A New Development in Pedestrian Safety: The FLEX-PLI GTR LS-DYNA® Model

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Abstract

The lower limb is one of the most frequently injured body regions in crashes involving pedestrians. A biofidelic FLEXible-Pedestrian Legform Impactor Global Technical Regulations (FLEX-PLI GTR) device has been developed under directions of the Flex-PLI Technical Evaluation Group (FLEX-PLI TEG). First Technology Safety Systems (FTSS) is developing a LS-DYNA model in addition to the hardware counterpart. The FLEX-PLI GTR is the latest development and successor of the earlier GT version.

The FLEX-PLI GTR device has three regions: femur, knee and tibia. Outer rubber and neoprene foam layers represent the skin and flesh. The femur and tibia regions are segmental to achieve flexible bending behavior representing human like responses during pedestrian crashes. The central bone cores of the tibia and femur have bending moment measuring capabilities at several locations. The knee region has ligament elongations measuring capabilities to be used as injury criteria in regulations.

This paper documents the development and dynamic validations of the FTSS FLEX-PLI GTR LS-DYNA model. The model geometry and inertia properties are obtained from available drawings and hardware. The model connectivity and structural integrity are inspected by experiments and verified against hardware. The model material properties are implemented from material test data. The model is then validated against dynamic calibration test for FLEX-PLI assembly without outer skin, and a full legform test against a flat rigid impactor (called inverse test). The femur and tibia bone bending moments and knee ligament elongations from the model output are compared to test data to evaluate model performance and injury predictability.

The FTSS FLEX-PLI GTR LS-DYNA model revealed very promising performance in all validation cases and can be potentially used in future pedestrian safety regulations. The model has a 0.85 micro second time step and was found to be very cost effective (in terms of CPU times) and reliable for pedestrian safety simulations.

Introduction

Pedestrian safety has posed new challenges and serious concerns in traffic accidents involving pedestrians and vehicles in recent years. The lower limb was found to be the most frequently injured body region with AIS 2 to 6 level injuries in 32.6% of cases worldwide.

In 1998, the European Enhanced Vehicle-Safety Committee proposed a test procedure to assess protection to the lower extremity of a pedestrian during a collision [1]. A legform Impactor composed of rigid long bones was utilized in this procedure. The Japan Automobile Research Institute (JARI) and the Japan Automobile Manufacturer Association, Inc. (JAMA) have been developing a biofidelic flexible pedestrian legform Impactor (FLEX-PLI) since 2002 [2]. As opposed to a legform impactor with rigid bone parts, the FLEX-PLI is more biofidelic especially for its long bone parts, which have human-like bending characteristics [3]. The FLEX-PLI also provides extended injury assessment capabilities, 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 FLEX-PLI hardware performance. Another objective of the FLEX-TEG is to assess 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 FLEX-TEG activities by conducting technical evaluation tests on the FLEX-PLI. The JAMA and JARI have continued to improve and upgrade FLEX-PLI, and in 2007 the 5th version, called Type GT (FLEX-GT) was produced. After the settlement of the FLEX-TEG, the FLEX-PLI GT was evaluated and improved its performance, and the final 6th version, type GTR (FLEX-GTR), was agreed by the FLEX-TEG members in April 2008 [4].

The objective of this paper is to present the development and evaluation of the FLEX-PLI GTR LS-DYNA model, the development of which is supported by a consortium comprised of auto makers.

FLEX-PLI GTR Model

The FLEX-PLI GTR LS-DYNA model v1.0beta is shown in Figure 1 and its hardware counterpart is shown in Figure 2. The FLEX-PLI GTR device has three major regions: femur, knee and tibia (Figure 1). These regions are covered with rubber and neoprene foam layers representing the skin and flesh of the device. Fundamental structures for the femur and tibia regions are constructed segmental with bone cores at the center to achieve bending flexibility representing human like responses during pedestrian crashes. The knee region is comprised of two knee blocks representing condyles like a human knee. Springs and cables are used to replicate the ligaments of the knee.

