CONCEPT DESIGN OF A 4-DOF PEDESTRIAN LEGFORM

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ABSTRACT

The new European car-to-pedestrian impact safety protection regulation has prompted many research efforts in this area. For knee and lower leg protection, the current regulation requires using a legform that consists of 2 degrees-of-freedom (DOF) for injury assessment. It mimics the shear and bending about the knee joint when the lateral side of a pedestrian is impacted by a vehicle. However, in a smaller portion, non-lateral impact accidents also exist in the real world. Moreover, even in a purely lateral impact, once the legform contacts with the bumper, it could rotate towards the other directions due to the curvatures of the bumper shape and the deformation of the bumper foam, causing the legform taking load from other directions. For assessing injuries under omni-direction impact, a concept design of a 4-DOF pedestrian legform is developed. The two added DOFs represent the natural human knee rotation and the shear with respect to the knee joint when a pedestrian is impacted from the front or the back. The bio-mechanical requirements of the 4-DOF legform are adopted from the existing 2-DOF pedestrian legform and the Hybrid III dummy knee. The challenge is to design all the 4-DOF mechanisms, including the motion and stiffness mechanisms, in a limited space of the legform. Design methodology is also documented in this paper.

INTRODUCTION

Car-to-pedestrian collisions are one of the main types of traffic accidents in cities. In the European Union more than 7,000 pedestrians are killed every year in road accidents [1]. In the US, pedestrian fatalities were over 4,700 in 2000 [2]. In China, there exists large amount of roads with mix traffic of pedestrians and vehicles in big cities. In 2003, China had 28,000 pedestrian fatalities, about 25% of the total fatalities in traffic accidents [3].

In car-to-pedestrian collisions, the lower limbs are usually struck first and the pedestrian's head arcs downward to strike the engine hood surface (see sketch in Figure 1). Head injuries are among the most life threatening form of injury for pedestrians and are predominantly caused by a direct blow to the head. Leg injuries account for more than half of the severe injuries. Although not life threatening, severe knee joint injuries often cause permanent disability.

Certain test methods are used for assessing pedestrian impact protection performance of a vehicle, in which dummy or dummy components are used as impactor forms. There has been a debate about whether standing dummy or dummy components such as headform and legform should be used in assessment test. Although using a standing dummy can account for full body kinematics similar to real world accidents, it is difficult to design test setup and control test process. For this and some other reasons, EEVC finally adopted the dummy components in the required test [1] as illustrated in Figure 2.

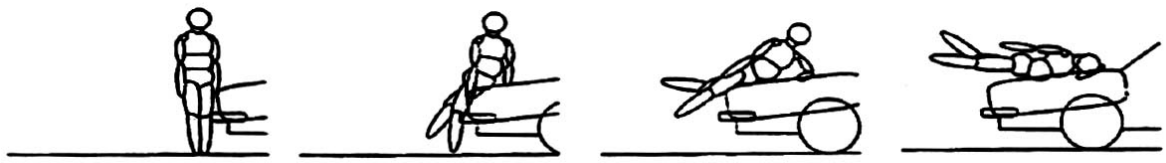


Figure 1. Sketch of car-to-pedestrian impact.

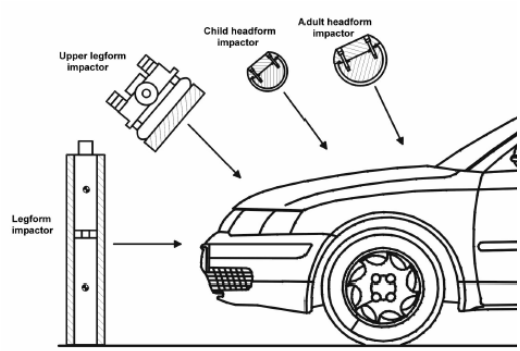


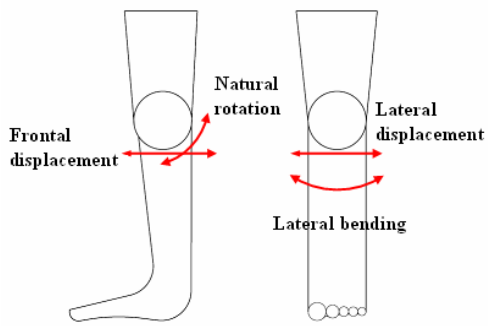
Figure 2. EEVC component tests for assessing pedestrian impact protection [1].

