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Long Bone Load Cell Instrumentation
A Revised Technique

Paul Manning BMedSci BM BS FRCS
Clinical Research Fellow in Orthopaedic Surgery
The Department of Orthopaedic and Accident Surgery
The University of Nottingham
United Kingdom

Adrian Roberts BSc MPhil
Senior Researcher
Transport Research Laboratory
United Kingdom

Clare Owen BSc MSc
Senior Researcher
Transport Research Laboratory
United Kingdom

Richard Lowne BSc FTRL
Head of Occupant Protection
Transport Research Laboratory
United Kingdom

W. Angus Wallace MB ChB FRCS (Ed &Eng) FRCSEd (Orth)
Professor of Orthopaedic and Accident Surgery
The University of Nottingham
United Kingdom

ABSTRACT

This paper describes a technique of load cell insertion into the tibia developed from two existing procedures. The insertion technique addresses the need to maintain overall bone length, rotation and alignment whilst minimising the disruption to the soft tissues and in particular the inter-osseous membrane. The insertion technique described can be applied to any long bone of sufficient length.

This technique was developed to facilitate a study to compare the mechanical behaviour of post mortem human surrogate legs in dynamic impact tests with volunteers and with anthropometric test devices. It is essential when implanting a load cell that longitudinal length, rotational and angular alignment are preserved. In addition it is vital to minimise soft tissue disruption especially of the tibio-fibula ligament. The inter-osseous membrane between the tibia and the fibula, with its diagonal fibre arrangement is necessary for correct anatomical and mechanical loading of the lower leg in compression, bending and rotation This method of load cell insertion satisfies these criteria.

INTRODUCTION

The Transport Research Laboratory in collaboration with the University of Nottingham, have embarked on a programme of biomechanical research focused on lower limb injuries. This project is called the LLIMP project (Lower Limb Injuries, Methods of Prevention). The work has already included a detailed investigation of accident data [1, 2] where the vehicle occupants have sustained lower limb injuries, as well as a substantial programme of experimental work [3]. The experimental work involves impact testing of post mortem human surrogate (PMHS) lower legs to explore the ability of anthropometric dummy legs to predict and measure injuries in a biofidelic manner. This has been achieved by performing identical impact tests on dummy legs of differing designs, so that a comparison can be made with the results from the tests with post mortem human surrogates (PMHS).

The test procedure for the dynamic tests has been based in part on the European Experimental Vehicles Committee (EEVC) New Foot Certification Test Procedure for the Hybrid III dummy in the EEVC Offset Front Impact Test Procedure and in part on tests designed specifically for the LLIMP project.

MEASUREMENT OF TIBIAL FORCE

A special implantable version of the Denton five-axis tibial load cell (Denton, USA) has been used to measure tibial force, originally designed for the University of Virginia. The transducer measures forces in three directions (Fx, Fy & Fz) as well as two bending moments (Mx & My). For this transducer data to be comparable with that obtained in other PMHSs and in dummy tests the load cell needs to be mounted not only in a correct orientation, but also with exact alignment of the tibial shaft in all planes. In addition overall leg geometry and load paths must be preserved.

The method of insertion of the tibial load cell described here has been developed specifically for this project and is a modification of techniques used by other research groups. The French 'Renault' technique implants the load cell and maintains tibial alignment by means of two intra-medullary pins [4]. The University of Virginia method involves the use of an external fixator and potting cups [5].

EXISTING TECHNIQUES

Portier et al [4] have described a method for tibial instrumentation with a large dummy based load cell. In their work the load cell is implanted as close as possible to the ankle joint and makes it possible to maintain the integrity of the calf musculature. This method requires a bolt and screw to be fitted into the intra-medullary space of both the proximal and distal tibial components and a sleeve of cement applied to the outer aspect of the bone ends. It is necessary that a section of the fibula bone be removed and that the distal fibula be secured to the distal tibial shaft by means of a large cortical screw.