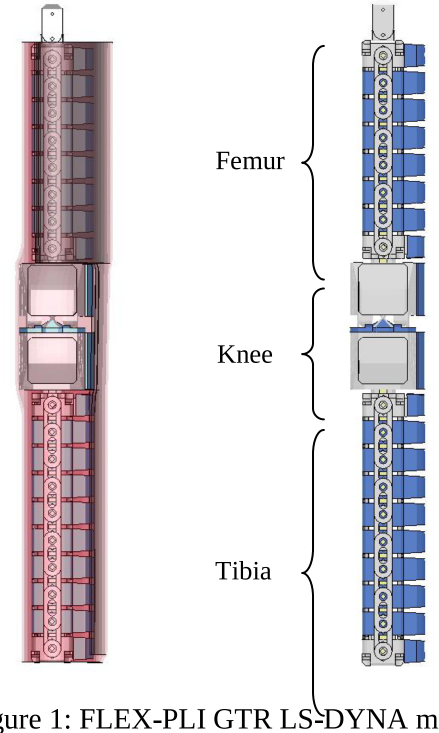


Figure 1: FLEX-PLI GTR LS-DYNA model

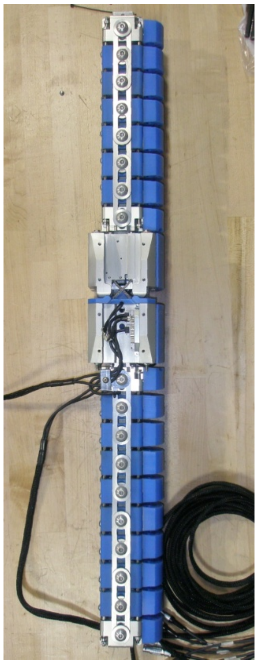


Figure 2: FLEX-PLI GTR hardware without skin

The model geometry and inertia properties are obtained from available drawings and detailed inspection of the physical impactor. The model connectivity and structural integrity are inspected by experiments and verified against hardware.

The mesh size in the model was developed to achieve sufficient accuracy at minimal CPU cost. The minimum mesh size of deformable parts was limited by imposing a 0.85 microsecond time step. The total element count is around 188K with deformable elements limited to 124K.

The FLEX-PLI GTR model v1.0beta was developed using LS-DYNA version 971 R2 [rev. 7600.1224]. The future version will be the FLEX-PLI GTR 1.0production release and will be tested using LS-DYNA version 971 R4.2.1.

Bone Core:

The femur and tibia bone cores are made of fiberglass reinforced plastic (FRP) material in the physical device. An appropriate material model is developed to be used for the bone core model. Strain gauges are used at top and bottom surface of the bone core to measure bending moments in the bones at several locations in the femur and tibia regions (Figure 3). Local section force outputs were used to model the strain gauges.

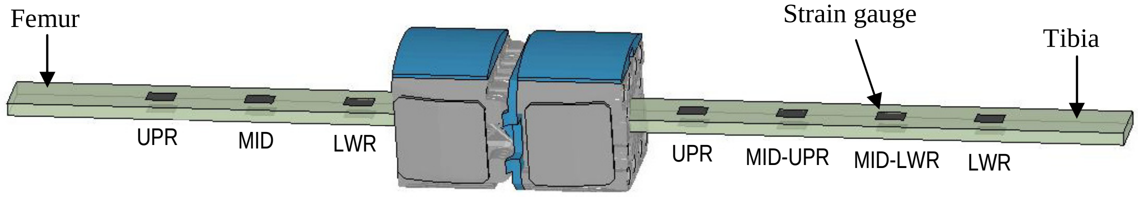


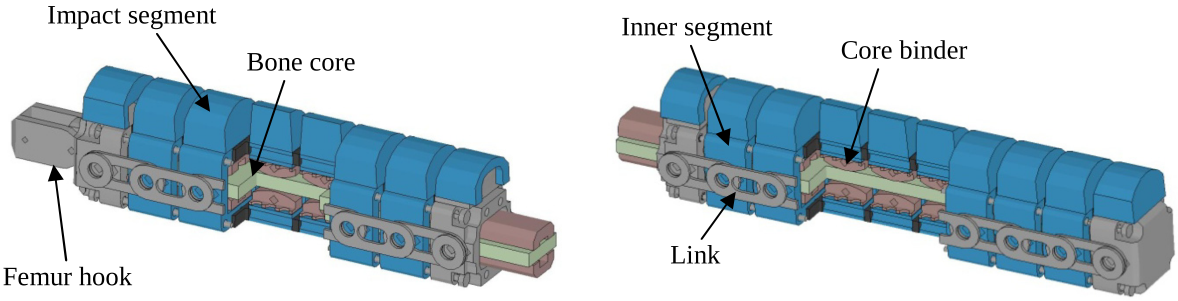
Figure 3: FLEX-PLI GTR bone cores

Femur and tibia:

Figures 4a and 4b show femur and tibia assemblies and a partial section cut through them. These regions are structurally similar with the only differences being the length and number of segments. The bone core lies in the middle of square housings (known as inner segments) which are chained together by links down their flanks. Additional deformable nylon pieces known as impact segments are attached to inner segments and function as a load path during impact. The stopper cables which limit the maximum bending of the bone cores are modeled explicitly to behave in the same way as the physical device. Rubber buffers are glued to the inner segments to avoid direct contact between the inner segments. Appropriate material models are used for all the deformable components in the femur and tibia regions.