Common injuries of pedestrian lower leg and knee joint as the result of impact with bumper include long bone fractures, knee femoral condyle and tibial condyle fractures, knee ligament tearing and rupture, etc. A joint study by University of Virginia and Honda R&D [4] found that knee bending tests are capable of reproducing real world pedestrian injuries. Pure shear of the knee joint is an extreme case that does not occur in real world pedestrian crashes. A more recent study using cadavers by the same group in University of Virginia [5] further concluded that the real world pedestrian knee injury patterns could only be produced under combined bending and shear. It implies that the combined bending and shear is the actual loading condition that the pedestrian knees experience in real world car-to-pedestrian collisions.

For knee and lower leg protection, the current EEVC regulation [1] requires using a legform that consists of two degrees-of-freedom (2-DOF) for injury assessment. It mimics the shear and bending about the knee joint when the lateral side of a pedestrian is impacted by a vehicle. However, if pedestrian is in walking stance or impacted from an oblique direction, the 2-DOF legform may not have an appropriate response. A study by Kuehn et al [6] found that 56% of car-to-pedestrian collisions occurred when the pedestrian was in walking stance. On the other hand, even the impact is perfectly lateral, once the legform contacts with the bumper, the legform could rotate towards the other directions due to the curvatures of the bumper shape and the deformation of the bumper foam, causing the legform taking load from the other directions. The anatomy of the human knee joint also determines that the knee joint response to external impact may have some degree of coupling effect between different directions. By allowing the knee joint appropriately responding in multi-direction impact, it may open a channel to better correlate the load transferred to the lower leg and upper leg. These manifest a need of a multiple-DOF legform.

To develop a pedestrian legform that can assess injuries from omni-direction impact, a concept design of a 4-DOF pedestrian legform has been developed and is documented in this paper. In fact, the new 4-DOF legform is a combination of the existing 2-DOF pedestrian legform (Figure 3(b)) and the Hybrid III dummy knee (Figure 3(a)), from which the joint stiffness data are also adopted. Whether superimposing the joint stiffness of different directions makes sense in biofidelity is beyond the scope of this study.

The most injury concerned DOFs already exist in the current EEVC legform (Figure 3(b)) for assessing the leg injury when the lateral side of a pedestrian (defined as the y-direction) is impacted. One is the relative shearing in the y-direction between the tibia and the femur, and the other is the relative bending about the x-direction (see the definition below).



(a) (b)

Figure 3. The 4 degrees-of-freedom of the knee joint are designed in the legform.

The 2 added DOFs represent the natural human knee rotation and the shear about the knee joint when a pedestrian is impacted from the front or the back (defined as the x-direction). This can be better explained as: when pedestrian faces to a coming car and the tibia is impacted by the bumper, the tibia may experience a shear displacement in the x-direction relative to the femur. It is the same injury displacement when a driver sits in a car and the tibia is impacted by the intruded engine in frontal impact accident. Therefore these two DOFs already exist in the Hybrid III dummy knee for assessing femur and knee injuries using the Hybrid

III dummy sitting in a car involved in frontal impact.

The challenge is to design all the 4-DOF mechanisms, including the motion and stiffness mechanisms, in a limited space of a legform. Several design options are developed and analyzed in this project. By ranking and weighting different design requirements, one of the designs is selected for further detailing it in a complete pedestrian legform.

DESIGN TASK AND REQUIREMENTS

As illustrated in Figure 3, the knee joint allows the shearing displacements along the two axes as well as the rotations about the same two axes. The design deals with a large school of requirements. The kinematic structure of the 4-DOF joint in a rather small design space is the first issue to tackle. Furthermore, except the natural knee rotation, all the other 3 DOFs are injury producing motions and need to satisfy certain stiffness and damping requirements such as bending moment vs. bending angle or shear force vs. shear displacement.

