# A MECHANISM OF INJURY TO THE FOREFOOT IN CAR CRASHES

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**ABSTRACT**
The purpose of this study was to determine a mechanism of injury of the forefoot observed in some frontal offset car crashes. To verify an injury mechanism, research was conducted in an effort to reproduce Lisfranc type injuries in the cadaver. Impact tests conducted at speeds of up to 16 m/s simulated knee-leg-foot entrapment, floor pan intrusions, whole-body deceleration, muscle tension and foot/pedal interaction. Two possible mechanisms of injury were investigated the Plantar Nominal Configuration and the Plantar Flexed Configuration. The configuration of the foot made a difference in the frequency and severity of the injuries.
**KEYWORDS** – Forefoot injuries, Lisfranc type injuries, Metatarsal injuries, Tarsometatarsal injuries, Ligamentous injury.

PASSENGER RESTRAINT SYSTEMS have improved to the point that, today, more and more people are surviving severe motor vehicle accidents, but they are suffering injuries to the lower leg, ankle and forefoot. Previously these lower limb injuries were insignificant because the upper body injuries were usually life threatening (Crandall et al., 1998 and Haland et al. 1998). Very few researchers have attempted to discover a mechanism for forefoot injuries in car crashes. Consequently there is little data regarding what happens to the foot in a car crash. Based on what few studies exist and an interview with a victim of a head on car crash this study proposes a scenario that in the laboratory does yield forefoot injuries. The authors propose an injury mechanism and tolerance level for the foot in car crashes based on the scenario so that car manufacturers can design safer cars.

## EPIDEMIOLOGY

As reported by Burroughs et al. 1998 the incidence of Lisfranc injuries is about 1 in 55,000 persons each year and these occur mostly as a result of car crashes. Previous researchers have attempted to identify an injury mechanism for the forefoot with minimal success (Haland et al., 1998, Richter et al., 2001, Wilson et al., 2001). Most of them have relied on post crash data to try to determine how a crash victim was injured. They state that many factors play a roles in the etiology of foot and ankle injuries, and speculate how these factors modulate foot and ankle injury. Alepuz et al. (1995) studied central metatarsal fractures of patients and found that 75% suffered injuries from car crashes and that the third metatarsal was most frequently injured. They hypothesized that the injury mechanism was direct trauma.

Crandall et al. (1998) found that foot and ankle injuries accounted for 8-12% of all moderate to serious injuries sustained by motor vehicle occupants involved in frontal crashes. They examined the correlation between impact characteristics and the frequency and severity of lower limb injuries and noted that footwell intrusion into the passenger compartment caused injuries, but sometimes injuries occurred with no intrusion. They found that 71% of the injuries were sustained with less than 30 mm of intrusion. The effects of $\Delta V$ and intrusion on lower limb injury were compared. For frontal crashes, 89% had a $\Delta V$ between 10-50 km/hr (2.8 to 13.9 m/s) and an intrusion of less than 30 mm, but only 6% of the occupants were injured. These 6% accounted for the majority of injuries sustained in car crashes. According to Crandall et al. (1998) the risk of injury increased as ΔV and intrusion increased. However only a small percentage of crashes occurred at these higher ΔV levels. They did not elaborate on the kinds of forefoot injuries that occurred in the accidents they studied.

**Injury Mechanisms**

The eponym Lisfranc injury has been used to cover a variety of forefoot injuries including bony fracture and/or ligamentous rupture with disruption of the planar joints formed by the junction of the metatarsals, cuneiforms and cuboid bones also known as the tarsometatarsal joints. The most famous Lisfranc injury occurs at the joint involving the $1^{st}$ and $2^{nd}$ metatarsals and the medial cuneiform. In this area the Lisfranc ligament between the $2^{nd}$ metatarsal and the medial cuneiform is ruptured and the joint becomes unstable. There is no ligament between the first and second metatarsal bones as there is with all of the other TMT joints and because of this uniqueness the ligament that provides strength and stability for the joint has been named the Lisfranc ligament.

To identify injury mechanisms, computer simulations and laboratory tests using cadavers and/or dummies have been conducted in the past in an attempt to reproduce the injuries observed in real life accidents. Rudd et al. (1998) conducted a series of sled tests using Hybrid III dummies and cadavers to examine the influence of foot placement on the brake pedal in frontal collisions. The average ΔV used was 16 m/s and the impacts simulated interaction of airbags, seatbelts and knee bolsters with the test specimen. Three of the eight tests used cadavers with no muscle tensing. These tests did not produce any lower limb injuries in the cadavers.

Portier et al. (1995) conducted studies using cadavers to research the interaction of the foot with the brake pedal during impact and to determine an injury criterion when extreme dorsiflexion occurred in the ankle. This study was based on radiographically diagnosed injuries resulting from offset frontal collisions. The principal injuries observed were bony fractures and minor joint dislocations. They identified two mechanisms of injury. The first was due to forces acting under the metatarsal condyles coupled with the inertial effect of a dorsiflexing foot, producing metatarsal fractures. The second mechanism dealt with ankle injuries. The sled test velocities were between 14.6 m/s and 15.8 m/s. Sixteen cadavers were tested producing numerous ankle injuries, but only one Lisfranc type injury. Lestina et al. (1992) studied 23 crash victims of frontal offset crashes and concluded that 65% of the injured ankles or feet were due to inversion or eversion.

In a study by Crandall et al. (1996) it was found that shorter drivers tend to lift their feet off the floor pan to transfer the foot from the accelerator pedal to the brake pedal and that in doing this their feet tend to be more planter flexed during braking than taller drivers who tend not lift their feet during braking. In addition the shorter drivers usually female experienced more foot injuries than taller drivers. Wilson et al. (2001) also indicates that smaller persons trying to reach the pedals could experience more immediate contact and higher peak deceleration following intrusion of a dashboard, pedal, or toe pan.

In another study Crandall et al. (1996) conducted computer simulations that modeled a $50^{th}$ percentile male in a mid-sized passenger car with a ΔV of 16 m/s, in a typical seating position. An important finding from this simulation was that the floor pan was moving rearward while the foot was moving forward so that there was a high relative velocity that could affect the forces and characteristics of the impact. In addition there may be two impacts of the foot during the collision: the first as the foot moved forward into the floor-pan and the second as the floor-pan intruded rearward into the foot.

Thus a high relative velocity could develop between the occupant foot and the interior of the vehicle when deformation of the instrument panel (IP) or floor pan occurs (Thelen et al, 1998). The resulting impact energy to the foot could be greater than the impact energy due solely to whole body deceleration.

This research assumes that most drivers can see a head-on collision coming and attempt evasive action by applying force to the brake pedal with the foot. It is thought that during the application of pressure to the brake pedal the forefoot can become plantar flexed and vulnerable to injury, (Goossens et al, 1983, Vuori et al, 1993, Crandall et al, 1996, Brunet 1996, Leibner et al, 1997, Wilson et al, 2001). This plantar flexed posture of the foot, shown in Figure 1, is thought to occur whether the knee is extended or flexed. It is also possible that muscle tensing during panic braking before a crash can modulate the foot-ankle response,making it more rigid and therefore easier to injure (Wilson et al, 2001, Kitagawa et al. 1998).

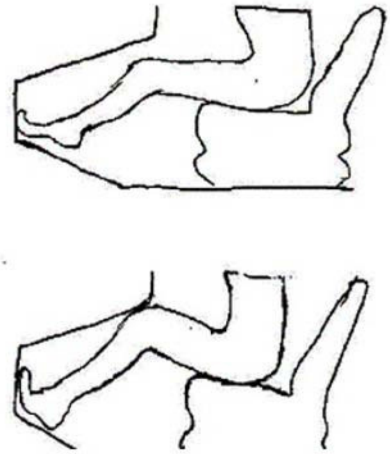

Figure 1. Plantar Flexed Configuration During Impact.

