DEVELOPMENT OF A BIOFIDELIC FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR TYPE GTR PROTOTYPE
PART2: TECHNICAL DETAILS

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ABSTRACT

In 1998 the European Enhanced Vehicle-Safety Committee (EEVC) proposed a test procedure to assess the protection vehicles provide to the lower extremity of a pedestrian during a collision. This procedure utilizes a legform impactor composed of rigid long bones. In order to improve biofidelity of the legform impactor, the Japan Automobile Research Institute (JARI) and the Japan Automobile Manufacturers Association, Inc. (JAMA) have been developing a biofidelic flexible pedestrian legform impactor (Flex-PLI) since 2002.

The Flex-PLI has high biofidelity especially for its long bone parts, which have human-like bending characteristics under a car impact condition, compared to other types of legform impactors, which have rigid long bone parts. The Flex-PLI also provides extended injury assessment capability, including long bone bending moment at multiple locations and knee ligament elongations in comparison to other pedestrian legforms.

In 2005, the Flex-PLI Technical Evaluation Group (Flex-TEG) was settled under the UN/ECE/WP29/GRSP/Informal Group on Pedestrian Safety in order to evaluate its performance to adopt the impactor as a regulatory purpose test tool for a Global Technical Regulation on Pedestrian Safety (PS-GTR: gtr 9). The Flex-PLI was evaluated and improved its performance under the Flex-TEG activity, and then its design of the final version, type GTR (Flex-GTR), was agreed by the Flex-TEG members in April 2008.

This paper provides technical details of the Flexible Pedestrian Legform Impactor GTR prototype (Flex-GTR prototype). Technical specifications on all important aspects of the Flex-GTR prototype are given: dimensions and mass at (sub-) assembly level; biomechanical responses of main components of the femur, knee and tibia; calibration procedures and corridors; standard and optional instrumentation channels, their capacity and position; handling; including details of electrical systems and data acquisition. The paper will present results of calibration testing, repeatability and reproducibility of three prototypes which are evaluated at First Technology Safety Systems (FTSS) before their release from the FTSS factory.

INTRODUCTION

In 1998, the European Enhanced Vehicle-Safety Committee proposed a test procedure to assess the protection vehicles provide to the lower extremity of a pedestrian during a collision [1]. This procedure utilizes a legform impactor composed of rigid long bones. In order to improve biofidelity of the legform impactor, the Japan Automobile Research Institute (JARI) and the Japan Automobile Manufacturers Association, Inc. (JAMA) have been developing a biofidelic flexible pedestrian legform impactor (Flex-PLI) since 2002 [2]. The Flex-PLI has high biofidelity especially for its long bone parts, which have human-like bending characteristics under a car impact condition, compared to other types of legform impactors, which have rigid long bone parts [3]. The Flex-PLI also provides extended injury assessment capability, including long bone bending moment at multiple locations and knee ligament elongations in comparison to other pedestrian legforms [3].

In 2005, the Flex-PLI Technical Evaluation Group (Flex-TEG) was settled under the ECE/WP29/GRSP/ Informal Group on Pedestrian Safety in order to evaluate its performance to adopt the impactor as a regulatory purpose test tool for a Global Technical Regulation on Pedestrian Safety (PS-GTR). The Ministry of Land, Infrastructure, Transport, and Tourism of Japan (J-MLIT) has been supporting this Flex-TEG activity, taking a task of a chair country of the group and conducting technical evaluation tests on the Flex-PLI. After the settlement of the Flex-TEG, the Flex-PLI was evaluated and improved its performance under the Flex-TEG activity, and then its design of the final version, type GTR (Flex-GTR), was agreed by the Flex-TEG members in April 2008 [4], and its prototype (Flex-GTR-proto) was released in November 2008. In the Flex-GTR development, First Technology Safety Systems (FTSS) is involved as a dummy development specialist company. This paper provides technical details of the Flex-GTR prototype and changes that were made with respect to the previous version, the Flex-GT. Technical evaluation test results on them under several impact conditions are presented separately in Paper Number 09-0145.

DESIGN IMPROVEMENTS

Methodology

As part of the Flex-TEG activities a design review of the Flex-GT version was completed. This activity highlighted a number of changes necessary to improve sensitivity, handling and durability. The recommendations resulting from the design review were the starting point for the Flex-GTR development. The most important issues found were:

1. The cruciate ligaments in the Flex-GT knee exert a twist moment causing misalignment between the femur and the tibia. It was recommended to balance these ligaments with an additional set of cruciate ligament springs.
2. The position of the ligament elongation sensors on the outside of the Flex-GT would cause a difference in sensitivity to left and right oblique loading. It was recommended to position ligament sensors at the centreline of the tool.
3. The high channel count of the Flex-PLI and associated larger umbilical cable might cause a higher influence on the free flight trajectory and reduced accuracy of hitting the target impact location. It was recommended to integrate an on-board data acquisition system (DAS).
4. Some umbilical cable damage was experienced during the Flex-GT evaluation and caused significant downtime of the Flex-PLI because of necessary repairs. It was recommended to provide better cable protection and to make a quick disconnect of the umbilical cable to off board possible. This would help continuation of testing and repair of spare cable simultaneously.
5. It was recommended to update the dynamic calibration procedure, to obtain a loading level closer to the injury tolerance level and loading during vehicle testing.