Geometry and Packaging

By referencing the overall geometrical requirements of the EEVC legform [1], it is determined that the optimal size of the 4-DOF knee joint is a cylinder with a diameter smaller than 70mm, the diameter of the femur and tibia of the EEVC legform. This size limit is actually difficult to house a 4-DOF joint, and therefore is quoted as optimal size, or a wish size. The 2-DOF EEVC knee joint is housed within the perimeter of the femur and tibia diameter, while in the 4-DOF knee joint design, in order to gain more packaging space, the knee joint is allowed to be slightly larger than the tibia and femur diameter ("extruding out"). This is more like human knee and Hybrid III dummy knee, and the flesh thickness in the knee joint area is reduced in order to maintain the overall size within a certain range. It is therefore determined that the maximum size for the design space is using a cylinder with diameter 100mm and covering it with 10mm flesh foam.

The human knee joint is like a spherical joint, in which all the axes meet at the same point. To achieve a high biofidelity, in the 4-DOF legform, all the axes should also be near each other. In fact, designing the 4-DOF knee joint as a spherical joint is one of our early options for its good similarity to the human knee. But a spherical joint might have great disadvantages compared to non-spherical ones in mechanical sense.

Stiffness Requirement of the Joints

The natural rotation of the human knee joint is not an injury concerned DOF and defined as a rotation from 0° to 120°, which seems to be a suitable range for the purpose of being a pedestrian legform. Although no bio-fidelity requirement, the joint should have certain friction damping, and the friction magnitude may be equivalent to, for example, resisting motion under gravity loading.

Since this work is not about developing more appropriate biofidelity requirements for the human knee and leg under impact loading, the stiffness requirements of the other 3 injury concerned degrees-of-freedom are adopted from that of the existing dummies and dummy components. When more appropriate stiffness requirements become available in the future, they may be built into the mechanical mechanisms of the design of this work.

For shearing in the x-direction, based on the test data in [7] and result of a Hybrid III dummy knee slider stiffness test, the shear stiffness curve in Figure 4 is adopted.

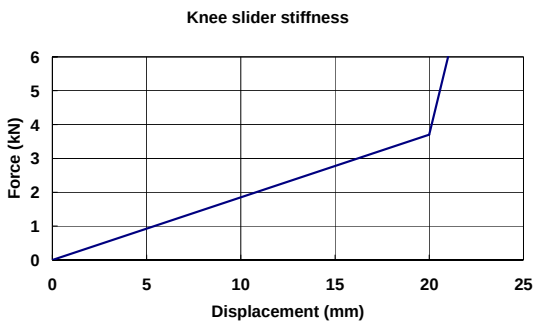


Figure 4. Frontal shear force vs. displacement of the knee joint.

For lateral impact to the legform, the EEVC document [1] has given the shear force vs. shear displacement shown in Figure 5 and the bending force vs. bending angle shown in Figure 6. Note that these requirements of the knee joint are derived from the static certification test of the EEVC legform. The bending moment can be calculated by multiplying the given force value in Figure 6 with 2m, the force arm length in the certification test.

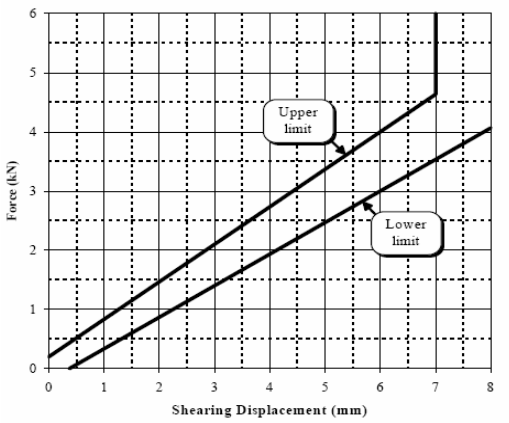


Figure 5. Lateral force vs. displacement of the knee joint [1].

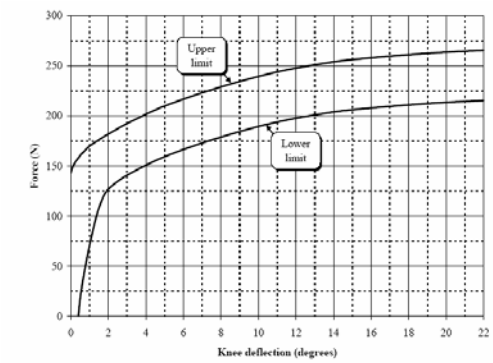


Figure 6. Lateral bending force vs. bending angle of the knee joint [1].

