DEVELOPMENT OF A NON-FRANGIBLE PEDESTRIAN LEGFORM IMPACTOR

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ABSTRACT

Standards to test the aggressiveness of vehicle front end geometry and its relation to pedestrian lower leg and knee injuries have been proposed by the International Standards Organization (ISO). These standards call for the use of a legform impactor designed to meet prescribed performance and physical criteria developed to represent a typical adult lower extremity.

The current effort focuses on developing a legform impactor subsystem to comply with the ISO standards. It is also the intention of this project to eliminate the necessity of using plastically deformable elements. This system is constructed with non-frangible knee elements and cylindrical segments representing the tibial and femoral components. Dynamic deformation of the legform subsystem is separated into isolated bending and shearing responses which can be directly measured. Bending is controlled by a clutch type mechanism which can be easily adjusted for calibration and certification purposes. The shearing characteristics of the legform are defined by viscoelastic elements which allow medial/lateral translation of the lower leg segment relative to the upper leg.

Bench testing has proven that this mechanism is a viable alternative to the current legform impactor designs which use frangible knee elements. Details concerning the design development, calibration results and practical testing are included in this paper.

INTRODUCTION

Approximately 5400 pedestrians were fatally injured by motor vehicles in the United States in 1996. On average, a pedestrian is killed in a traffic crash every 97 minutes (NHTSA, 1996). Head and thorax injuries were the major causes of pedestrian fatalities, however, lower extremity injuries accounted for most of the non-fatal injuries.

Injuries to the lower extremities and specifically to the knee are generally not life-threatening but often present long term consequences with the possibility of permanent disability. The long-term mobility of the victim is often significantly affected causing not only an emotional burden on the victim, but a monetary burden on society as a whole (Cesari, et al., 1994).

Pedestrians are generally struck when crossing a road with an impact direction close to the perpendicular of the vehicles motion axis. These pedestrian crashes generally occur in urban areas where the vehicle speed at impact is relatively low, most times below 48 km/h (29.83 mph) (Tanner, 1992).

BACKGROUND

The frequency of lower leg injuries due to contact from with the vehicle bumper, and the resulting long term impairment constituted the basis for experimental research dealing with the response of the human knee during lateral impact. Parameters as to physical dimensions and biofidelic performance characteristics were then generated (Kajzer, 1991). These characteristics were adopted by ISO and used as the basis for a legform impactor test device.

This test device is an impactor subsystem, the legform will be propelled into a stationary vehicle, not vise-versa (ISO, 1997). The impactor must simulate the biofidelic nature of a human leg while being constructed soundly enough to endure multiple impacts to a vehicle.

ISO Standard

The ISO standard for the legform impactor includes physical dimensions, inertial parameters and force-time histories for both bending and shearing at the knee joint (Table 1 and Figure 1). Also included in the ISO standard are certification procedures and a procedure for practical testing of the legform impactor on vehicles.

Table 1.
ISO Legform Impactor Parameters

Parameter	ISO Standard
Lower Leg Length	493±5 mm
Lower Leg Center of Gravity	233±10 mm
Lower Leg Mass	4.8±0.1 Kg
Lower Leg Moment of Inertia	0.120±0.001 Kg-m^2
Lower Leg Outside Diameter	120±10 mm
Upper Leg Length	428±10 mm
Upper Leg Center of Gravity	218±10 mm
Upper Leg Mass	8.6±0.1 Kg
Upper Leg Moment of Inertia	0.127±0.001 Kg-m^2
Upper Leg Outside Diameter	120±10 mm
Legform Total Mass	13.4±0.1 Kg
Flesh Thickness	30±5 mm

Internationally, several programs have developed impactor subsystems (Lawrence and Thornton, 1996, Cesari, 1994, Ishikawa, et al., Tanner, 1992). However, all of these systems share a common characteristic of using frangible knee elements in their design. These frangible knee elements are designed to permanently deform during each impact test.

