Review of the Flexible Pedestrian Legform Impactor Technical Evaluation Group (Flex-TEG) Activity

- Summary -

- ver.111021-

November 3rd, 2011
Japan

Outline

1. Biofidelity
2. Performance/Injury Criteria
3. Benefit
4. Durability
5. Reproducibility and Repeatability
6. Vehicle Countermeasures
Outline

1. Biofidelity
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1. Biofidelity

◆ Component Level
  • Leg/Thigh bending stiffness
    ➢ Within the human corridor (TEG-021)
  • Knee bending stiffness
    ➢ Much closer to the human corridor compared to that of the EEVC PLI (TEG-021)
1. Biofidelity, contd.

◆Full Assembly Level
  • Evaluated by Accident Reconstruction Tests
    ➢ Showed possibility of good injury assessment ability of Flex-PLI. (TEG-022)
  • Evaluated by using Human and Flex-PLI FE Model
    ➢ Good correlation between Human and Flex-PLI (extended rubber spec.) was observed
      regarding Tibia bending moment and MCL elongation outputs. (TEG-096)
    ➢ + 50 mm higher impact height to a car, compared to human one, was selected by
      compensating for the lack of the human upper body part in the specification of Flex-PLI.
      (TEG-032)

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2. Performance/Injury Criteria

◆ Discussions
  • Detailed discussions were made in the Flex-TEG.

◆ Conclusions of Flex-TEG
  • Finally, Flex-TEG made conclusions as follows (TEG-127):
    - Tibia: 340 Nm
    - MCL: 22 mm
    - ACL/PCL: seek guidance to GRSP
  • Besides, Flex-TEG proposed to do not use rebound phase test data for car evaluation (TEG-130)

◆ Information: GRSP proposals
  • After the GRSP discussions, following values were proposed:
    - Tibia: 340 Nm, 380 Nm (relaxation zone)
    - MCL: 22 mm
    - ACL/PCL: 13 mm
    - Does not use rebound phase test data
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3. Benefit

◆ Estimations
  • Lower limb protection level provided by Flex-PLI was estimated by JAMA-JARI using NHTSA method (GRSP/2006/7). (TEG-049)

◆ Results
  • Following number of injured person can be decreased by introduction of Flex-PLI in U.S..
    ➢ 2,438 person (in pedestrian - passenger vehicle (PV) accidents)
    ➢ 359 person (in pedestrian - large truck vehicle (LTV) accidents)
4. Durability

◆ Evaluations
  • A lot of durability tests were conducted by FlexTEG members in many countries. (TEG-037, TEG-063, TEG-112, TEG-113)

◆ Results
  • No serious issues occurred.
  • NHTSA would like to conduct additional durability test against a car which has poor performance in EEVC PLI test.
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5. Reproducibility and Repeatability

◆ Evaluations
  • A numerous revaluation tests regarding reproducibility and repeatability of Flex-PLI were conducted by Flex-TEG members in many countries. (TEG-021, TEG-034, TEG-036, TEG-038, TEG-039, TEG-043, TEG-045 Rev.1, TEG-047, TEG-051 Part1-3, TEG-063, TEG-064, TEG-071, TEG-072 Rev.1, TEG-087, TEG-089, TEG-093, TEG-094, TEG-105, TEG-112, TEG-113)

◆ Results
  • Repeatability and reproducibility of Flex-PLI is accepted by Flex-TEG members.
1. Biofidelity
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6. Vehicle Countermeasures

◆ Evaluations
  • Various comparison tests, Flex-PLI and EEVC PLI, were conducted by Flex-TEG members in many countries. (TEG-035, TEG-036, TEG-091, TEG-112, TEG-113)

◆ Results
  • The comparison results were not revealed concrete trend between the Flex-PLI test results and EEVC PLI test results because specifications and measurement items are differed by Flex-PLI and EEVC PLI.
Thank you for your attention!

Appendix

Summary, results and important slides from all of the past Flex-TEG documents relevant to the agenda items of the IG PS2

November 3rd, 2011
Japan
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1. Biofidelity
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# 1. Biofidelity

- List of Relevant TEG Documents -

<table>
<thead>
<tr>
<th>Doc. #</th>
<th>Affiliation</th>
<th>Version</th>
<th>Summary</th>
</tr>
</thead>
</table>
| TEG-021 | JARI        | Flex-GT | - Dynamic 3-point bending test of the thigh and leg of Flex-GT  
- Dynamic knee bending test of the knee of Flex-GT  
- Comparison with human response corridors  
**Results**  
- Flex-GT thigh and leg bending responses fell within human response corridors  
- Flex-GT knee bending stiffness was higher than human response corridor but lower than that of TRL-LFI |
| TEG-022 | JARI        | Flex-GT | - Kinematics comparison between Flex-G, Flex-GT and human FE model  
- Reconstruction test of 2 full-scale PMHS tests using Flex-GT  
- Reconstruction test of 2 car-pedestrian accidents using Flex-GT  
**Results**  
- Flex-GT knee response was closer to that of human compared to Flex-G  
- Reconstruction of both PMHS tests and pedestrian accidents showed a possibility that Flex-GT has a good injury assessment capability |
| TEG-032 | JAMA-JARI   | Flex-GT | - Correlation study using a human FE model and a Flex-GT FE model  
**Results**  
- Impactor height of 75 mm provided best correlation by compensating for the lack of the upper body |
| TEG-096 | JAMA-JARI   | Flex-GTR| - Development of Flex-GTR FE model  
- Analysis of injury measure correlations between human and Flex-GTR models  
**Results**  
- Human-Flex-GTR correlation using 18 simplified vehicle models resulted in correlation coefficient of 0.90 for tibia and 0.55 for MCL  
- Extended rubber yielded better tibia correlation |
Long Bones
Bending characteristics (Thigh)

Flex-G and Flex-GTα

Flex-GTα (Thigh) has slightly smaller bending stiffness than that of Flex-G.

