Nov. 2, 2009
AAMP
San Diego, CA

"Update on Biomechanics of Oral & Maxillofacial Implants"

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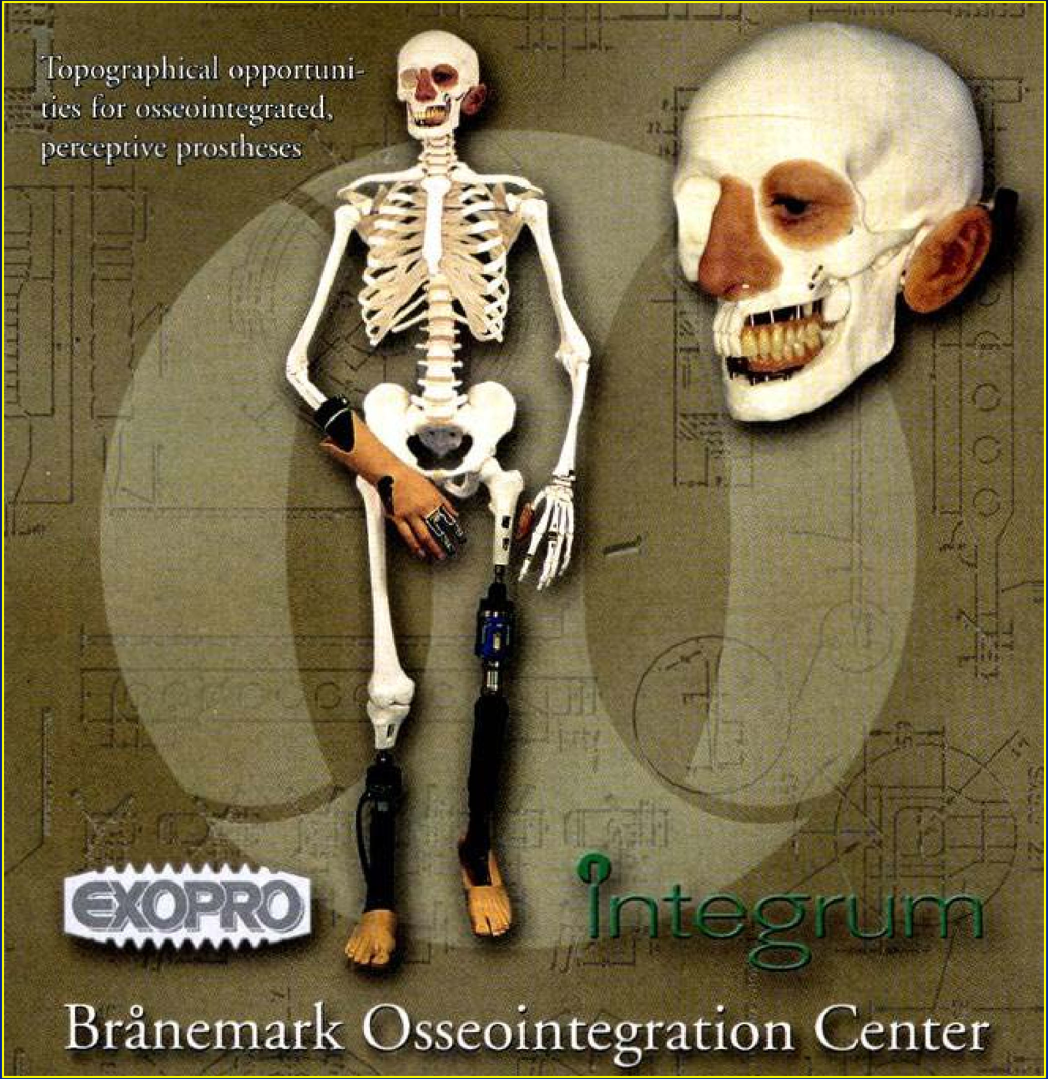
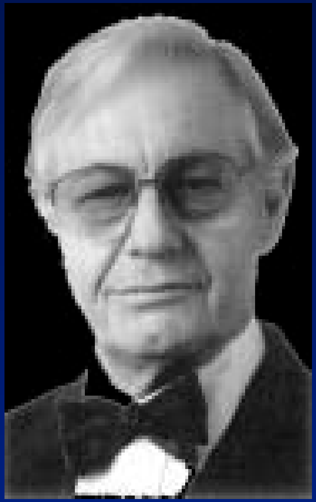
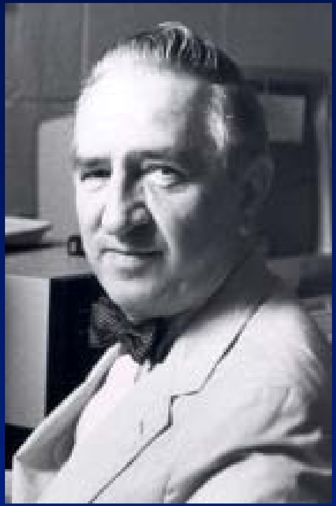
Senior Research Engineer, Dept. of Surgery, Stanford Univ., Stanford, CA

Osseointegration is successful.
So is this *The End of History**?





P-I Brånemark



Richard Skalak

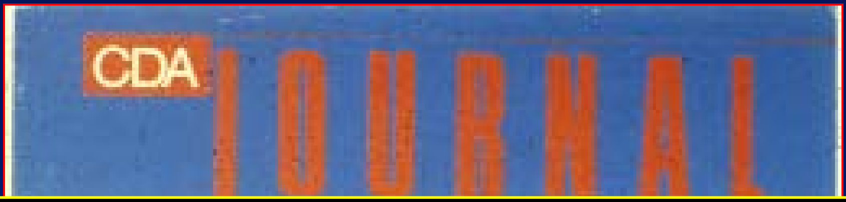
*title of an oft-quoted 1989 essay by Francis Fukuyama

Installation Tips

- 50 lb. max. working load (in 1/2" drywall) intended as a guideline only and cannot be guaranteed
- Max. load may be less based on quality/thickness of drywall and dimensions of object to be hung
- Fastening point on object to be hung should not exceed 3/4" in thickness
- Not recommended for ceiling applications

= 222 N

Do we have analogous data on the loading, and load-bearing capacities, of all our implants?

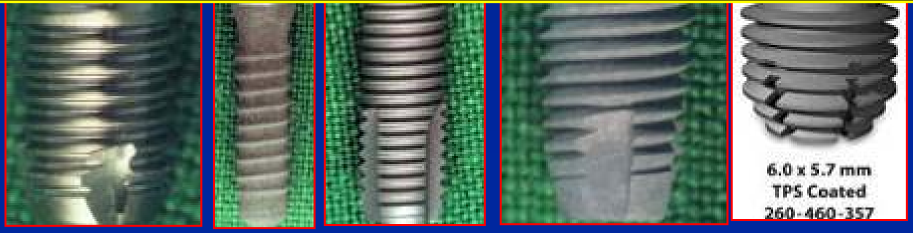


- www.fdiworldental.org/resources/assets/implants/implants.html lists ~103 oral implant companies as of 2006

The answer is: “No”.

“…the current state of the oral implant field is such that a myriad of *different types of implants* are being used in a *very wide variety of clinical indications*, under *largely undocumented loading conditions* in *different quantities and qualities of bone that has healed to varying extents*.”

from Brunski, Nanci and Puleo, IJOMI 2000;15:15-46.



Outline

- Reinforce a few ideas about:
  - implant design
  - key terms in biomechanics: force (load), stress, strain, moment (bending moment, torque)
- Discuss ways to assess implant loading *in vivo*
  - Typical intraoral prosthetic situations
  - A few maxillofacial situations
- Summary

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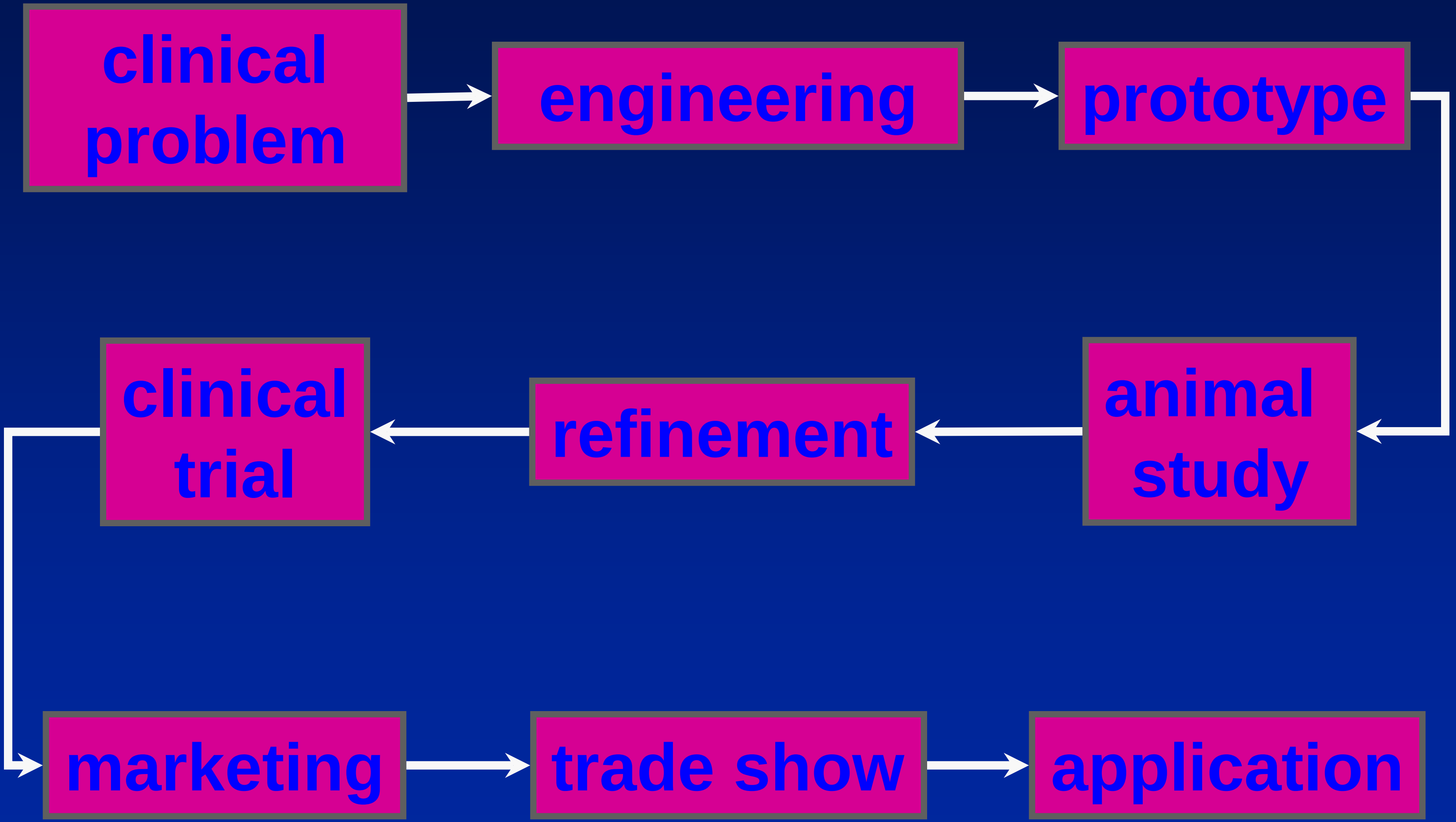
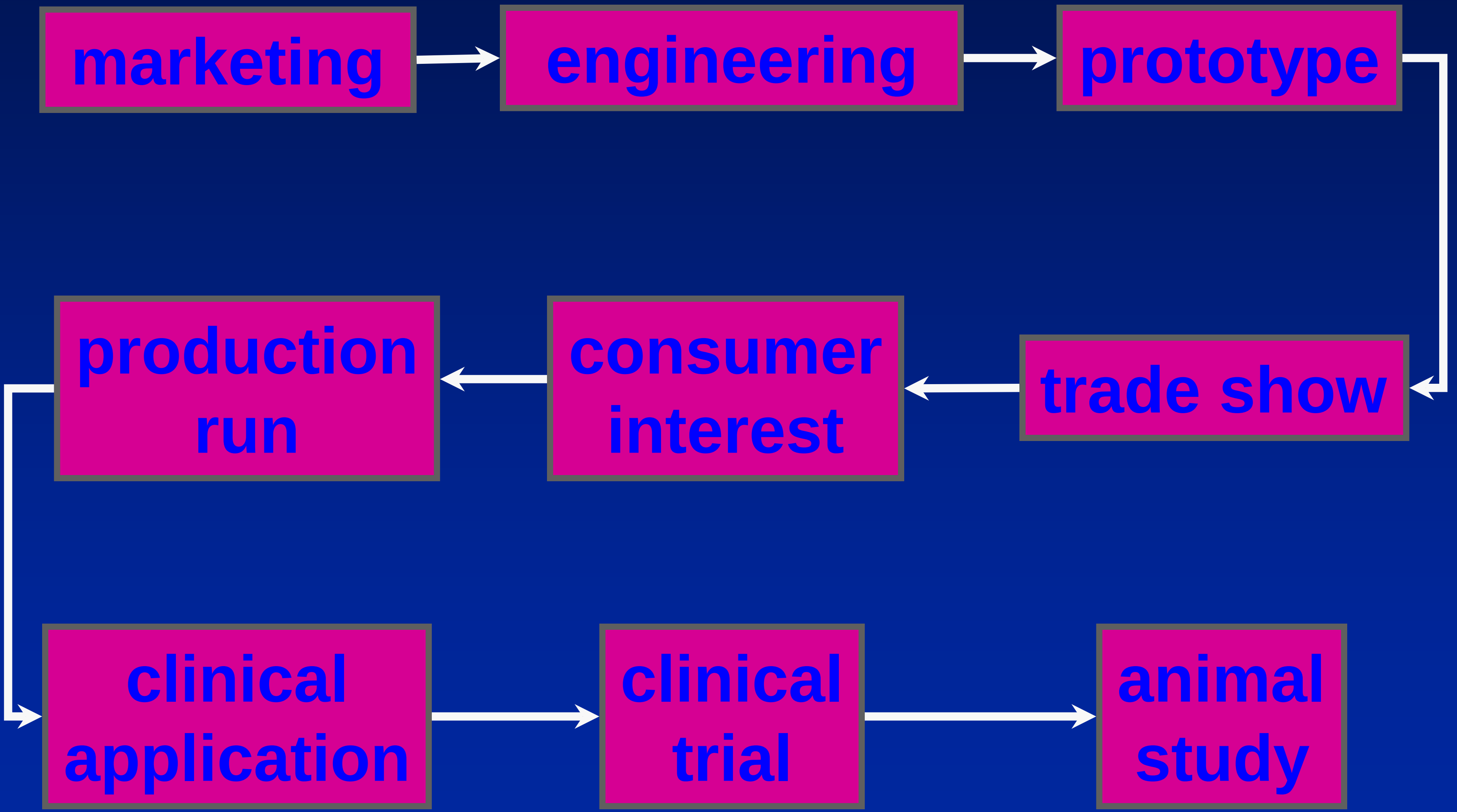
Device design – as it's *supposed* to occur (Courtesy Paul Thomas)

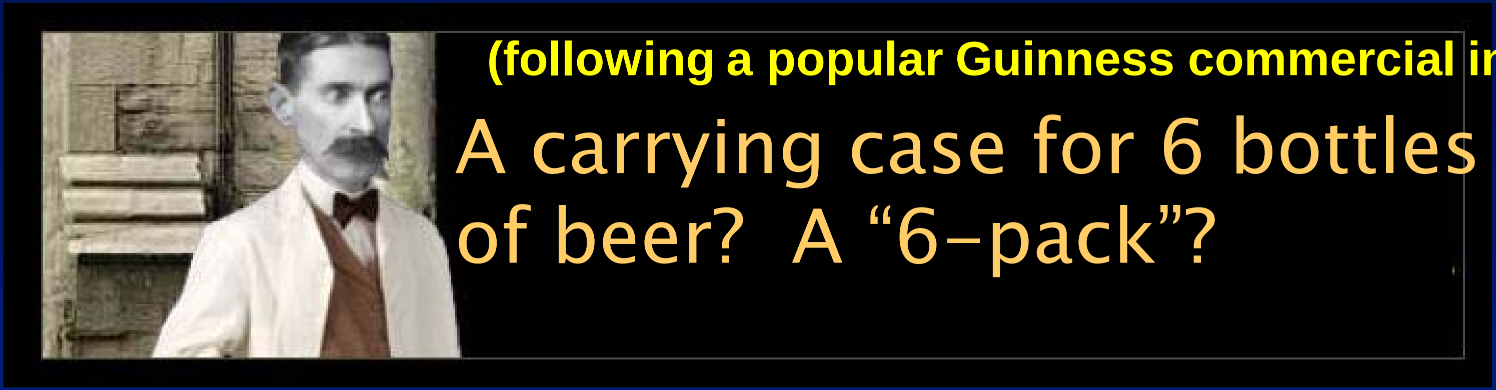


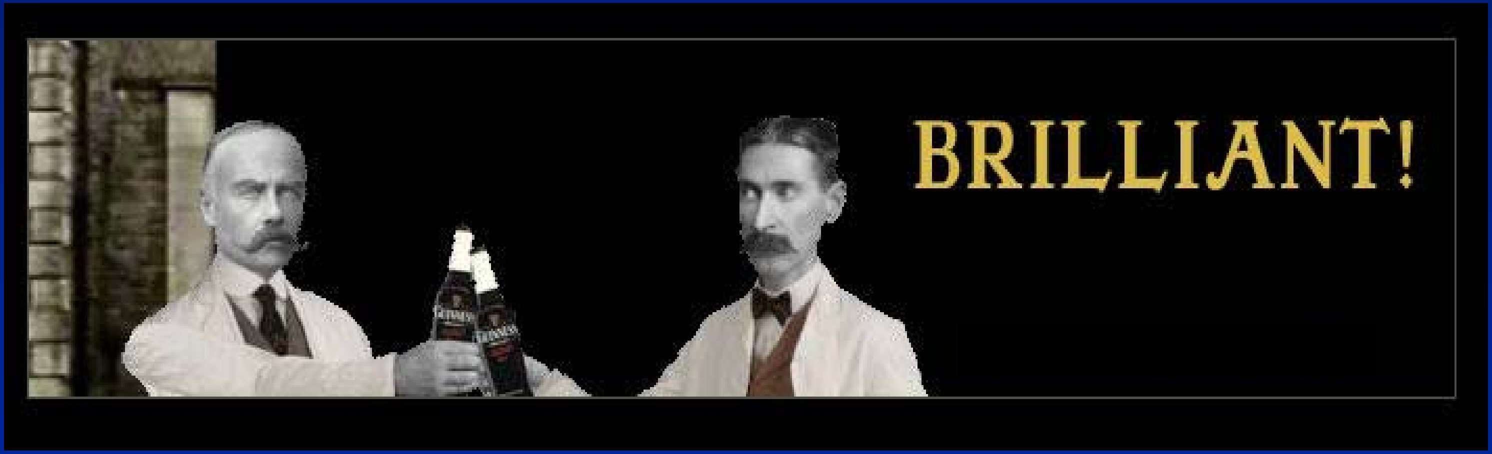
Device design – as it (often) *actually* occurs (Courtesy Paul Thomas)

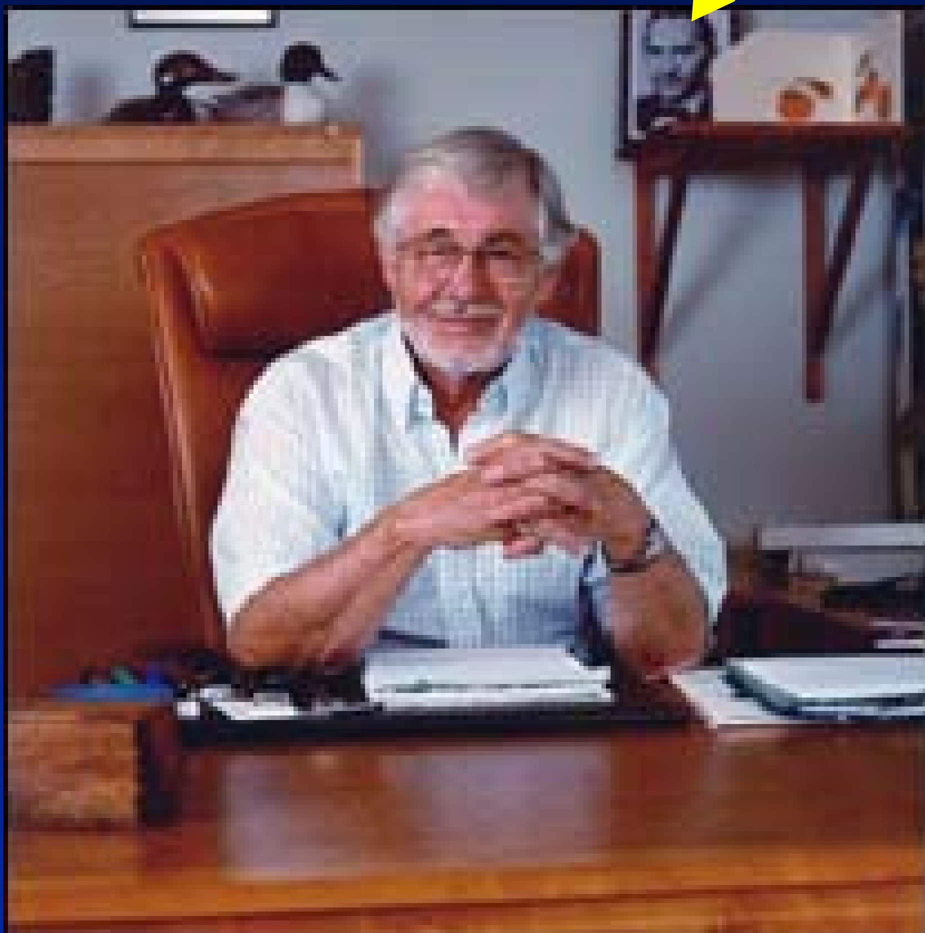


And speaking of design and inventions…

(following a popular Guinness commercial in the U.S.)



