Low-firing thick-film piezoresistive sensors for medical instruments

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Outline

1. Introduction - Instrumentation of medical operations
2. Piezoresistive sensing - Low-firing thick-film materials
3. Application - Ligament-balancing knee sensor for TKA
4. Conclusions & outlook

Outline - 1

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Instrumenting surgical devices

CO-ME
COMPUTER AIDED AND IMAGE GUIDED MEDICAL INTERVENTIONS

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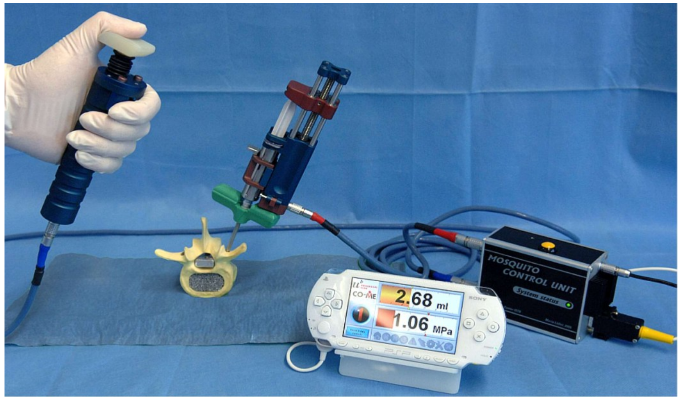
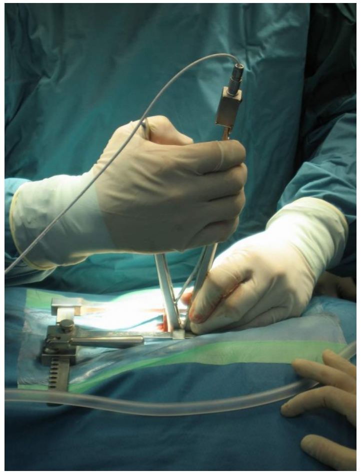
- Improved reliability of operations
- Better quality control
- Haptics for minimal invasiveness
- Improved patient outcome
- *Possible extension to fixtures & implants*



Vertebral cement injector
Loeffel-M, thesis, Univ. Bern (CH), 2007.



Spinal distractor
Ambrosetti-Giudici-S, thesis, Univ. Bern (CH), 2009.

Piezoresistive load sensing

Outline - 2

1. Introduction - Instrumentation of medical operations

2. **Piezoresistive sensing - Low-firing thick-film materials**

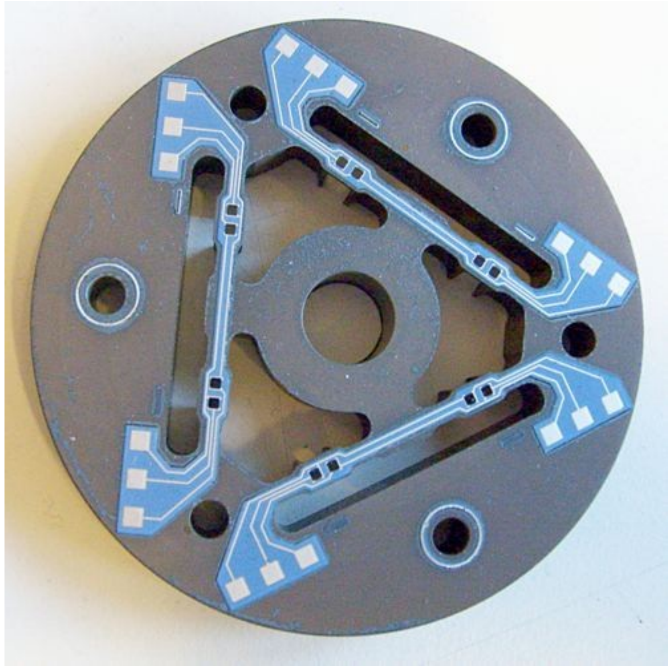
3. Application - Ligament-balancing knee sensor for TKA

4. Conclusions & outlook

Why thick-film on metal?

- Vs. **thin-film on metal**:
  - Low cost (no vacuum processes)
  - Compatible with larger devices
- Vs. **thick-film on ceramic**:
  - High strength & reliability
  - Facile assembly (welding)
- Vs. **glued strain gauges**:
  - More stable signal (sterilisation, …)
  - Easy hermetic encapsulation

Thin-film force sensor for spinal distractor
Ambrosetti-Giudici-S, thesis, Univ. Bern (CH), 2009.



Thick-film 6DOF force sensor for wrist rehabilitation
Jacq-C et al., Eurosensors 2009, Lausanne (CH)

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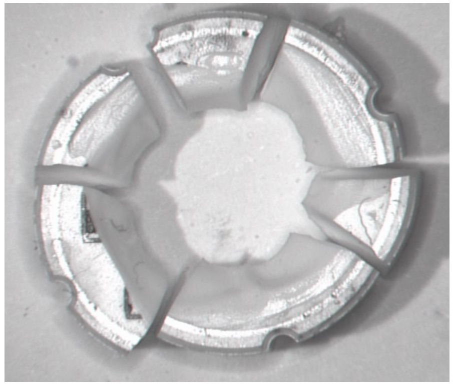
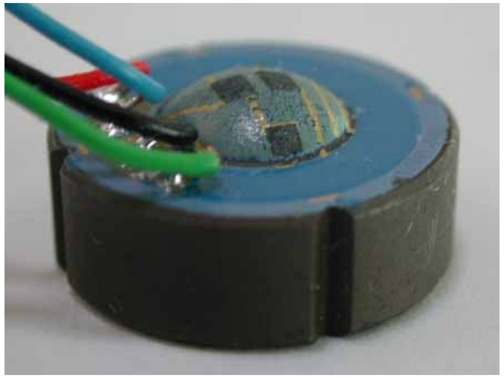
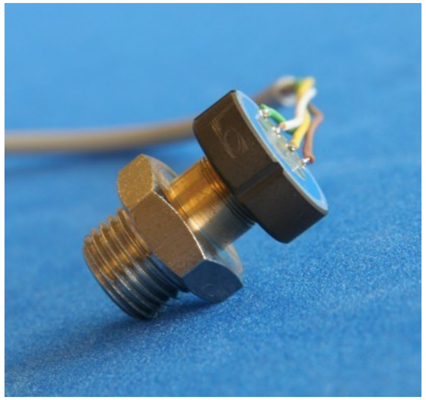