→ The difference gives Flex-GTα a better injury assessment ability than that of Flex-G.

Long Bones
Bending characteristics (Leg)

Flex-G and Flex-GIα

Flex-GIα (Leg) has slightly smaller bending stiffness than that of Flex-G.

→ The difference gives Flex-GIα a better injury assessment ability than that of Flex-G.
Knee

Bending characteristics (Knee)

Flex-G, Flex-GTα, and TRL-LFI

Improved knee bending limit (+30%)

Flex-GTα (Knee) has slightly greater bending stiffness than that of Flex-G (but not stiffer than that of TRL-LFI).

→ The difference gives Flex-GTα a better injury assessment ability than that of Flex-G.

Comparison

Flex-G bending is the severest of the three.
PMHS Test Data

<table>
<thead>
<tr>
<th>Car</th>
<th>Test No.</th>
<th>Impact Speed (m/s)</th>
<th>Gender</th>
<th>Age (year)</th>
<th>H_T (cm)</th>
<th>W_T (kg)</th>
<th>Thigh</th>
<th>Knee</th>
<th>Lower extremity injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>T3</td>
<td>8.9</td>
<td>Male</td>
<td>48</td>
<td>170</td>
<td>62</td>
<td>-</td>
<td>-</td>
<td>FX (fibula and tibia)</td>
</tr>
<tr>
<td>T4</td>
<td></td>
<td>8.9</td>
<td>Male</td>
<td>58</td>
<td>185</td>
<td>85</td>
<td>-</td>
<td>-</td>
<td>FX (fibula and tibia)</td>
</tr>
<tr>
<td>C3</td>
<td>Y1</td>
<td>8.3</td>
<td>Male</td>
<td>70</td>
<td>167</td>
<td>68</td>
<td>-</td>
<td>-</td>
<td>FX (fibula and tibia)</td>
</tr>
</tbody>
</table>

C1: Ishikawa et al. (1993); C3: Schroeder et al. (2000)

H_T: Total body height, W_T: Total body weight, FX: Fracture

Test Conditions

Reconstruction test conditions on PMHS tests

<table>
<thead>
<tr>
<th>Car</th>
<th>Impact speed (m/s)</th>
<th>Impactor</th>
<th>Impact location (mm) * horizontal</th>
<th>vertical (HKR**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>8.9</td>
<td>Flex-GTα</td>
<td>R 200</td>
<td>537</td>
</tr>
<tr>
<td>C3</td>
<td>8.3</td>
<td>Flex-GTα</td>
<td>R 200</td>
<td>bumper center height</td>
</tr>
</tbody>
</table>

* Estimated from literature (C1: Ishikawa (1993), C3: Schroeder (2000)).
** HKR: Knee height relative to car.

Discussion and Conclusions on Part 2

- In this study, a reconstruction test on PMHS tests was conducted.
- It has a possibility that the Flex-GTα has good injury assessment ability on PMHS tests.
- However, 1) cannot change length, mass and bending stiffness of impactor for each test, besides, 2) cannot know strength of each pedestrian leg and knee, therefore, it has a high limitation on this evaluation methodology.
Car-Pedestrian Traffic Accident Data

<table>
<thead>
<tr>
<th>Car No.</th>
<th>Model year</th>
<th>Impact speed (km/h)</th>
<th>Braking</th>
<th>Gender</th>
<th>Age (year)</th>
<th>H (cm)</th>
<th>W (kg)</th>
<th>Lower extremity injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car 2</td>
<td>1997</td>
<td>30</td>
<td>Activated</td>
<td>Male</td>
<td>70</td>
<td>150</td>
<td>45</td>
<td>FX (femur) *</td>
</tr>
<tr>
<td>Car 3</td>
<td>1994</td>
<td>25</td>
<td>Activated</td>
<td>Male</td>
<td>70</td>
<td>170</td>
<td>48</td>
<td>FX (tibia) *</td>
</tr>
</tbody>
</table>

* First contact side of lower extremity. ** Secondary contact side of lower extremity.

Estimated Test Conditions

<table>
<thead>
<tr>
<th>Car</th>
<th>Impact speed (m/s)</th>
<th>Impactor</th>
<th>Impact location (mm) *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>horizontal</td>
</tr>
<tr>
<td>Car 2</td>
<td>8.3</td>
<td>Flex-GTα</td>
<td>L 100</td>
</tr>
<tr>
<td>Car 3</td>
<td>6.9</td>
<td>Flex-GTα</td>
<td>L 410</td>
</tr>
</tbody>
</table>

** HKB: Knee height relative to car.

Reconstruction Test Results (Car: Car2)

• Flex-GTα recorded a high bending moment (close to fracture level) on its thigh at around 20 ms.

Discussion and Conclusions on Part 3

• In this study, a reconstruction test on car-pedestrian traffic accidents was conducted.
• It has a possibility that the Flex-GTα has good injury assessment ability on car-pedestrian traffic accidents.
• However, 1) cannot change length, mass and bending stiffness of impactor for each test, besides, 2) cannot know strength of each pedestrian leg and knee, therefore, it has a high limitation on this evaluation methodology.
**Computer simulation models**

**Examination of Simplified Car Model**

*Overview - oblique front projection drawing*

**Specifications of the simplified car models (total 18 types)**

*Based on design of experiment method, L18 orthogonal table is utilized*

**Measurement points of the human model and the Flex-GT prototype model**

*In this study, the bending moment of Flex-GT prototype model is obtained from analysis of those measured bending moments. As for the Flex-GT prototype model, the impact height at base +50 mm and base +75 mm is also calculated.*

