

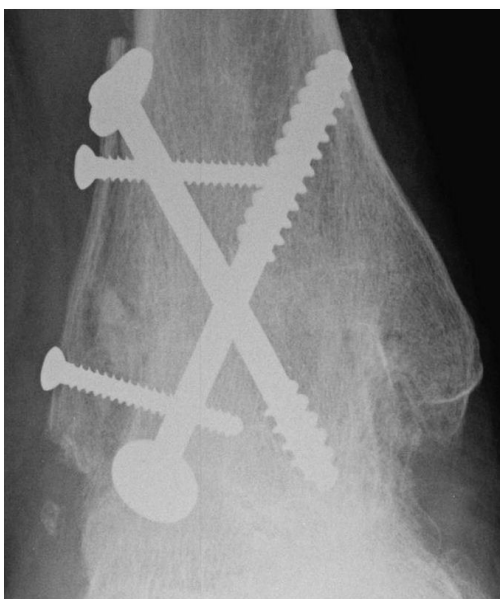
Engineering of the Musculoskeletal System and Rehabilitation

5.2 Numerical methods

Ankle

Clinical Background

TAR midterm results



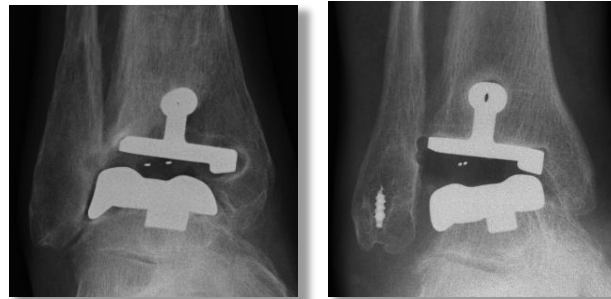
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- Pain ↓
- Function ↑
- Satisfaction
- Sports

Clinical Background

Revision **5-25 %**

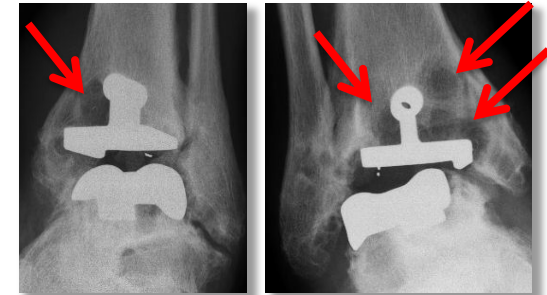


Labek G et al FAI 2011

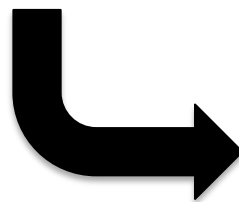
Survival
at 10 years
70-80 %

*Henricson A et al
Acta Orthop 2011*

Cysts **0-60%**



*Besse J FAI 2009
Anderson T JBJS-A 2008*

 How can this be improved?

How numerical modeling can help?

- Replicate TAR on a computer model
- Compare alternative solutions (on patients)
- Evaluate effects on mechanical quantities:
 - Bone strain (deformation)
 - Bone implant fixation (interfacial stress)
 - Range of motion, Joint stability
- Avoid/reduce supposed critical values
- Optimal implant design, surgical technique

Fixed vs Mobile TAR



Fixed (Salto Talaris)

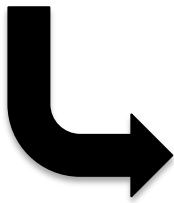


Mobile (Salto)

Fixed vs Mobile TAR

The mobile bearing is thought to

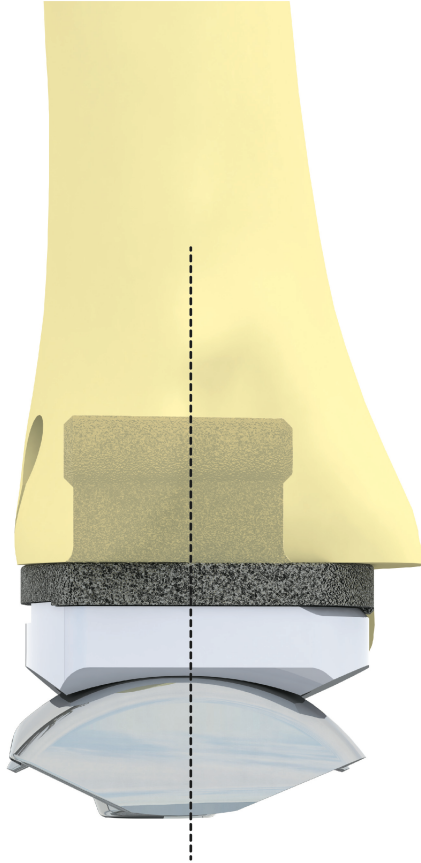
- Provide greater mobility
- Reduce polyethylene wear
- Reduce bone and bone-implant stress



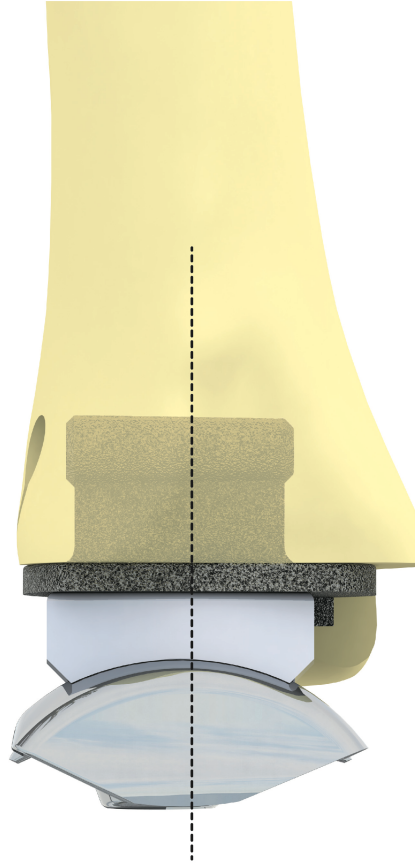
Is there an advantage to using a mobile-bearing vs fixed-bearing implant?

3 Cases Compared

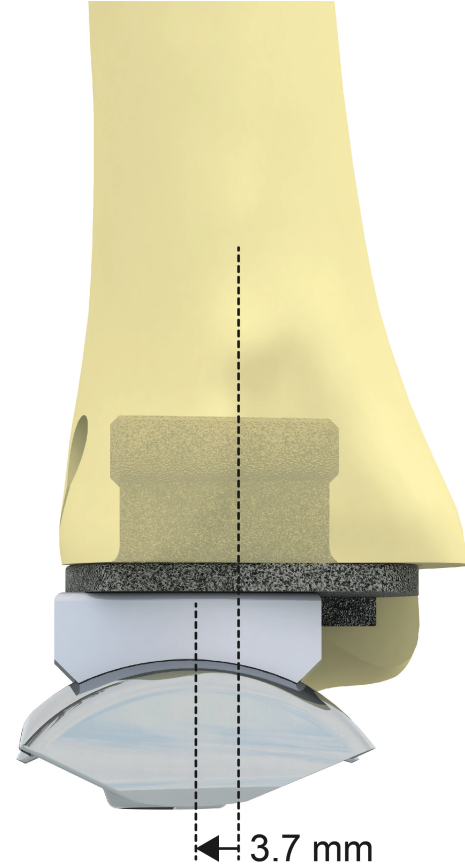
Fixed Centered



Mobile Centered



Mobile Eccentric



3.7 mm anterior shift
(Leszko et al.)

Mobile Eccentric

Table 1: Average magnitudes (avg), standard deviations (SD) and the absolute range of motion (avg range) of the anterior-posterior translation (mm) of the medial and lateral contact points of the mobile bearing insert, as well as the midpoint translation relative to tibial coordinate system

Mobile bearing insert anterior-posterior translation (mm)						
	Lateral contact point		Medial contact point		Midpoint	
	avg	SD	avg	SD	avg	SD
Gait						
HS	0.84	2.99	0.38	2.59	0.61	2.32
33%	1.18	2.57	-0.16	2.16	0.51	2.00
66%	1.64	3.43	0.10	2.76	0.87	2.80
TO	1.51	3.23	0.14	2.63	0.82	2.57
Avg range	2.04	1.05	2.05	1.00	1.54	0.98
Step-Up						
HS	0.94	2.03	0.38	3.13	0.66	2.26
33%	1.07	2.44	0.75	3.10	0.91	2.33
66%	1.64	3.23	1.00	3.29	1.32	2.81
TO	1.86	3.41	1.25	2.78	1.55	2.55
Avg range	2.77	1.20	2.85	1.32	2.32	1.02

LESZKO ET AL.

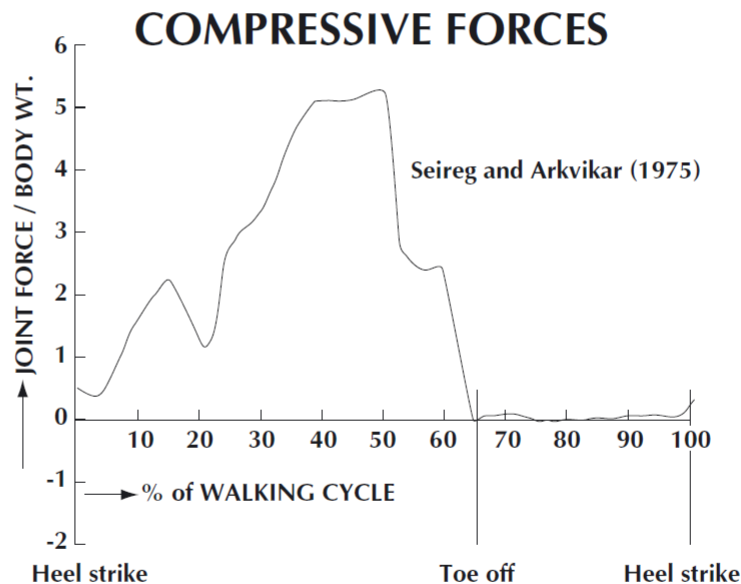
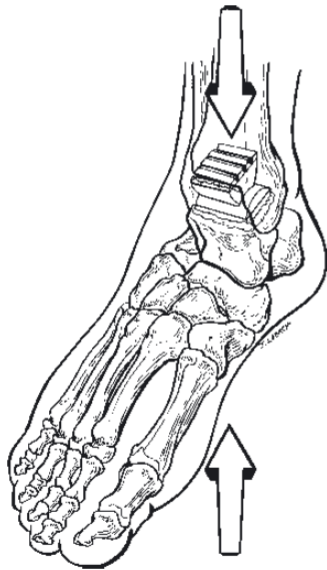
Foot & Ankle International/Vol. 29, No. 11/November 2008

3.7 mm ←

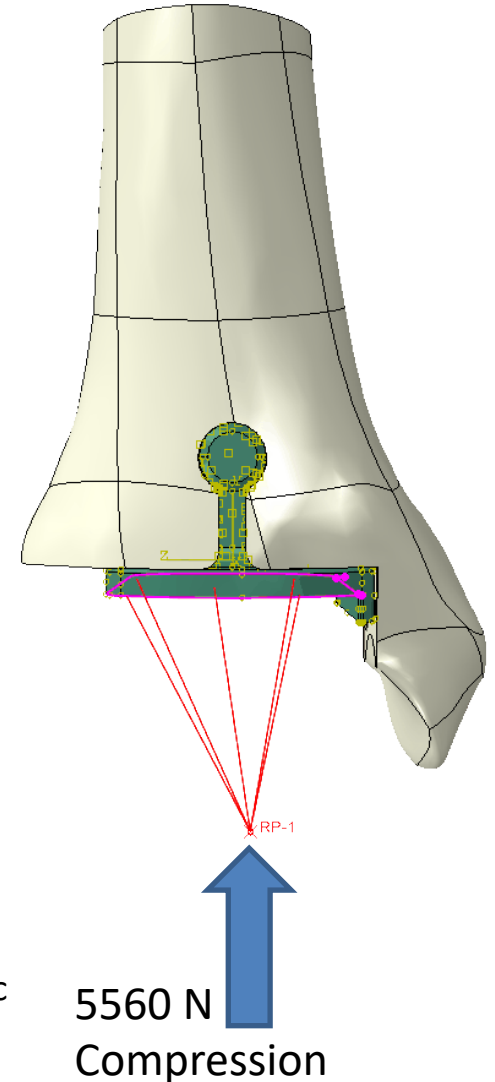
Compression

5x Body weight = $5 \times 1112 \text{ N} = 5560 \text{ N}$

ASTM Protocol

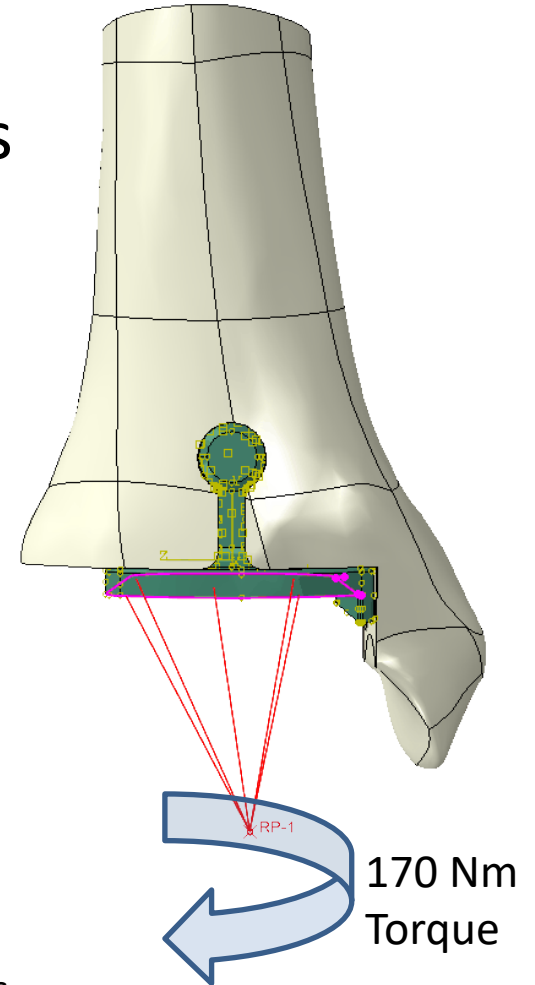
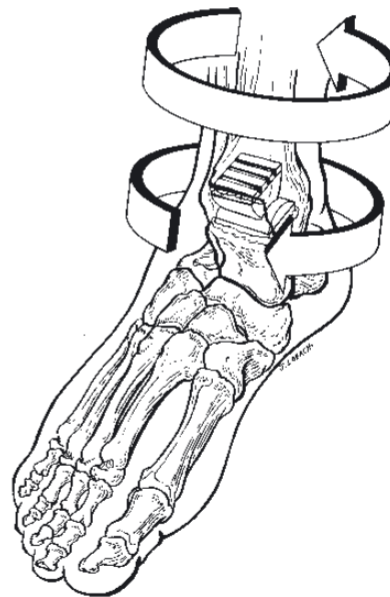
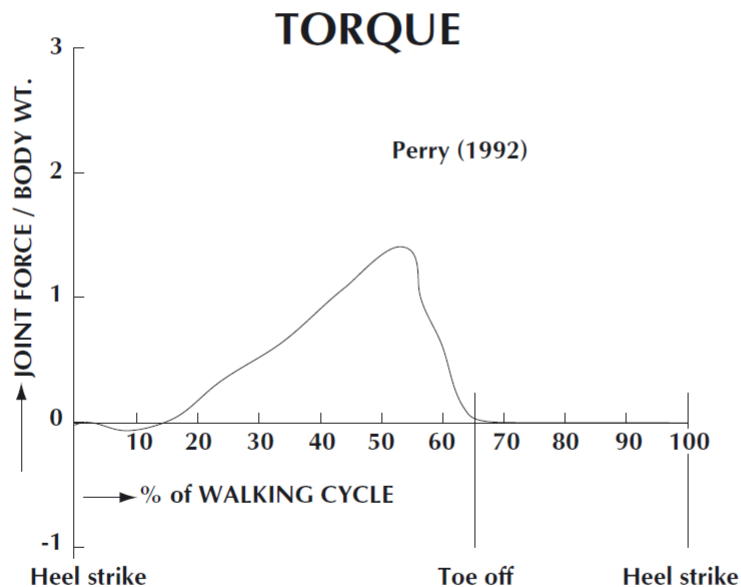


Raikin SM et al, Mobility Characteristics of Total Ankle Replacements, Orthopaedic Research Laboratories (2000).



Torque

$$1.5 \times \text{Body weight} = 1.5 \times 1112 \text{ N} / 9.8 \text{ m/s/s} = 170 \text{ Nm}$$

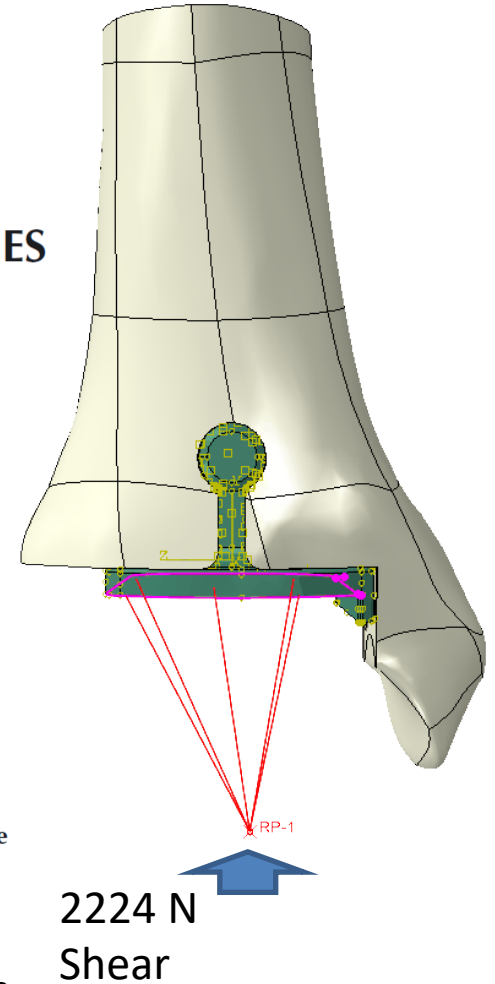
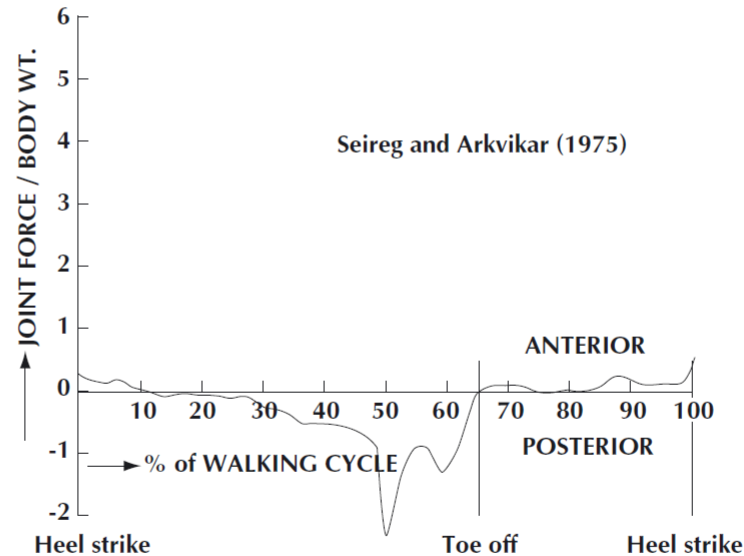
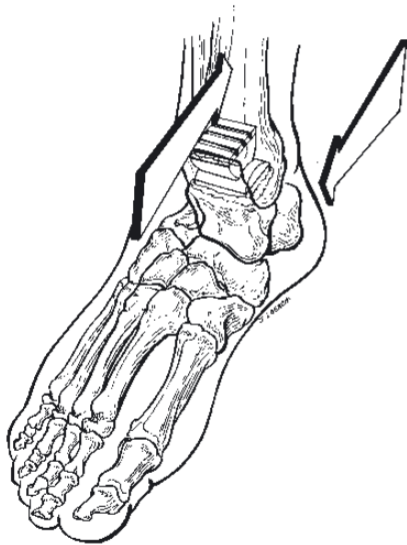


Raikin SM et al, Mobility Characteristics of Total Ankle Replacements, Orthopaedic Research Laboratories (2000).