Knee:

The FLEX-PLI GTR knee model is shown in Figure 5. The knee has two blocks or condyles, one attaching to femur and the other attaching to the tibia. The condyle surface on the tibia block has nylon material to reduce friction and to avoid metal to metal contact.



(a) Femur (b) Tibia

Figure 4: FLEX-PLI GTR femur and tibia models

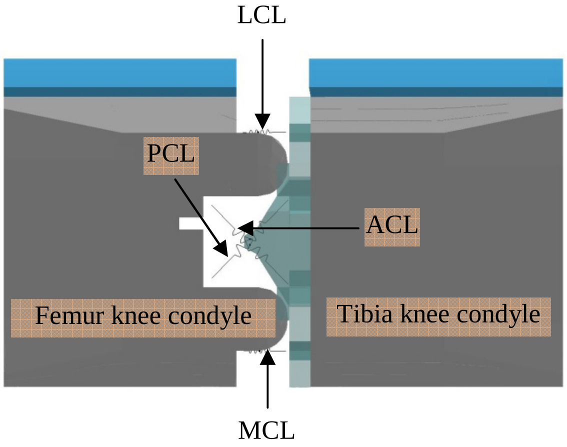


Figure 5: FLEX-PLI GTR knee model

Four kinds of ligament cables, ACL (Anterior Cruciate Ligament), MCL (Medial Collateral Ligament), PCL (Posterior Cruciate Ligament) and LCL (Lateral Collateral Ligament) are modeled as weak spring elements to represent potentiometers to measure knee ligament elongations at ACL, MCL, LCL and PCL locations. Deformable springs and cables in the knee area are modeled to achieve appropriate knee behavior similar to the physical impactor. Appropriate material models are used for all the deformable components in the knee region.

Flesh:

The flesh of the FLEX-PLI GTR model is comprised of several layers of neoprene and rubber sheets as shown in Figure 6. Appropriate material models are developed from quasi-static and dynamic material tests to model layers of the neoprene and rubber sheets.

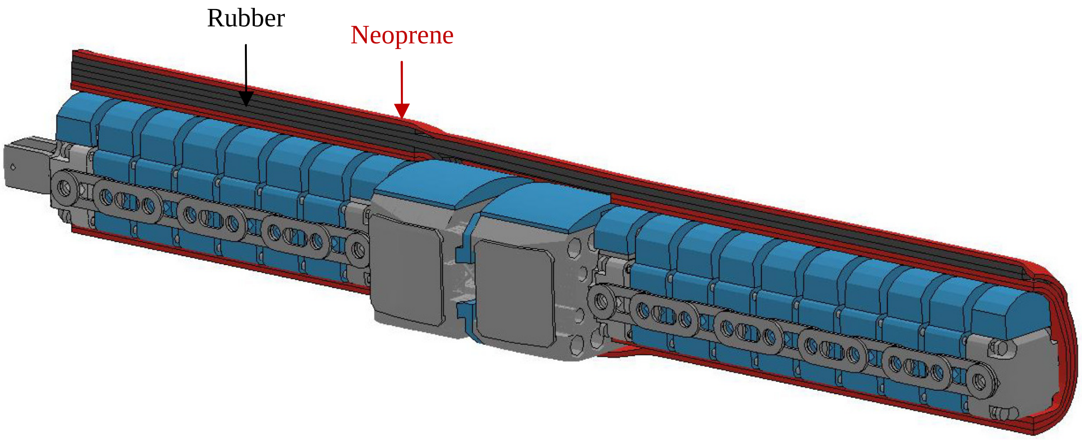


Figure 6: FLEX-PLI GTR flesh model

Model Validations

Model Assembly dynamic calibration validation:

The whole internal structure of the FLEX-PLI GTR was assembled from the calibrated femur, tibia and knee models and a model of the test jig was created according to the dynamic calibration test specification. As shown in Figure 7, the lower end of the tibia is connected to the jig via a pin joint and the leg is released to freely swing down from a position 15 degrees above horizontal. Additional ballast mass was attached to the femur end to reach injury threshold levels.

