and therefore the rig must allow for it.

- ***Range***. The units can be adjusted across a range of responses and any checking or testing must be able to be performed regardless of the range setting it has.
- ***Permanent attachment***. It would be ideal if the test rig could be incorporated into the design of a prosthesis and give feedback to the user as well as the clinician as to its decay characteristics, life of knee left and amount of work the knee has done.
- ***Indication of percentage of decay***. An indication of percentage decay/performance possibly as "time before next service" would be of benefit to both user and clinician. This would allow for planning of subsequent servicing. This indication would most likely require data that has been accumulated as a result of putting a prototype into service.
- ***Repeatability***. The test rig must give a repeatable response. As there is not a current system in place it is impossible to establish the error margin for that repeatability.

Source alternatives

The following alternatives to were investigated which may meet some of the criteria as stated above.

1. Test rig as per study using a displacement transducer
2. Instrom 8501 dynamic tester
3. Prototype tester
4. New design

Each of the potential alternatives has been assessed according to each of the criteria, however Table 2 shows some of the major points with regards to the criteria.

Table 2 - Alternatives - list of advantages & disadvantages

ALTERNATIVE	ADVANTAGES	DISADVANTAGES
1. Test rig as per study[1] using a displacement transducer	• accuracy • available commercially • The cost of this set up is quite low	• hydraulic unit needs to be removed from prosthesis • Connection to computer limits environments in which test can be made
2. Instrom 8501 dynamic tester	• accuracy • repeatability	• The cost would immediately rule this out • Size • hydraulic unit needs to be removed from prosthesis • clinical availability
3. Prototype tester[1] which has been mocked together as a possible test rig.	• Clinically suitable • Allows for feel of unit • Relatively inexpensive	• Set up required making it difficult to use in variety of clinical situations. • Completeness. The design is not complete. • hydraulic unit needs to be removed from prosthesis • Accuracy • Size /weight
4. New design	design dependant	design dependant

New design-Specific criteria

Each aspect of the design has particular constraints, criteria or objectives. These relate to the general objectives however introduce issues more specific to the test rig design.

Specific assumptions / compromises

The time frame result is the most accurate way of assessing the decay response of a hydraulic or pneumatic knee control unit - future data to determine validity of this

Objective

Test type to be single deflection with timed return.

Specific criteria

The specific criteria of the design are those derived from the general criteria and objectives but are unique to the proposed prototype or solution.

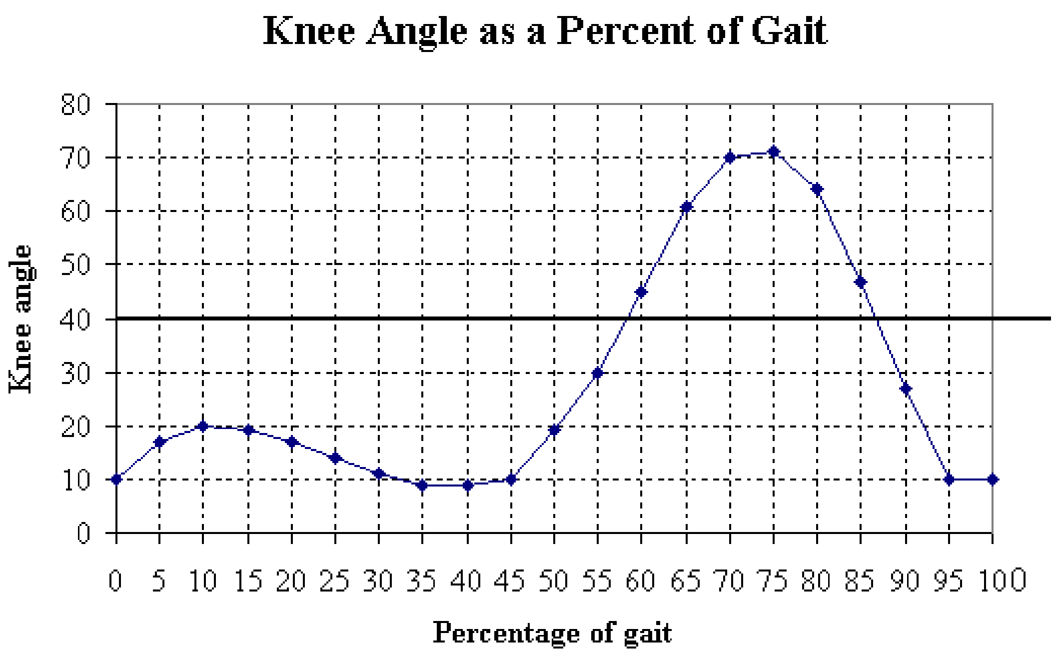


Figure 2, Knee Angle During Gait

From the knee geometries and Figure 2, a knee angle of 40 ^{o} was chosen for the initial deflection angle. This provides around 20 mm deflection in the cylinder and is typically encountered in normal gait (Figure 3).

Due to the geometry of the knee frames, larger knee angles only provide a marginal increase in stroke length.

