First Technology Safety Systems

Design Freeze Status

FLEX-PLI-GTR Development
Mechanical Design

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FTSS Europe
Updated according Design Freeze meeting
February 20th 2008, JARI, Tsukuba, Japan
Update March 27th, 2008
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- Mechanical design
- Problems addressed
- Packaging standard components
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<th>DAS</th>
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<tr>
<td>Femur moment 1, 2 and 3</td>
<td>Calibration</td>
<td>3</td>
<td>0</td>
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<td>Tibia moment 1, 2, 3 and 4</td>
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<td>-1</td>
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<tr>
<td>MCL elongation</td>
<td>Injury</td>
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<td>0</td>
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<tr>
<td>ACL elongation</td>
<td>Calibration</td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>PCL elongation</td>
<td>Calibration</td>
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<td>0</td>
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<td>LCL elongation</td>
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<tr>
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<td>Motion</td>
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<td>3</td>
<td>Lab</td>
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<tr>
<td>Femur bottom acceln ax, ay, az</td>
<td>Motion</td>
<td>0</td>
<td>3</td>
<td>Lab and optional</td>
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<tr>
<td>Tibia top acceln ax, ay, az</td>
<td>Motion</td>
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<td>3</td>
<td>i-dummy</td>
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<tr>
<td>Tibia angular rate ωx, ωy, ωz</td>
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<td>3</td>
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<tr>
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<td>Motion</td>
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<td>3</td>
<td></td>
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<tr>
<td>Tibia bottom acceln ax, ay, az</td>
<td>Motion</td>
<td>0</td>
<td>3</td>
<td>Lab</td>
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<td>Segment acceln ax</td>
<td>Research</td>
<td>0</td>
<td>15</td>
<td>Lab</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>12</strong></td>
<td><strong>32</strong></td>
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</table>
Conceptual Design

- To avoid A-symmetric sensitivity
  - Move MCL & LCL at centerline
  - Move ACL & PCL close to centerline

- To avoid knee twist
  - Use two sets of cruciate ligaments
  - To neutralize twist moment

- Cruciate ligaments 8 springs
  - DBØ12xØ6x40mm; 71.6N/mm
  - May need to go Ø3mm cable
  - Optimized space for DAS & connector

- Lateral ligaments 16 springs same
  - DBØ18xØ9x80mm; 76.7N/mm
Cruciate Ligament Springs

- 2 springs
- DBØ18xØ9x80mm
- 76.7N/mm rate
- 16mm stroke
- 2 spacers

\[ F_{\text{ligament-GT}} = 76.7 \times 16 = 1227N \]
\[ \text{Total } F_{\text{ligament-GT}} = 2 \times 1227 = 2454N \]

- 8 springs
- DBØ12xØ6x40mm
- 71.6N/mm rate
- 2*8mm stroke

\[ F_{\text{ligament-GTR}} = 71.6 \times 8 = 573N \]
\[ \text{Total } F_{\text{ligament-GTR}} = 4 \times 71.6 \times 8 = 2292N \]

- 8 Lateral ligaments DBØ18xØ9x80mm
- Cruciate ligaments contribute ~22% to bending moment
- Effect ~-1.3%
# Knee Bending Moment Comparison

<table>
<thead>
<tr>
<th>Knee Bending Moment Comparison GT-GTR</th>
<th>GT</th>
<th>GTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral ligament peak force FL</td>
<td>1227</td>
<td>1227</td>
</tr>
<tr>
<td>Cruciate ligament peak force FC</td>
<td>1227</td>
<td>573</td>
</tr>
<tr>
<td>Distance lateral ligament- Rotation point 72-10=62</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Distance crucuate ligament- Rotation point 26+15=41</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Lateral ligament Moment peak contribution ML [Nm]</td>
<td>304</td>
<td>304</td>
</tr>
<tr>
<td>Cruciate ligament Moment peak contribution MC [Nm]</td>
<td>71</td>
<td>66</td>
</tr>
<tr>
<td>Total moment before spring bottom out [Nm]</td>
<td>375</td>
<td>371</td>
</tr>
<tr>
<td>Difference GT-GTR [%]</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

GT version

\[
ML = 4*FL*62/1000 \\
MC = 2*FC*41/\sqrt{2}/1000
\]