Anterior-Posterior Shear

$$2 \times \text{Body weight} = 2 \times 1112 \text{ N} = 2224 \text{ N}$$

ANTERIOR-POSTERIOR SHEAR FORCES

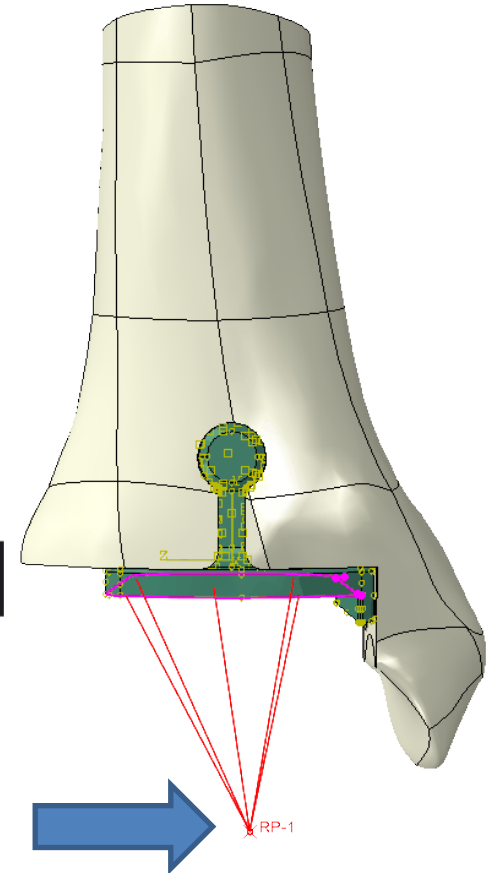
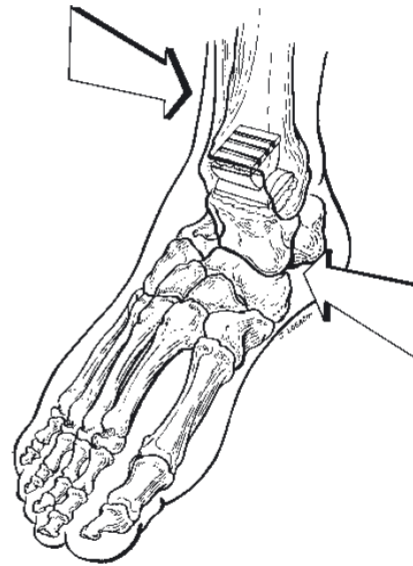
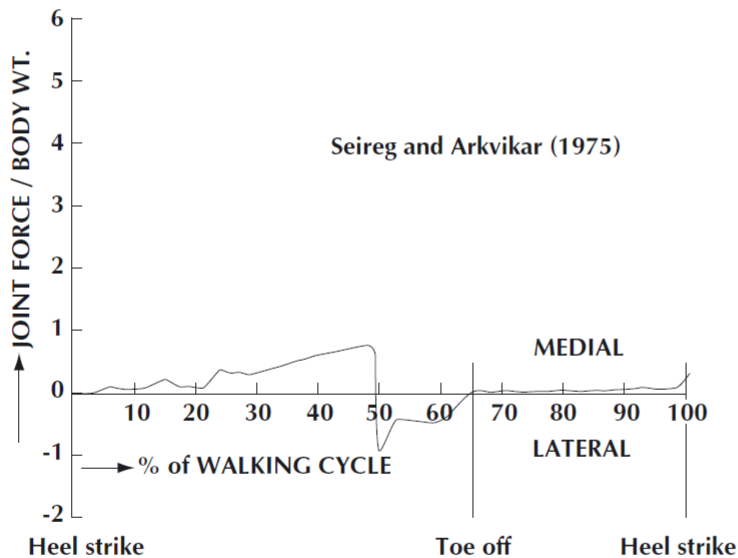


Raikin SM et al, Mobility Characteristics of Total Ankle Replacements, Orthopaedic Research Laboratories (2000).

Medial-Lateral Shear

$$1 \times \text{Body weight} = 1 \times 1112 \text{ N} = 1112 \text{ N}$$

MEDIAL-LATERAL SHEAR FORCES



1112 N
Shear

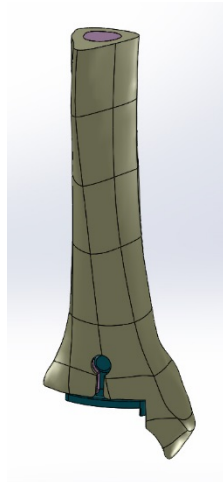
Raikin SM et al, Mobility Characteristics of Total Ankle Replacements, Orthopaedic Research Laboratories (2000).

Model Validation

7 Cadaver Tibias



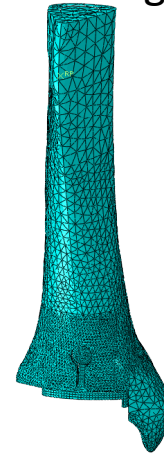
Virtual Surgery



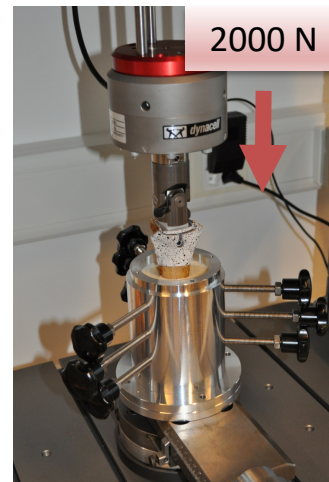
Surgery



Simulated Loading

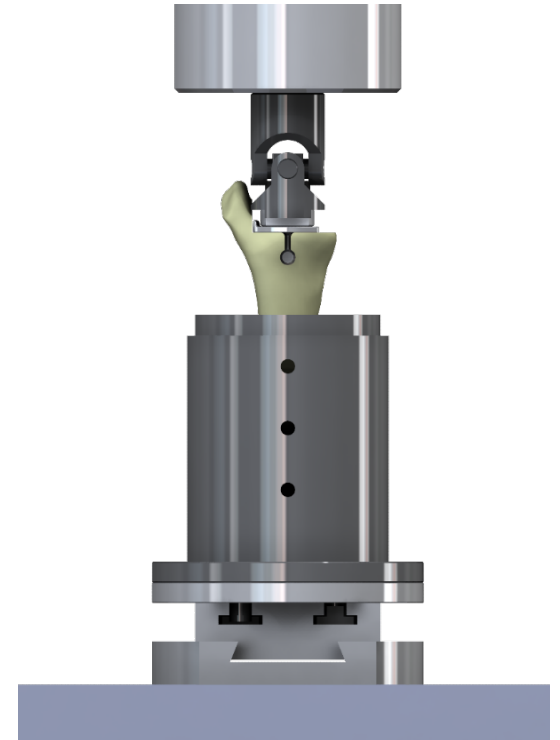
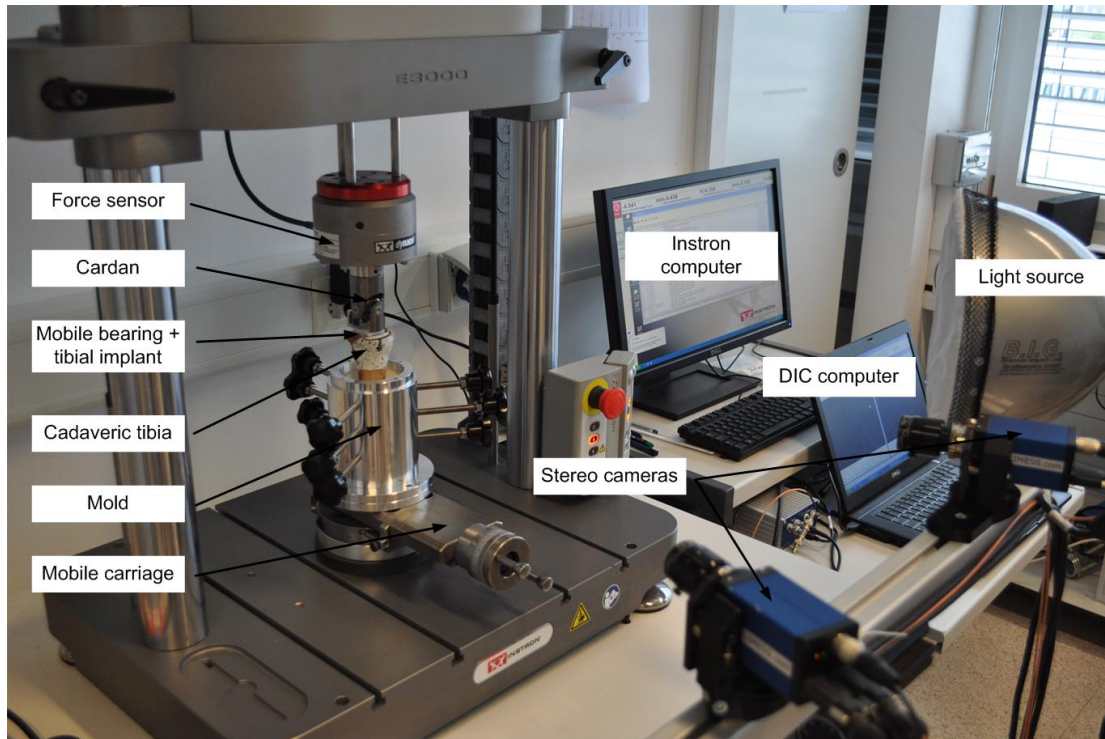


Mechanical Loading

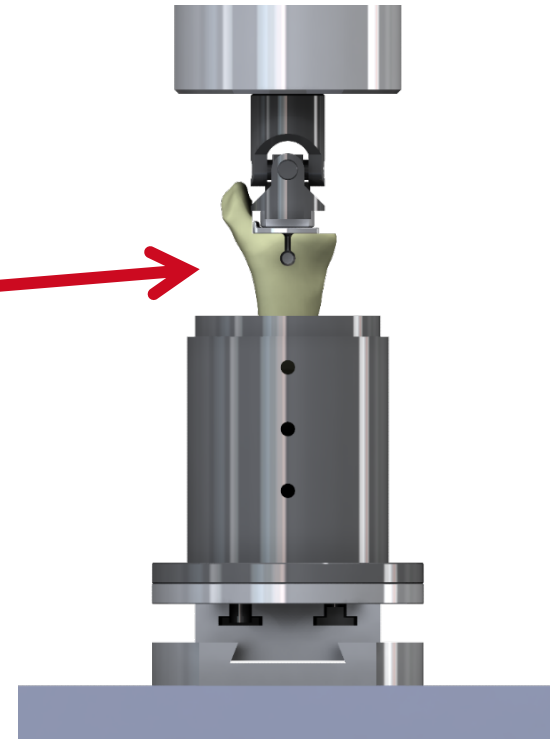
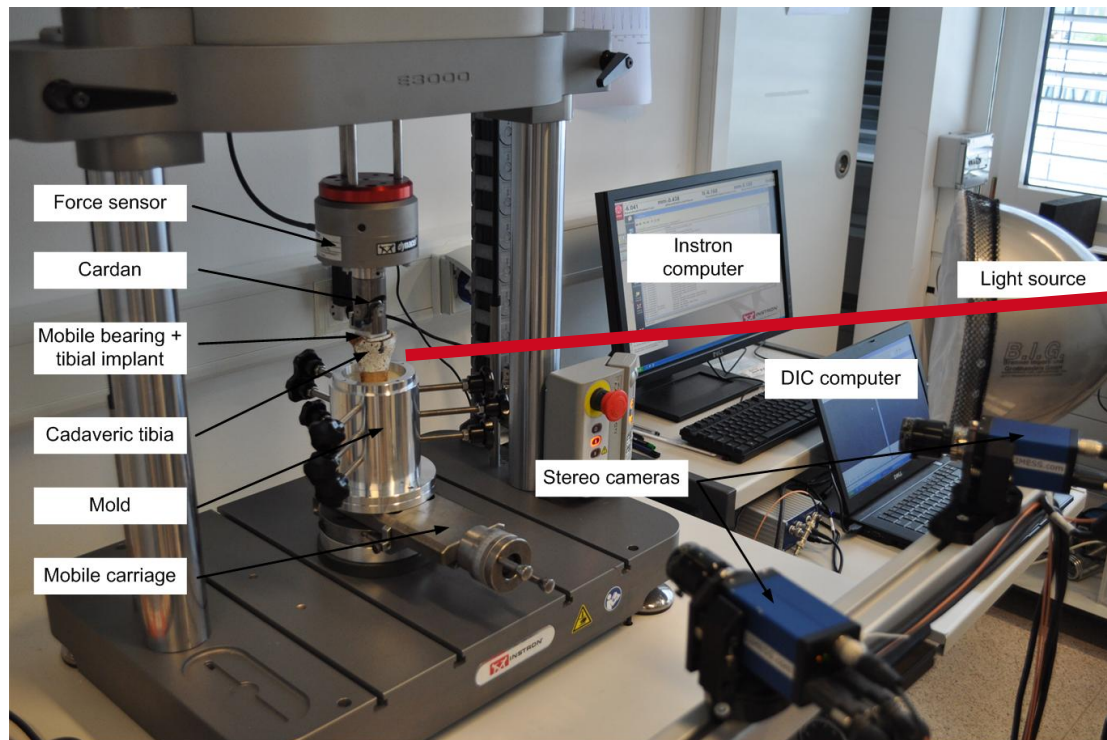


Comparison
&
Validation

Model Validation

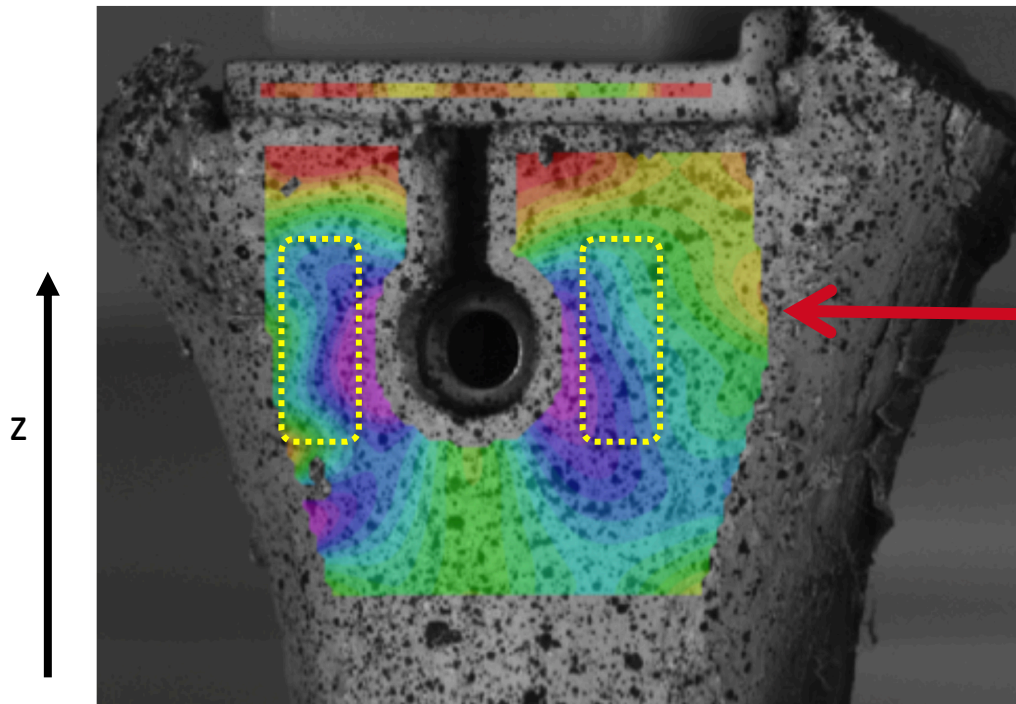


Model Validation

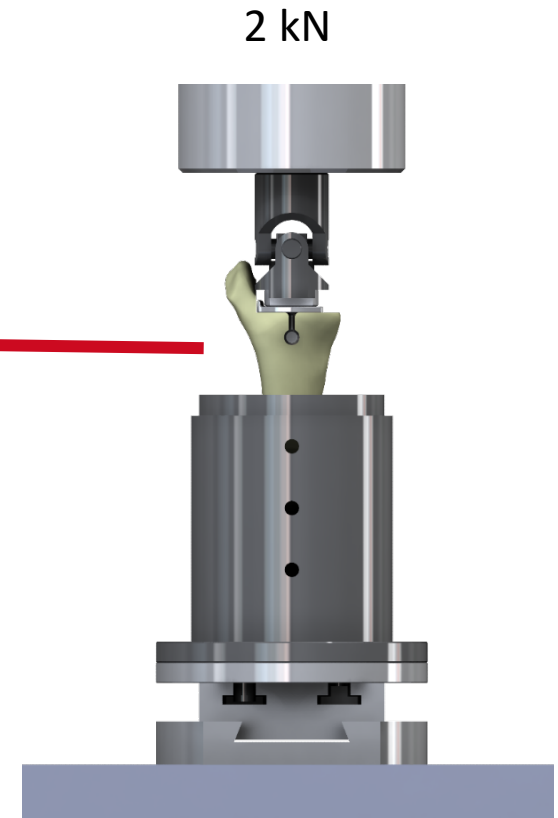


Model Validation

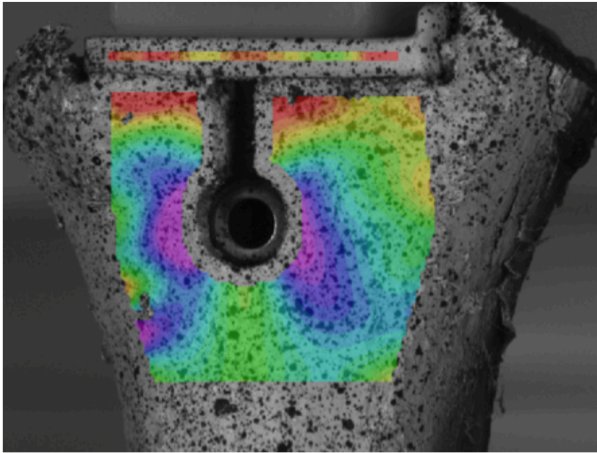
stereo digital image correlation



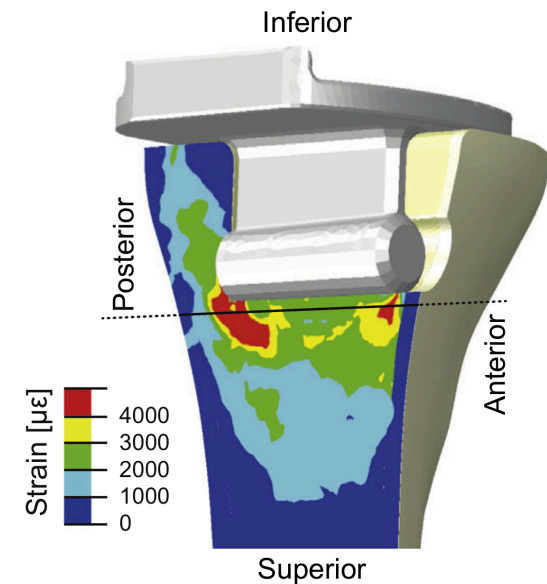
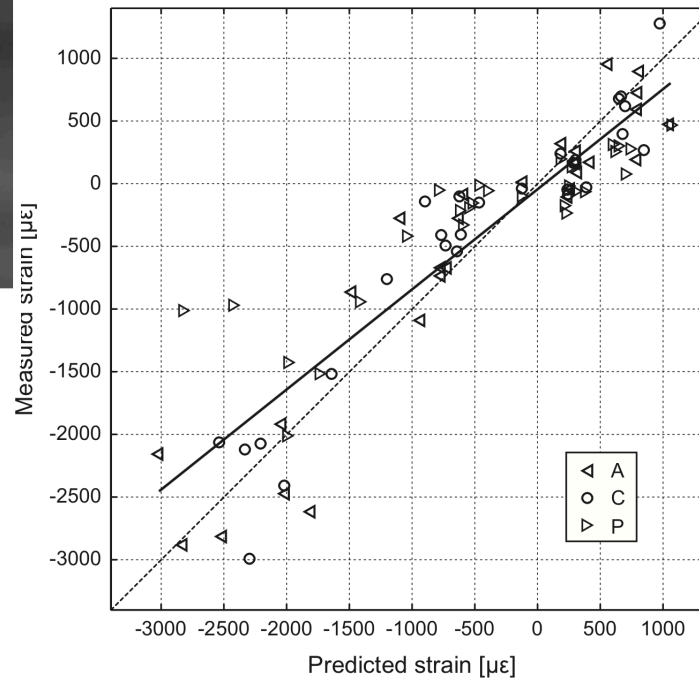
Experiment axial strain
 du/dz



