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*INJURY BIOMECHANICS RESEARCH*
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## Design and Evaluation of Measurement Instrumentation Used for High Energy Impacts on Fresh Post-Mortem Human Subjects

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*This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.*

## ABSTRACT

*The femur injury criterion for anthropomorphic test devices (ATDs), used in car crash testing, is well established in crash biomechanics literature: however, the knee slider criterion and the tibial injury indices have less well-developed biomechanical bases. There is a need to investigate the biomechanical properties and behavior of the posterior cruciate ligament (PCL) and tibia during high energy impacts and verify these knee and tibia criteria. The Ohio State University Injury Biomechanics Research Laboratory has been conducting high energy tibia impacts on fresh post-mortem human subjects (PMHS). This research project uses PMHS and focuses on the displacement of the tibia in relation to the femur while the tibia is loaded from an anterior location as seen in frontal car crashes.*

*The objective of this research is to design and evaluate a measurement system used in high energy tibia impact testing on PMHS, allowing accurate measurement of PCL and tibia displacements as well as identifying the time of failure. From February 2005 through April 2006, seven PMHS (13 tibias) have been tested. A number of constraints have been placed on the test setup in order to reduce the number of test variables, allowing the tibia and PCL displacements to be examined in greater detail. These constraints include eliminating applied tibia load from previous research, testing a single femur angle and securing the foot to the test platform. The tibia displacement is currently measured using three tri-axial accelerometers, one attached to the femur and two attached to the tibia, one anteriorly and one medially. A positive comparison has been made between the relative tibia-to-femur displacements recorded from the accelerometers and the displacements recorded from high speed video. In all tests resulting in a tibia fracture the time of failure can be clearly identified; however, determining the time of failure in a test which results in a ligament injury has proven to be more difficult. A small Differential Variable Reluctance Transducer (DVRT) [displacement transducer]r is attached to the PCL to identify stretch and rupture. With the use of the accelerometers to determine tibia displacement and improvements in the method for attaching the DVRT to the PCL, determining the time of failure for both tibia fractures and PCL injuries has been achieved.*

*With time of injury for both tibia and PCL failures determined and the relative tibia-to-femur displacement accurately measured, the next step in this research is to start removing the constraints placed on the test setup. This will provide a more "real world" situation improving our understanding of the biomechanical properties of the knee in a frontal car crash. Finally, the test data can be used to improve the knee slider criterion and tibia displacement injury index.*

## INTRODUCTION

Currently, knee injuries account for 10% of all frontal car crash injuries (Atkinson and Atkinson, 2000). Although knee injuries account for a small percentage of frontal car crash injuries they are attributed to an estimated annual 225-720 million dollars in cost (Hendrie et al., 1994; Miller et al., 1998). The femur injury criterion for anthropomorphic test devices (ATDs), used in car crash testing, is well established in crash biomechanics literature. However, research efforts to establish the knee slider criterion and the tibial injury indices have been limited in scope and effort. There is a need to investigate the biomechanical properties and behavior of the knee, including posterior cruciate ligament (PCL) and tibia, during high energy impacts.

Knee injuries in frontal car crashes are predominately caused when the lower extremity of a frontal passenger comes in contact with the knee bolster or steering column. When the knee bolster contacts the lower extremity below the knee, an anterior load is placed on the tibia causing the tibia to sublux posteriorly in relation to the femur. This posterior displacement may result in a PCL injury.

Viano et al. (1978) conducted research, in which ten cadavers (twenty legs) were tested to investigate knee and tibia impact biomechanics and kinematics. Viano used three different dynamic test configurations; knee impacts with a 110$^{o}$ flexion angle, lower leg impacts with a 90$^{o}$ flexion angle and knee-tibia impacts with a 90$^{o}$ flexion angle. Following dynamic testing, Viano also potted the tibia and femur of five of the lower limbs for further testing. Viano quasistatically displaced the tibia, while keeping the femur flexed at 90$^{o}$, until failure occurred to determine the stiffness of the knee and displacement tolerance of the tibia. Viano documented that the PCL failed at 14.4 mm of tibia displacement.

The currently accepted injury criterion of 15 mm of tibia displacement, based on the knee slider displacement, is derived from these values obtained by Viano during the quasistatic testing. The tibia injury criterion and knee slider stiffness for ATDs, used in car crash testing, are not based on dynamic biomechanical test data.

Balasubramanian et al. (2004) attempted to dynamically verify the PCL injury criterion. Balasubramanian dynamically tested fourteen legs in three different test setups. The tests conducted by Balasubramanian produced a number of various injuries. Of these injuries, a total of six PCL related injuries were recorded with an average tibia displacement of 17.2±2.8 mm at time of injury. Although the dynamic test data obtained by Balasubramanian was within range of the values obtained by Viano, the test setup that was used was not supported by any real world conditions.

Bartsch (2004) conducted cadaver and ATD research in which the proximal tibia was dynamically impacted. Bartsch developed a test setup to accurately replicate real world test conditions. Bartsch analyzed the lower extremity loading conditions of a Hybrid III 50$^{th}$ percentile ATD from a series of twenty-eight frontal barrier to vehicle or vehicle to vehicle crash tests from late model vehicles. Bartsch isolated the lower extremity from the Hybrid III ATD and developed a test setup that produced results that were similar to the vehicle crash data. Bartsch then conducted dynamic impacts on eight isolated post-mortem human subject (PMHS) legs. Although the test setup developed by Bartsch has been verified to produce a real world crash test condition, the accuracy of the measurement instrumentation used in the PMHS test was less certain.

