An Extensometer for Measurement of Principal Strain

A Device Suitable for Use *In Vivo* in Humans

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Presentation Outline

Background and Importance	• Motivation – measure strain in bone • Current methods and limitations • Design of new extensometer
Methodology and Results	• Four-point bending validation tests • Supporting experiments / data • *In vivo* test in human calcaneus
Conclusion	• Benefits and limitations of new method

Motivation for developing new device

Zero Gravity Simulator

In vivo strain measurement was part of a NASA-funded study investigating **jumping exercises** as a means to maintain bone mass in space. No commercially-available device was suitable.

KC-135 Microgravity Laboratory

Background and Importance

Why measure bone strain?

Astronauts experience bone loss due to a reduced demand on their musculoskeletal system.

Exercise is one of the most promising countermeasures to bone loss; no regime has yet been fully successful in preventing bone loss.

Long-duration human presence in space requires effective countermeasures to bone loss

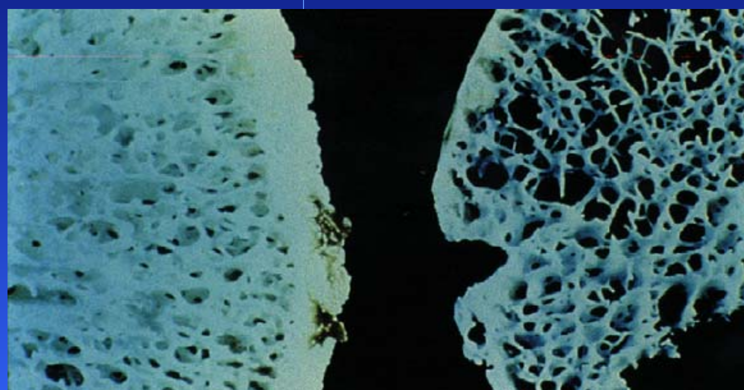
Background

Human Calcaneus (heel bone)

Background

Basic definitions

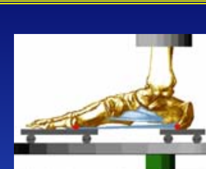
Normal Bone | Osteoporotic Bone



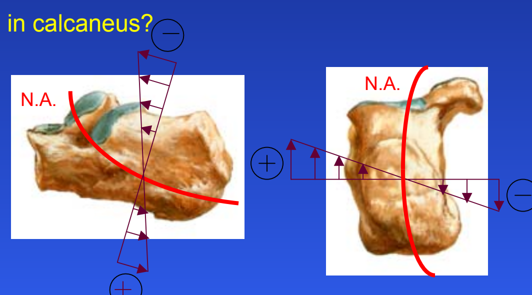
Background -- Design

Bending loads

Rubin and Lanyon (1982) concluded that bending moments are responsible for over 80% of the strain at the bone surface.



Possible bending planes in calcaneus?



Left calcaneus - lateral view | **Posterior view**

Presentation Outline

Background and Importance

- Why measure bone strain
- Current methods and limitations
- Design of new extensometer

Methodology and Results

Conclusion

Background -- Current Methods

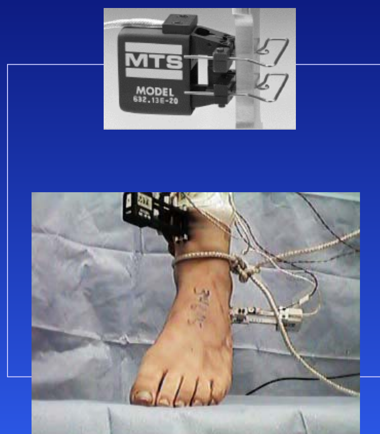
Bonded strain gages have limitations for use *in vivo* in humans:

- surface preparation -- requires smooth, dry surface for good bond (*in vivo*, requires removing periosteum, degreasing, sanding),
- invasiveness is high,
- biological compatibility of bonding agents a concern,
- must access opposing sides of specimen to measure bending.

Uniaxial strain gage

60 degree rosette

Background



In cadaver feet, we measured strain in tibia and calcaneus using extensometers mounted to intracortical (intraosseus) pins.

Measured a strain artifact due to the relatively large mass of extensometer.

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Design of New Extensometer

Specific Aims:

- Design device capable of measuring physiologic levels and rates of bone strain;
  - up to and exceeding 4,000 $\mu\varepsilon$ strain magnitude (0.4 %),
  - up to and exceeding 40,000 $\mu\varepsilon$ / sec strain rate,
  - capable of measuring strain due to bending and principal strain magnitudes and their direction
- Test in dynamic four-point bending and compare output to a “standard”.
- Determine system characteristics and limitations;
  - sensitivity of probes to angle,
  - range of frequencies over which device can operate.
- Test design *in vivo* in human subject.