Model validation



Experiment axial strain

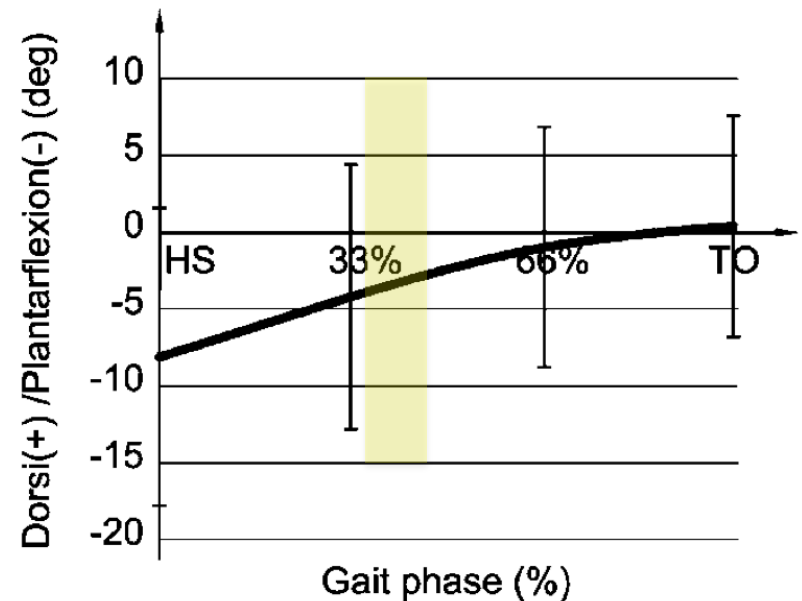
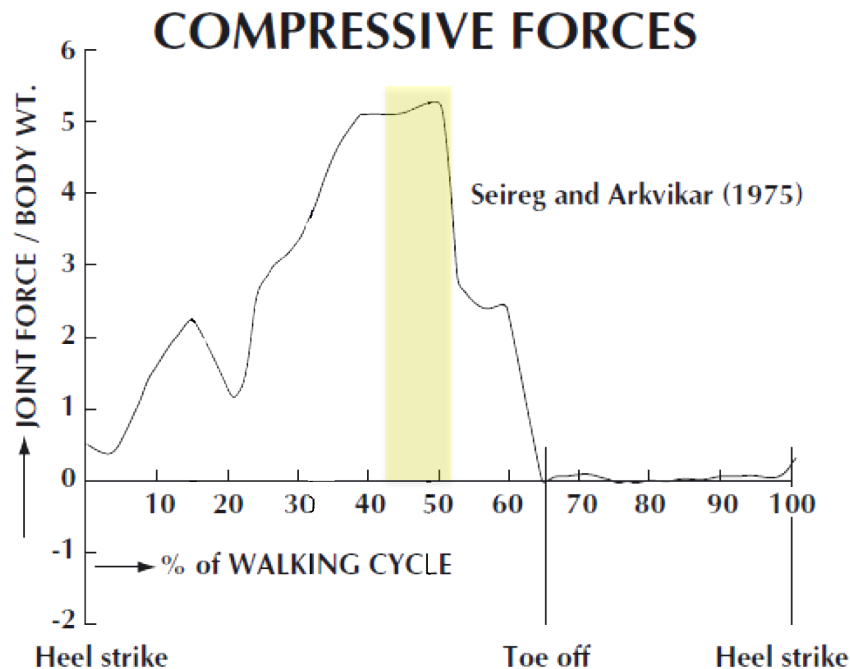


Numerical prediction

Testing Protocol

- ASTM protocol (F2665)
- Axial force of 5560 N
(5x body weight of an overweight person)
- Force applied at the center of the ankle joint
- Constrain (zero) rotations to correspond maximal force during walking

Loading



LESZKO ET AL.

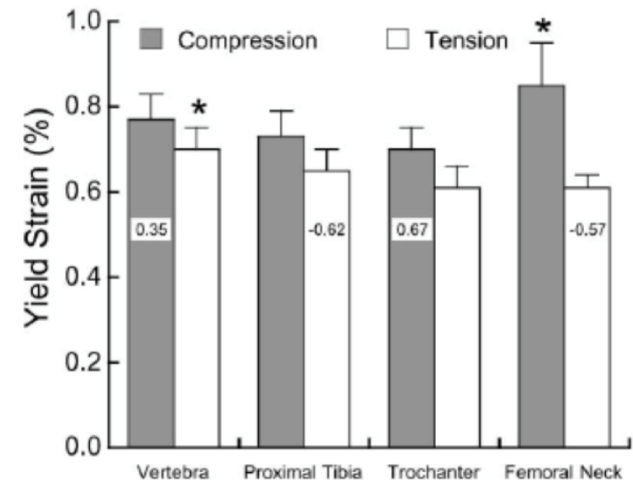
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Maximal Joint Force → about 50% of Gait Cycle → about 0° ankle flexion

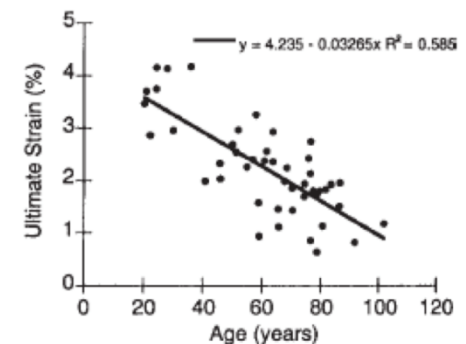
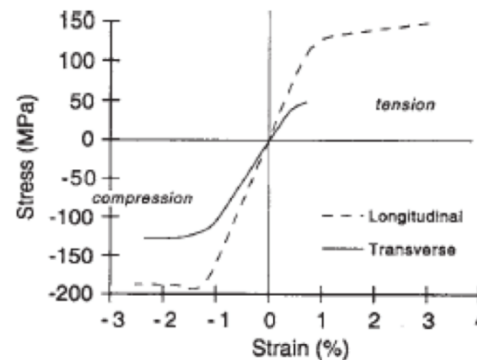
Overweight patients : BW= 1112 N → Compression force = 5 * BW = 5560 N (ASTM 2665)

Bone Strain Limit: 1%

- Carter, D. R., W. E. Caler, D. M. Spengler, and V. H. Frankel, Fatigue Behavior of Adult Cortical Bone: The Influence of Mean Strain and Strain Range. *Acta orthop*, 1981. 52(5): p. 481-490.
- Morgan, E. F., T. M. Keaveny, Dependence of yield strain of human trabecular bone on anatomic site, *Journal of Biomechanics*, 2001. 34: p. 569–577.
- Morgan, E. F., T. M. Keaveny, O. C. Yeh, Bone Mechanics, Myer Kutz: Biomedical Engineering and Design Handbook, 2009, Volume 1, Chapter 8.

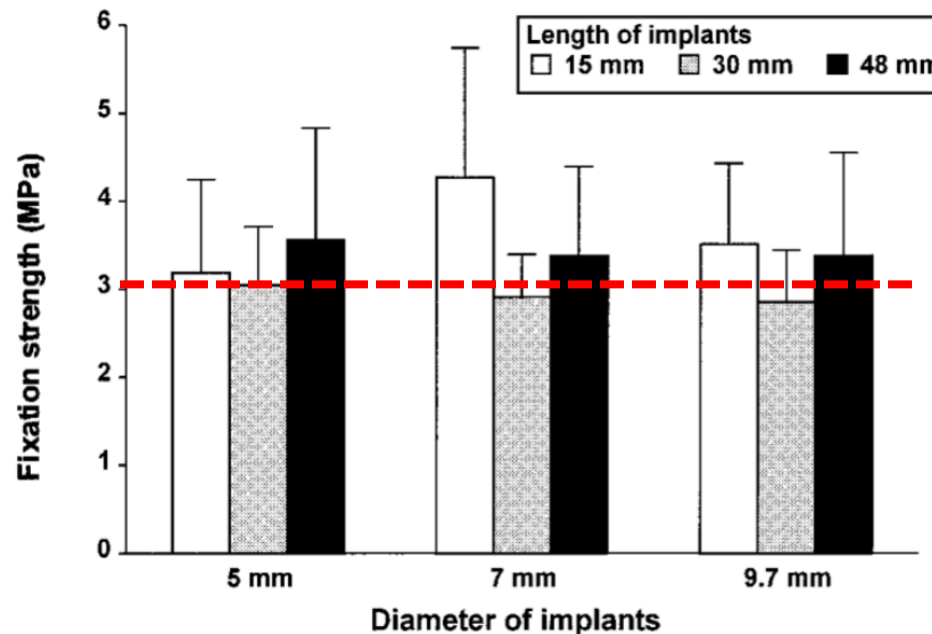


Mechanical Property	Mean	(S.D.)
Elastic Modulus E (GPa)	17.5	(1.9)
Yield, Strain* ϵ_y (mm/mm)	0.0068	(0.0004)
	0.0084	(0.0005)
Ultimate Strain ϵ_u	0.0157	(0.0038)
Yield Stress* σ_y (MPa)	129	(11)
	121	(11)
Ultimate Stress σ_u (MPa)	140	(12)

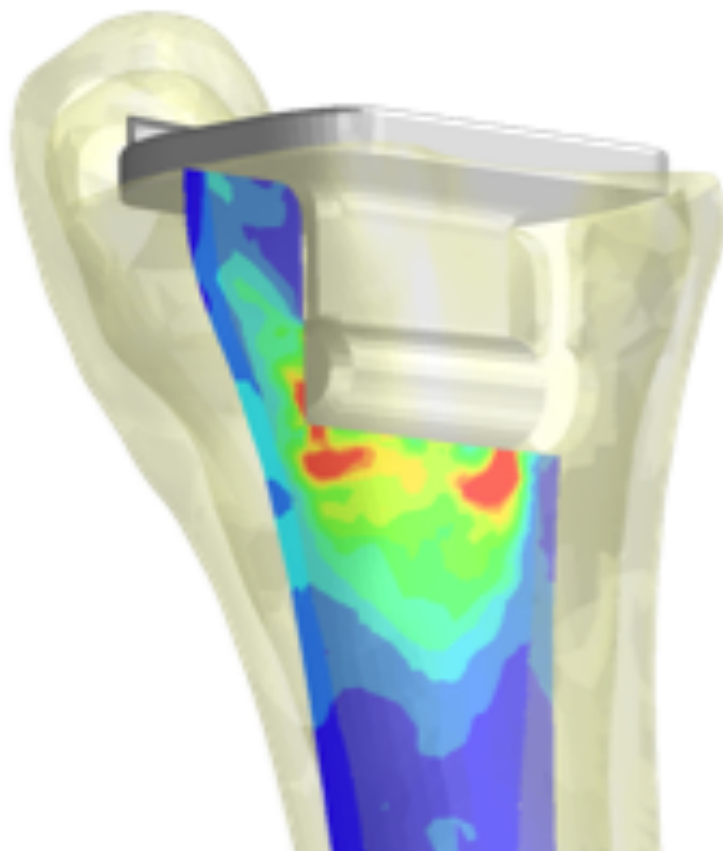


Bone-Implant Shear Stress: 3 MPa

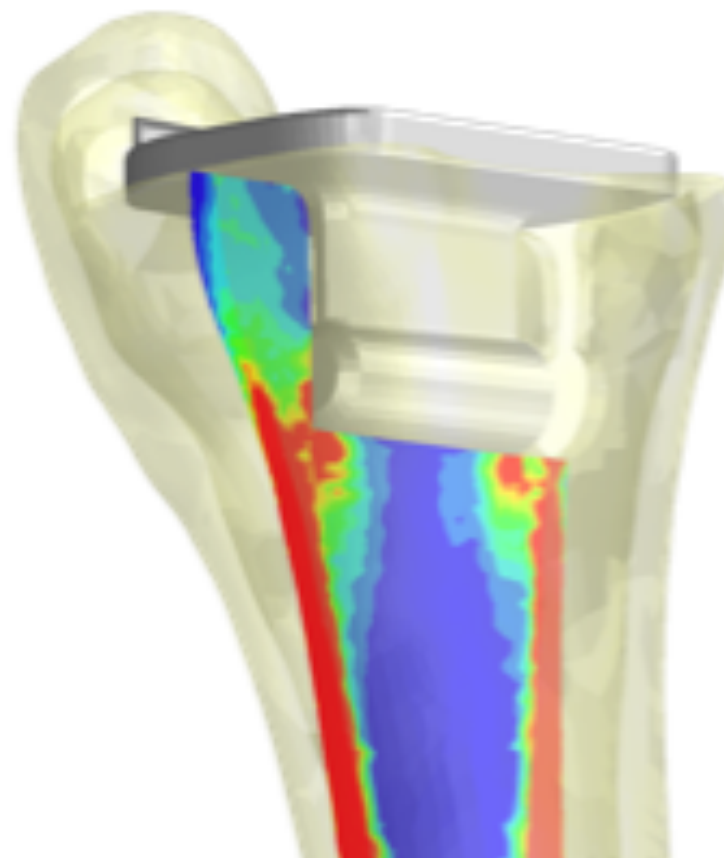
- Berzins, A., B. Shah, H. Weinans, and D.R. Sumner, Nondestructive measurements of implant-bone interface shear modulus and effects of implant geometry in pull-out tests. J Biomed Mater Res, 1997. 34(3): p. 337-40.
- Terrier, A., P. Buchler, and A. Farron, Bone-cement interface of the glenoid component: stress analysis for varying cement thickness. Clin Biomech (Bristol, Avon), 2005. 20(7): p. 710-7