It is known from other experimental series that these intra-medullary screws can cause considerable problems, including the production of tibial shaft fractures. Kennett et al [5] report a series of sled tests using eight full cadavers in which 8 of 16 of the legs sustained one or more iatrogenic fractures, due to the presence of the load cell. Despite a number of modifications, including the introduction of a potting medium into the intra-medullary canal, adding circumferential clamps and facing the load cell flange directly up to the cut bone faces, this problem remained. Using a finite element model the cause was identified and attributed to the abrupt transfer of load at the termination of the rod in the bone to the inside cortical tube of the bone.

It has been estimated that the fibula can transmit up to 28% of the axial load of the lower leg during eversion injury [6]. If the entire axial load is directed through the tibia (by dividing the fibula and securing to the distal tibia) interpretation of the tibial load cell data becomes more complex with a significantly different mechanical behaviour compared with the real world situation. In addition the ligaments of the syndesmosis are artificially constrained and observed injury patterns may not be biofidelic.

Skraba and Greenwald [7] found that the interosseous membrane played a critical role in transferring loads to the fibula. They established a 50% drop in the loading of the fibula if the membrane was cut. They hypothesised that the membrane constrained the fibula from bowing laterally under load, thus maintaining its vertical orientation and enabling it to bear more axial load. In the light of both these findings, preservation of fibula integrity and as much of the inter-osseous ligament is essential to maintain the biofidelity of the PMHS specimen.

Kennett [5] has reported an alternative insertion technique using a smaller implantable load cell, whereby the stronger cortical bone of the proximal and distal tibial shaft is used as the principle constraint for the load cell. Using finite element modelling he has shown that the technique, using potting cups surrounding the bone and filled with an epoxy resin, reduced the Von Mises stress recorded at the end of the load cell in similar bending tests by over 50%. The technique used in this case keeps the fibula intact but requires the use of an external fixation device to maintain tibial alignment. This external fixation in itself can potentially damage a PMHS specimen during instrumentation. The method has been used in more than 30 PMHS lower limbs for dynamic sled and pendulum tests at the University of Virginia. During these tests no iatrogenic injuries due to the load cell and its mounting system have been recorded. The authors also comment that they have used their technique successfully in the humeral bone.

THE LLIMP PROJECT TECHNIQUE

In the LLIMP project the authors wanted to develop existing techniques to allow use of a load cell while attempting to reduce soft tissue damage and possible mal-alignment of the specimen. A drawing of the tibial transducer and LLIMP support system is shown in Figure 1. Prior to insertion all PMHS specimens are manually worked through a full range of articulation about fifty times.

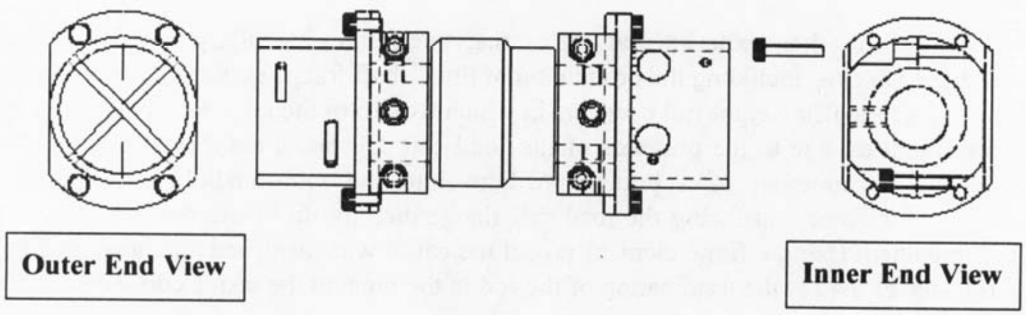

Figure 1 - LLIMP Tibial Load Cell Assembly

Surgical Technique

To demonstrate this technique the procedure has been applied to a saw bone (Figure 2) A 12 x 5cm area of skin with superficial tissue is removed from the anterior surface of the leg at a point defined by the subcutaneous surface of the tibia 6cm above the ankle joint. The area of tibia thus exposed is then stripped of periosteum using a periosteal elevator. The 12-cm section of the tibia is then freed from all surrounding tissues by gentle sharp dissection around its circumference. Particular attention is paid to preserving the soft tissue integrity around the posterior aspect of the tibia. The fibula shaft is vulnerable to fracture and care is taken to preserve its integrity. The inter-osseous membrane is only divided over the 12cm resection length and care is taken to preserve the structure both proximally and distally at the syndesmosis.