**Results: Relationship between the Human model and Flex-GT prototype model**

*Upper body effect (1): Lifting up the lower limb*

*Upper body effect (2): Inhibition of thigh behavior*

**Upper body effect (2): Angle of the thigh, leg, and knee (511, example)**

*Human model, L1 base*
TEG-096
Flex-GTR-prototype and Developed FE model (Overview)

Flex-GTR-prototype

- Femur (Flexible)
- Knee (Ligament restraint system)
- Tibia (Flexible)

FE Model

- Femur (Flexible)
- Knee (Ligament restraint system)
- Tibia (Flexible)

Tibia bone core 3-point bending validation

Knee 3-point bending validation

Overall validation under the Simplified Car Impact
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<tbody>
<tr>
<td>TEG-035</td>
<td>JAMA</td>
<td>Flex-GT</td>
<td>- Tentative injury thresholds for Flex-GT Results - Human tibia bending moment: 312 – 350 Nm, human knee bending angle: 18 – 20 deg (MCL failure) for 50% injury probability - Converted Flex-GT tentative threshold range: 299 – 337 Nm for tibia bending moment, 18 – 20 mm for MCL elongation</td>
</tr>
<tr>
<td>TEG-076</td>
<td>JAMA</td>
<td>Flex-GT</td>
<td>- Review of proposed MCL failure threshold - Human-Flex-GTR correlation using simplified vehicle models including high bumper vehicles - Incorporation of muscle tone effect taken into account with the threshold for TRL-LFI - New proposal of 23 mm for Flex-GTR MCL elongation Results - Human-Flex-GT knee response correlation analysis using FE human, Flex-GT and simplified vehicle models including high bumper vehicles - The correlation function converted human MCL elongation of 15-17 mm to 19.3-21.9 mm of Flex-GT MCL elongation - Proposed MCL elongation threshold for Flex-GT: 23 mm (taking into account 10% increase in knee stiffness due to muscle tone)</td>
</tr>
<tr>
<td>TEG-077</td>
<td>JAMA</td>
<td>Flex-GT</td>
<td>- Review of proposed tibia bending moment threshold Results - Average value of proposed tibia bending moment threshold is 318 Nm</td>
</tr>
</tbody>
</table>
## 2. Performance/Injury Criteria

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<th>Summary</th>
</tr>
</thead>
</table>
| TEG-078 | BASI | Flex-GT | - Correlation study between Flex-PLI and TRL-LFI showed no comparable assessment of ACL/PCL protection.  
  **Results**  
  - 12.7 mm ACL/PCL elongation limit for monitoring purpose only proposed based on one paper presenting 2 human data.  
  - First estimation of MCL elongation limit: 18-20 mm, muscle tone already taken into account. |
| TEG-084 | JAMA | Flex-GTR | - Injury probability function for human tibia fracture.  
  - Data scaling options.  
  **Results**  
  - Different data scaling options resulted in the range of bending moment of 312 – 397 Nm for 50% fracture probability. |
| TEG-095 | JAMA | Flex-GTR | - Proposal for bending angle threshold (50% probability) of human MCL failure.  
  **Results**  
  - For injury timing definition options from Ivarsson et al., the use of Definition B (time of maximum moment) is recommended based on the injury distribution in the experiment (1/8 complete MCL failure, 6/8 partial MCL failure, 1/8 no injury).  
  - Proposed human knee bending angle threshold: 19 deg. |

### Additional Notes

- Proposal for Flex-GTR injury thresholds based on human thresholds for 50% injury probability and human vs Flex-GTR correlation analysis.  
  **Results**  
  - Estimated human threshold for 50% injury probability: Tibia bending moment = 361 Nm, MCL elongation = 15.9 mm.  
  - Human – Flex-GTR correlation function developed using the Flex-GTR FE model incorporating an extended rubber flesh.  
  - Converted Flex-GTR thresholds for 50% injury probability: Tibia bending moment = 380 Nm, MCL elongation = 21 mm. |

- Human tibia fracture probability function using scaled data.  
  - Conversion to Flex-GTR threshold (50% risk) using human vs Flex-GT correlation analysis and Flex-GT vs Flex-GTR correlation.  
  **Results**  
  - 6 data from Nyquist et al. scaled to German anthropometric data. 10% increase of peak moment due to filtering, and cumulative normal distribution method, resulted in 265 Nm for 50% probability of tibia fracture.  
  - Converted Flex-GTR tibia bending moment threshold: 260 – 301 Nm.
2. Performance/Injury Criteria
- List of Relevant TEG Documents -

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<thead>
<tr>
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<th>Affiliation</th>
<th>Version</th>
<th>Summary</th>
</tr>
</thead>
</table>
| TEG-127 | Flex-TEG    | Flex-GTR| -Generic trace of Flex-TEG injury criteria discussion
|         |             |         | - Different studies resulted in different threshold proposals
|         |             |         | - As a result of Flex-TEG discussion, a consensus was reached as to the threshold values for the Flex-GTR: Tibia bending moment = 340 Nm, MCL elongation = 22 mm
|         |             |         | - Seek for a guidance from GRSP as to the injury thresholds for ACL/PCL |
| TEG-128 | ACEA        | Flex-GTR| - Example car test results (time histories of all injury measures)
|         |             |         | - In one example test, maximum PCL elongation occurred in the rebound phase
|         |             |         | - Proposal to ignore injury measures during and after the rebound phase |
| TEG-129 | ACEA        | Flex-GTR| - Review of literature on ACL/PCL injury threshold
|         |             |         | - Bhalla et al.: Two tests, a likely ACL failure at 17.8mm and 12.7mm shear displacement, NOT ACL elongation
|         |             |         | - Kajzer et al.: One ACL avulsion at 23mm shear displacement
|         |             |         | - Teresinski et al.: ACL failure occurred after MCL rupture
|         |             |         | - Criteria without a sufficient data base is not advisable |
| TEG-130 | BASst       | Flex-GTR| - Car test (1 one-box, 2 sedans, 1 SUV) and dynamic certification test
|         |             |         | - Correlation analysis between TRL-LFI and Flex-PLI
|         |             |         | - Geometric analysis of correlation between Flex-PLI shear displacement and ACL elongation
|         |             |         | - Proposal for ACL/PCL injury thresholds
|         |             |         | - Conversion from Shear Displacement: 8 mm ACL elongation
|         |             |         | - Conversion from MCL elongation: 10 mm ACL elongation
|         |             |         | - Proposal: ACL = 13 mm (mandatory), PCL = 13 mm (monitoring) |
**Flex-GT Tentative Threshold Values**