# METHODS

## Objective

Due to the visco-elastic properties of biological materials, the current knee injury criterion needs to be verified by dynamic impacts using a "real world" test setup. Therefore, there is a need to develop measurement instrumentation that will allow accurate measurements during dynamic tibia impacts on PMHS without affecting the biomechanical response of the subject. The objective of this research is to develop measurement instrumentation technique that will complete the following tasks:

- Accurately measure tibia displacement relative to the femur
- Accurately measure PCL displacement
- Identify the time of injury for both ligament and bone failures

## Anatomy of the Knee

The femur as shown in Figure 1 is the only bone of the thigh. The femur is the longest and heaviest bone in the human body. The head of the femur articulates in a circular depression of the pelvis known as the acetabulum. The shaft of the femur has a slight curve to allow the knee joint to be in line with the body's center of gravity. The distal end of the femur is characterized by two rounded structures known as the medial and lateral condyles. These femoral condyles are the articulating surfaces of the femur in the knee joint.

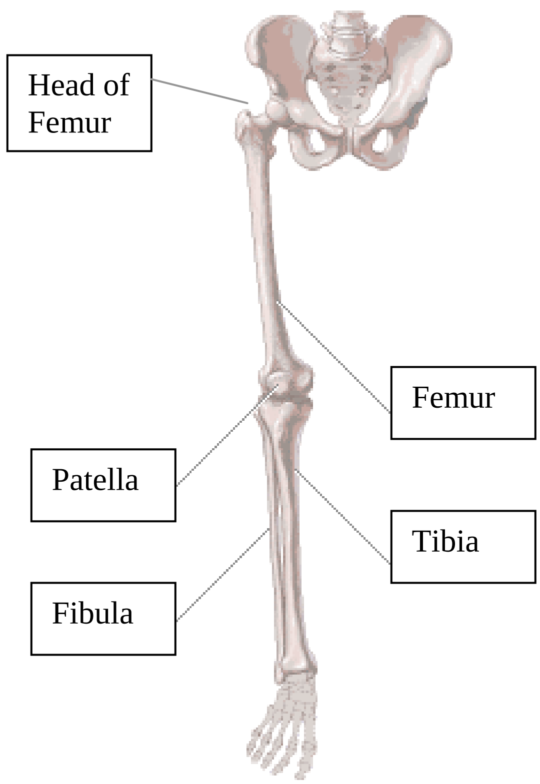


Figure 1: Bones of the Leg (from: www.encarta.msn.com).

The patella commonly known as the knee cap is located on the anterior surface of the knee joint as shown in Figure 1. The patella serves to protect the knee joint and increase the leverage of the quadriceps femoris muscle as it extends the leg at the knee.

The tibia is the main weight bearing bone of the lower leg. The proximal end (head) of the tibia is characterized by two slightly concave surfaces known as the medial and lateral condyles. These tibial condyles are the articulating surfaces of the tibia in the knee. The proximal end of the tibia is often referred to as the tibia plateau. The tibia tuberosity is located on the anterior portion of the tibia, just below the plateau, and is the attachment site of the patellar tendon.

The fibula is a long slender bone that runs parallel to the tibia as shown in Figure 1. The fibula is more important for muscle attachment than for weight bearing support.

The ligament that connects the patella to the tibial tuberocity is known as the patellar ligament. The ligaments that are responsible for stability in the anterior/posterior direction are known as the posterior cruciate ligament (PCL) and the anterior cruciate ligament (ACL). The PCL lies deep within the knee joint and runs from the anterior femur to the posterior tibia. The ACL, which lies anterior to the PCL, runs from the posterior femur to the anterior tibia. The locations of the ACL and PCL are shown in Figure 2.

The ligaments that are responsible for the medial/lateral stability of the knee are known as the lateral collateral ligament (LCL) and the medial collateral ligament (MCL). The LCL is located on the lateral portion of the knee, connecting the femur to the fibula. The MCL is located on the medial portion of the knee, connecting the femur to the tibia. The locations of the LCL and MCL are shown in Figure 2.

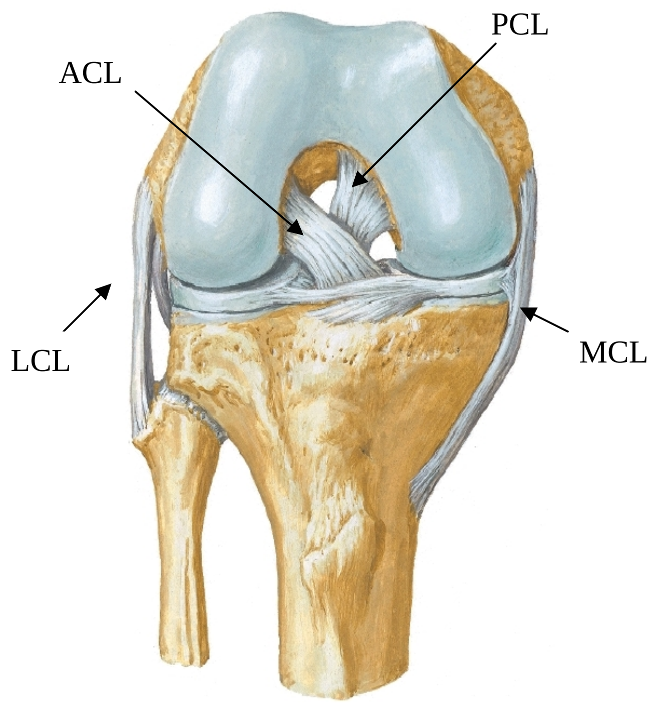


Figure 2: Major Ligaments of the Knee [The Netter Presenter].