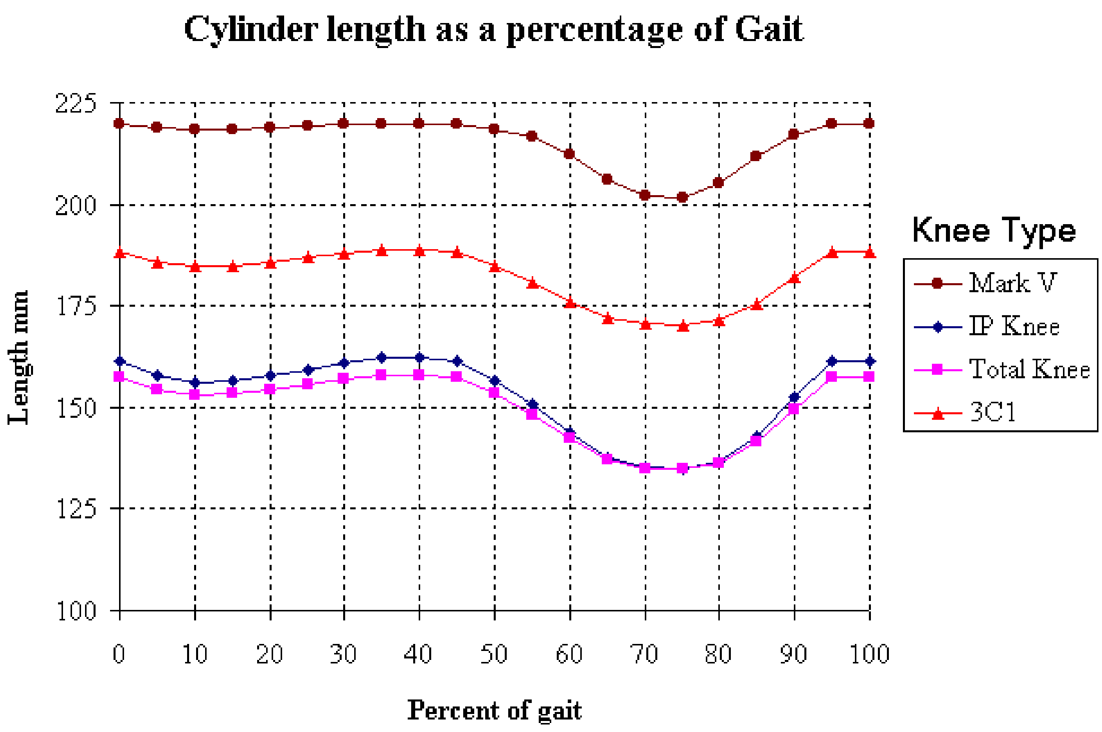


Figure 3, Cylinder Displacement during Gait

Knee Unit	Cylinder length at $\alpha = 40^{o}$, mm	Change in cylinder length, mm
USMC Mark V	172	20
Blatchford IP Knee	146	21
Blatchford Total Knee	144	18
Otto Bock 3C1	178	15
USMC Blackmax	172	20
Hosmer QSA	172	20

Table 3, Stroke Length for Test

Response of knee unit to desired test

The cylinder is preloaded to a set deflection. The load is released and the response is measured. This test can be modelled as a spring damper 1 st order system, with an applied load equivalent to a unit step function multiplied by the pre loading force.

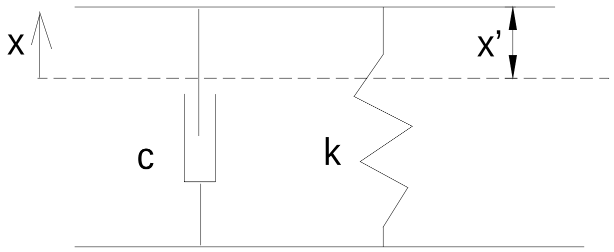


Figure 4, Spring Damper System

this system has a response of $x(t) = x'(1 - e^{\frac{-k}{c}t})$, where x' is the initial deflection, k is the spring stiffness and c is the damping. (see appendix).

Using this response the ratio of k/c can be calculated for different cylinder settings using testing information obtained in earlier studies [1].

Cylinder condition	**k/c**
Minium flexion minium extension	0.5
Minium flexion medium extension	0.37
Minium flexion maximum extension	0.11
Medium flexion minium extension	0.6
Medium flexion medium extension	0.42
Medium flexion maximum extension	0.3
Maximum flexion minium extension	0.38
Maximum flexion medium extension	0.22
Maximum flexion maximum extension	0.04

Table 4, Ratio of k/c for different cylinder settings

Ideally altering the flexion characteristics of the unit should not effect extension. However this is not the case. With the an increase in flexion resistance causing a increase in extension resistance.

As would be expected the cylinder is overdamped (c/k >1).