### Human value

<table>
<thead>
<tr>
<th>Body regions</th>
<th>Human value</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg (Tibia)</td>
<td>BM (312 - 350 Nm)</td>
<td>Kriegan et al., 2004; NIST; INF GRIP/S32</td>
</tr>
<tr>
<td>Knee (MCL)</td>
<td>BA (90 - 20 deg)</td>
<td>Ivarsion et al., 2004; BA (20 deg); INF GRIP/S32</td>
</tr>
</tbody>
</table>

AM50: 50 percentile of American male
BM: Bending moment, BA: Bending angle, EL: Elbow, SD: Shoulder displacement.

**Convert: Human value >>> Flex-GT value**

<table>
<thead>
<tr>
<th>Human</th>
<th>Human Model</th>
<th>Flex-GT Model</th>
<th>Flex-GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibia bending moment (Nm)</td>
<td>$H_{max}$</td>
<td>$H_{max}$</td>
<td>$F_{GT}$</td>
</tr>
<tr>
<td>350</td>
<td>365</td>
<td>337</td>
<td>299</td>
</tr>
<tr>
<td>312</td>
<td>375</td>
<td>367</td>
<td>294</td>
</tr>
</tbody>
</table>

Assumption: $F_{GT} = 0.9875$ or $F_{2} = 12.325$ (from regression curve)

<table>
<thead>
<tr>
<th>Human</th>
<th>Human Model</th>
<th>Human Model</th>
<th>Flex-GT Model</th>
<th>Flex-GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee bending angle (deg)</td>
<td>$H_{max}$</td>
<td>$F_{GT}$</td>
<td>Knee MCL</td>
<td>$F_{GT}$</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>18</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Assumption: $H_{max} = F_{GT} = 0.9875$ (from human model output)

Convert human tolerance values to the Flex-GT ones (use correlation ratio/formula)

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**References (referred contents)**

**Injury Risk Curve for Mid-Leg**

<table>
<thead>
<tr>
<th>Human value</th>
</tr>
</thead>
</table>

**Injury Risk Curve for Knee (Bending)**

| Human value |

---

**References (referred contents)**

**Injury Risk Curve for Knee (Bending)**

| Human value |

**Proposed Injury Threshold for Tibia bending: 350 Nm**

---

**Injury Risk Curve for Knee (Bending)**

| Human value |

**Proposed Injury Threshold for Knee bending: 20 deg**

---

**References (referred contents)**

**Injury Risk Curve for Knee (Bending)**

| Human value |

---

**References (referred contents)**

**Injury Risk Curve for Knee (Bending)**

| Human value |

---

**References (referred contents)**

**Injury Risk Curve for Knee (Bending)**

| Human value |
Current Proposal

**Effect of Muscle Tone**

- Lloyd and Buchanan (1996) – Muscles are activated to support about 15% of static varus-valgus loads. Muscular contribution increased with increasing magnitude of VV moments.
- Lloyd and Buchanan (2001) – For volunteers, average contribution to varus is 17 ± 9.7% and to valgus is 10 ± 6.3% of externally applied moment.

The effect of muscle tone has been addressed in Lloyd and Buchanan (1996, 2001) from the Journal of Biomechanics.

**Estimation of MCL Failure Threshold**

Flex vs. Human model (INCLUDING high-bumper vehicles)

Parameter study was carried out using simplified car models.

Flex-GT MCL elongation thresholds will be 19-22 mm when the correlation obtained using the FE simulation results with simplified vehicle models INCLUDING those representing high-bumper vehicles is used.

Effect of Muscle Tone

- Flex-GT MCL elongation thresholds: 19.3-21.9
- Based on the correlation obtained using the FE simulation results with simplified vehicle models INCLUDING those representing high-bumper vehicles.
- Effect of muscle tone: 10% in varus bending.
- Flex-GT MCL elongation thresholds taking into account the effect of muscle tone: 21.2-24.1 mm (average: 22.7 mm)

**Proposed Flex-PLI MCL elongation threshold: 23 mm**

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**EGT077**

Current Proposal

**Flex-GT Tentative Threshold Values**

<table>
<thead>
<tr>
<th>Joint</th>
<th>Tentative Threshold Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg ( Tibia)</td>
<td>BM (212 – 335 Nm), Kerrigan et al., 2004</td>
</tr>
<tr>
<td>Knee (MCL)</td>
<td>BM (20 – 30 Nm), BM (30 – 50 Nm), Kerrigan et al., 2004</td>
</tr>
</tbody>
</table>

Based on the SAE paper by Nyquist et al. and the ICRASH paper by Kerrigan et al., the threshold values were set at 299 and 337Nm.

New Proposal

Injury threshold for Flex-PLI Tibia bending moment (JAMA proposal): **318Nm**

Average value of the two threshold values shown in this presentation.
**ACL/PCL injury thresholds**

- Therefore, it appears more appropriate to stick with PMHS knee shearing results evaluated by Bhalla et al (2003) that state a tolerance of at least 12.7 mm for knee shear displacement of the 50th male, even though the timing of injury could not be clearly identified.