An important boundary condition for the Flex-GTR development was that the performance of the Flex-GT version should be maintained, as not to invalidate what was achieved with the GT version in the Flex-TEG. Therefore existing size, mass and materials were to be maintained as much as possible. Numerous smaller changes were recommended and integrated into the Flex-GTR design to improve handling and durability.

Design improvements

To balance the twist moment, additional springs were added in the knee. The distribution of the load required smaller springs and thinner ligaments to be used. The spring rate and the stroke of the springs were adapted to maintain the original response. Bronze bushes were introduced and plastic cable sleeves were omitted to reduce friction and wear.

To address sensitivity to oblique load, new and smaller ligament elongation sensors were positioned on the centreline of the knee (see Figure 1). Also for ligament sensors, bronze bushes were introduced to reduce friction and wear.

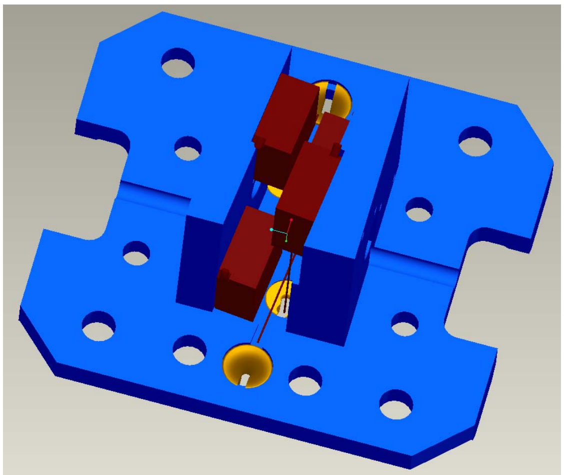

Figure 1: Ligament sensor arrangement at centreline

The addition of optional on-board data acquisition systems was achieved within the dimensions of the Flex-GT specifications. The smaller cruciate springs gave additional space in the front and rear sides for integration of on-board DAS. Two systems from different DAS equipment manufacturers were integrated: DTS-SLICE and MESSRING M=BUS. As off-board DAS is also considered, three different version prototypes were manufactured: with off-board, 'M=BUS' and 'SLICE' data acquisition systems.

The Flex-GTR is standard equipped with a connector system that allows quick disconnection of umbilical cables to the various data acquisition systems and for sensor exchange.

The dynamic calibration procedure was enhanced by running the test with the leg upside down, the addition of a 5 kg mass at the femur end, addition of an accelerometer to the knee and introduction of a stopper block performance test.

Further enhancements were introduced especially to improve handling and durability. To name a few: to protect the ends of the leg after rebound from a test, moulded polymer bumpers were added to the tibia base and femur top; locking nuts were used on the knee ligaments and bone cables to better maintain adjustment settings; to improve free flight stability, the umbilical cable exit locations were brought closer to the centre of gravity of the leg; to enhance the assembly of the tight fitting Neoprene outer covers, a larger plastic zipper was selected and hook and loop flaps were added to protect the zipper.

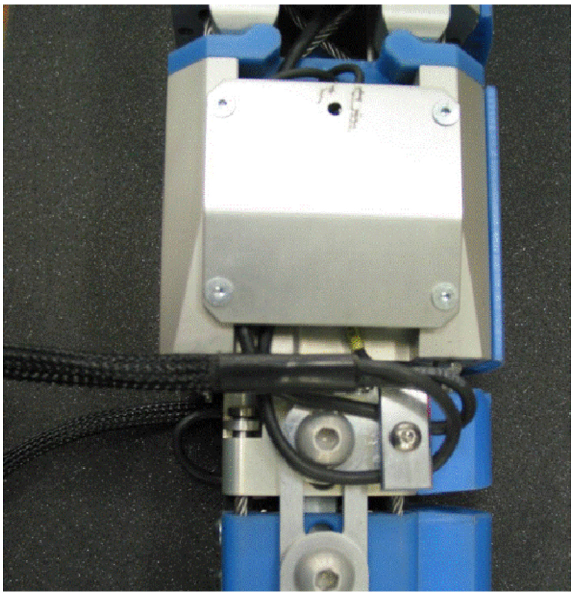

Figure 2: Off board cable clamp arrangement

ANTHROPOMETRY

Figure 3 shows the Flex-GTR from the rear identifying the knee joint position and the bone lengths next to a picture of the human right leg for orientation purpose. Also the co-ordinate system convention for automotive testing [5] is shown, with x –direction, forward away from the observer. Table 1 provides details of these dimensions and the component masses.

Table 1: Comparison of human leg to GTR

Length, C.G. Location [mm], and Mass [kg]	50th percentile male [6]	Flex-GTR
a) Thigh length	428	433
b) Leg length	493	495
C.G. location of thigh**	218	195
C.G. location of leg **	233	188
Total legform impactor mass	13.4	12.94
Thigh mass	8.6	7.16
Leg mass	4.8	5.78

