Introductory Biomechanics

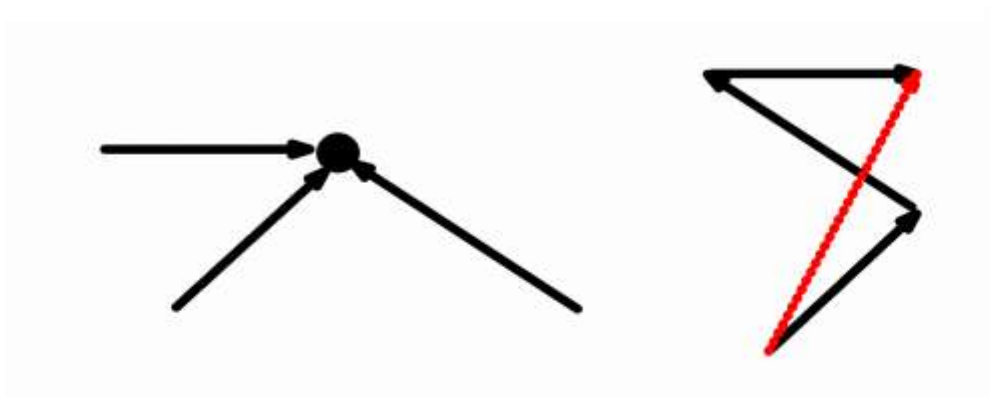
Garth R Johnson FREng
Emeritus Professor of Rehabilitation Engineering
School of Mechanical and Systems Engineering
Newcastle University

The Basics

- Overall objective is an overview of the underlying principles of biomechanics with relevant examples
- We will discuss:
  - Equilibrium of forces and moments
  - Kinematics of joints
  - Degrees of Freedom
  - Determinacy
  - A clinically relevant application of biomechanical modelling

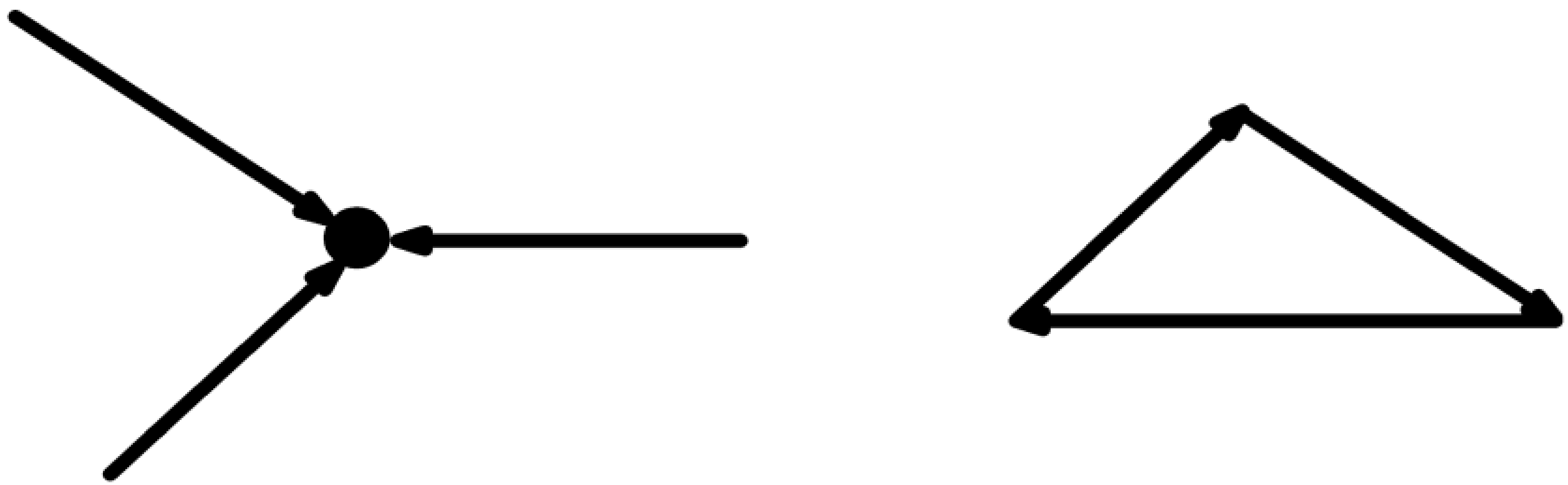
Vectors and Resultants

Forces are vectors – they have direction and magnitude
They can be added head to tail – resultant from first tail to last head



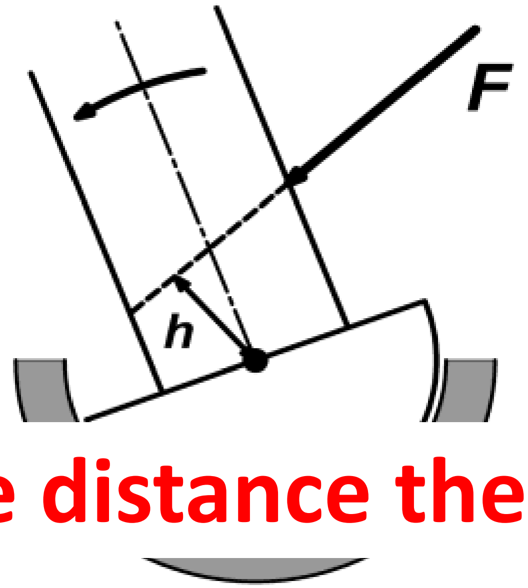
If a set of forces act together at a point, this is equivalent – in both magnitude and direction to the vector sum of the applied forces