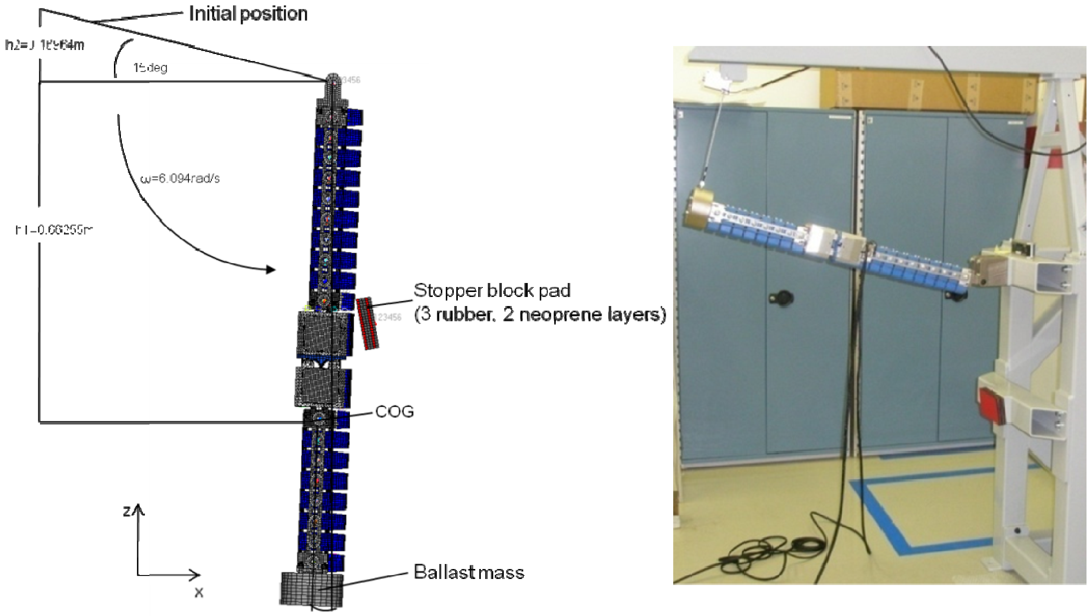


Figure 7: Assembly dynamic calibration setup

Calibration requirements are defined by peak value of knee MCL, PCL, ACL, and LCL elongations, three femur bending moments and four tibia bending moments. The graphs in Figures 8 through 10 show that the FLEX-PLI GTR model satisfies all calibration requirements and also predicts the shape of output over time with great accuracy.