For this research, two possible causes of injury were tested, the first simulating the driver braking hard with the brake pedal in contact with the foot behind the ball of the foot and at 0 deg plantar flexion. This configuration is named the Plantar Nominal Configuration and could represent tall drivers that do not lift their feet during braking. The second possible cause of injury simulated hard braking action by the driver with the ball of the foot on the brake pedal and/or striking the floor pan with the foot plantar-flexed 35 to 50 degrees. This configuration is named the Plantar Flexed Configuration, as shown in Figure 2 and could represent short drivers who lift their foot during braking. The aim of this research is to discover a mechanism of injury and an injury tolerance level for the forefoot in head on car crashes. The study is limited by the vagueness of what actually happens to the feet during a head on car crash, however assumptions were made based on the research of others and the victim of an actual head on car crash.

## METHODS

There are many ways a lower limb can be injured in a car crash. The conditions chosen are from lessons learned from previous research and study of an actual head on collision victim:

1. Frontal collisions, including offset collisions of up to 16 m/s (limit of testing speed).
2. The driver's foot is on the brake pedal applying pressure or has slipped off and is on the floor.
3. A foot that is 35 to 50 degrees plantar flexed or not plantar flexed.
4. A floor pan intrusion of 38 mm (1.5 in).
5. Knee entrapment by the IP.

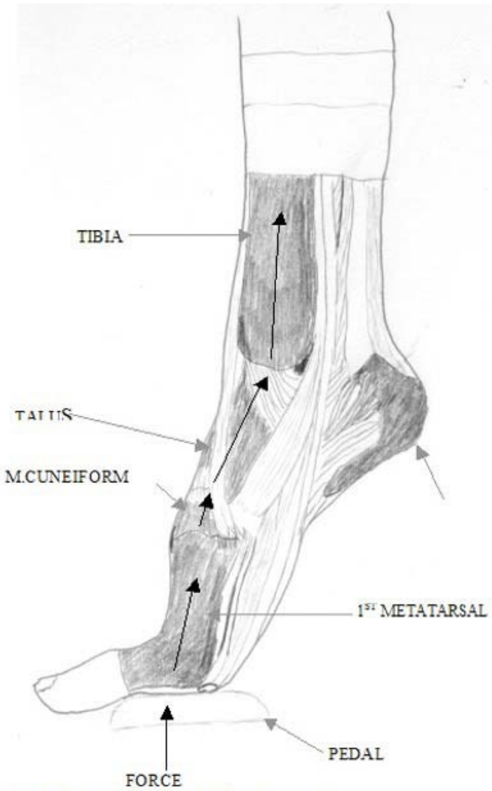


Figure 2. Plantar Flexed Configuration, Transfer of Force.

A total of 54 cadaver lower legs were obtained for this study through the Willed Body

Program of Wayne State University and the University of Michigan and the International Institute for The Advancement of Medicine. The mean age of the cadavers was 79 years and the range was from 54 to 91 years. Half of the cadavers were female. None of the cadavers was embalmed and all were kept frozen except during preparation and testing. Each foot was x-rayed before and after testing in three positions; anterior to posterior at 10 deg, lateral to medial at 30 deg and 80 deg. These positions showed the metatarsals and the tarsometatarsal joints revealing most injuries to the bones, however ligamentous damage and joint dislocation were not readily seen in the x-rays. As a result an autopsy was conducted on each foot after impact to document any ligamentous disruptions and joint dislocations. The Foot and Ankle Injury Scale (FASS) proposed by Manoli et al., (1997) was used as the injury scale for this research. FASS is composed of two scales that describe the injury and the resulting impairment. For injury severity, the FASS-S scale is used, with a range of 0 to 6. There is also an impairment scale, the FASS-I that also has a range of 0 to 6. Generally, for an FASS-S of 2 or less, there is no long-term impairment as a result of the injury. The severity levels for FASS-S and impairment levels for FASS-I are defined in Tables 1 and 2.

Table 1. FASS-S Injury Severity Levels

| | |
|---|---|
| 0 | No Injury |
| 1 | Minimal injury |
| 2 | Mild injury |
| 3 | Moderate injury |
| 4 | Severe injury |
| 5 | Very severe injury |
| 6 | Currently untreatable |

The cadaver legs were cut orthogonal to the tibia, to a length of 300 mm from the bottom of the heel to approximately mid shaft. Approximately 50 mm of soft tissue was removed from the proximal end of the tibia and fibula to allow for potting of the bones with Bondo. The bones were fixed in an aluminum pot for mounting onto the test fixture. Up to five tendons were dissected out of the calf of each lower leg; the Achilles, peroneus longus and brevis, tibialis posterior and flexor digitorum. Each tendon was threaded into a tendon catcher made of steel mesh and sutured with string to prevent the tendon from slipping when pulled, using the method first described by Kitagawa et al (1998). There was no slippage or tearing of the tendons during testing. The tendon catcher allowed tension to be applied to each tendon to simulate muscle contraction at the time of impact and to simulate plantar-flexion due to aggressive breaking. The Achilles tendon force was applied through a block and tackle system with a 3:1 mechanical advantage after the load cell. The force was applied using a manual winch so that optimum tendon load could be achieved without damaging the specimen. A load cell measured the force in the Achilles tendon. A crushable paper honeycomb prevented overloading the tendon during impact. The applied tendon force to the Achilles tendon ranged from 0.5 to 1.8 kN depending on the anatomical specimen. The greater the stature of the cadaver the more tendon force was applied. Force was applied to the tendon until the foot began to slide off the brake pedal either by hyper plantar flexion, inversion, eversion or a combination of these movements. The Achilles tendon pre-load simulated muscle force required to apply braking force to the brake pedal (Kitagawa, 1998). The other tendons were loaded using dead weights connected to a rope attached to the tendon catcher. The force applied to the peroneus longus and brevis and tibialis posterior tendons was approximately 300 N. As the foot is plantar flexed these tendons pull on opposite sides of the TMT joint making it stiffer and preventing inversion/eversion. Because the muscles that pull on these tendons are smaller and have a shorter lever arm than the muscles that pull on the Achilles tendon, their efficiency is only 1/5$^{th}$ that of the muscles of the Achilles tendon (Jenkins, 1991).

Table 2. FASS-I Long-Term Impairment Levels

| | |
|---|---|
| 0-No impairment | Patient has no residual signs or symptoms associated with the injury |
| 1-Minimal impairment | Able to do all desired activities but may be limited at impact sports. |
| 2-Mild impairment | Unable to do impact activities. |
| 3-Moderate impairment | Walking limited can do most activities but unable to walk for long periods. |
| 4-Severe impairment | Unable to walk about living quarters. Can bear weight but may need cane. |
| 5-Very severe impairment | Barely gets around house w/o cane. Uses cane or wheelchair out of home. |
| 6-Total Impairment | Unable to bear weight. |

The speed of the impacting ram simulated the closure velocity of the occupant moving forward and feet hitting the floor pan or brake pedal, which may be moving rearward. In these tests this velocity was measured to be between 1 and 16 m/s and was based on vehicle crash tests procedures from FMVSS 208. The impactor was accelerated by hydraulic fluid and was assumed to have an infinite mass as it was driven into the specimen. The range of travel of the impactor was controlled by the Instron computer and set by the operator. The impactor accelerated to the set velocity just prior to impact and was driven into the foot to the desired displacement. The impactor had some overshoot, which was predictable and was factored into the displacement. The overshoot ranged from 25 to 38 mm depending on the velocity of the impactor. This research assumed intrusion of the floor pan and rearward movement of the brake pedal to be 38 mm. The proximal end of the tibia was mounted to a rigid structure to represent entrapment of the knee by the lower dash.