Design

Capacitive-based sensors:

In contrast to using capacitors to store charge (where a DC voltage is applied and removed), capacitive-based sensors require dynamic excitation.

Typically, the probe is driven with an AC current at a particular frequency and peak to peak voltage (e.g., 15 kHz, 3 Volts P-P).

All capacitive signal conditioning designs contain an internal oscillator and signal demodulator to provide static capable outputs (Pierson, 1999).

Examples of capacitive-based sensors:

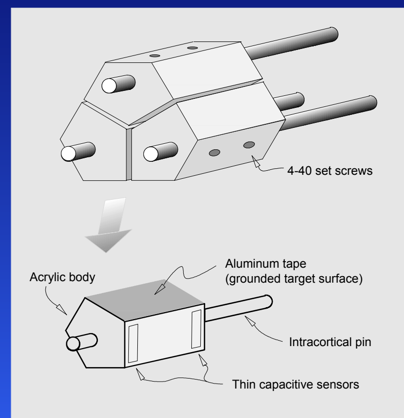
Proximity detectors, pressure sensors, accelerometers, digital levels.

Design

Delta extensometer

Features:

- Thin capacitive sensors (6)
- Five-sided acrylic bodies to adapt sensors to pins
- Three target faces; flat, conductive aluminum tape
- Air gap 1.02 mm maximum
- +/- 7 % strain range



Design

The device works like a 60 degree bonded strain gage rosette.

Is pinned into specimen instead of bonded.

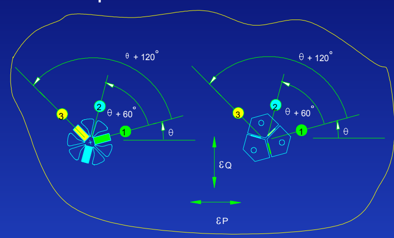
Uses six paired capacitive sensors – can measure small changes in distance between pins, at very high rates.

"Delta Extensometer"

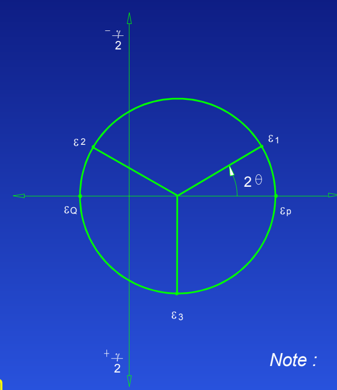
United States Patent No. 6,059,784.

Design

On the specimen:



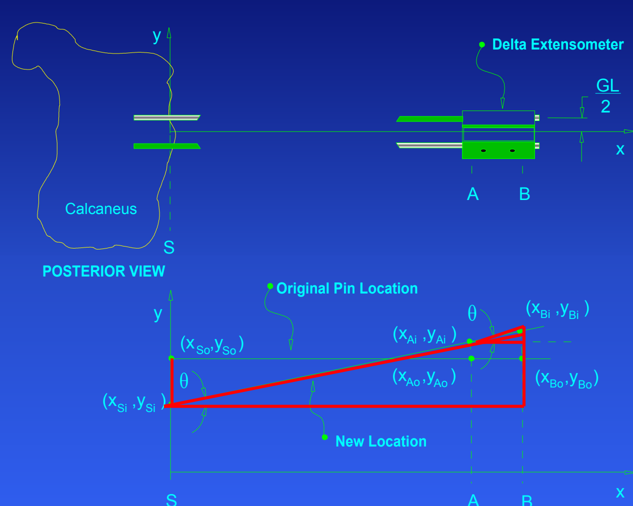
Mohr's circle for strain:



- Can calculate principal strains (ε P and ε Q) and their direction (φ P,Q)
- Can calculate maximum shear strain (γ max = ε P - ε Q)
- Can measure degree of bending in specimen with extensometer