The use of plastically deformable elements causes a concern about the response variation between pairs of knee ligaments. It is not possible to experimentally validate the performance characteristics of each specific set of ligaments used in testing (Tanner, 1992). Calibration and certification must be done using random samples from each batch of the deformable knee ligaments produced. This causes concern about production and material viability within each batch of deformable knee elements.

Legform Impactor Certification

In order to qualify for ISO acceptance, the legform impactor must conform to the prescribed ISO biofidelic performance corridors as illustrated earlier.

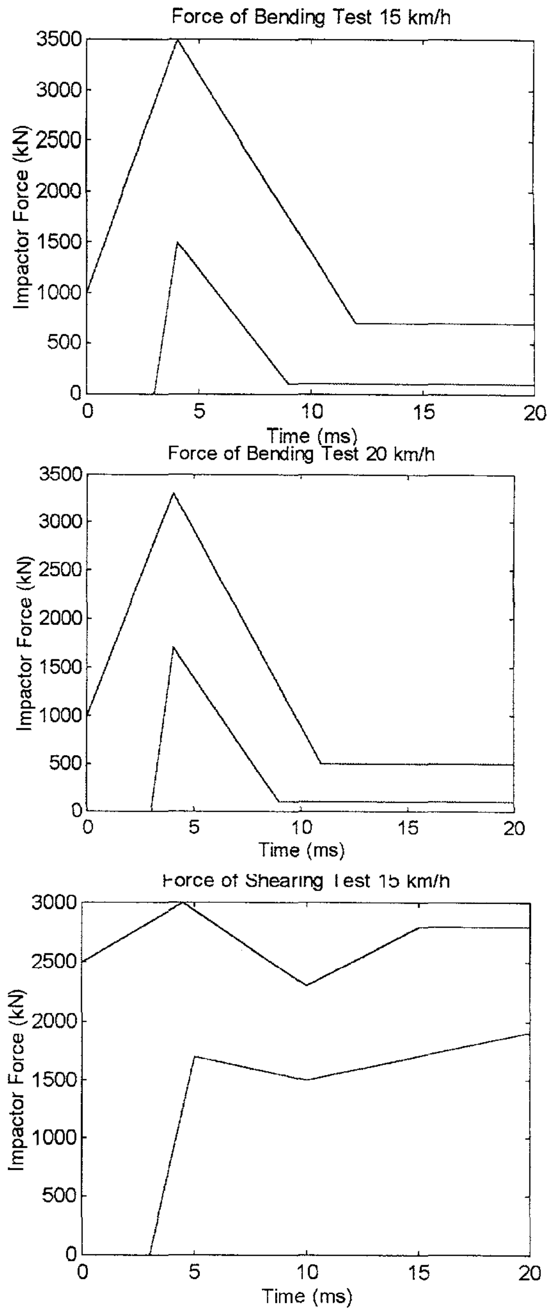

Figure 1. Three ISO biofidelity response corridors corresponding to (top to bottom) two bending tests at 15 and 20 kph and one shearing test at 15 kph.

The ISO standard precisely describes the conditions for the certification tests, including details of the testing configuration and methods. A test fixture was fabricated which allowed both bending and shearing certification tests to be performed on the same fixture. This test fixture is illustrated in Figures 2 and 3.