The PMHS specimen is held with the leg in its anatomical position such that the foot rests at 90° to the tibial shaft with the 2nd toe pointing vertically upwards. The two posterior end sections of the drilling jig (Figure 3) are passed around the tibia along with securing ties. The anterior section of the jig is positioned to join with the two posterior sections and secured (Figure 3). The whole drilling jig is then manipulated and adjusted around the tibia by four adjusting screws to ensure that the orientation is correct in all planes, both radially and axially. The drilling jig is marked with the central longitudinal axis, to assist with this task. Locating holes are drilled through the tibia through which four fixing pins are placed, two at right angles to each other at each end (Figure 4). Care is exercised when drilling through the tibia to minimise the risk of mal-alignment, as the hole is drilled obliquely into the surface of the tibia. The tibia is also marked for cutting through the jig. The tibia is divided with a Desoutar saw and the removed section kept for further physical property analysis (Figure 5). A fine cutting ring is then placed over the ends of the tibia and fixing pins reinserted to maintain its position. The sawn end of the tibia is then ground down to exactly the right length (Figure 6).

The cut tibial ends are prepared, over a 25mm length from the cut edge, with a degreasing agent. The potting cups are then placed on the tibial ends and realigned with the fixing pins to maintain their position and a dummy tibial load cell is inserted to maintain the alignment of the leg (and stop any relative movement due to dehydration or degradation) (Figure 7). Potting media is pressure injected into the cups via two 6mm holes (Figures 8, 9 & 10).