Ligaments only provide resistance when placed in tension. As shown in Figure 3, the PCL provides resistance to posterior tibia displacement relative to the femur. The ACL provides resistance to anterior tibia displacement relative to the femur. As the knee becomes flexed, the tension on the PCL increases while the ACL tension decreases. The increased tension on the PCL in the flexed position makes the PCL vulnerable to injury due to posterior tibia displacement from frontal impact loading.

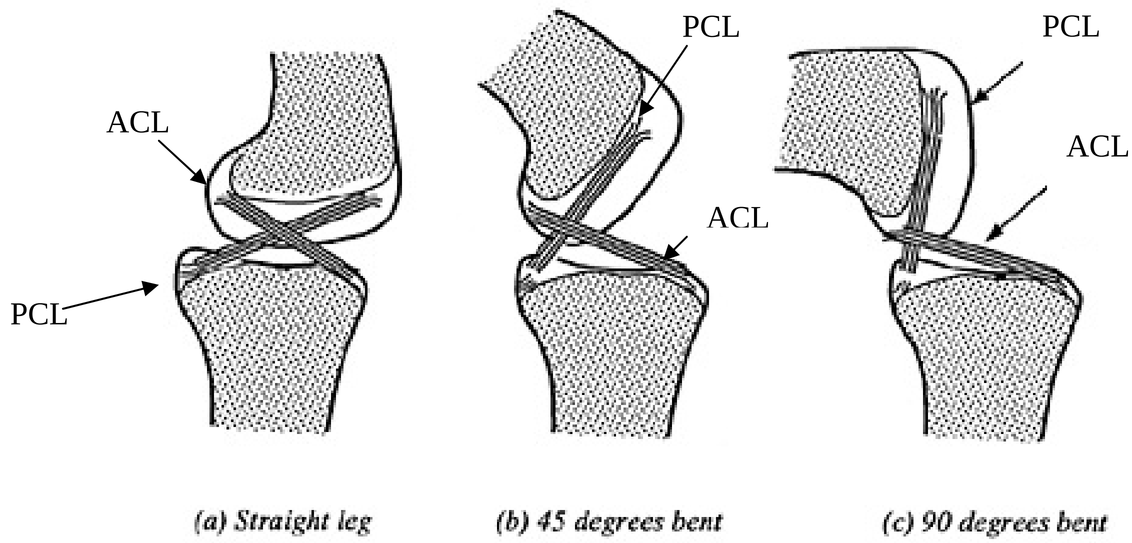


Figure 3: ACL and PCL Stability Properties.

## Instrumentation and Setup

The legs of each PMHS were removed at approximately mid-femur leaving seven inches of femur attached to the knee. The femurs were then securely potted using Bondo Ultimate Filler™ [Bondo Corporation, Atlanta, GA] to the test platform, shown in Figure 4. A six axis load cell (Model #2667 RA Denton Inc., Rochester, MI) was located behind the femur to measure the forces and moments acting on the femur. Forces transmitted through the foot were measured in the z and x axis using two load cells (Models 1210AF-5K and 1210AF-2K respectively, Interface, Scottsdale, AZ) as shown in Figure 4. A constant force of 222 N was applied to the quadriceps muscle by clamping the muscle to a tensioned cable.