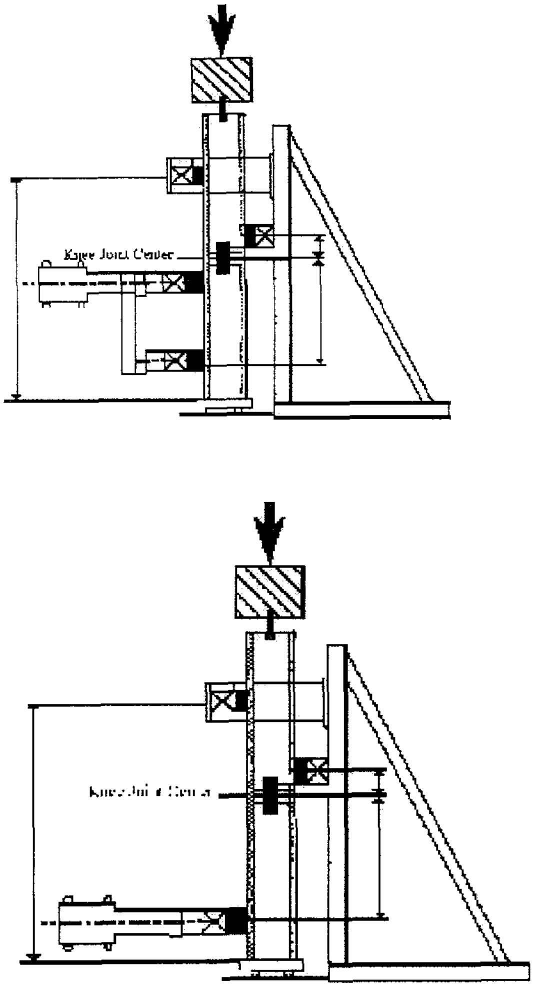

Figure 2. ISO certification test fixtures for shearing (top) and bending (bottom).

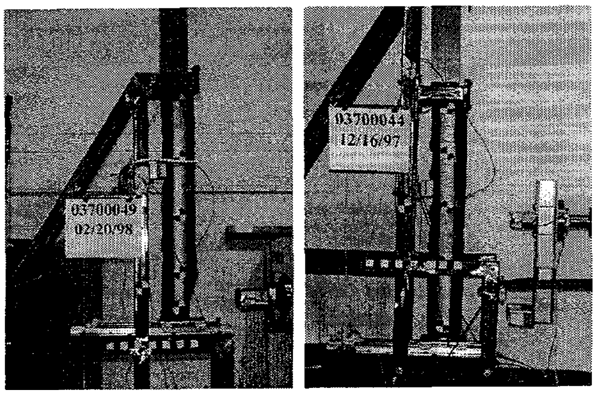

Figure 3. NHTSA certification test fixtures for bending (left) and shearing (right).

NHTSA PROTOTYPE DEVELOPMENT

In order to overcome the problems inherent in calibration and consistency of frangible knee elements, NHTSA has pursued the development of a legform impactor system constructed without the use of frangible elements. Based on this premise, work began on an initial prototype in 1996 (Longhitano, 1997). In this prototype, shearing and bending responses were separated, but constrained about the same axis (Figure 4).

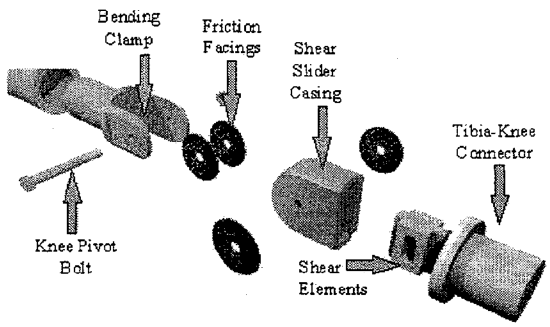

Figure 4. NHTSA prototype pedestrian legform impactor.

The bending response of the knee was defined by a clutch-type knee mechanism constructed of parallel friction plates compressed by a clamp and center pivot bolt. Variation in the torque of the bolt caused a corresponding change in the clamping force between the friction plates. The level of clamping force defined the bending response of the legform during impact event.

Elastic shear elements located in the center of the shear slider casing controlled shear in the medial/lateral direction. These shear elements were constructed from a viscoelastic damping material and sized to give performance within the ISO biofidelic corridor. The elements were designed to elastically deflect 6 mm for an applied load of 4kN.

The initial prototype proved the viability of a legform impactor constructed with non-frangible elements, with the results of the bending tests falling reasonably well within the required ISO biofidelity corridors for both 15 and 20 kph tests. The shear elements however, were not robust enough to withstand the shearing certification test. In this prototype, the shear elements were bonded with an adhesive to a smooth surface, but the bonding strength of this method proved to be inadequate.