** From the knee joint centre; Flex-GTR C.G values are estimates from CAD.

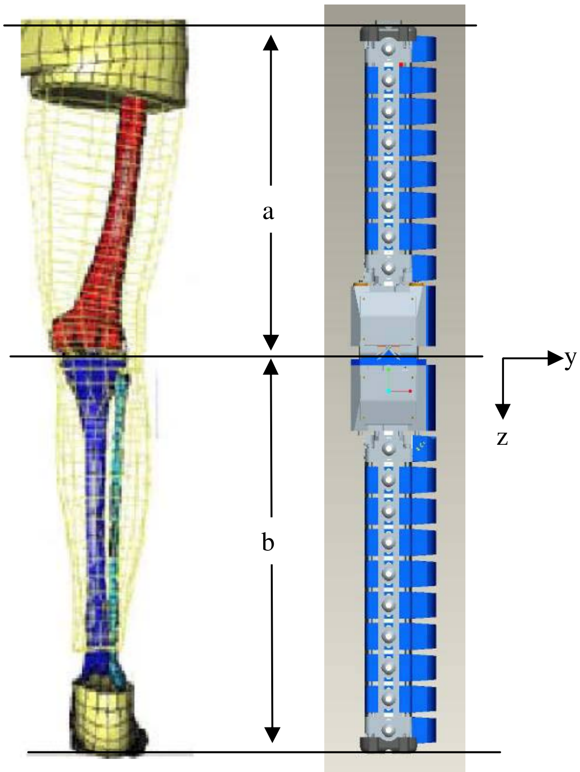

Figure 3: Human bone dimensions and Flex GTR

Figure 4 shows the position of ligament elongation sensors in a plan view of the tibia knee side (femur knee side removed). Refer to legend for identification.

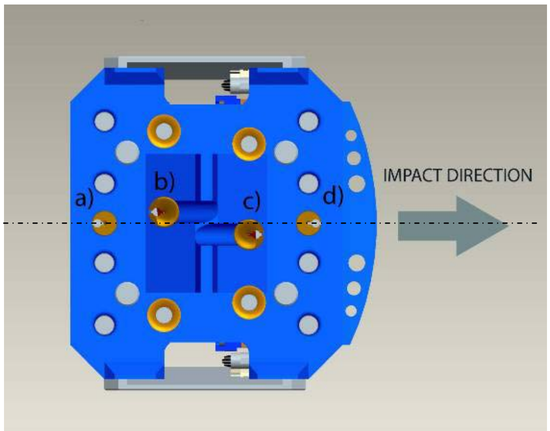

Figure 4: Ligament sensor positions in knee joint

a) Medial Collateral Ligament, MCL
b) Posterior Cruciate Ligament, PCL
c) Anterior Cruciate Ligament, ACL
d) Lateral Collateral Ligament, LCL

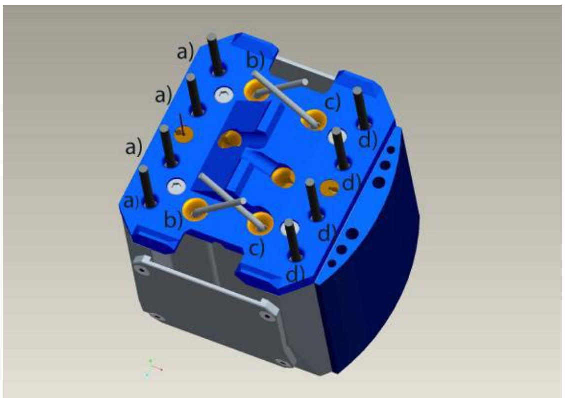

Figure 5: Ligament wire positions

Figure 5 shows the tibia knee block with ligament wires cut through to help identification.

INSTRUMENTATION

Standard Instrumentation

The standard instrumentation channels are listed in Table 2. The table also gives details on the senor vertical distance from the knee centre. Channel numbers are proposed for a standard sensor numbering for the Flex-GTR. To obtain control over the dynamic calibration deceleration pulse, an accelerometer was added to sensor list in the GTR version.

The strain gages on the bones, measuring bone bending moments in the impact direction ‘Y’ (X bending moment) were made into a half bridge configuration incorporating both the tension and compression sides of the bone in one channel, two resistors per each set of gages complete the full bridge. The bridge completion resistors and sensor identification (ID) chips are encapsulated in a PCB located on each bone. The completed full bridge configuration makes the output of the sensor insensitive to elongation due to tension in the bone and length variation due to thermal expansion and also increases the voltage output compared to application of single strain gages per the GT version.

The durability of the gage bonding was confirmed in a production test submitting the gages to 50 quasi-static deflections to check bonding process.

Table 2: Standard instrumentation and the sensor distance from the knee joint

Channel Number	Channel	Distance (mm)
1	Femur moment 3	297
2	Femur moment 2	217
3	Femur moment 1	137
4	LCL elongation	0
5	ACL elongation	0
6	PCL elongation	0
7	MCL elongation	0
8	Tibia moment 1	134
9	Tibia moment 2	214
10	Tibia moment 3	294
11	Tibia moment 4	374
12	Lower knee acceln.	47

Optional Instrumentation

FTSS was requested by JAMA to consider the addition of optional sensors for research and development purpose. The optional sensors are listed in Table 3. It is recommended to use the additional sensors only for research purpose and not to deviate from standard during tests for official purpose (future legislation or consumer rating) to assure proper test mass and inertial properties.

Figure 6 shows the optional sensor positions in the tibia. Item 1 in green shows the tri-axial accelerometer inside an Aluminium mount. Item 2 shows the single axis ay accelerometer mounted inside a dedicated impact segment. The segment y-accelerometer can be positioned at any of the inner segments if required. Item 3 shows the subassembly with a tri-axial linear accelerometer and the three angular rate sensors inside a mount and its dedicated impact segment. The optional sensors on the femur are the mirror image of that shown in Figure 6 and share the same components.