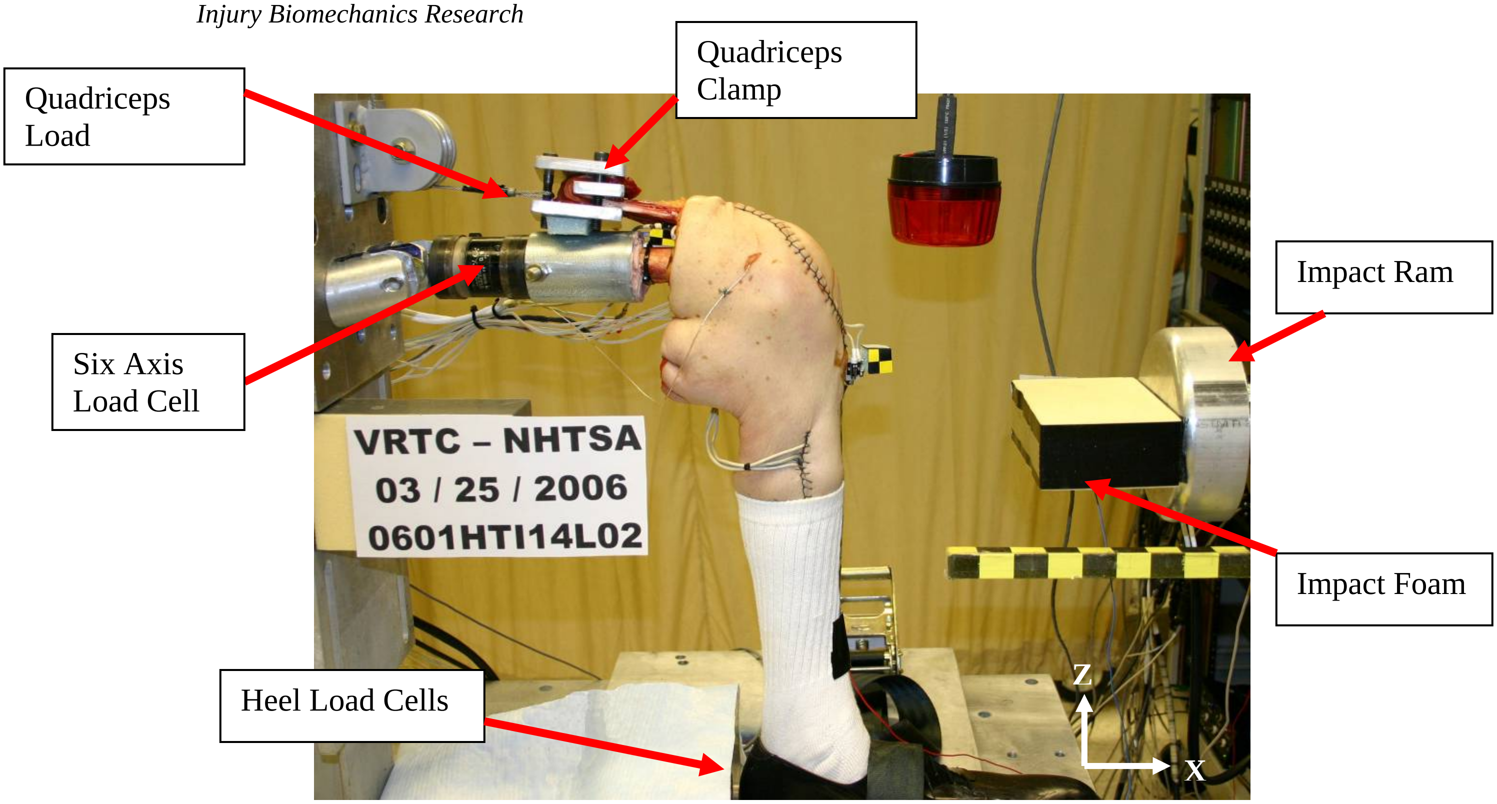


Figure 4: Test Setup.

Foam padding with a stiffness of 151.6 ± 24.4 N/mm (Last-A-Foam, General Plastics Manufacturing Company, Tacoma, Washington) was placed on a 23.8 kg ram. The knee flexion angle was 90$^{o}$, which is measured by number of degrees the knee flexed from the straight position. When the knee is straight the flexion angle is zero degrees. One tri-axial accelerometer was placed on the anterior femur while the other two where placed on the anterior and medial aspects of the tibia. The locations of the three tri-axial accelerometers are shown in Figure 5.

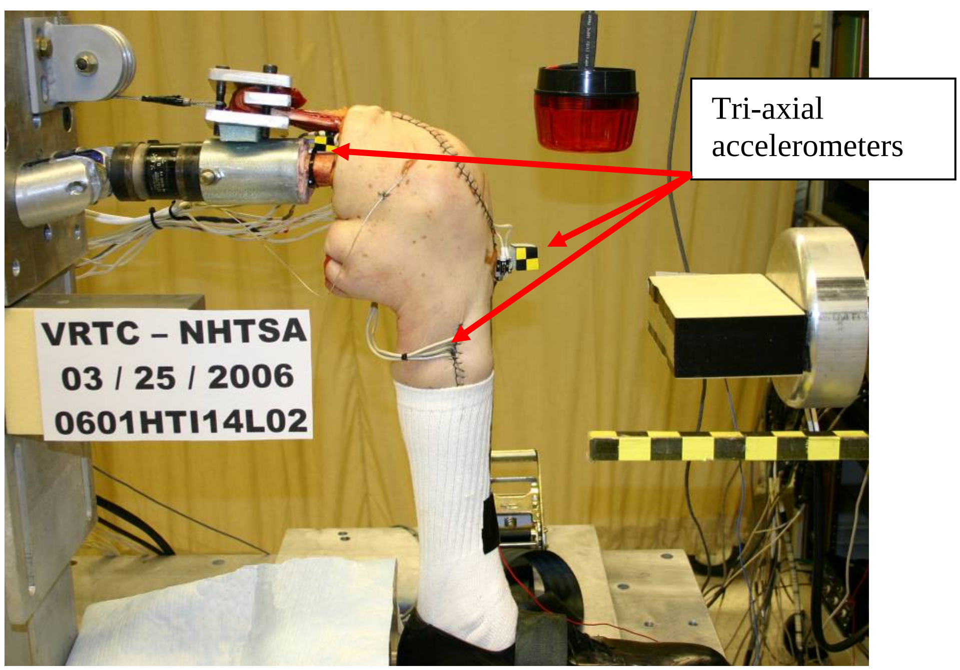


Figure 5: Tri-axial accelerometer locations.

The tri-axial accelerometer placed on the anterior femur is securely attached using wire ties as shown in Figure 6(a). To attach the accelerometer on the anterior tibia, a small piece of subcutaneous tissue was removed and the bone was smoothed using a Dremel tool (Robert Bosh Tool Company, Racine Wisconsin). The accelerometer block was then attached directly to the bone using polyurethane glue (Gorilla Glue, The Gorilla Glue Company, Cincinnati Ohio) as shown in Figure 6(b). Finally, the tri-axial accelerometer placed on the medial tibia was attached directly to the bone using wood screws as shown in Figure 6(c).