The physical and inertial properties of this prototype were not experimentally verified and compliance with the ISO standards for mass, center of gravity and mass moment of inertia was not established.

During practical tests on vehicles, the ISO standards require measurement of bending angle of the knee and shear displacement. The first prototype included direct measurement of each of these parameters. Bending angle was measured, by a rotary potentiometer, as the relative angle between the shear slider casing and the bending clamp. Shear displacement was measured using a miniature string potentiometer which indicated the relative displacement between the shear slider casing and the center post of the tibia cap. The instrumentation for this prototype was not sufficiently robust for repeated impact and thus was found to be inadequate for dynamic testing.

SECOND PROTOTYPE DEVELOPMENT

In construction of a second prototype legform impactor, three goals were set forth: 1) redesign of the shear elements to alleviate the failures found in the first prototype, 2) verification of inertial and physical properties, and 3) redesign of the system instrumentation to give reliable and accurate performance.

Shear Element Revisions

In the initial prototype, the shear elements were bonded to the interior of the shear slider casing and to the center post of the upper tibial cap, both smooth surfaces. The rapid impulse of the dynamic impact exceeded the bonding strength of the chosen adhesive. To overcome this problem, mechanical fixation of the shear elements has been added and the need for an adhesive eliminated. The shape of the elastic shear elements has been modified to include tabs which fit into slots added to the shear slider casing and knee center post (Figure 5).

Physical and Inertial Parameters

During the first prototype development, calculations were made to determine the physical dimensions of the legform impactor that would best meet the ISO standards for physical properties. Design parameters were evaluated in MATLAB software using custom written routines. Design parameters such as element lengths, widths and bore depths were altered in the computer algorithms until the values for the physical properties were within the specified ISO values. Using the MATLAB results, fabrication proceeded for the first prototype.

In the interest of sound design, it was decided that for the second prototype the physical properties of the legform impactor should be experimentally verified. The Human Effectiveness Branch of The Air Force Research Laboratory at Wright Patterson Air Force Base was contacted and agreed to donate the time and expertise for testing.

Using the U.S. Air Force Standard Automated Mass Properties (STAMP) Testing and Calibration Procedure, physical properties can be found experimentally with great accuracy and precision. Using a moment table and an inverted torsional pendulum, mass, centers of gravity and mass moments of inertia were all experimentally verified. The results of the testing and a comparison to the MATLAB results are given in Tables 2 and 3.

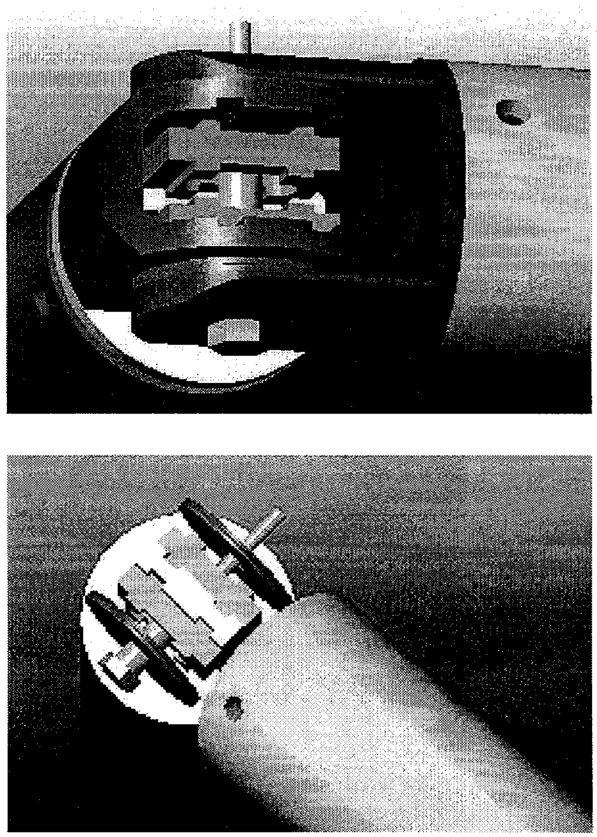

Figure 5. Two views showing the second prototype knee elements illustrating mechanical fixation of the elastic shear elements.