As the legform is used under impact loading condition, damping mechanisms must be considered when designing the kinematic structure of the joint. It is also desirable that recoverable deformation and motion mechanisms, as opposed to any destructive elements, are used in achieving the required stiffness.

Summary of Design Requirements

Other design requirements include measurement of displacements and forces needed for assessing the injury severity. Therefore, there must be space in the legform to install sensors and make measurement with high repeatability and reliability. This work is still ongoing and will be reported in future publications.

The design requirements and evaluation criteria can be summarized as follows: (a) high biofidelity, (b) flexible characteristics of stiffness and damping mechanisms to meet different characteristic curves, (c) small design space, (d) good measurement possibilities, (e) easy use, and (f) high durability. Among them, high biofidelity and good measurement possibilities are more important.

DESIGN OF 4-DOF LEGFORM

Design Methodology

Based on the requirements and functions established above, some principle solution variants are first developed to fulfill the requirements of each of the 4 degrees-of-freedom. By this way a complex problem is divided into several simple problems, for which solutions can be found more easily. Then the kinematic chain of the knee device is considered to sort out many different possibilities of arranging the 4 degrees-of-freedom. Following that, these solutions are combined into solution concepts by analyzing their merits and drawbacks. In the last step, the concepts are evaluated according to certain criteria. The best solution emerged from this evaluation process is the solution that fulfils all the requirements best and therefore is further designed with details.

To identify rotational or translational motion mechanisms that fulfill the required stiffness and damping, the following elements are considered and their advantages and disadvantages are analyzed: pressure spring, Belleville spring, gas spring, leaf spring, friction spring, leg spring, spiral spring, torsion spring, rubber element, plastically deformable element, rolling bearing, plain surface bearing, sliding plane, ball joint, hydraulic damper, rotation brake, etc.

To realize 4-DOF, one can use 4 single joints, 2 double joints, 1 triple joint and 1 single joint, 1 quadruple joint, or any other combinations. An advantage of using triple joint or quadruple joint is that it can lead to small design space, but it is very difficult to achieve the required stiffness in a combined joint, and measurement would be nearly impossible. In contrast, it would be easy to achieve the required stiffness by using 4 single joints, but it would occupy a large space and result in complex connections between the joints. Therefore a knee structure consisting of 1 double joint and 2 single joints or 2 double joints would be appropriate. The first joint may be a translation joint, followed by a rotation-rotation double joint and another translation joint; or the first joint may be a translation-rotation

double joint, followed by a translation joint and a rotation joint; or some of their permutations.

By combining the partial solutions, matrix of different variants is established. To achieve the best combination, it is important to combine the sub-functions without creating a conflict between the solution variants. A clear arrangement of the sub-functions to prevent conflicts is using morphological matrix. The selection of solutions from the morphological matrix sometimes requires a certain kinematic chain, in which the evaluation criteria summarized in an earlier section are used. These processes lead to the following design.

Embodiment Design of Chosen Solutions

Figure 7 shows the legform in unloaded posture and Figure 8 shows the legform stances under different loadings. The mechanisms of the 4-DOF are illustrated in the following.

The lateral displacement DOF and the natural rotation DOF are realized in a double joint. It allows a lateral shear displacement of 8mm in each direction, leading to a total movement of 16mm, with the force-displacement relationship shown in Figure 5. It is achieved by a rubber element with a certain stiffness and damping characteristic. The basic idea can be seen in Figure 9 and Figure 10. This solution offers a small design space and flexibility to design the rubber element characteristic in a wide range. Additionally, although no stiffness requirement, a rotation stopper must be included to the natural rotation of the knee joint to limit range of its rotation angle to a desired value.