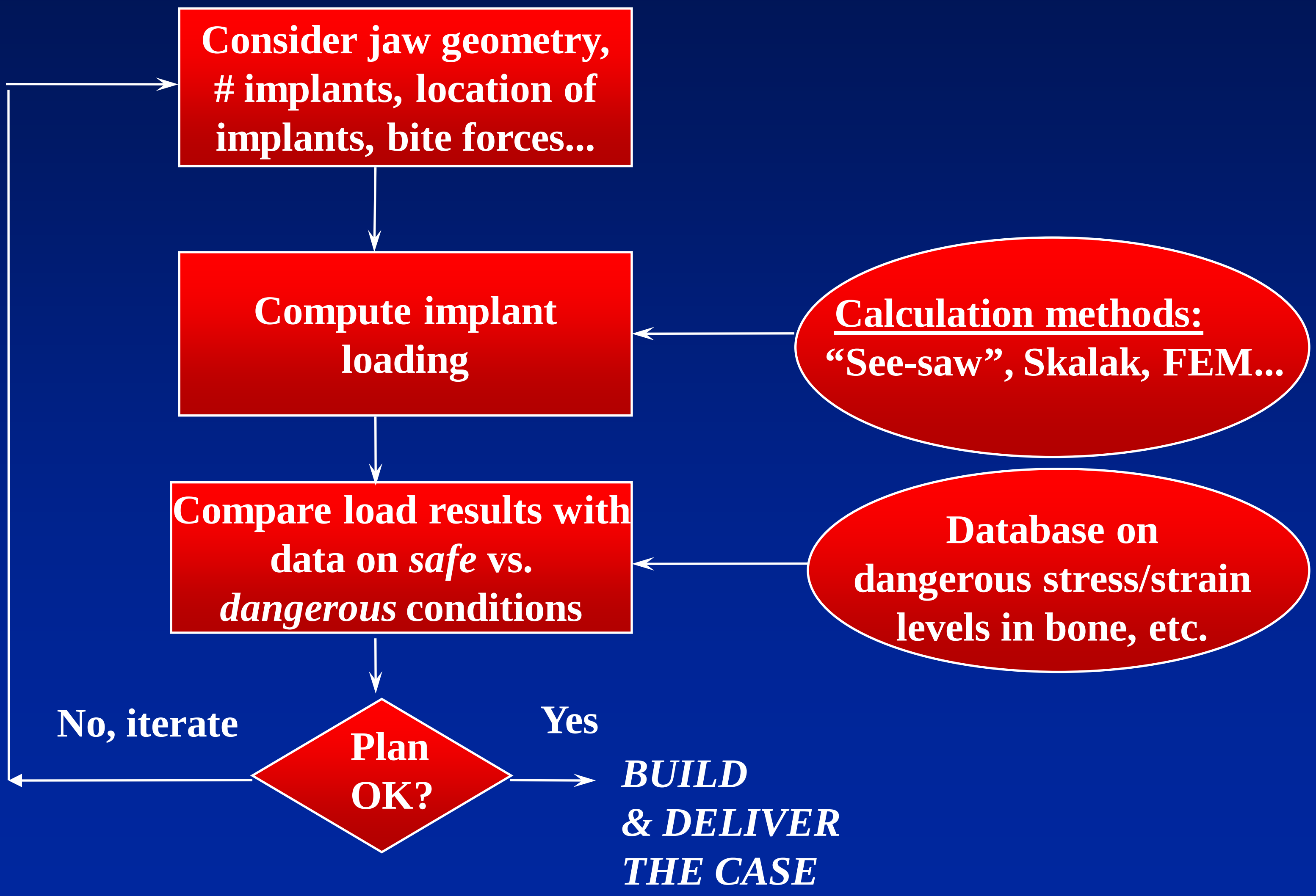




replaces
? A dental

Richard Skalak, P-I's biomechanics expert

Biomechanical case planning



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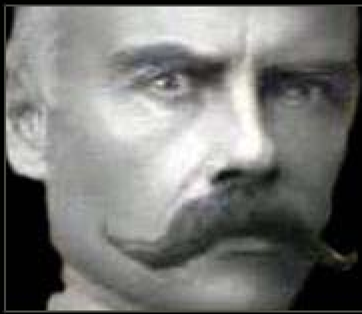
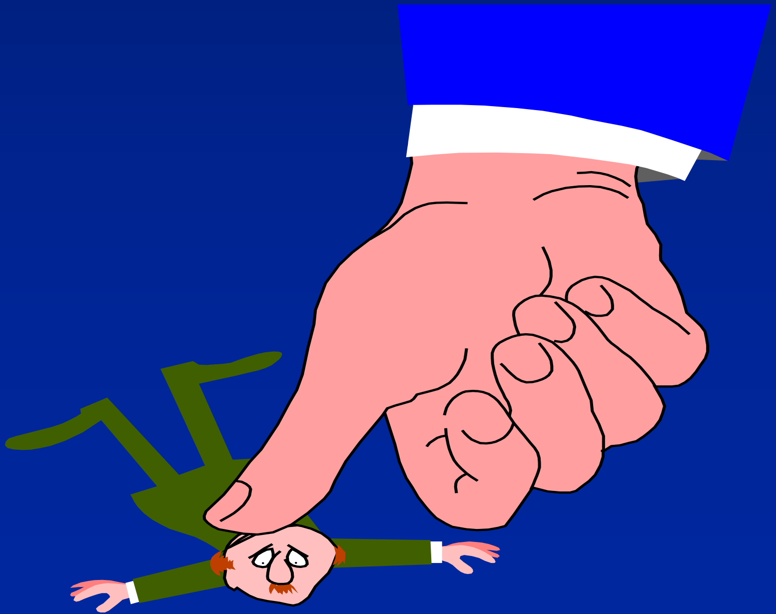
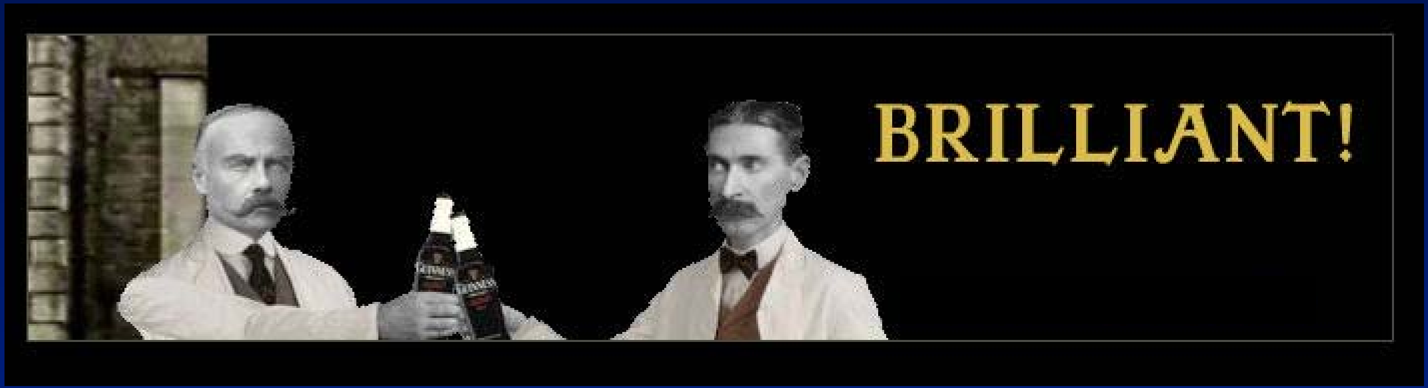
T or F?

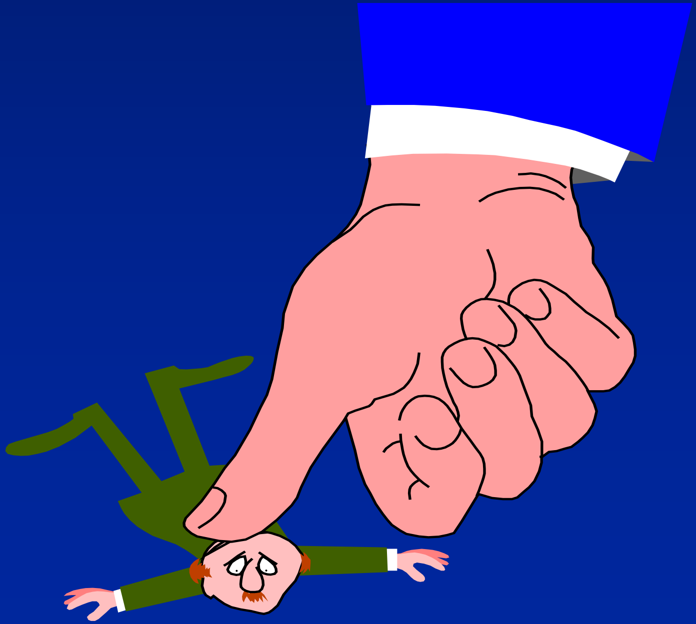


Stress is the same thing as *force* or *load*. It's accurate to say: "The bite force is 250 pounds per square inch (250 psi)."



False





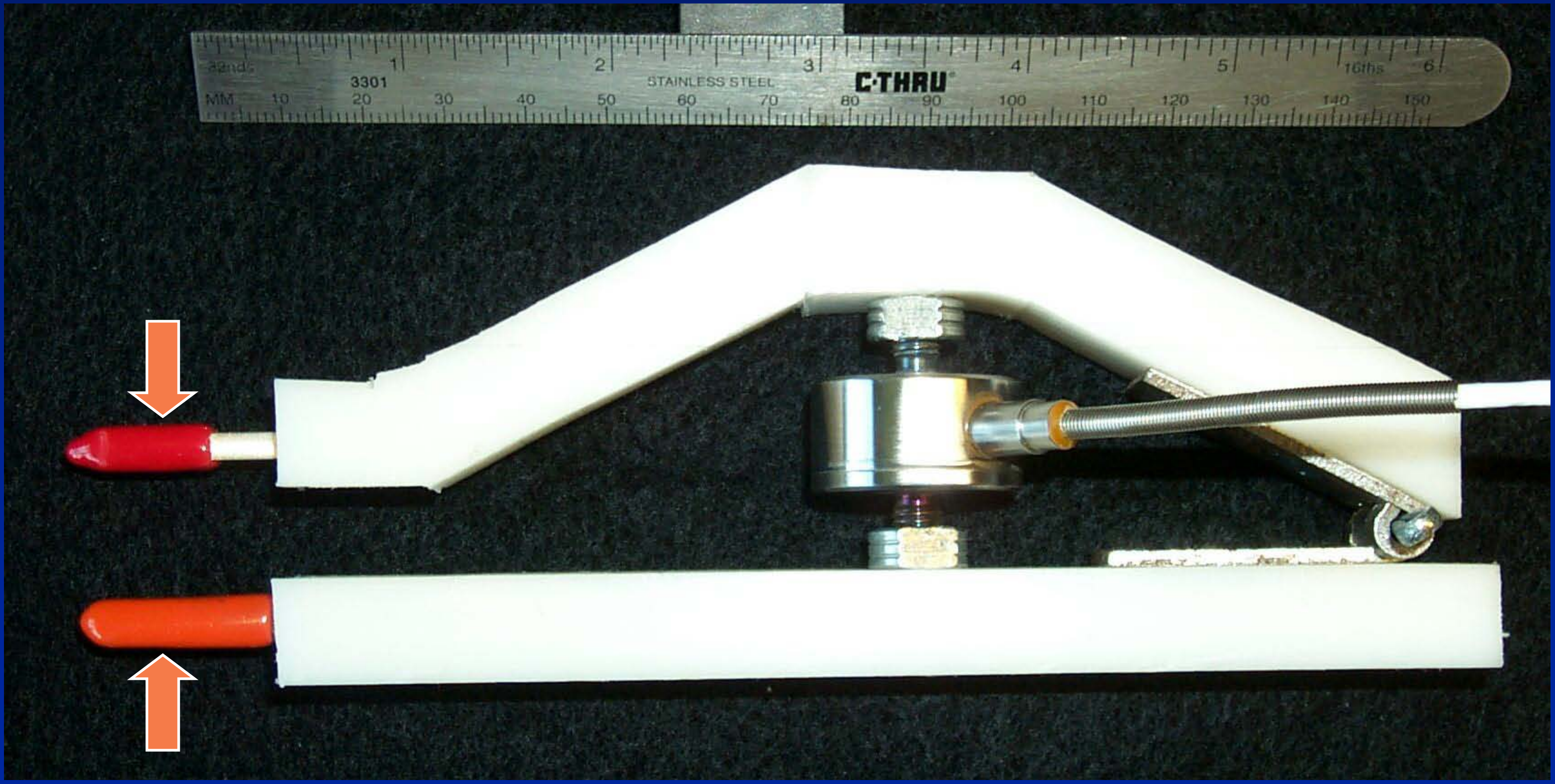
Stress is *force/area*, e.g., common units are psi, N/m^2 (Pa), 10^6 Pa = MPa

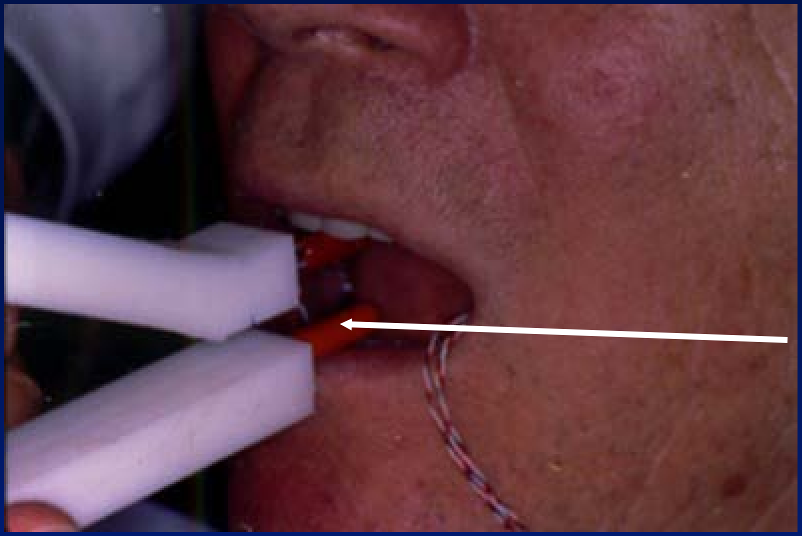
Force: common units include lb, N and 1 lb = 4.448 N

large force/small area = high stress

Example of force

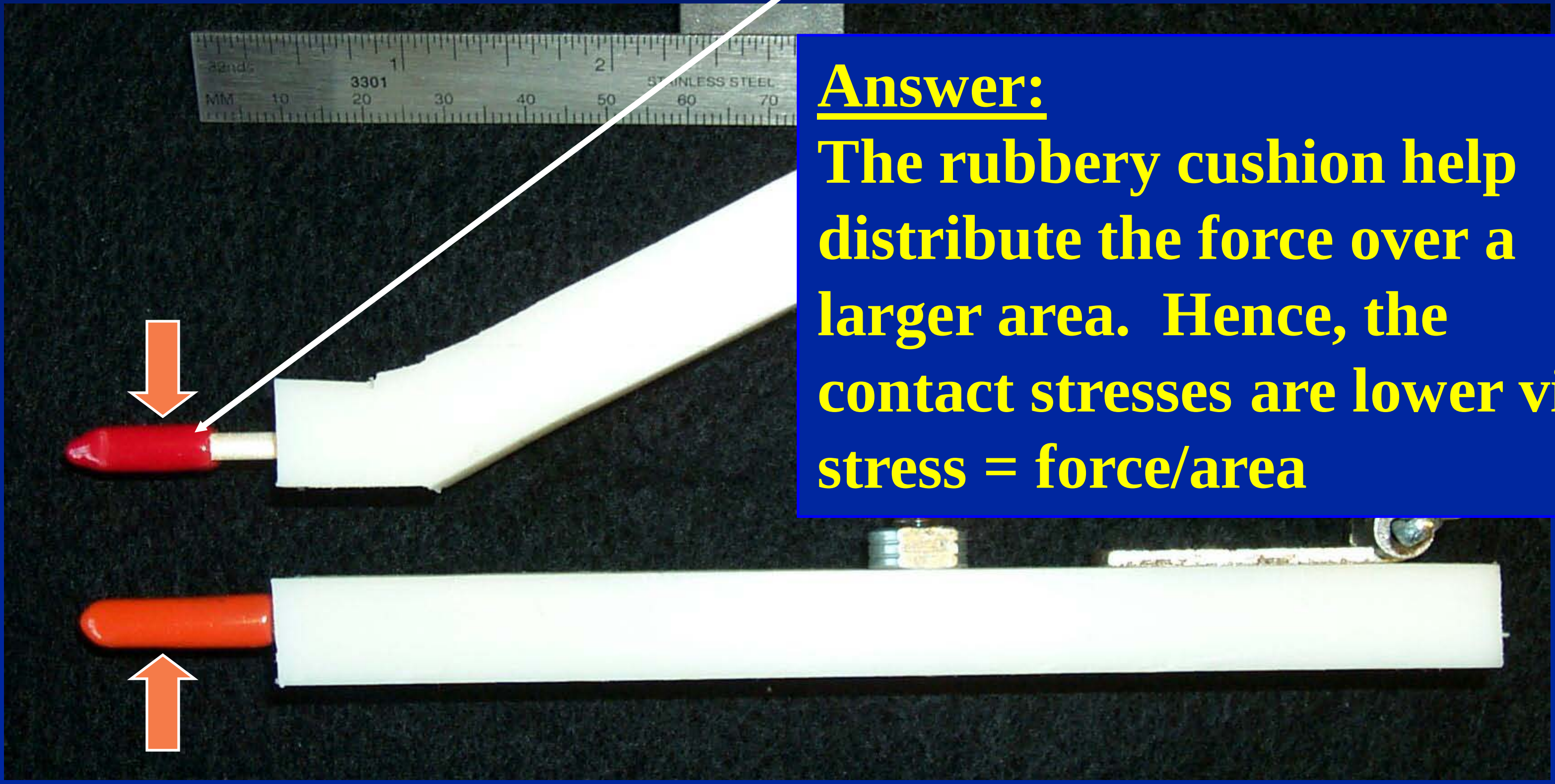
Our home-made bite *force* transducer measures *force* exerted by the teeth on the small beams.





<u>Example of the difference between *force vs. stress*:</u>

In this bite *force* transducer, why did we put rubber cushions over the small metal beams on which the patient bites?