![Image of knee shearing tests](image)

**MCL injury threshold**

- Why injury definition B (injury occurrence at the time of maximum moment) and not definition A (injury occurrence at time of first peak)?
- Why no use of the dynamic response corridor (16.20 ± 12.6 ± 15°) but just the average value?

![Image of MCL injury threshold](image)

**Conclusions / Proposal:**

1. Using the previously made observations, the following, first estimation could be done:
   - Flex-GT ACL/PCL elongation upper performance limit: 12.7 mm

2. In the next step, a more detailed correlation study between shearing displacement and cruciate ligament elongation could be done, using an appropriate amount of simulations by simplified test rigid and/or real car tests, representing the current vehicle fleet.

Anyway, as the cruciate (ACL) ligament injuries are expected to occur in conjunction with other (MCL) injuries, the common injury mechanisms have to be better understood.

Therefore, and for the comparatively low relevance of real pedestrian accidents, for the time being, a threshold of 12.7 mm ACL/PCL elongation could be proposed as performance limit for monitoring purposes only.

![Image of MCL injury threshold](image)

**TEG-084**

**Scaling Factor used in Kerrigan et al. (2004)**

**Data Scaling**

Equation 1 shows that the stress arising in a bone modeled as a linearly elastic beam is proportional to the moment applied and the cross sectional geometry of the bone. To provide a basis for comparing responses, it is common to assume that cross sections are geometrically similar and thus can be scaled to a reference geometry. Thus, the bones in this study are scaled to a reference geometry using a scale factor (L / L_ref)

- Assume geometric similarity between the leg specimens.
- Tibia bending moment was scaled using the following equation:
  \[ \frac{L}{L_{ref}} = \frac{M}{M_{ref}} \]

where
- \( L_{ref} \): Reference tibia length
- \( M \): Measured tibia bending moment
- \( L_{scaled} \): Scaled tibia bending moment

**2. Scaling Factor used in Kerrigan et al. (2004)**

**Scale Factors for Option-1**

- **Length Scale Factor Comparison**
  
  ![Graph of scale factors](image)

- **Option-1 yields average scale factor identical to average height scale factor while allowing individual variation**

**Option 1**

- Determine reference length such that the average length scale factor coincides with the average height scale factor.
- Assume that overall tibia length distribution should correlate well with overall height distribution.
- Assume the same ratio of tibia plateau height to tibia length as used by Kerrigan et al. (2004).
- Reference tibia length (for measuring Kerrigan data): 397.4 cm
- Reference tibia plateau height (for measuring Nyquist data): 483.5 cm

**Option 2**

- Use unscaled data.
- Average height of the specimens (176.6 cm) is close to 50th percentile

Reanalyse injury risk curves using the same statistical procedures as those used by Kerrigan et al. under these two options.

**2. Scaling Factor used in Kerrigan et al. (2004)**

**Injury Risk Curves for Original, Option-1 and Option-2 Datasets**

- **Options**
  - Option-1: Modified Scaling
  - Option-2: No Scaling

![Graph of injury risk curves](image)
**TEG-095**

**Original Proposal (TEG-035)**

<table>
<thead>
<tr>
<th>Flex-GT Tentative Threshold Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Threshold</strong></td>
</tr>
<tr>
<td>MCL</td>
</tr>
<tr>
<td>Tibia</td>
</tr>
<tr>
<td>Femur</td>
</tr>
</tbody>
</table>

**Questions Raised at 7th Flex-TEG**

- Originally proposed threshold for human MCL (TEG-035)
  - 18 deg based on Ivarsson et al. (2003)
  - 20 deg based on Konosu et al. (2001)
  - No single value proposal

- Proposed for Human MCL Threshold
  - No data duplication between Konosu et al. (2001) and Ivarsson (2004) — simple average can be justified to take into account as many data as possible
  - Data scaling does not affect injury risk functions for the MCL (bending angle) in both Konosu et al. and Ivarsson et al.
  - Use of Injury Definition B in Ivarsson et al. is more appropriate to reasonably represent failure of the MCL

- 95% CI curves in Ivarsson et al. should not be used because the estimated risk function provide the best fit to the data

- Proposed bending angle threshold for human MCL: 19 deg (virtually the same as previously proposed value)
- Flex-GTR MCL elongation threshold needs to be investigated based on the response correlation between the Flex-GTR and human lower limb

**TEG-097**

**Proposed Human Thresholds**

- Proposed Threshold for Human MCL
  - Knee Bending Angle: 19 deg

- Proposed Threshold for Human Tibia
  - Tibia Bending Moment: 361 Nm

**MCL Injury Measure Conversion**

- Tibia Bending Moment for Human Model: 361 Nm
- MCL Elongation for Human Model: 0.835 • 19 deg = 15.9 mm

**Human - Flex-GTR Response Correlation**

- Better correlation for tibia bending moment with extended flesh rubber
- Use results for extended flesh rubber to convert injury thresholds from human to Flex-GTR

**MCL Threshold Conversion**

- Converted Flex-GTR MCL Elongation: 19.2 mm
**TEG-097**

### Effect of Muscle Tone

gtr Preamble

These studies suggest a bending limit is the range of [2.5 to 24] for knee protection. The recent group determined that a bend to the upper limit (24) of this range should be considered, and not the upper limit. The degree of risk varies in [2.5 to 24] with the lower stiffness of the subject, and the lack of ability of the impact forces to be absorbed in the knee area if part of the impact force is not distributed by the involvement of human long bones. For these reasons, a bending limit of 13 was selected for this gtr.