Table 3: optional sensors position and parameters

Sensor location	Measurement Parameter
Femur top	Acceleration ax, ay, az
Knee top	Acceleration ax, ay, az Angular rate ωx, ωy, ωz
Knee bottom	Acceleration ax, ay, az Angular rate ωx, ωy, ωz
Tibia bottom	Acceleration ax, ay, az
Segments	Acceleration ay

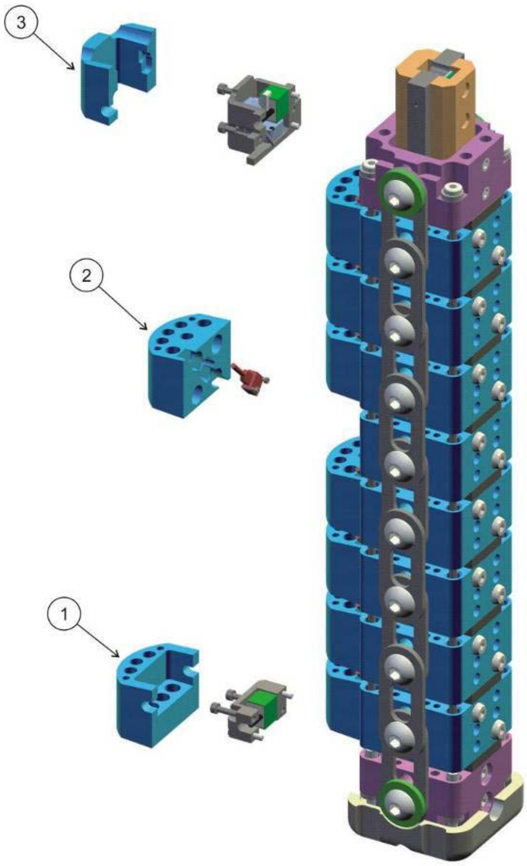

Figure 6: Optional sensors in the tibia

DATA ACQUISITION SYSTEMS (DAS)

Off-board data acquisition

To connect the instrumentation to a static laboratory data acquisition system, two umbilical cables are used, both handling 6 channels of instrumentation.
To enable a quick disconnect of the umbilical cable to off-board in case of damage, the Flex-GTR is equipped with two connector blocks installed on either side of the tibia knee. Each connector block handles 6 standard channels and each has additional capacity of 6 channels for optional instrumentation. It is possible to expand the channel count to a total of 24 channels with the use of the standard connector blocks.

The modular system makes it easy to exchange defunct sensors and damaged umbilical cables and also to change between on-board and off-board DAS. The connector block can be seen in the tibia section of the knee in Figure 7. The use of very small nano-D military spec connectors was essential to meet the space constraints.

On-board data acquisition systems

On-board data acquisition is an important addition to the Flex-GTR. Its use helps prevent cable damage particularly on violent rebound with the floor. Off-board umbilical cables could also affect free flight trajectory, therefore on-board DAS would make hitting the intended target more precisely, giving better control and improving repeatability. The use of on-board DAS can reduce operational costs.
The standard 12 channels could be expanded here with the advantage of not affecting free flight stability. The on-board DAS systems use the same connector blocks to interface between the sensors and the DAS.

Two on-board DAS systems were selected for the Flex-GTR prototype to offer customer choice. Both systems had to be very small and light weight to meet the challenging space limitations on the leg. At customer request, alternative DAS systems could be considered, if suitable in terms of mass and size.

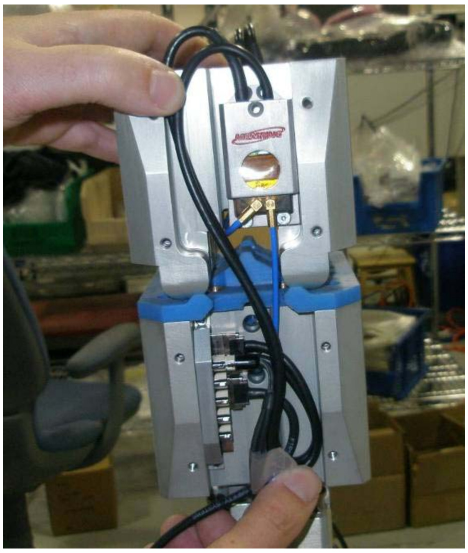

Figure 7: MESSRING M=BUS installation and connector block

<u>MESSRING M=BUS®</u> - The M=BUS® is a data acquisition system based on independent 6 channel data loggers (40x25x14)mm in size (without its aluminium housing). The units can be daisy chained together via a single coax cable ending in a terminator, which checks system integrity and signal quality. Two units were required for the Flex-GTR standard instrumentation and packaged on either side of the femur knee block, see Figure 7. Each logger is equipped with its own battery, allowing gathering data entirely wireless, even without external power supply. The system is equipped with a low friction disconnect fitting, which is located just below the knee. At launch, the disconnect fitting releases and the DAS starts to register data automatically. The units will record for

17 seconds. An external trigger defines t0. After the test, the cable is reconnected and the test data is downloaded to a PC. Time synchronisation of all channels is guaranteed over an integrated master and slave clock concept.

DTS SLICE - The DTS SLICE was under development at the same time as the Flex-GTR. The SLICE data recorder is a modular system built up from functional units by stacking modules of the required functionality. The Base SLICE contains the processor and memory; the Bridge SLICE's are stacked on top providing channel functionality, each Bridge SLICE handles 3 channels. The functional units are interconnected by integrated connectors for easy replacement (see Figure 8). Two super capacitors provide on-board power after disconnect allowing to operate for sufficient time. The super caps could be quickly charged for the next test but had a short record time (the 1 second), a battery will be considered for future use. Like the M=BUS system, there is a disconnect feature, which is reconnected to download test data. The DTS SLICE is triggered on disconnect and a tape switch can also be connected to establish t0.