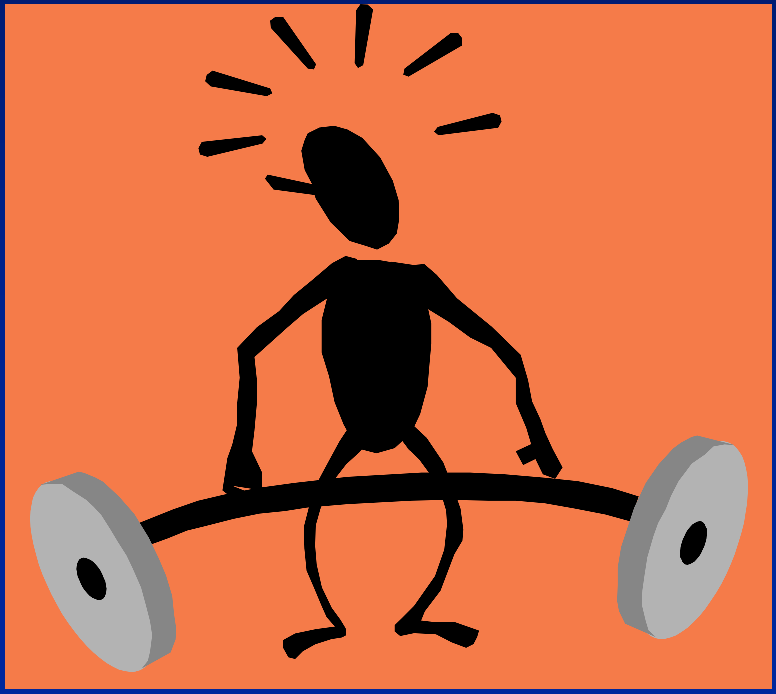


<u>Answer:</u>

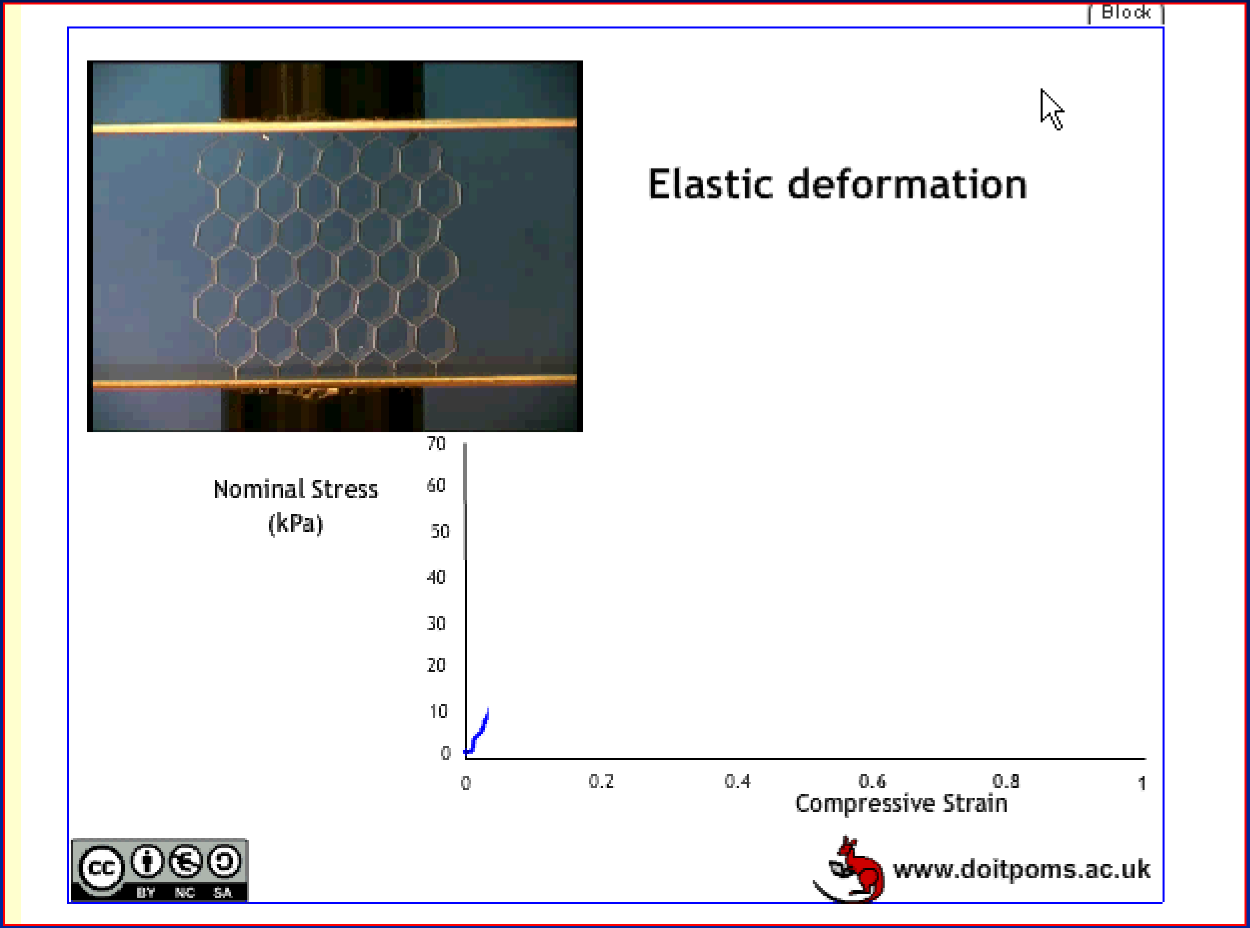
The rubbery cushion help distribute the force over a larger area. Hence, the contact stresses are lower via: stress = force/area

T or F?

- **Strain** is a measure of deformation.
- **Strain** and stress are related.



Yes, true for both. Note an example stress-strain test of a polymeric foam in uniaxial compression



Note that the foam yields (fails) at a strain of about 0.1 = 1%

1% strain in bone (= 0.01 = 10,000 με) is already large enough to damage bone; cortical bone yields at about 1% strain

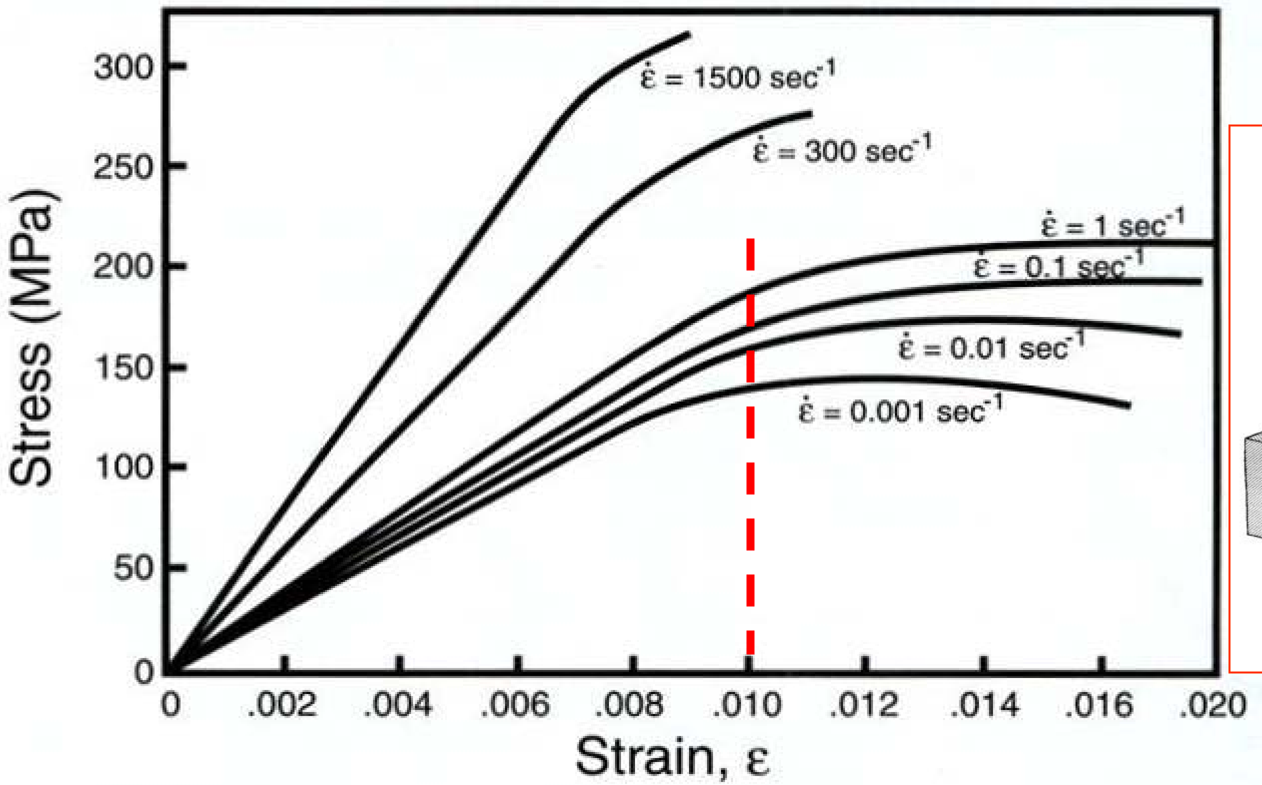
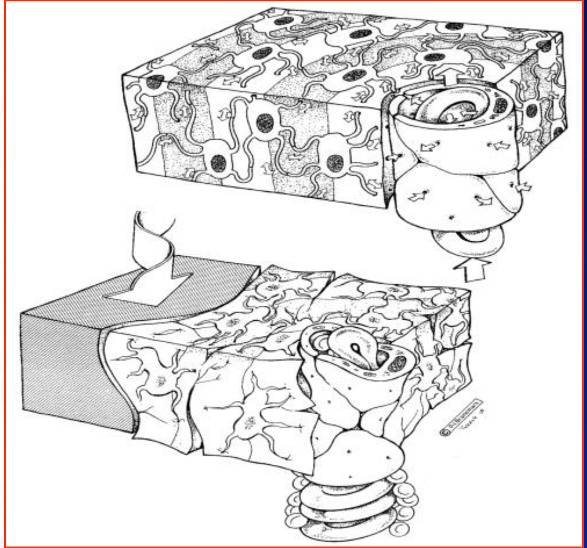
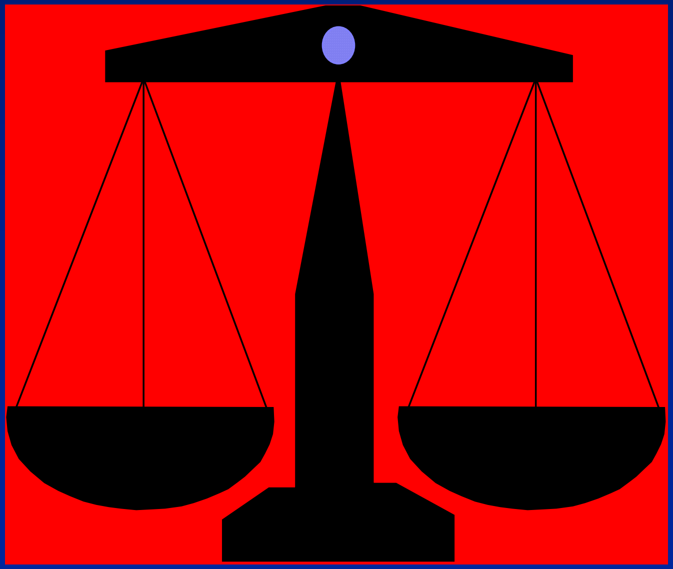


Figure A.8. The effect of strain rate on the stiffness and strength of cortical bone (adapted from McElhaney, 1966.)



T or F?

- In mechanics, a ***moment*** (or torque) describes the tendency of a force to produce rotation about a point or an axis.



True

- Typically, a moment, or torque, is produced by a force acting through a moment arm.
- A moment tends to produce a rotation about an axis or point.
- Sometimes we also speak of a *bending moment* on a prosthesis or an implant.

Moments in the era of Galileo, ~1638

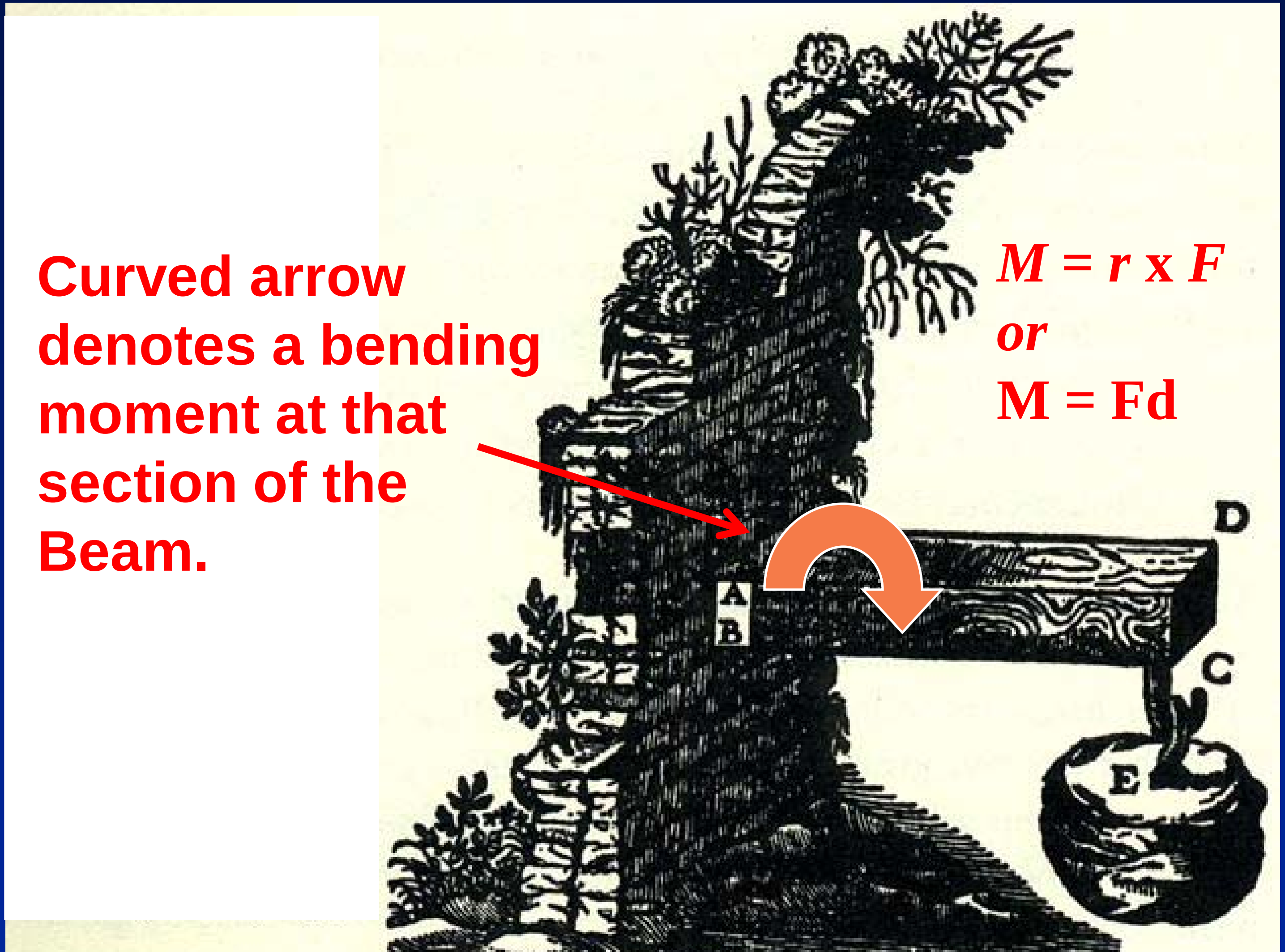
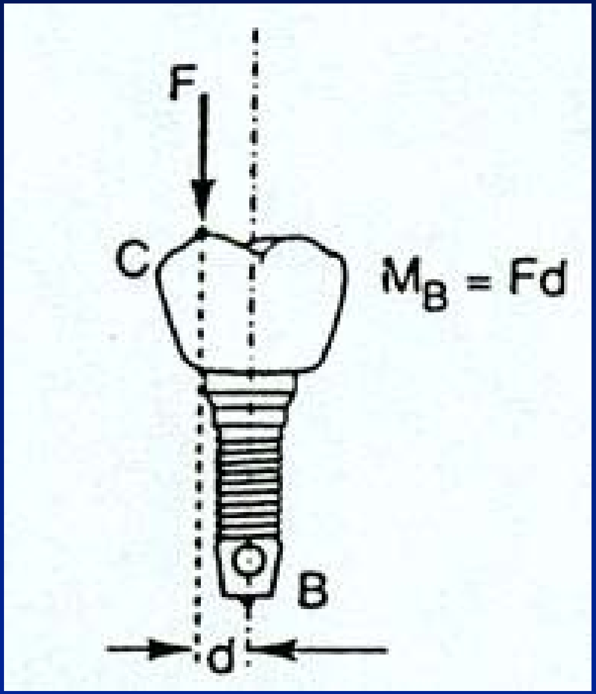


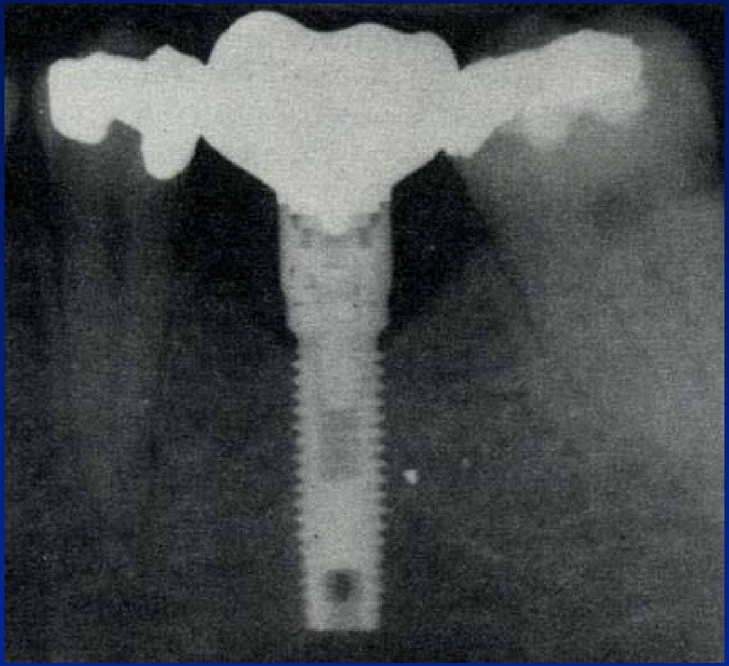
Figure 5.2. Galileo's cantilever beam (Galileo, 1638).

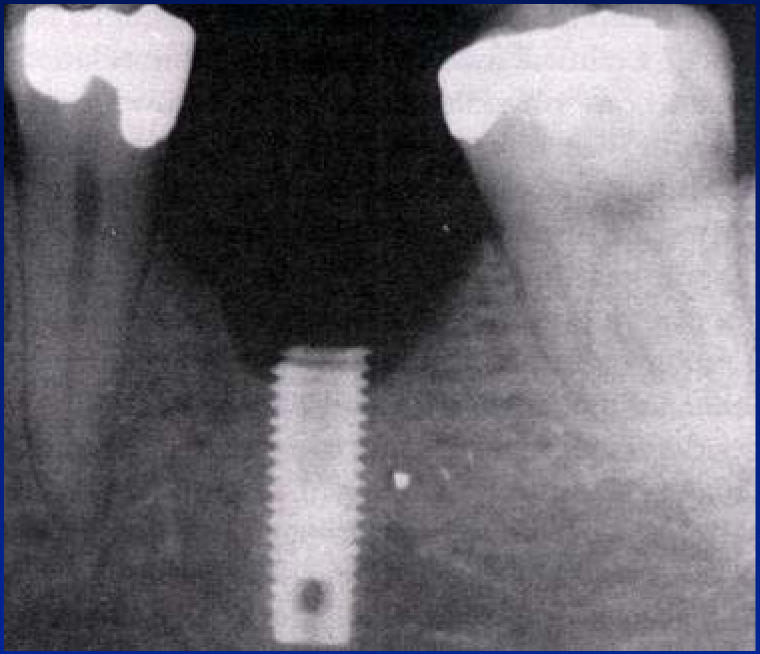
Example of a moment on an implant loaded slightly eccentrically

- An implant loaded by an off-axis (eccentric) vertical force experiences a force and a moment.
- Relevance: A narrow occlusal table diminishes the moment on the implant and the bone.



Possible outcome if the moment is large enough and applied repetitively for a long enough period:





Metallurgical fatigue of the implant – and a somewhat analogous fatigue process in the bone.

Rangert et al. (1995) *IJOMI* 10:326-334

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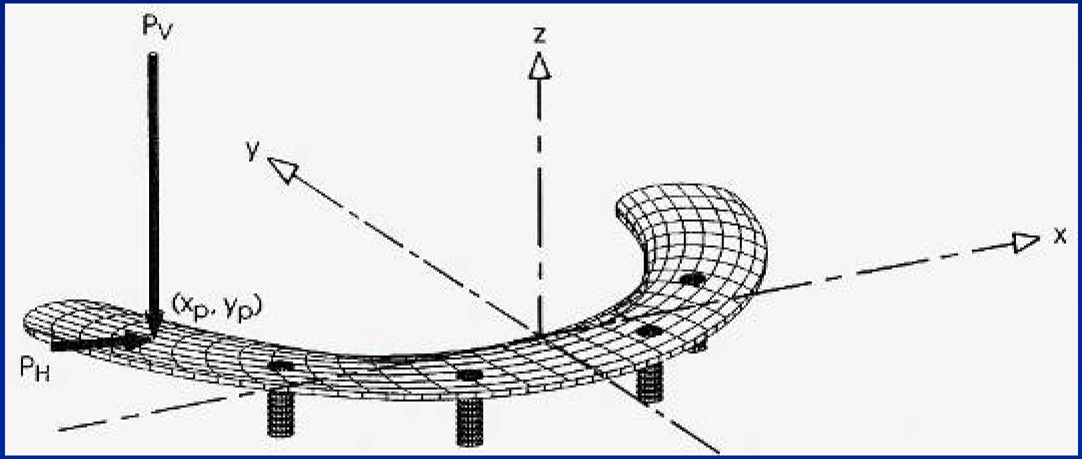
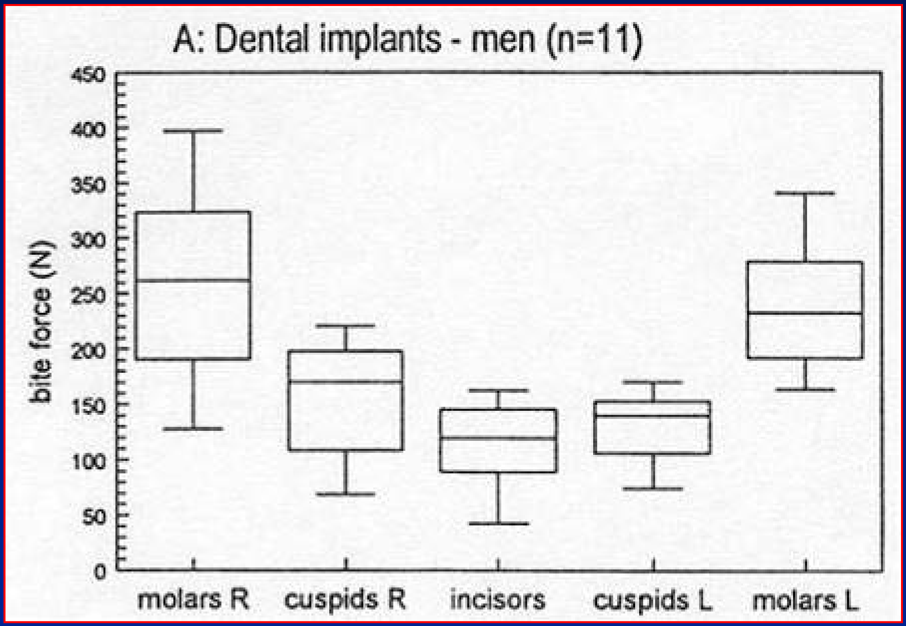
1. How large are typical forces on natural teeth and prostheses?