Overloaded ceramic & steel sensors



Easy assembly of metal sensors

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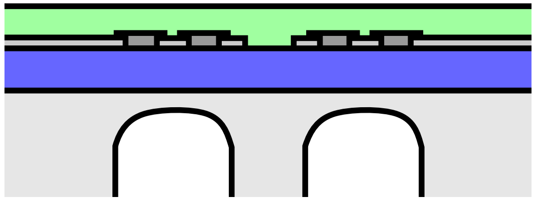
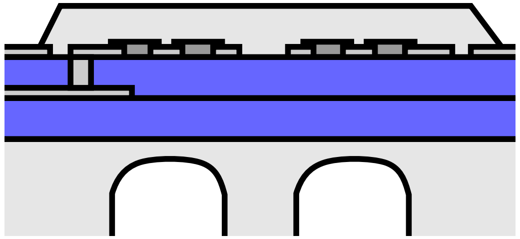


Thick-film hermetic bridge: hermetic overglaze

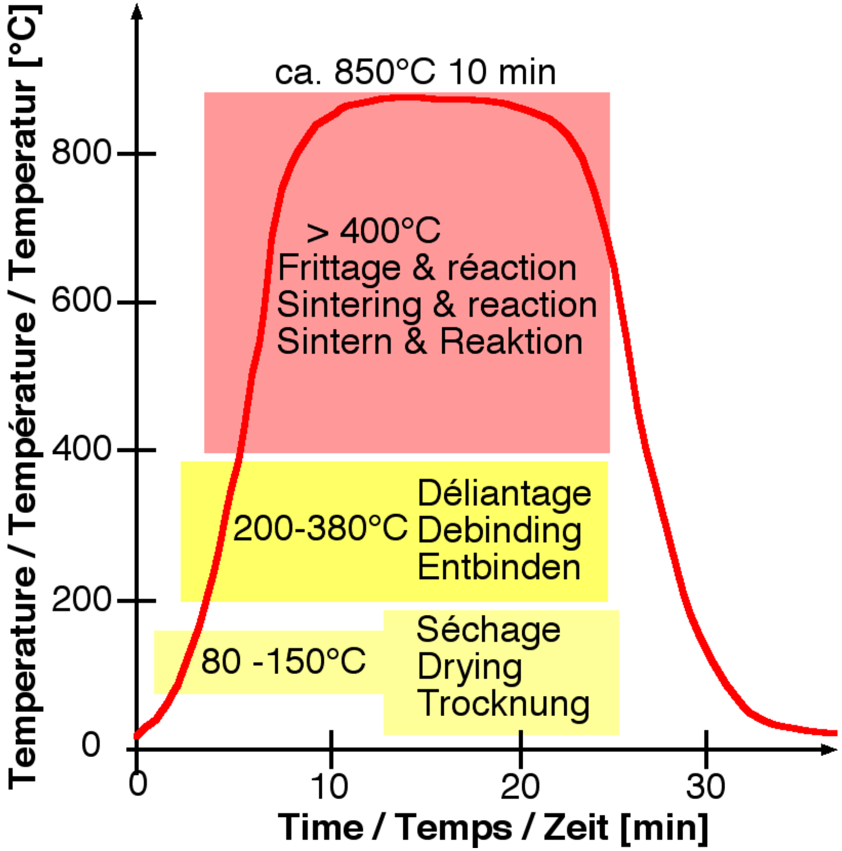
- Vs. **glued strain gauges**:
  - More stable signal (sterilisation, …)
  - Easy hermetic encapsulation



Thick-film hermetic bridge: soldered lid

Issues with thick-film on metal

- **Standard thick-film materials**
  - High processing temperatures
  - Firing at 850°C
- **Thermal behaviour of steels**
  - Martensitic phase transformation - destruction of overlying layers
  - Annealing - reduction of strength
  - Oxidation
- **CTE mismatch**
  - Delamination of layers, esp. with high-CTE austenitic steels



Typical thick-film firing profile

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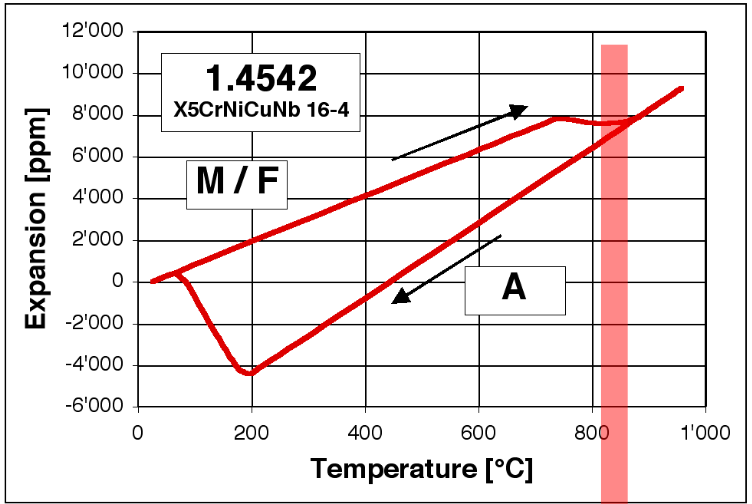
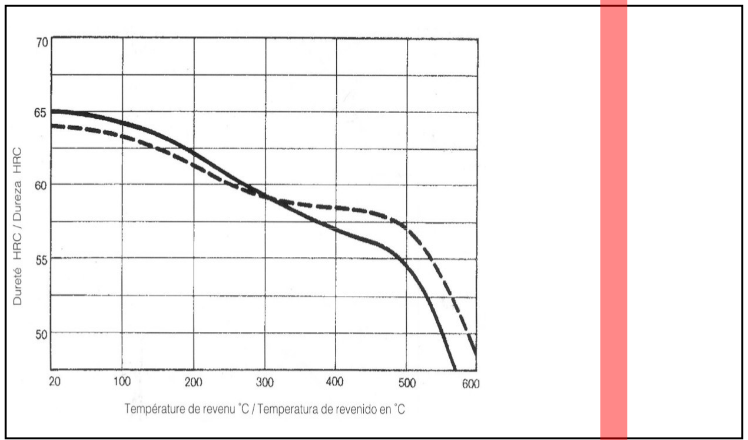
Austenite-martensite transitions in 1.4542 ≈ 17-4 PH