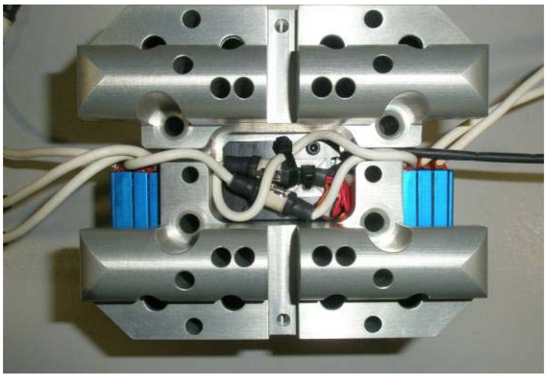

Figure 8: DTS SLICE installation

CALIBRATION

Method

Table 4 provides an overview of the complete Flex-GTR prototype calibration procedures, including the purpose of the test. Five calibration steps and a total of 12 tests are required.

Proposed calibration frequency for all steps:

- At manufacture
- Each year
- [After exceeding injury assessment reference value (IARV)]
- After failure of dynamic test
- After parts exchange

Additionally proposed frequency for step 4 and 5:

- [Each [1-10] tests]

Some of the figures are given between brackets as these are still under discussion and may change.

Table 4: Full calibration test procedure overview

Test	Test Nr	Purpose
Step 1 Bone Core	7	1) Control Bending Characteristic 2) Obtain individual Sensor sensitivity
Step 2 Fumur & Tibia Assembly	2	1) Control Bending Characteristics 2) Check ultimate bending moment
Step 3 Knee Assembly	1	1) Control Bending Characteristics 2) Control Ligament Elongation
Step 4 Dynamic stopper block	1	1) Control deceleration pulse dynamic test 2) Evaluate consistency of the stopper block
Step 5 FLEX-PLI Dynamic	1	1) Simple test to control output of sensors 2) Evaluate consistency of the assembly

The Flex-GTR calibration procedures were further developed: single gage calibration to establish gage sensitivity and roller supports under end pivots to rule out elongation and tension-compression loads on bone, femur, tibia and knee assemblies.

The dynamic calibration procedure was enhanced to induce higher loads to the level of loading in actual vehicle tests and closer to the injurious level. Also the fixture was enhanced to improve handling and reproducibility.

Bone calibration

Bone Calibration Fixture Design – To improve the accuracy of the gage response, each gage channel (tension and compression) is certified to establish the sensitivity of each gage in a separate test. To achieve this, a fixture was designed to load centrally over each gage over a pivot distance of 165mm.

Bone/Gage Calibration Procedure – To calibrate the bone, an Instron machine is used with a high definition load cell on the loading ram. The bone is mounted in the bone calibration fixture and is placed over the roller carriages on a hardened steel base. With a support distance of 165mm, the bone is loaded precisely in the middle between the end supports to 10 kN (325 Nm) at a rate of 10mm/min.

Femur and Tibia Calibration

The same fixture parts are used as the Flex-GT tibia and femur assemblies. The only changes made to these fixtures from the Flex-GT specification was the addition of roller cages under the pivots (to prevent linear friction when in bending) and update of the knee-to-leg interface.

Femur and Tibia Calibration Procedure – As with the bones, an Instron machine is used with a high definition load cell. The same base and roller cages are utilised (see Figure 9 and Figure 10). The femur is loaded on the forth segment from the knee and for the tibia the fifth segment. A piece of Neoprene protects the impact segment from the loading block.

Both assemblies are loaded to 3.76kN. The gage outputs are recorded to check functionality and the moment is calculated from the load multiplied by the known fixture arm.
Femur Moment $M_f = [F(N) / 2] \times 0.165(m)$
Tibia Moment $M_t = [F(N) / 2] \times 0.205(m)$

Figure 9: Tibia calibration fixture

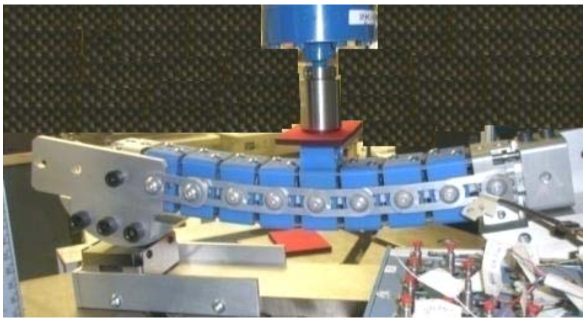

Figure 10: Tibia under load in calibration fixture

Knee Calibration

Similar to the leg assemblies, the same knee fixture design as that of the Flex-GT is used, except the leg interface has been changed and the end pivots sit on roller cages. The Flex-GT procedure had load cells on each support, whereas the Flex-GTR setup just uses one centre load cell on the loading ram.