Forces on the prosthesis *are not* always the same as the forces that develop on the implants.



Morgan & James, *J. Biomech.* (1995)

Vertical bite forces: example data



Fontijn-Tekamp et al., *JDR 77*:1832-1839 (1998) “Bite forces with mandibular implant-retained overdentures”

Table 3. Maximum Occlusal Force, Occlusal Contact Area, Maximum Gape, and Maximum Displacement from the CO Position at Each Point in the Adult Control and Open-bite Groups

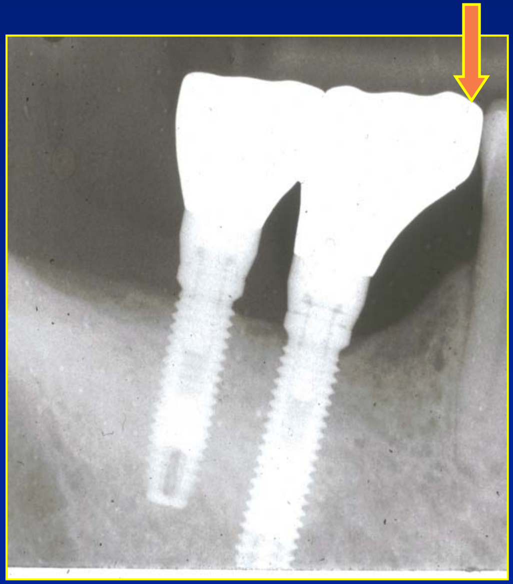
Variables	Control Group (n = 14) Mean	SD	Open-bite Group (n = 13) Mean	SD
Occlusal force (N)	850.4	231.9	308.3	156.5[b]
Contact area (mm^2)	19.6	6.6	6.6	3.9[b]
Maximum gape (mm)				
at right condyle	14.4	3.3	9.5	3.2[b]
at left condyle	15.2	4.3	10.0	4.2[b]
at lower incisor	47.6	5.7	39.1	6.8[b]
Maximum disp.[a] (mm)				
at right condyle	0.2	0.1	0.2	0.1
at left condyle	0.2	0.1	0.2	0.1
at lower incisor	0.2	0.1	0.2	0.1

[a] Maximum displacement during maximum clenching from the CO position.
[b] $p < 0.01$ (unpaired *t* test or Mann-Whitney U test).

Miyawaki et al. *JDR 84(2)*: 133-137, (2005) “Occlusal force and condylar motion in patients with anterior open bite.”

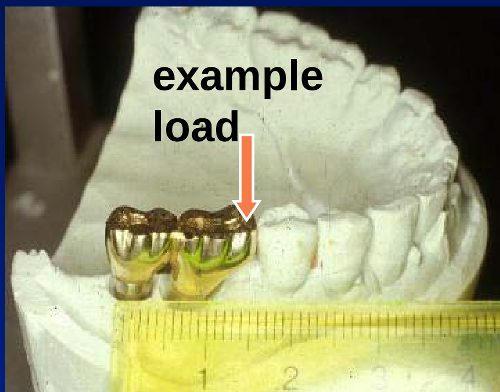
2. Given bite forces ***on a prosthesis***, what forces develop ***on the supporting implants***?

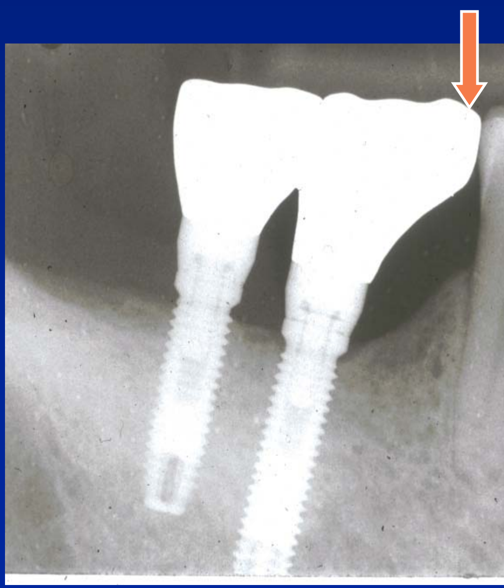
Example #1:
2 implant case

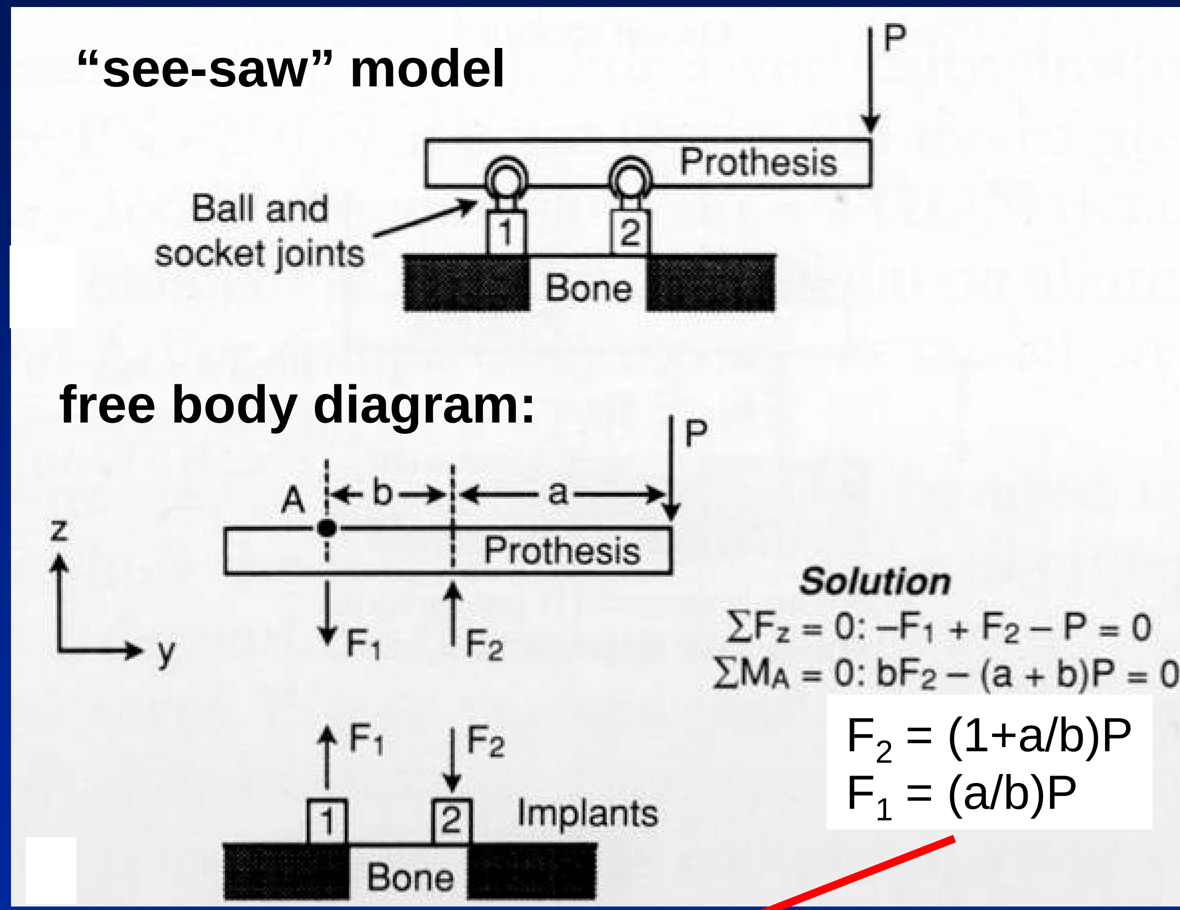


Courtesy of N. Van Roekel,
P. Sheridan, Mayo Clinic

In analyzing forces on 2 implants, the simplest model is based on introductory mechanics







If bite force $P \approx 250$ N (a moderate value) and a/b ~0.87, then $F_1 = 218$ N (*tension*) and $F_2 = 468$ N (*compression*).

So what? Who cares how big the forces are on the implants? Here's why:

Fig. 3. Pullout failure modes of HA coated implants. Adhesive (left) and cohesive (right). Dark areas are implant body, white areas are HA.

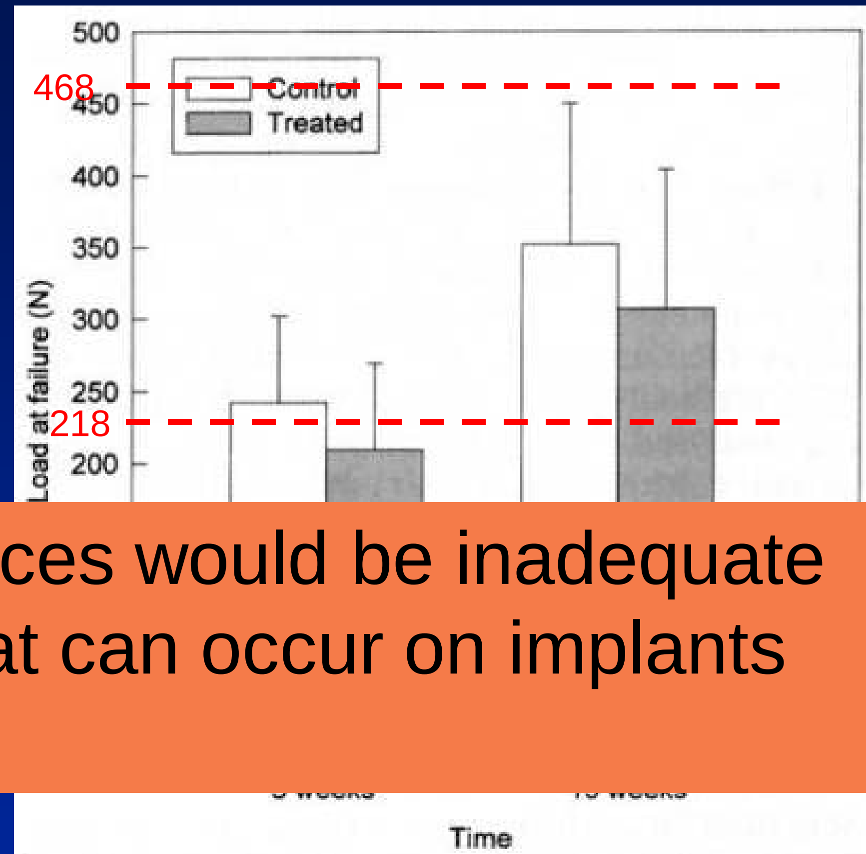


Fig. 2. Pullout forces for treated and control coated implants, showing pooled data from all samples. Mean and standard deviation shown.

Some bone-implant interfaces would be inadequate to carry the force levels that can occur on implants *in vivo*!

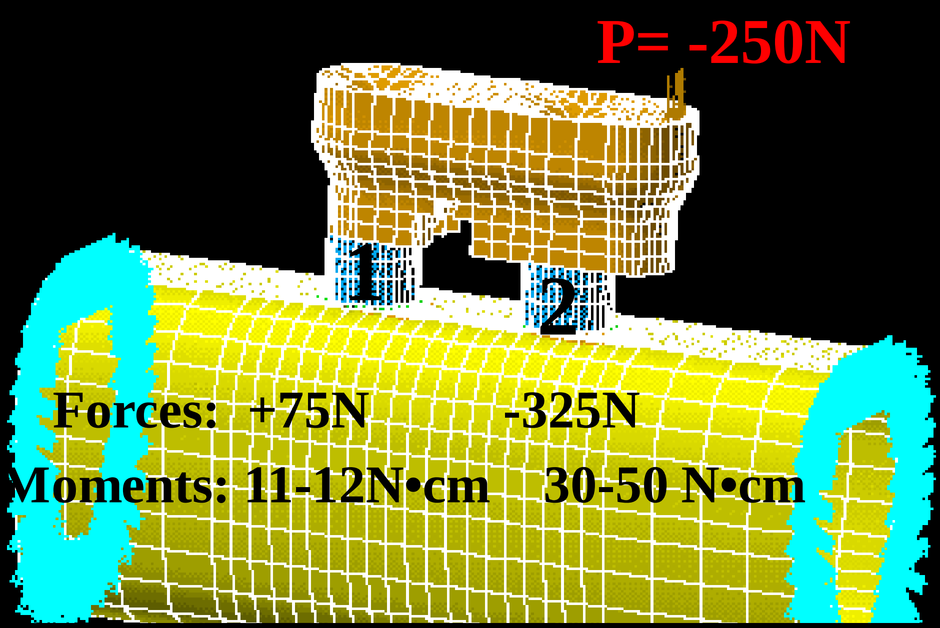
Burgess et al. (1999) "Highly crystalline MP-1™ Hydroxylapatite coating Part II: *in vivo* performance of endosseous root implants in dogs." *COIR 10*:257-266.

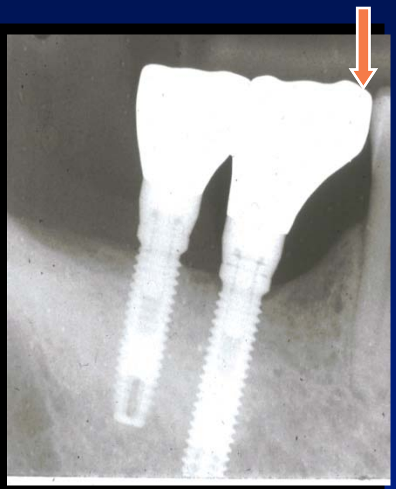
A short anecdote about Dick Skalak from a meeting in Belgium several years ago:

"Dr. Skalak, what is all this engineering stuff, and all this talk about loading and failure? Are you just trying to scare us?

Yes, I am!

More complex models show that both forces *and bending moments* can exist on implants





results from a finite element computer model

Brunski & Skalak, Chap. 2 in *Osseointegration in Craniofacial Reconstruction* (Eds. Brånemark and Tolman), Quintessence, 1998, pp. 15-35.

3. Given bite forces ***on a prosthesis***, what forces develop ***on the supporting implants***?

Example #2: fully edentulous cases

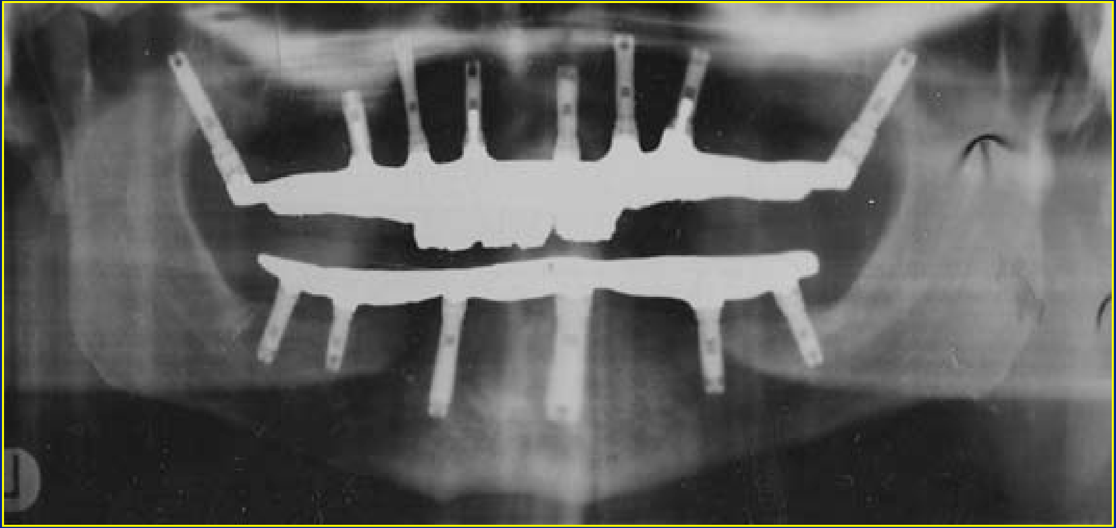
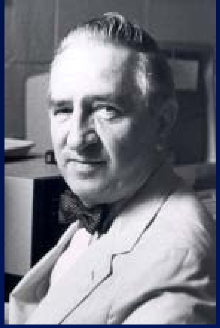
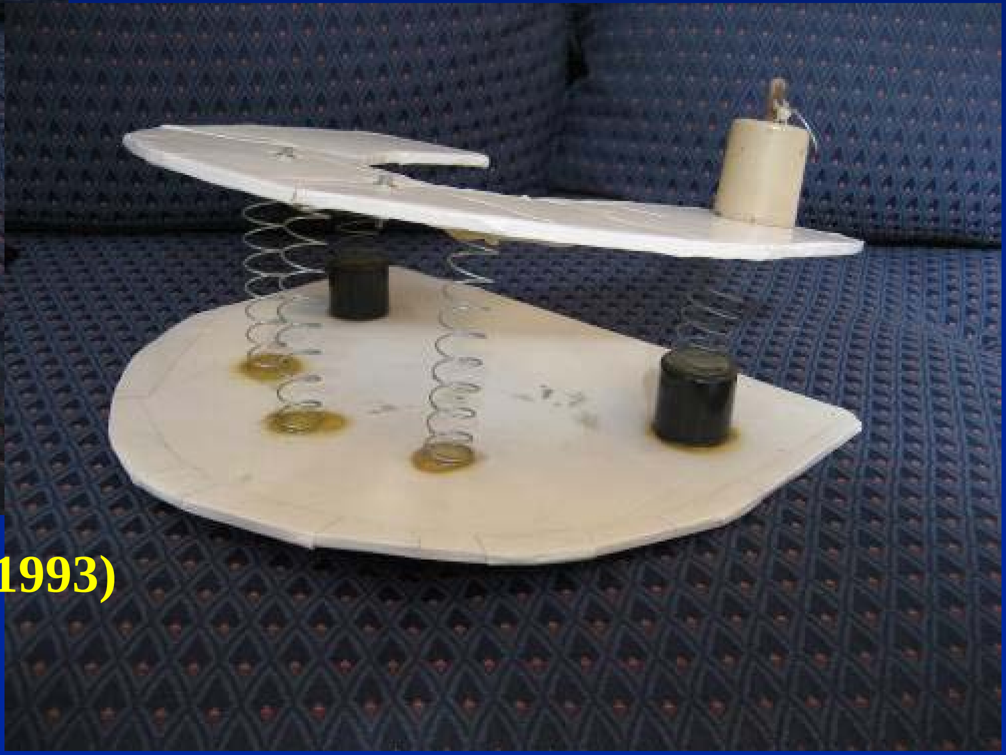


Image courtesy of *Prosthodontics Intermedica*, Drs. Balshi & Wolfinger, Ft. Washington, PA

Skalak's model, *J Prosth Dent* (1983)



- assumes a rigid prosthesis
- assumes spring-like implants + interfaces
- assumes a ball & socket joint at each bridge-implant connection



Additional similar models:

- **Skalak, Brunski & Mendelson (1993)**
- **Morgan & James (1995)**
- **Brunski & Hurley (1995)**

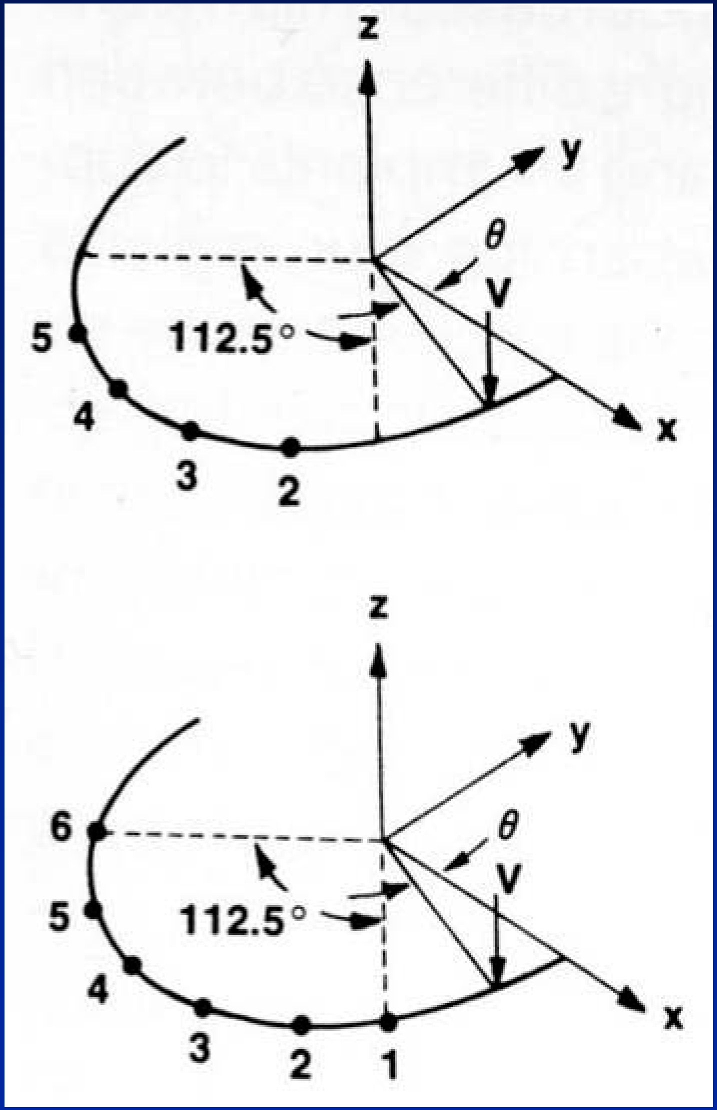
How might a clinician use the Skalak model?