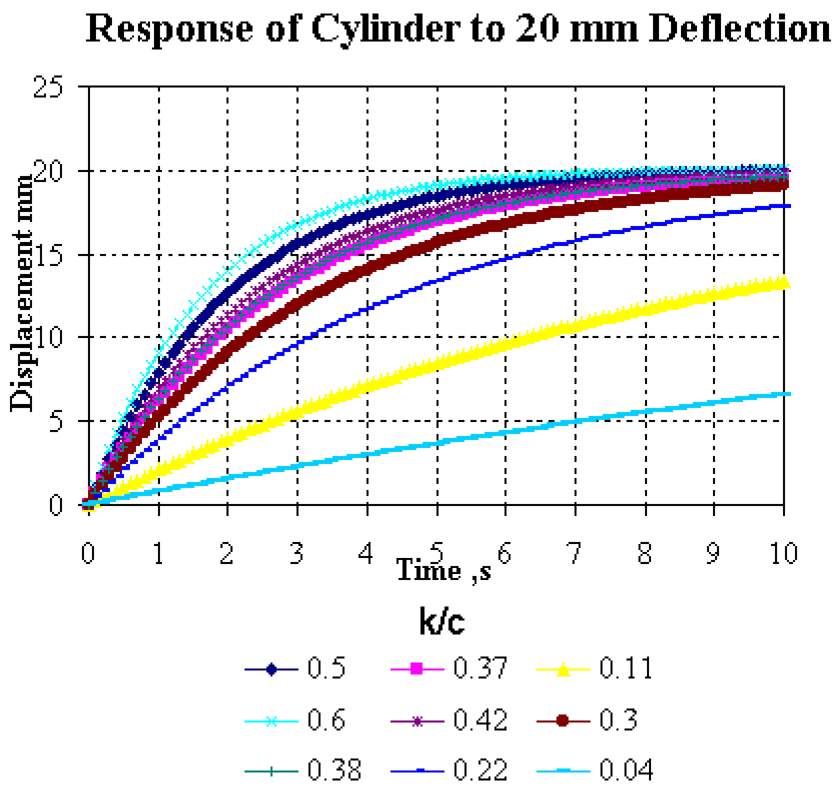


Figure 5, Response of Cylinder to 20 mm Deflection.

As can be seen in Figure 5, the greater the damping, the longer it takes the cylinder to return. From this only two representative tests should be required. These would correspond to k/c = 0.5 and k/c ≈ 0.38. For k/c = 0.5 the cylinder settings are minimum flexion and extension. This test would be a good indication of effectiveness of the seals, air content and the amount of fluid, as if any of these where having problems the response would be very dramatic. The k/c ≈ 0.38 test is indicative of medium extension values. This will show the effectiveness of the cylinder settings. Two tests at this range could also be used, such as minimum flexion and medium extension should produce a similar result to maximum flexion and minimum extension.

The test can be used in the knee frame geometries. If the socket is removed the mass in the system can be assumed to be negligible. If the knee is functioning correctly friction in the knee joint should be negligible. The knee angle is function of the cylinder response and can be predicted.

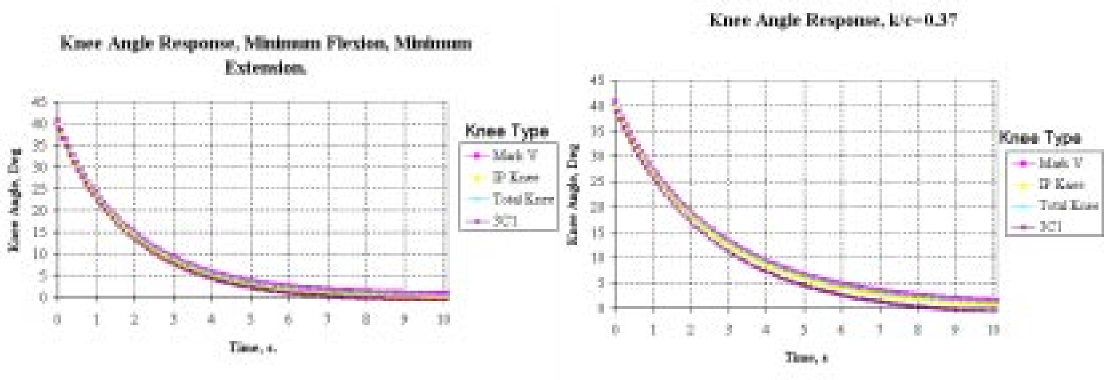


Figure 6, Response of Knee Unit, with different settings.

From the Figure 6 acceptable times for k/c = 0.5 would be 4 ± 1 second and 5 to 6 seconds for k/c = 0.37 for all knee geometries. Response times earlier than these indicate the fluid is not operating correctly. This gives a stopping knee angle of 5 degrees. Going to 0^{o} is not recommended due to the exponential nature of the response.

Failure criteria.

From plots of cylinder responses (Figure 6) failure criteria can be determined.

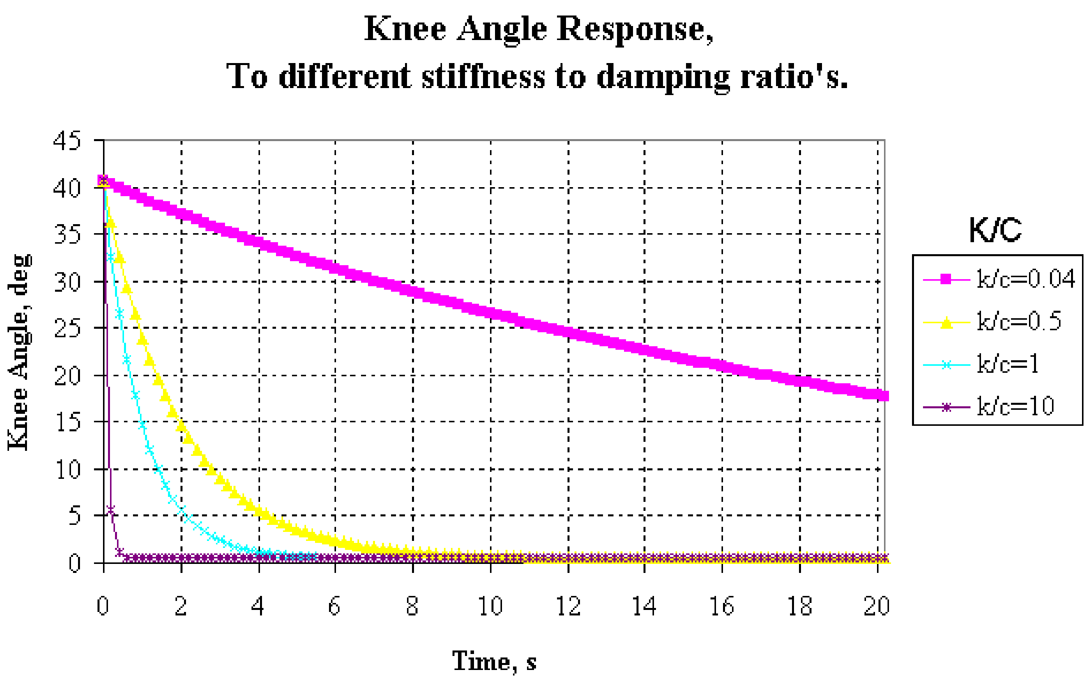


Figure 7, Knee Units Response to different values of k/c.