Table 2.

Upper Leg	ISO	MATLAB	Experimental
Mass	8.5 - 8.7 Kg	8.5491 Kg	7.34 Kg
Center of Gravity (From Knee Center)	208 - 228 mm	208.2 mm	209.6 mm
Mass Moment of Inertia	0.126 - 0.128 Kg-m^2	0.1273 Kg-m^2	0.1204 Kg-m^2

Table 3.

Lower Leg	ISO	MATLAB	Experimental
Mass	4.6 - 4.9 Kg	4.336 Kg	4.10 Kg
Center of Gravity (From Knee Center)	223 - 243 mm	241.6 mm	204.8 mm
Mass Moment of Inertia	0.119 - 0.121 Kg-m^2	0.0970 Kg-m^2	0.07876 Kg-m^2

Results show that the MATLAB calculations are in agreement with the ISO specifications for the upper leg segment. For the lower leg, the calculated mass and mass moment of inertia were below specified values. This was due to simplifications made in the MATLAB algorithm and will be corrected in future revisions.

The differences in the experimental and theoretical values for the lower leg are due to the lower cap of the lower leg having been constructed of Delrin and not steel. The lower cap was fabricated from Delrin to reduce the friction between the legform impactor and the certification fixture. If an increase in material density due to steel are factored into the experimental values for the lower leg, the properties are much closer to the prescribed values. The experimental values were also made without the flesh covering, which resulted in a decrease in mass, but had negligible influence on centers of gravity and mass moments of inertia.

Instrumentation Revisions

In the initial prototype, bending angle between the leg segments was measured by a rotary potentiometer. The potentiometer was configured to directly measure the rotation of one segment relative to the other. During testing, this method was found to be inadequate and was abandoned.

Measurement of shear displacement in the initial prototype involved the use of a miniature string potentiometer transducer mounted within the knee structure. Because of the repeated failures of the shear elements, the viability of this method was not verified.

For the second prototype, miniature string potentiometers were used for both the bending angle and shear displacement measurements. Data collected with the redesigned instrumentation system was found to be reliable and repeatable. Sample output is given in Figures 6 and 7.

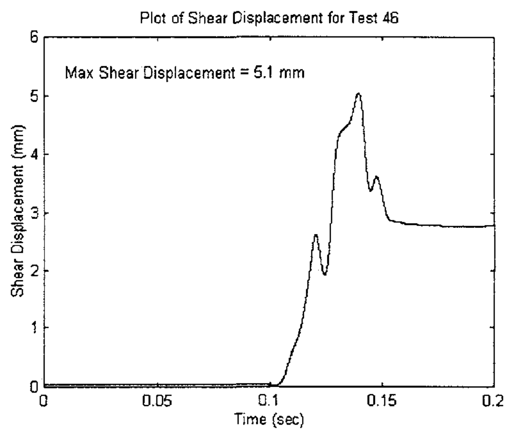

Figure 6. Sample output for shear displacement.

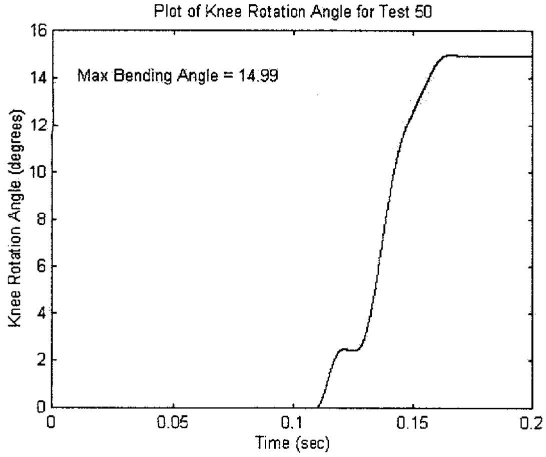

Figure 7. Sample output for knee rotation angle.