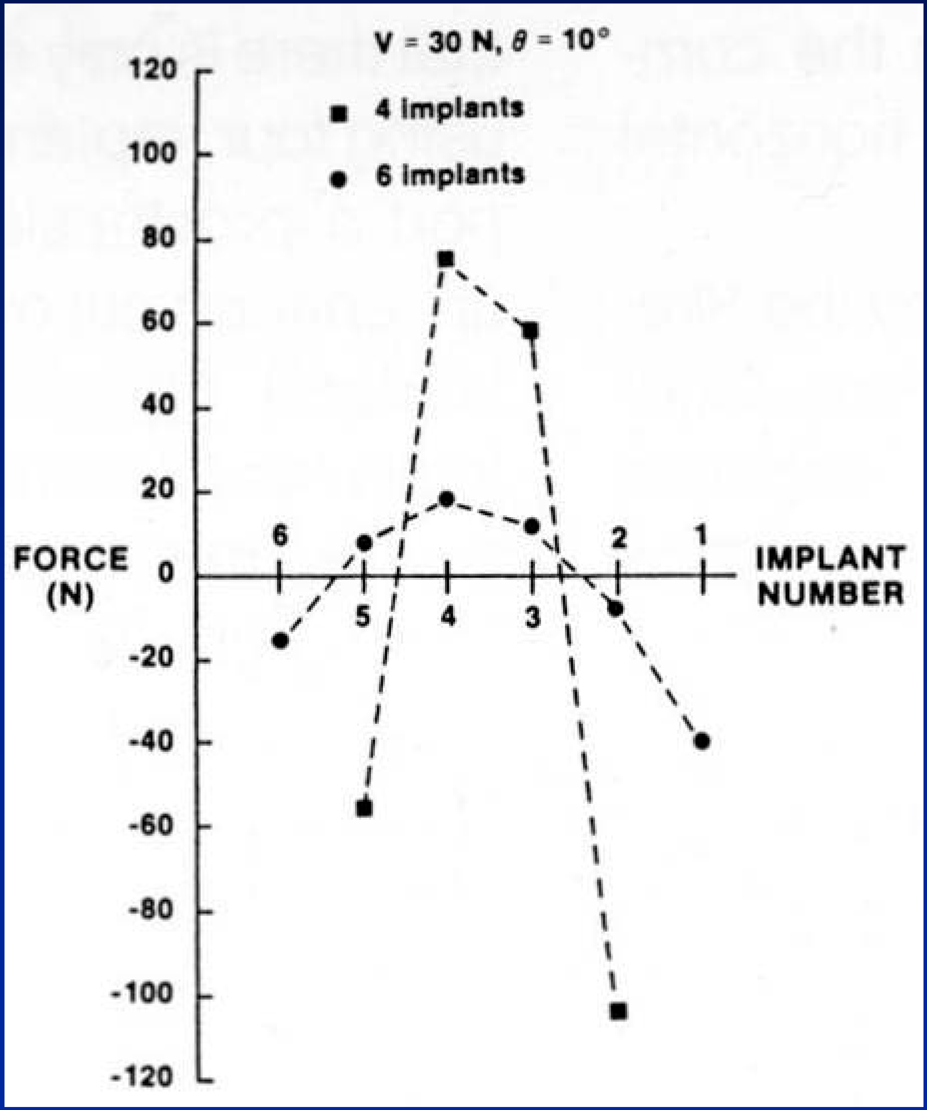
- *T or F: In designing a full-arch prosthesis, it's always better to use six (6) implants rather than four (4).*

Hmmm…6 x \$2000/implant = \$12,000
4 x \$2000/implant = \$ 8,000

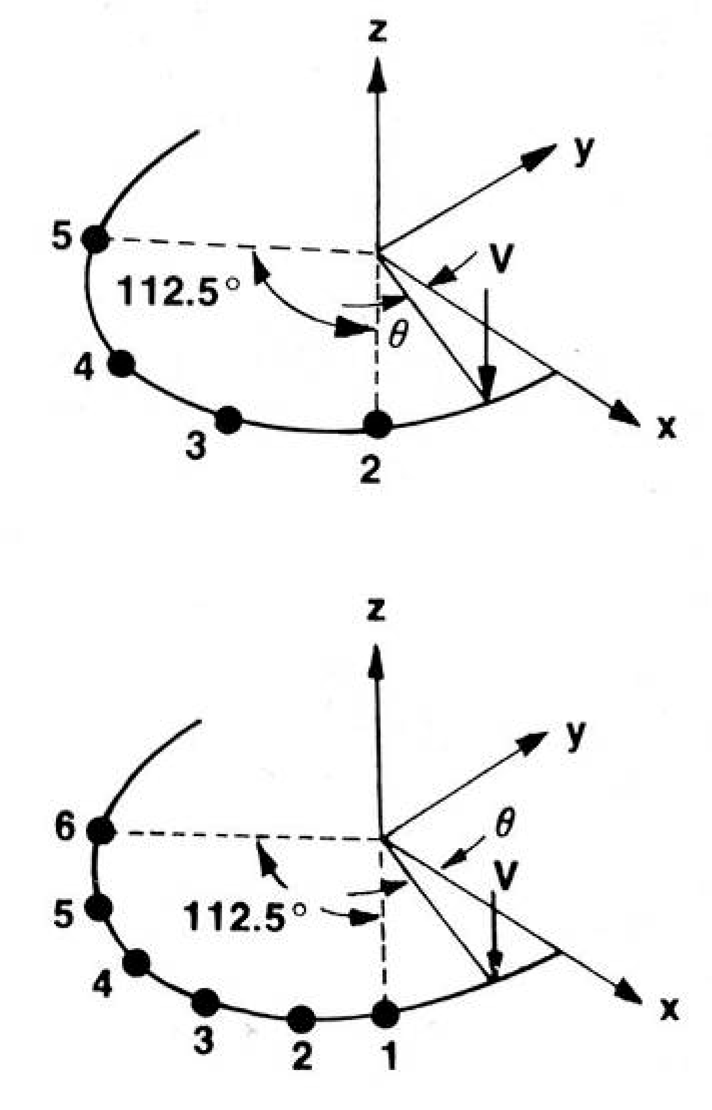
\$12,000 > \$8,000, therefore 6 is better than 4!

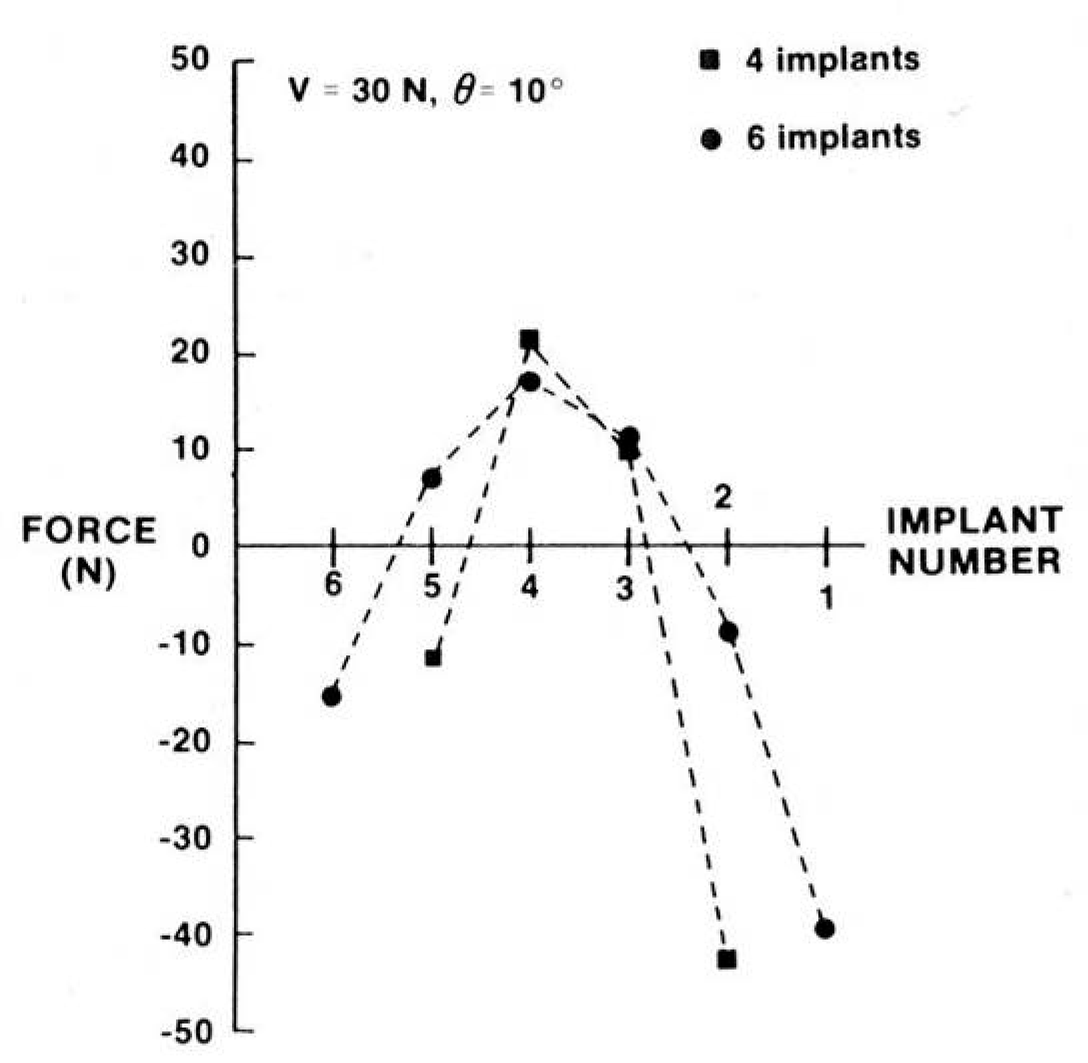
6 implants better than 4? Maybe yes!





6 implants better than 4? Maybe no!





CAUTION

For a complete-arch restoration, in-line placement of implants creates a severe risk of overload. Implants must therefore be spread along the alveolar ridge (Figs 3-13 and 3-14).

Fig 3-13 Clinical occlusal view. For a complete denture, it is *important to spread implants effectively along the alveolar* crest. The long cantilever extension is made possible only by appropriate implant placement.

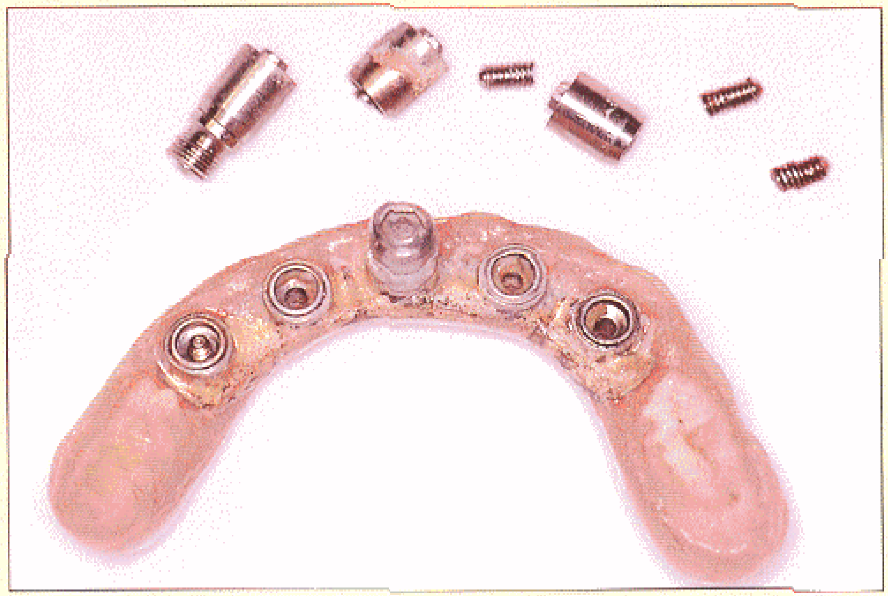


Fig 3-14 View of a loosened fixed partial denture. The straight-*line placement of the implants in combination with large exten-*sions risks mechanical complications, especially if this situation is combined with an unfavorable occlusion. After several incidences of screw loosening, the abutment screws and two implants fractured.

Renouard & Rangert (2008)
Risk Factors in Implant Dentistry

Example failure rates of Ti implants

Analysis of Incidence and Associated Factors with Fractured Implants: A Retrospective Study

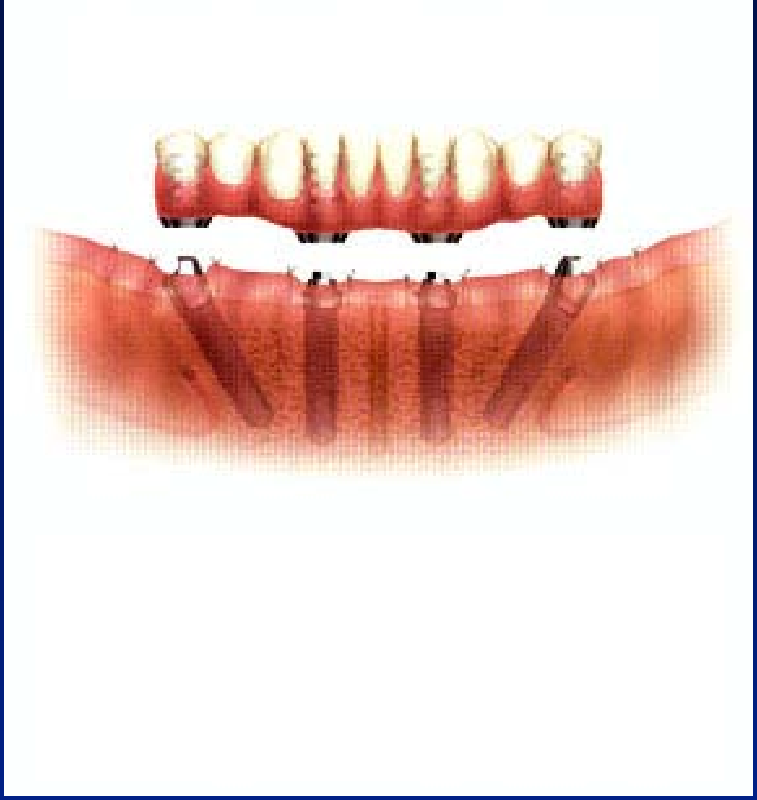
Steven E. Eckert, DDS, MS[1]/Stephen J. Meraw, DDS, MS[2]/
Ebru Cal, DDS, PhD[3]/Richard K. Ow, BDS, MSc[4]

Osseointegrated threaded titanium screw-type implants rarely lose integration after the first year of clinical function. Implant failure can occur for other reasons, with implant fracture being one of the major reasons for late failure. The purpose of the present study was to determine the incidence of implant fracture in completely edentulous and partially edentulous arches and to determine what factors may predispose an implant to a higher fracture risk. A retrospective evaluation of 4,937 implants was performed to determine the incidence of and factors common to fractured implants from a sample of implants placed and restored in one institutional setting. Based on the results of this study, the following observations were made: implants fracture at similar rates in the maxilla as in the mandible (0.6%), implant fractures occur more frequently in partially edentulous restorations (1.5%) than in restorations of completely edentulous arches (0.2%), all observed fractures occurred with commercially pure 3.75-mm-diameter threaded implants, and prosthetic or abutment screw loosening preceded implant fracture for the majority of the implants. More studies would be helpful to further explore the relationship and progression of factors associated with implant fracture. (Int J Oral Maxillofac Implants 2000;15:662–667)

Salvi & Bragger, *IJOMI* 2009; 24(Suppl):69-85
“Mechanical and technical risks in implant therapy”

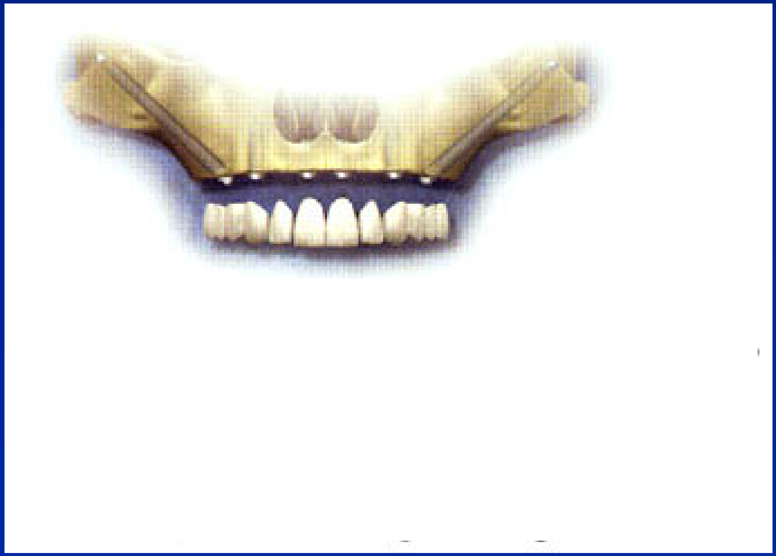
- Factors associated with increased mechanical/technical complications were:
  - absence of a metal framework in overdentures
  - cantilever extensions > 15 mm
  - bruxism
  - length of the reconstruction
  - history of repeated complications

4. Another example of the value of the Skalak model…



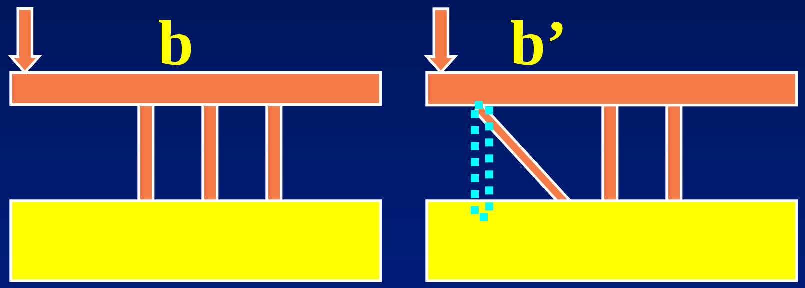
T or F:

Tilting of implants is detrimental.



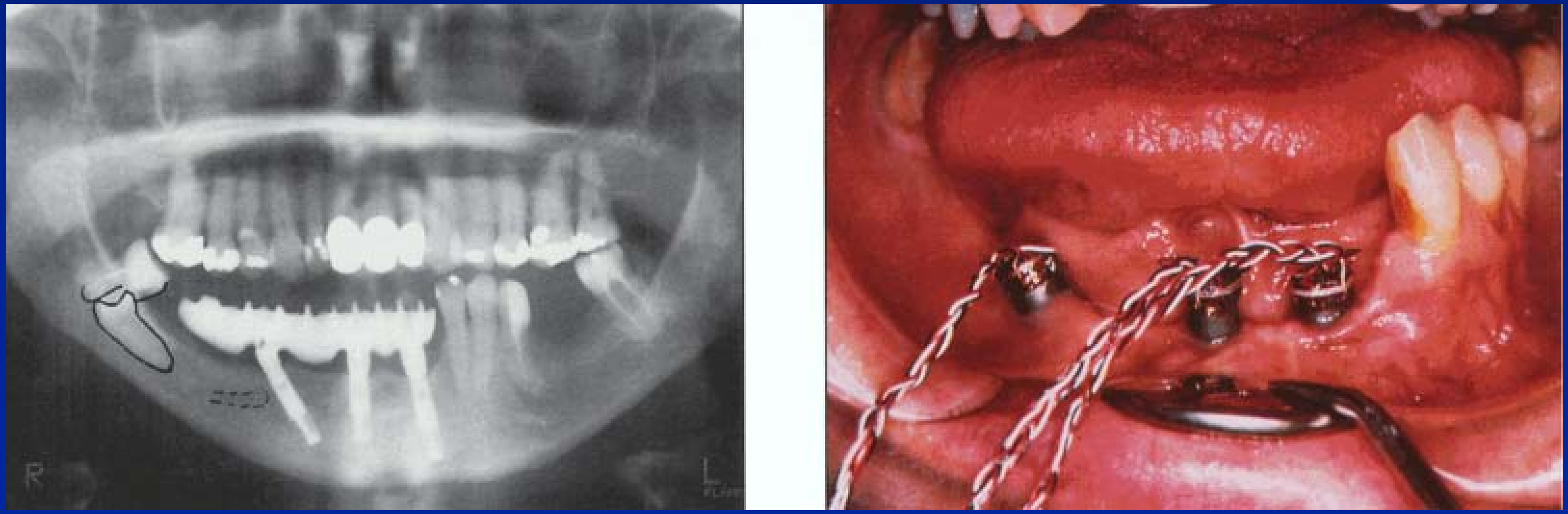
***Answer*: Not necessarily. Sometimes tilting can lead to lower forces per implant.**

Upright vs. tilted implants: the idea



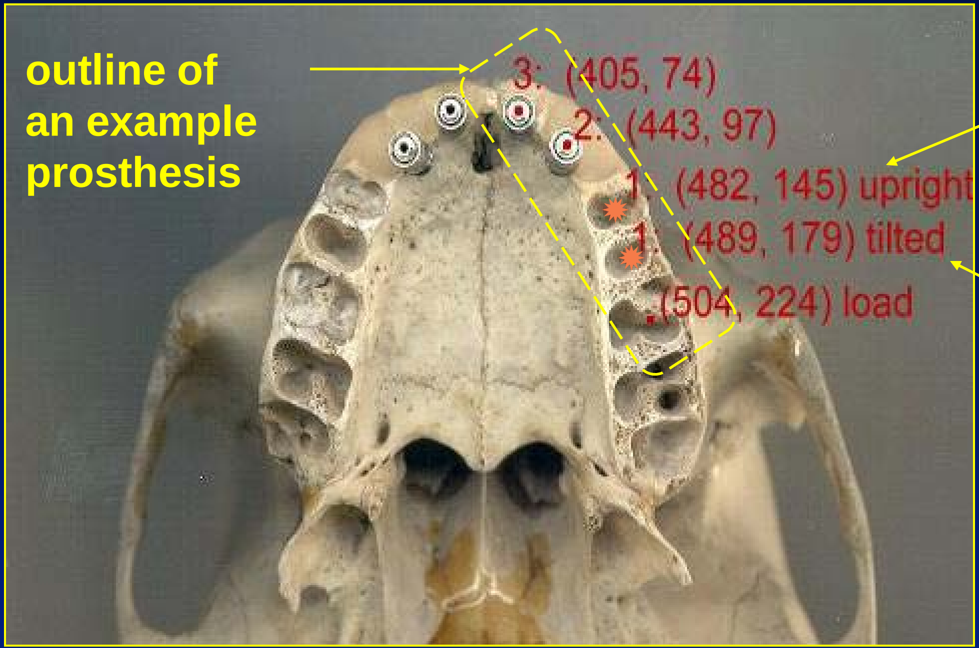
- Force per implant will change if we change spacing b to spacing b’, where b’ > b

The tilting allows you to (in effect) have an implant where the upright green one is located.