Equilibrium



If the vector diagram produces a closed figure then the resultant is zero. This is **EQUILIBRIUM**

Moments

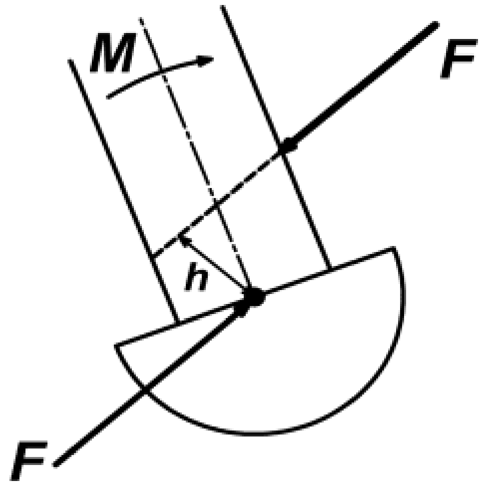


N.B The smaller the distance the bigger the force!

A MOMENT about a point is defined as the product of the force * the perpendicular distance

$$M = F*h$$

Equilibrium of a Joint – forces and moments



Force equilibrium achieved by a pair of equal and opposite forces F

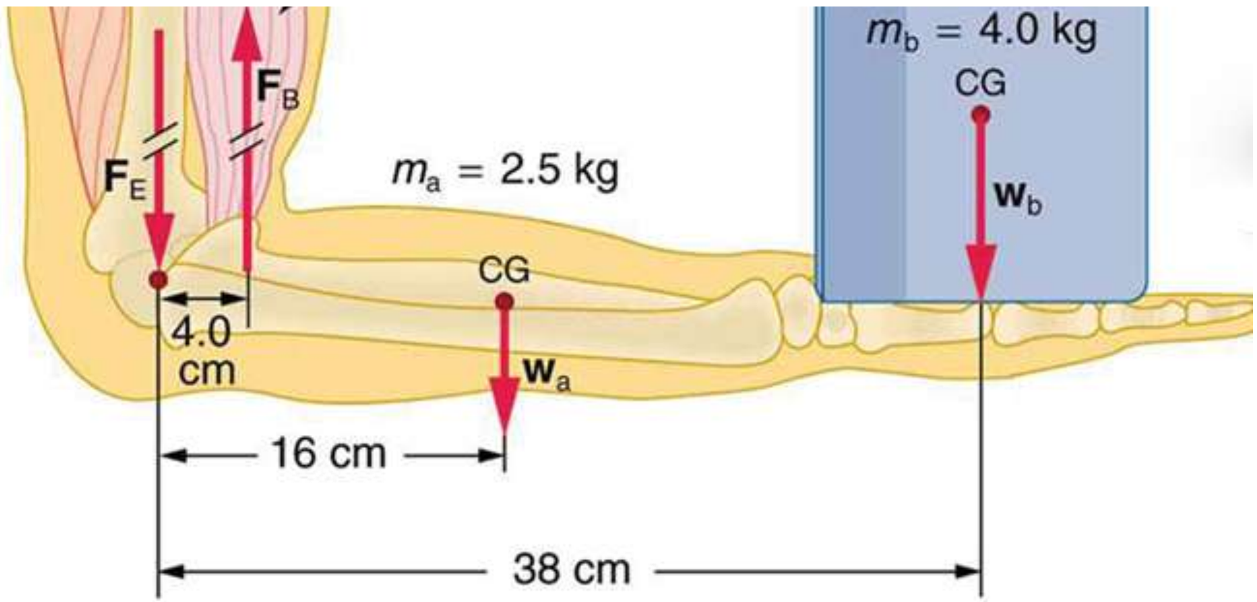
Rotational equilibrium achieved by a applied moment ***M*** opposing **COUPLE** produced by pair of forces separated by distance **h**

Mass, Weight and Force

- According to Newton's Laws (see later), the acceleration of a body is equal to its mass * the acceleration.
- The units of force are Newtons
- If a body falls under gravity it will fall at the acceleration due to gravity (g = 9.81 m/s2) and is subjected to a force = mass*9.81.
- This force is defined as the weight = W = mg Newtons