Figure 7 plots the response of the knee to different cylinder conditions at the knee. If the response is almost instantaneous (k/c >1), the resistance from the damper is negligible, indicating failure in this region. Similarly if the time of the response over a long period, 30 seconds, the effect of spring is minimal.

Test condition	**Possible cause of failure**	**Repair Option**
Test time is shorter than time specified.	Fluid leakage in system.	Send unit into be serviced
Test time is longer than specified time, cylinder does not return at all.	Spring failure.	Send unit into be serviced or replaced.
Test time is longer than time specified.	Excess friction in knee.	Clean and replace bearings at knee joint
Squishing noise in cylinder during motion	Air in cylinder	Compress the unit, raise the mode lever (entering flexion lock), extend unit and lower mode lever to allow flexion. May need to be repeated until all air is out of unit.[4] (suitable for CaTech and Mauch units only).
Rough feel when rotating piston rod.	Worn seals	Send unit into be serviced.[5]

Table 5, Types of Failure and Possible Causes

Further testing is required to verify the test times. Test times for other hydraulic and pneumatic controllers need to be established. If the time displacement plot is recorded further information regarding causes of knee failure maybe obtained. Such as a response that had jumps could indicate air in the unit.

Tests procedure.

The socket and cosmetic cover is removed from the prosthesis. The testing rig is attached to the knee frame and hydraulic unit. The hydraulic controller settings are moved to minimum flexion and extension. The knee is then flexed 40^{o} using the test frame. The frame is then released allowing the knee to return to the original upright position.

The time the knee takes to return from the flexed position to the 5^{o} mark is recorded. The time of response should be 4 ± 1 second.

The test is then repeated with the controller settings on medium extension and minimum flexion. The time of response should be 5 to 6 seconds.

Prediction of outcomes

Model

As part of the prediction of outcomes it was first decided to establish the rig system as a model using the mechanism software SAM 3.0 a for Windows[6] This software allows for the inclusion of a damper and spring and the variation of the properties of these. The spring constant has been previously established[7] as 4 N/mm and the stroke of the damper was 32 mm(Figure 3). The damper constant can be varied on the model as it also can be in the actual hydraulic / pneumatic units by adjusting the flexion and extension response.

Four different models were established each representing the different frames and therefore mechanism designs available.

These were:

- The Mark V[8] ,Black Max[9] and QSA[10]
- The Blatchford IP[11]
- 3C1[12]
- Total Knee[13]

The models was given an angular input of $\pm 40^{o}$ *(Figure 2, Knee Angle During Gait)* representing the range through which the rig would test the knee unit.

Figure 8 - Typical SAM[6] window

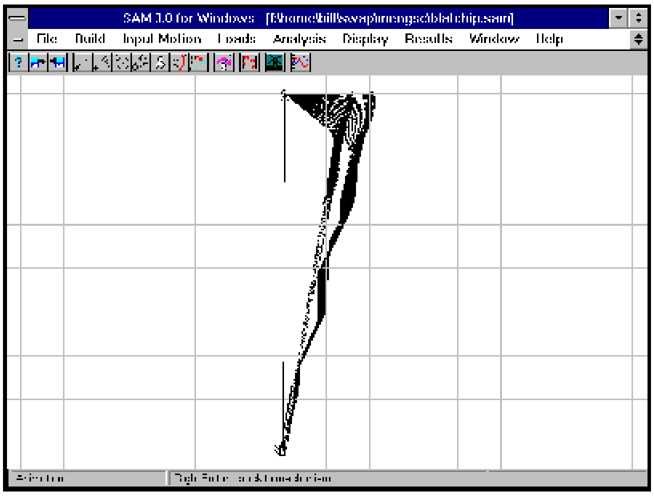


Figure 9 - Typical SAM[1] window showing path of mechanism, damper and spring

Due to the limitations of the software the spring element has a 5 mm offset to the damper.

The cylinder spring stiffness can be calculated from previous work, [14] where a new CaTech cylinder which is placed under compression at a constant velocity using an Instrom testing machine. The slope of the force displacement plot will be equivalent to spring stiffness.

Test Condition[14]	Test velocity, cm /min	Slope, N/mm
Minimum Flexion	50	3.6
Medium Flexion	50	4
Maximum Flexion	50	4
Maximum Flexion	20	3.1
Medium Flexion	20	3.1
Minimum Flexion	20	3

Table 6, Spring Stiffness

Having established the model it can be used to correlate with the response in the actual system and then determine the damping response for a given setting. This can then be replicated in the model for each frame. This iterative process should lead to an improved and accurate model for prediction of responses for a variety of frames.