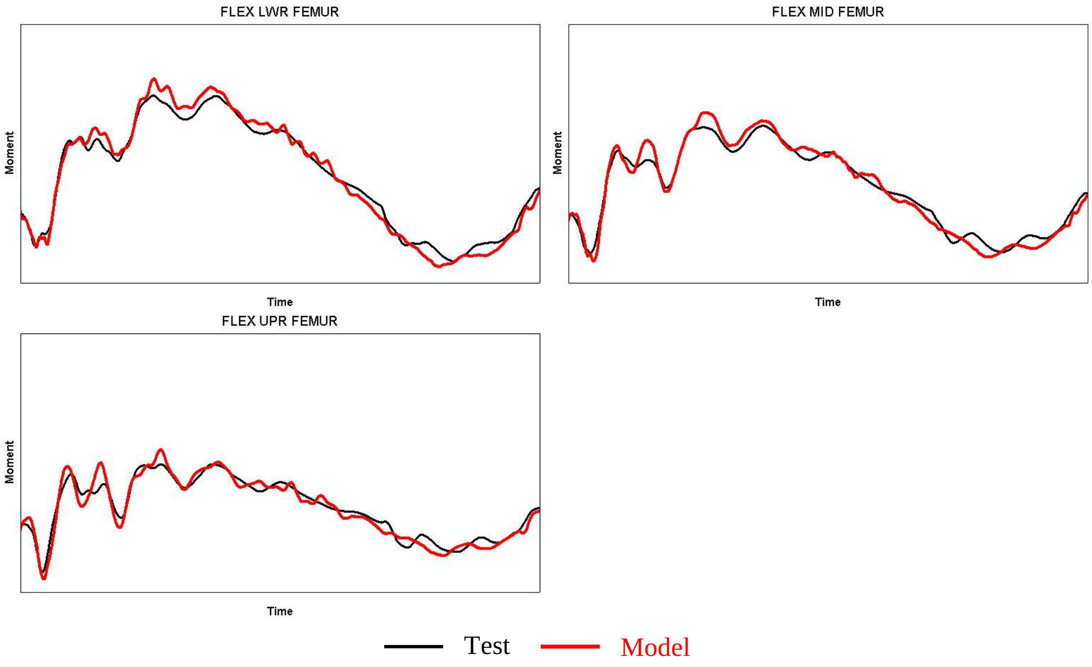


Figure 8: Assembly dynamic calibration femur moment results

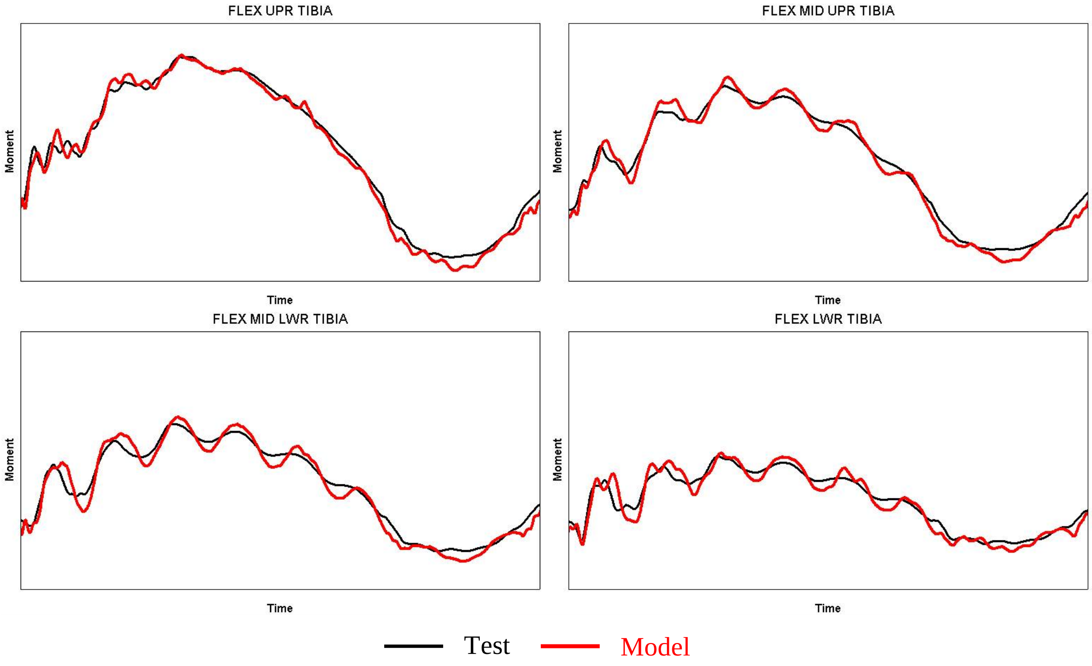


Figure 9: Assembly dynamic calibration tibia moment results

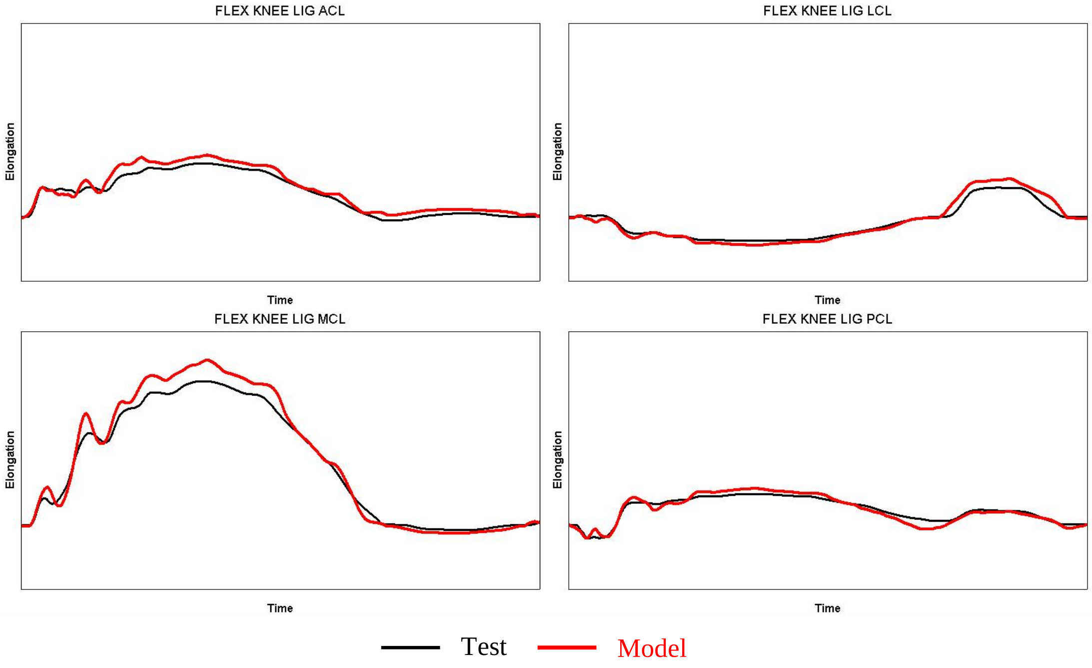


Figure 10: Assembly dynamic calibration knee ligament elongation results

Full legform validation:

The FLEX-PLI GTR model was also evaluated for the performance at full legform level. A rigid flat impactor was used to impact the leg at different locations at an initial speed of 8 m/s. The physical legform was hung at the femur attachment hook with a quick release mechanism. The release provided quick detachment of the leg after initial impact contact. Three such cases (LC1, LC2, and LC6) are presented here as shown in Figure 11.

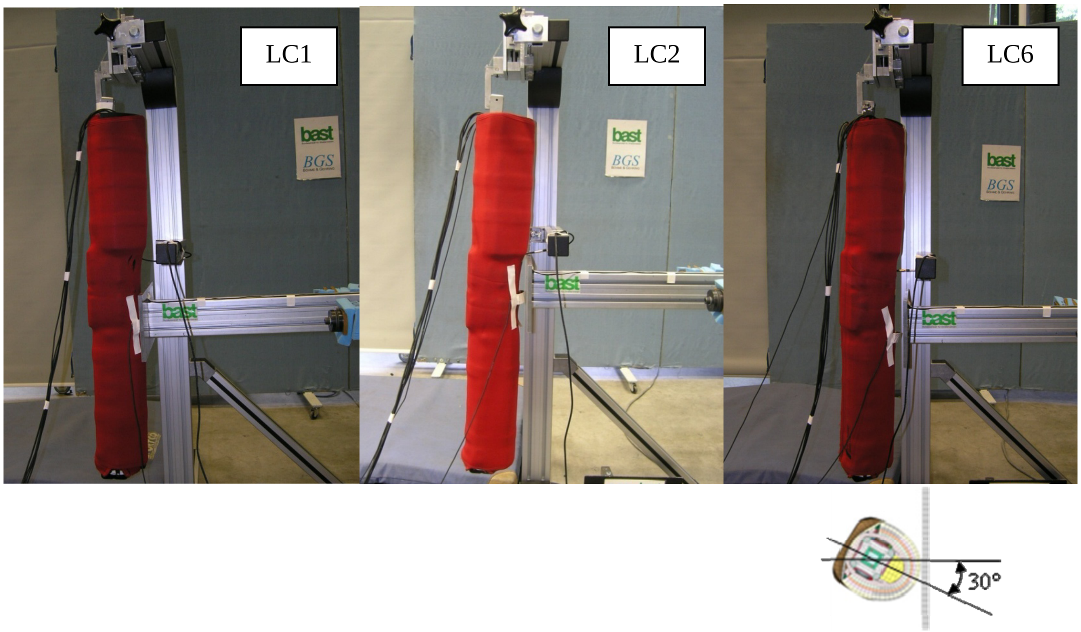


Figure 11: Full legform validation test setups

The model was set up to mimic these tests and ligament elongations and bending moments are compared with test data. Results of the simulation output for the bending moments and knee ligament elongations compared to test data for case LC1 is presented in Figures 12 through 14. Similar level of correlation was achieved for the other two load cases, LC2 and LC6.