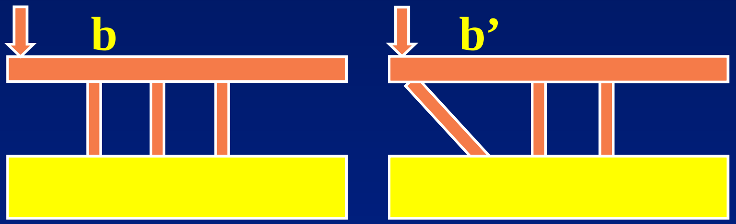


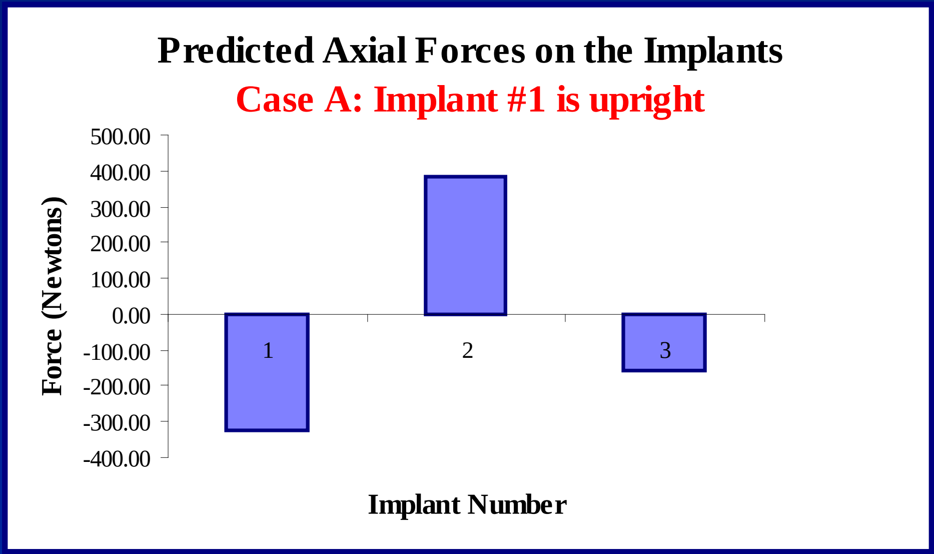
From Krekmanov *et al. IJOMI* 2000

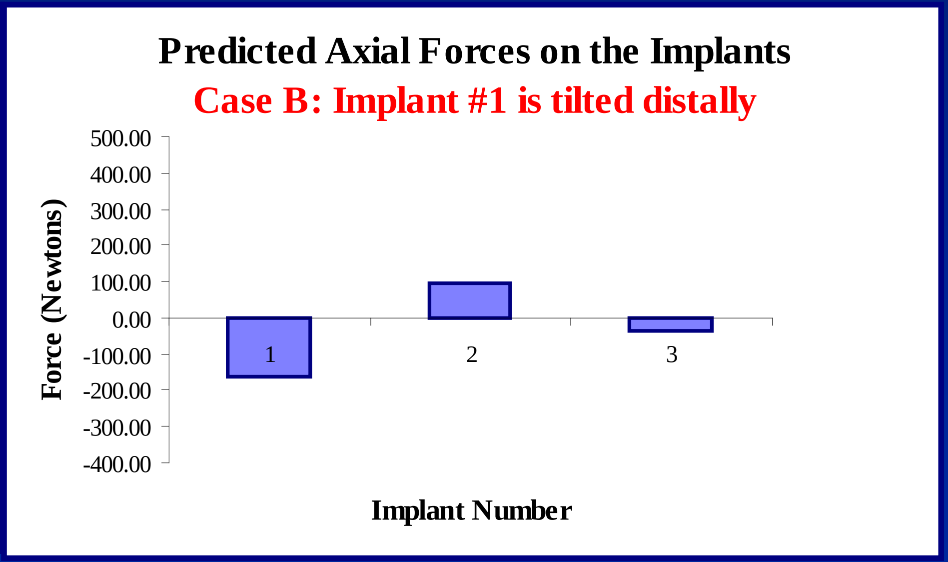
Illustration of the tilting effect -- using the Skalak Model



When implant 1 is <u>upright</u>, the load distribution among the implants involves larger forces than when implant 1 is <u>tilted</u> distally. (In effect, you’re increasing b to b’ .)

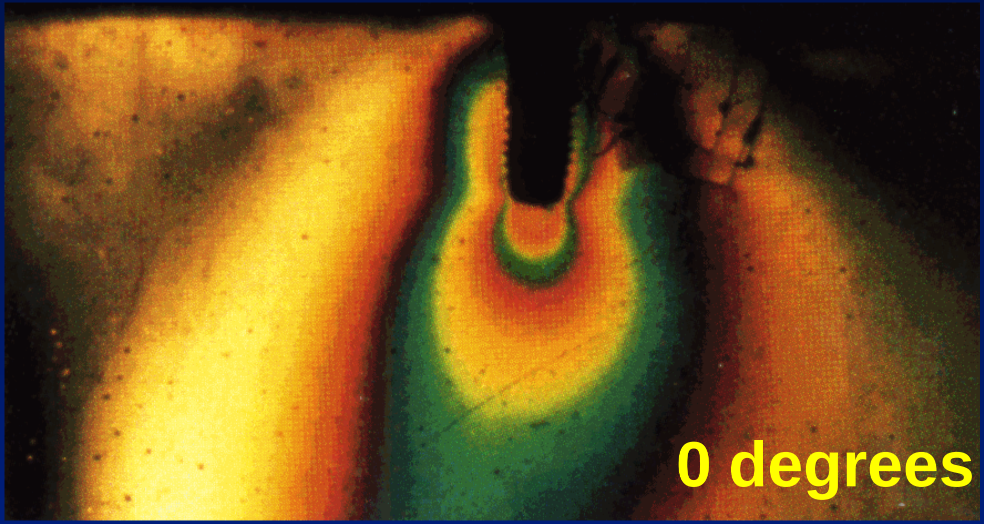


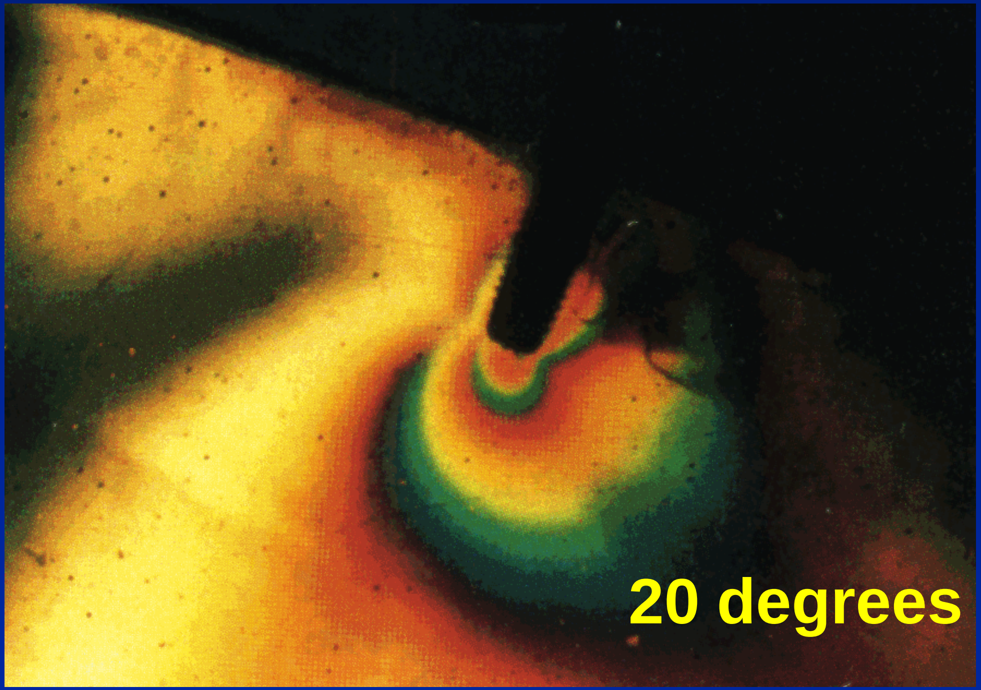




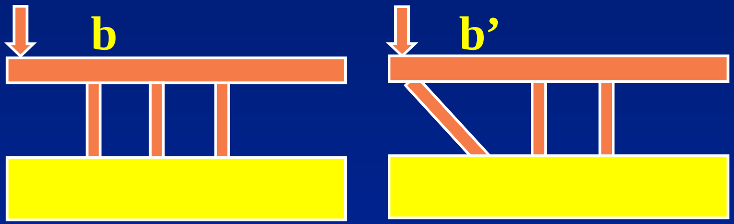
-100 N load applied to the prosthesis at its distal end

Tilting will increase strains in bone if the applied force is the same as when the implant is upright…





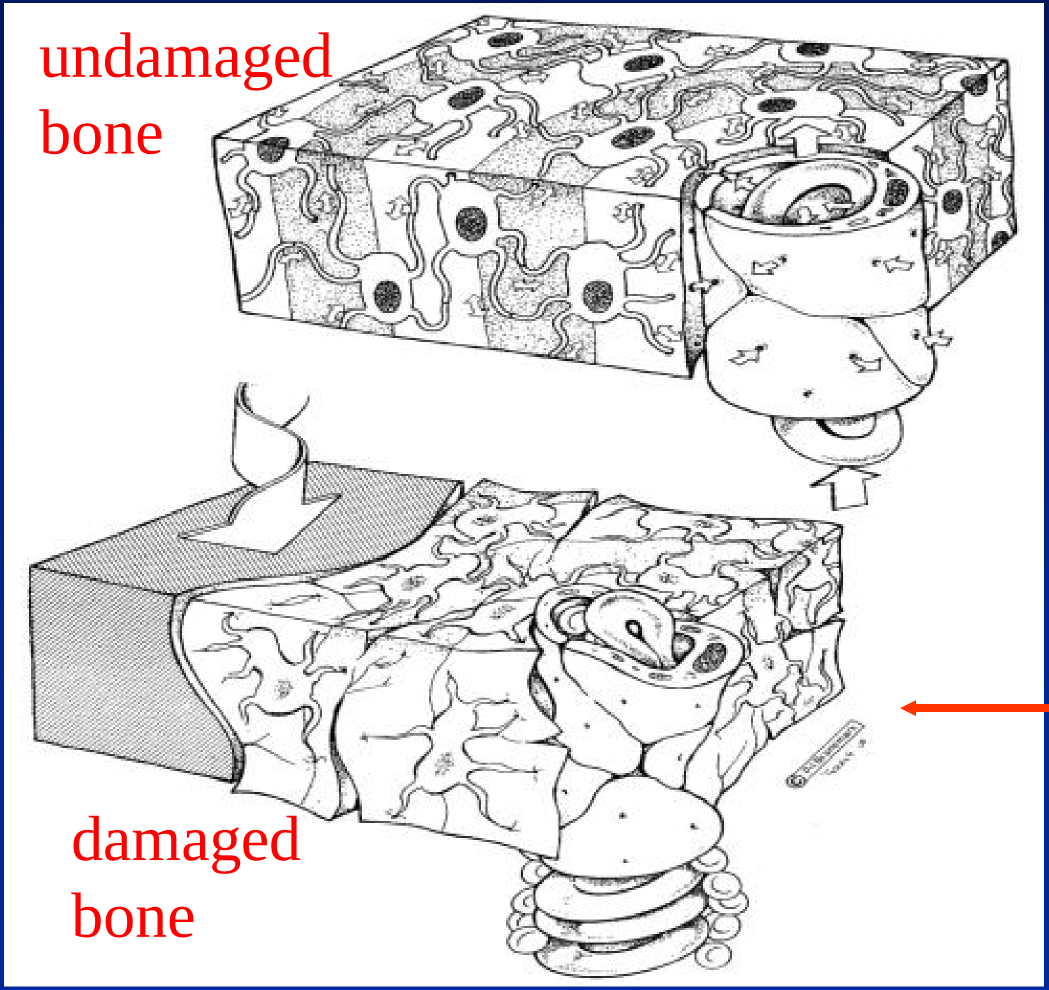
…but the tilting decreases the force on the implant relative to what it would have been if the implant had been upright.

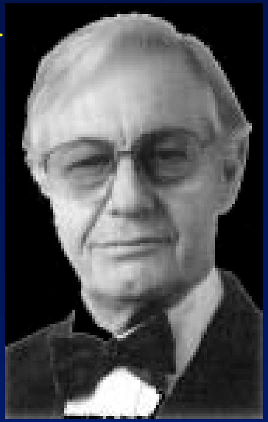


Stress-strain distributions in interfacial bone depend on the angle of loading of the implant.

Clelland et al.
IJOMI 1993;8:541-548

As for how much strain the bone can take…





- **P-I Brånemark's depiction of interfacial damage from loading...**
- **...illustrates the possibility that large strain (deformation) in bone can damage the cells, vasculature, and bone matrix.**

And we know that 1% strain in bone (= 0.01 = 10,000 με) is already large enough to damage cortical bone.

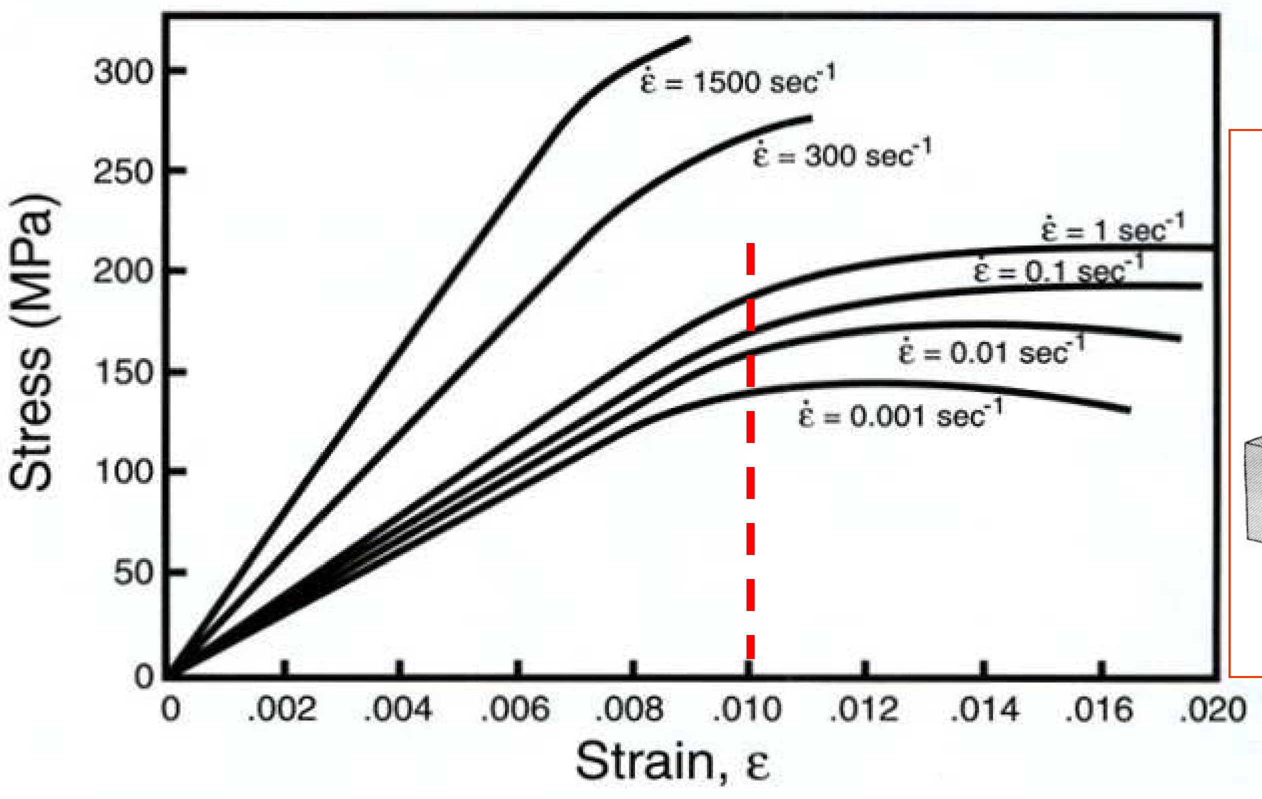
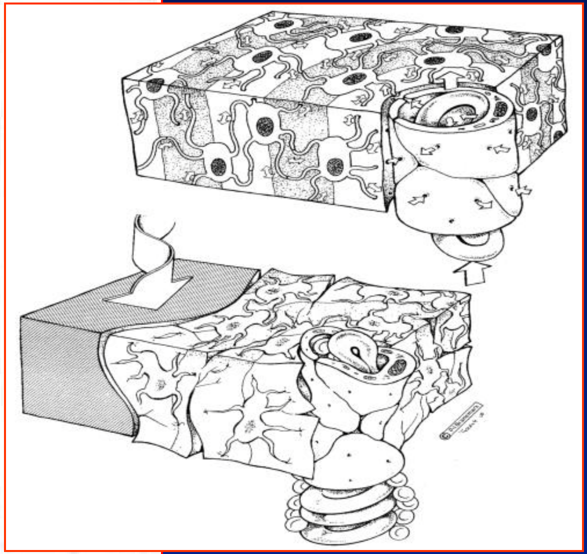


Figure A.8. The effect of strain rate on the stiffness and strength of cortical bone (adapted from McElhaney, 1966.)