Total Ankle Replacement



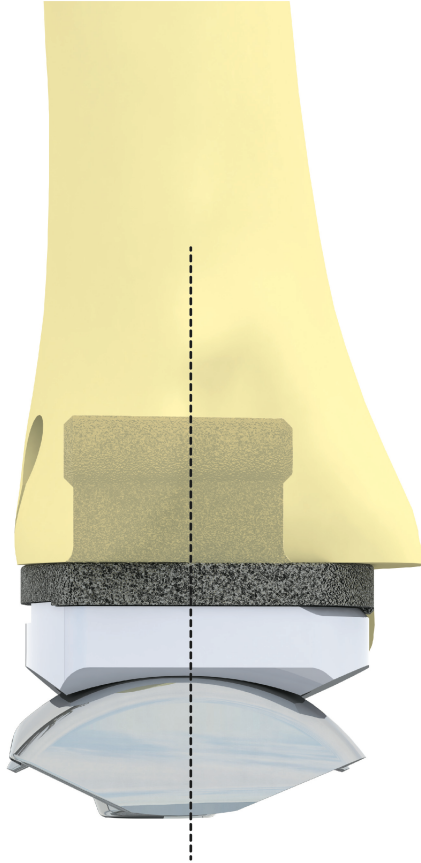
Bone strain



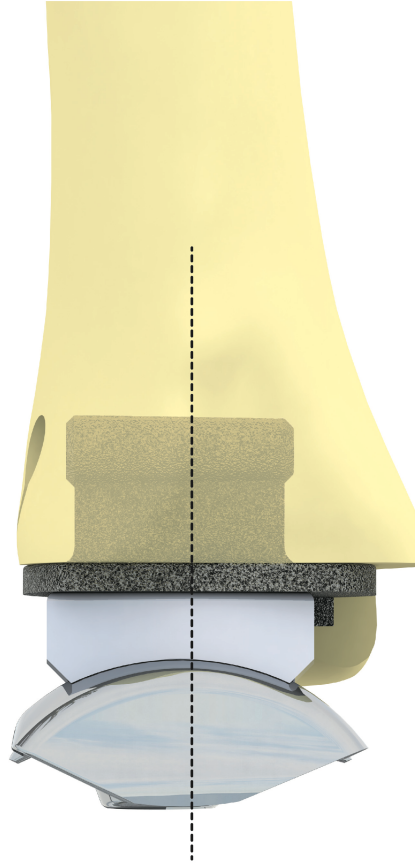
Bone stress

3 Cases Compared

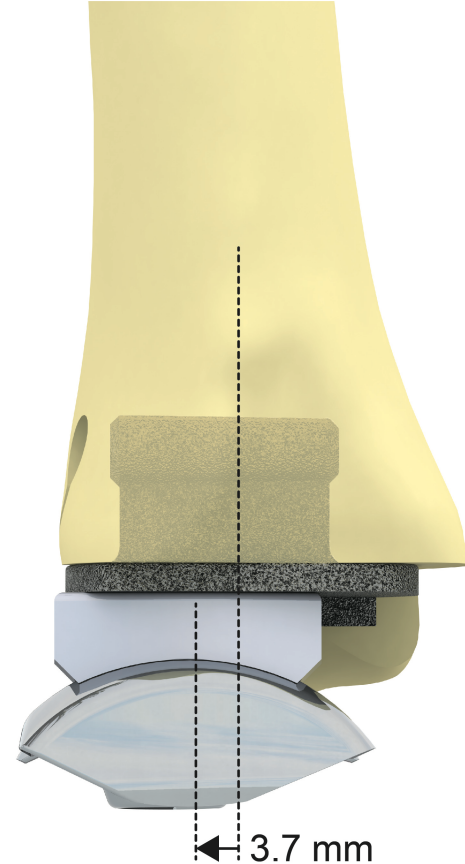
Fixed Centered



Mobile Centered



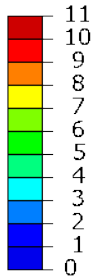
Mobile Eccentric



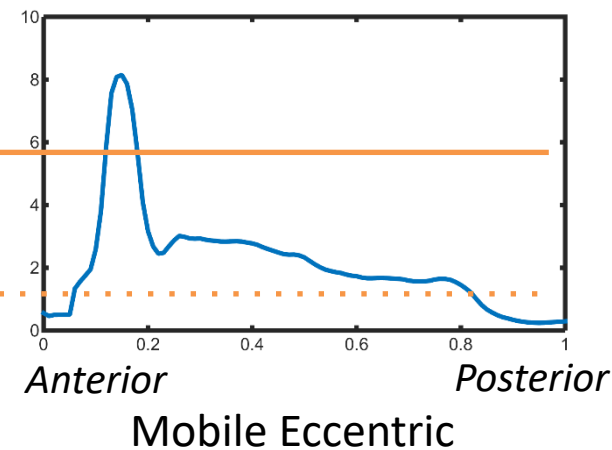
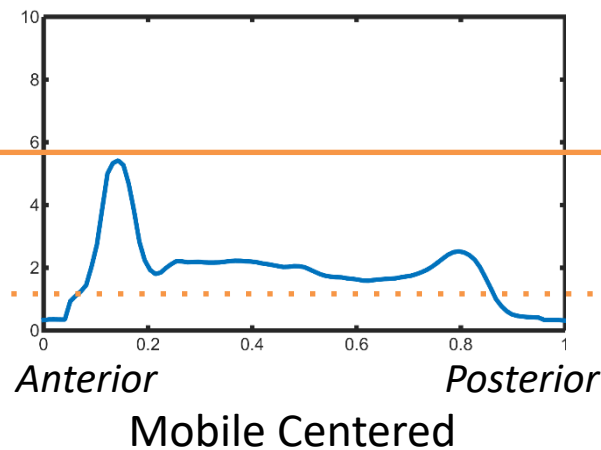
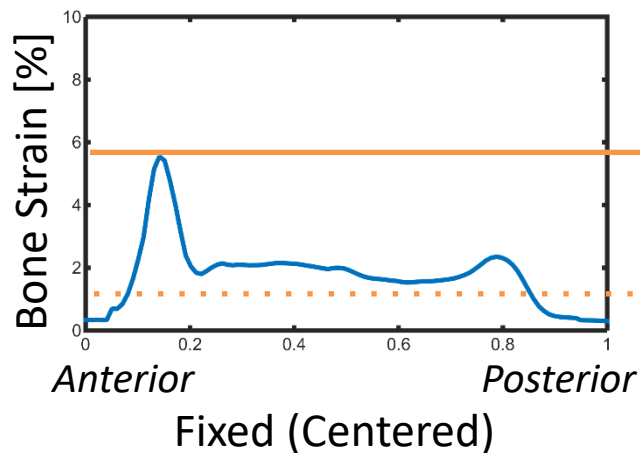
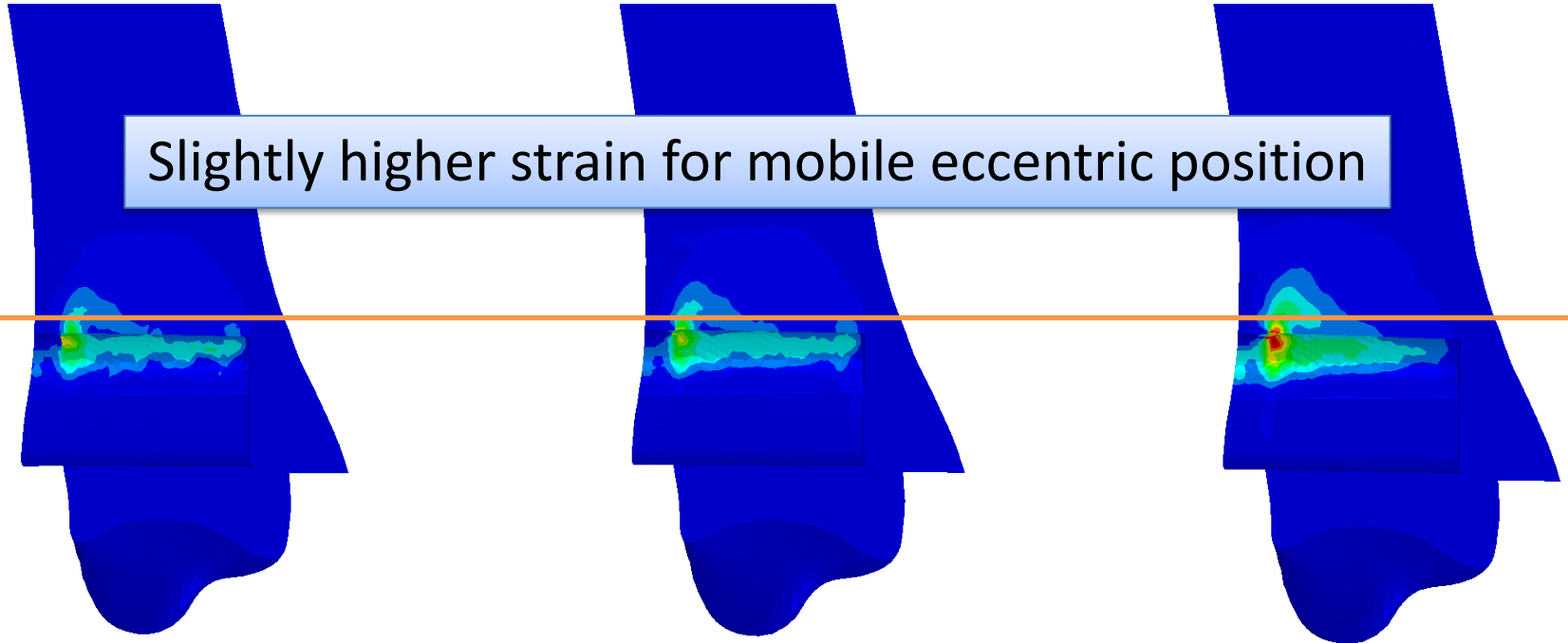
3.7 mm anterior shift
(Leszko et al.)

Bone strain (T02, compression)

OctShearStrain
(Avg: 75%)

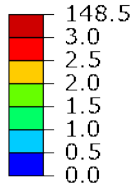


Slightly higher strain for mobile eccentric position

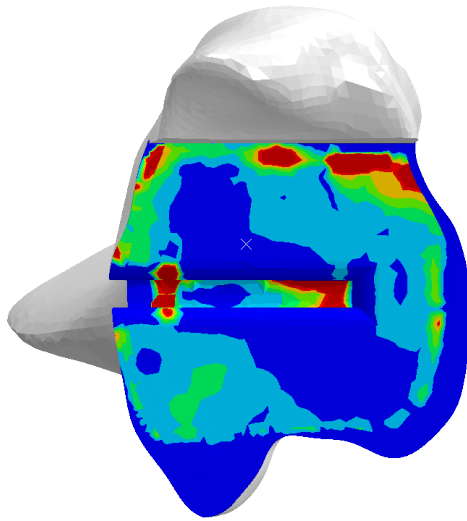


Bone-Interface Stress (T02, compression)

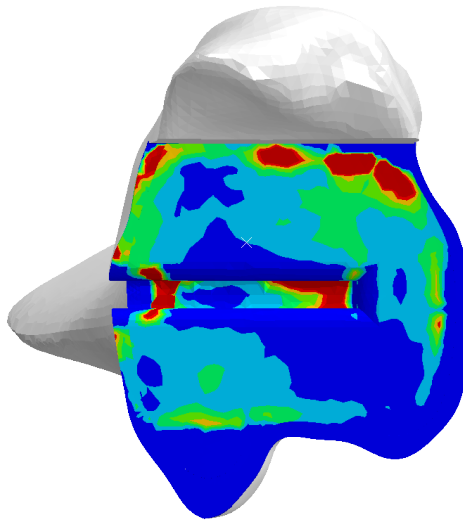
SHEAR_CONTACT



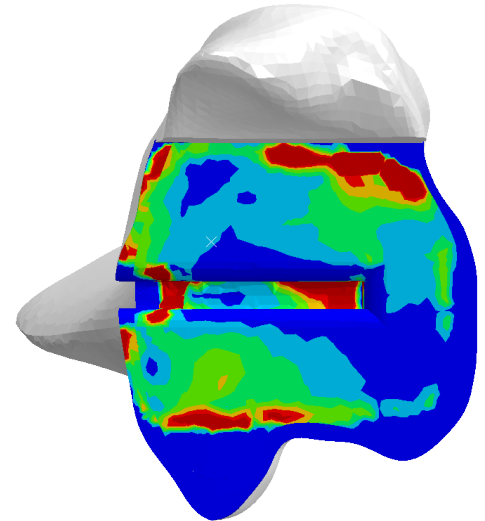
Slightly higher strain for mobile eccentric position



Fixed (Centered)