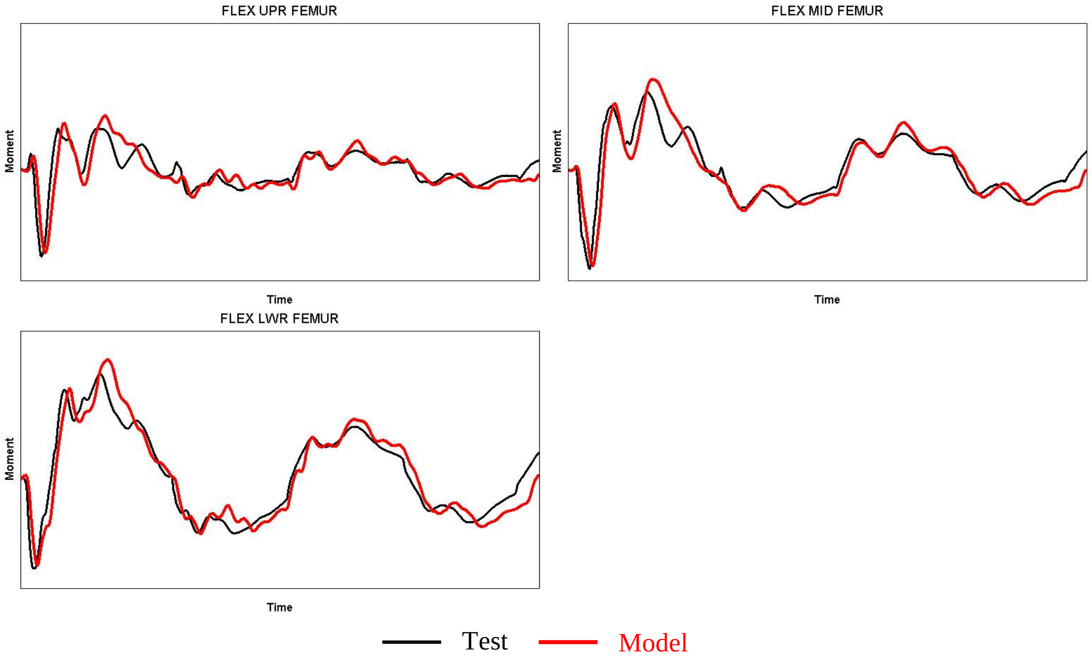


Figure 12: Full legform femur moment results for case LC1

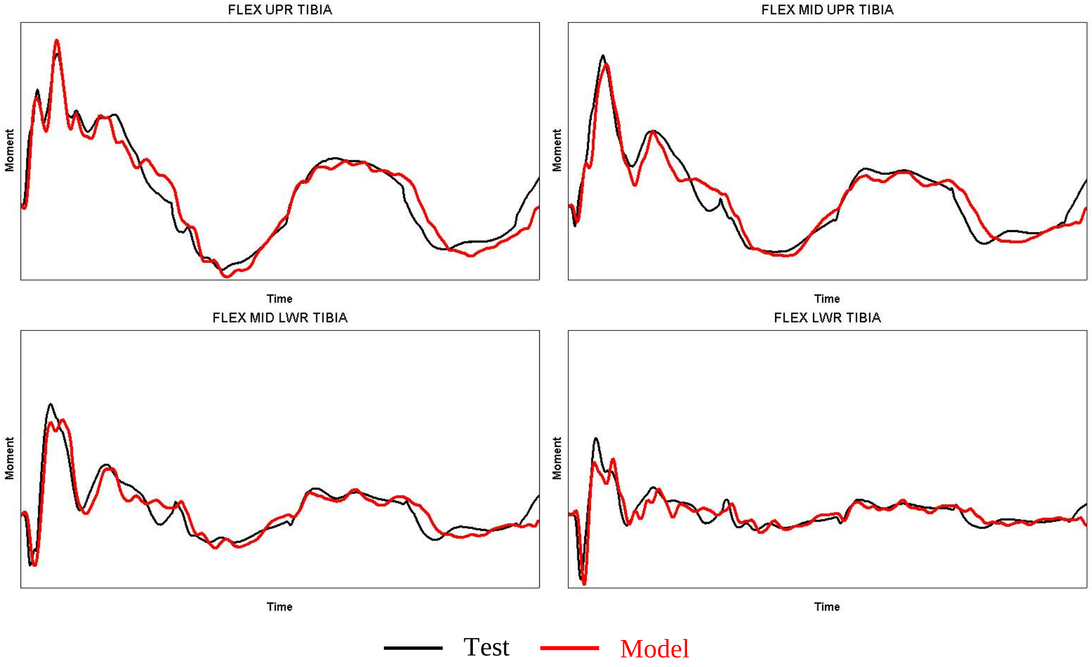


Figure 13: Full legform tibia moment results for case LC1

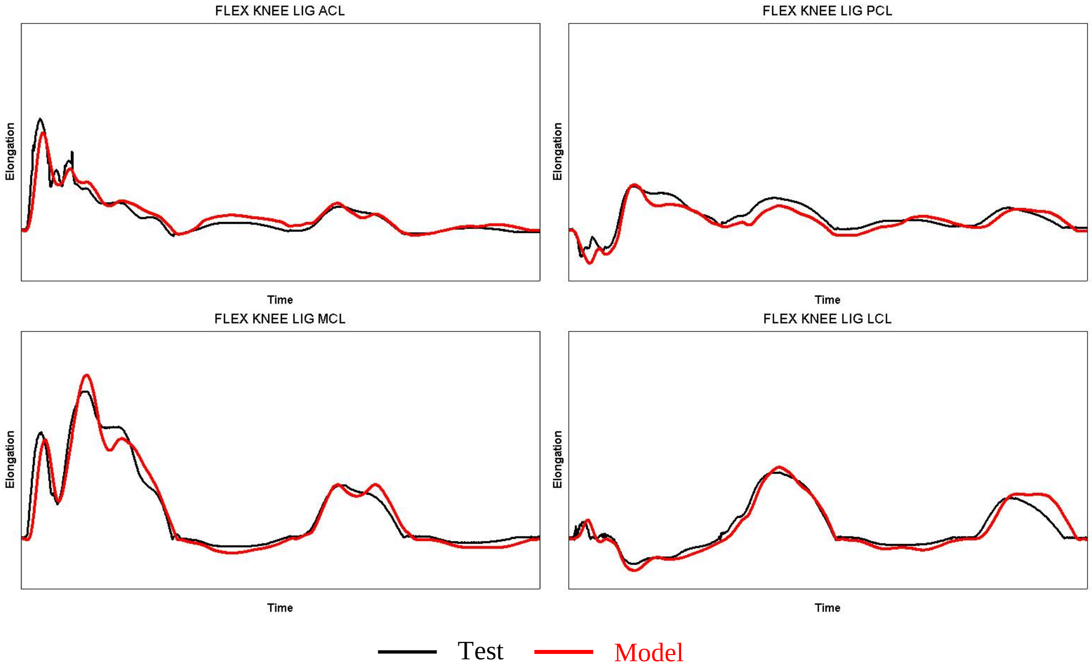


Figure 14: Full legform knee elongation results for case LC1

Results

The maximum peak values for the highest tibia moments and MCL knee elongations between tests and model are compared in Figures 15 and 16, respectively. Most of the peak value errors fell within 15% for all the validation cases. The overall performance of the model was very good in predicting peak values and overall curve shape.