Solution Specification - Tester

The test rig or tester can be separated into two components

- the structure or frame
- and the timer

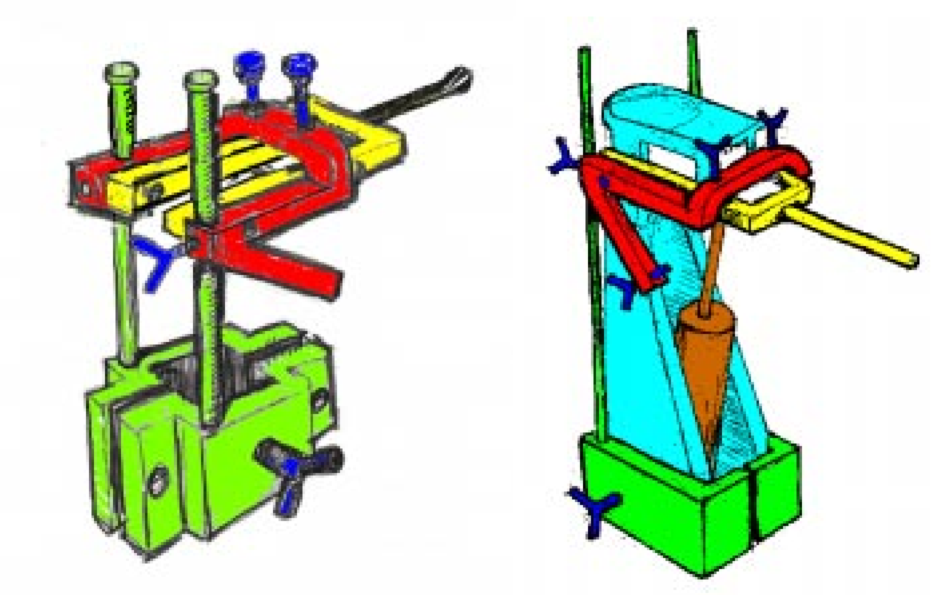


Figure 10 - Proposed design of tester, with and without knee unit (note: timer not visible)

Structure

The structure of the test rig needs to ensure:

- each test starts and stops at the same position for each knee.
- Fit different knee frame types

The only common structure for all the knee frames is where they attach to the hydraulic cylinder and the knee axis. This is at the distal cylinder attachment point, knee axis and proximal cylinder attachment point. Even though the relative position of these varies with each knee it is the only constant for the knees (Figure 11).

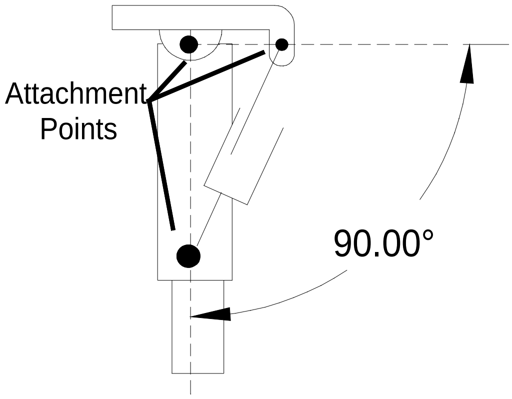


Figure 11, Test Rig Attachment Points

These points are used for both location, rotation and attachment of the testing rig. This stops any 3 dimensional effects as all the knees will be rotating in one plane, around the regular knee axis.

The 0 ^{o} knee angle or test starting point for all knee frames is a perpendicular line between the upper and lower axis (Figure 11).

As the knee frames vary greatly in size, distal and proximal attachment types to the prothesis, it was decided to use the knee frame as part of the test rig, stopping the need for a different test frame for each knee.

The test rig is shown in Figure 10. It consists of three sections. A lower frame which attaches to the distal axis. This is in two independent halves. Once the entire rig is attached to the prosthesis the lower frame is placed in a vice for convenience in conducting the tests.

The lower frame is attached to a fixed upper frame by two steel bars on each side. The steel bars allow the upper frame to be raised or lowered for each knee. The upper frame is attached to the knee axis and does not move in the test. It consists of two "V" shaped bars on each side joined at the top end of the V. The angle of the V is 50 ^{o}. This frame acts as the starting and ending reference points (flexion and extension limits) for the tests. The 50 ° angle allows for the knee to rotate 40 ° and have room for time switches. Adjustment screws will provide minor adjustment to reference points and timer positions (Figure 12).

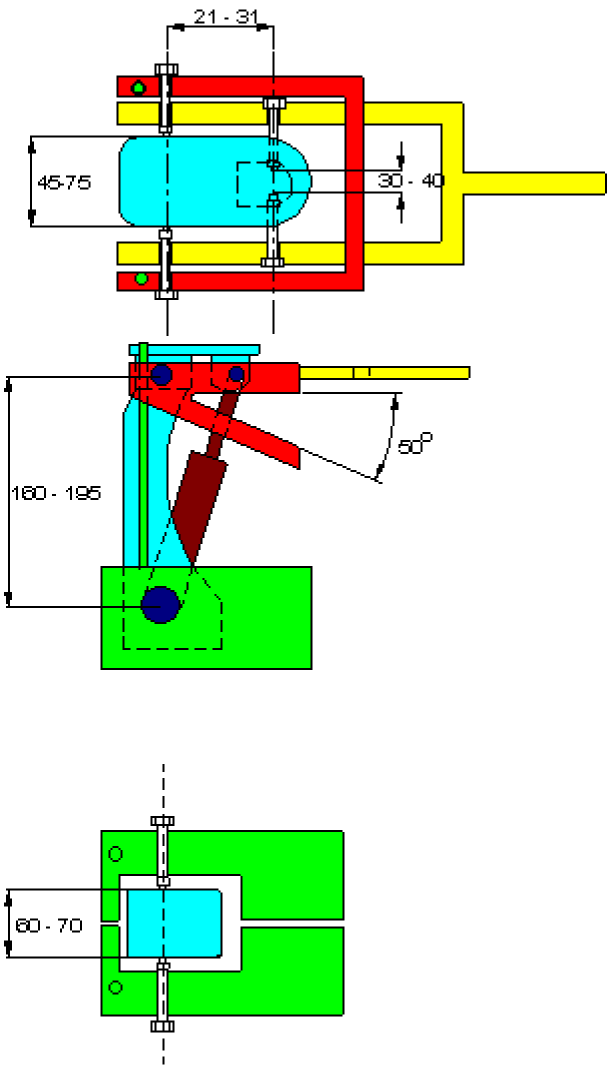


Figure 12, Plane views of Test rig, with knee.