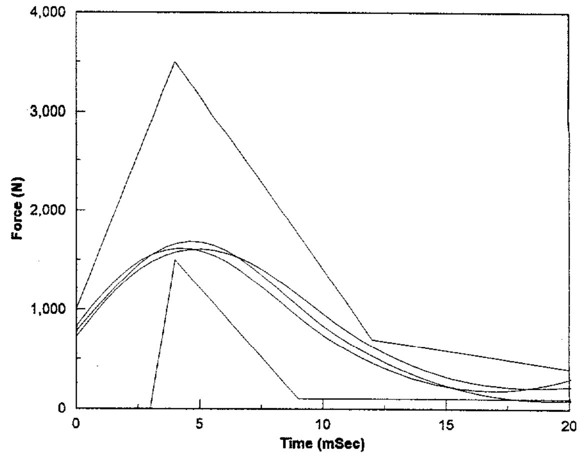

Figure 8. Certification results for the 15 kph bending test.

Certification of Second Prototype

Upon completion of the second prototype, certification of the prototype proceeded. Results of the bending and certification tests are given in Figures 8, 9 and 10.

The results of both bending tests are well within the ISO biofidelic corridor. The results of the shear tests are correct for magnitude of the force, but are only within the ISO corridor for the first 10 ms and fall rapidly after 10 ms.

One explanation of this discrepancy is the method used to measure the contact force during impact. For both bending tests, the contact force was measured using a load cell affixed to the end of the impactor ram. In the shear tests, force measurements were made indirectly using an accelerometer mounted on the lower leg segment. This indirect method of force measurement caused the discrepancy in the shear test. Further testing with a direct force measurement is needed before certification of the shear tests is established.

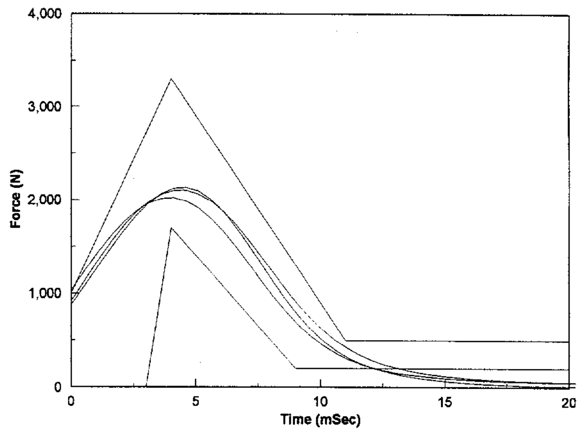

Figure 9. Certification results for the 20 kph bending test.

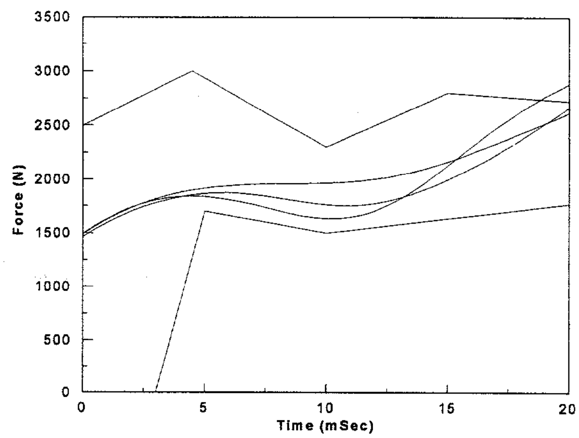

Figure 10. Certification results for the 15 kph shearing test.

NHTSA VEHICLE IMPACT TESTS

The first phase of vehicle bumper tests was fabrication of a propulsion system to launch the legform impactor into the stationary vehicle (Figure 11). A system was fabricated using a hydraulic ram to accelerate the legform impactor. During propulsion, the legform impactor is supported at the center of gravity for both the upper and lower leg segment as well as at the center of knee rotation.