To test the Plantar Nominal Configuration, two different test setups were used attempting to cause Lisfranc injuries in 13 lower leg specimens. The test setup for the Plantar Nominal Configuration was very much like that for the Plantar Flexed Configuration shown in Figure 3. All 13 specimens were placed in the test apparatus so that the tibia was horizontal and the foot perpendicular to the tibia as much as possible (0 deg plantar-flexion). Five tendons were pulled as described above to simulate braking. Instrumentation included a load cell and accelerometer on the impactor, a load cell and accelerometer attached to the test fixture at the proximal end of the tibia and a load cell attached to the Achilles tendon. The brake pedal impacted the plantar aspect of the foot. The dimensions of the brake pedal were 44.4 X 139.7 mm and the centerline of the long axis of the brake pedal struck the foot between 15 and 45 mm posterior to the ball of the foot. One edge of the pedal was placed 20 - 35 mm medial or lateral to the centerline of the long axis of the foot. These variations were an attempt to account for the different braking habits of drivers. The speed of impact for the 13 specimens of the Plantar Nominal Configuration was 16 m/s and after causing only 3 Lisfranc type injuries the Plantar Nominal Configuration was abandoned.

The Plantar Flexed Configuration used 41 lower leg specimens. The test setup shown in Figure 3 was used for all of the specimens tested in the Plantar Flexed Configuration and consisted of a trapeze that pivoted from below the test specimen. The brake pedal attached to this trapeze consisted of a flat aluminum plate 76 X 102 mm and rested against the ball of the foot. Instrumentation included a load cell and accelerometer on the impactor, two accelerometers (pedal1, pedal2) attached to the free end of the trapeze, a 3-axis load cell attached to the pivoting end of the trapeze. A load cell and accelerometer attached to the test fixture at the proximal end of the tibia and a load cell attached to the Achilles tendon. The foot was plantar flexed 30 to 50 degrees to achieve the Plantar Flexed Configuration simulating braking action. The high rate Instron provided a linear impact that pushed the brake pedal into the plantar aspect of the foot. Four tendons were pulled instead of five: the peroneus longus, peroneus brevis, tibialis posterior and Achilles. The same method described above for the Plantar Nominal Configuration was used to apply a constant force to the Achilles and other tendons. Proximal tibial loads were measured with a six-axis load cell to record axial force in the Z (longitudinal tibia) axis and bending moments about the other two orthogonal (X and Y) axes. For all tests

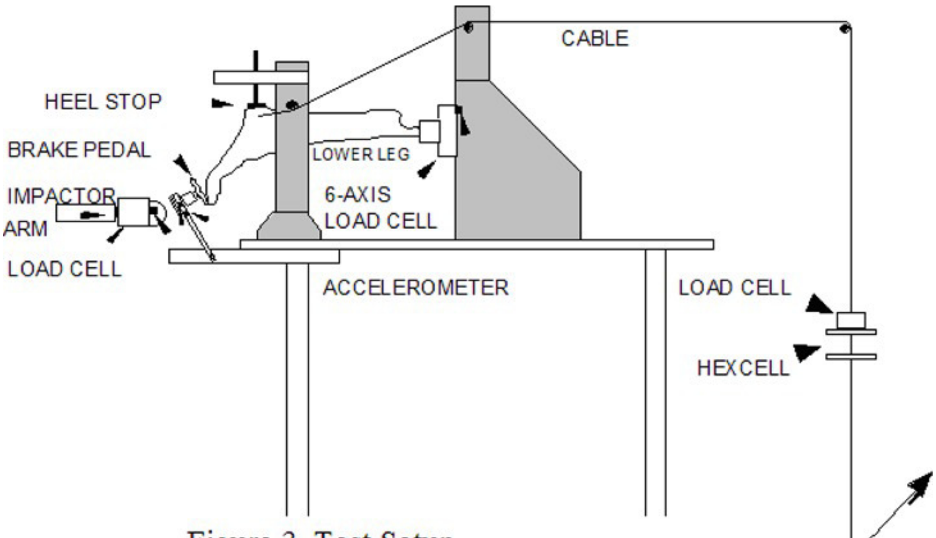

Figure 3. Test Setup

a load cell was attached to the end of the impactor arm with a bolt and on the other end of the load cell an aluminum bar was attached to the load cell also with a bolt. The aluminum bar impacted the back of the brake pedal and spread the impact force over the width of the brake pedal. Also an accelerometer was attached to the bar to record the accelerations of the impactor.

Accelerometers were also attached to the trapeze and the fixture at the proximal end of the tibia for use in mass corrections. A 6-axis load cell was mounted at the pivoting end of the trapeze to account for reaction forces from the impactor and to account for mass correction of those forces. All of the plantar flexed tests were conducted with the brake pedal on a trapeze that was free to swing from below the specimen in the direction of impact (Setup A, Figure 3). The mass of the brake pedal, and all hardware used to attach the pedal to the impactor or trapeze for all test configurations were recorded. The pivot point of the trapeze was adjustable in order to place the pedal against the ball of the feet, which varied from cadaver to cadaver. The trapeze and brake pedal were held against the ball of the foot as the foot was plantar flexed, simulating the driver stepping on the brake pedal, or floor pan.

Compensation for the mass in front of the load cells was accomplished by using Newton's second law of motion. The mass correction was applied to the load cell data by subtracting the product of the mass and acceleration from the measured force. A second mass correction was conducted for the acceleration of the trapeze and the forces at the pivot end of the trapeze during impact. This correction was necessary because of the moving trapeze. Its linear acceleration and mass were used to compute the correction force and determine foot load. The reaction forces at the pivot end of the trapeze were small and statistically insignificant. This procedure was also performed for the load cell at the end of the tibia because the test fixture holding the proximal end of the tibia was not totally stationary. Its acceleration was measured and the mass in front of the load cell, in this case, included the foot, mounting cup and Bondo auto body filler. Not all tests could be mass compensated due to a lack of accelerometers or malfunctioning accelerometers and their data could not be used in the statistical analysis of foot load.

The data were recorded and conditioned using a digital data acquisition system (IDDAS) and were filtered with an eight-pole, Butterworth, low pass filter. The sampling rate for digitization was 10,000 samples per second. The anti-aliasing filter frequency was 2,500 Hz and the data were filtered at Channel Class 1000 before being analyzed. High-speed video at 1000 frames/second was used to analyze the motion of the foot, impactor and the table on which the fixture was mounted. Data synchronization was achieved by simultaneously recording the impact as an electrical signal on the IDDAS and as an electronic flash on the video. Each foot was autopsied after the test by an orthopedic surgeon who noted bone, joint and ligament damage.

## RESULTS

Tables 3 and 4 show the cadaver test results and tables 3A and 4A highlight the cadaver injuries. Sixty five percent of the feet tested in the Plantar Flexed Configuration were injured, at speeds ranging from 1 m/s to 16 m/s. Five (5) of those feet had a stretched, ruptured or avulsed injury to the Lisfranc ligament. The most common injury was multiple metatarsal fractures and the most common injury severity level was a FASS-S level of 3. Only 23% of the feet tested in the Plantar Nominal Configuration, at 16 m/s, were injured. Test results from cadavers 9L, 9R, 19R and 21R were excluded from the general analysis because of poor contact with the impactor during testing. Tests results from other cadavers denoted by *** in the Tables 3, 3A, 4 and 4A were excluded from some modes of analysis because data were lost or not recorded during testing.