Knee Calibration Procedure – The same set - up is used here as on the femur and tibia assemblies, except the loading is done using a 100 mm diameter profile (see Figure 11). The loading profile is aligned with the edge of the knee centre and loaded to 4 kN. Force and elongation are recorded for the MCL, ACL and PCL. In this test, the LCL is in compression and therefore LCL elongation is not recorded. The knee moment is calculated using the following equation:
Knee Moment $M_k = [F(N) / 2] \times 0.2(m)$

Figure 11: Knee during calibration under load

Dynamic Calibration

The whole leg assembly with flesh is calibrated on a new pendulum calibration fixture (see Figure 12). In order to achieve a similar load level as in a vehicle test, some changes were proposed to the Flex-GT procedure. The leg has been turned upside down so that the tibia is now at the top pivot end; a 5 kg mass was added to the femur end at the bottom. The leg is raised 15 degrees above the horizontal and released via a solenoid latch impacting the upper knee area onto the stopper block buffer. To obtain feedback from the test pulse, an accelerometer was placed in the knee to check repeatability. All 12 standard channels are recorded.

Stopper block calibration

This is a simple fixture (see Figure 13), comprising of a long cylindrical 50 mm diameter 7 kg mass dropped via a solenoid release through a linear bearing onto the stopper block. The impact edges of the mass are radiused to prevent damage to the stopper block. The drop height to the block is 200 mm (2 m/s). An accelerometer is attached to the top of the mass to record deceleration.

Figure 12: Dynamic calibration fixture

Figure 13: Stopper block calibration fixture

Prototype Calibration Results

Bone/Gage Calibration Results

An analysis of the results of three Flex-GTR prototypes from nine gages on three femurs and 12 gages on three tibias is shown in Table 5 and Table 6. The nonlinearity and hysteresis meet SAE J2570 [7] performance specification for transducers, which applies to rigid load cells.

Table 5: Femur bone strain gage calibration summary

Femur	Offset mV/V	Non linearity % Full scale	Hysteresis
Average	0.00007	0.27	0.71
St Dev	0.00036	0.07	0.29

Table 6: Tibia bone strain gage calibration summary

Tibia	Offset mV/V	Non linearity % Full scale	Hysteresis
Average	-0.0029	0.45	0.64
St Dev	0.0061	0.24	0.29

Femur and Tibia Assembly Calibration Results

Figure 14 shows the femur assembly prototype responses in the corridors that were established with the GT version. The Flex-GTR femur meets the Flex-GT calibration corridors. These corridors will be adopted for the Flex-GTR femur.

Figure 15 shows the tibia assembly prototype responses in the corridors that were established with the GT version. The Flex-GTR tibia meets the Flex-GT calibration corridors and will be adopted for the Flex-GTR tibia assembly.

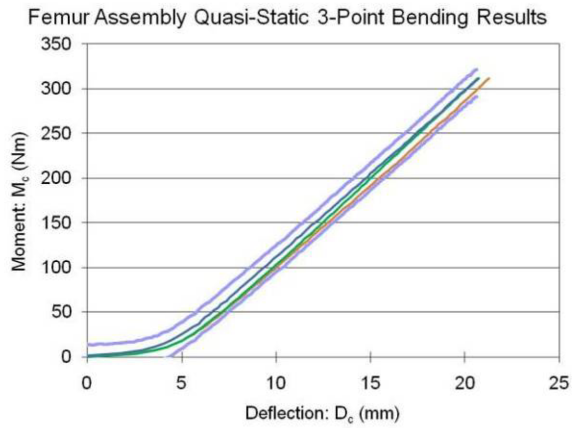

Figure 14: Femur assembly moment/deflection and corridor

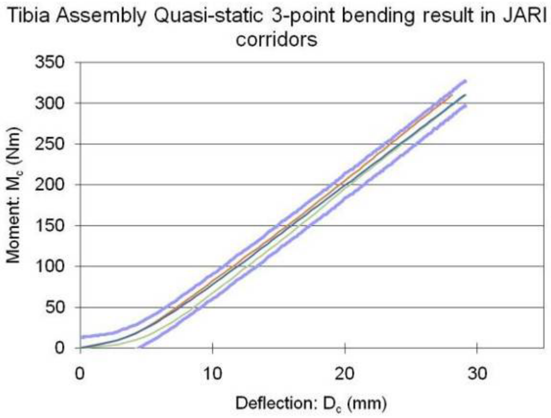

Figure 15: Tibia assembly moment-deflection and corridor

Knee Calibration Results

Figure 16 and Figure 17 show the Flex-GTR knee calibration results in the Flex-GT corridors. The Flex-GTR MCL ligament elongation vs. bending moment is below the lower Flex-GT corridor beyond 18 mm MCL ligament elongation. The reason for this is most likely due to the reduction in friction of the supports by introduction of the roller supports. A possible contributor is the reduction in friction due to the removal of the plastic wire sleeves on the Flex-GT knee and use of bronze bushings in the cruciate ligaments. These hypotheses can be examined by subjecting the GTR version to the Flex-GT calibration procedure without the roller supports. The ACL and PCL ligament elongations were slightly outside the Flex-GT corridors.

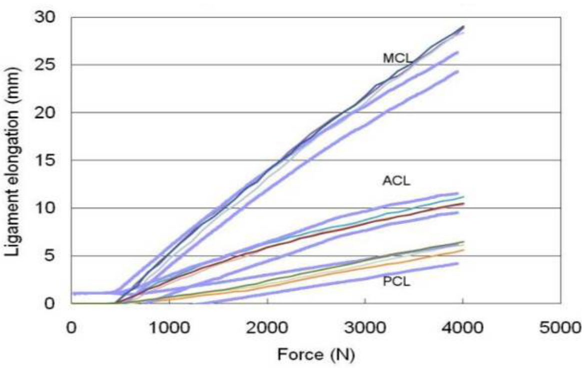

Figure 16: MCL, ACL and PCL elongation to force in the GT corridors

The MCL, ACL and PCL corridors need to be adapted to the new procedure and the Flex-GTR design.