(a) (b) (c)

Figure 6: (a) anterior femur tri-axial accelerometer, (b) anterior tibia tri-axial accelerometer, (c) medial tibia tri-axial accelerometer.

The locations of the accelerometers, as well as, specific anatomical landmarks were digitized using a Faro Arm (Faro Arm Technologies, Lake Mary FL). The digitized three-dimensional point data from the impact location (Point A), one point on the anterior tibia (point B) and one point on the superior femur (point C) as shown in Figure 7, were used to create the subjects coordinate system. From these three points, one vector and two cross products were used to create the subject's global coordinate system. For all three accelerometer mounting blocks, three points were digitized, in a clockwise manner on the face of the accelerometer block, as shown in Figure 8. The numbered dots in Figure 8 represent the three points recorded by the Faro Arm. The numbered arrows in Figure 8 represent the directions in which each accelerometer is recording.

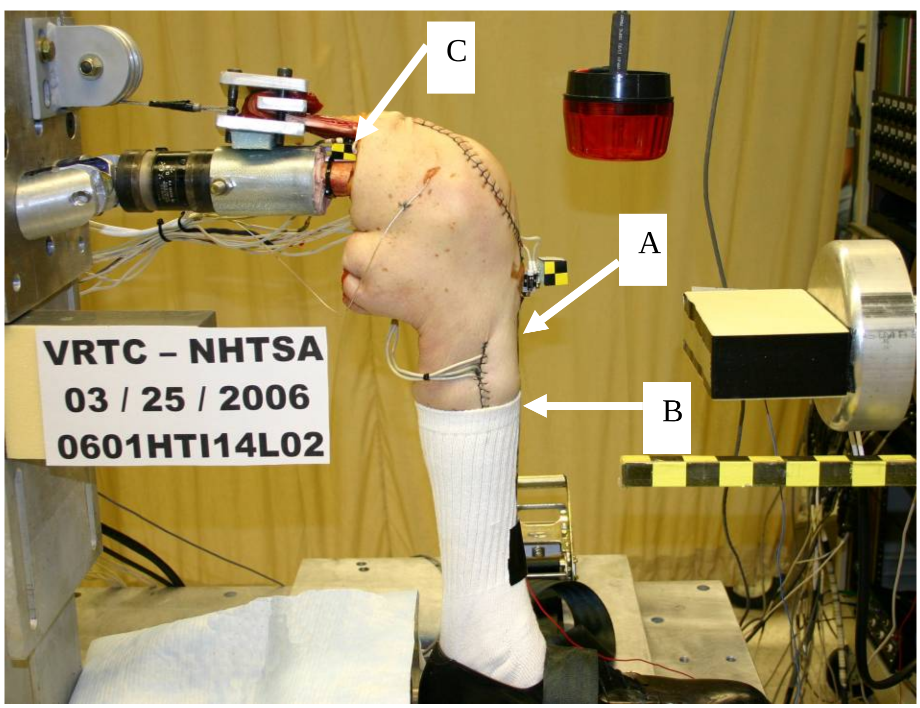


Figure 7: Subject Point Location.

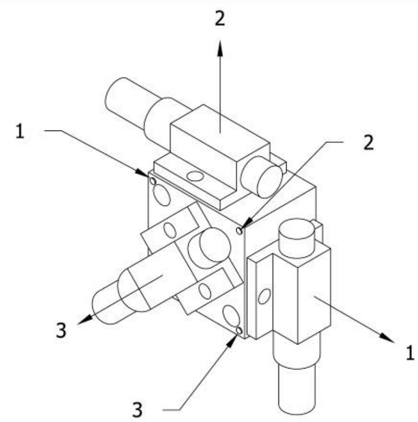


Figure 8: Accelerometer Block Point Digitization.

Using the three points recorded on the block, two vectors and their cross product were created to define the coordinate system of the accelerometer block. By knowing both the accelerometer block's coordinate system as well as the subject's coordinate system, the signals from each accelerometer block could be rotated into the coordinate system of the subject. This process of coordinate system transformation was adapted from Shaw (2005).

One micro-differential variable reluctance transducer (DVRT) [DEMOD-DVRT, MicroStrain Inc., Burlington, VT] was sutured to the medial band of the PCL to record PCL displacement. It was found in previous testing that the medial band of the PCL experiences the greatest displacement during posterior tibia displacement. The ACL of each knee was removed to allow room to instrument the PCL. It has been shown that the ACL does not contribute to the stability of the flexed knee in posterior tibia displacement (Butler et al., 1977). It was found from previous research that suturing the DVRT barbs to the PCL provided a repeatable PCL displacement measurement (Markolf et al., 1998). A DVRT is shown in Figure 9 and the implanted DVRT is shown in Figure 10. The DVRT does not measure the displacement of the entire PCL. However, it measures a portion of the PCL's displacement. The signal from the DVRT was appropriately scaled to measure full PCL stretch. After acquiring data during an impact, the acceleration signals were double integrated to calculate three dimensional displacements of the femur and tibia.

Figure 9: DVRT.