**TABLE 3. CADAVER TEST RESULTS PLANTAR NOMINAL CONFIGURATION**

| CAD # | FOOT PLANTAR FLEXION | MEDIAL OFFSET (mm) | DISTANCE FROM BALL(mm) | PEAK VEL m/s | PEAK ACCEL G's | PEAK TABLE ACCEL G | PEAK PEDAL ACCEL G | ACHILLES TENDON PRE LOAD N | TIBIA PRE-LOAD N | MAX TIBIA LOAD N | MCOR MAX TIBIA LOAD N | IMPACT LOAD N | FOOT LOAD N | FASS-S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1L | $0^0$ | 0mm | 10mm | 16 | 220.8 | 17 | *** | 1050 | 809 | 2936.6 | 2923.7 | 13242.3 | *** | |
| 1R | $0^0$ | 0mm | 35mm | 16 | 407.3 | 18 | *** | 690 | *** | *** | *** | 17781.8 | *** | 5 |
| 2L | $0^0$ | 0mm | 35mm | 16 | 596.1 | 23 | *** | 1030 | 1039.8 | 5633.4 | 5061 | 12937.2 | *** | |
| 3L | $0^0$ | 0mm | 15mm | 16 | 608.6 | 14 | *** | 1090 | 1337 | 3956.9 | 3818 | 2715.4 | *** | 3 |
| 3R | $0^0$ | 0mm | 20mm | 16 | 638.4 | 12 | *** | 1100 | 1616 | 4246.2 | 4079 | 3628.4 | *** | 5 |
| 4R | $0^0$ | 20mm | 30mm | 16 | 542.9 | 11 | *** | 1076 | 1200 | 3223.9 | 3014 | 2721.5 | 2287.7 | 0 |
| 4L | $0^0$ | 25mm | 30mm | 16 | 561.7 | 15 | *** | 1233 | 813.2 | 4720.2 | 4610 | 3589.3 | 3764.1 | 0 |
| 5L | $0^0$ | 22mm | 45mm | 16 | 534.7 | 27 | *** | 1243 | 1100 | 6840.4 | 6092 | 4239.3 | 4066.2 | 2 |
| 5R | $0^0$ | 15mm | 42mm | 16 | 567.2 | 26 | *** | 1491 | 1262 | 5667 | 5304 | 2789.2 | 5042.7 | 0 |
| 6L | $0^0$ | 25mm | 32mm | 16 | 530.4 | 19 | *** | 1450 | 1087 | 4555.2 | 4345 | 3569.2 | 3137.1 | 0 |
| 6R | $0^0$ | 25mm | 42mm | 16 | *** | *** | *** | *** | *** | *** | *** | *** | *** | 0 |
| 7L | $0^0$ | 32mm | 25mm | 16 | 557.8 | 11 | *** | 1238 | 808.3 | 2876.4 | 2675 | 1840.1 | 2575.7 | 0 |
| 7R | $0^0$ | 38mm | 38mm | 16 | 528.1 | 12 | *** | 1370 | 1305.8 | 5110.7 | 4864 | 2477.6 | 2745.6 | 0 |