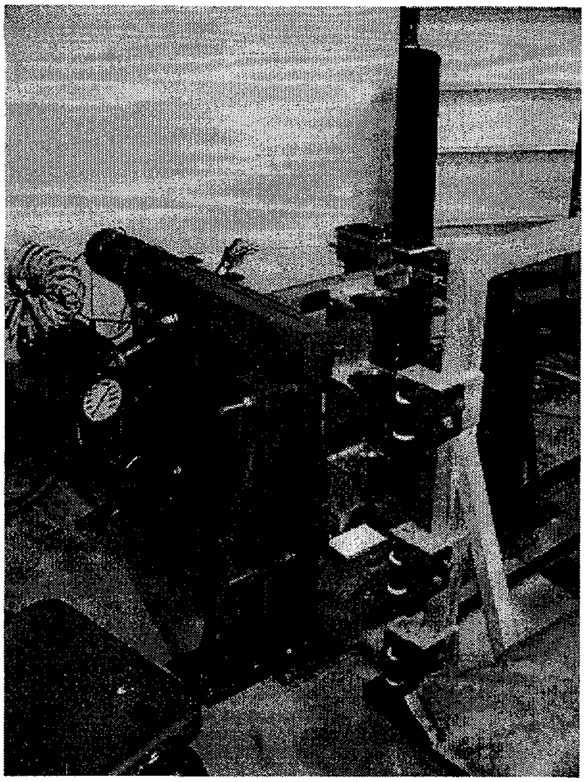

Figure 11. NHTSA legform propulsion system.

As stated in the ISO standards, the legform impactor must be in free flight at the time of impact with an angular velocity less than 50 deg/sec, and within 10 mm of ground level. Further tolerances for yaw, pitch and roll of the legform impactor at impactor are also stated in the ISO document.

Verification of the above parameters was made using motion analysis software and digital film of several test firings. Motion analysis verified that the legform impactor rotational velocity, vertical displacement and vertical tolerances were all acceptable as shown in Table 4.

Table 4.

Parameter	ISO	Experimental
Angular Velocity	< 50 deg/sec	30 deg/sec
Deviation From Vertical	± 6 deg	5.37 deg
Distance From Ground Reference Level	< 10 mm	4.56 mm
Yaw, Pitch and Roll	± 5 deg	< 1 deg

Testing of several vehicles is currently in process at VRTC. Sample output for a completed test are illustrated below. The test vehicle shown in Figures 12 through 16 is a 1993 Ford Explorer.

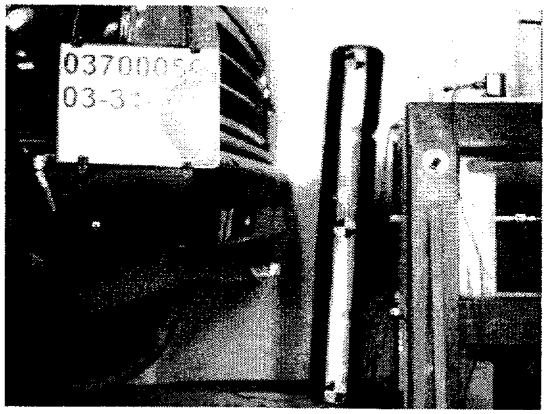

Figure 12. NHTSA legform impact immediately before impact to a 1993 Ford Explorer.

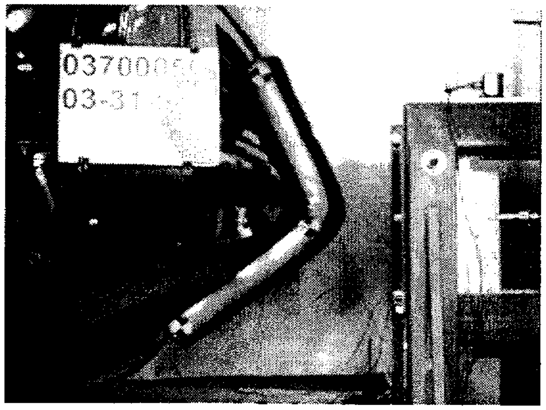

Figure 13. NHTSA legform impact immediately after impact to a 1993 Ford Explorer.