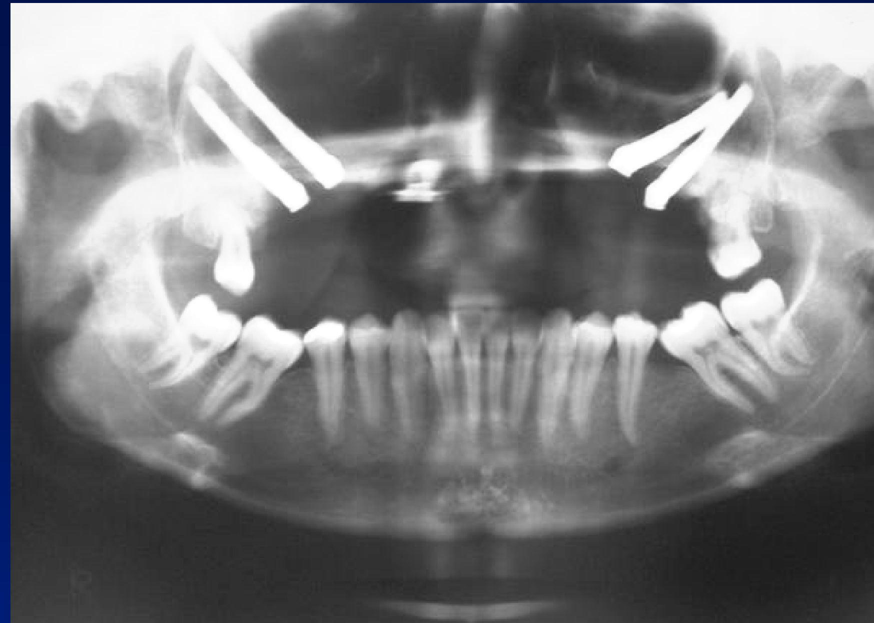


Outline

- Reinforce a few ideas about:
  - implant design
  - key terms in biomechanics: force (load), stress, strain, moment (bending moment, torque)
- Discuss ways to assess implant loading *in vivo*
  - Typical intraoral prosthetic situations
  - A few maxillofacial situations
- Summary

5. Analyses with the Skalak model can also be done for zygoma implants.

Surgical treatment using “double zygoma fixtures” to the (R) and (L) residual zygomas



Surgeon : P-I Brånemark
Anaplastologist :
Dr. Marcelo Oliveira
São Paulo, Brasil

P-I BRÅNEMARK INSTITUTE BAURU

Slide courtesy of Dr. Kenji W. Higuchi, Spokane, WA

6. How about analyses of craniofacial cases?

(Images courtesy of Dr. Kenji W. Higuchi, Spokane, WA)

2006

P-I BRANEMARK INSTITUTE BAURU

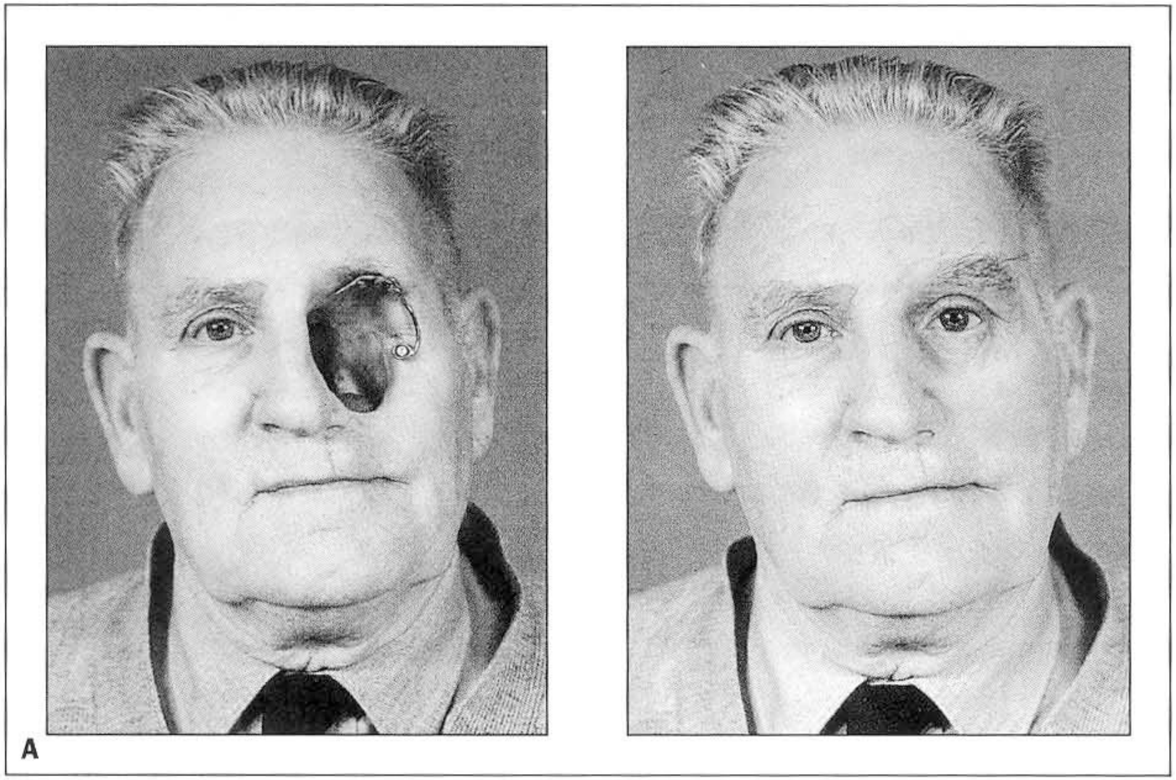
Anaplastologist : Dr. Marcelo Oliveira, São Paulo, Brasil

Yes, methods are available for craniofacial cases as well.

The next few cases are discussed further in:

Brunski & Skalak, Chap. 2 in *Osseointegration in Craniofacial Reconstruction* (Eds. Brånemark and Tolman), Quintessence, 1998, pp. 15-35.

1



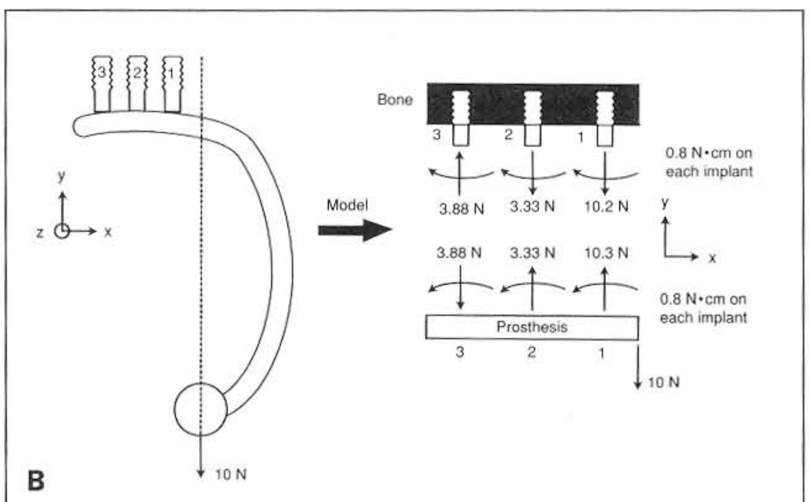


Fig 2-16. Orbital case. *A,* Three implants support a semicircular framework. *B,* Skalak model predictions of framework and abutment loading when a 10-N load acts in the negative y-direction at the point shown. (*A* from Thomas.[56] By permission of Quintessence Publishing Company.)

2

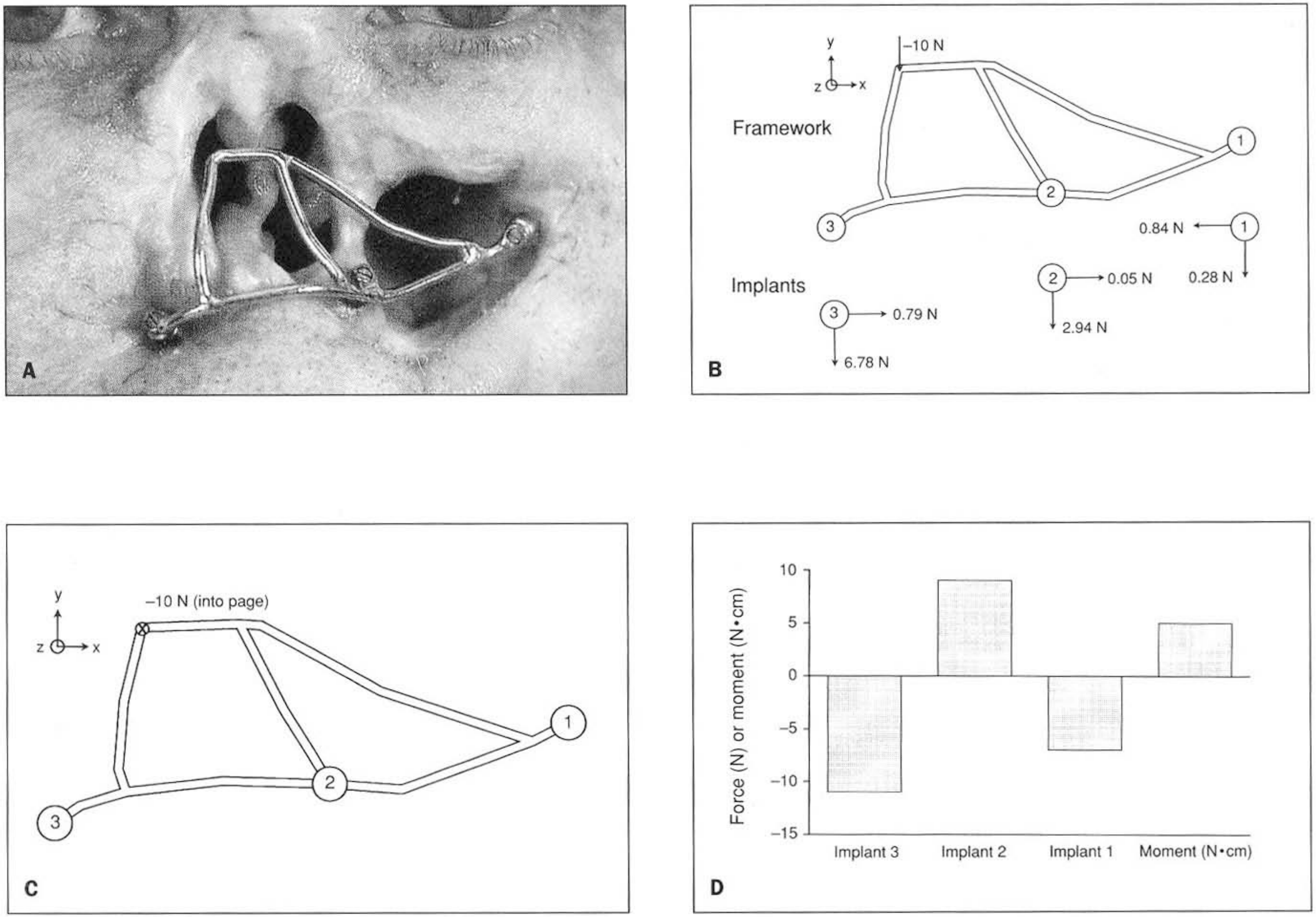


Fig 2-17. Midfacial case. *A,* Three implants support a framework for a midfacial prosthesis. *B,* x- and y-components of loading on the implants when a 10-N force acts on the framework in the negative y-direction at the point shown. *C,* Diagram showing a 10-N force acting on the framework in the negative z-direction (into the page) at the location shown. *D,* Forces and moments on implants 1, 2, and 3 for z-component loading of framework. (*A* from Thomas.[56] By permission of Quintessence Publishing Company.)

3, 4

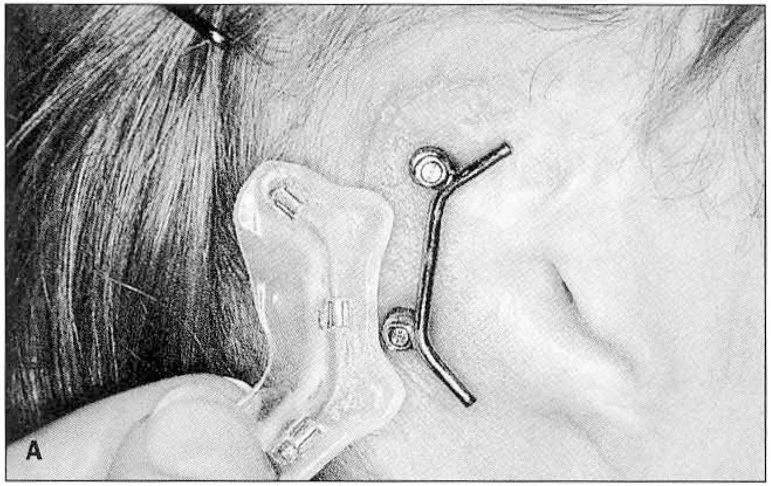
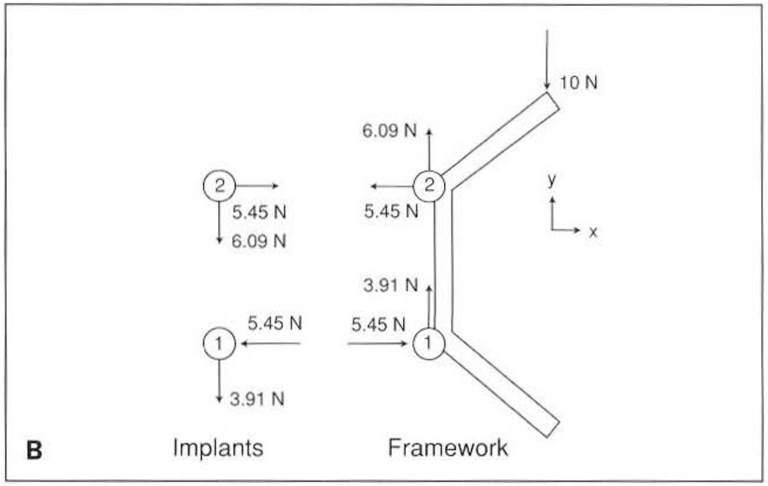



Fig 2-14. Auricular case. *A*, Two implants support a metal framework that can attach to an auricular prosthesis. *B*, Skalak model predictions of framework and abutment loading when a 10-N load acts in the negative y-direction at the point shown. (*A* from Tjellström et al.[55] By permission of Quintessence Publishing Company.)

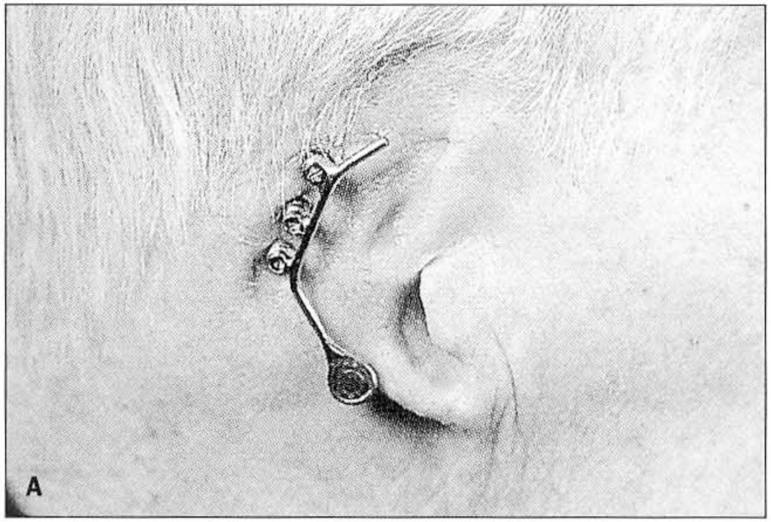
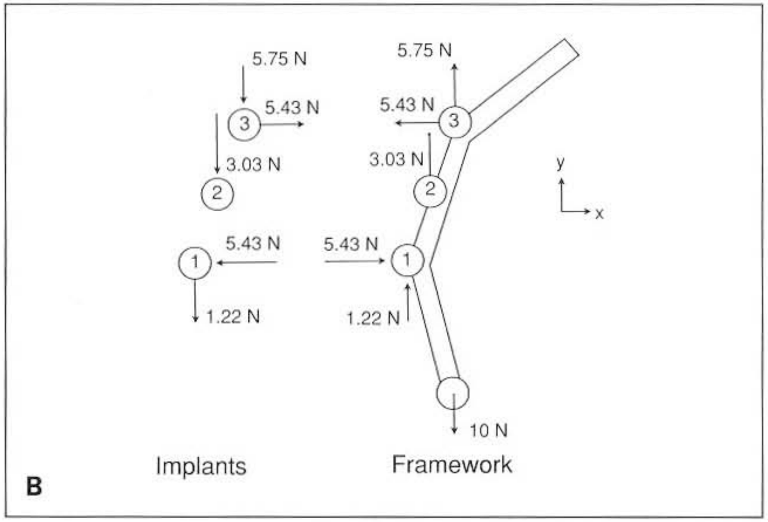
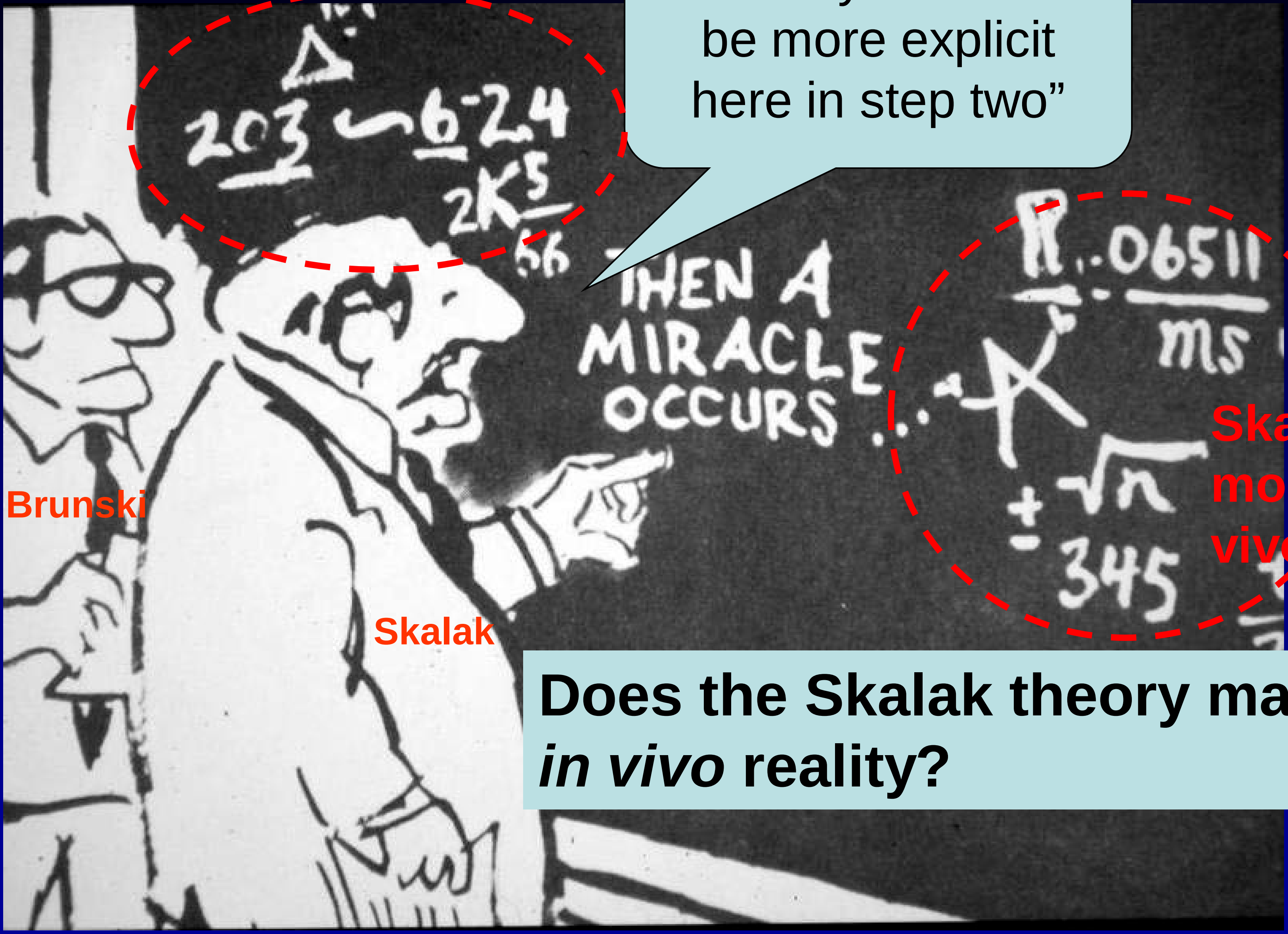



Fig 2-15. Auricular case. *A*, Three implants support a framework that attaches to an auricular prosthesis. *B*, Skalak model predictions of framework and abutment loading when a 10-N load acts in the negative y-direction at the point shown. (*A* from Thomas.[56] By permission of Quintessence Publishing Company.)

Skalak model in the lab

“I think you should be more explicit here in step two”



Brunski

Skalak

Skalak model in vivo

Does the Skalak theory match *in vivo* reality?