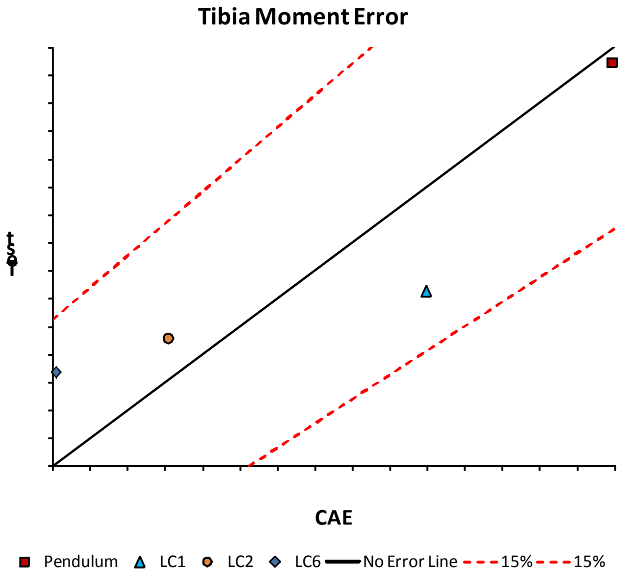


Figure 15: Peak of highest tibia moment error in CAE simulation compared to test values

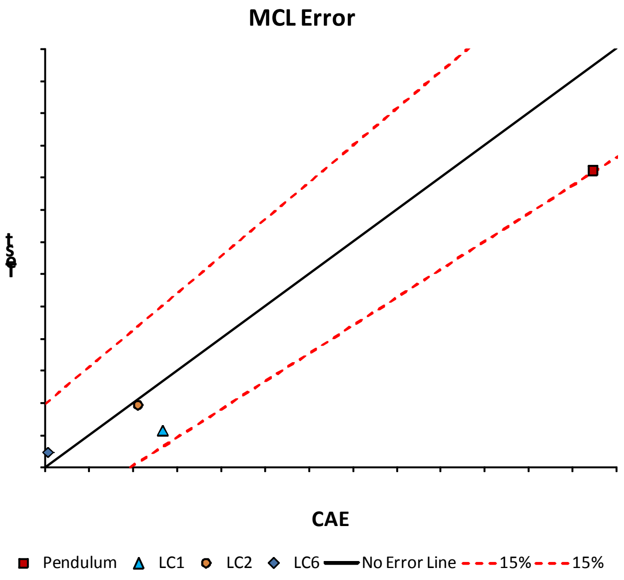


Figure 16: Peak MCL Error in CAE simulation compared to test values

Conclusions

The following conclusions can be drawn from the current study:

- A FLEX-PLI GTR model is being successfully developed within an industry consortium
- Excellent correlation of injury values were achieved for all validation cases
- The model has an efficient CPU time

Acknowledgment

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