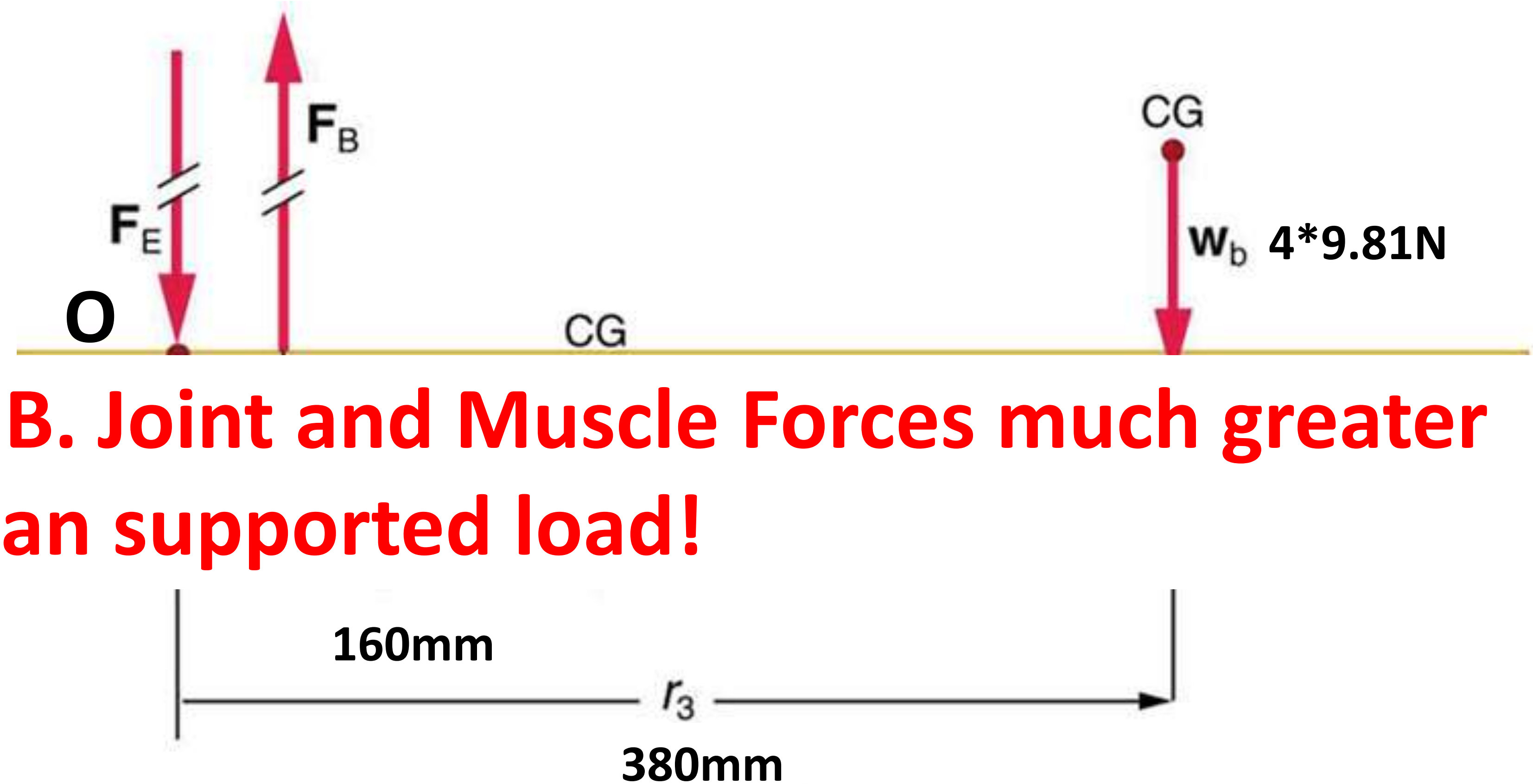
Equilibrium at the Elbow

For equilibrium, the elbow extension moment resulting from the forearm weight and the weight of the book must be counterbalanced by the biceps tension



(a)

Free Body Diagram

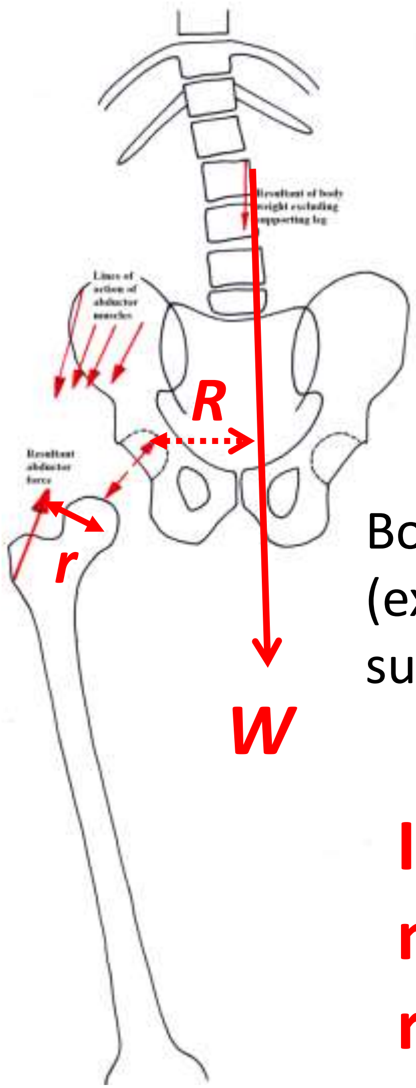


N.B. Joint and Muscle Forces much greater than supported load!

To find Fb: Take moments about O: Fb*40 = (2.5*9.81*160) + (4*9.81*380)
Fb = (3924 + 14911)/40 = 471N

Joint Force Fe = Fb – wa – wb = 471 – 25 – 40 = 406N

Standing on one Leg – why is joint force greater than body weight?