Lloyd and Buchanan (2001)

For volunteers, average contribution to varus is 17 ± 9.1% and to valgus is 10 ± 6.3% of externally applied moment

**Flex-GTR MCL threshold incorporating effect of muscle tone:** 19.2 mm * 1.1 = 21.1 mm

---

### Proposal for Flex-GTR Injury Threshold

- Correlation functions derived from data NOT INCLUDING high bumper vehicles were used for threshold conversion
- Correlation functions with an extended flesh rubber were used for significantly improved correlation for the tibia bending moment
- Converted thresholds were 19.2 mm for MCL, and 381.7 Nm for Tibia
- Incorporation of muscle tone effect yielded the MCL elongation threshold of 21.1 mm

**Proposed elongation threshold for Flex-GTR MCL:** 21 mm

**Proposed bending moment threshold for Flex-GTR tibia:** 380 Nm

---

**TEG-098**

### Calculation of Maximum Tibia BM

**Flex-GTR Tibia Bending Moment** = \[1.11 \times (0.9977 \times \text{Human Tibia Bending Moment} - 12.32)\]

**Flex-GTR BMmax** = 0.9977 \times 264.9 - 12.32 = 252 Nm

Increase of Flex-GTR BMmax values compared to Flex-GTR BMmax:
- 41 ± 1.47%, 42 ± 1.33%, 43 ± 1.67%, 44 ± 1.56%

**Means** of Flex-GTR BMmax compared to Flex-GTR BMmax measured were 11% (Flex-GTR and Flex-GTR readings within ACEA/SANS pain protocol on Flex-GTR evaluation)

---

### Calculation of Maximum Tibia BM

**Flex-GTR Tibia Bending Moment** = \[1.11 \times (0.9977 \times \text{Human Tibia Bending Moment} - 12.32)\]

**Flex-GTR BMmax** = 1.11 \times (0.9977 \times 264.9 - 12.32) = 278.7 Nm

- Maximum deviation of tibia value from mean value within inverse tests:
  - 7.66%
- (Comparison to Tibia A)

**Nine inverse tests with Flex-GTR:**
- Three with S6N6, S6N2, S6N3 each, at 60 km/h

**Upper Performance Limit (ULP) = Flex-GTR BMmax** = 1.11 \times 0.9977 \times 264.9 = 259.3 Nm

**Lower Performance Limit (LPL) = Flex-GTR BMmax** = 1.11 \times 0.9977 \times 264.9 = 251.4 Nm

As type approval requires pass/fail threshold:
- Proposed Threshold Value for Flex-GTR Max. Tibia Bending Moment: 303 Nm
TEG-127
7 December 2009

As this was almost the same value proposed by BAU as an average value between the 62% and former IAMA proposals, the group agreed at its 9th TEG meeting on September 9th - 10th, 2009, on a consensus of the rounded value of 340 Nm.

2) MEL Elongation Threshold Value 22 mm

MEL developed an MEL injury risk function as an average between the IAMA functions proposed by Kramar et al. (2001) and IAMA in this function, a 25% risk of low MEL EL was corresponded to a human knee bending angle of 18 degrees. This value was converted to 18.2 mm MEL elongation. Using a corresponding transition equation from computer simulation. After incorporating the effect of muscle tone the threshold value was calculated to 21 mm. In vivo value was converted to 21.8 degrees of EVIC W177 knee bending angle by using a corresponding transition equation which would be by 18% more conservative than the currently defined MEL in vitro value of 21 mm, a 3% more conservative approach, equivalent to 20.7 degree EVIC_W177 knee bending angle was proposed and transferred to 22 mm MEL elongation, using the same transition equation as before.

b) 22 mm (MEL)

As MEL is not in the position to validate or double check these results, they investigated a direct correlation between the EVIC_W177 knee bending angle and the FEIM MEL elongation at verification of the MEL results. Attention was given to develop, based on the test results of different McKee et al. and related tests. Thus, a knee bending angle of 12 degrees corresponded to 22.7 mm MEL elongation. In order to provide at least the same level of protection as the current MEL, a threshold value of 21 mm was proposed which was in line with the IAMA proposal at the 8th TEG meeting on September 9th, 2009, that group agreed on a 22 mm MEL elongation threshold value for McKee et al. elongation of 22 mm.

c) 20.7 mm (MEL)

Currently, no injury risk function is available. MEL proposed to therefore use the same injury risk function proposed for McKee et al. 2007, which is not the displacement of 12.7 mm sufficient value needed to provide to the worst scenario. Thus, with the absence of more data but having in mind that the FEIM should provide at least the same level of protection as the EVIC_W177 knee, MEL proposed a mandatory threshold value of 20.7 mm for McKee et al.

2) Monitoring against a threshold of 22 mm (MEL)

In contrast, IAMA stated that the percentage of failed ACL injury in real world data is low (few with ACL and most ACL injuries are located in isolated tests), which does not allow development of an injury probability function. However, the tentative threshold value should be set for monitoring, subject to future modification to the tentative threshold on additional information data.

d) No consideration (MEL)

As pointed out by both, IAMA and BAU, the biomechanical data available to define an injury risk curve is limited. In addition, it is not that ACL/LCL elongation usually corresponds to MEL elongation. In addition, the given data does not provide for the necessary data on parameters. Thus the used threshold value, the threshold value in pm 9 was correlated to 20.7 mm EVIC_W177 knee bending angle.

As discussed in this meeting, the group agreed to either come to a conclusion or to provide guidance to future works.


TEG-127
7 December 2009

As pointed out by both, IAMA and BAU, the biomechanical data available to define an injury risk curve is limited. In addition, it is not that ACL/LCL elongation usually corresponds to MEL elongation. In addition, the given data does not provide for the necessary data on parameters. Thus the used threshold value, the threshold value in pm 9 was correlated to 20.7 mm EVIC_W177 knee bending angle.