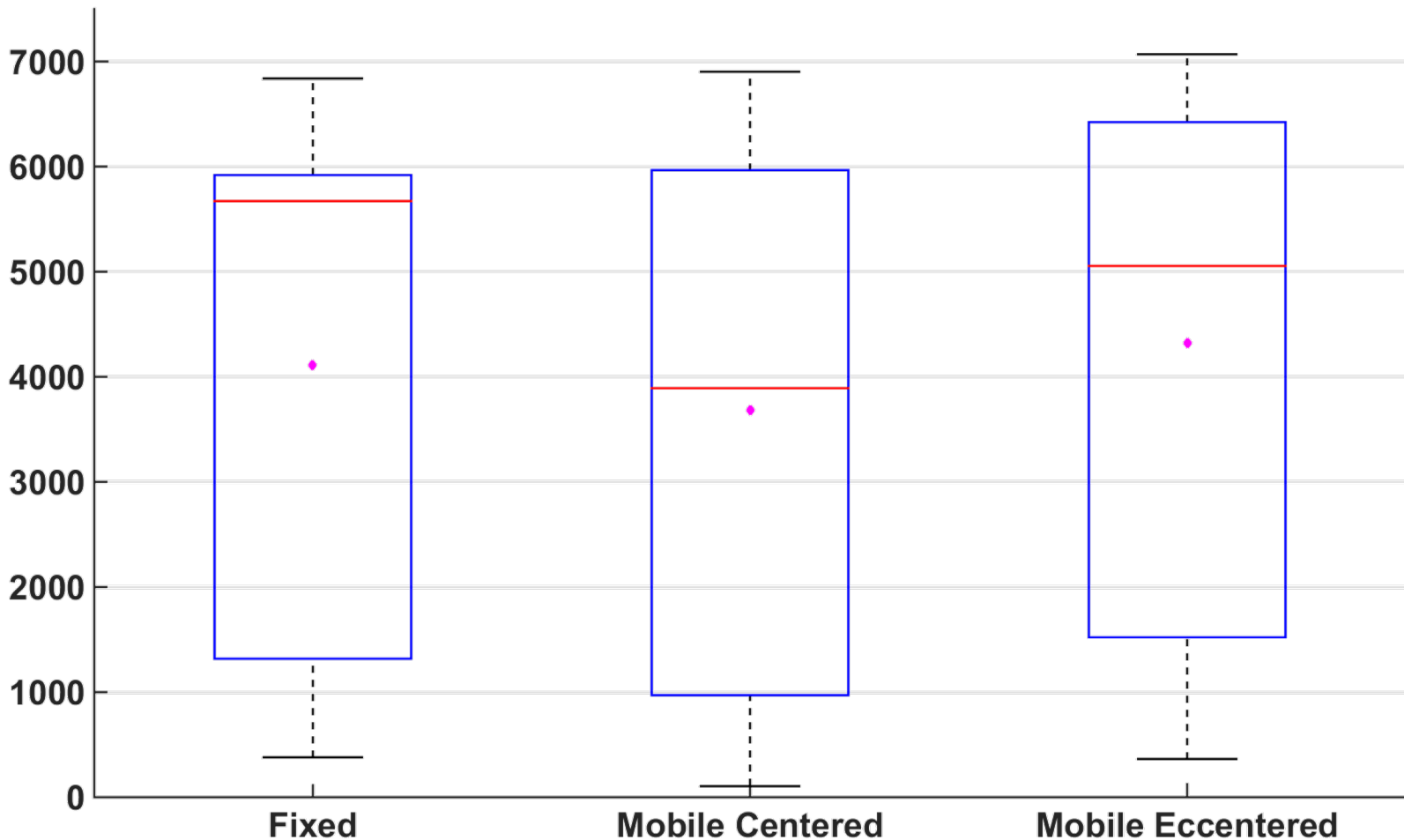
Mobile Centered



Mobile Eccentric

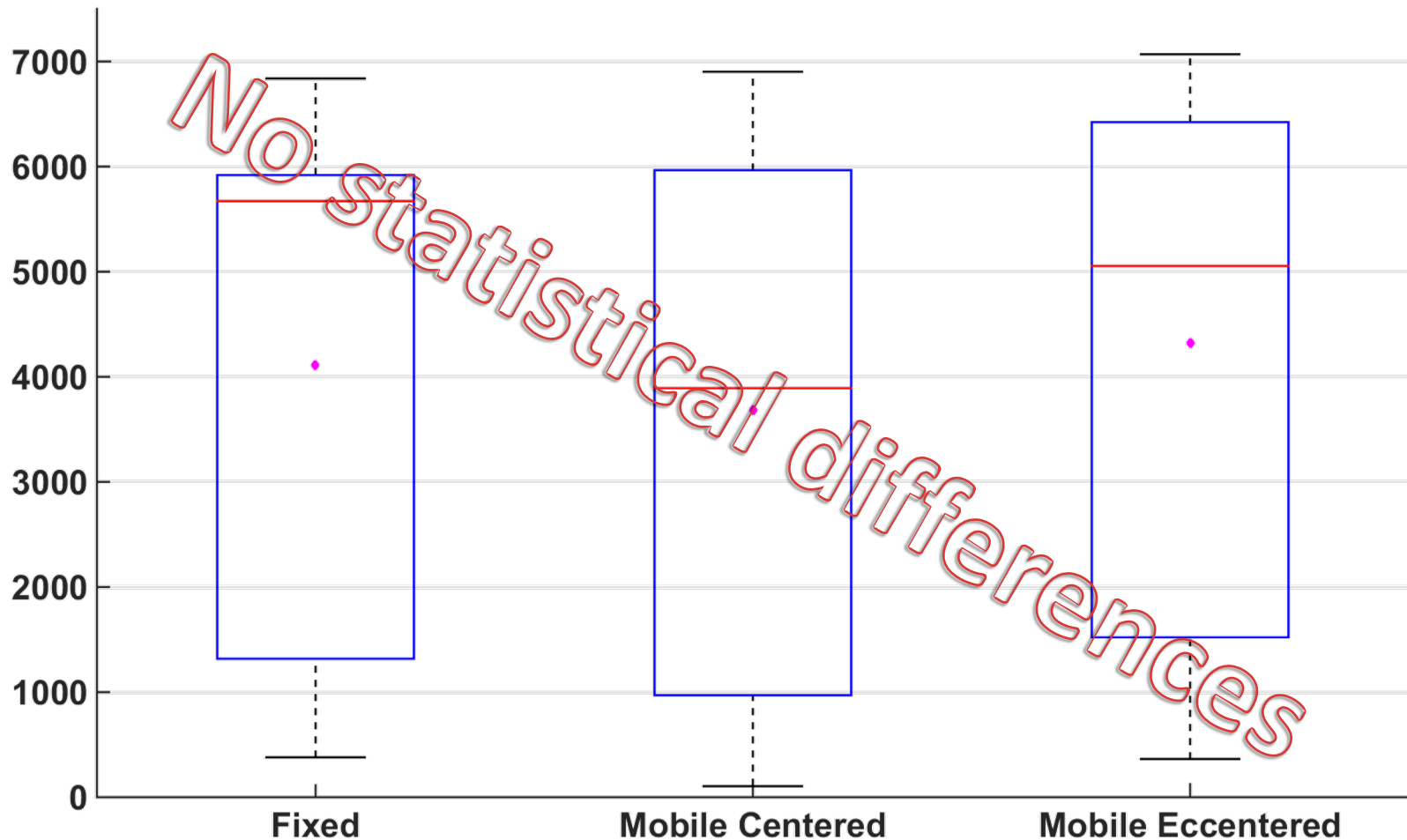
Bone Strain by Implant

Volume [mm³] of Bone with Octahedral Shear Strain $\geq 1\%$



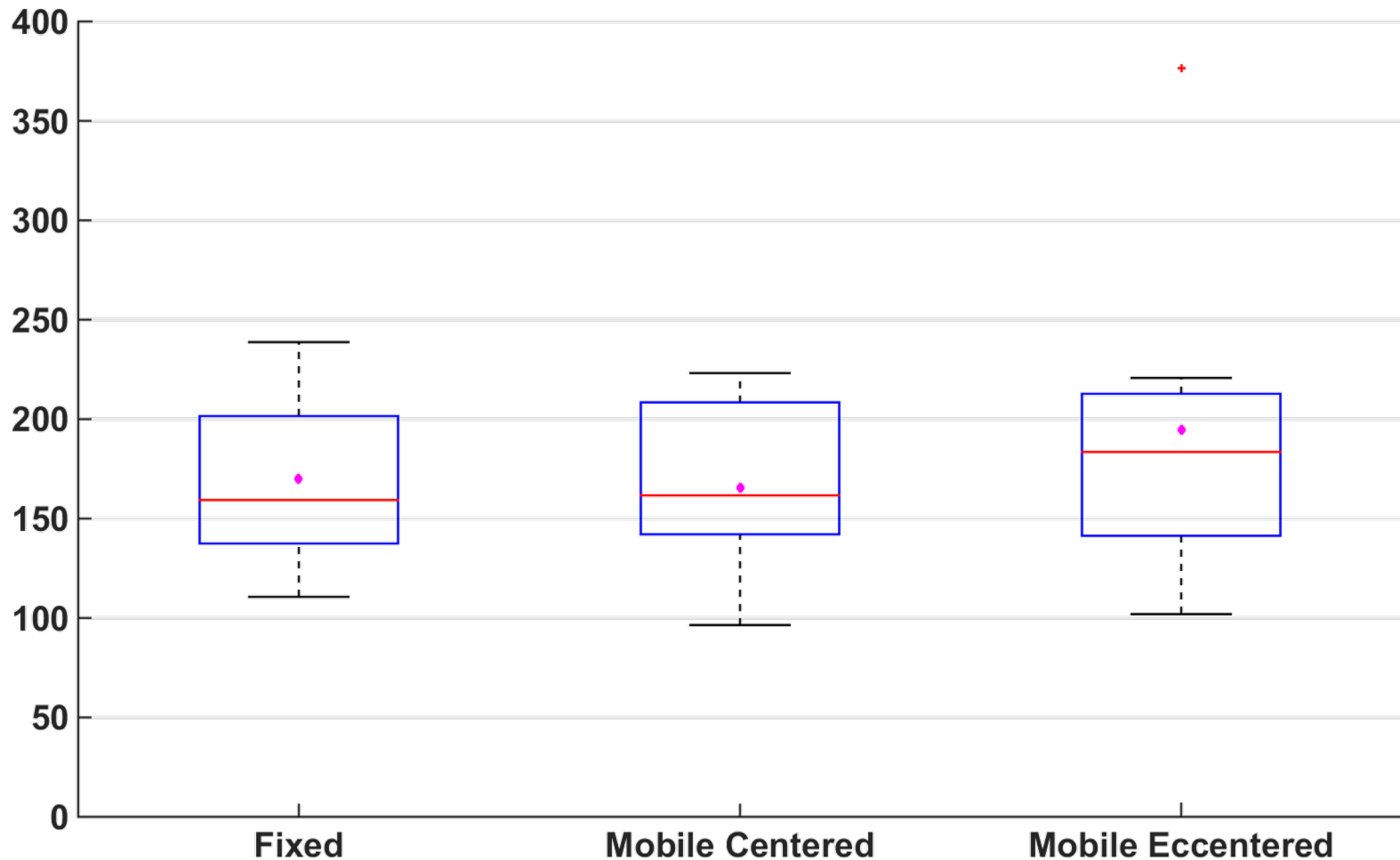
Bone Strain by Implant

Volume [mm³] of Bone with Octahedral Shear Strain $\geq 1\%$



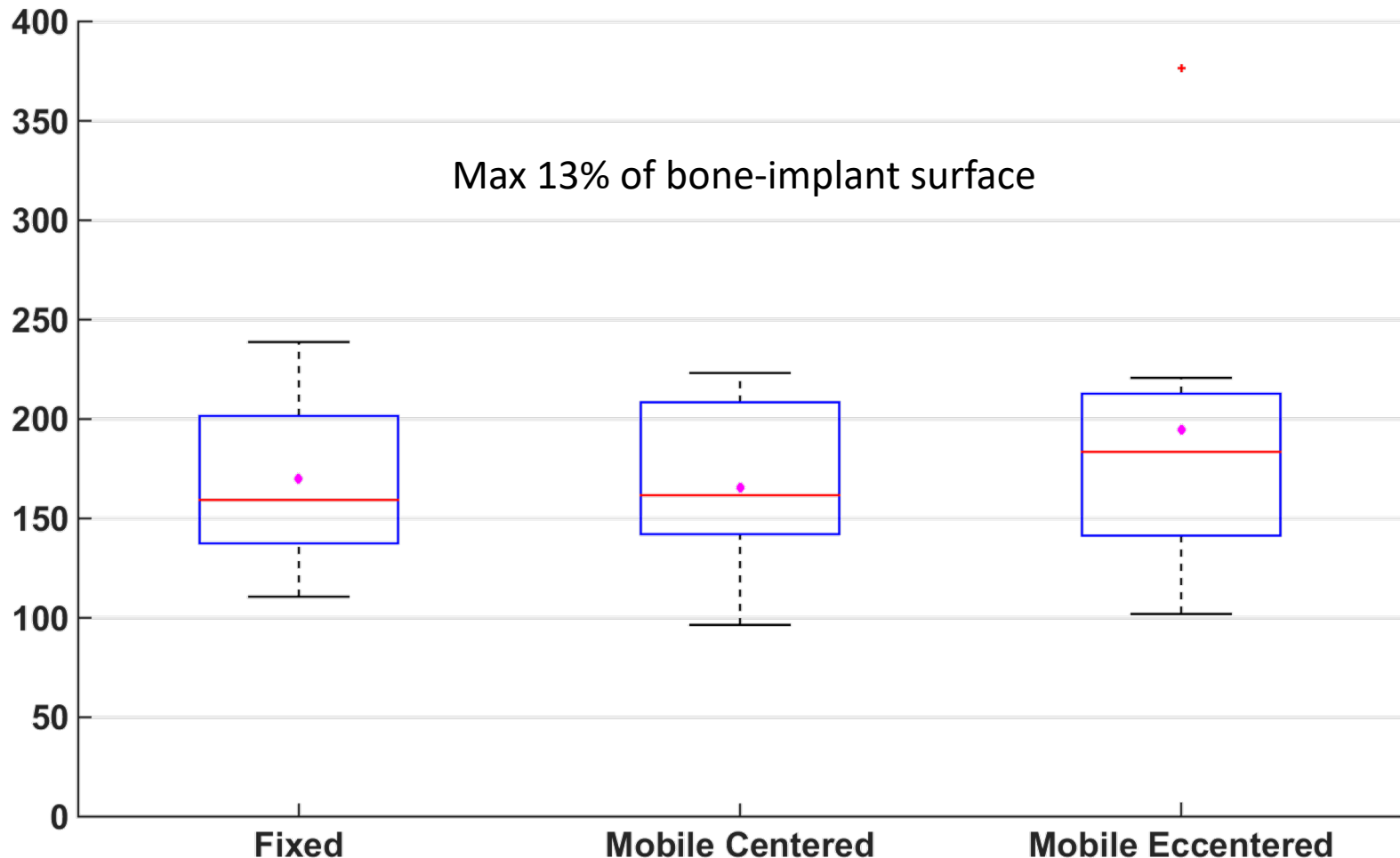
Bone-Interface Stress by Implant

Area [mm²] of Bone with Interfacial Shear $\geq$ 3 MPa



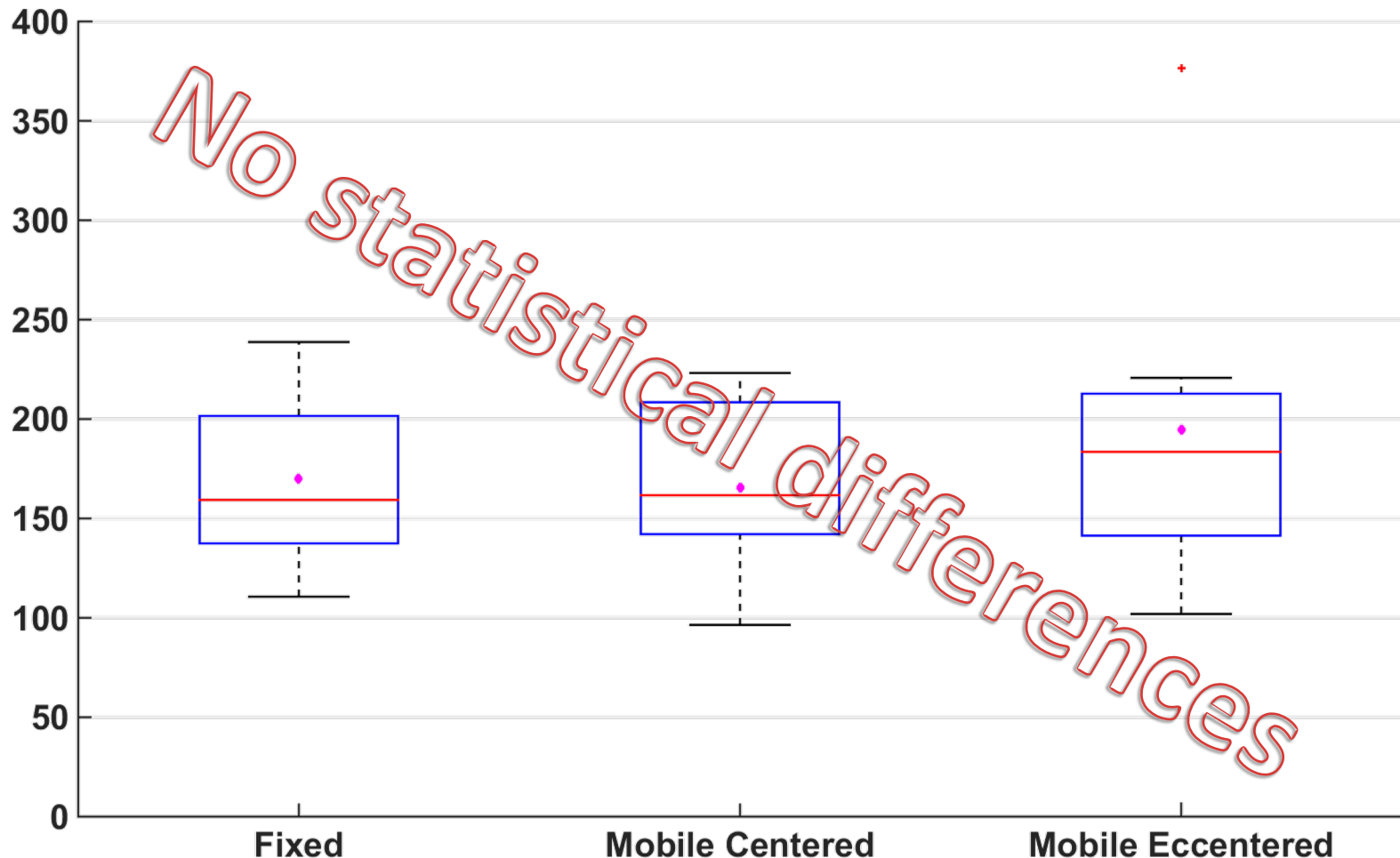
Bone-Interface Stress by Implant

Area [mm²] of Bone with Interfacial Shear $\geq$ 3 MPa



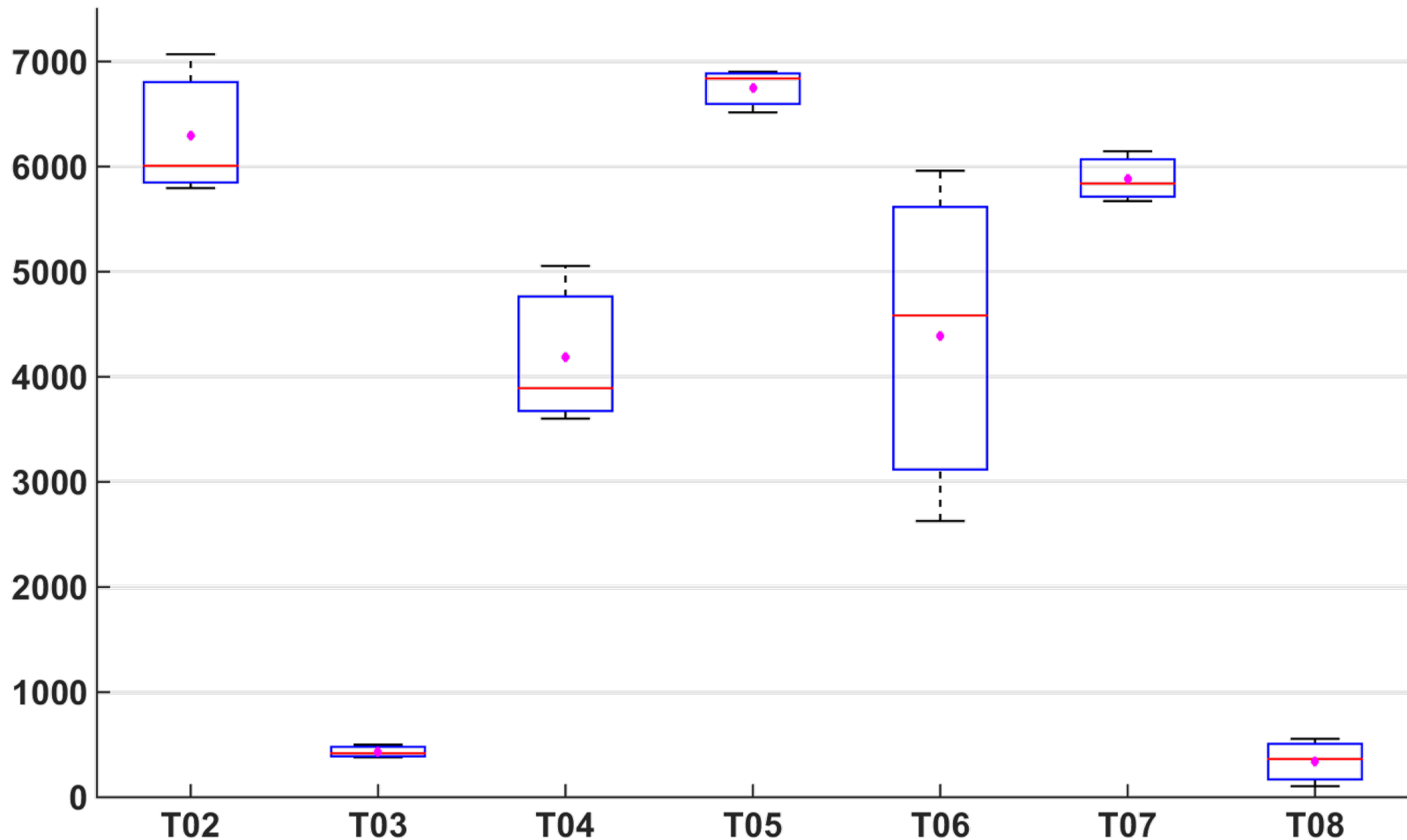
Bone-Interface Stress by Implant

Area [mm²] of Bone with Interfacial Shear $\geq$ 3 MPa



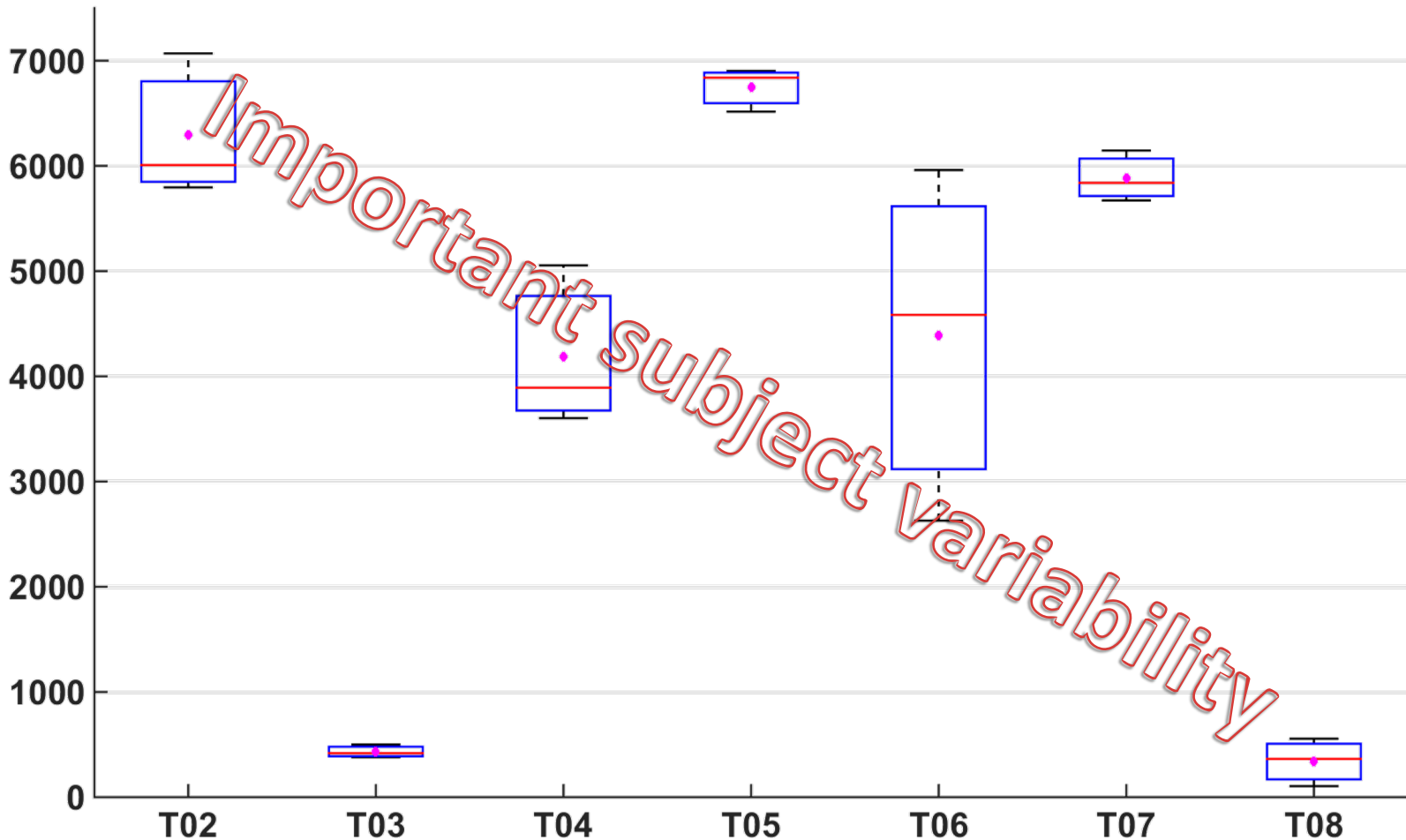
Bone Strain by Tibia

Volume [mm³] of Bone with Octahedral Shear Strain $\geq 1\%$



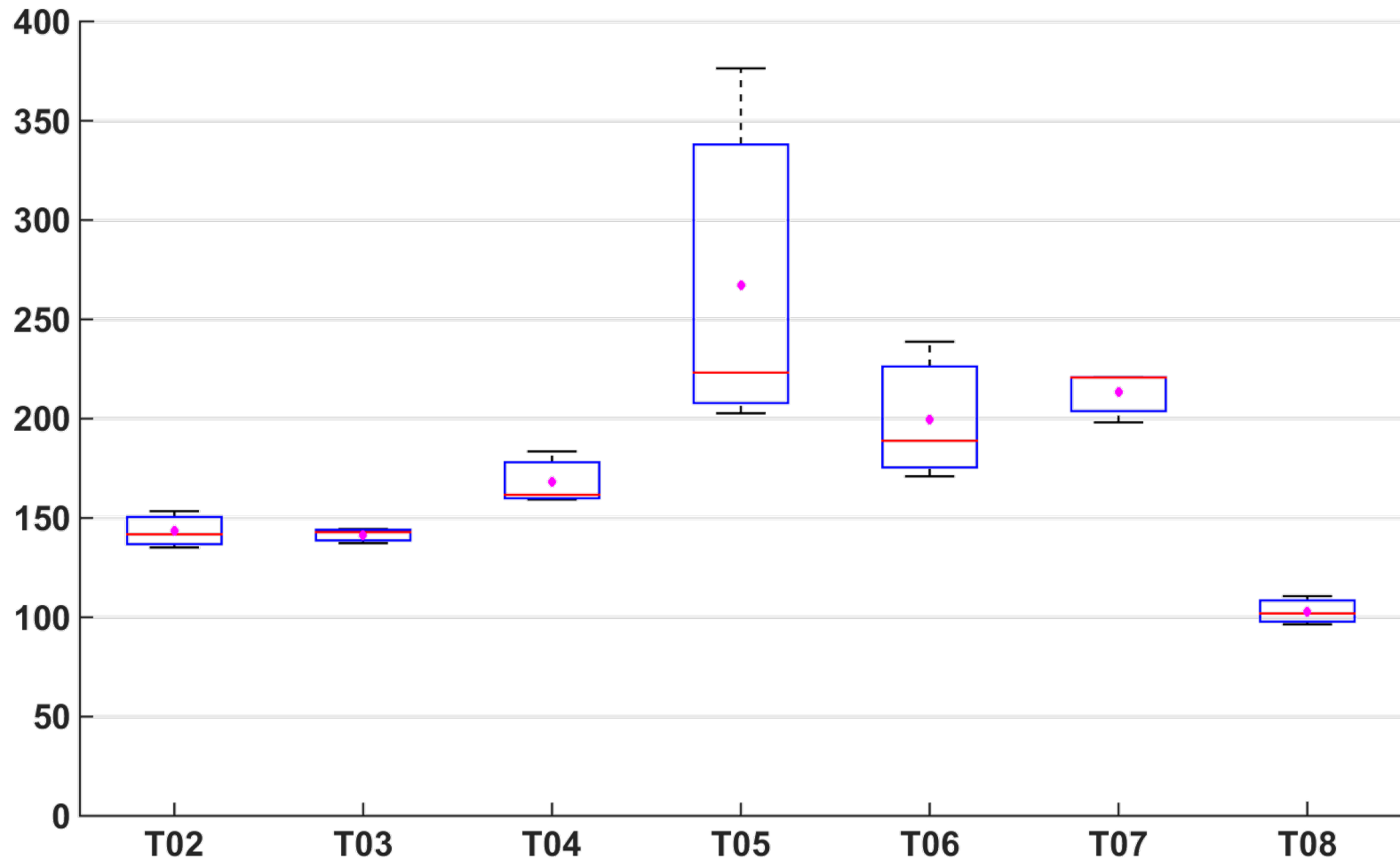
Bone Strain by Tibia

Volume [mm³] of Bone with Octahedral Shear Strain $\geq 1\%$



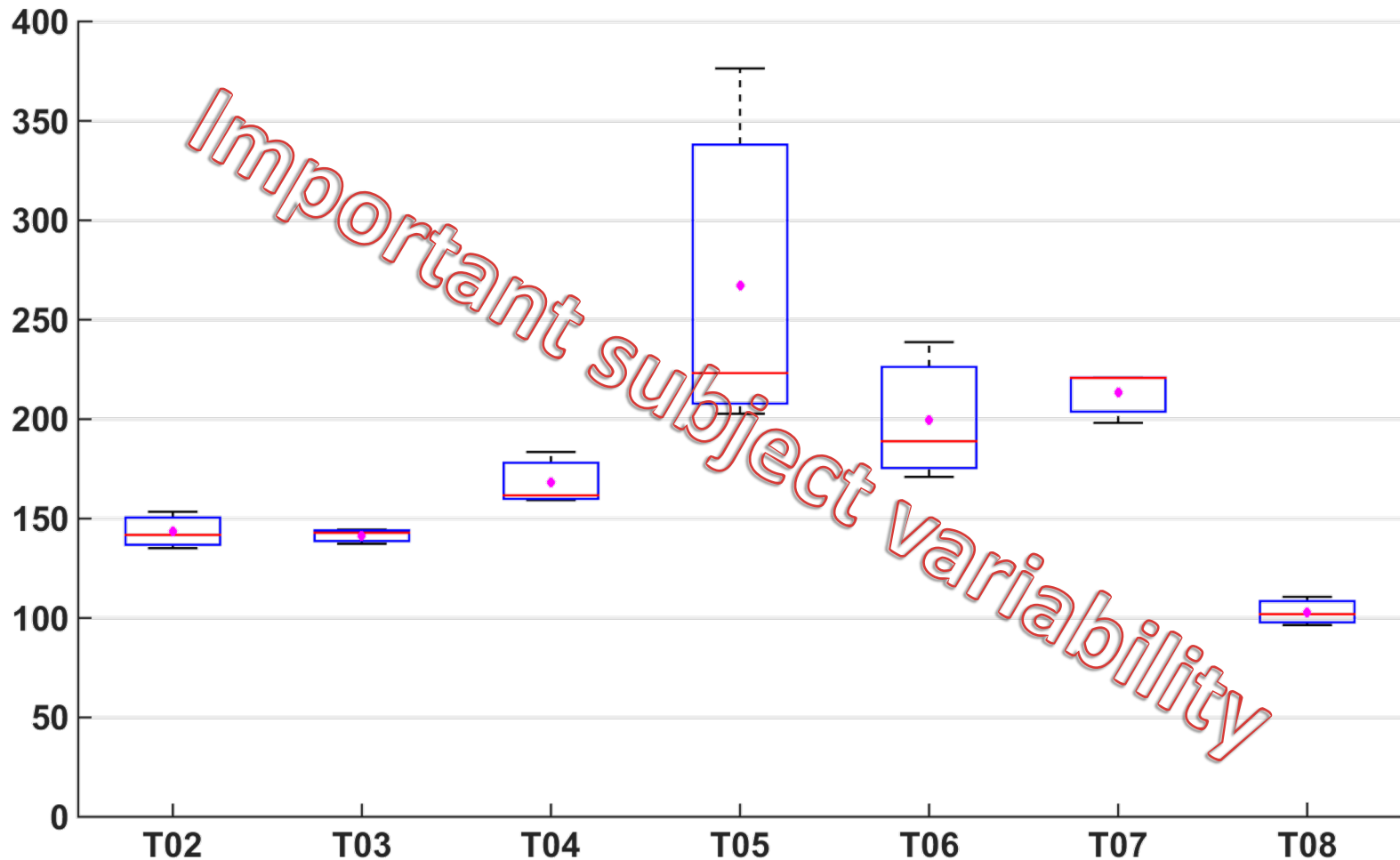
Bone-Interface Stress by Tibia

Area [mm²] of Bone with Interfacial Shear ≥ 3 MPa

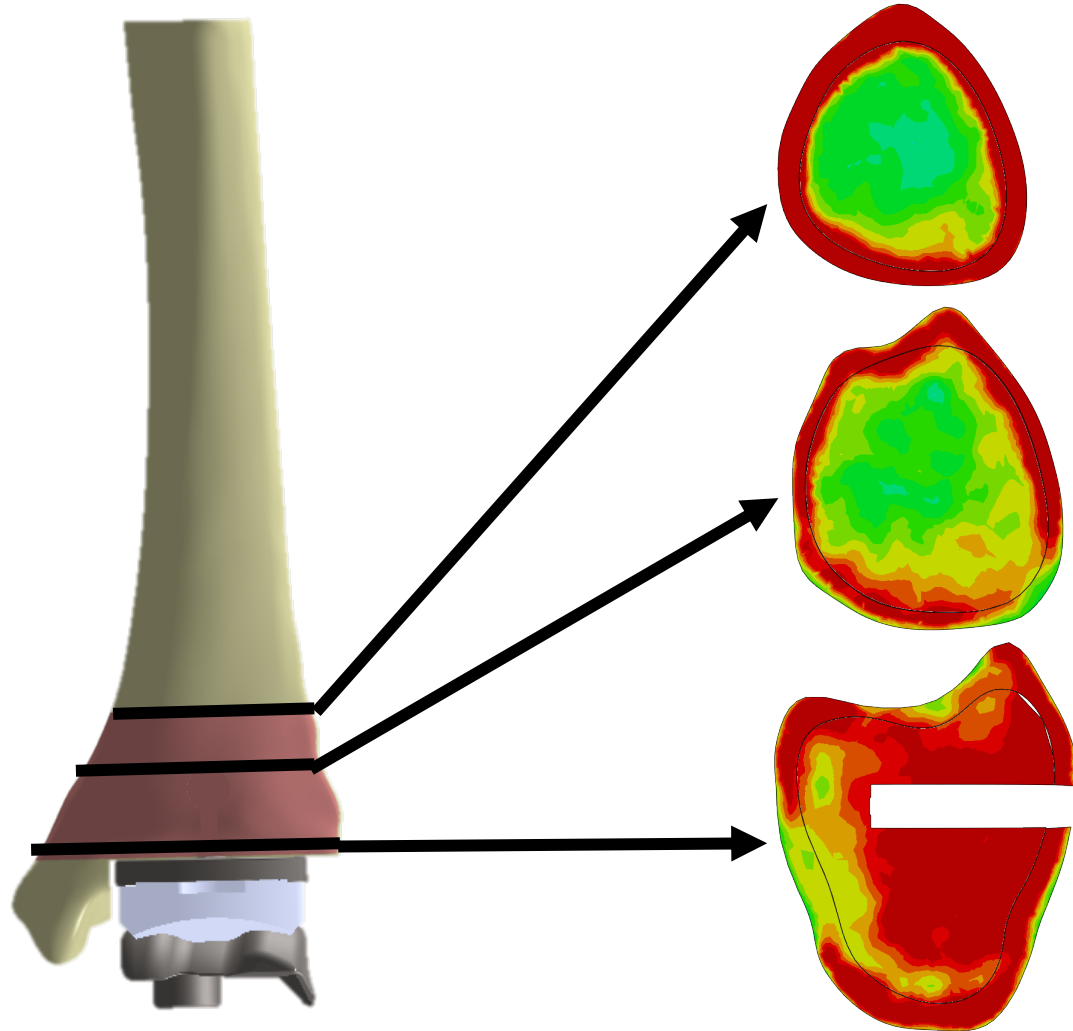


Bone-Interface Stress by Tibia