GTR version

\[
ML = 4*FL*62/1000 \\
MC = 4*FC*41/\sqrt{2}/1000
\]
Ligament Wear

- Prevent wear of ligament cable plastic sleeves
  - Remove plastic sleeves from cables
  - Apply bronze guides cross ligaments
- The plastic tube is the source of the problem; it cannot sustain high surface strain
- Omitting plastic sleeve will avoid the damage
- Larger bending radius and reduced friction will protect the cable
- Ø3mm cable for cruciate ligaments agreed
  - May go to Ø4mm if problems arise
- Ø4mm 7*19 cable break strength 8.73kN
  - Alternative 7*7 cable break strength Ø4mm 9.52kN
  - Knee bending moment break strength 60mm * 9kN * 4 = 2160Nm
- Ø3mm 7*19 cable break strength 5.00kN
Friction Double Cruciate Ligaments

- A concern raised on change in friction of the double cruciate ligaments
- Friction is **undesired** unpredictable phenomena
  - Static and dynamic friction, slip-stick effect, effect of wear, state of lubrication, moisture
- GT version is unpredictable because of three material layers: steel-PVC tube-aluminium
- Friction force ($F_{fr}$) is dependent on two parameters
  - material pairing and friction coefficient ($c$)
  - force perpendicular to friction plane ($F_n$)
- In GTR version the total perpendicular force remains the same
- In GTR version friction coefficient will reduce
  - GT Plastic to steel ~ 0.2-0.5 friction coefficient
  - GTR Steel to bronze ~ 0.1 friction coefficient
- Cruciate ligaments only contribute ~ 20% to knee bending moment
  - Influence of friction is further reduced in GTR version
  - Knee bending characteristic dependent on spring tension and controlled by calibration
Ligament Spring Adjustment

- Problem of spring adjustment access
- Problem of spring adjustment loss (no retention of position)
Ligament Spring Adjustment

• Ligament springs made flush
• M5 Nyloc locking nuts
• Male thread on ligament wires
• Flats on end fittings for locking
• Improved access for ligament adjustment
• Less frequent adjustments required with locking nut
Proposed Cables

- New cable end fitting design
- Metric threads and fasteners

Bronze bushing
Rounded corners
Knee interface

GT retained with six M5 screws

GTR Retained with four M5 screws
Bronze wire guides
Packaging Ligament Elongations

Sensors at Centre Line

Space Age Control
150 series
19*19*10mm
49G acceleration
38mm stroke
2xLH & 2xRH pull
Bronze wire guides
Potentiometer String Assembly

• Assembly of potentiometer string fittings is always difficult due the tension on the string and small fitting size
• This method enables mounting string fittings without tension
Packaging Space

Side cavities: DAS, wiring, connectors
Central cavity: Auxiliary components: battery, terminator, etc.
Integration of connector blocks and wiring
Integration Connector Blocks
Single axis accelerometer x-direction for certification

- Mounted behind Nylon Impact Cover
- Threaded metal inserts to enable thread repair
- Kyowa ASE, Measurement specialties M62, Endevco 7264
Protective Covers on Side Cavities

- Side cavity covers are 2mm thick and bent for strength
Protective rubber bumpers to distal and proximal ends

- Rubber bumper mass 0.04kg each
- Mounted with Nylon screw for mass reduction
- Provision of threads for catch ropes
  - Catch ropes and bumper may be used simultaneously
  - But may need special fixture
Top of femur launching Bracket

- Lower pivot is clamped
- Function 1: protection of bracket under secondary impact
- Function 2: angle adjustment to achieve stable suspension on ejection platform
- Bumper on distal femur
  - Cut outs for cables
Segment C1A_AL
Bottom tibia segment C3_AL

• Increase strength of C1A_AL:
  • Counter bores removed
  • Additional mass +10gr

• Increase strength of bottom tibia segment C3_AL
  • Increase bottom to 4mm thickness
  • Additional mass +18gr

• Shorten the bone by 2mm
Proposed impact cover designs

- **FLEX-PLI-GT mounting maintained with double sided tape**
- **Button head screws maintained**
  - To allow dislocation to protect against overload
  - Hole centers reduced in to avoid thin section at edge
  - Minimum section 1.7mm
Screw clearance

1mm clearance on screw current design

Propose 0.5 mm?
Segment links

Material between holes 1mm  
Material between holes 2mm
Rubber and Neoprene sheets