As discussed in this meeting, the group agreed to either come to a conclusion or to provide guidance to future works.
Correlation: EEVC WG 17 PLI and FlexPLI

Correlation: EEVC WG 17 PLI and FlexPLI

Correlation: MCL and ACL/PCL

Test results:

\[ y = 0.5720x + 2.3912 \]

Correlation: FlexPLI SD and ACL EL

- Bhullar et al (2000) found tolerance of 12.7 mm and 17.8 mm for human knee shear displacement of the 5th male
- The knee shear displacement can be transformed to FlexPLI ACL/PCL elongation, taking into account the knee measurement locations

Proposal for ACL/PCL injury thresholds

Conclusions / Proposal:
1. Under the previously made observations, the following first estimation was made:
   - Flex-GTR ACL elongation performance limit: 8 mm (SD transition)
   - Flex-GTR ACL elongation performance limit: 10 mm (ECB transition)
2. In absence of injury risk functions for the cruciate ligaments and lacking information on transition between human and Flex-GTR ACL/PCL elongation a threshold value of 13 mm ACL/PCL elongation is proposed as performance limit.
3. German in-depth accident data gives evidence of clearly defined cruciate ligament ruptures.
4. ACL was proved to be the more critical because under the defined impact conditions less protected ligament. Therefore, the threshold value regarding PCL may be set as monitoring.
5. Anyway, so the FlexPLI should provide at least the same level of protection when being compared to the EEVC WG 17 PLI, the ACL limit should be set mandatory.
### Outline

1. Biofidelity
2. Performance/Injury Criteria
3. Benefit
4. Durability
5. Reproducibility and Repeatability
6. Vehicle Countermeasures

### 3. Benefit

- **List of Relevant TEG Documents**

<table>
<thead>
<tr>
<th>Doc. #</th>
<th>Affiliation</th>
<th>Version</th>
<th>Summary</th>
</tr>
</thead>
</table>
| TEG-049 | JAMA-JARI   | Flex-PLI | - Estimation of lower limb protection level provided by Flex-PLI  
- Follow NHTSA methodology (GRSP/2006/7), based on PCDS data  
**Results**  
- Estimated number of injury-prevented pedestrians by PV: 2,438  
- Estimated number of injury-prevented pedestrians by LTV: 359 |
Evaluation Method for Flex-PLI (for discussion)

Outline

1. Biofidelity
2. Performance/Injury Criteria
3. Benefit
4. Durability
5. Reproducibility and Repeatability
6. Vehicle Countermeasures
## 4. Durability

- List of Relevant TEG Documents -

<table>
<thead>
<tr>
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<th>Summary</th>
</tr>
</thead>
</table>
| TEG-037 | BGS | Flex-GT | - Dec 2006 - Apr 2007 BAST test programme  
- 70 tests at 40 km/h using Flex-GT  
- Durability check  
**Results**  
- Flex-GT withstood more than 70 tests @ 40 km/h  
- No major mechanical defect  
- Cable defects outside the impactor  
- Minor design and wiring modifications required |
| TEG-063 | NHTSA | Flex-GT | - Car test using Flex-GT : 2 cars, 1 location for one car, 2 locations for another car, 2 impactor heights per location  
- 2 additional car tests : same car, same location, same impactor height for repeatability  
- Durability check  
**Results**  
- Several minor issues but no catastrophic damage  
- Need to test more aggressive vehicles to evaluate durability for US fleet |
- Durability comparison between Flex-GT and Flex-GTR  
**Results**  
- Improved durability  
- Poor performers in TRL legform tests have not been tested |
| TEG-113 | KATRI | Flex-GTR | - Flex-GTR car test (1 car)  
- Durability check  
**Results**  
- No serious issues on durability |
inspection after test

- Visual inspection of the impactor components and the cabling

April 2nd, 2007

[Images of inspection process]

inspection after test

- Verification of the torque of 8 screws

April 2nd, 2007

[Images of torque verification process]

inspection after test

- Check of the length of the 20 knee spring ends

April 2nd, 2007

[Images of knee spring end check process]

inspection after test

- Check of the length of the 4 upper leg bending stopper cable ends

April 2nd, 2007

[Images of upper leg bending stopper cable check process]

inspection after test

- Check of the length of the 4 lower leg bending stopper cable ends

April 2nd, 2007

[Images of lower leg bending stopper cable check process]

inspection after test

- New tool for cable clearance checks:
  - Thicknesses: 9 mm and 8 mm

April 2nd, 2007

[Images of new tool for cable clearance]

inspection after test

- Check for distortion

April 2nd, 2007

[Image of distortion check process]
**TEG-037**

**Summary**

- Flex GTa withstood more than 70 impact tests at 40 km/h
- No greater mechanical defect
- Cable defects outside the impactor lead to measurement faults and time-intensive repairs
- Improvement of endurance through minor design and wiring modifications required
- Preparations for the test laboratory are comparatively negligible
- Handling effort comparable with EEVC legform
- Significantly more measurement channels than in other pedestrian protection impactor tests
- The necessity of a certification test after every single impact test should be reconsidered

April 2nd, 2007
Dirk-Uwe Gehring
Slide 25

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**TEG-063**

**Tests Performed**

- 2002 Mazda Miata
- 2005 Honda CR-V

- Each location: 25 mm / 75 mm above ground reference level
- Two additional tests performed on Miata at 75 mm for repeatability

**Mechanical (cont.)**

- Zippers need to be made more durable
  - Broken pull rings due to repeated high tension when assembling leg
- Slices and cuts were common
  - When does accumulated damage require replacement of flesh?
- Addition of threaded holes in standard location for accelerometer attachment at knee
  - Recommended for impact speed redundancy & comparison to TRL-measuredibia acceleration

**Mechanical**

- Knee Twist
- Bent Tabs
- Rubber Spacer
- Damaged Casings
- Seized Bolt/Sleeve
- Tibia Plate Damage/Rotation