Figure 2

Saw Bones to Demonstrate Technique

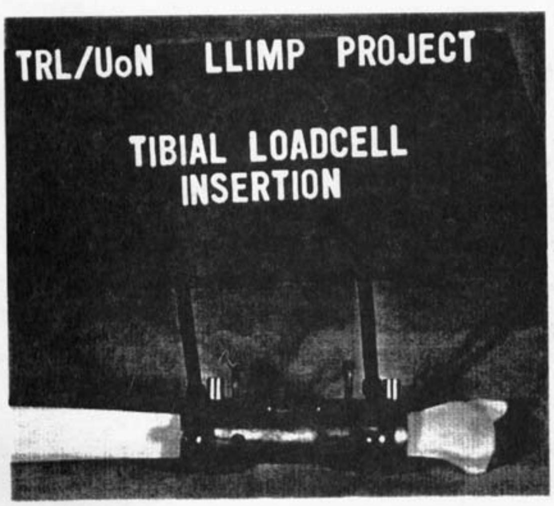

Figure 3

Cutting Clamp Applied Secures with Cable Ties

Figure 4

Drilling of Guide Wires

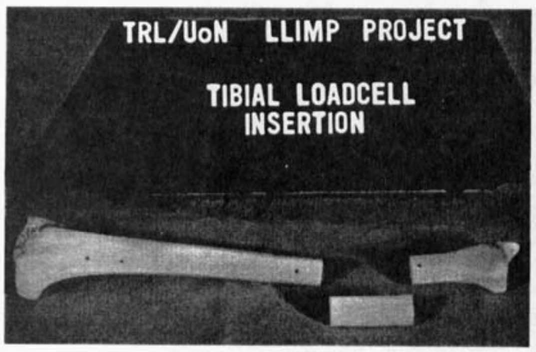

Figure 5

Divided Tibia

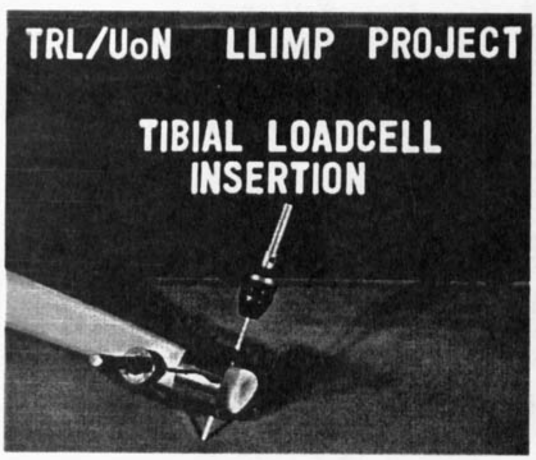

Figure 6

Cutting Jig in Situ

Locating Pins Shown

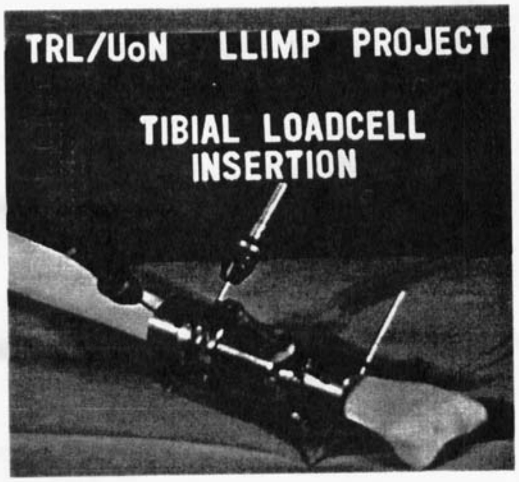

Figure 7

Dummy Load Cell and Cradle in Situ, Held by Locating Pins

Figure 8

Pressure Injection Equipment

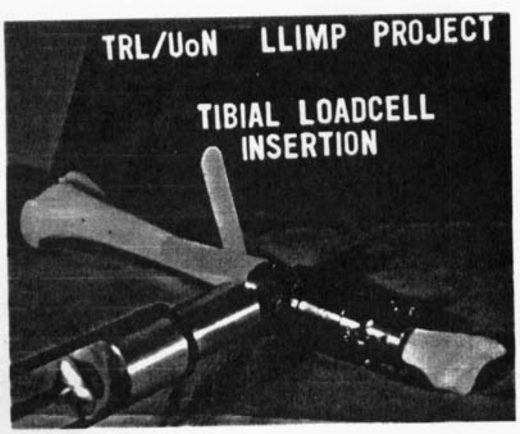

Figure 9

Pressure Injection of Potting Medium

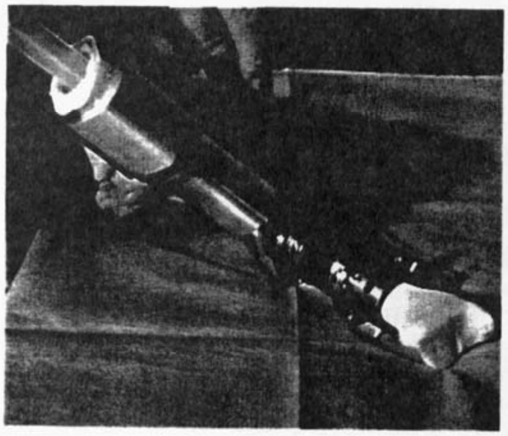

Figure 10

Pressure Injection

Figure 11

Completed Assembly

Figure 12

Completed Assembly

When the specimen is to be tested the dummy load cell is removed and replaced with the force measuring transducer. After the test the dummy load cell is reinserted to maintain limb alignment for radiography.

The potting cups are universal and it has been possible to fit them to all PMHS specimens to date (Figures 11 & 12), although in the case of a very large tibia the anterior surface has required minor re-profiling. No failures of the system have been observed in the test programme so far carried out.