Similar to the displacement in the lateral shear DOF, the joint characteristic of the frontal shear (Figure 4) is achieved by a rubber element too. However, the shear displacement in the frontal direction is much larger, 20mm in front and rear directions, respectively, with a linear force-displacement relationship. With a total displacement of 40mm, it is very difficult to install a rubber element in the radial direction (only 100mm diameter cylinder by the requirement). On the other hand, there is a relatively large space available in the axial direction in the upper and lower leg tubes. By using ligament cables, it is possible to transform the radial direction displacement into the axial one and install rubber elements in the lower tube. Figure 11 shows such a design.

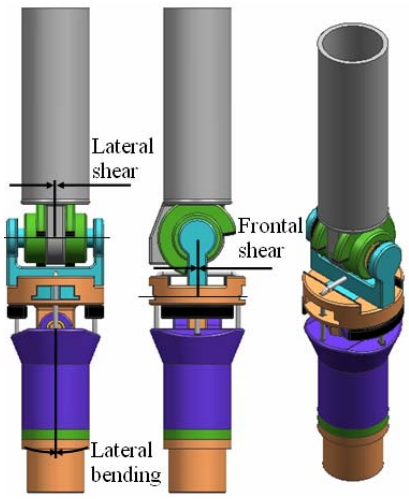


Figure 7. Legform impactor in unloaded position.

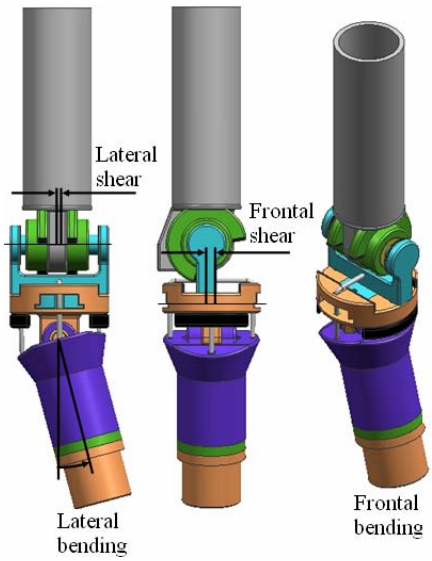


Figure 8. Legform impactor in loaded position.

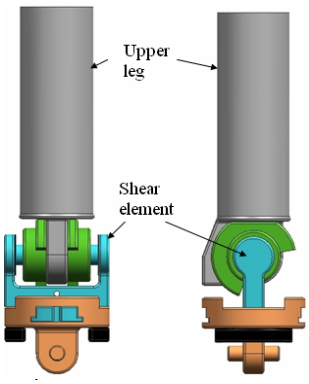


Figure 9. Double joint for lateral displacement and natural rotation.

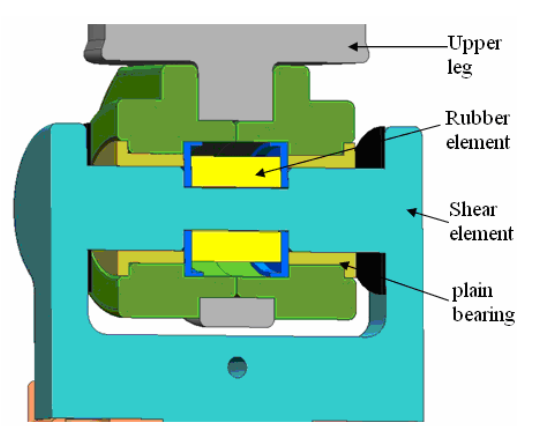


Figure 10. Interior view of lateral displacement system.

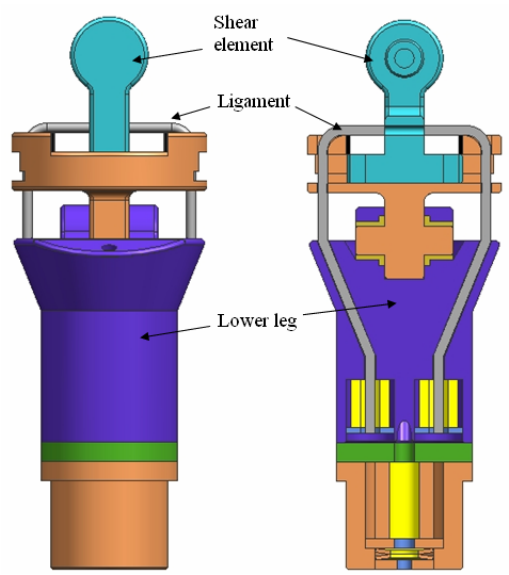


Figure 11. Frontal displacement system.