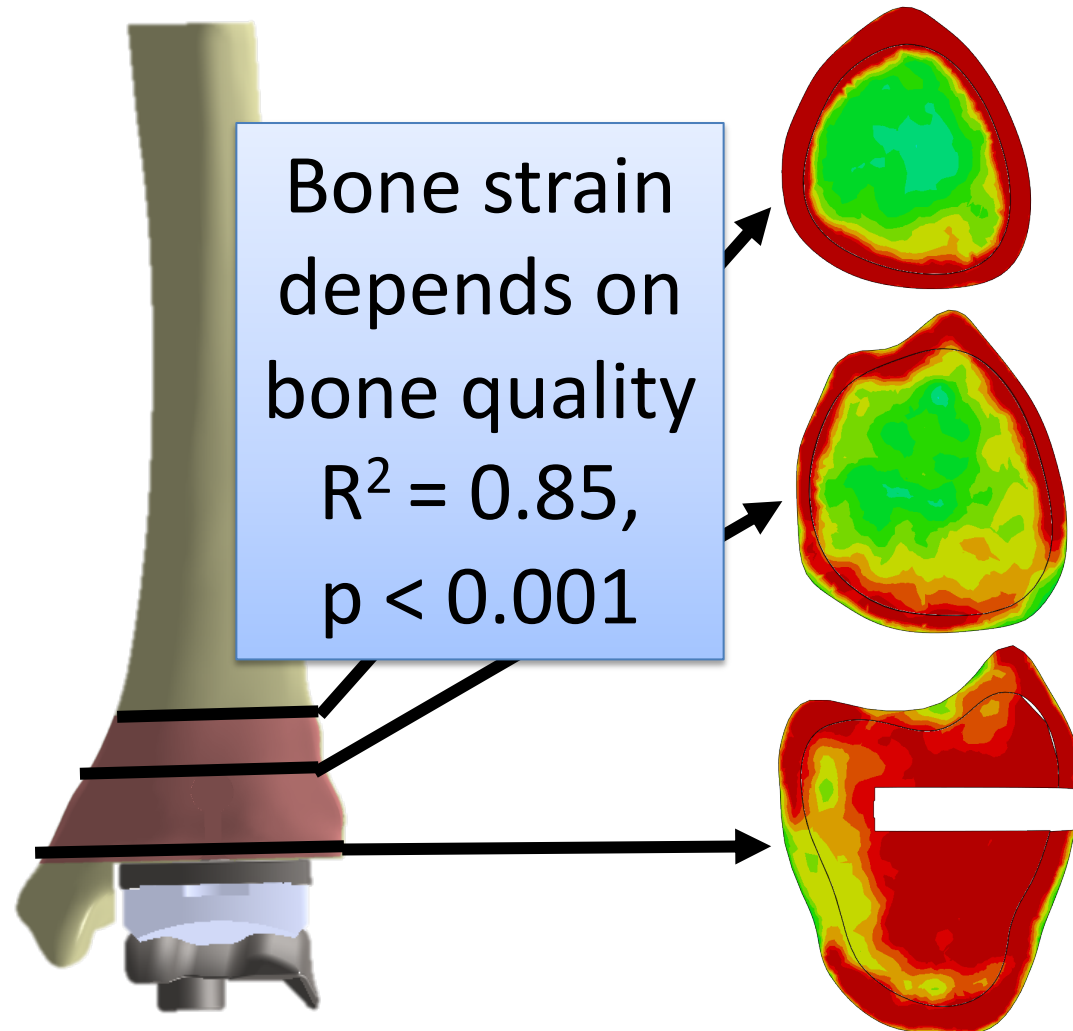
Area [mm²] of Bone with Interfacial Shear ≥ 3 MPa



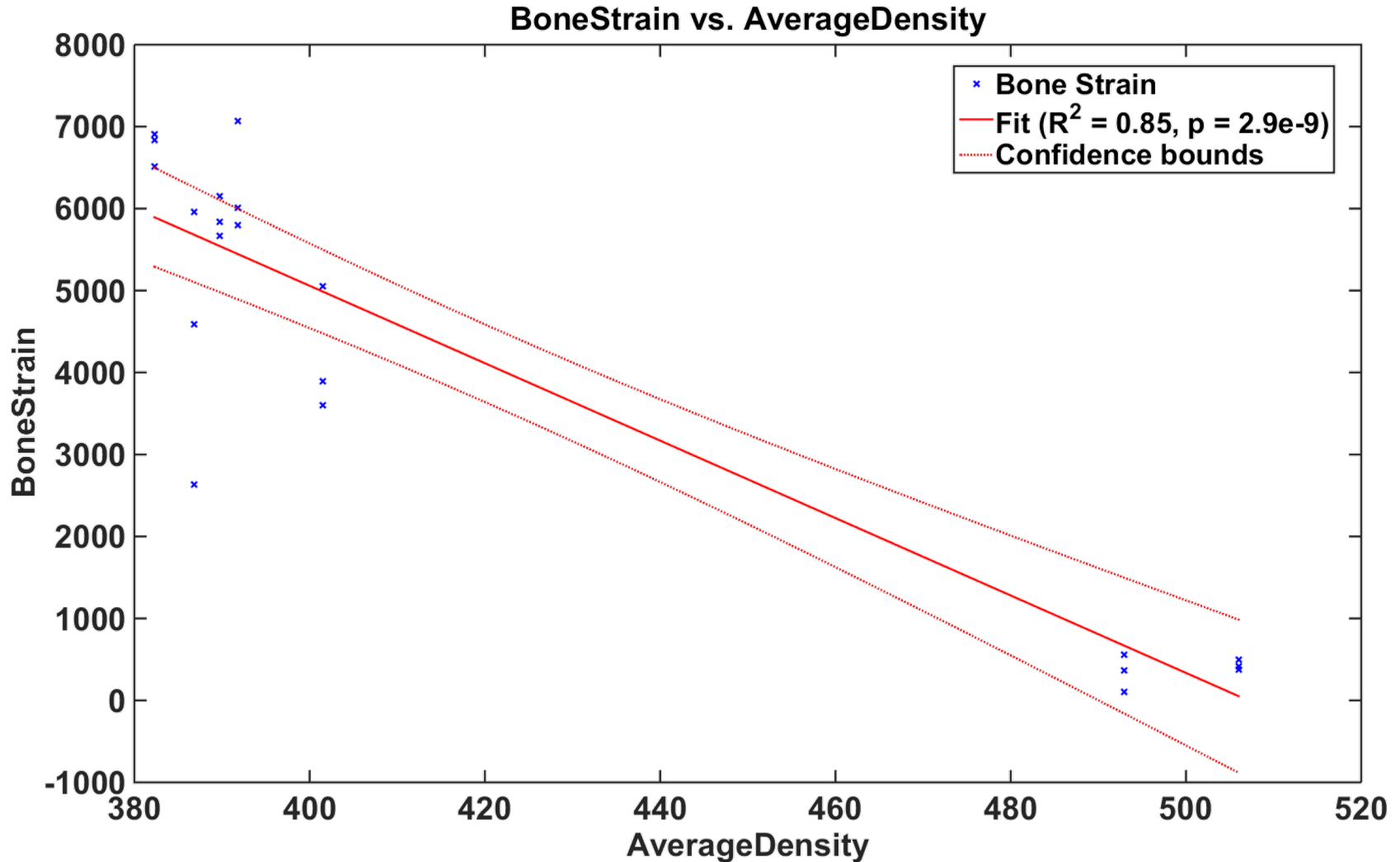
No differences between implants, but
large variability between tibia
→ Bone quality dependence?



No differences between implants, but
large variability between tibia
→ Bone quality dependence?



Bone Strain vs Bone Density

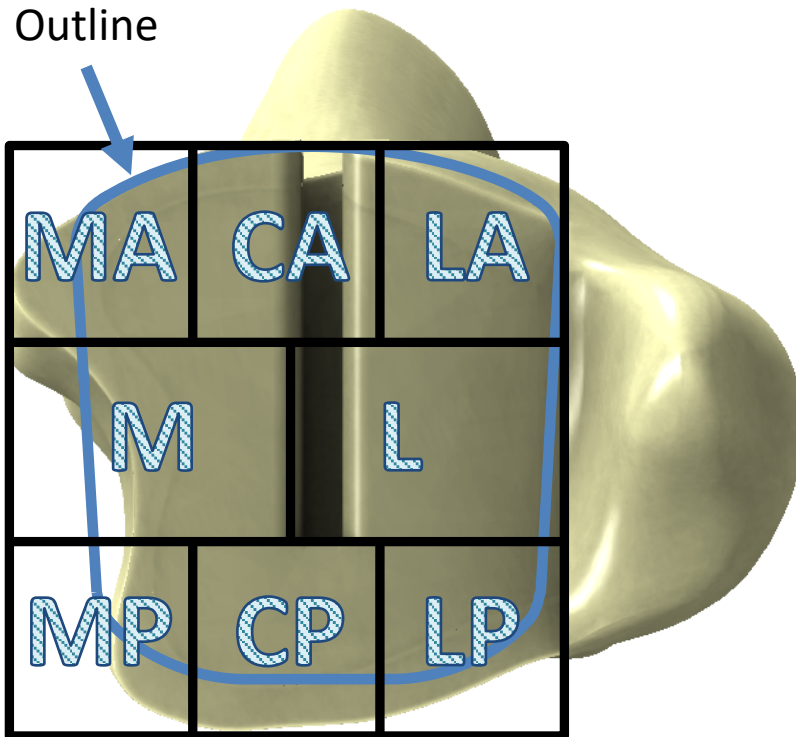


Bone Support

- We know anecdotally that antero-posterior and medio-lateral support is important
- We know approximately 19% of cases have no posterior bone support
- Can we quantify the impact of bone support?

Bone Support Regions

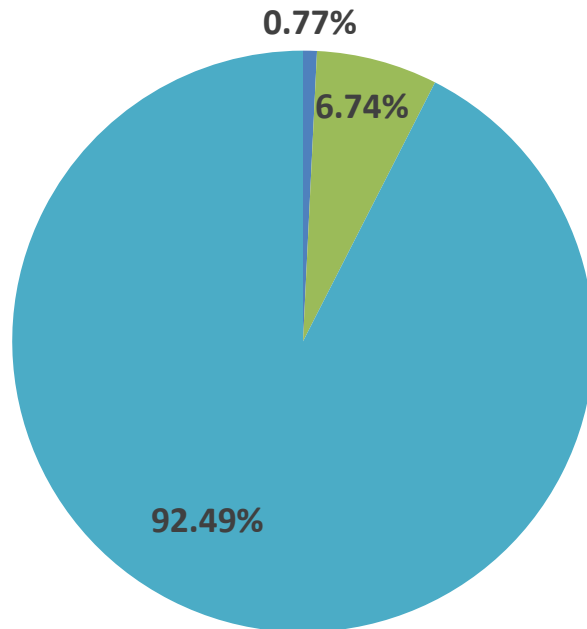
Implant
Outline



- MA – Medial Anterior
- CA – Center Anterior
- LA – Lateral Anterior
- M – Medial
- L – Lateral
- MP – Medial Posterior
- CP – Center Posterior
- LP – Lateral Posterior

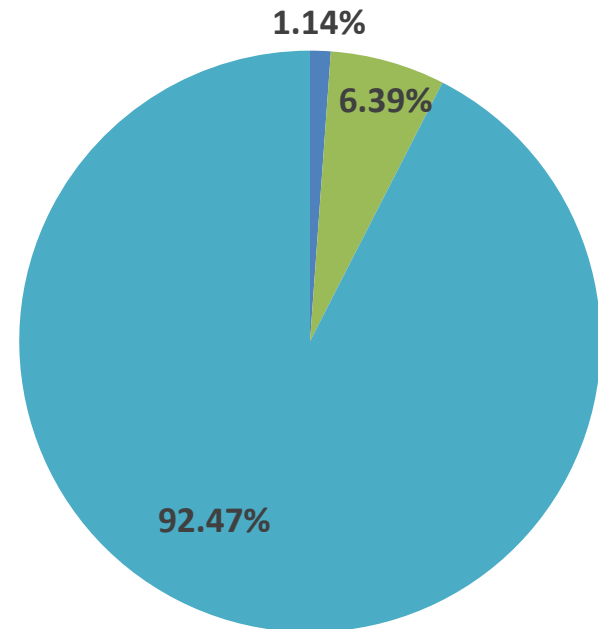
Overall Bone Support (T02)

Fixed Implant Support



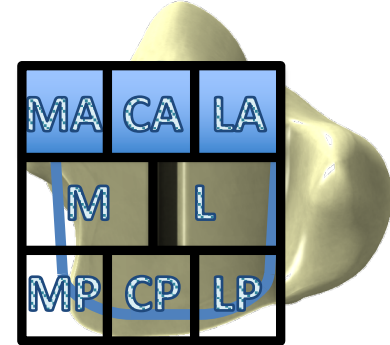
■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

Mobile Implant Support

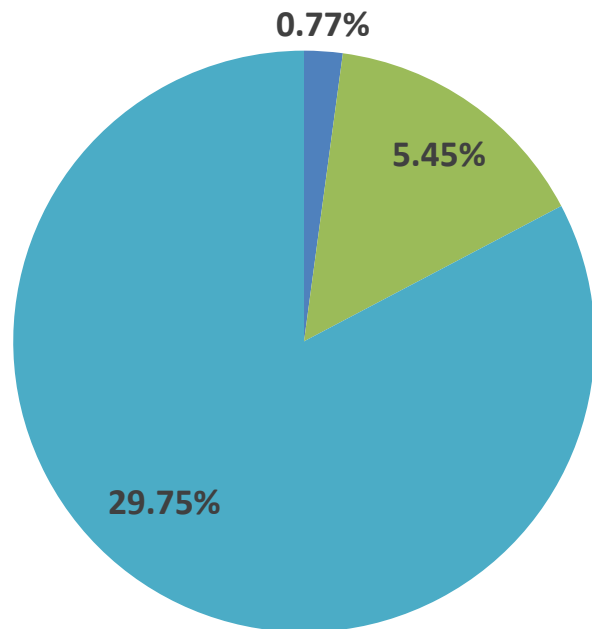


■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

Anterior Bone Support (T02)