**TABLE 4. CADAVER TEST RESULTS PLANTAR FLEXED CONFIGURATION**

| CAD # | FOOT PLANTAR FLEXION | MEDIAL OFFSET (mm) | DISTANCE FROM BALL(mm) | PEAK VEL m/s | PEAK IMPACT ACCEL G | PEAK TABLE ACCEL G | PEAK PEDAL ACCEL G | ACHILLES TENDON PRE LOAD N | TIBIA PRE-LOAD N | MAX TIBIA LOAD N | MCOR MAX TIBIA LOAD N | IMPACT LOAD N | FOOT LOAD N | FASS-S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8L | $45^0$ | 0 | 0 | 3 | 36.81 | 4 | *** | 498 | 540 | 1919.6 | 1823 | 2965.3 | *** | 0 |
| 8R | $45^0$ | 0 | 0 | 3 | 31.17 | 3 | *** | NO TENDONS | NONE | 99.7 | 99.7 | 748.7 | *** | 0 |
| 9L | $45^0$ | 0 | 0 | 13 | *** | 27 | *** | 1223.5 | 1110 | 8237.7 | 7536 | 28277.3 | *** | 0 |
| 9R | $40^0$ | 0 | 0 | 13 | *** | 16 | *** | NO TENDONS | NONE | 4965.7 | 4515 | 33903.7 | *** | 0 |
| 10L | $45^0$ | 0 | 0 | 2.75 | *** | 1 | *** | 1000 | 635 | 1639.2 | 1639.2 | *** | *** | 0 |
| 10R | $30^0$ | 0 | 0 | 2.75 | 36.4 | 2 | *** | NO TENDONS | NONE | 99.9 | 99.9 | 727.5 | *** | 2 |
| 11L | $40^0$ | 0 | 0 | 10.2 | 292.8 | 12 | *** | 790.3 | 823 | 3140.46 | 3140.46 | 17960.7 | *** | 3 |
| 11R | $50^0$ | 0 | 0 | 4.2 | 36.3 | 6 | *** | 458.3 | 790 | 3306.9 | 3306.9 | 2952 | *** | 0 |
| 12R | $40^0$ | 0 | 0 | 4.2 | 35.3 | 9 | *** | 1112.1 | 1115 | 4142.6 | 4142.6 | 3126.7 | *** | 2 |
| 13L | $40^0$ | 0 | 0 | 12.5 | 348.69 | 32 | *** | 1313 | 1045 | 6544 | 6419 | 20941.34 | *** | 5 |
| 13R | $40^0$ | 0 | 0 | 6.2 | 80.1 | 10 | *** | 1150 | 1163 | 3687 | 3687 | 28082.4 | *** | 5 |
| 14L | $40^0$ | 0 | 0 | 15.5 | 349.4 | 30 | *** | 1078 | 1393 | 6764.5 | 6764.5 | 24016.4 | *** | 4 |
| 14R | $40^0$ | 0 | 0 | 15.5 | 330.8 | 31 | *** | 1445 | 1435 | 7138.7 | 7138.7 | 23822.9 | *** | 5 |
| 15L | $42^0$ | 0 | 0 | 13.5 | *** | *** | *** | *** | *** | *** | *** | *** | *** | 3 |
| 15R | $42^0$ | 0 | 0 | 13.5 | 187.3 | 35 | 660 | NO TENDONS | NONE | 5368.6 | 4485.7 | 23196.7 | 11679.6 | 3 |
| 16L | $45^0$ | 0 | 0 | 4.5 | 122 | 28 | 1167 | 190 | 380 | 6197 | 6123 | 15849 | 7017.4 | 3 |
| 16R | $45^0$ | 0 | 0 | 4.5 | 301 | 20 | *** | NO TENDONS | NONE | *** | *** | 6829.5 | *** | 1 |
| 17L | $40^0$ | 0 | 0 | 13.5 | *** | 42 | *** | NO TENDONS | NONE | *** | *** | 16822 | *** | 3 |
| 17R | $40^0$ | 0 | 0 | 13.5 | 248.7 | 39 | 553 | 1162.5 | 588.5 | 5536.9 | 5385.5 | 24064.2 | 12375.7 | 4 |
| 18L | $45^0$ | 0 | 0 | 10.5 | 289.5 | 37 | 788 | 1200 | 1246 | 8543 | 8396 | 21009.6 | 10146.2 | 5 |
| 18R | $45^0$ | 0 | 0 | 10.5 | *** | *** | *** | *** | *** | *** | *** | *** | *** | 3 |
| 19L | $45^0$ | 0 | 0 | 9 | 150 | 19 | 439 | 1096.3 | 496 | 3475 | 3420.7 | 12432.8 | 7430.7 | 6 |
| 19R* | $45^0$ | 0 | 0 | 15.5 | 128.5 | 9 | 104 | NO TENDONS | *** | *** | *** | 4876.7 | 2850 | 0 |
| 20L | $45^0$ | 0 | 0 | 13.5 | 338.9 | 34 | 1344 | 945.5 | 188.5 | 5371.5 | 5234.5 | 19645.6 | 10316.7 | 6 |
| 20R | $45^0$ | 0 | 0 | 13.5 | 306.1 | 48 | 1370 | NO TENDONS | NONE | 100 | *** | 19628.4 | 8283.3 | 0 |
| 21L | $45^0$ | 0 | 0 | 15 | 312.28 | 35 | 2002 | 573 | 0 | 5039.46 | 4930 | 30888 | 14787 | 6 |
| 21R* | $45^0$ | 0 | 0 | 15 | 313 | 34 | 1346 | NO TENDONS | NONE | 4981 | 4879.4 | 14189 | 5581 | 0 |
| 22L | $45^0$ | 0 | 0 | 10 | 207.4 | 25 | 1545 | NO TENDONS | NONE | 3999.3 | 3282.3 | 22192.6 | 12580.5 | 3 |
| 22R | $45^0$ | 0 | 0 | 10 | 200.4 | 26 | 1239 | 467.9 | 218.1 | 3536.2 | 2900.2 | 14130.8 | 6693.3 | 3 |
| 23L | $40^0$ | 0 | 0 | 7.5 | 87.86 | 31 | 471 | NO TENDONS | NONE | *** | *** | 12625.4 | 8250.2 | 3 |
| 23R | $45^0$ | 0 | 0 | 7.5 | 117.2 | 22 | 765 | 1010 | 418.7 | 2954.7 | 2484 | 8554.2 | 4498.5 | 4 |
| 24L | $47^0$ | 0 | 0 | 1 | 32 | 4 | 38 | 885 | 357 | 1647 | 1604 | 2667 | 1987 | 0 |
| 24R | $50^0$ | 0 | 0 | 2 | 33 | 7 | 52 | 850 | 155 | 1880 | 1768 | 3645 | 3909 | 0 |
| 25L | $45^0$ | 0 | 0 | 2.5 | 56 | 9 | 32 | 1000 | 248 | 2532 | 2345 | 3676 | 3605 | 0 |
| 25R | $45^0$ | 0 | 0 | 5 | 88 | 10 | 103 | 648 | 344 | 2607 | 2331 | 4550 | 4865 | 5 |
| 26R | 45 | 0 | 0 | 4 | 30 | 15 | 124 | 1232 | 808 | 6042 | 5827 | 3207 | 3207 | 0 |
| 26R | 45 | 0 | 0 | 1 | 7 | 2 | 23 | 600 | 357 | 2790 | 2790 | 1826 | 1819 | 0 |
| 26R | 45 | 0 | 0 | 2 | 12 | 2 | 27 | 1385 | 878 | 3513 | 3500 | 2260 | 2108 | 0 |
| 26R | 45 | 0 | 0 | 5 | 40 | 18 | 200 | 1000 | 816 | 5502 | 5118 | 3358 | 4998 | 3 |
| 26L | 45 | 0 | 0 | 6 | 188 | 9 | 383 | 1138 | *** | *** | *** | 7209 | 5319 | 3 |
| 27R | 45 | 0 | 0 | 7 | 104 | 28 | 1083 | 810 | 448 | 7013 | 6245 | 15100 | 12840 | 3 |
| 27L | 45 | 0 | 0 | 9 | 184 | 23 | 968 | 1090 | 525 | 6490 | 5816 | 12019 | 9000 | 4 |
| 28R | 45 | 0 | 0 | 7 | 245 | 26 | 726 | 871 | *** | *** | *** | 11400 | 7129 | 3 |
| 28L | 45 | 0 | 0 | 8 | 121 | 20 | 976 | 890 | *** | *** | *** | 13830 | 11066 | 5 |

* RUN NOT USED DUE TO BAD TEST

*** DATA NOT AVAILABLE

**TABLE 3A. CADAVER TEST INJURIES PLANTAR NOMINAL CONFIGURATION**

| CAD # | FOOT PLANTAR FLEXION | MEDIAL OFFSET (mm) | DISTANCE FROM BALL(mm) | PEAK VEL m/s | PEAK ACCEL G's | IMPACT LOAD N | FOOT LOAD N | FASS-S | INJURIES |
|---|---|---|---|---|---|---|---|---|---|
| 1L | $0^0$ | 0mm | 10mm | 16 | 220.8 | 13242.3 | *** | | Lisfranc injuries and metatarsal fractures |
| 1R | $0^0$ | 0mm | 35mm | 16 | 407.3 | 17781.8 | *** | 5 | NO INJURIES |
| 2L | $0^0$ | 0mm | 35mm | 16 | 596.1 | 12937.2 | *** | | NO INJURIES |
| 3L | $0^0$ | 0mm | 15mm | 16 | 608.6 | 2715.4 | *** | 3 | intermetatarsal disruption between MT 1st and 2nd a typical Lisfranc dislocation |
| 3R | $0^0$ | 0mm | 20mm | 16 | 638.4 | 3628.4 | *** | 5 | multiple metatarsal fractures. Medial Cuneiform FX, 2nd TMT Disruption |
| 4R | $0^0$ | 20mm | 30mm | 16 | 542.9 | 2721.5 | 2287.7 | 0 | NO INJURIES |
| 4L | $0^0$ | 25mm | 30mm | 16 | 561.7 | 3589.3 | 3764.1 | 0 | NO INJURIES |
| 5L | $0^0$ | 22mm | 45mm | 16 | 534.7 | 4239.3 | 4066.2 | 2 | MT FX |
| 5R | $0^0$ | 15mm | 42mm | 16 | 567.2 | 2789.2 | 5042.7 | 0 | NO INJURIES |
| 6L | $0^0$ | 25mm | 32mm | 16 | 530.4 | 3569.2 | 3137.1 | 0 | NO INJURIES |
| 6R | $0^0$ | 25mm | 42mm | 16 | *** | *** | *** | 0 | NO INJURIES |
| 7L | $0^0$ | 32mm | 25mm | 16 | 557.8 | 1840.1 | 2575.7 | 0 | NO INJURIES |
| 7R | $0^0$ | 38mm | 38mm | 16 | 528.1 | 2477.6 | 2745.6 | 0 | NO INJURIES |