Figure 13

Tibial Load Cell in Situ

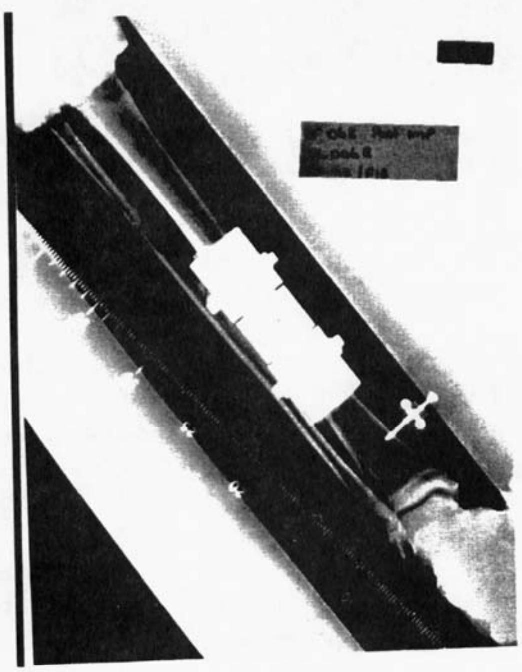

Figure 14

Tibial Load Cell in Situ

Radiographs (Figures 13 & 14) are taken to confirm alignment. Such a mounting technique could be used for the insertion of any load cell into any long bone (Tibia, Femur, Humerus, Radius or Ulna)

To date, in the LLimp project, methylmethacrylate has been used as the injection medium. Figure 15 shows that after injection a tight bond to the cup has formed and that there is no ingression into the medullary canal. Some further investigation into potting media may be necessary as the severity of impact increases in the future phases of the research programme. Provided the potting medium passes through a viscous period for one to two minutes it should be possible to inject alternative materials.

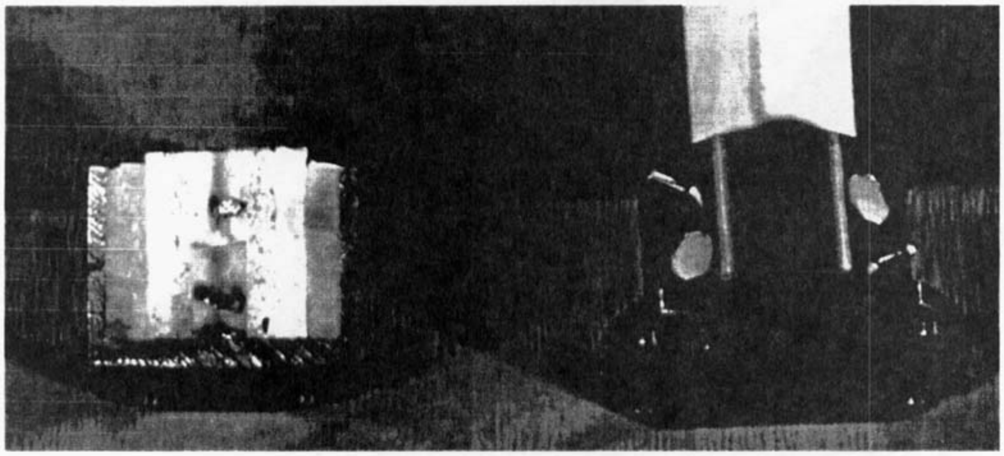

Figure 15 - Divided potting cup showing potting medium in place.

SUMMARY

This technique of inserting a load cell into the tibia is simple and can be completed in less than one hour. All parts of the system are reusable apart from the potting cups that remain cemented to the bone. The most difficult part of the technique is drilling the four locating holes through the drill jig. Care and precision must be exercised to ensure that the holes are in the correct positions and do not deviate from their intended course. Welding drill guides on to the drill holes to maintain good drill alignment during drilling has facilitated this.

As with the insertion of any load cell the distribution of mass and resulting stiffness in the limb is altered. With this technique the limb mass is increased by 694gm (comprising of the load cell, cradle, potting cups less removed bone mass). The length of the complete module including the pots is 120mm compared to the 70mm of removed bone.

CONCLUSIONS

1. The measurement of forces transmitted through the long bones of a PHMS specimen is difficult to achieve without compromising important anatomical structures.