Note : $\phi = -\theta$

Design – Data Reduction Algorithm



Presentation Outline

Background
and Importance

Methodology and
Results

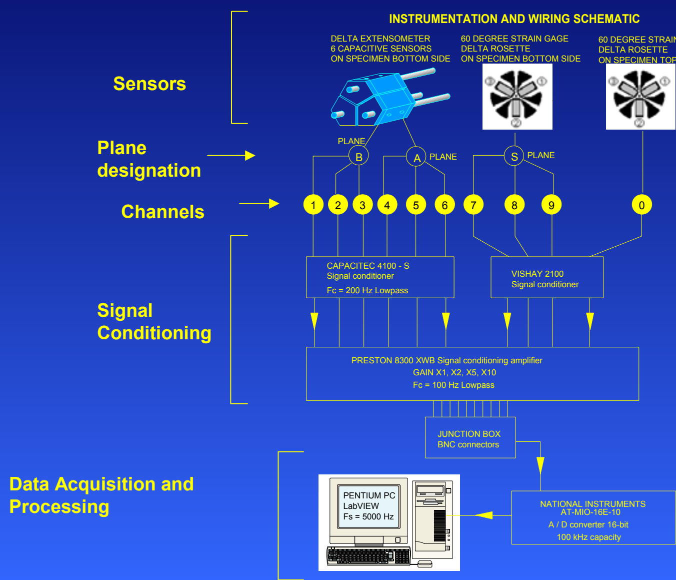
- Four-point bending validation tests
- Supporting experiments
- *In vivo* test in human calcaneus

Conclusion

Methodology - Four-Point Bending Tests

Dynamic Four-Point Bend Setup - Delta Extensometer

Methodology - Four-Point Bending Tests



Methodology - Four-Point Bending Tests

Four-Point Bend Tests (Delta)

Sinusoidal inputs at 1, 5, 10, 19 and 20 Hz

Square wave inputs at 2 Hz

Maximum strain magnitude 5,000 $\mu\varepsilon$

Maximum strain rate 50,000 $\mu\varepsilon$ / sec

26 data trials collected

Each trial lasted 1 second

Results

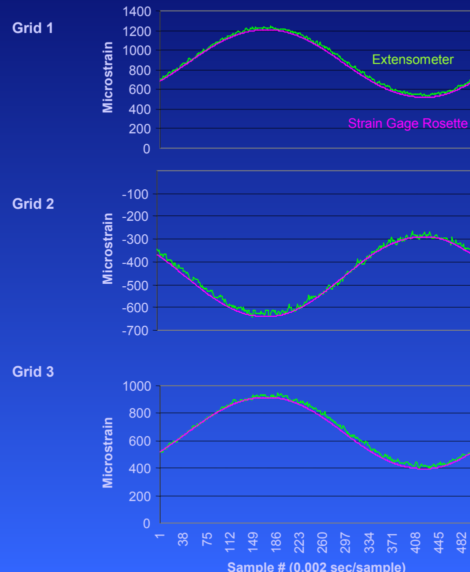
Methodology - Four-Point Bending Tests

Delta Extensometer 1 Hz

Correlation (0.999)
Max. difference = 55 με

Correlation (0.997)
Max. difference = 37 με

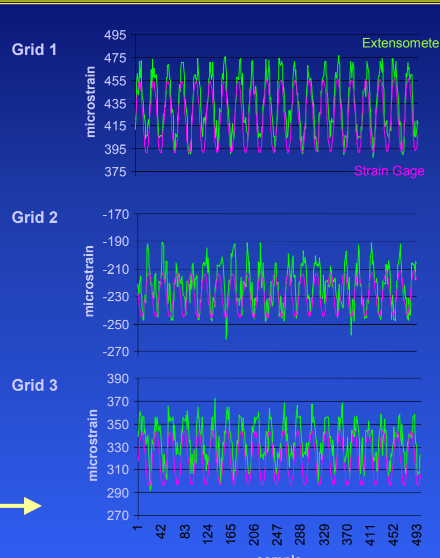
Correlation (0.998)
Max. difference = 54 με



Results - Four-Point Bending Tests

Delta Extensometer 20 Hz

Worst correlation (0.711)
Max. difference = 35 με



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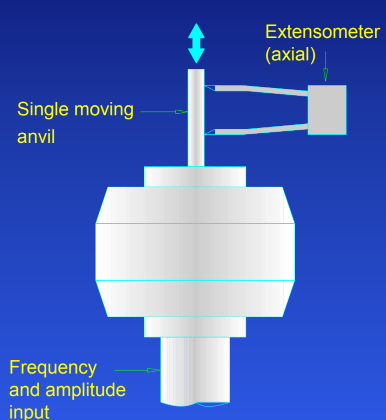
Methodology - Supporting Experiments

Frequency Response (ASTM E-83)



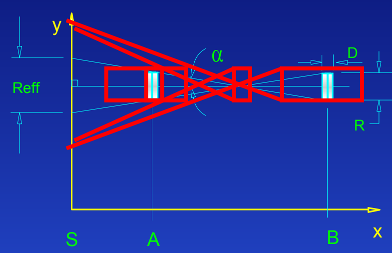
Results

Extensometer remained at **zero output** up to 500 Hz and 0.076 mm peak to peak amplitude.