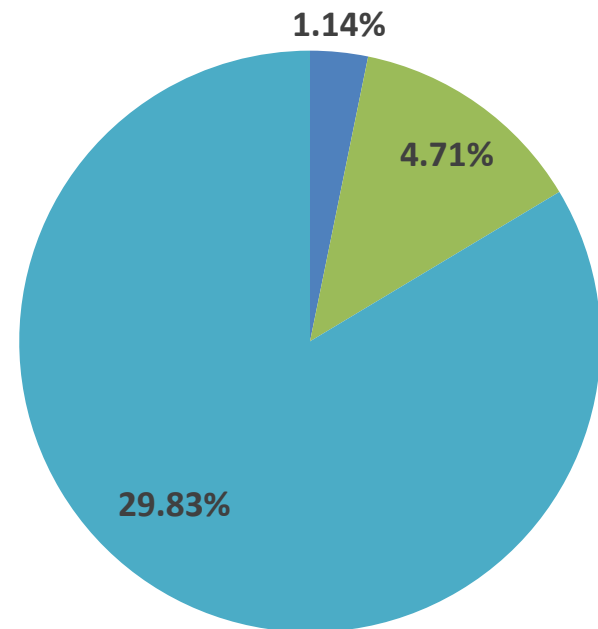


Fixed Implant Anterior Support



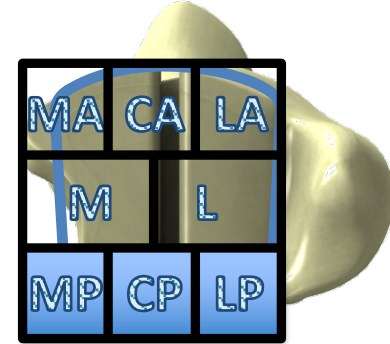
■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

Mobile Implant Anterior Support

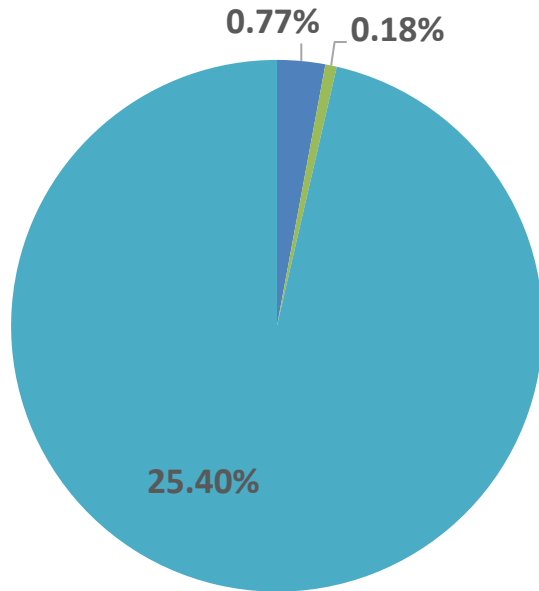


■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

Posterior Bone Support (T02)

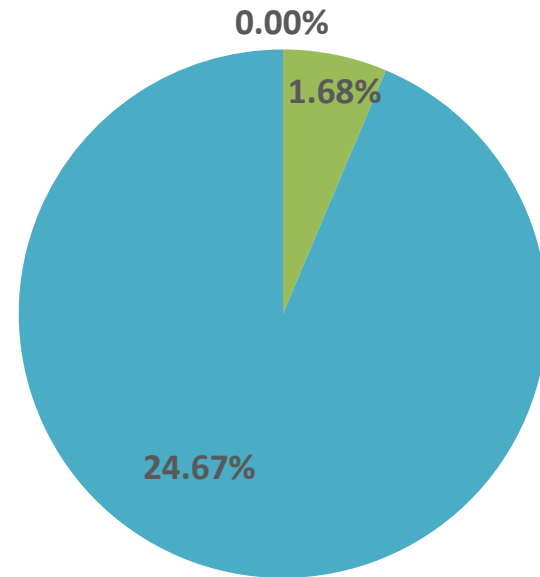


Fixed Implant Posterior Support



■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

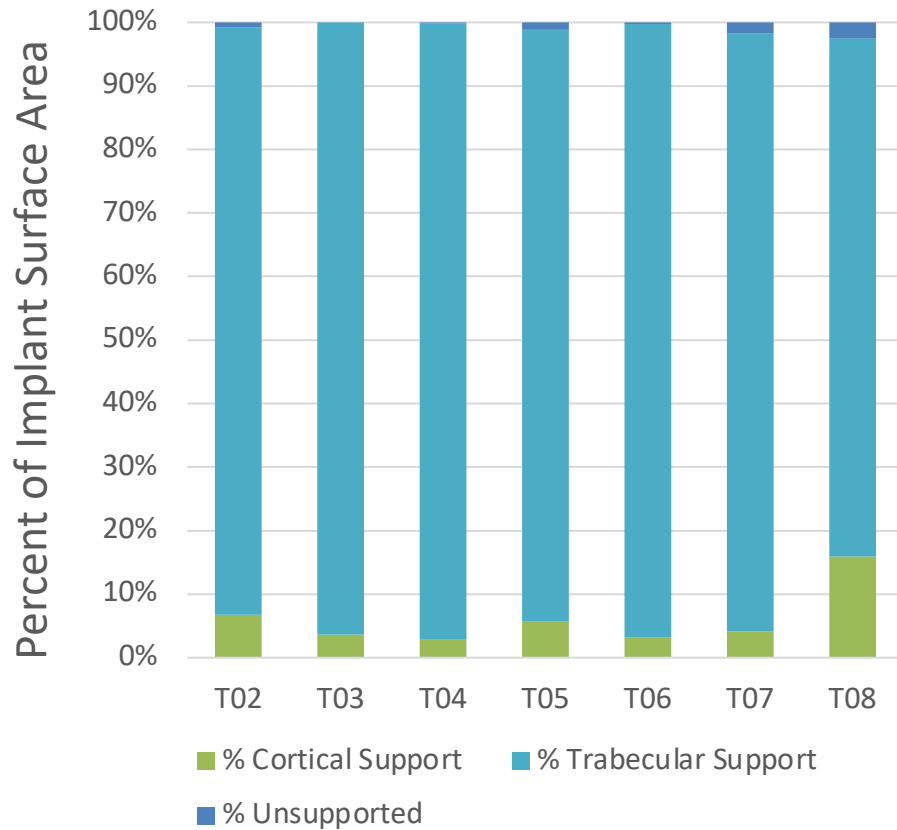
Mobile Implant Posterior Support



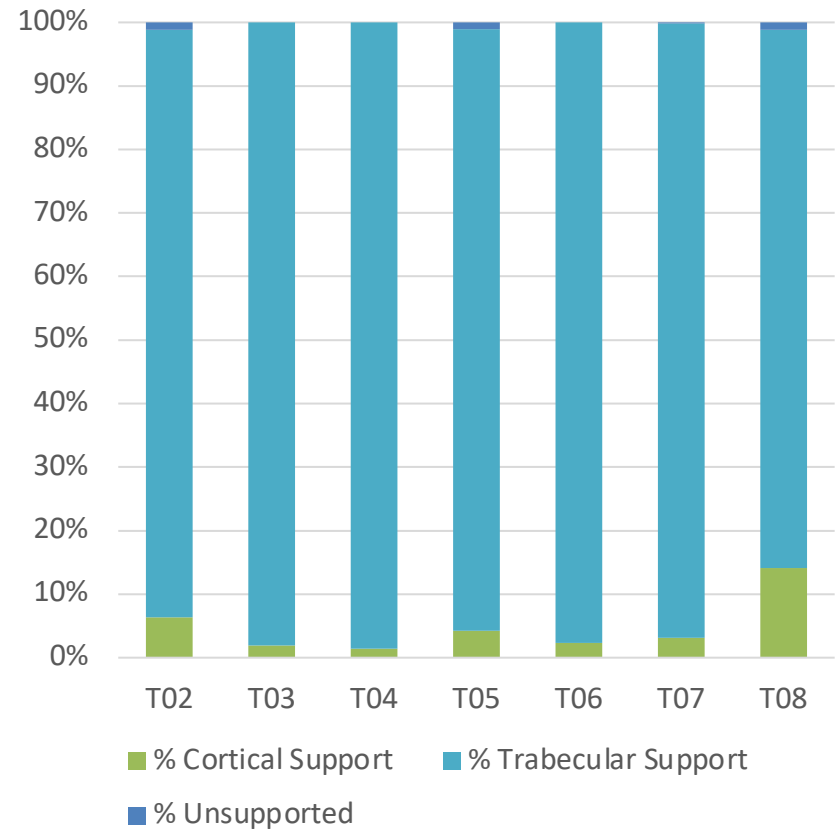
■ % Unsupported ■ % Cortical Support
■ % Trabecular Support