Reduction of hardness in 1.2080 (Böhler K100)



850°C

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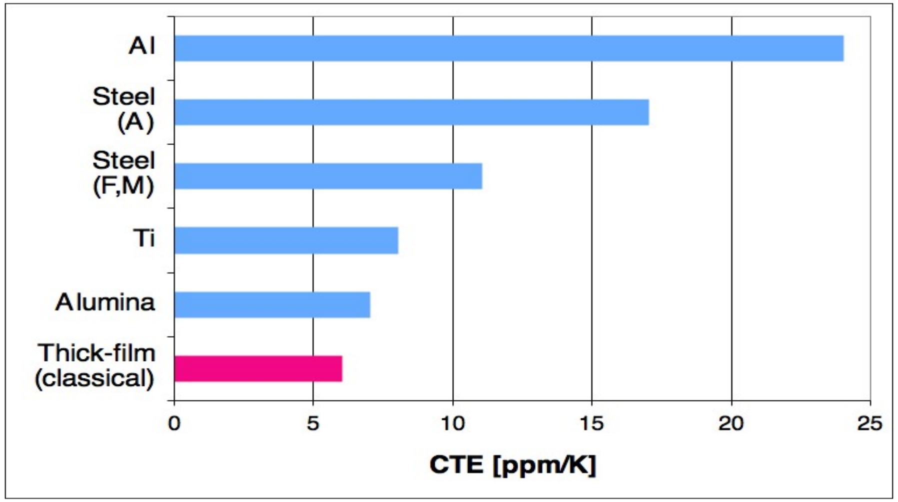
Delamination in overstressed layers



CTE of thick-film materials & substrates

Issues with thick-film on metal

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Low-firing compositions needed

- Ideally fire at max. 600°C
- Low oxidation (esp. Ti)
- Avoid phase transitions
- Matched CTE

Materials: glass-filler (≈625°C)

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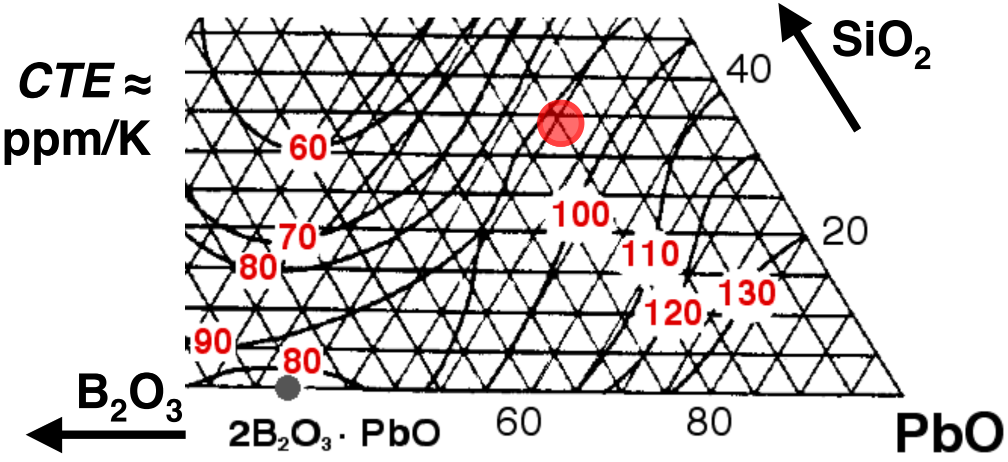
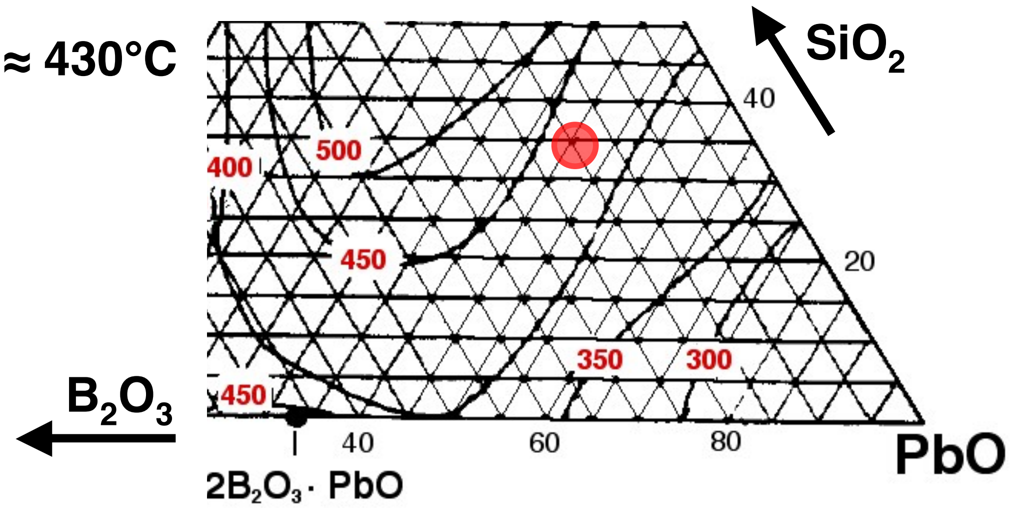
- **Glasses : PbO-B_2O_3-SiO_2**
  - Matrix of thick-film resistors
  - Shifted to lower temperature
- **Dielectrics**
  - Adhesion on steel: Fe_2O_3, …
  - CTE: a-SiO_2, Al_2O_3, quartz, cristobalite, …
  - Chemical compatibility: Al_2O_3
- **Conductors: Ag-based**
- **Resistors: RuO_2 + …**