Body weight (excluding supporting leg)

Distance of weight vector from joint centre R much greater than distance of muscle vector

Muscle force *r = W*R

Muscle force FM>>W

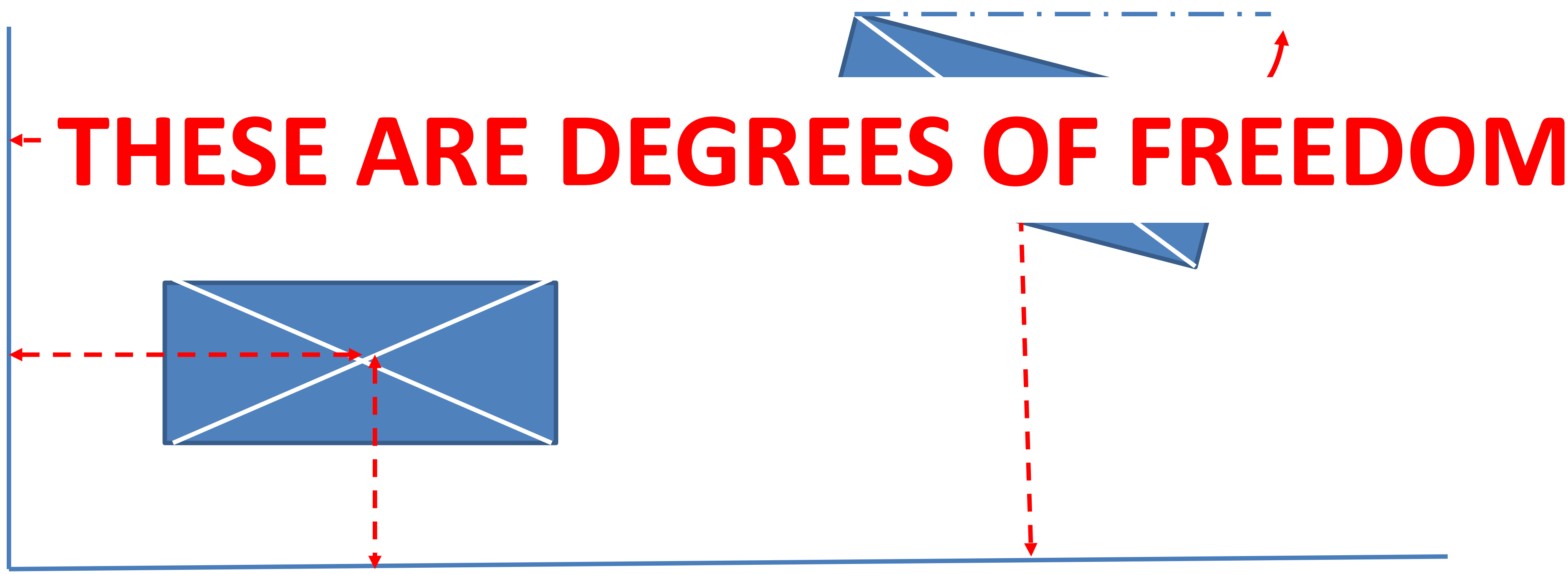
Joint force = vector sum of FM + W

In general, muscles lie close to joints and so must produce large forces to achieve required moments

Degrees of Freedom and Constraints

In two dimensions, the position of a rigid body requires three pieces of information - coordinates