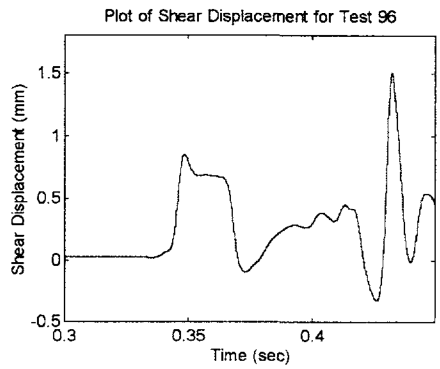

Figure 14. Sample output of shear displacement for test 96, a 1993 Ford Explorer.

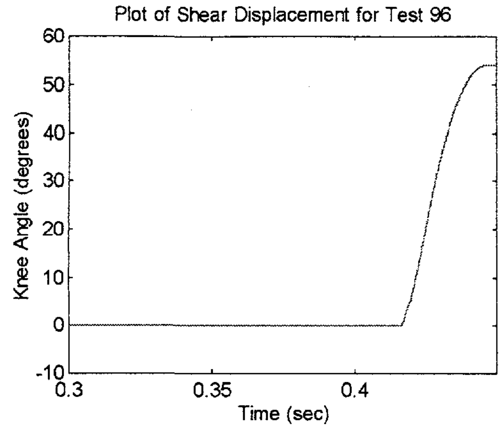

Figure 15. Sample output of knee rotation angle for test 96.

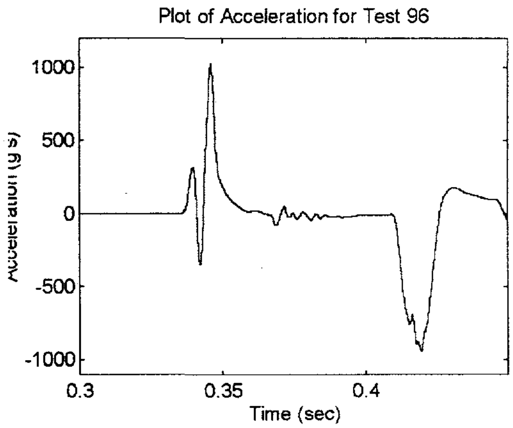

Figure 16. Sample output of leg acceleration for test 96.

Testing of the current system has shown that the system gives reliable, repeatable output and has been tested for durability in test impacts up to 32 mph (51.5 kph).

FINAL PROTOTYPE DEVELOPMENT

There are a number of items which should be addressed in the development of a final prototype:

1. The inertial and physical parameters outlined by the ISO standard must be achieved and verified.
2. The shear response of the legform must be validated using a load cell on the certification ram.
3. Flesh and skin components must be developed using materials that are not required to be replaced with each test.
4. Repeatability of the test device must be confirmed using the propulsion system and a stationary test fixture representing the front end of a vehicle.
5. Durability of the current system must be verified over a larger number of tests and varying testing conditions.
6. Legform impactor performance should be correlated with real-world injury data through a series of crash reconstructions with different impact velocities, vehicle profiles, and injury outcomes.
7. Feasibility, including cost, manpower and resources of a production version of the legform impactor must be explored.

CONCLUSIONS

This legform impactor developed by VRTC is the first known proposal of a pedestrian leg subsystem which is designed to adhere to the ISO standard which does not require the use of frangible elements. The bending response characteristics have been experimentally verified with respect to the biofidelity corridors for pure bending impacts at 15 kph and 20 kph. The shear slider response has demonstrated characteristics consistent with the ISO requirement, but final validation has not yet been achieved.

Repeated testing of these prototypes has demonstrated that the construction is robust. The system is capable of producing data for impacts much more severe than is outlined by ISO. Further design refinements are needed for a final design construction, but development of the legform impactor is near completion.

Finally, with the development of this legform it has been proven that the concept of using non-frangible elements is feasible.

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