The inner frame is free to rotate around the knee axis. It is attached at both the knee axis and proximal cylinder axis. It is U shaped with a handle at the end. The U needs to be large enough to operate freely from interference of the knee frame. The handle is used to compress the cylinder, mimicking the compression due to normal knee rotation.

Using the handle, the operator manually compresses the cylinder, giving "*feel* " back to the operator. The amount of compression is limited by the top frame. The handle is then released which activates the timer. When the frame reaches 5 ° flexion the timer stops. The difference in time determines the effectiveness of the cylinder.

Aluminium is used for construction. This will reduce the overall weight of the test rig. More importantly it will reduce the weight and inertia of the inner frame section.

The tests should be conducted with the knee in an upright position. Slight variations are acceptable. Excessive deviations will change the response of the cylinder as the force of the knee plate and the inner section of the test frame will vary depending on if gravity is working with or against the cylinder.

The test rig should give good repeatability of tests, as all axis of rotation remain constant regardless of orientation.

Obviously with different size knees there are minimum sizes that the test rig needs to be. These are set so the test rig will not interfere with the knee frame.

This leaves the critical construction being how the test rig actually attaches to the knee frame at the specified points. The attachment mechanisms needs to accommodate all frames, and provide a secure attachment. This is complicated by the knees having different axis heads, from hex, screw and 2 point. The attachment points also need to allow the frame to rotate at these points.

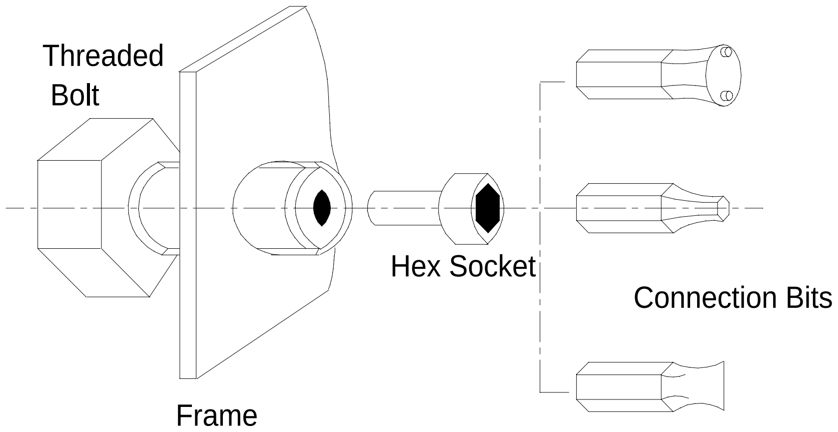


Figure 13, Schematic of attachment system

The end attachments will be commercially available tool bits. These are available in different shapes and sizes, with a common hex shaped base. The end bits will then attach to a hex head which is positioned inside a large bolt. The bolt goes through the test rig and screws into position, locating and securing the test rig.

Timer

The specific monitoring function can be described as a simple timer with the following general criteria:

- No permanent record is required of specific tests, therefore no hardcopy
- Time indication is only required for the return stoke of the unit
- Some type of indication of pass/ fail is required
- Some type of indication of scale or % performance is required

These criteria can be further analysed into specific functions which can be defined as being required in two stages.

The first is those required to conduct the testing in order to establish the validity of this process and then the actual details of acceptable time intervals for different systems, assuming the process is valid. These are:

- Timer start at bottom of range
- Timer stop when unit returns to top
- Output of time taken to return

This information would then be recorded manually and a series of tests conducted on hydraulic and pneumatic knee control units of various cycle age to determine the characteristic response.

The second set of functions is used once the performance characteristics have been established and are:

- The ability to store the desired response
- Timer start at bottom of range
- Timer stop when unit returns to top
- An alert as to pass or fail
- A monitor at fail to indicate the percentage (not accurately known at this stage) of ideal performance.

An electronic timer [15] has been sourced which is commercially available and can provide the required functions at both stages of the test rig use. The timer has a ‘count up’ and ‘timer’ function , both of which operate from a single contact which toggles on and off. The timer has a 10 mm LCD display and operates on a single LR44 1.5 volt battery. The dimensions of the entire unit is H 65 mm x W 50 mm x D 10 mm. It is a commercially available for approximately $6 however a modification would be required which involves the main operating contact switch being mounted onto the structure of the test rig.

The first stage of the testing would involve the ‘count up’ setting which would simply time the return in seconds. This time is repeated and monitored for the same and other units.

The second stage, or general clinical use stage, involves the timer being set to the ‘timer’ option and the required performance characteristic is stored in memory (available in the basic unit). If the unit passes the test, that is reaches the top of the rig within the appropriate time, an alarm will sound and reset the unit for a further test. If the unit reaches the top prior to the appropriate time (which is the mode of failure of the damper as only the spring is now operating), a different alarm sounds and the stop watch function holds the time remaining for the optimal response. It is hypothesised that this time compared to the ideal time will give an indication of the percentage decay of the unit.