Overall Bone Support

Fixed Implant Support

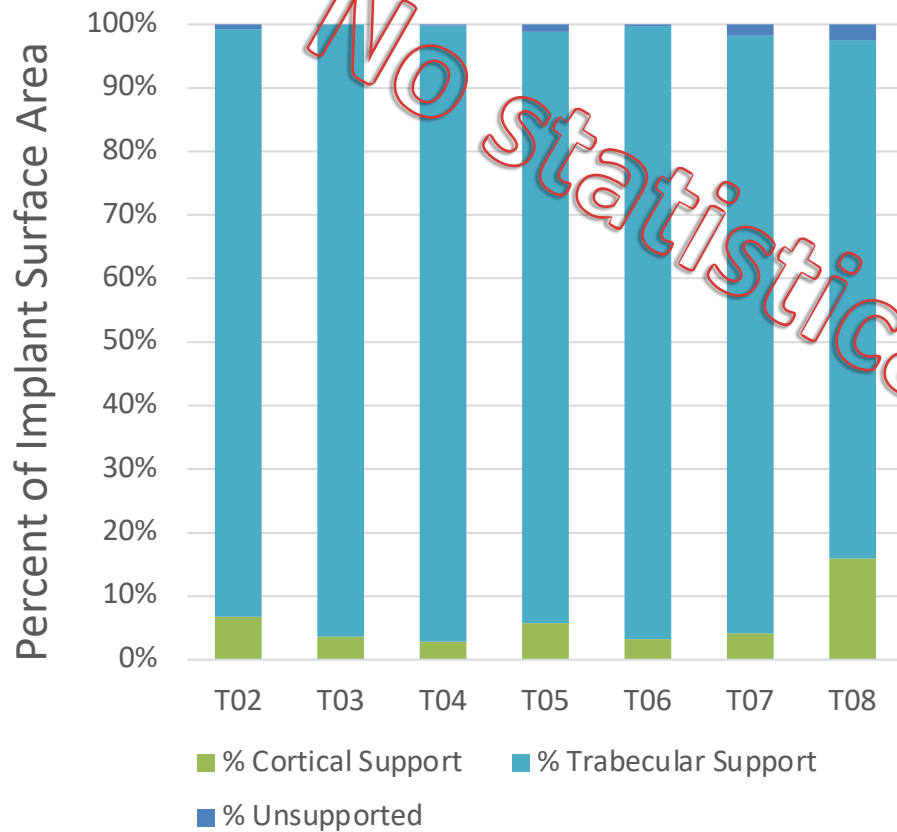


Mobile Implant Support

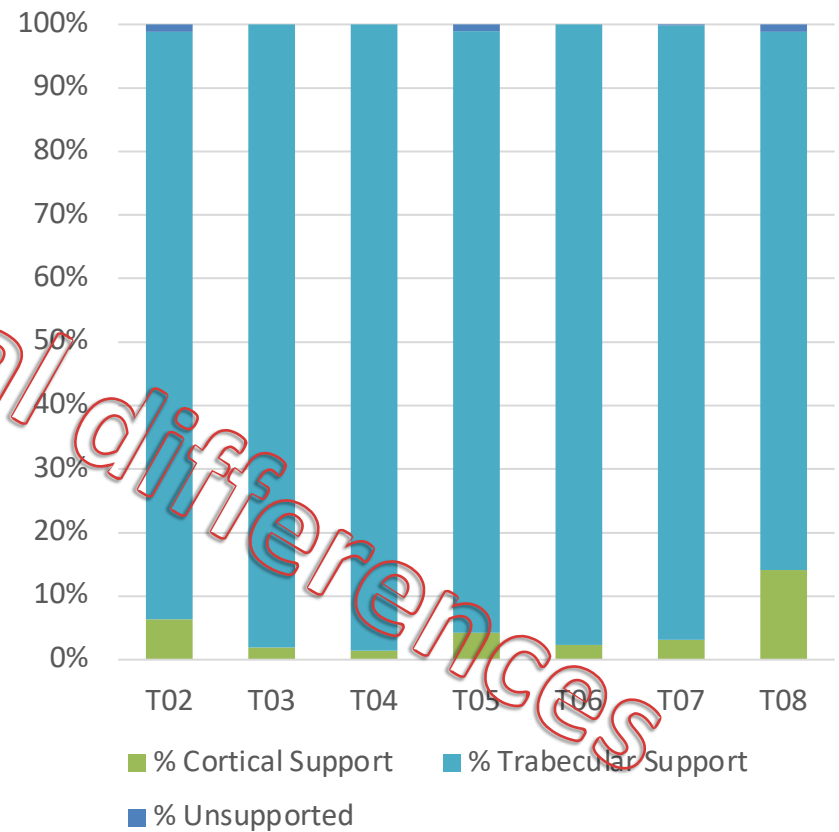


Overall Bone Support

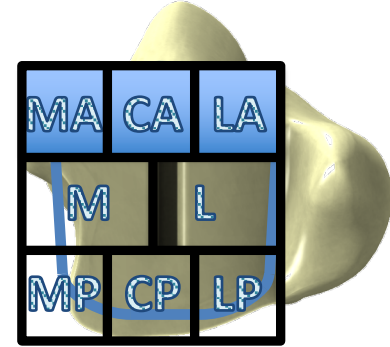
Fixed Implant Support



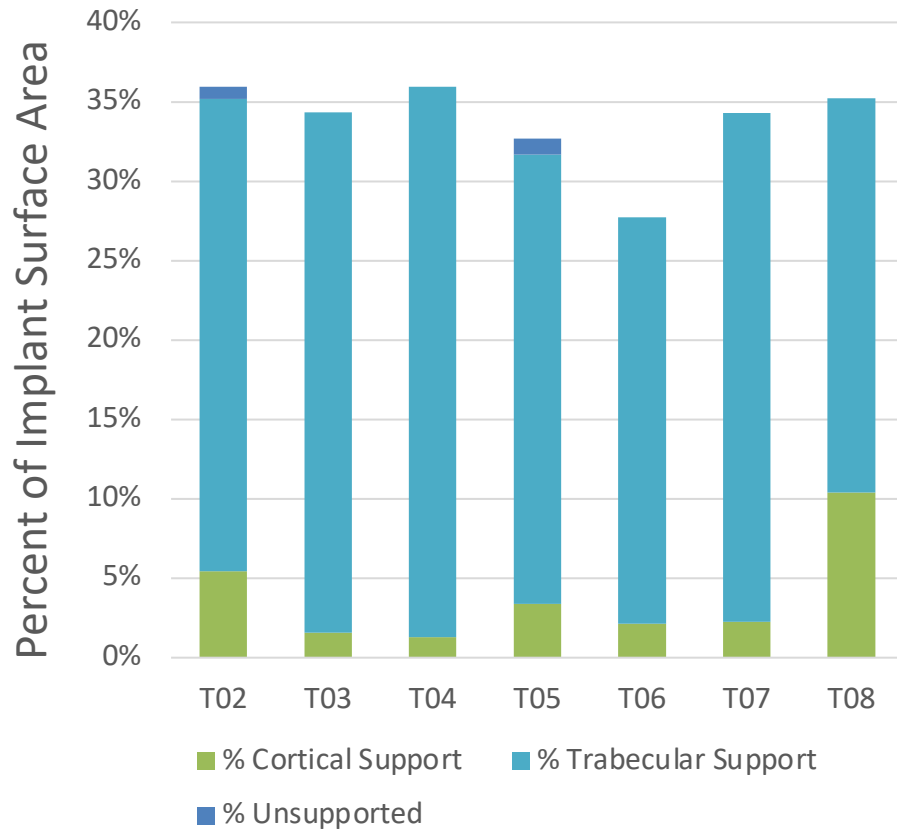
Mobile Implant Support



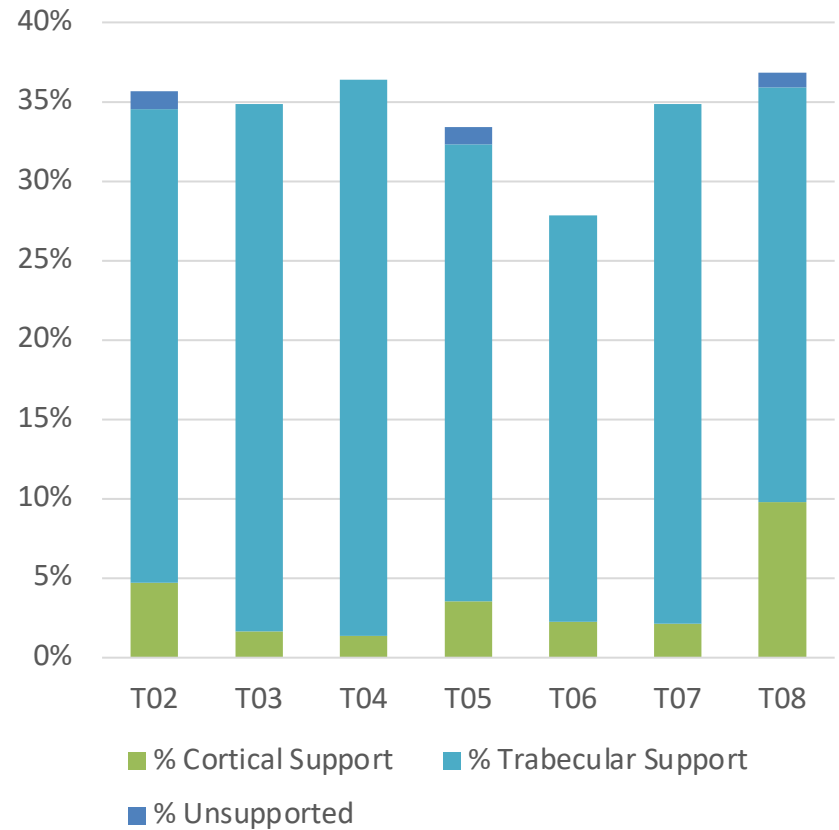
Anterior Bone Support



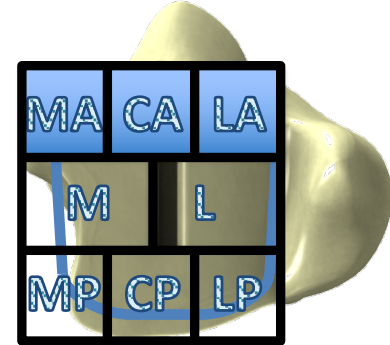
Fixed Implant Anterior Support



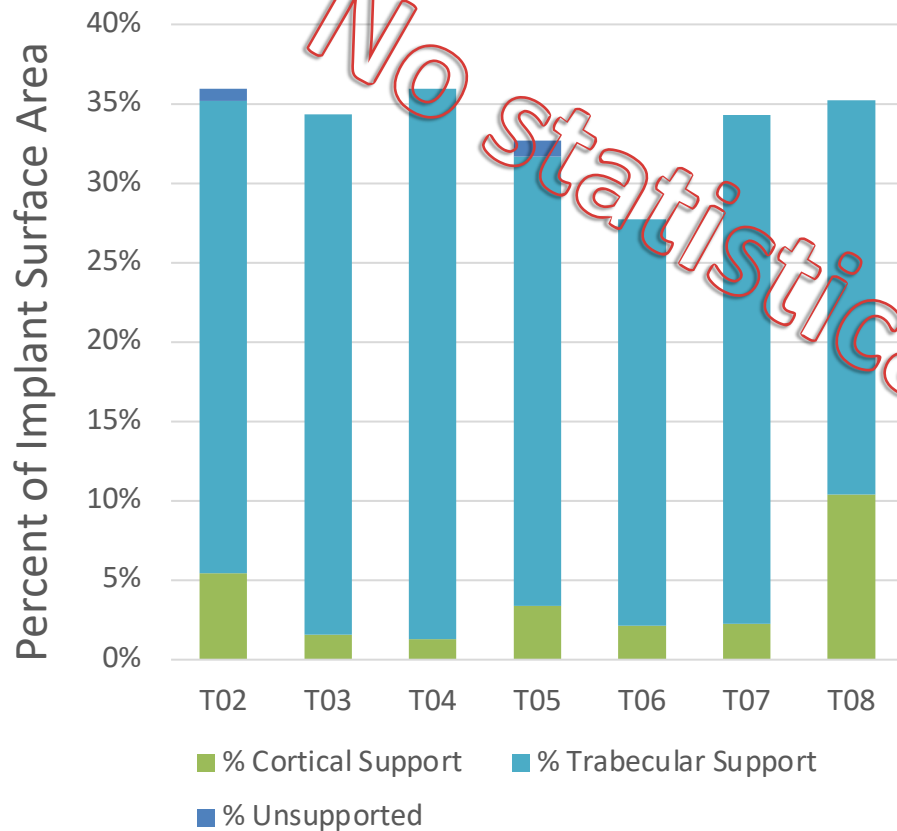
Mobile Implant Anterior Support



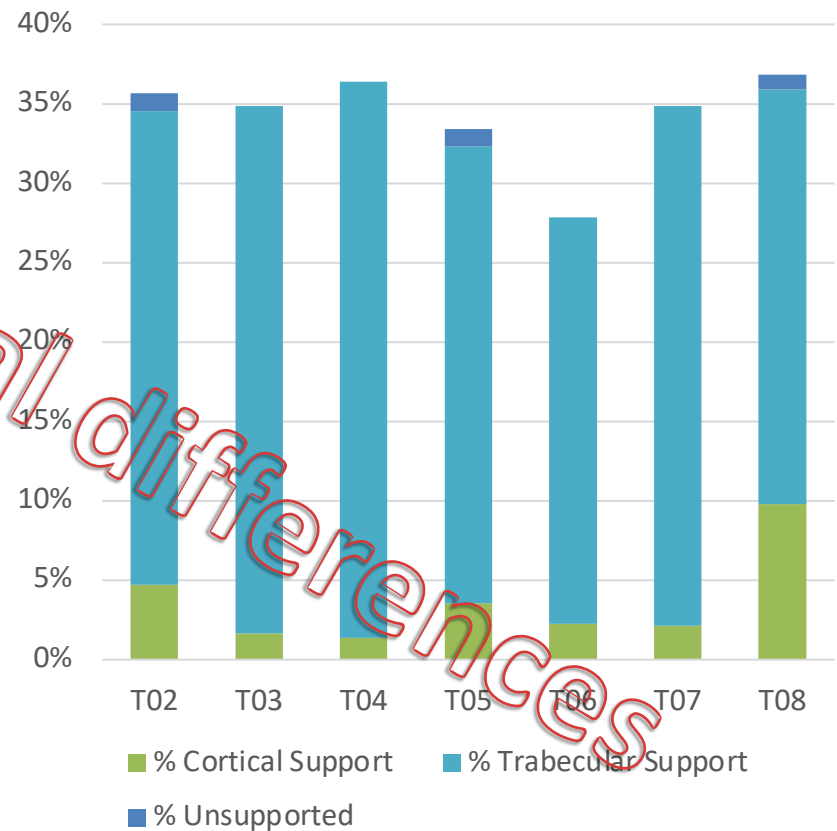
Anterior Bone Support



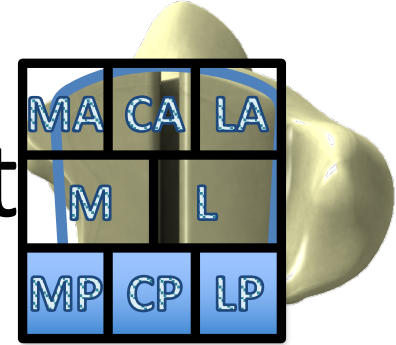
Fixed Implant Anterior Support



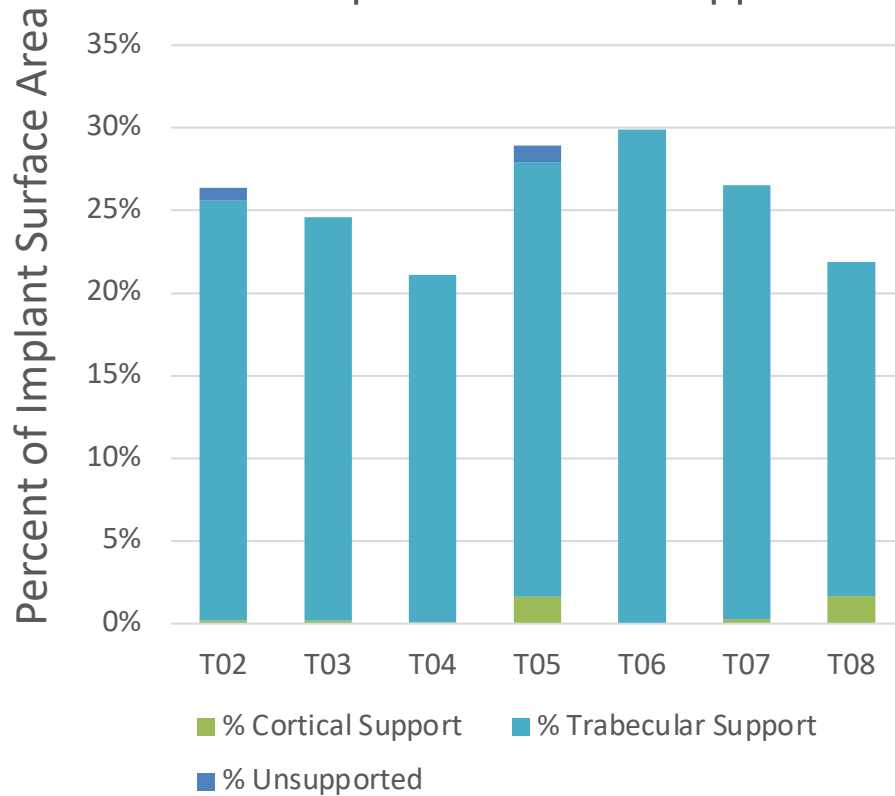
Mobile Implant Anterior Support



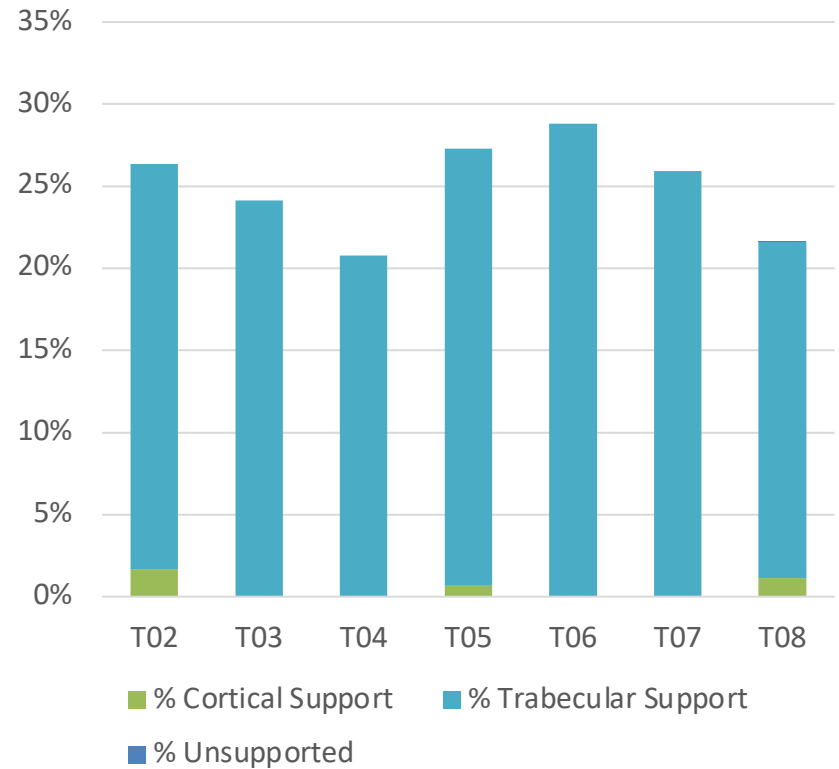
Posterior Bone Support



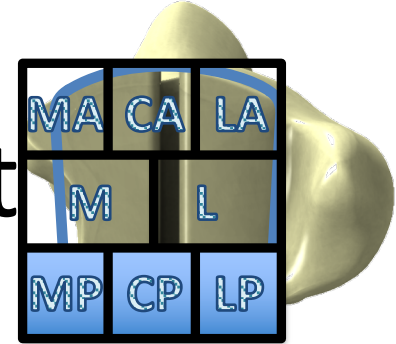
Fixed Implant Posterior Support



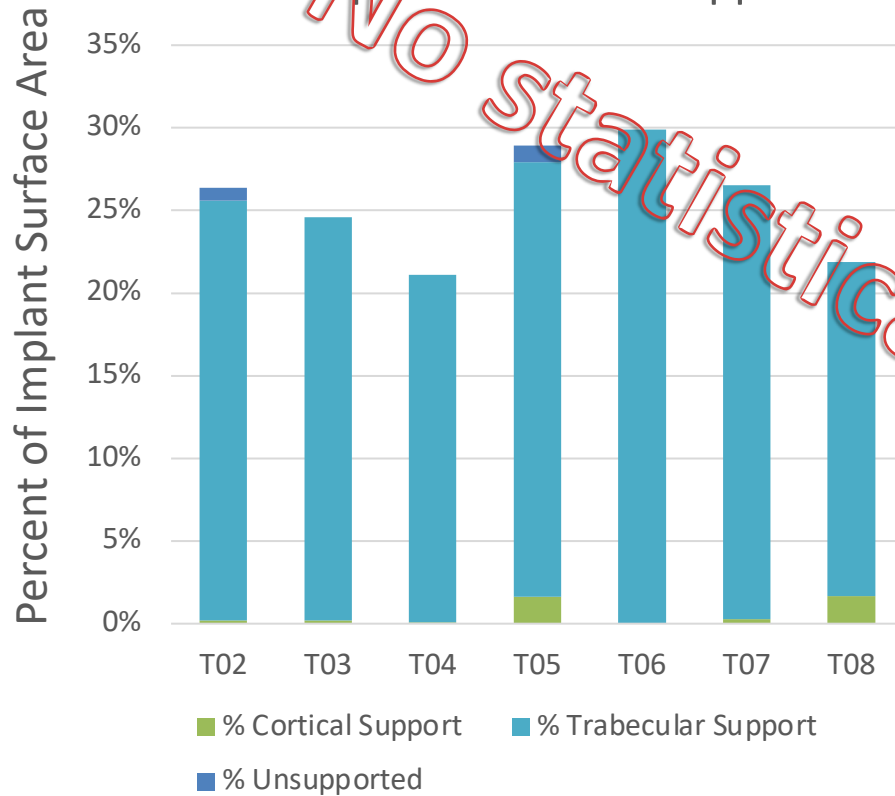
Mobile Implant Posterior Support



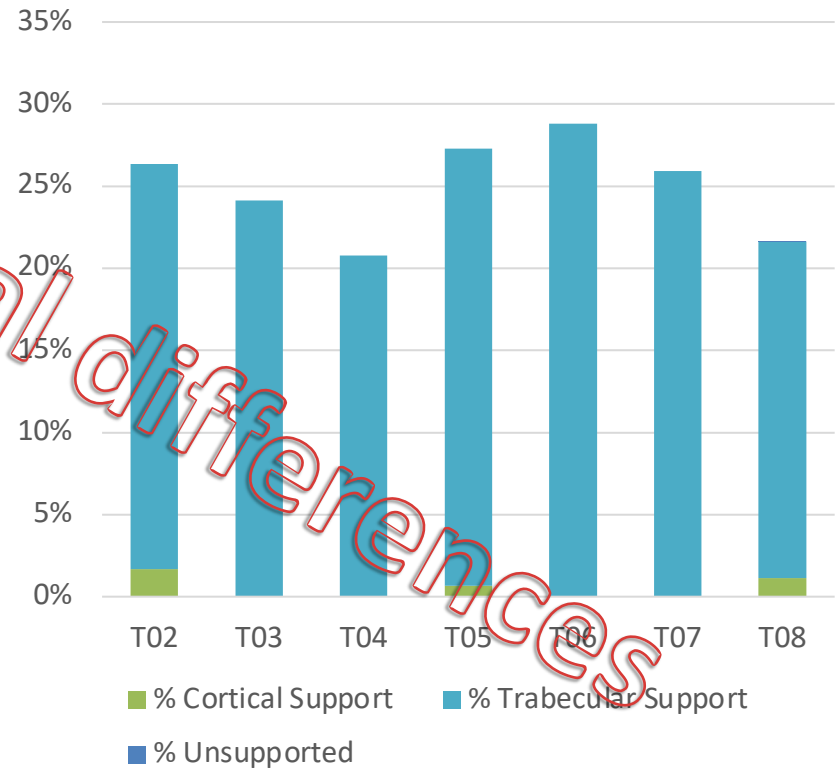
Posterior Bone Support



Fixed Implant Posterior Support



Mobile Implant Posterior Support



Bone support

- No statistical difference between fixed and mobile implants
- Anterior support correlated to bone strain ($R^2 = 0.6235$, $p = 2.08E-05$)
- Bone support correlated to interfacial stress ($R^2 > 0.54$, $p \leq 0.0001$)
- **Poor posterior support in all cases**

Conclusions

- No superiority of one of these implants
- Importance of bone quality
 - Importance for comparative analyzes
- Perspectives:
 - Extend to talus implant, entire joint, stability
 - Optimal implant design (bone preserving)
 - Revision implants
 - Patient-specific models (patient database)

Patient-specific Model

Cadaver Model

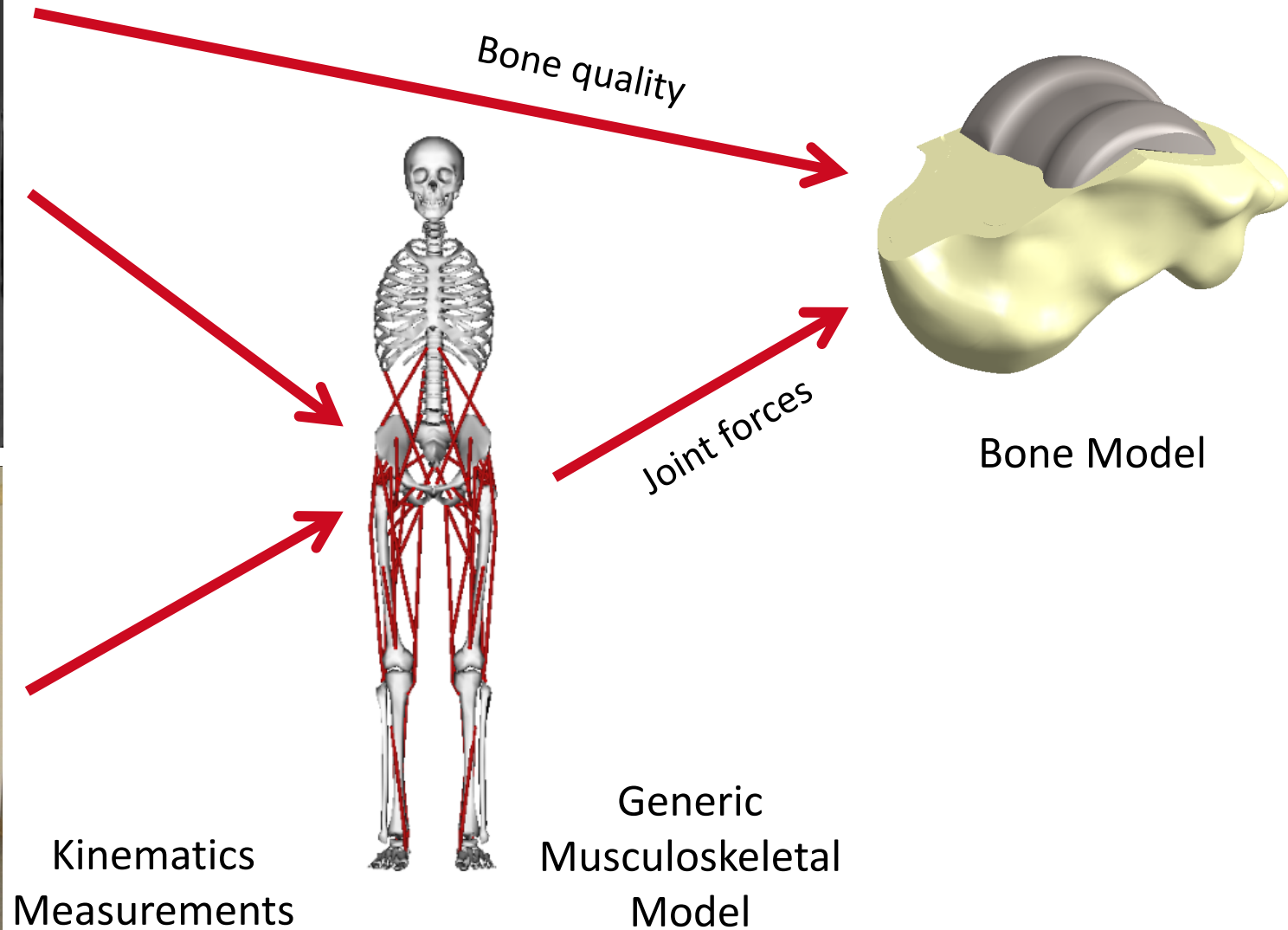
- **Validation**
 - + Bone density
 - Availability
 - Anatomical position of bones and ligaments
 - Patient kinematics

Patient Model

- **Patient-specific analysis**
 - + Bone density
 - + Availability (preop CTs)
 - + Anatomical position of bones and ligaments
 - + Patient kinematics

Patient-specific Model

Preoperative CT



Pre-op CT protocol

- Specific protocol (Fabio Becce, CHUV)
- Dual-energy CT
- FOV includes entire foot (optimal resolution)
- Extra slices to locate knee and hip joint center
- Extra slice to evaluate muscle volume
- Brace to hold foot in neutral position
- Loading device (30-50% BW in supine position)
- Bone density obtained from phantom calibration

Pre-Op CT



Pre-Op CT



Kinematics measurements

- Use existing protocol (Chopra, JOR 2014)
- Ambulatory gait analysis (Physilog[®] / Pedar[™])
- Multi-segment foot Kinematics / Kinetics
- Spatio-temporal parameters
- Salto : 15 patients measured
- Talaris : 10 patients planed
(+ new CT protocol → joint model)

Kinematics Patient Measurements

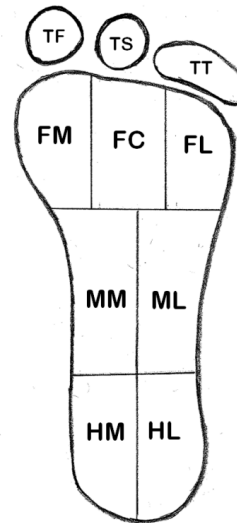
Calibrate Sensors

Favre J et al J Biomech 2009



Data Collection

- 50 m walkway
- 2 trials for each foot
- Average of all gait cycles



Musculoskeletal Model

