DEVELOPMENT OF AN ALTERNATIVE FRANGIBLE KNEE ELEMENT FOR A PEDESTRIAN SAFETY LEGFORM

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ABSTRACT

The design of a novel four ligament instrumented knee element for pedestrian safety testing is described. Knee shear and bending tolerances from PMHS (Post Mortem Human Surrogate) testing in the literature and current pedestrian safety testing procedures are considered for comparative purposes. Validation at component level of individual textile ligaments is compared to reported biological data for ligaments tested in tension. Testing and validation of the knee element in shear and bending at quasi-static rates is presented. The knee element offers an instrumented lightweight biofidelic frangible kneeform which is able to predict failure in individual ligaments and measure knee bending and shear displacement.

Keywords: Pedestrians, Knees, Frangible, Legform

FOLLOWING THE INTRODUCTION of new pedestrian safety legislation, there has been a need for effective tools to assess pedestrian injury in pedestrian vehicle collisions. The EEVC Working Group 17 (1998) set out a series of legislative tests designed to measure the aggressiveness of vehicle fronts towards pedestrians. These tests involved a lower legform, upper legform and two headform impacts. The original lower legform, designed by TRL used two rigid steel limbs with steel knee ligament bars to assess bending and shear damage. JAMA-JARI have recently published work on the development of a flexible pedestrian legform impactor, known as the FlexPLI, which uses flexible limbs and a more biofidelic kneeform (Konosu, 2003). The research objective of the current study was the development and validation of a knee element for pedestrian safety testing constructed using biofidelic materials. The aim was to provide an instructive biofidelic research tool, not a legislative testing tool.

Legform Knee Element Design

This study introduces a novel four ligament instrumented knee element and describes the initial design and validation of the kneeform. The main body is constructed from Nylon 66 in order to minimise weight, and thereby produce a more biofidelic legform, while still using a durable material. It is of key importance that the knee form can simulate varus and valgus rotation and lateral shear, but it is not required to simulate knee flexion, therefore a simplified articular surface was used. The tibial plateau was assumed to be flat and femoral condyles were represented by simple radii. Bending and knee shear were assumed to occur in the lateral plane only. It was considered that knee flexion would have distorted the results and was an unhelpful and unnecessary additional parameter. Textile material ligaments were used to provide the restraint for the kneeform, with two different designs of ligament to represent the cruciate and collateral types of ligament. Both collateral ligaments and both cruciate ligaments were each assumed to have the same properties; this produces a symmetrical kneeform and simplifies analysis. The kneeform design is shown in Figure 1.

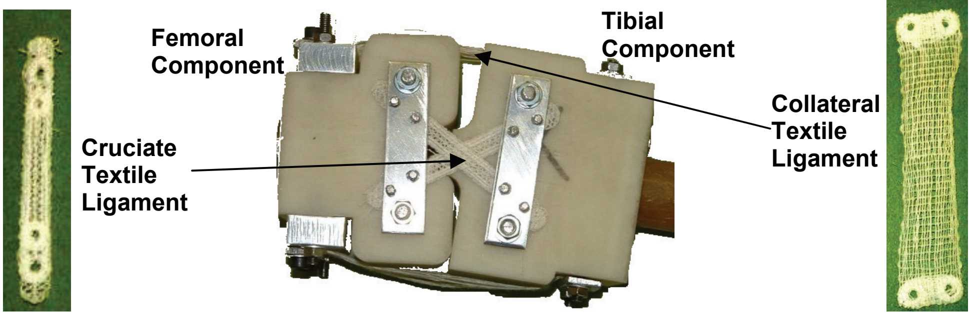

Figure 1 - Frangible knee element design with textile ligaments, shown in bending

The kneeform is instrumented using three linear potentiometers, capable of independently measuring knee bending angle and knee shear. Knee shear and bending is measured in order to comply with the EEVC test criteria and for comparative purposes with literature data. These parameters can be directly related to the strains in individual ligaments; however these are not measured in the current design.

TEXTILE KNEE LIGAMENT TESTING AND VALIDATION: Two designs of polypropylene textile material ligaments manufactured from designs based on replicate implant ligaments were used to provide the restraint for the frangible kneeform. Overall ligament strength and stiffness was varied by changing either the material or the design. The ligaments were bolted through attachment points and clamped in place on the kneeform.
A literature search was conducted to obtain a specification for the four knee ligaments, which are divided into two groups; the cruciate ligaments, ACL (Anterior Cruciate Ligament) and PCL (Posterior Cruciate Ligament) and the collateral ligaments MCL (Medial Collateral Ligament) and LCL (Lateral Collateral Ligament). Reported quasi-static literature values for rupture force of ACL ligaments tested individually in tension ranged from 734 N (± 266) reported by Trent et al (1976) to 2160 N (±157) for adults aged 22-35 reported by Woo et al (1991). Trent reported the PCL rupture force as 560.2N. Since the PCL and ACL were to be represented by a single design, a specification value of 1000 ±100 N was chosen for the cruciate collateral ligaments to represent a mid-range value.
Values for the rupture force of MCL and LCL were taken from recent experiments designed to determine ligament tolerance for pedestrian safety research by Kerrigan (2003). LCL values were quoted as being 387.1 (±92) N for 1.6 mm/s and 571.1 (±148) N for 1600 mm/s test speed. MCL values were 1305.0 (±278) N for 1.6 mm/s and 1214.6 (±209) N for 1600 mm/s test speed. Other studies have typically found slightly lower values for the MCL tolerance. A specification value of 800 ±100 N was selected for the textile collateral ligaments to represent a mid-range value.
Textile ligaments were then designed to the specifications, based on ligament length data taken from Takashi (2000).These were tested in tension on an Instron test machine at 10mm/min, results are shown in Table 1.