**TABLE 4A. CADAVER TEST INJURIES PLANTAR FLEXED CONFIGURATION**

| CAD # | FOOT PLANTAR FLEXION | MEDIAL OFFSET (mm) | DISTANCE FROM BALL(mm) | PEAK VEL m/s | PEAK IMPACT ACCEL G | IMPACT LOAD N | FOOT LOAD N | FASS-S | INJURIES |
|---|---|---|---|---|---|---|---|---|---|
| 8L | $45^0$ | 0 | 0 | 3 | 36.81 | 2965.3 | *** | 0 | NO INJURIES |
| 8R | $45^0$ | 0 | 0 | 3 | 31.17 | 748.7 | *** | 0 | NO INJURIES |
| 9L | $45^0$ | 0 | 0 | 13 | *** | 28277.3 | *** | 0 | NO INJURIES |
| 9R | $40^0$ | 0 | 0 | 13 | *** | 33903.7 | *** | 0 | NON RELEVANT INJURIES |
| 10L | $45^0$ | 0 | 0 | 2.75 | *** | *** | *** | 0 | NO INJURIES |
| 10R | $30^0$ | 0 | 0 | 2.75 | 36.4 | 727.5 | *** | 2 | MT5 MID SHAFT FX |
| 11L | $40^0$ | 0 | 0 | 10.2 | 292.8 | 17960.7 | *** | 3 | Transverse MT5 base FX |
| 11R | $50^0$ | 0 | 0 | 4.2 | 36.3 | 2952 | *** | 0 | NO INJURIES |
| 12R | $40^0$ | 0 | 0 | 4.2 | 35.3 | 3126.7 | *** | 2 | MT3 FX |
| 13L | $40^0$ | 0 | 0 | 12.5 | 348.69 | 20941.34 | *** | 5 | TMT1 disrupted dorsal medial, plantar ligaments disrupted, Lisfranc ligament torn. TMT2 disrupted dorsal. MT3 base FX. MT4 base/shaft FX. MT5 shaft FX. |
| 13R | $40^0$ | 0 | 0 | 6.2 | 80.1 | 28082.4 | *** | 5 | Dorsal capsule ligament disruption TMT 2-5& MT4 neck FX |
| 14L | $40^0$ | 0 | 0 | 15.5 | 349.4 | 24016.4 | *** | 4 | MT2 shaft FX. MT3 shaft FX. MT4 neck FX. MT5 neck FX |
| 14R | $40^0$ | 0 | 0 | 15.5 | 330.8 | 23822.9 | *** | 5 | TMT1 partial disruption-hypermobile/laxed. TMT2 disruption dorsal. MT1 base FX-plantar half, intra-articular longus attached to fracture. MT2-C3 disruption. MT3 shaft FX. MT4 shaft FX. MT5 Shaft FX. |
| 15L | $42^0$ | 0 | 0 | 13.5 | *** | *** | *** | 3 | MT5-3 Shaft Fx 5,4 Comminuted, TMT1-2 Hyperlaxity, Lisfranc intact but Loose |
| 15R | $42^0$ | 0 | 0 | 13.5 | 187.3 | 23196.7 | 11679.6 | 3 | MT2-4 Head FX, Cuboid FX |
| 16L | $45^0$ | 0 | 0 | 4.5 | 122 | 15849 | 7017.4 | 3 | MT3-Cunieform ligament disruption, MT3-5-cunieform hyperlaxity |
| 16R | $45^0$ | 0 | 0 | 4.5 | 301 | 6829.5 | *** | 1 | Medial malleolus FX |
| 17L | $40^0$ | 0 | 0 | 13.5 | *** | 16822 | *** | 3 | TMT1 Hyperlaxity,MT2-4 shaft&neck FX, MT1 Plantar medial disruption |
| 17R | $40^0$ | 0 | 0 | 13.5 | 248.7 | 24064.2 | 12375.7 | 4 | MT2-4 Comminuted shaft&neck FX,MT1 Base capsule disruption medial |
| 18L | $45^0$ | 0 | 0 | 10.5 | 289.5 | 21009.6 | 10146.2 | 5 | MTP1-5 Dorsal Capsular Tears, MT3-5 Comminuted Fx, TMT2 dorsal capsular dislocation, TMT1dislocation dorsal capsular and peroneous longus avulsion |
| 18R | $45^0$ | 0 | 0 | 10.5 | *** | *** | *** | 3 | MT3-5 head Fx, MT2 Shaft Fx, Spiral Fx of Tibia |
| 19L | $45^0$ | 0 | 0 | 9 | 150 | 12432.8 | 7430.7 | 6 | TMT1 Fx & Dislocation, MT 2-5 comminuted Fx, Ruptured/Torn Lisfranc ligament dorsal |
| 19R* | $45^0$ | 0 | 0 | 15.5 | 128.5 | 4876.7 | 2850 | 0 | NO INJURIES |
| 20L | $45^0$ | 0 | 0 | 13.5 | 338.9 | 19645.6 | 10316.7 | 6 | 1,2,3 Cunieform Fx, 1-5TMT Dorsal capsule rupture, 1st MT base Fx, 2-4 MT Head Fx,1st MTP dislocation, Tibia Sesmoid Fx, Lisfrac ligament torn through. |
| 20R | $45^0$ | 0 | 0 | 13.5 | 306.1 | 19628.4 | 8283.3 | 0 | NO INJURIES |
| 21L | $45^0$ | 0 | 0 | 15 | 312.28 | 30888 | 14787 | 6 | 1st Proximal Phalanx Fx Interarticular, MT 2,3,4 Head Fx |
| 21R* | $45^0$ | 0 | 0 | 15 | 313 | 14189 | 5581 | 0 | NO INJURIES |
| 22L | $45^0$ | 0 | 0 | 10 | 207.4 | 22192.6 | 12580.5 | 3 | MT 2,3,4,5 Head FX |
| 22R | $45^0$ | 0 | 0 | 10 | 200.4 | 14130.8 | 6693.3 | 3 | MT 2,3,4 Head FX Proximal Phalanx FX |
| 23L | $40^0$ | 0 | 0 | 7.5 | 87.86 | 12625.4 | 8250.2 | 3 | MT 2,3,4 Head FX |
| 23R | $45^0$ | 0 | 0 | 7.5 | 117.2 | 8554.2 | 4498.5 | 4 | MT 3,4,5 Head FX, MT 3,4 Base FX |
| 24L | $47^0$ | 0 | 0 | 1 | 32 | 2667 | 1987 | 0 | NO INJURIES |
| 24R | $50^0$ | 0 | 0 | 2 | 33 | 3645 | 3909 | 0 | NO INJURIES |
| 25L | $45^0$ | 0 | 0 | 2.5 | 56 | 3676 | 3605 | 0 | NO INJURIES |
| 25R | $45^0$ | 0 | 0 | 5 | 88 | 4550 | 4865 | 5 | 1st Cuneiform Transverse FX, Dorsal Capsule 2nd TMT Joint torn, Calcaneus Cuboid joint capsuler injury, Anterior process calcaneus avulsion Fx, 1st MT base Capsuler injury lateral and plantar. Lisfranc avulsion from base of cuneiform. |
| 26R | 45 | 0 | 0 | 4 | 30 | 3207 | 3207 | 0 | NO INJURIES |
| 26R | 45 | 0 | 0 | 1 | 7 | 1826 | 1819 | 0 | NO INJURIES |
| 26R | 45 | 0 | 0 | 2 | 12 | 2260 | 2108 | 0 | NO INJURIES |
| 26R | 45 | 0 | 0 | 5 | 40 | 3358 | 4998 | 3 | MT 2,3,4,5 Head FX |
| 26L | 45 | 0 | 0 | 6 | 188 | 7209 | 5319 | 3 | MT 2,3,4,5 Head FX |
| 27R | 45 | 0 | 0 | 7 | 104 | 15100 | 12840 | 3 | MT 2,3,4,5 Head FX |
| 27L | 45 | 0 | 0 | 9 | 184 | 12019 | 9000 | 4 | MT2 shaft FX. MT3 shaft FX. MT4 neck FX. MT5 neck FX |
| 28R | 45 | 0 | 0 | 7 | 245 | 11400 | 7129 | 3 | MT3-5 head Fx, MT2 Shaft Fx, Spiral Fx of Tibia |
| 28L | 45 | 0 | 0 | 8 | 121 | 13830 | 11066 | 5 | MTP1-5 Dorsal Capsular Tears, MT3-5 Comminuted Fx, TMT2 dorsal capsular dislocation, TMT1dislocation dorsal capsular and peroneous longus avulsion |

* RUN NOT USED DUE TO BAD TEST
*** DATA NOT AVAILABLE

PLANTAR NOMINAL CONFIGURATION RESULTS There were so few (23%) injuries using the Plantar Nominal Configuration, that that method of testing was abandoned after 13 tests. The biomechanical results are included and listed in Table 3 and 3A. This mechanism of injury (Plantar Nominal Configuration and direct trauma) was not representative of what happens in an offset head-on collision to short people who suffer more foot injuries than taller people according to (Crandall et al, 1996, Wilson et al, 2001).