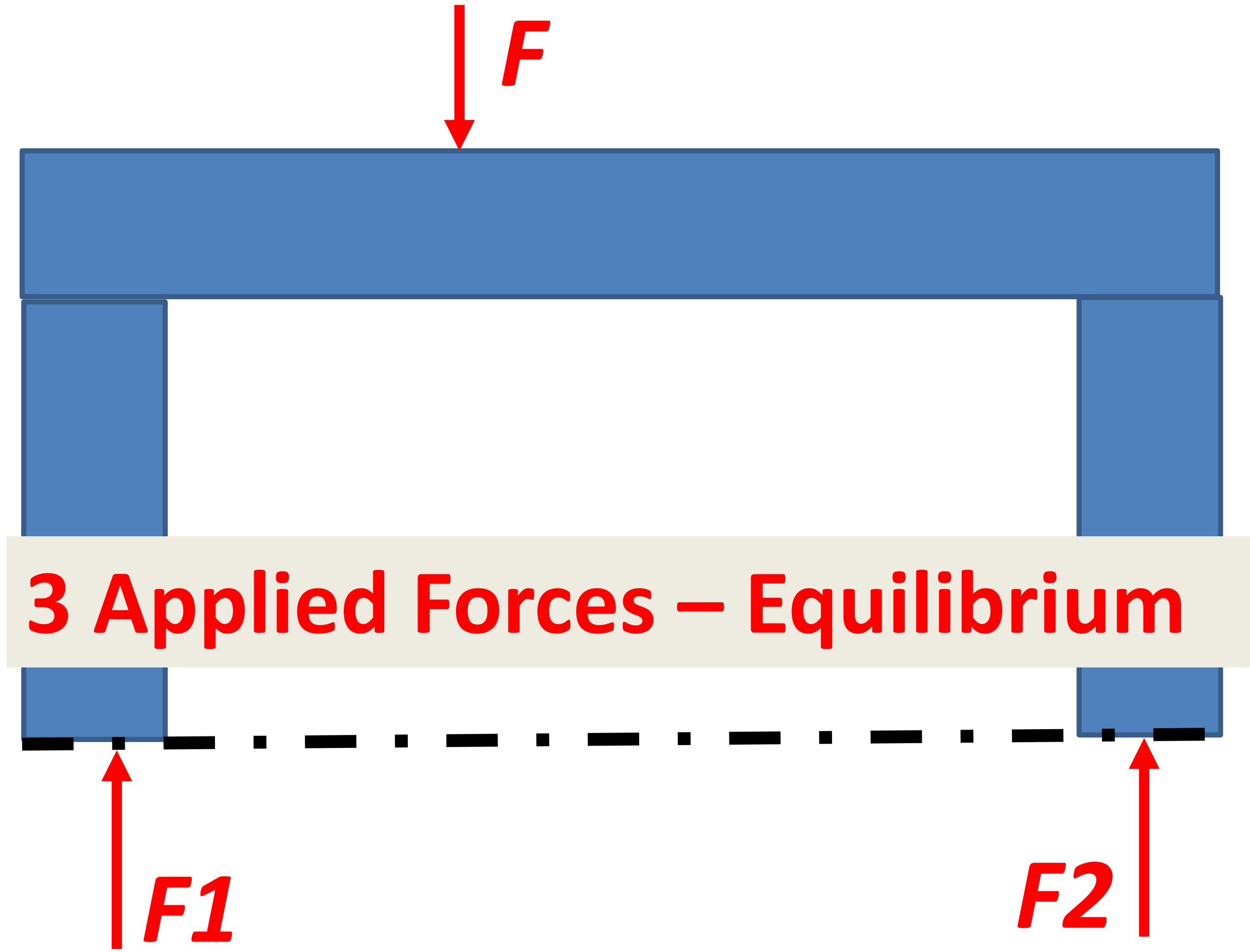
Two distances and one angle



Degrees of Freedom and Constraints

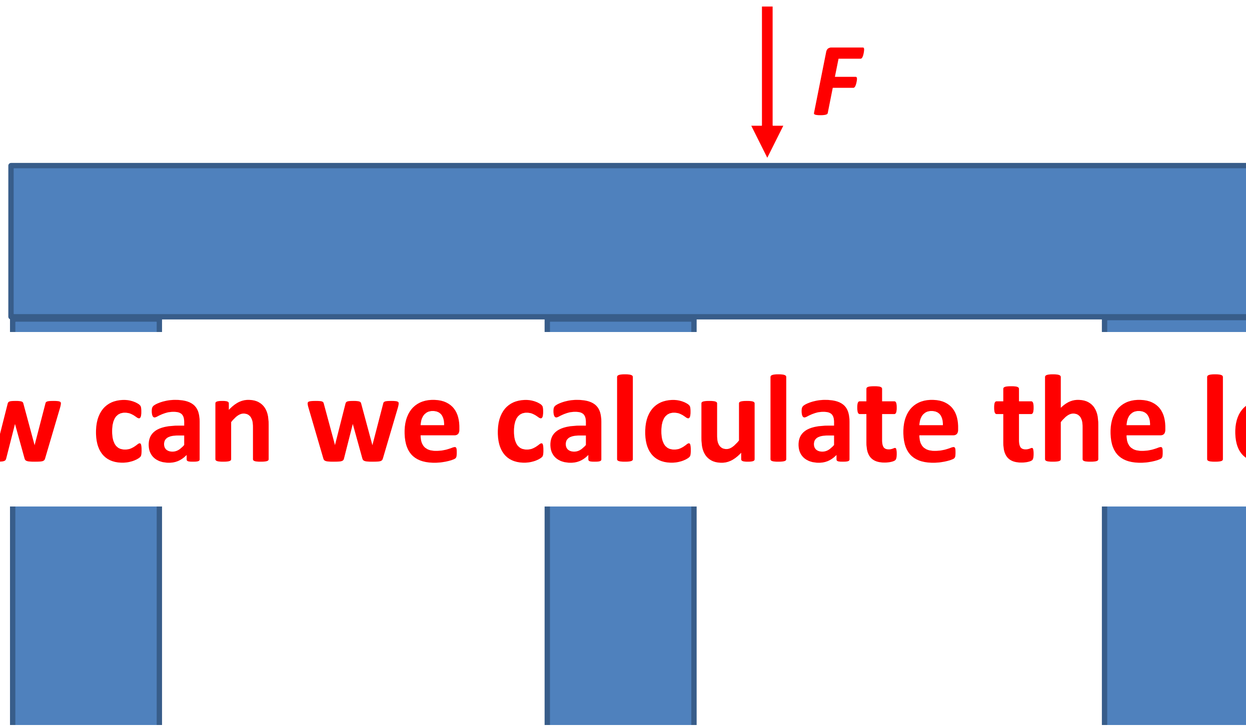
- In 2D space an object has 3 degrees of freedom – require 3 coordinates to define its position
- In 3D space, we require 6 coordinates – 3 distances + 3 angles
- Any connection of a body imposes a CONSTRAINT and reduces the number of degrees of freedom