Specimen	Mean	SD	Units	n
Textile Collateral	735.6	28	N	6
Textile Cruciate	1026.9	31	N	6

Table 1 – Textile ligament properties

KNEE ELEMENT TESTING: Testing and validation of the knee element in both shear and bending at quasi-static rates was conducted and compared to literature values. Bending testing was achieved by applying an angular displacement to the kneeform and measuring bending moment, using a Dartec dual axis test machine. The femoral component of the kneeform was rigidly fixed while the rotational displacement was applied by using an offset cylindrical bar at a distance of 350mm from the axis of rotation. The bending test setup is shown in Figure 2 (a). The complete kneeform was tested in shear in the setup shown in Figure 2 (b). The femoral component of the kneeform was fixed in position and a lateral shear displacement was applied by an actuator that was rigidly fixed to one half of the kneeform and applied load perpendicular to the lower leg to ensure pure shear loading.

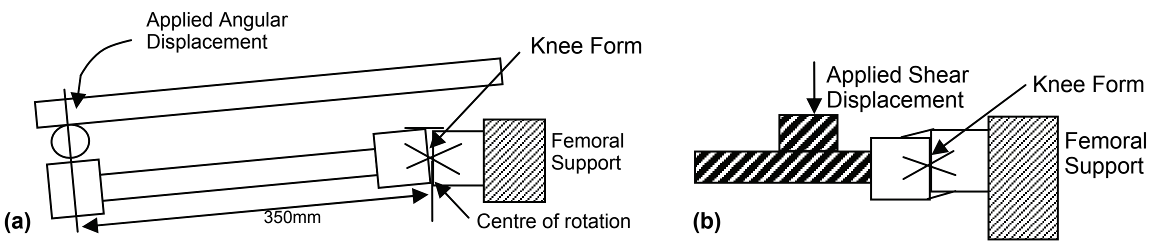

Figure 2 – (a) Bending and (b)Shear setup

Results were compared with published quasi-static and dynamic biological test data. Quasi-static test data is taken from Ramet (1995) and dynamic data at various speeds is taken from Kajzer (1999, 1997) and Kerrigan (2003). It should be noted that dynamic test results for bending at 11m/s from

Kajzer et al have been included in the graphs but not further analysis due to concerns about the validity of the results highlighted by Konosu (2003). Bending test results are compared to the literature and as shown in Figure 3, the bending moment at failure is about 75Nm which is slightly lower than seen in PMHS studies, the angular displacement is similar however.

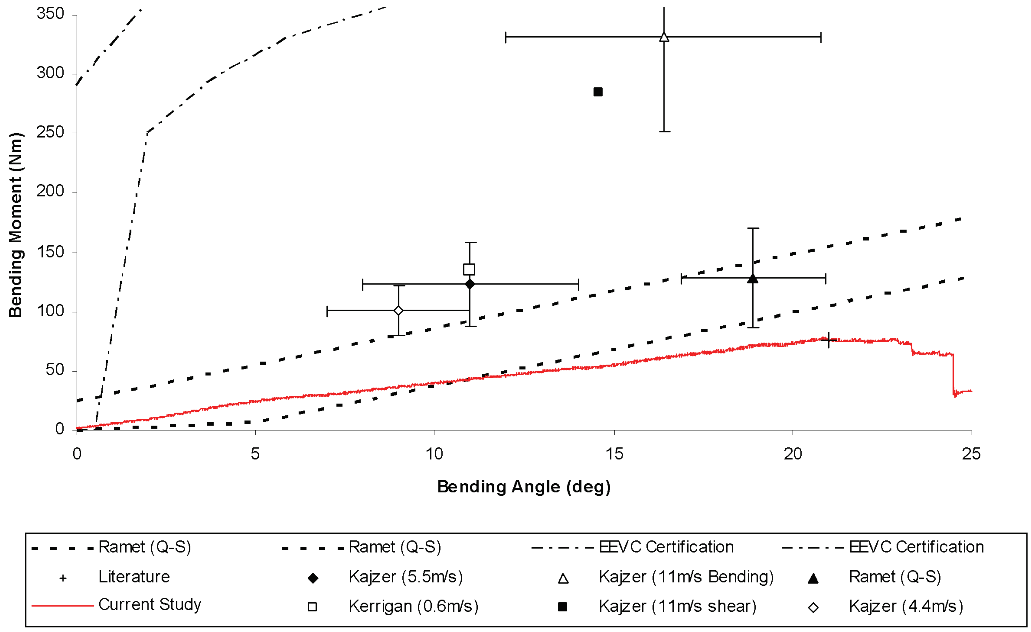

Figure 3 - Bending test results

Results from the shear testing are shown in Figure 4. The kneeform shows an initial failure at about 35mm shear displacement and 1400N load. This shows a slightly lower shear force than the PMHS studies at initial failure.