Note: (0.076 / 12.7 = 5984 $\mu\varepsilon$)

Methodology - Supporting Data

Analysis of Effective Resolution (Reff):



R = resolution of individual sensor
(+/- 8 με - axial)
(+/- 14 με - delta)
(+/- 0.1 micron)

D = "diameter" of sensor
(1.91 mm - axial)
(1.0 mm - delta)

Effective resolution (Reff) can be written as:

$$Reff = 2 [SB - ((AB - D) /2) (\tan \alpha)]$$

	Axial	Delta (acrylic)	Delta (*in vivo*)
Effective Resolutions:	+/- 28 με	+/- 22 με	+/- 60 με

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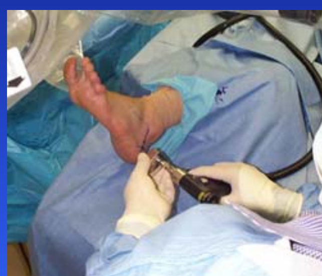
In Vivo Study

Experimental protocol for *in vivo* study

Orthopedic surgeon implanted stainless steel pins under sterile conditions, local anesthesia, and prophylactic oral antibiotic therapy. IRB Approved.

Intraosseus pins were K-wire, trochar tip, 1.57 mm dia.

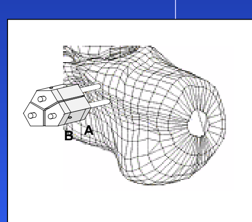


Pins implanted approx. 1/2 way into calcaneus

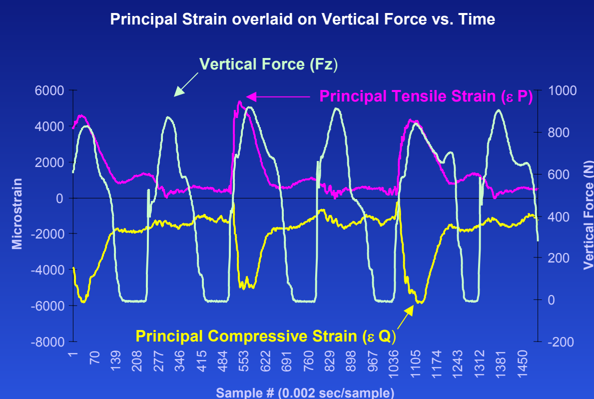
Pin separation = 7.1 mm (GL)

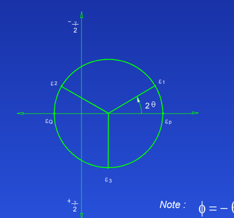
Drilling jig and fluoroscopy used to guide pin placement