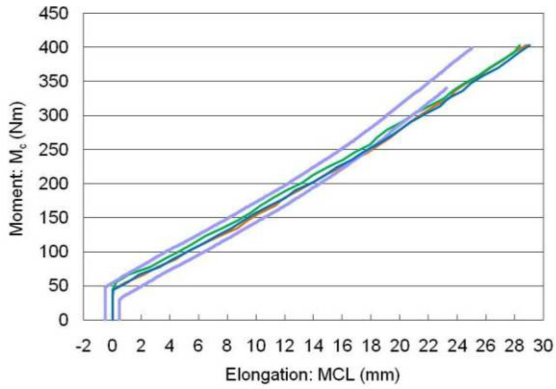

Figure 17: Knee moment to MCL elongation in GT corridor

Proposed Flex-GTR Knee calibration corridors

The responses of the 3 Flex-GTR prototypes were analysed and new corridors were developed. The corridors for the MCL were derived from the average of three prototype MCL responses. A second order polynomial was derived from the average. The upper and lower bounds were determined by addition and subtraction of 15 Nm from the average. The corridors and responses are shown in Figure 18.

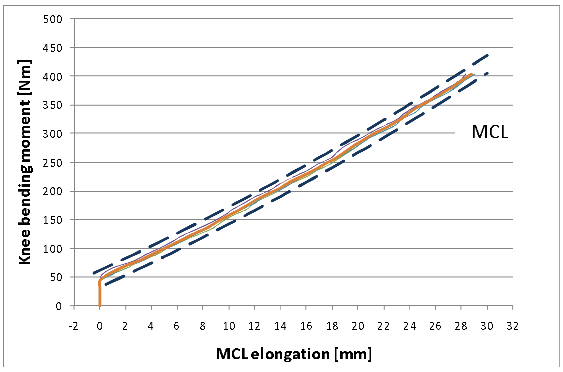

Figure 18: Knee moment to MCL elongation in proposed GTR corridor

The corridors for the ACL and PCL were derived with a similar method. The corridors for the ACL and PCL were derived from the average of three prototype ACL and PCL responses. Second order polynomials were calculated from the average. The upper and lower bounds were determined by addition and subtraction of 1 mm from the average. The corridors and responses are shown in Figure 19. To avoid possible conflicts, no MCL corridor is given for elongation-force (see Figure 16 and Figure 19).

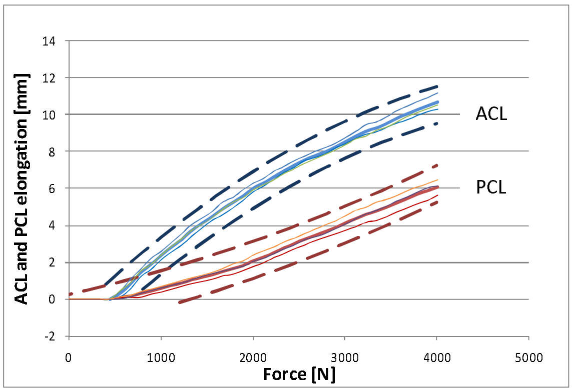

Figure 19: ACL and PCL elongation to force in proposed GTR corridors

Stopper Block Calibration Results

Before the start of the dynamic calibration matrix, the stopper block was tested to establish repeatability and reproducibility. The stopper block calibration was carried out on 3 different assembled stopper blocks to assess its response variation. Tests were repeated twice. Table 7 shows the results including proposed corridors. The reproducibility is good with 2.1% variation.

Table 7: Stopper block drop test results and propose corridor

	Acceln. [G]	Force [kN]
Block #1	56.2	3.859
	55.8	3.832
Block #2	54.5	3.743
	54.2	3.722
Block #3	52.7	3.619
	54.0	3.708
Average	54.6	3.749
St Deviation	1.2	
CV (%)	2.1	
Upper corridor		4.00
Lower corridor		3.50

Dynamic calibration

Table 8 shows the dynamic test matrix and the use of two stopper blocks to look at variation. The last 2 tests were known to have an inclination of 15.1° as opposed to 15°.

Table 8: Dynamic test matrix

Test Nr	DAS type	Stopper block
Test 1	Off board	block #1
Test 2	Off board	block #1
Test 3	Off board	block #1
Test 4	Off board	block #2
Test 5	MESSRING	block #2
Test 6	MESSRING	block #1
Test 7	MESSRING	block #2
Test 8	MESSRING	block #1
Test 9	MESSRING	block #1
Test 10	DTS	block #1
Test 11 (15.1°)	DTS	block #1
Test 12 (15.1°)	DTS	block #1

Results

The result of 12 dynamic tests are summarised in Table 9. The table shows the average, standard deviation, coefficient of variation (CV), the draft criteria and standard deviation divided by the criteria. The coefficient of variation is generally well below 3%, which is considered excellent. On tibia gage 3 of leg 3, there was a higher reading than expected. This was due to a fault on the gage, which had a linearity error of 2.5% and was not picked up during gage calibration as a problem. The ACL and PCL were higher than 3% variation; however the variation is larger due the small absolute output. The CV relative to the tentative injury assessment reference values (t-IARV), which are used in Paper Number 09-0145, is closer to 3% for both parameters. The variation of the knee peak acceleration was also higher. This is believed to be due to problems with one of the accelerometers.