Feasibility /Evaluation

re evaluate criteria/compromises to objectives

- ***Inexpensive-***
  At this stage it is difficult to define an accurate cost, particularly while the prototype has not been completed. The estimate of cost is as follows:

Table 7 - Costs for prototype

Material	*Cost $*
Aluminium	50
Bolts	20
hexagonal adaptors	24
Timer	10
Labour	0
Structure/ frame	600
Timer modification	200
Total	904

This figure is between the cost of a new unit and servicing, however it should be within the acceptable range of the cost of assessment equipment ($600 - $3000)

- ***Small*** and ***minimally intrusive*** -
  The tester is small enough to be portable and should weigh less than a kilogram. This means that it would not be obtrusive in the clinical environment. A compromise of the structure is that it ideally needs to be fixed in a vice. This improves the structural integrity of the unit and is ideal for the repeatability of the tests. The unit will however function outside of a vice but this may effect the results and is yet to be investigated as the prototype is required for this.
- An adequate indication of ***time response*** as per study[1] will be achieved. Further verification as to the validity will have to be determined.
- The current tester design can cope with the ***variety of prosthetic knees frames***. Table 1.
- The current tester design allows for the ***investigation of knees*** as per the protocol.
- ***Feeling -***
  The current design allows the clinician to manually deflect the unit while in the prosthesis.
- ***Range-***.
  The units can be adjusted across a range of responses and this does not alter the checking or testing process which will be performed. The tester also does not need to be removed or re- adjusted to alter the range.
- ***Permanent attachment***.
  It is impractical to permanently attach this design. This criterion was compromised for the performance of the tester and the ability to provide feeling.
- ***Indication of percentage of decay-***.
  An indication of percentage decay/performance is available due to the timer mechanism providing a value at which a certain test parameter was reached (ie too soon by ***x*** seconds, or too late by ***y*** seconds.) The testing will establish if these are valid values or indicators.
- ***Repeatability-***
  The test rig should give a repeatable response particularly when

mounted on a vice. The prototype will need to be tested to establish the error margin for that repeatability.

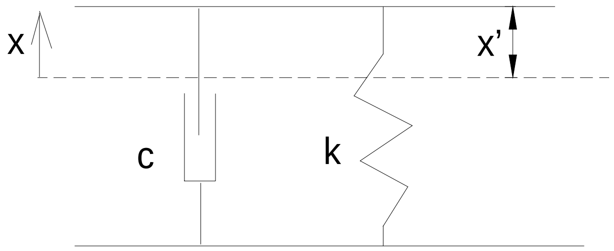
The criteria and objectives have generally been met with a compromise affecting the size and portability of the tester. This should mean that the tester can be used to establish the test validity of the performance response of hydraulic and pneumatic knee control units in the clinical situation.

Implementation/development

A prototype is currently (11/96) being constructed and is expected to be completed by the end of this year.
The Amputee unit of Caulfield General Medical Centre has agreed to be involved in the initial trialling of the tester as they see a need for such a unit. This is expected to commence in early 1997 with an aim of conducting 50 tests by mid 1997. The validity of the tests and tester will then be reassessed.

Appendix

Response of Hydraulic unit to Test



$c\dot{x} + kx = Fi\mu(t)$, $Fi = \frac{k}{x'} =$ preloading force, $x'=$ displacement due to applied force

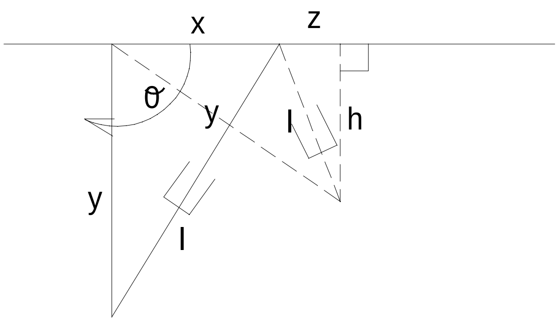
$c\left(s\bar{x}(s) - x(0)\right) + k\bar{x}(s) = \frac{Fi}{s}$, $c =$ damping coefficent, $k =$ spring stiffness

$\bar{x}(s) = \frac{Fi}{s(cs+k)}$ $\mu(t) =$ Unit step function

$$x(t) = x'(1 - e^{\frac{-k}{c}t})$$

$$e^{\frac{-k}{c}t} = -\frac{x(t)}{x'} - 1$$

Geometry of Knee Frames.



$$h = y\sin\theta$$

$$l^2 = h^2 + z^2 \Rightarrow z = \sqrt{l^2 - h^2}$$

$$\cos\theta = \frac{x+z}{y} = \frac{x + \sqrt{l^2 - h^2}}{y}$$

$$\Rightarrow (y\cos\theta - x)^2 = l^2 - y^2\sin^2\theta$$

$$\therefore \cos\theta = \frac{y^2 + x^2 - l^2}{2xy}$$

$$l = \sqrt{y^2 + x^2 - 2xy\cos\theta}$$

Figure 14,Geometry of cylinder at θ = 90 ^{o} and random.