**Electrical**

- We had 10 – 12 instances of a broken cable in our testing
- Improvements needed:
  - Better routing schemes
  - Dull sharp edges on knee structure
  - Stronger wire covers
  - Smaller bundle (can redundant gauges be coupled somehow to reduce the number of wires?)
  - Onboard DAS is a very good solution!
**TEG-063**

**Summary**

- Test experience and repeatability
  - Improved axial rotation with new roller support
  - Excellent repeatability
- Injury evaluation
  - Flex GT results ranked severity of impacts similarly to TRL testing but indicated higher injury severity
  - At least one Flex GT proposed injury limit exceeded for all three impact locations for 25 mm impact height
  - Effect of raising impact height to 75 mm varied
- **Damage and durability**
  - Several minor issues but no catastrophic damage
  - Need to test more aggressive vehicles to evaluate durability for US fleet

---

**TEG-112**

**Test Matrix**

- **Selection Criteria**
  - Vehicle location did reasonably well in TRL tests (Mallory, ESV 2006 & more recent testing)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Torsion Acceleration (GTR: 179 g)</th>
<th>Seating Angle (GTR: 19 deg)</th>
<th>Shear Displacement (GTR: 6 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Honda CR-V</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>2002 Mazda Miata</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>2004 Toyota Camry</td>
<td>Pass</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>2001 Honda Civic</td>
<td>Full (marginal)</td>
<td>Full (marginal)</td>
<td>Full (marginal)</td>
</tr>
</tbody>
</table>

**Durability**

- **Flex-GT (2006)**
  - Knee Twist
  - Bent Tabs
  - Rubber Spacers
  - Damaged Casings
  - Seized Bolts
  - Fracture Plate Rotation

**Durability Comparison**

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Twist (needed manual fix)</td>
<td>X</td>
</tr>
<tr>
<td>Bent Tabs</td>
<td>X</td>
</tr>
<tr>
<td>Rubber Spacer Fall Out</td>
<td>X</td>
</tr>
<tr>
<td>Damaged Casings</td>
<td>X</td>
</tr>
<tr>
<td>Seized Bolts</td>
<td>X</td>
</tr>
<tr>
<td>Broken Zipper Ring</td>
<td>X</td>
</tr>
<tr>
<td>Cut/Pulled Instrumentation Cables</td>
<td>X (sensors)</td>
</tr>
<tr>
<td>Scuffing of Support Piece</td>
<td>X (replaced)</td>
</tr>
<tr>
<td>Blue Cap Camel Oil</td>
<td>X (partially replaced)</td>
</tr>
<tr>
<td>Longitudinal Lamination Lines on Bone?</td>
<td>Not considered damage</td>
</tr>
</tbody>
</table>
**TEG-112**

**Summary**

- Very good repeatability
  - In two repeat tests, center impact, 5 vehicles
- Improved durability
  - But we have not tested vehicles that were poor performers in TRL legform tests
- SLICE is functional & improvement over conventional DAS
  - But does have some bugs that need to be worked out

---

**TEG-113**

**Introduction of Test Vehicle and Test Method**

- **Test Vehicle**
  - Vehicle meets the criteria of the TRL-UI to test according to existing legislation
  - Vehicle was rated completely green in the TRL-UI to tests of Euro-NCAP
  - Vehicle is considered to be pedestrian friendly in this area

- **Test Method**
  - Impact type: Flex-Pu-ETR Prototype
  - Impact velocity: 11.1 ft/s (3.4 m/s)
  - Impact zone: ENPC W17 (1/2 by EURO NCAP)
  - Impact point: 3/4 to 1/4 of vehicle
  - Impact angle: 25 degrees (frontal impact)

---

**Conclusion**

- In the round robin test for Flex-Pu-ETR and so the result
- Comparison between ENPC W17 (1/2 by EURO NCAP) and Flex-Pu-ETR
  - Flex-Pu-ETR
  - In state of existing regulation, the margin of Flex-Pu is shorter than ENPC W17 (1/2)
  - This result should not apply for every vehicle, it is only applicable to our tested vehicle

- Durability and usability:
  - Some improvements are needed
    - As for design and durability: No, minor general No, minor fracture, considerable slap
    - As for usability: More convenient and automatic control program
    - As for stability: Better data download and electrical ground connection
    - More consideration is necessary to unexpected and without-control rebound phenomenon
Outline

1. Biofidelity
2. Performance/Injury Criteria
3. Benefit
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6. Vehicle Countermeasures

5. Reproducibility and Repeatability

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</thead>
<tbody>
<tr>
<td>TEG-021</td>
<td>JARI</td>
<td>Flex-GT</td>
<td>- Dynamic certification test (pendulum)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Comparison of 36 tests for femur and tibia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Comparison of 18 tests for MCL, ACL and PCL</td>
</tr>
<tr>
<td>TEG-034</td>
<td>J-MLIT /NTSEL</td>
<td>Flex-GT</td>
<td>- Bending test of femur, tibia, knee of Flex-GT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Dynamic certification test (Pendulum) using Flex-GT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Car test using Flex-GT (two impactors)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- R&amp;R evaluation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Results</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Flex-GT test results were repeatable in 3-point bending tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and pendulum tests</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Flex-GT test results were reproducible in car tests</td>
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<td></td>
<td></td>
<td></td>
<td>- No evaluation of Coefficient of Variation</td>
</tr>
<tr>
<td>TEG-036</td>
<td>BASSt</td>
<td>Flex-GT</td>
<td>- Car test (2 cars) using Flex-G and Flex-GT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Dynamic certification test (Pendulum)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Repeatability evaluation</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Results</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Maximum tibia bending moments: SD between good and acceptable at all</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>impact locations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Knee elongation: SD still acceptable in 5/12 cases</td>
</tr>
</tbody>
</table>