Table 9: Summary dynamic calibration

GTR Dynamic calibration results	Peak Acceleration at Knee	Peak Moment @ Femur Gauge 1	Peak Moment @ Femur Gauge 2	Peak Moment @ Femur Gauge 3	Peak Moment @ Tibia Gauge 1	Peak Moment @ Tibia Gauge 2	Peak Moment @ Tibia Gauge 3	Peak Moment @ Tibia Gauge 4	Peak ACL Elongation	Peak MCL Elongation	Peak LCL Elongation	Peak PCL Elongation
Average	75.3	179	137	91.6	242	201	160	108	8.19	22.4	4.37	4.91
St.Dev	4.2	3.1	1.9	1.7	3.7	3.3	6.8	1.5	0.3	0.1	0.1	0.3
CV	5.6%	1.7%	1.4%	1.9%	1.5%	1.6%	4.3%	1.4%	3.7%	0.4%	2.3%	6.1%
t-IARV	-	-	-	-	318	318	318	318	12.7	20	-	12.7
St.Dev/ t-IRAV	-	-	-	-	1.2%	1.0%	2.1%	0.5%	2.4%	0.5%	-	2.4%

Preliminary dynamic calibration corridors

The results of the tests with three prototypes were analysed to derive draft dynamic certification corridors. The results of questionable tests were excluded from the database: the faulty accelerometer and one tibia strain gauge. The upper and lower limits are defined according to standard procedures: average measured values plus and minus 10 % or plus and minus two times the standard deviation, whichever gives the broadest corridor.

The final corridors shall be established after there are a minimum number of legs manufactured and delivered (typically at least 10). Also final certification parameters shall be established based on a large number of tests, conducted at a substantial number of different laboratories to account for lab-to-lab variations. Such process is often referred to as 'Round Robin Tests'. Typically, establishment of final corridors is part of the process for regulation of a dummy.

Table 10: Draft GTR dynamic certification corridors

GTR Dynamic calibration results	Peak Acceleration at Knee	Peak Moment @ Femur Gauge 1	Peak Moment @ Femur Gauge 2	Peak Moment @ Femur Gauge 3	Peak Moment @ Tibia Gauge 1	Peak Moment @ Tibia Gauge 2	Peak Moment @ Tibia Gauge 3	Peak Moment @ Tibia Gauge 4	Peak ACL Elongation	Peak MCL Elongation	Peak LCL Elongation	Peak PCL Elongation
Average	73.3	179	137	91.6	242	201	160	108	8.19	22.4	4.37	4.91
CV	3.3%	1.7%	1.4%	1.9%	1.5%	1.6%	2.0%	1.4%	3.8%	0.3%	1.8%	7.0%
Upper	80.6	197	150	101	267	221	172	119	9.0	24.6	4.8	5.4
Lower	66.0	161	123	82	218	181	141	97	7.4	20.2	3.9	4.4

The draft dynamic calibration corridors are given in Table 10. The improvement of the CV of the knee acceleration and tibia 3 moment can be observed in this table. All prototype responses, except some of the ones that were excluded, are well within the proposed corridors.

PROTOTYPE MASSES

The segment masses of the three prototypes are shown in Table 11. The Flex-GT segment masses are given for comparison. The three versions of the GTR prototypes were all very close together, however the knee segment mass of the off-board version was about 0.1kg lower. To account for the umbilical cable mass, 0.1 kg was added to the knee segment mass of the off-board DAS version in the table. Table 11 also gives a proposal for segment mass tolerances.

Table 11: Mass comparison of GT and three GTR prototype leg configurations

Part	GT Off board	GTR Off board	GTR On board	Proposed GTR Tolerance
Femur	2.43	2.43	2.44	±0.05
Knee	4.18	4.28*	4.28	±0.1
Tibia	2.61	2.63		±0.05
Flesh	3.72	3.59		±0.2
Total	12.94	12.93	12.94	±0.4

*including 0.1 kg cable to off-board DAS

DISCUSSION AND CONCLUSIONS

Three Flex-GTR prototypes were manufactured in three different versions. The equivalence of the GTR version with previous GT version in terms of mechanical response and mass has been demonstrated. The Flex-GTR test results proved to reproduce the Flex-GT responses closely at the calibration level.

The concerns over the GT version observed during evaluation and the design review were all successfully addressed.
Improvements were made to ligament elongation measurement sensitivity and the twisting moment in the knee was removed. On-board data acquisition was integrated and many additional handling improvements were also made.

The linearity and hysteresis of the gages were established not to exceed 1 % of full scale. This was a design target, but it was uncertain this could be achieved due to the highly flexible nature of the bones.

The Flex-GTR dynamic calibration was updated with respect to the GT version with the target of higher loading closer to vehicle test condition and better reproducibility. This has been achieved and new certification corridors have been proposed.

It may be expected to introduce up to 24 channels for on-board data acquisition. Possibly some modularity of the electrical cables will be lost to keep within the mass tolerances.

It can be concluded that all design targets have been well met and three prototypes are ready for further evaluation by stakeholder groups worldwide.

The difference of the response of the Flex-GTR MCL corridor may be further investigated by subjecting the GTR version to the Flex-GT test condition.

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