CTE ≈ 9 ppm/K



T_g ≈ 430°C



Trubnikov-IL, Refr. Ind. Ceram., 41 (5-6), 169-171, 2000.

Materials: glass + filler

- Glasses : PbO-B_2O_3-SiO_2
  - Matrix of thick-film resistors
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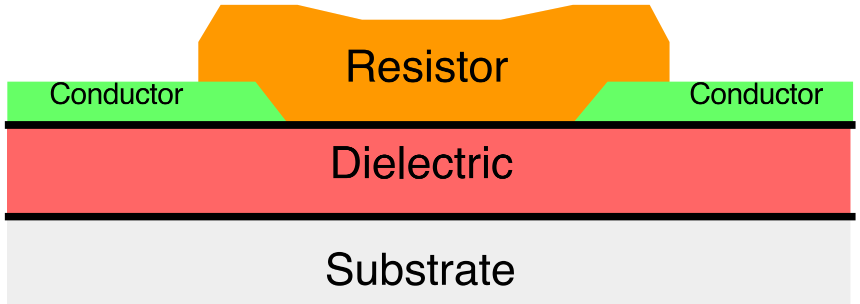

Overall structure

- **Dielectrics**
  - Adhesion on steel: Fe_2O_3, …
  - CTE: a-SiO_2, Al_2O_3, quartz, cristobalite, …
  - Chemical compatibility: Al_2O_3

Measuring bridge	Conductor & resistor layers (+ overglaze)
Dielectric 3 : compatibility	Chemical compatibility with conductors & resistors
Dielectric 2 : main layer	Good CTE matching Electrical insulation Refire stability (no re-melting)
Dielectric 1 : adhesion	Adhesion promoters + good CTE matching
Substrate	Medical alloy – steel

Roles of the dielectric

- Conductors: Ag-based
- Resistors: RuO_2 + …

Materials: glass + filler

- Glasses : $PbO-B_2O_3-SiO_2$
  - Matrix of thick-film resistors
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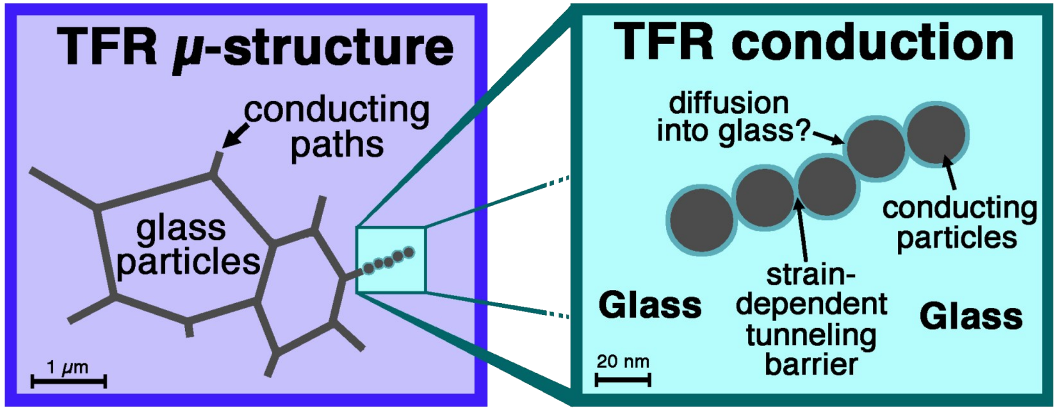
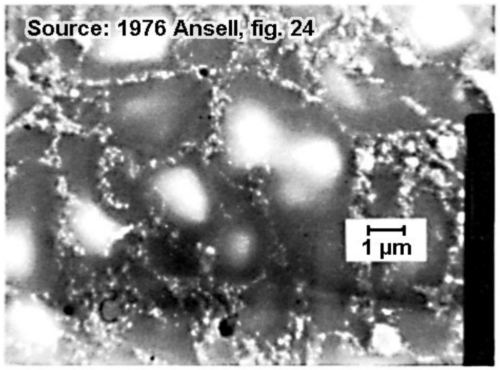
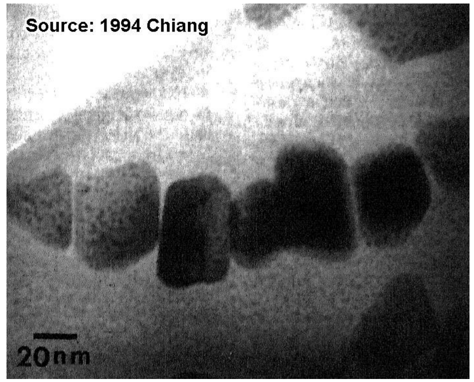
  - Chemical compatibility: Al_2O_3
- **Conductors: Ag-based**
- **Resistors: RuO_2 + …**
  - Gauge factor ≈ 10



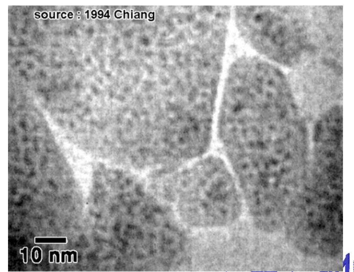




Thick-film resistor micro- & nanostructure

Chiang-IM et al., J.Am.Ceram.Soc. 77(5), 1143-1152, 1994.