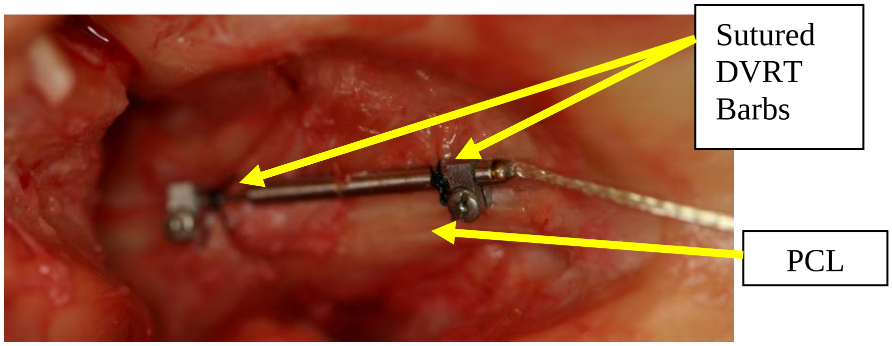


Figure 10: Implanted DVRT.

The foot of each subject was strapped down to the test platform to reduce vertical motion during the tests. All tests were recorded using high speed video that was recorded at 1000 frames per second. All signals were acquired using a 32-channel data acquisition system with a sampling rate of 20,000 Hz (Yokagowa Corporation of America).

## Test Conditions

Each leg was impacted three times at 1.45 m/s. The legs were impacted at this low speed to precondition the knee ligaments and to provide a baseline knee response. After the three low energy impacts, the impact speed was gradually increased until failure was suspected. Injury was detected from: rapid drops in the DVRT plots or ram force, rapid increase in the rate at which the tibia displaced, physical inspection of the knee, or visual inspection of the high speed video. Upon suspicion of injury, the legs were impacted at the initial 1.45 m/s to evaluate any changes from the baseline knee response. The test matrix is shown in Table 1.

Table 1. Test Matrix.

| Test Subject | Leg | Nominal Impact Speed (m/s) | Nominal Impact Energy (J) |
|---|---|---|---|
| Subject 1 | Right | 1.45, 1.45, 1.45,<br>2.9,<br>1.45 | 25,<br>100,<br>25 |
| | Left | 1.45, 1.45, 1.45,<br>2.9,<br>1.45 | 25,<br>100,<br>25 |
| Subject 2 | Right | 1.45, 1.45, 1.45,<br>2.9,<br>3.2,<br>3.55,<br>3.9,<br>1.45 | 25,<br>100,<br>125,<br>150,<br>175,<br>25 |
| | Left | 1.45, 1.45, 1.45,<br>2.9,<br>1.45 | 25,<br>100,<br>25 |

# RESULTS

## Test Results

After all tests were complete for a PMHS, an autopsy was conducted to determine the type and degree of injury. The type of injury, tibia displacement and PCL stretch at time of injury for all tests are shown in Table 2.

Table 2. Test Results.

| Test Subject | Leg | Nominal Impact Speed (m/s) | Nominal Impact Energy (J) | Tibia displacement at time of injury (mm) | PCL Stretch at time of injury (mm) | Injury |
|---|---|---|---|---|---|---|
| Subject 1 | Right | 1.45, 1.45, 1.45, 2.9, 1.45 | 25, 100, 25 | 20 | 4 | PCL avulsion at distal attachment |
| | Left | 1.45, 1.45, 1.45, 2.9, 1.45 | 25, 100, 25 | 17 | 3 | PCL avulsion at distal attachment |
| Subject 2 | Right | 1.45, 1.45, 1.45, 2.9, 3.2, 3.55, 3.9, 1.45 | 25, 100, 125, 150, 175, 25 | 18 | 8 | PCL tear in distal third |
| | Left | 1.45, 1.45, 1.45, 2.9, 1.45 | 25, 100, 25 | 25 | 6 | PCL avulsion at distal attachment |

After the method of using tri-axial accelerometers to calculate displacement was validated, it was found that the displacement measurements could be used to find time of injury. The tibia displacement for all impacts on the left leg of subject 2 are shown in Figure 11. On the fourth impact at 2.9 m/s, the rate at which the tibia displaces abruptly increases at 22.7 ms, indicating an injury has occurred. The tibia displacement measurements also show that the post-injury knee response (fifth impact at 1.45 m/s) differs greatly from the base line knee response (first , second , and third), indicating the structural integrity of the knee has indeed been compromised.