Degrees of Freedom and Constraints



No of applied forces= number of degrees of freedom

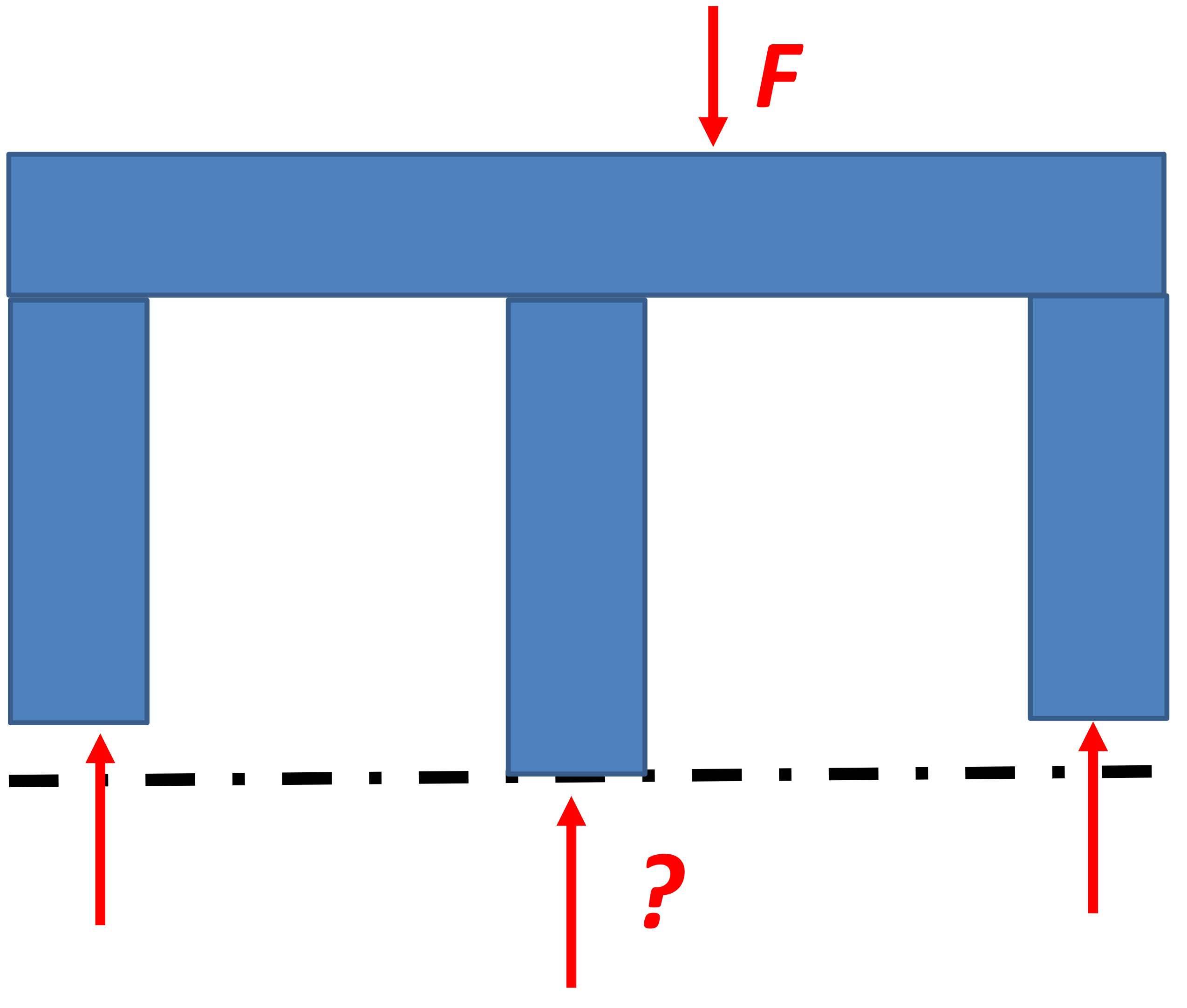
Three legs - overconstrained



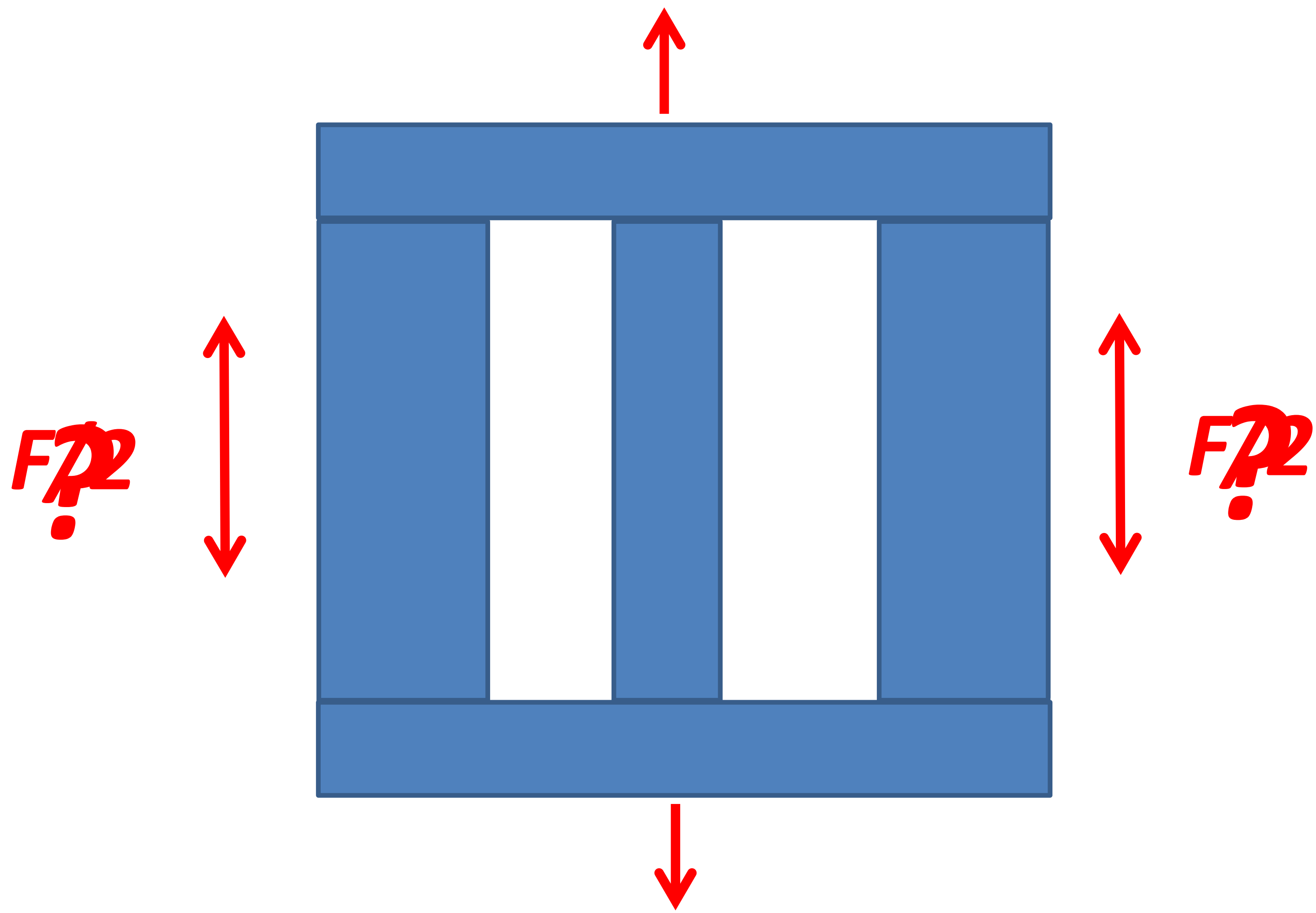
How can we calculate the loads?

This is a *stress analysis* problem where the load transmission is influenced by material properties and geometry