Ansell-MP, Electrocomp. Sci. Tech. 3(3), 131-140, 1976.



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1. Introduction - Instrumentation of medical operations
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3. **Application - Ligament-balancing knee sensor for TKA**
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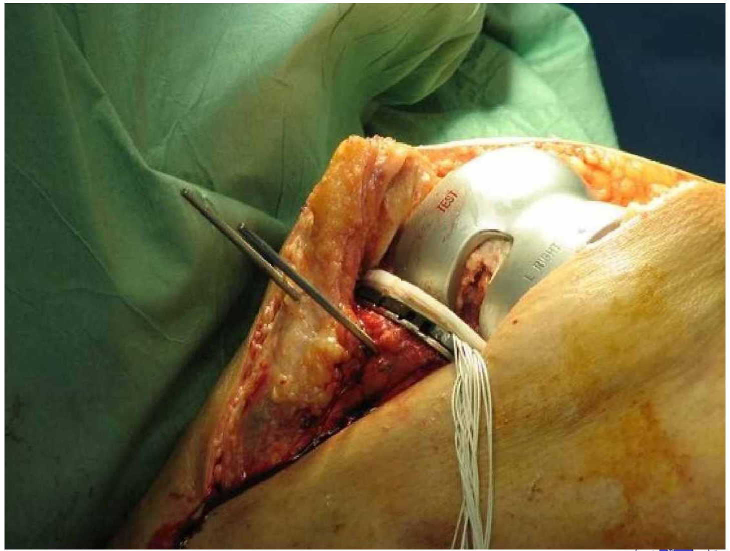
Knee force sensor for TKA

- **Total knee arthroplasty**
  - Total replacement of knee joint
  - Conservation of ligaments
  - Need accurate balancing of ligament forces & moments

- **Force sensor**
  - One sensor per condyle
  - Each sensor: position & amplitude
  - 3 forces = pillar-bridge structures



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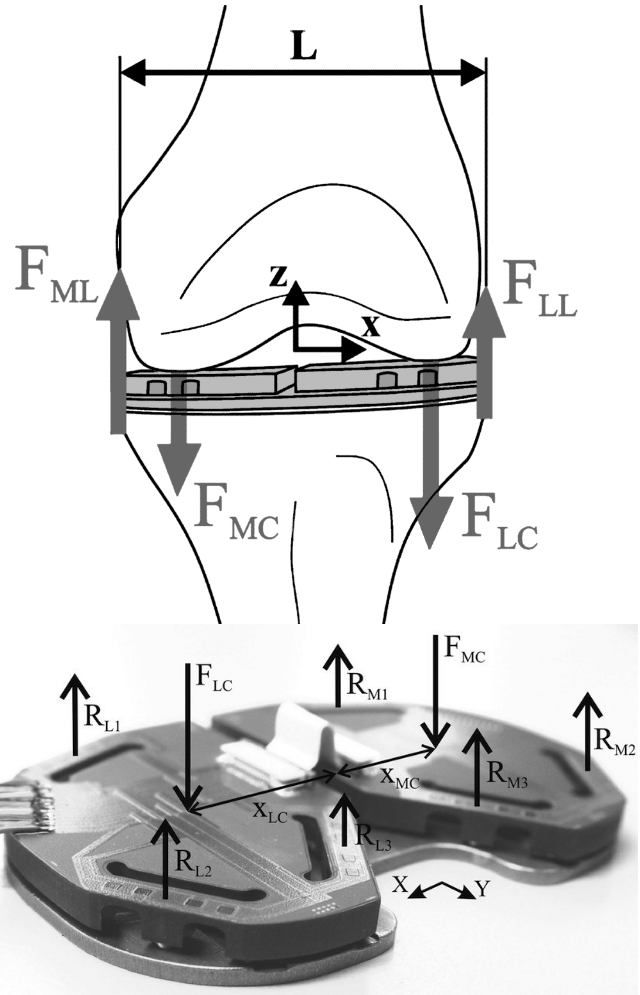

Crottet-D et al., IEEE Trans. Biomed.Eng. 52 (9), 1609-1611, 2005.

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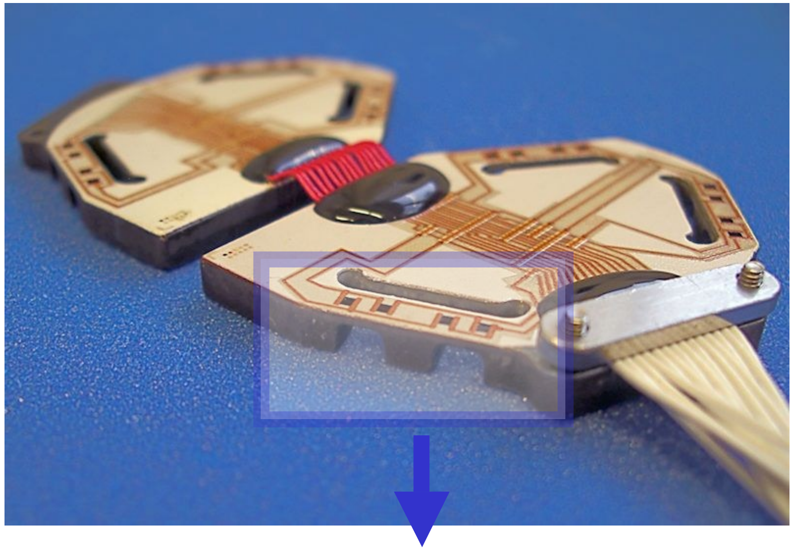