PLANTAR FLEXED CONFIGURATION RESULTS The biomechanical data for the Plantar Flexed Configuration is presented in Table 4. Sixty five percent of the 35 feet tested in the Plantar Flexed Configuration experienced Lisfranc injuries. Cadavers 13L, 15L, 19L, 20L and 25R experienced Lisfranc ligament injuries, four of which were disruptions. In these five feet, the impact velocities were between 5 and 13.5 m/s with an average of 11.6 m/s (± 3.7 m/s). The most common injury was metatarsal (MT) fractures, which occurred 51% of the time. Another significant injury was dislocation and or fracture at the TMT joints, these types of injuries occurred 29% of the time. These injuries did occur would occur simultaneously in the same foot. For instance, if there was a Lisfranc ligament rupture there was also a TMT joint injury. Twelve or 34% of the feet tested would have suffered permanent impairment according to FASS impairment injury scale (FASS-I > 2).

DATA ANALYSIS The loads causing injury to the feet ranged from 4.5 to 14.7 kN with an average of 7.8 kN (± 3.6 kN). The impact velocity causing injury ranged from 4.5 to 15.5 m/s with an average of 9.0 m/s (± 4.9 m/s). High-speed video analysis showed that while the foot was positioned in the Plantar Flexed Configuration at the beginning of impact with tendons pulled it did not stay plantar flexed. As the impactor drove into the foot simulating 3 cm of intrusion the foot began to dorsiflex. Injury to the foot happened in the 1 to 2 ms after impactor contact when the foot was still plantar flexed and prior to the start of dorsiflexion. The video showed compression of the forefoot along the metatarsals and at the tarsalmetatarsal joints

Logistic regression analysis was used to determine trends between the modes of impact and injury. Chi-Squared ($\chi^2$) and p values provide an indication of the fit of the trends. Higher $\chi^2$ values and smaller p values represent a better fit. A logistic regression statistical model p=1/(1+Exp(a-b*X) was used to analyze the data. Using injury as the dependent variable and comparing the effects of the independent variables velocity, load and tendon pre-load were analyzed. For the statistical analysis an injury level of 3 was selected based on the FASS scale for injury severity, the FASS-S. Injuries that fit the criterion of FASS-S ≥ 3 were considered an injury and given a value of one and considered responding in the logistic regression analysis. Injuries at level 2 and below were given a value of zero and considered non-responding in the logistic regression analysis.

It was found that tendon pre-load had no effect on injury. The Chi-Squared result reveals no significant difference in injuries between feet that had tendon pre-load and those that did not. The $\chi^2$ value was about 0.4 and the p-value was greater than 0.05. Thus, the data from the tests without tendon pre-load were combined with those with preload in the logistic regression analyses. Impact Velocity and Injury The association between impact velocity and injury is shown in Figure 4 for the Plantar Flexed Configuration tests. Velocity correlated to injury exhibited the best fit with a $\chi^2$ = 19.2 and a p value of 0.0001. The regression suggests that, at a 25% probability of a Lisfranc injury, the velocity required is 4.4 m/s and, at a 50% probability of a Lisfranc injury, the velocity required is 5.5 m/s. Foot Load and Injury The association between foot load and injury is shown in Figure 5. The fit of foot load to injury is fair with a $\chi^2$ = 17.25 and a p value of 0.0001. The logistic regression analysis suggests that, at a 25% probability of a Lisfranc injury, the load required is 3300 N and, at a 50% probability of a Lisfranc injury, the load required is 4450 N. A comparison of the results of the two impact configurations using cadaver 4L at an impact velocity of 16 m/s in the Plantar Nominal Configuration and cadaver 20L at an impact velocity of 13.5 m/s in the plantar flexed configuration is shown in Figure 6. The initial velocities differed only by 2.5 m/s, or about 10%, but the deceleration of the impactor into the foot differed by 230 g or about 40%. The peak foot load for Plantar Flexed Configuration was almost 3 times as high as that for the Plantar Nominal Configuration. The vast difference in the foot load is attributed to the configuration of the foot during testing. The soft tissue in the arch of the foot absorbing the impact explains the Plantar

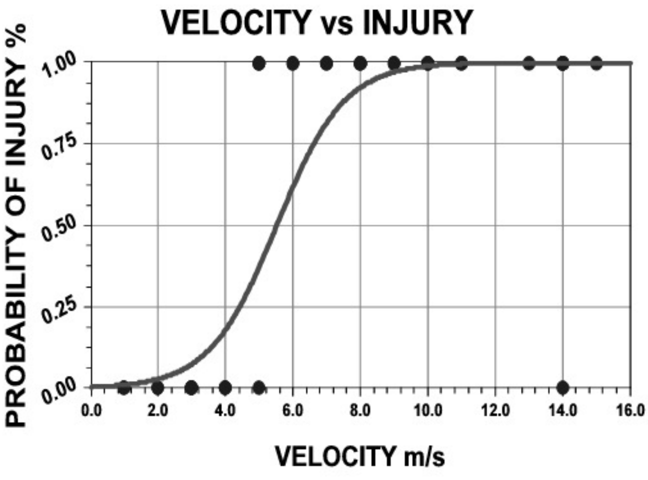


Figure 4. Logistic Regression Analysis of Velocity vs Injury

Nominal Configuration's lower foot load. The bones of the foot absorbing the impact explain the Plantar Flexed Configuration's higher foot load.

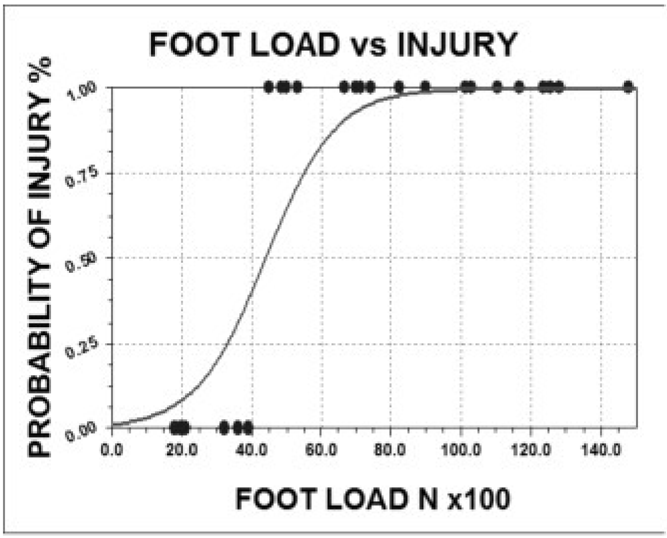

Figure 5. Logistic Regression Analysis of Load vs Injury

DISCUSSION

This research has determined that a mechanism of injury to cause Lisfranc injuries to the forefoot is to load the foot through the ball of the foot, in the Plantar Flexed Configuration. This view is supported by several studies (Goossens et al, 1983, Vuori et al, 1993, Crandall et al, 1996, Brunet 1996, Leibner et al, 1997, Wilson et al, 2001). The impact force is directed along the long axis of the metatarsals, posteriorly to the TMT joints. This loading configuration causes a combination of compression, axial bending and torsion on the metatarsals. If the impact velocity is high, the metatarsals will have comminuted fractures and the TMTs' will experience few dislocations. If the impact energy is applied at a moderate rate the MT's experience few fractures and the TMT joints experience fractures and dislocations. That is, larger loads at high loading rates caused the metatarsals to fail before the load can be transmitted posteriorly. Thus, at moderate rates of loading, the injury to the MT's are less severe and the loads are transmitted to the TMT joints, causing dislocations and ligamentous ruptures.