Wobbly table – what are the support forces?

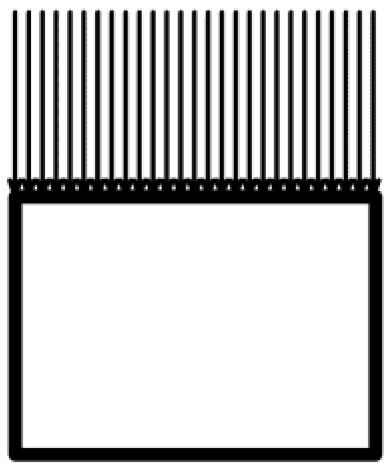


Largest force passes through stiffest element

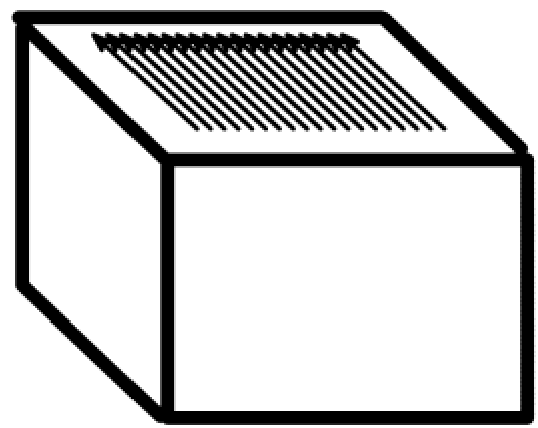


Forces and Stresses

Stress may be defined as the intensity of force = force per unit area: Units of stress = N/m2 = Pascals



Normal stress



Shear stress

Stress Shielding – Huiskes (1992)