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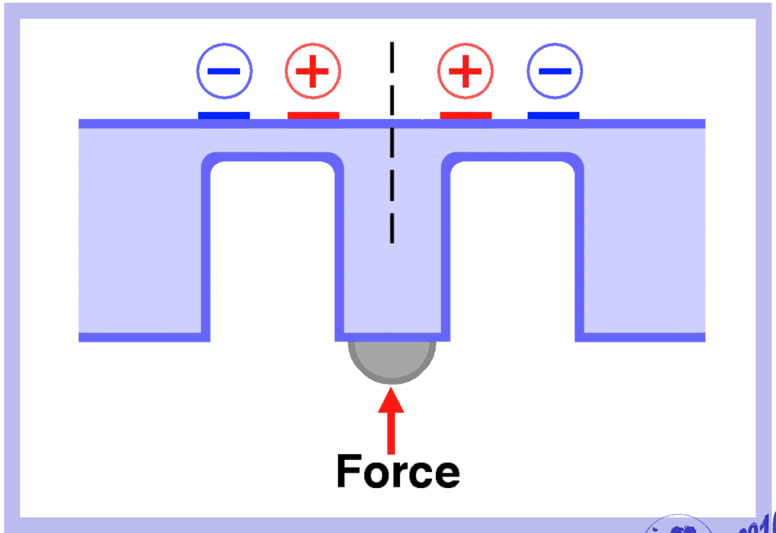
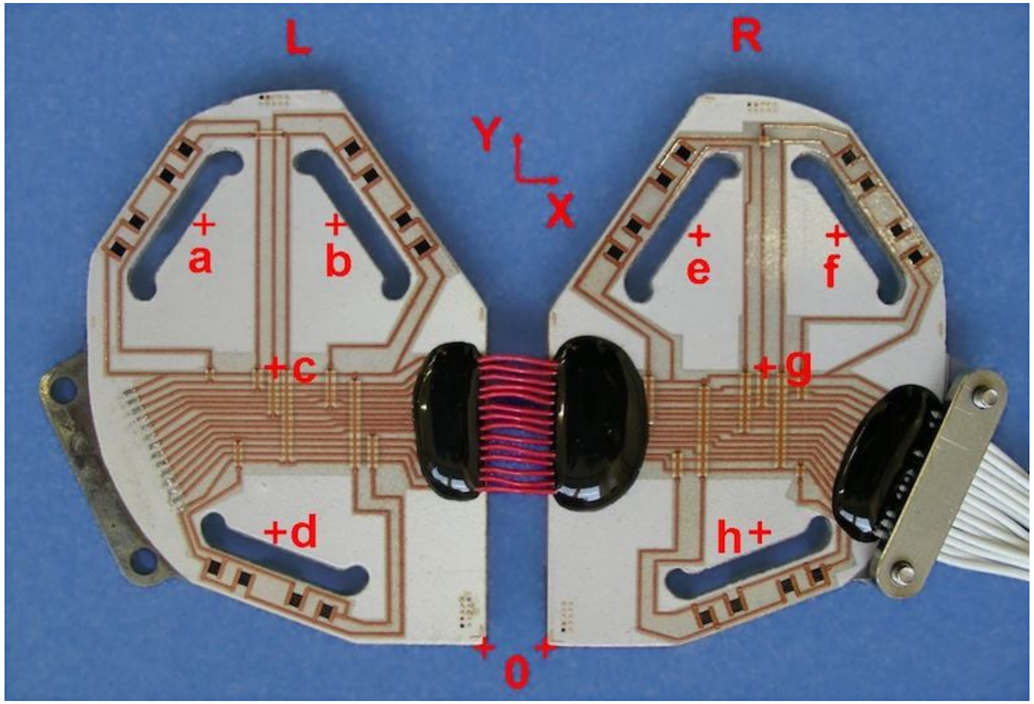
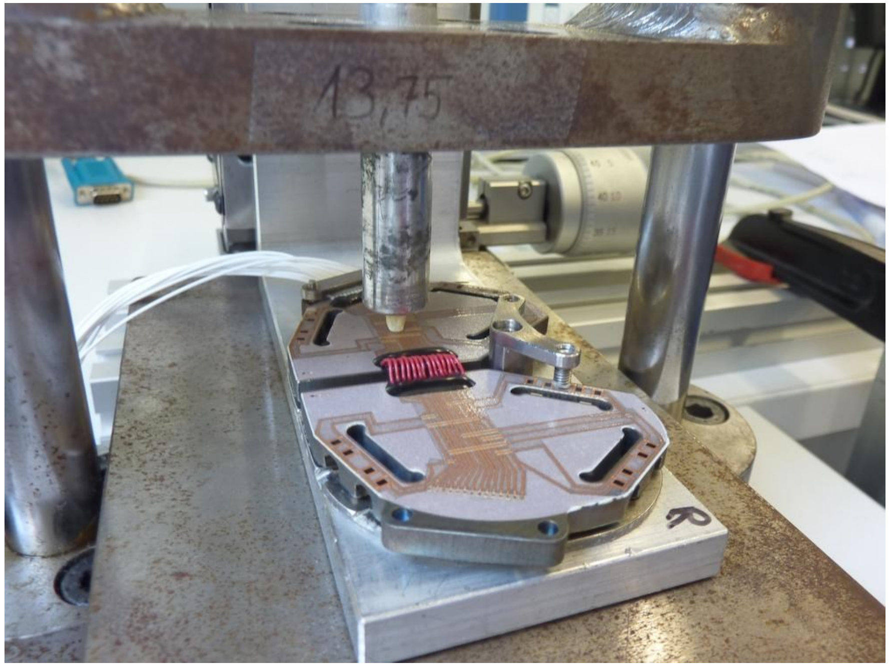


Test of the sensor

- Set of calibrated weights
- Tested in centre & near bridges
- Measurement vs. calibration?