Outer Neoprene Sheet with alignment marks to aid assembly

- Neoprene Type, Color and Thickness
- Alignment marks and text
- Zipper
- Velcro hooks and loops
- Schoeller Keprotec lining inside
Rubber and Neoprene sheets

Inner Neoprene Sheets (only Leg shown, Thigh similar)
Neoprene Type, Color and Thickness
Alignment marks and text
Zipper
Rubber and Neoprene sheets

Rubber Sheets

- Rubber sheet Type, Hardness and Thickness
- Velcro hooks and loops tape
- Velcro to rubber sheet adhesive
- Adhesive between rubber sheets
Glass Fiber Bone Specifications

- Glass Fiber Reinforced Plastic
- Supplier PL Alloy Japan
- Material specs JARI SPEC F45
- Bone painted to retain glass fibers
  - JARI please provide specs
Comparison GT - GTR

• The project aims at keeping the dynamic response of the GTR as close as possible to current GT version

• GTR aimed to maintain GT Mass and Mass distribution
  – FLEX-GT mass breakdown study was performed

• GTR aimed at maintaining GT dynamic response
  – FTSS will perform material characterization tests
  – GTR materials will be as close as possible
  – Bone material and dimensions will remain the same

• Changes in the knee will not affect bending moment
  – Lateral Ligaments and springs and spacing in y- direction (impact) remain the same
  – Cruciate ligaments total force may slightly change, spacing in y-direction and pull direction remain the same
  – Elongation sensors MCL, PCL, ACL, LCL remain in line with ligaments, position projected to mid knee position
Comparison GT - GTR

- GT and GTR cruciate ligament and spring location remain the same
- All dimensions and interactive geometry remain the same
- Accommodation connectors and DAS -> larger space in the side -> mass compensated
# CAD Mass Estimate GT-GTR-Options

<table>
<thead>
<tr>
<th></th>
<th>Femur Assy</th>
<th>Knee Assy</th>
<th>Tibia Assy</th>
<th>sub Total</th>
<th>Suit</th>
<th>Total</th>
<th>[%]</th>
<th>[gram]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT Assy without wires</td>
<td>2432</td>
<td>4176</td>
<td>2608</td>
<td>9216</td>
<td>3723</td>
<td>12939</td>
<td>±2</td>
<td>±259</td>
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<tr>
<td>GTR Assy without DAS</td>
<td>2432</td>
<td>4126</td>
<td>2626</td>
<td>9184</td>
<td>3723</td>
<td>12907</td>
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<tr>
<td>GTR Assy with DTS Das 12 channels</td>
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<td>4146</td>
<td>2626</td>
<td>9204</td>
<td>3723</td>
<td>12927</td>
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<td>-12</td>
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<tr>
<td>GTR Assy with Messring Das 12 channels</td>
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<td>4250</td>
<td>2626</td>
<td>9308</td>
<td>3723</td>
<td>13031</td>
<td>0.71</td>
<td>92</td>
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<tr>
<td>GTR Assy with Messring Das, Distal &amp;Prox accls and knee accls</td>
<td>2478</td>
<td>4250</td>
<td>2718</td>
<td>9446</td>
<td>3723</td>
<td>13169</td>
<td>1.78</td>
<td>230</td>
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<tr>
<td>GTR Assy Messring DAS with all accls incl all segment accls</td>
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<td>4250</td>
<td>2778</td>
<td>9551</td>
<td>3723</td>
<td>13274</td>
<td>2.59</td>
<td>335</td>
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</table>

Target tolerance ±2% total mass, ±259gram
There is a small reduction adjustment included for CAD screw for actual mass
No wire mass is included in these figures
Suit mass aim to maintain existing mass of 3723g
Further Activities

- Completion Calibration design
- Development of User Manual, including procedures, training.
- Material sourcing and tests
  - Characterize dynamic response of current and new source materials
    - Neoprene, Synthetic rubber 30 Shore A, 45 Shore A
Schedule, future activities, etc.

- 6th FLEX-PLI-TEG meeting, March 31st Germany
- Manufacturing Drawing release 15th April
- Prototype Manufacturing 15th April – 28th July
- Prototype assembly, Testing and Calibration 29th July- September
- GTR prototype Delivery End September 2008
Design frozen