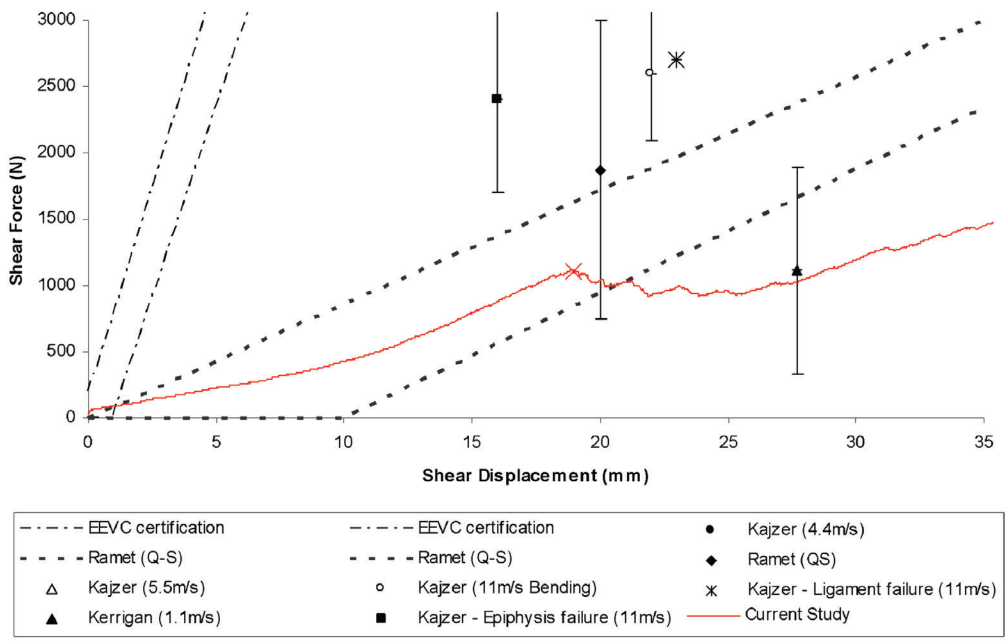

Figure 4 - Shear testing compared to literature results

Conclusions

The kneeform exhibits a similar response in both shear and bending to literature studies and the textile ligaments show a gradual rupture after initial failure similar to that seen in cadaver studies at quasi-static speeds. Initial failure is shown to occur slightly later in the frangible kneeform than the

PMHS literature studies in both shear and bending. The complete knee element has a lower bending stiffness than found in literature results for PMHS knees when using individual ligaments with similar tolerance to literature values reported here. This is likely to be due to other structures which contribute to knee bending stiffness. It has been reported by Fu (1991) that the lateral collateral ligament resists approximately 55% of the load in varus angulation when at full extension, and approximately 25% of the load is taken by the cruciate ligaments. From this information it could be expected that a kneeform using only ligamentous restraint would be only 80% of the strength of a complete knee, which is consistent with the results obtained. Knee shear stiffness and initial failure load are within the quasi-static corridor proposed by Ramet. Knee bending and shear stiffness can be further tuned to the same levels as literature studies by varying ligament strength and stiffness and extension at failure through different materials and design. It is possible to vary the ligament strengths considerably whilst still conforming to the specification based on literature values.

The new design of the knee element offers an instrumented lightweight biofidelic frangible kneeform which is able to predict failure in individual ligaments. The textile ligament design allows for a non-linear ligament (and therefore knee) response to be simulated, and consequently a more biofidelic response of the kneeform. The textile ligaments provide a repeatable and cost effective replaceable component. The cartilage deformation and potential damage to the femoral condyles is not considered in the current design. Although condyle damage has been shown to be a factor in knee injury, it has been noted by Terenski (2001) that this normally occurs after the initial ligament rupture which has therefore been used as an indicator for initial knee injury.

It is shown that a biofidelic knee response can be achieved using the current kneeform design. Limitations of the study include a simplified geometric design of the knee element common to all current legform knee designs, which dictates that the knee form is only appropriate for predicting the response of a fully extended leg. High speed (up to 11m/s) validation testing of the complete kneeform is the subject of continuing work and initial results indicate strain rate dependant properties in the textile ligaments are similar to real ligaments.

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