α = knee angle, θ = 90^{o} - α

Knee frame variations

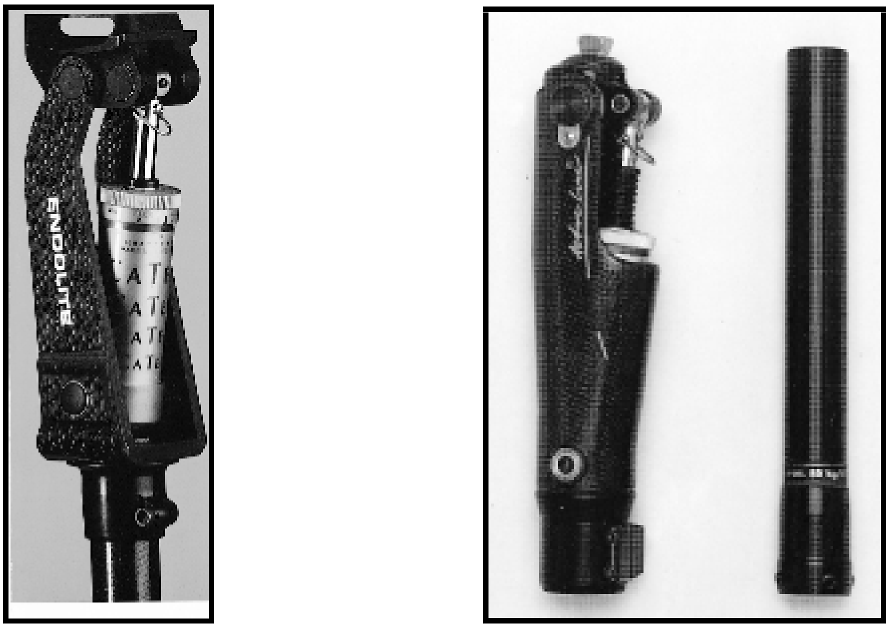


Figure 15, Blatchford Total Knee, left, Otto Bock 3C1, right.

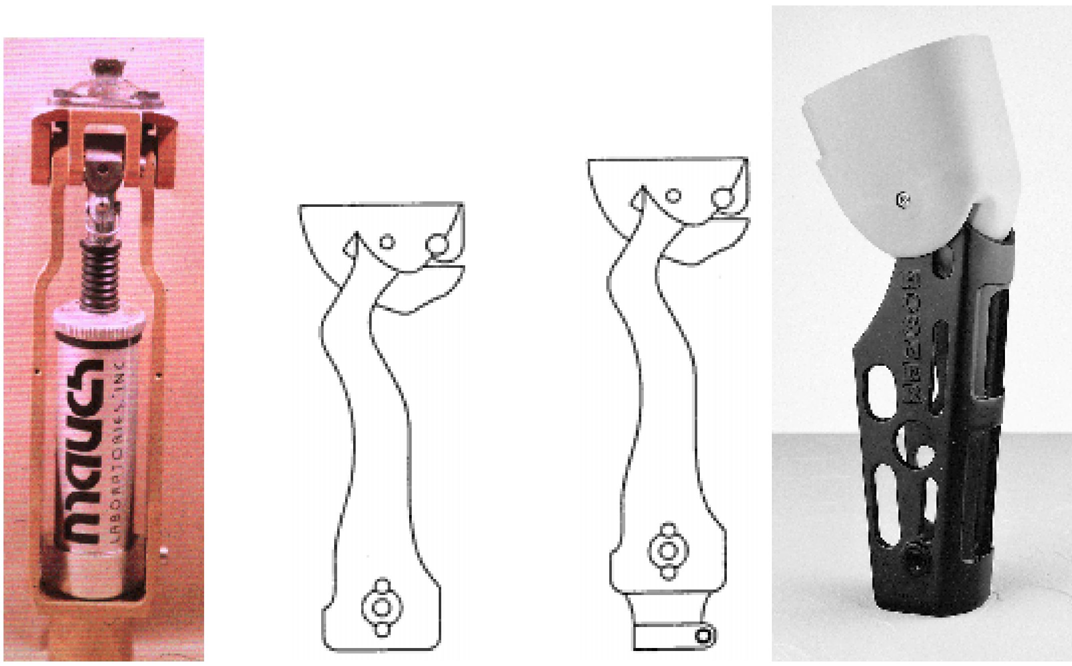


Figure 16, USMC Mark V, USMC Blackmax, Hosmer QSA

Figure 17, Mark V knee in Prosthesis, Different Knee Hydraulic Units

References

[1] Experimental Investigation of the decaying Performance of hydraulic knee controllers, Devenport. J., Mechefske. C.. 1995. Final Year Project, VUT.

[2] Price of CaTech unit from TechGUIDE, 1996.

[3] Price of service from G.W. Masson & Sons.

[4] From Manual for the Henschke - Mauch "Hydraulik", Mauch Laboratories, 1976.

[5] From discussions with Martin Masson, G.W. Masson & Sons.

[6] SAM 3.0 a for Windows, ARTAS -Engineering Software, Het Puyven 162, NL - 5672 RJ Nuenen, The Netherlands.

[7] Spring Constant trial with John Miller, Mechanical Engineering Laboratory, January 1995.

[8] Mark V knee frame from - USMC - 180 N.San Gabriel Blvd, Pasadena, CA, USA

[9] Black Max knee frame from - USMC - 180 N.San Gabriel Blvd, Pasadena, CA, USA

[10] QSA Knee frame from - Hosmer - 561 Division St Cambell, CA, USA

[11] Blatchford IP from Endolite system- Blatchford Unit 6 Sherrington Way, Basingstoke, Hampshire RG22 4LU, England.

[12] 3C1 - Otto Bock Orthopadishe Industrie GmbH & Co, Postfach 12 60 D-37105 Duderstadt, Germany.

[13] Total Knee from Endolite system- Blatchford Unit 6 Sherrington Way, Basingstoke, Hampshire RG22 4LU, England.

[14] From tests conducted at the Mechanical Engineering Laboratory

[15] 'Electronic TIMER CLOCK - Registered design no. 1 049 496, available in Australia through RS