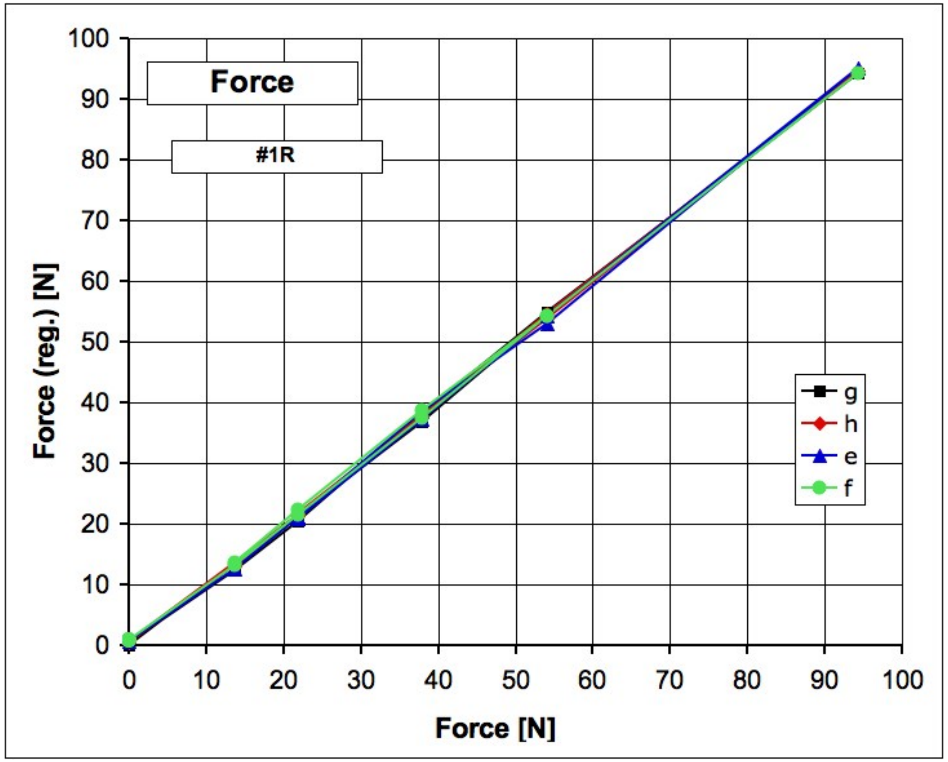


Testing jig: application of calibrated weights at specific XY positions

Ligament-balancing knee sensor with low-temperature thick-film system

Results

- **Good apparent linearity**
- Error ≤ 1 N
- Good position accuracy for sufficiently large force



Measured total force vs. applied force

Results

- Good apparent linearity
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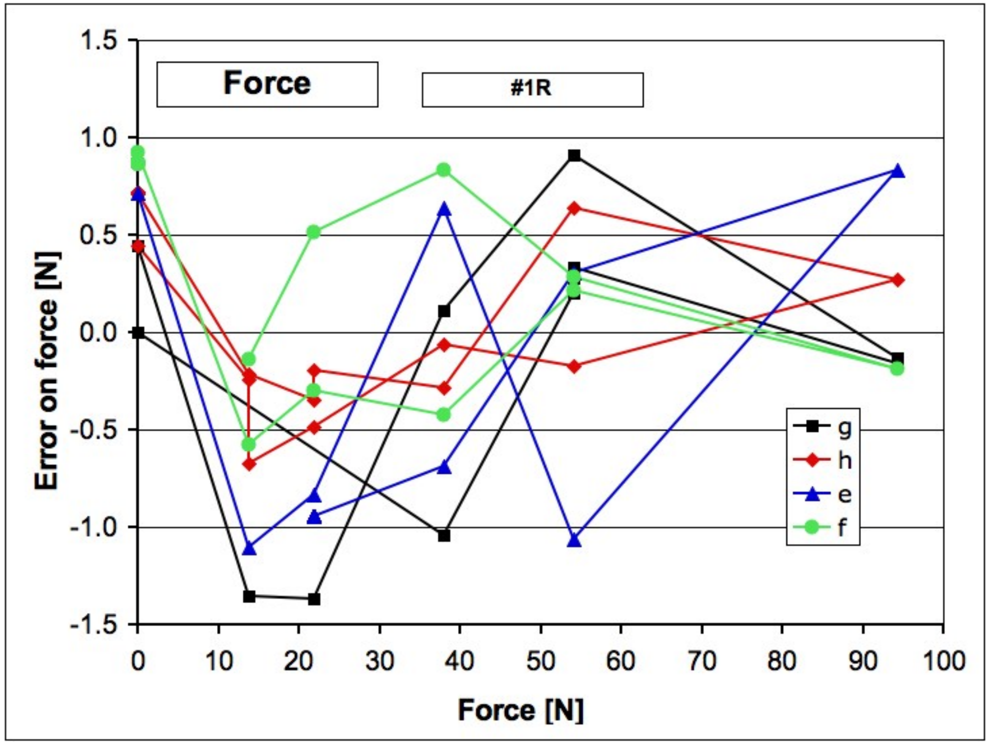