Courtesy of Paul Thomas

An test of the validity of the Skalak model

In Vivo Axial Forces on Implants: Theory vs. Experiment

J. B. Brunski*, J.A. Duyck[#], T. Vanasse*, N. White*, and M. Doshi*[&]

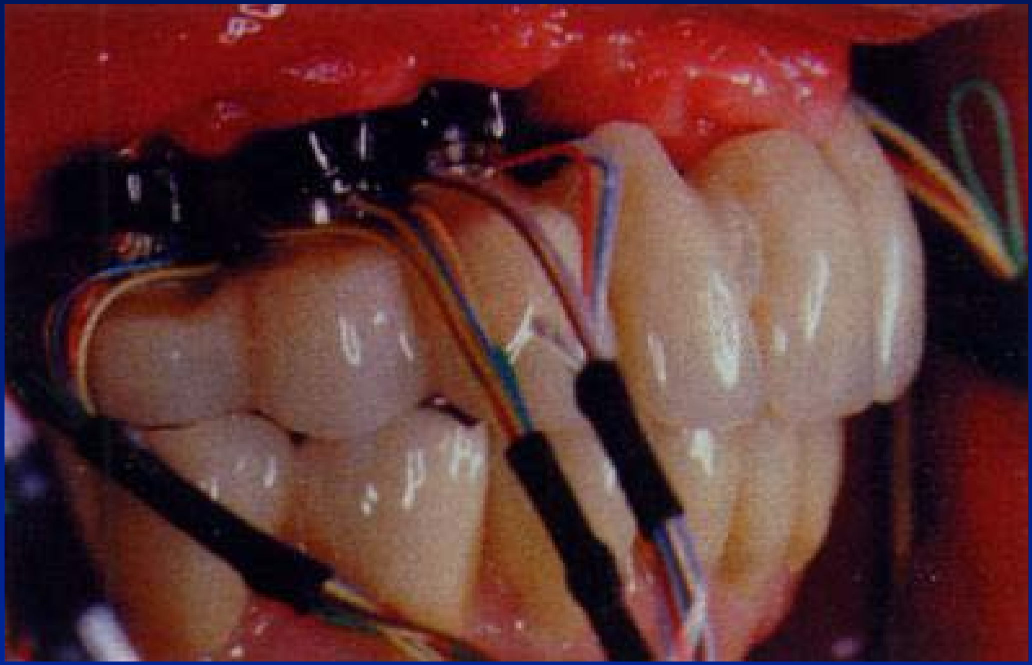
*Rensselaer Polytechnic Institute, Troy, NY

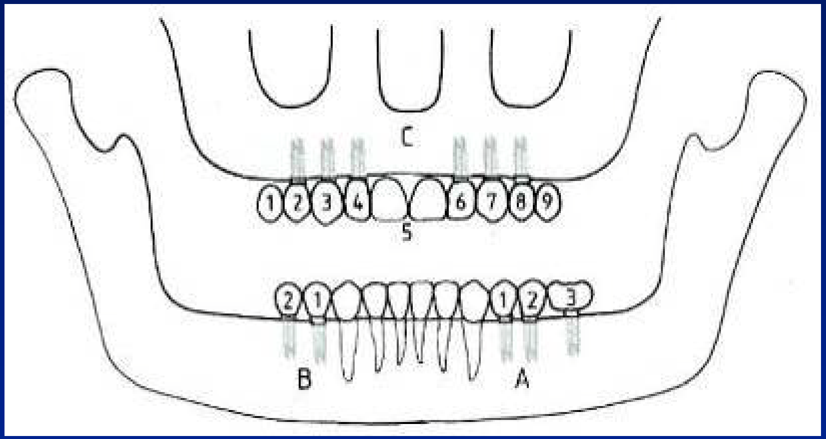
[#]Catholic University of Leuven, Belgium

[&]University of Pennsylvania, Phila., PA

March 10, 2004, IADR meeting, Hawaii

Duyck et al. (2000) *COIR* 11:465-475

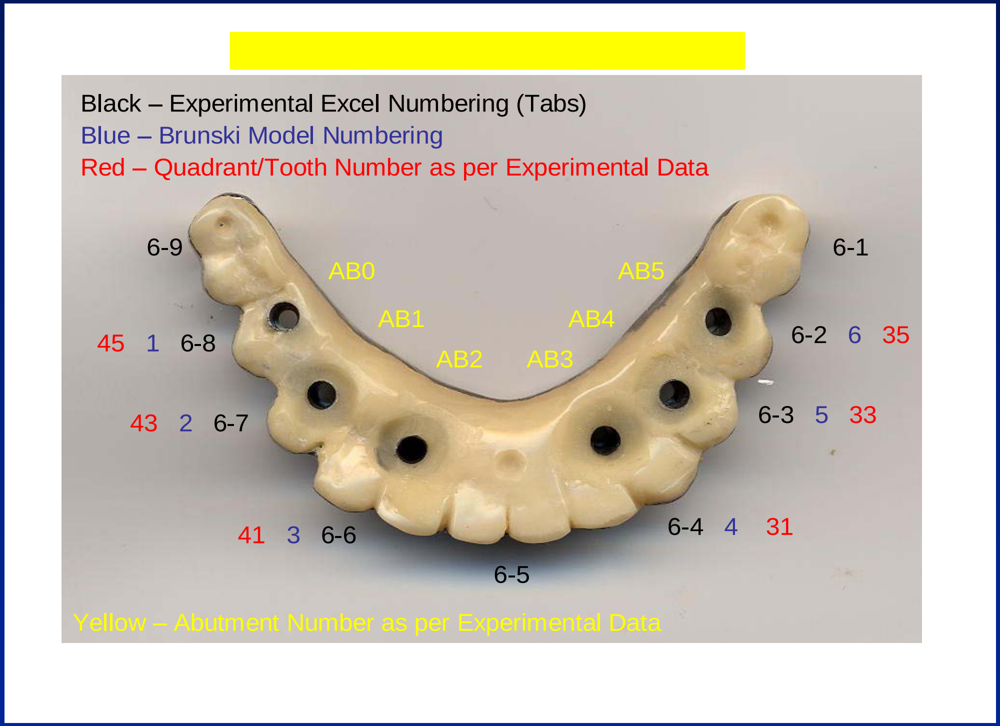




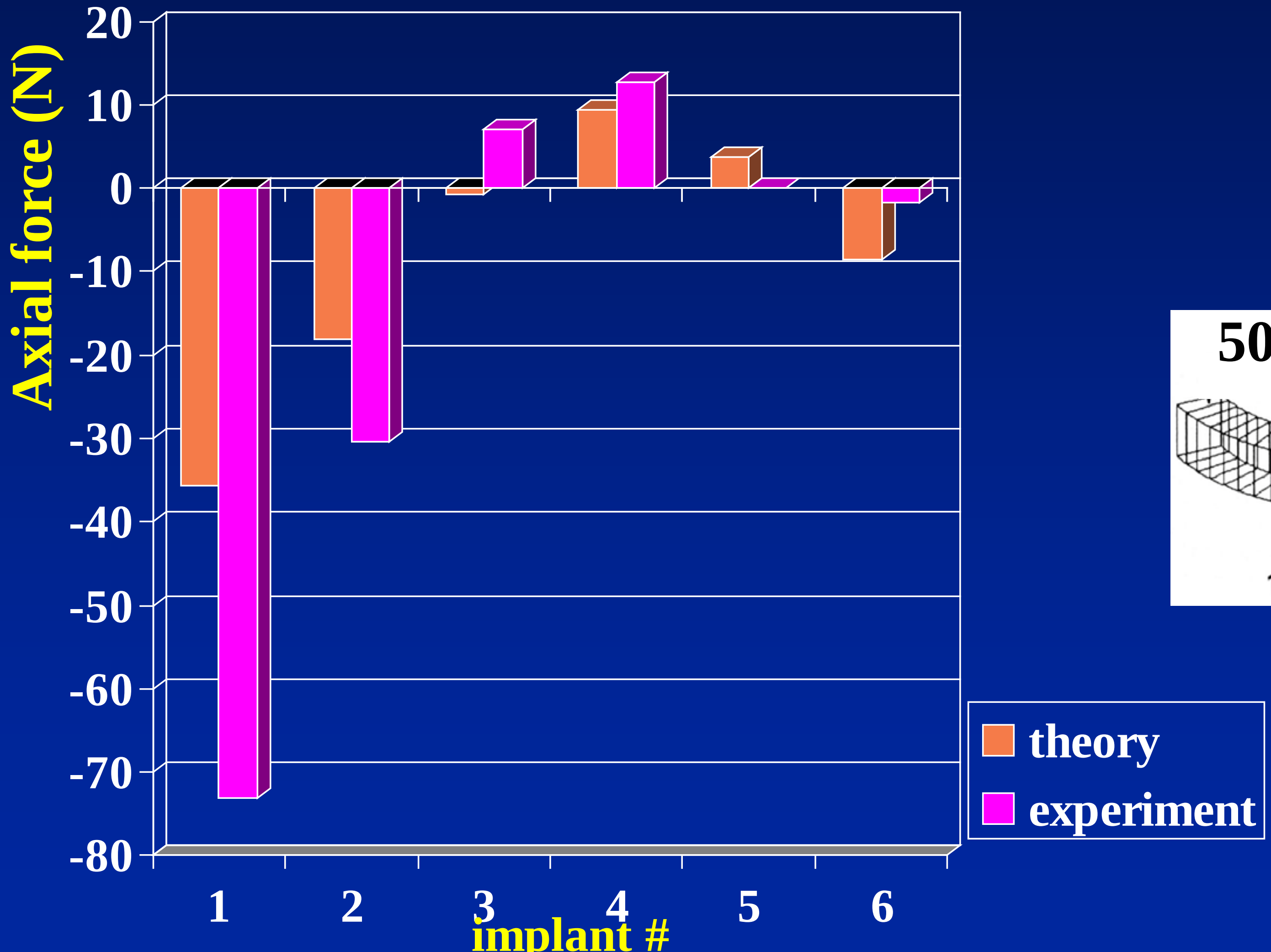
Duyck et al. used strain-gaged abutments to sense axial forces and bending moments on each implant in patients (Fz, Mx, My).

Methods & Materials, cont'd.

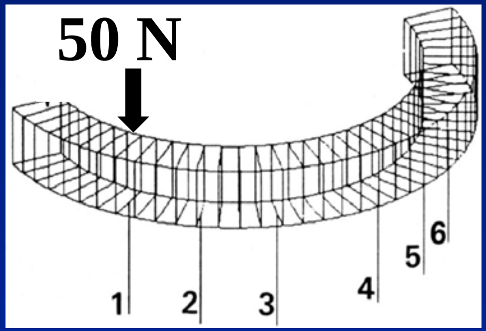
- 50 N compressive force at specific locations on prostheses of cases H (mandibular) and C (maxillary) implants:
  - **compare <u>measured</u> *in vivo* forces from Duyck *et al*....**
  - **...with <u>predicted</u> forces from the Skalak model**



Case H

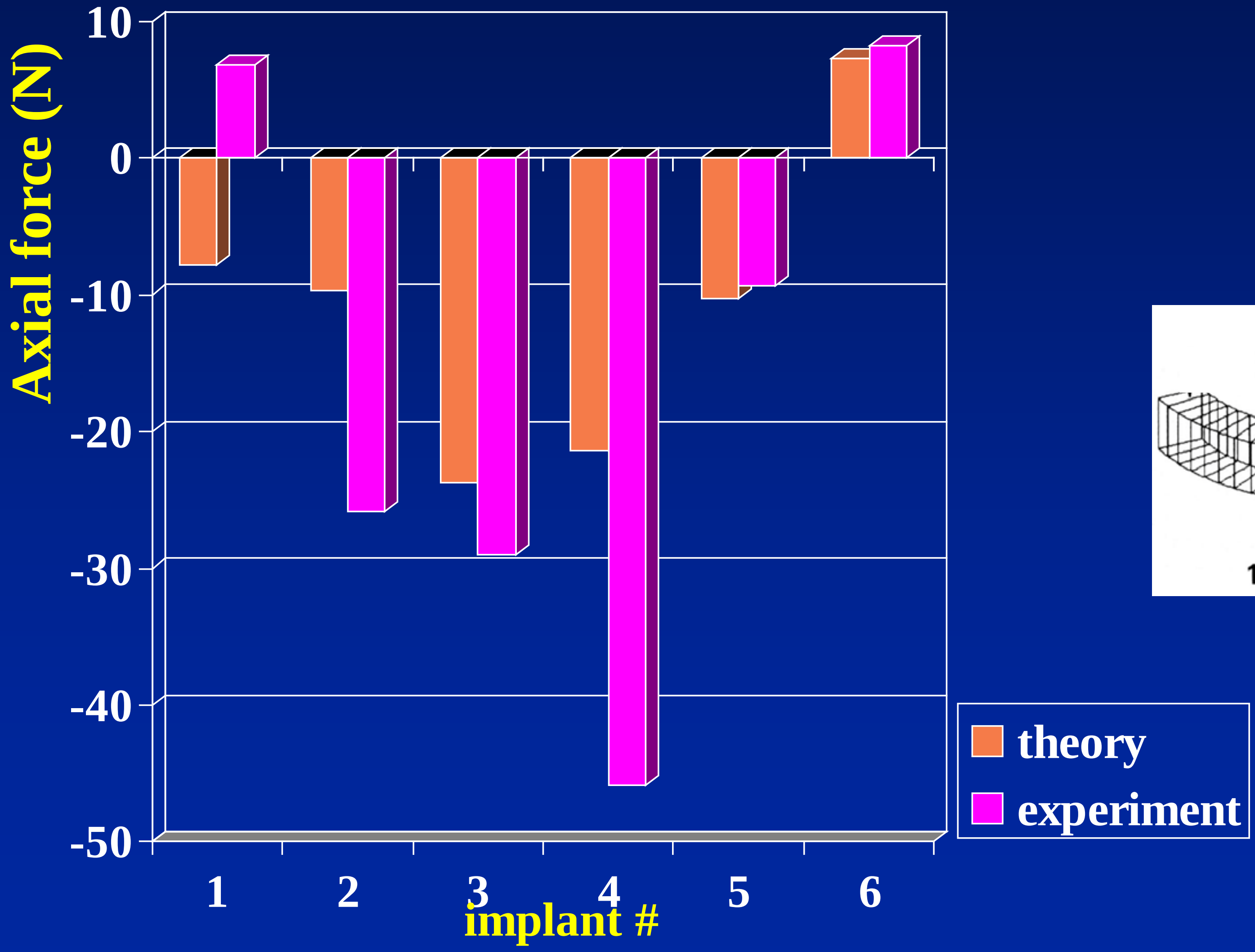


Axial force (N)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
1
2
3
4
5
6
implant #
theory
experiment



50 N
1
2
3
4
5
6

Case H



10
0
-10
-20
-30
-40
-50
Axial force (N)
1
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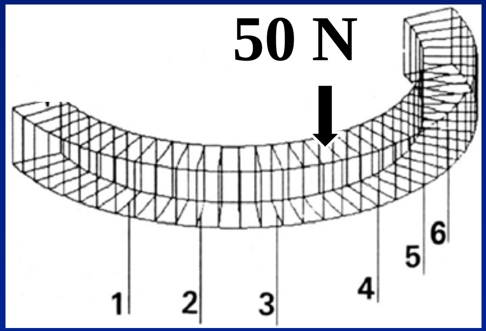
implant #
theory
experiment



50 N
1
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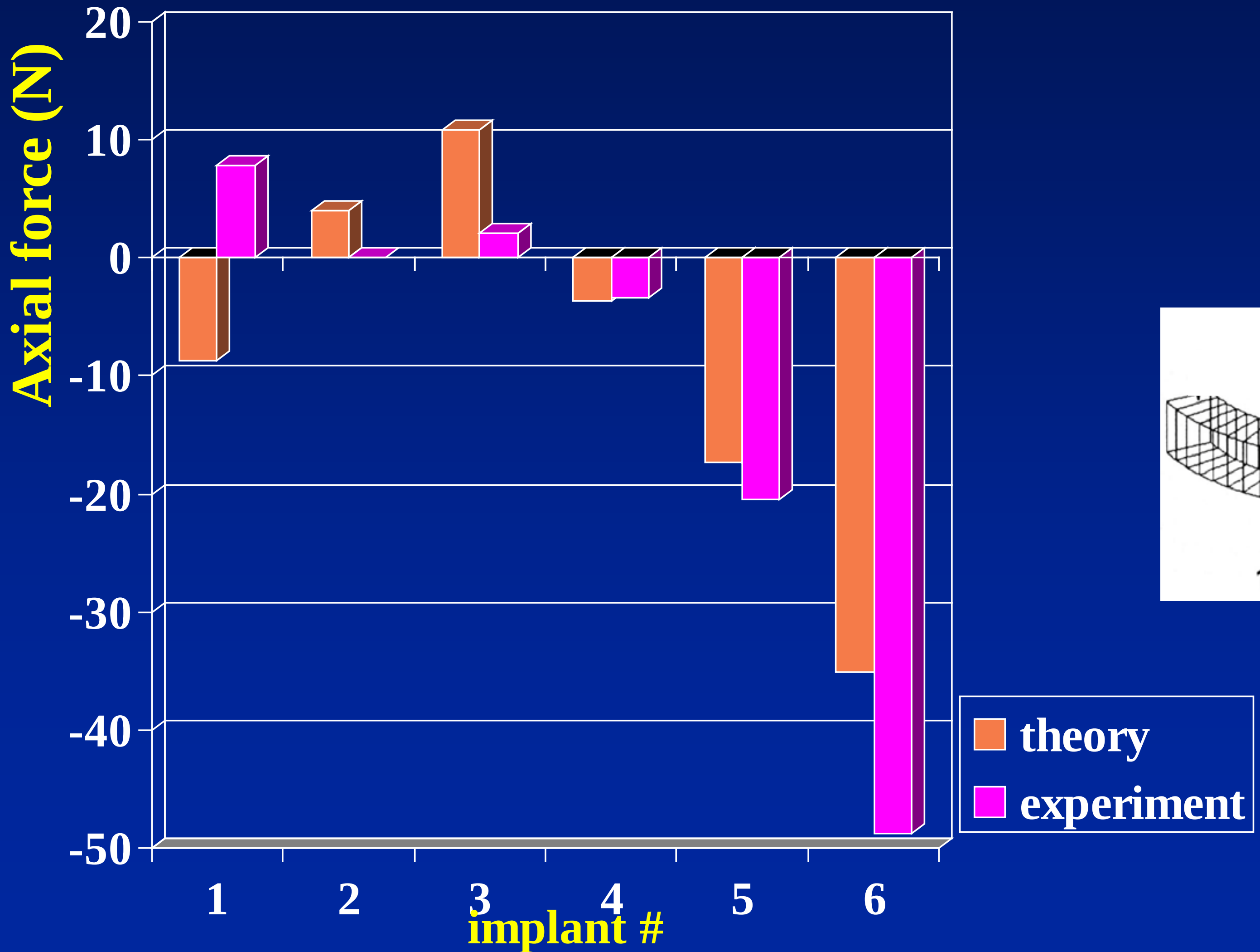
Case H



Axial force (N)
20
10
0
-10
-20
-30
-40
-50
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2
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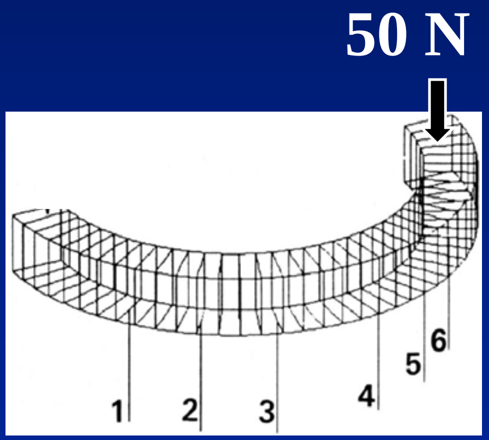
4
5
6
implant #
theory
experiment



50 N
1
2
3
4
5
6

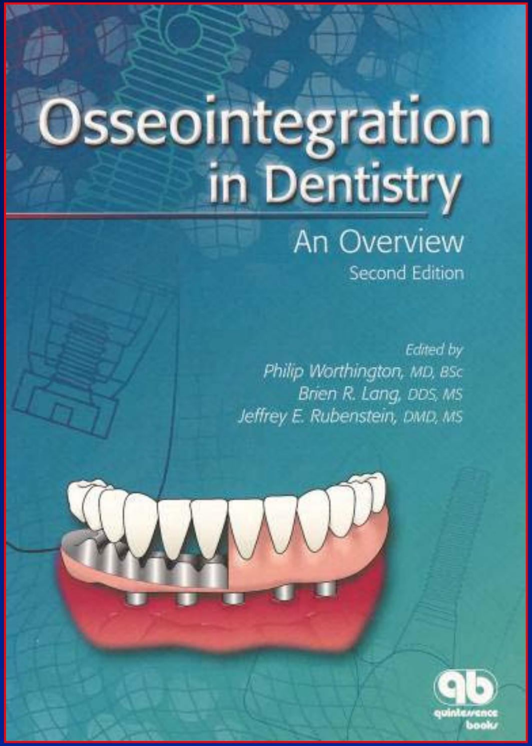
Discussion

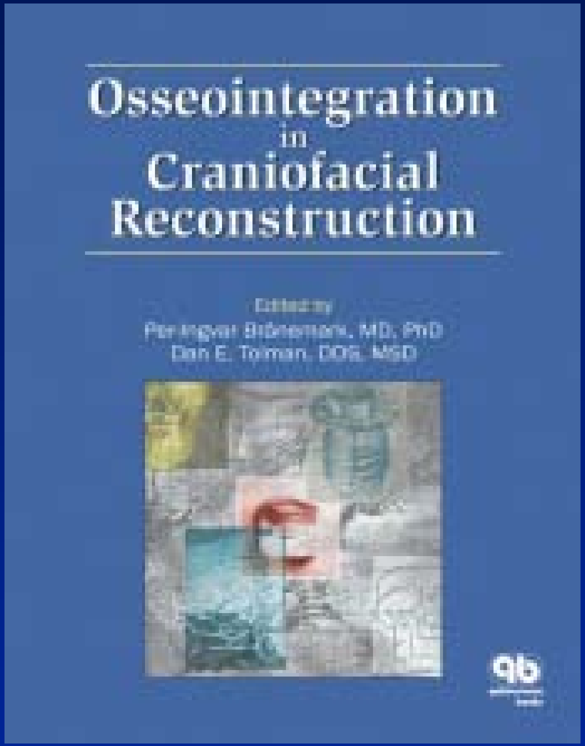
- So, the Skalak theory and experiment agree *qualitatively*, but not so well *quantitatively*.
- Reasons for discrepancies:
  - *Not* due to experimental errors in measurements
  - Probably the assumptions in the Skalak model do not quite match reality, e.g.:
    - » It's likely that all implants in bone don't have the same stiffness.
    - » A real prosthesis is not infinitely rigid.
    - » The jaw is not infinitely rigid.

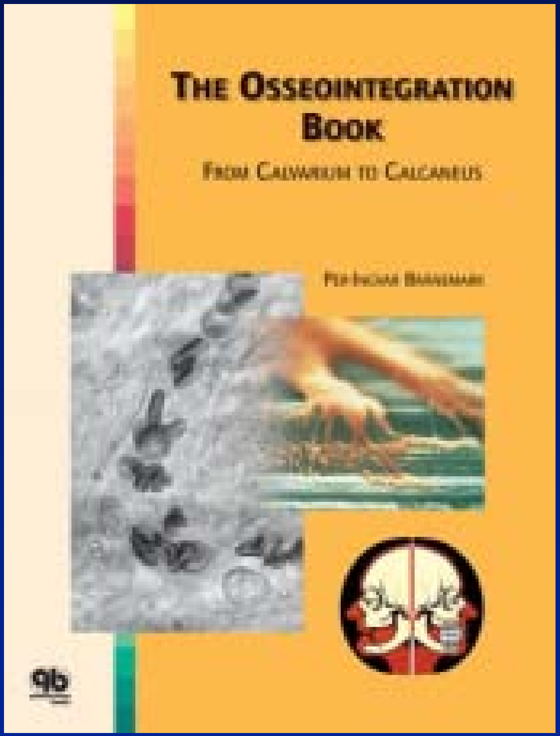
Summary

- Tools for predicting implant loading are available and clinically helpful.
- The tools include the Skalak model and also finite element models based on CT scan data.
  - Additional *in vivo* verification of the models is needed.

Readings







Acknowledgments: Dr. K. Higuchi and NIH grant EB00504-06 (NIBIB)