By transforming the direction of movement, the design allows a greater flexibility to change the rubber elements. It would even be possible to install a spring-damper system. When the shear element moves (Figure 11), it pulls the ligament cable to make the rubber element compressed. As the forces are relatively high, it may be necessary to calculate the resulting force-displacement curve by including the stiffness of the cable. Additionally, the friction between ligament cables and the supporting elements should be minimized (for example, using pulleys).

As shown in Figure 6, the joint characteristic of lateral bending DOF is nearly bi-linear and is more difficult to achieve than that of the lateral and frontal shear DOFs, which are linear. In the EEVC 2-DOF legform, it is achieved by using plastically deformable elements. In this design, it is hoped not to use any destructive elements.

The design is shown in Figure 12. It uses a system consisting of a Belleville spring and a preloaded rubber element to generate the required stiffness. Again, ligament cables are used to transform rotation into translation. This is not only for using the space in the lower leg tube, but also for easy to achieve the nonlinear force-displacement characteristic in translational movement. The rubber element is preloaded to the maximum force of the Belleville spring. Thus, when the force reaches the maximum, the Belleville spring cannot be compressed any further and the rubber element is compressed instead. A difficulty with this design is to achieve the high required force to generate a bending moment as large as 500Nm.

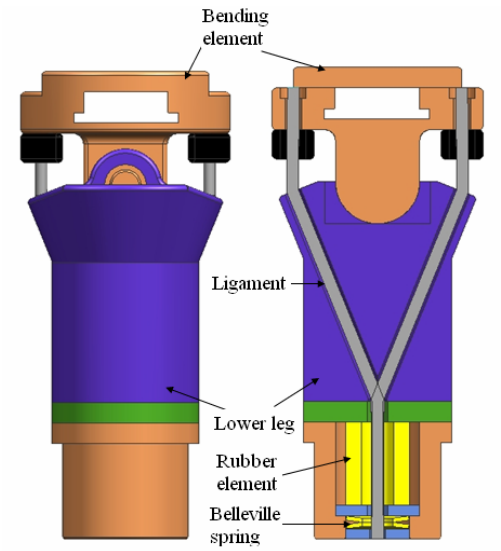


Figure 12. Lateral bending spring system.

CONCLUSIONS

A concept design of a 4-DOF pedestrian legform is documented in this paper, together with summary of the design requirements and the design methodology. This is the first phase work of the 4-DOF pedestrian legform development. The design improvements are still ongoing. The next steps include design of the measurement means of injury parameters (deformation, acceleration, force, etc.) and their packaging. For protection and damping purpose, like in all other dummies, a certain cushion envelope, especially around the knee joint, is also be needed.

A finite element model of the legform is also under development. A prototype will then be built, evaluated and tested.

ACKNOWLEDGMENT

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REFERENCES

[1] EEVC. 2002. "Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars." European Enhanced Vehicle Safety Committee, Working Group 17. www.eevc.org.

[2] NHTSA. 2000. "Traffic Safety Facts 2000 – Pedestrians." DOT HS 809 331. The US National Highway Traffic Safety Administration.

[3] China Traffic Control Bureau. "2003 Data of traffic accidents in China."

[4] Bhalla K, Bose D, Madeley NJ, Kerrigan J, Crandall J, Longhitano D, and Takahashi Y. 2003. "Evaluation of the response of mechanical pedestrian knee joint impactors in bending and shear loading." The 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan.

[5] Bose D, Bhalla K, Rooij LV, Millington SA, Studley AF, and Crandall JR. 2004. "Response of the Knee Joint to the Pedestrian Impact Loading Environment." SAE 2004-01-1608. SAE Congress.

[6] Kuehn M, Froeming R, and Schindler V. 2003. "An advanced testing procedure for the pedestrian-car-collision." The 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan.

[7] Viano D, Culver C, Haut R, Melvin J, Bender M, Culver R, and Levine R. 1978. "Bolster impacts to the knee and tibia of human cadavers and an anthropomorphic dummy." SAE-780896.