2. This paper reports a new technique as a further development of techniques used at both the Renault in France and the Automotive Safety Laboratory at the University of Virginia, USA.

3. The LLimp technique, based on drill and cutting jigs, does not use any external fixation equipment and can ensure very accurate alignment of the bone with the load cell in terms of length, axial alignment and rotation.

4. The size of the implant load cell necessitates the removal and disruption of some tissue. This method minimises soft tissue disruption.

5. No failures have been observed in over 100 PMHS tests performed to date.

6. The technique reported could be used in other long bones.

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DISCUSSION

PAPER: **A Revised Technique To Locate Accurately A Load Cell In A Long Bone**

PRESENTER: Adrian Roberts, Transport Research Laboratory, United Kingdom

QUESTION: Guy Nusholtz, Chrysler Corporation

What techniques and methodologies did you use to determine what the effect of the load cell was in terms of changing the system?

ANSWER:

In the particular tests we have been doing, we have been holding the knee in a hinged bracket. I acknowledge that implanting a load cell into the tibia is going to change the stiffness of the tibia itself, and also the mass and inertial characteristics of the system. However, in all the tests we've been doing so far, the limb itself is being held horizontal allowing some rotation at the knee joint. We'll acknowledge that when you put any load cell into the tibia it is going to make some significant changes but, for the type of work we have been doing at the moment, we don't believe that has been significant.

Q: The question wasn't whether you think there was a change, because obviously there is going to be a change. Have you thought of doing something to quantify or qualify that change so that you have an understanding of what that load cell means beyond just that it will increase the stiffness. How much will it increase the stiffness?

A: Well, alongside this study we are doing a lot of computer modeling as well. We will be able to investigate the change in stiffness through some of our modeling. In addition, we have been doing some strain gauging of the tibia adjacent to the load cell, but we haven't had an opportunity to fully analyze that data yet. So, at the moment, I can't quantify what the actual effect is; only that we know it is there and we are looking into it.

Q: So, the methodology you are thinking about using is to do a finite element model.

A: Yes, we have a finite element model which we are developing. One of the reasons we are doing that is to attempt to use that model in normalization of the test data, but that is another subject which I'm not going to address here.

Q: OK. Thank you.

Q: Kelly Kennett, Failure Analysis Associates, Inc.

Just to answer some of Guy's questions, a good bit of the subject of my thesis research was the loading error created by this tibial load cell. We created a finite element model and also ran several different tests to assess the effect of the load cell on the tibia. One of the things that we've seen is that most of the compliance in the leg actually occurs at the joints and not in the bone as you may imagine. The stiffness changes in the overall system from the knee down are not affected by the load cell substantially. We also ran some calculations on the inertial loading error. I think that is on the order of just a couple of Newton-meters error on the bending channels, and maybe as much as a few pounds on the shear channels. That is down in the noise of the general type of test that has been run with these load cells. Finally, we confirmed with a finite element model that the strain field was basically unchanged at a distance of about a diameter to a diameter and a half of the tibia away from the potting site.

A: I'd like to thank Kelly because he has given us a lot of assistance in setting up and developing this technique.

Q: Laurent Portier, Renault

I have one comment about the fibula. You leave it completely intact and therefore will have a problem in calculating the moments within the ankle joint. You won't know exactly what will happen within this joint, which is the primary information we want from this load cell.

A: Yes, it depends on what data you are looking for from the tibia load cell. If you divide the fibula and attach it rigidly to the tibia, you do potentially change the characteristics of the ankle joint. We are particularly interested in maintaining the integrity of the human ankle so that, if there is any separation of the tibia and fibula, we will be getting it in our particular tests. So we are looking at slightly different things, I'll grant you.

Q: Maybe you could implant a load cell into the fibula also.

A: Yes, one might be able to do that. Using a technique very similar to this, one should be able to implant a load cell so that both ends of the lower limb would be in very good alignment. Again, you are going to be adding a lot more mass into the leg and are going to change its stiffness but, in principle, yes you could.