In Vivo Study



Results - *In Vivo* Study

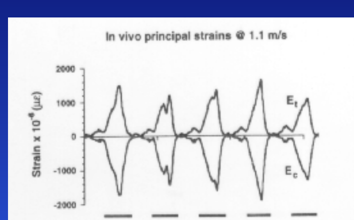


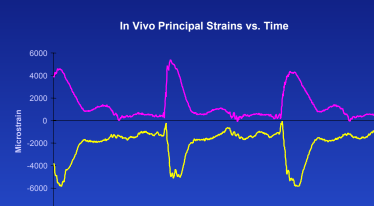


Walking at 5 km/hr on treadmill

Results - *In Vivo* Study

Principal strains in calcaneus measured *in vivo*

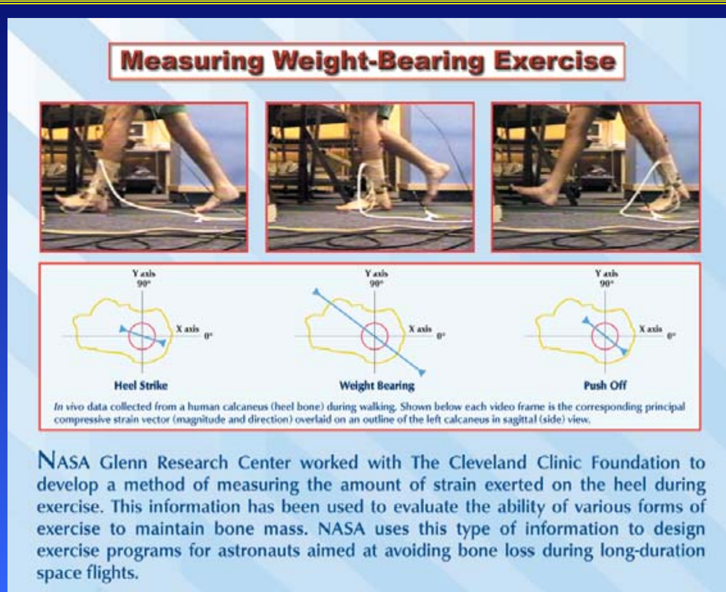




Biewener, et. al.(1996), potoroo walking at 4 km/hr

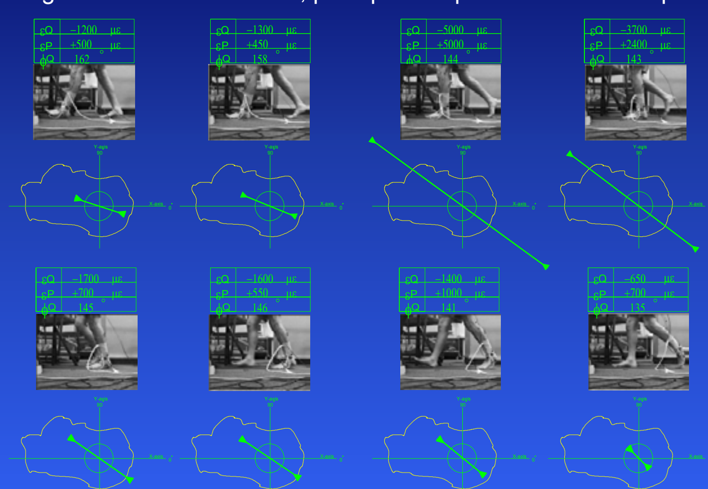
Human walking at 5 km/hr

Results - *In Vivo* Study



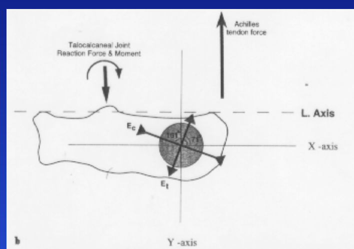
Results - *In Vivo* Study

Walking at 5 km/hr on treadmill, principal compressive strain comparison



Results - *In Vivo* Study

Principal compressive strain angle in calcaneus



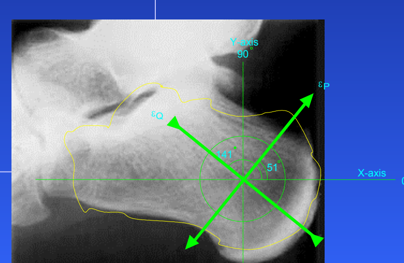
In a study by Biewener, et. al.(1996) principal compressive strain in calcaneus of potoroos during walking was 161 +/- 7 degrees.

Found quantitative agreement with trabecular orientation, experimental support of Wolff's Law (Julius Wolff, 1897).

For this study in human, do principal strains orient themselves similarly?

Results - *In Vivo* Study

Principal compressive strain angle in the calcaneus was found to align with bone architecture. This was a validating result.



Presentation Outline

Background

Methodology
and Results

Conclusion

- Benefits and limitations of new method

Conclusion (1 of 4)

Advantages of capacitive delta extensometer design (compared to other extensometers):

- Can measure principal strain magnitudes and their direction.
- Can measure degree and sense of bending in plane normal to pin axis.
- Device is lightweight.
- Device has a high frequency response.
- A wide range of gage lengths possible.

Conclusion (2 of 4)

Advantages of capacitive extensometer design (compared to bonded strain gages):

- Less invasive when used *in vivo*, less complicated surgical procedure.
- No bonding agents required, no special surface preparation.
- Possibly more reliable -- not exposed to biological environment.
- No reinforcing effect (non-contact probes).
- Device is reusable.

Conclusion (3 of 4)

Limitations of capacitive extensometer design:

- Must implant pins into specimen. Method is **invasive.**
- Resolution **is lower** than bonded strain gages and other extensometers (+/-10 to 20 $\mu\varepsilon$ at best vs. +/-1 to 2 $\mu\varepsilon$).
- More expensive than bonded strain gages.
- Method requires precise measurement of geometry or some form of medical imaging (MRI or fluoroscopy) when used *in vivo.* Strain calculation is *v*ery sensitive to geometry definition, such as gage length.

Conclusion (4 of 4)

In summary...

- A method of strain measurement for use in humans was designed and validated. Strain data was captured *in vivo* in a human calcaneus **for the first time**.
- Uses non-contact capacitive linear displacement probes, coupled together to provide principal strain and bending information -- a novel capability for an extensometer.
- Has **limitations** which were quantified as far as possible.
- Has certain **benefits** over both existing extensometer designs and bonded strain gage methods.
- Is a potentially **valuable research tool,** with possible applications to materials other than bone.