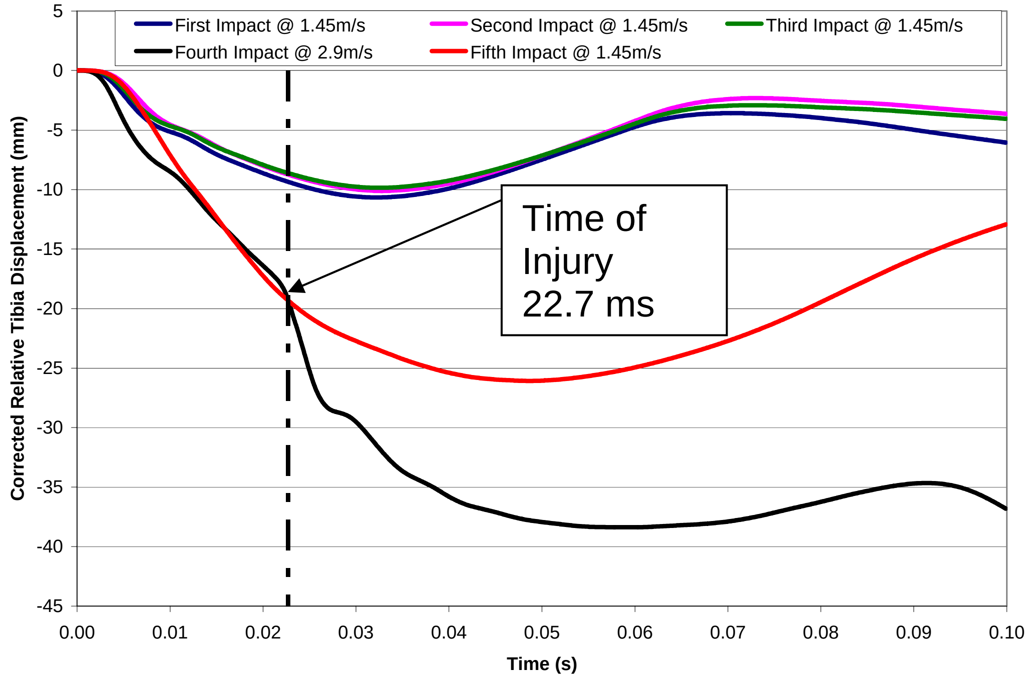


Figure 11: Tibia displacement for all impacts on the left leg of subject 2.

The PCL stretch for all impacts on the left leg of subject 2 is shown in Figure 12. The second and third impacts provide a repeatable baseline knee response as shown in Figure 12. A rapid drop in PCL displacement at 22.7 ms can be seen in the fourth impact, (2.9 m/s) thus, indicating an injury has occurred.

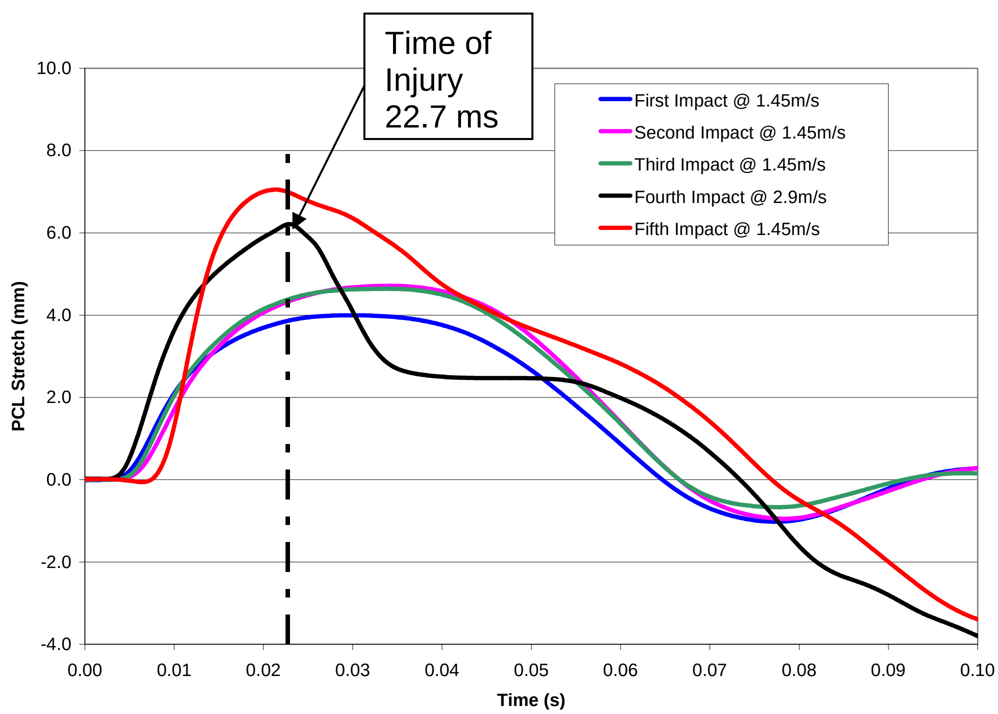


Figure 12: PCL stretch for all impacts on the left leg of subject 2.

The forces acting on the femur provide insight into the amount of force that is actually transmitted through the knee. Overlaying the femur forces in the z axis for each impact will provide information about any change in knee response during an impact or set of impacts. The femur forces in the z axis for all impacts on the left leg of subject 2 are shown in Figure 13. A 1,500 N drop in applied femur force occurs at 20.8 ms, which is 1.9 ms prior to sudden increase in tibia displacement at 22.7 ms as shown in Figure 13. It is believed that the ligament injuries can occur over a period of 2-3 ms. The force begins to drop as microscopic tears in the ligament begin to take place. It is also observed that in the post injury impact (fifth impact), the knee does not posses the same ability to transmit force to the femur as in the pre-injury impacts (first impact, second impact, third impact).