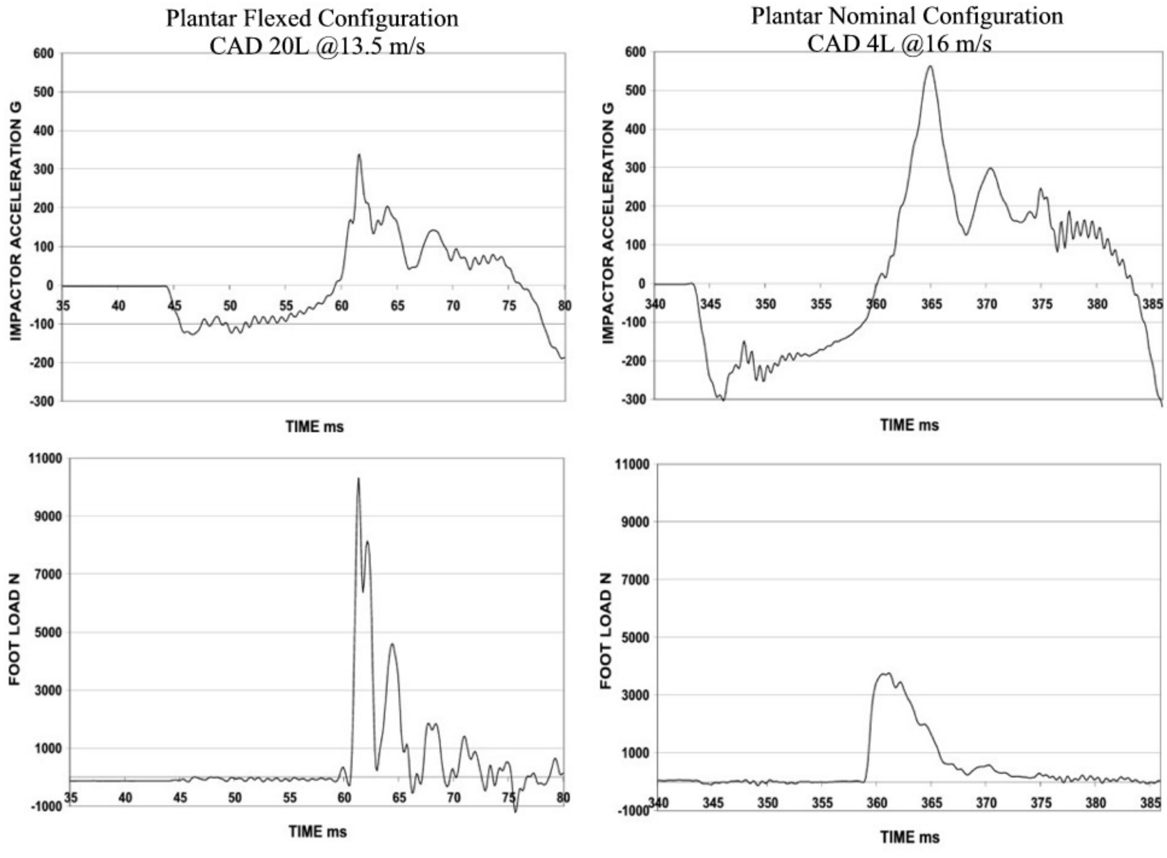

Figure 6. Comparison of Plantar Flexed Configuration vs Plantar Nominal Configuration

The Plantar Nominal Configuration has been used by other researchers (Crandall et al, 1996, Yoganandan, et al, 1997, Rudd, et al, 1998) to try to develop an injury criterion for the forefoot and only one (Portier, 1995) has been able to reproduce a Lisfranc type injury. Reproduction of the injury is critical to the determination of an injury mechanism and injury tolerance. This research started by using the test methods of these researchers that resulted in few injuries even at high impact velocities. During tests in the Plantar Nominal Configuration the feet were impacted between the ball of the foot and the tarsometatarsal joints in an attempt to simulate the foot being on the brake pedal and applying maximum braking pressure. It seems that in this configuration, the soft tissues in the arches of the foot absorbed a significant amount of the impact energy.

Even at low to mid impact velocities, very high foot loads were sustained by the feet tested in the Plantar Flexed Configuration. In this configuration, the foot is much stiffer because the load is borne by bone minimizing the energy absorbed by the soft tissues of the foot. The Plantar Flexed Configuration is not a natural position of the foot when walking or running except at the toe-off phase. In this plantar flexed configuration, the foot was not designed to bear weight or sustain impact. Thus, it does not absorb the same amount of impact energy as in the Plantar Nominal Configuration, and therefore does experience more injuries. The test conditions were similar in both configurations except impact velocities where the Plantar Flexed Configuration velocities varied from 1 to 16 m/s with a 50% probability of severe injury at 5.5 m/s. The simulated intrusion was also similar for both configurations as was preparation of the feet for testing. The only other difference was the configuration of the foot where the Plantar Flexed Configuration yielded injuries consistently at medium and high impact velocities.

## CONCLUSIONS

Under the same test conditions cadaveric feet tested in the Plantar Flexed Configuration experienced significantly more injuries than those tested in the Plantar Nominal Configuration. The biomechanical results indicate that the configuration of the foot made the difference in the frequency and severity of injuries. The foot was less susceptible to injury in the Plantar Nominal Configuration due to the double arch bone structure and soft tissues on the plantar aspect of the foot. Feet tested in the Plantar Flexed Configuration were more susceptible to injury due to transference of impact energy to bone instead of to the soft tissues of the foot even though the foot stayed plantar flexed momentarily. This follows real life accidents for short female and male drivers. The driver sees the impending head on collision and lifts the foot from the gas pedal to the brake pedal and reaches for the brake pedal putting the foot in the Plantar Flexed Configuration (Crandall, et al, 1996). If the foot misses the pedal the foot assumes the Plantar Flexed Configuration and impacts the floor. The short stature allows the knee to become entrapped under the IP and forward movement of the body puts load on the foot through the long bones of the leg allowing injury to the forefoot to occur and yet the foot stays plantar flexed only momentarily.

Impact velocities less than 13 m/s tended to produce typical Lisfranc injuries while higher impact velocities tended to produce comminuted fractures of the metatarsals. A proposed injury mechanism of this research is a Plantar Flexed Configuration coupled with direct trauma to the ball of the foot. Above an impact velocity of 5.5 m/s or an impact load of 4450 N, logistic regression analysis of the test data indicates a 50% probability of a Lisfranc injury occurring (see Figures 4 & 5). The logistic regression analysis of the test data also indicates that as impact velocity and impact load increase so does the probability of injury.

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