Error in total force vs. applied force

Results

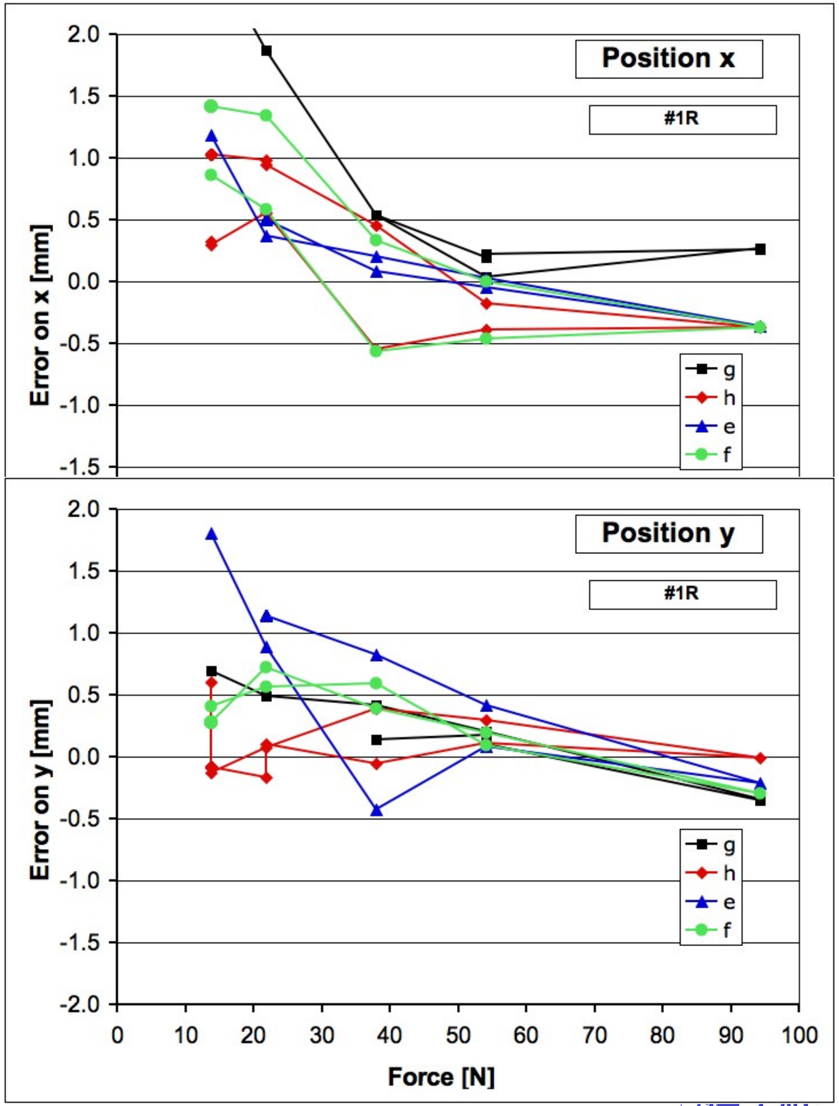
- Good apparent linearity

- Error ≤ 1 N

- **Good position accuracy for sufficiently large force**

X position error

Y position error



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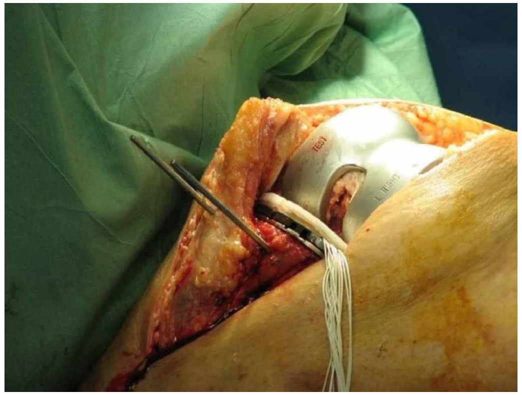
Conclusions & outlook

- **Model low-firing piezoresistive thick-film materials system achieved**
  - Instrumentation of surgical tools
  - Low-cost & good stability
  - Matching to high-strength medical alloys

- **Application to knee sensor**
  - Complex sensor on austenitic high-CTE steel
  - Good measurement characteristics



- **Outlook**
  - Replace with lead-free materials system

Conclusions & outlook

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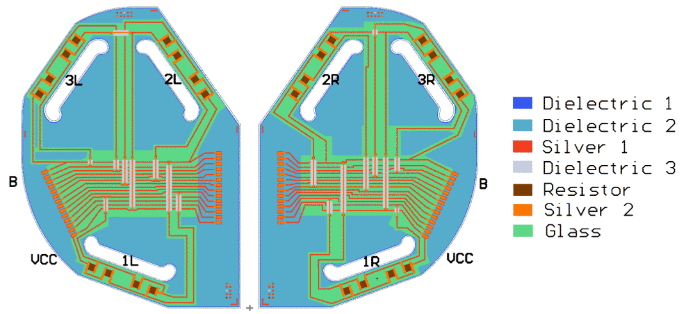

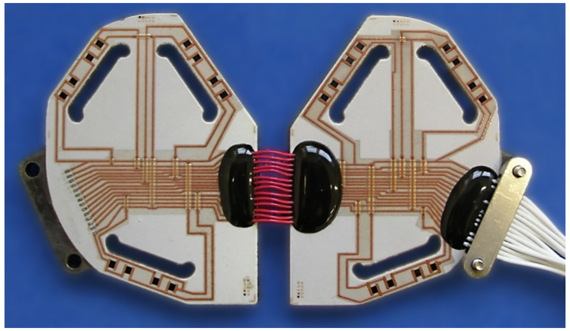

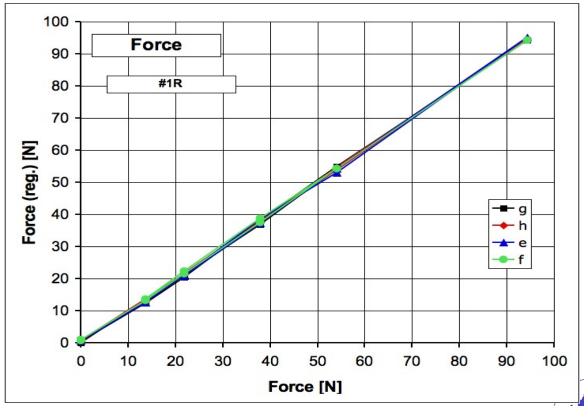

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  - Complex sensor on austenitic high-CTE steel
  - Good measurement characteristics

- **Outlook**
  - Replace with lead-free materials system
  - Slightly lower processing temp. (≈550…600°C)