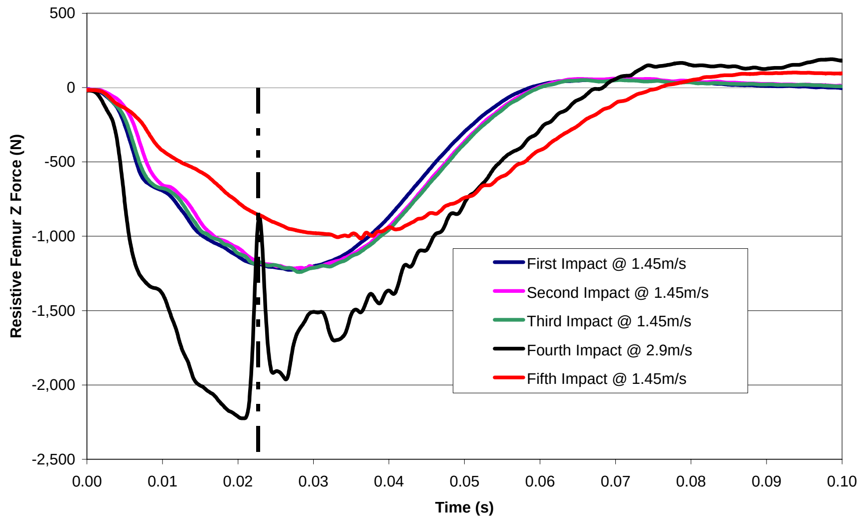


Figure 13: Resistive femur force for all impact on the left leg of subject 2.

## CONCLUSION

Using one DVRT sutured to the medial band of the PCL provided repeatable PCL displacement measurements and greater sensitivity to changes in PCL response. The use of tri-axial accelerometers to find displacement provided accurate tibia displacement measurements in three dimensions. After implementing the tri-axial accelerometers and suturing the DVRT to the medial band of the PCL, time of injury was determined for ligament and bone injuries.

Now that the time of injury for tibia and PCL failures can be determined and the relative tibia displacement can be accurately measured, the next step in this research is to start removing the constraints initially placed on the test setup. Removing the constraints placed on the test setup will provide a more “real world” situation allowing future researchers to obtain the biomechanical properties of the knee in a frontal car crash. A test matrix can be created that will allow efficient investigation of the biomechanical properties of the knee. Sufficient modeling should also be conducted to evaluate the sensitivity of each test parameter. As a result of the sensitivity analysis, researchers will be able to reduce variation while still providing a real world test setup. Using the measurement instrumentation developed in this research, investigators will be able to obtain test data that can be used to develop a more biomechanically-based knee slider criterion and tibia displacement injury index.

## ACKNOWLEDGEMENTS

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# DISCUSSION

PAPER: **Design and Evaluation of Measurement Instrumentation Used for High Energy Impacts on Fresh Post-Mortem Human Subjects**

PRESENTER: ***Kyle Pfefferle, The Ohio State University***

**Q**UESTION: *Peter Martin*
What is the DVRT? That's a displacement transducer?

**A**NSWER: A displacement: a Differential Variable Reluctance Transducer or displacement transducer.

**Q:** *Pat Fyhre, General Motors*
So what would you propose that your tibia femur displacement be as opposed to the 15 mm for the Hybrid, for the 50th percentile: up to 25 mm?

**A:** No. I'm not proposing any injury criterion at this time. I'm just explaining that we have developed the test setup to further investigate this and then upon more research, we can—

**Q:** But you had indicated that you thought it was going to be quite a bit more—or maybe I heard incorrectly.

**A:** Through these two subjects, we found that it is more displacement than what's currently—

**Q:** And what were the size, you know, the mass of the cadavers? Were they approximately 50$^{th}$ percentile size?

**A:** One was actually below and one was a little bit above.

**Q:** And were there any differences between the two that you could see? I mean, I couldn't tell quite the detail.

**A:** Oh, well, one was a small female and one was a large male.

**Q:** But what did the small female have? You know, was it smaller displacements until you saw injury in her before you--?

**A:** Yes.

**Q:** Okay.

**A:** If you look back—here, you can see that the large male on the left leg, he took much more impacts until injury occurred and we believe that there was some difference in pathology in his right leg than a lot of failure before.

**Q:** Okay. It was a very good study. I enjoyed it.

**A:** Thank you.

**Q:** *Guy Nusholtz, Daimler Chrysler*
Did you look at the relationship between the loading force and the force that you measured in the load cell, in the tibia?

**A:** Yes.

**Q:** Because you can see clearly that the force starts to drop off as soon as you start to lose the force. But, what happened to the contact force? In terms of loading the leg, that's a force that's used primarily with the dummy. So what would be the relationship between those two types of forces? Does it show up? Does that drop-off show up in the loading force?

**A:** Yes, the drop-off shows up, but there's a little bit of time shift because the padding that we use absorbs some of the force when it begins to load up. But, it does show that it's a drop in force, the ram force.

**Q:** Why would padding cause the time shift? I mean, the only thing I think that would happen is if you had a mass effect and you're transmitting the load through some sort of mass effect to cause a time shift. Could be the mass of the leg is what's doing that.

**A:** Okay.

**Q:** Not the padding. Okay. Thank you.

**A:** Well, yes.

**Q:** *Erik Takhounts, NHTSA*
Just one question: Are you going to look at the effect of the DVRT itself, suturing to the ligament and then you test the ligament for failure? Because you introduced, sort of, micro failure by suturing. Are they going to try to run tests, at least one of them, without DVRT and see whether it actually fails at the same velocity as you have over there?

**A:** That is a good question. We have not thought of that. The barbs are very small and we don't expect our sutures to have a big effect on the stability of the ligament, but we can look into that.

**Q:** It would be a good idea to confirm that.

**A:** Yeah.

**Q:** Okay. Thank you.