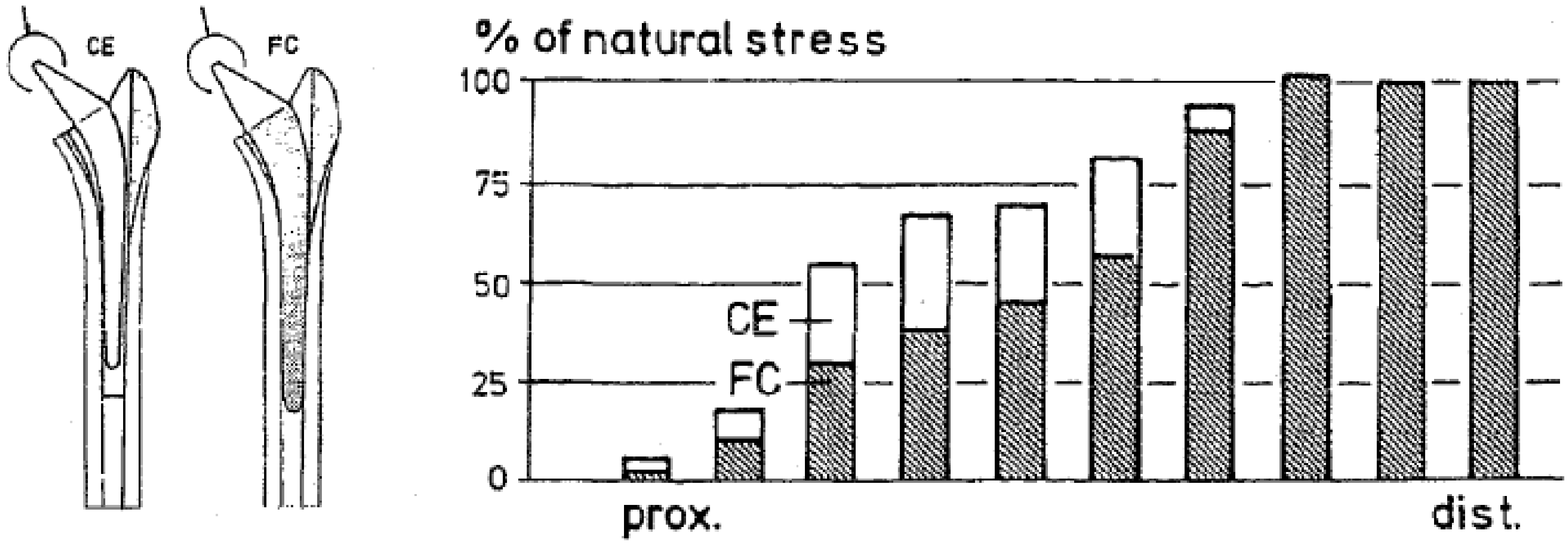
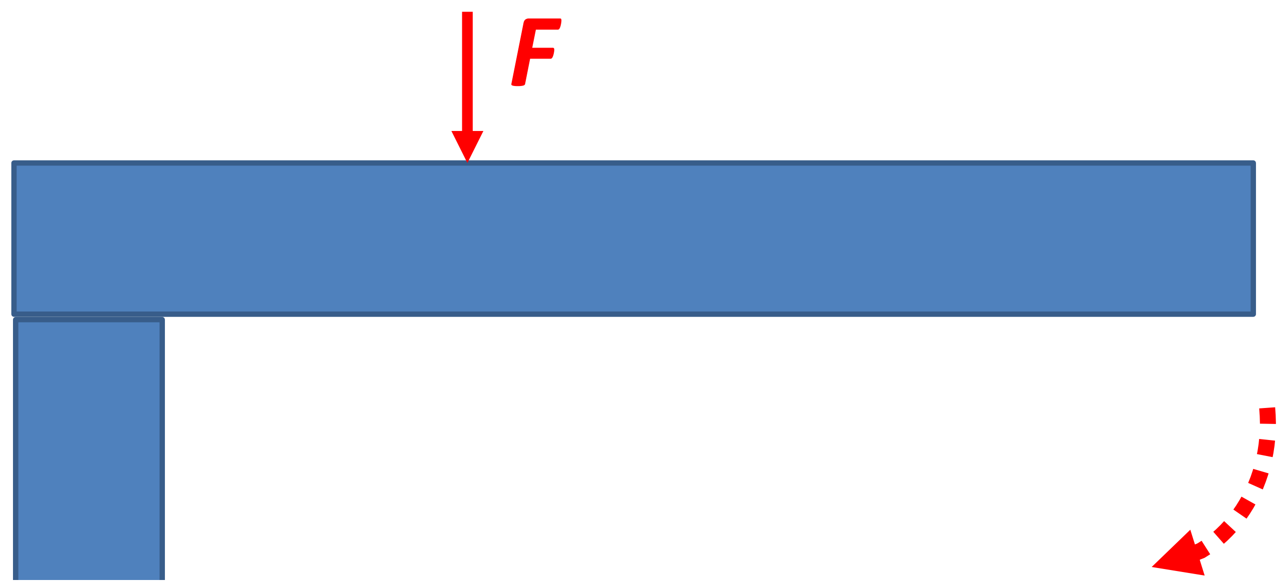


Fig. 1. — An illustration of 'stress shielding' around a cemented (CE) and a noncemented (FC) femoral stem. The cortical bone stresses are shown, in each case, as a percentage of the 'natural' case for the same hip-joint load if the stem were not present. The difference between natural and actual is the extent of stress shielding (13).

Underconstrained!



Dynamics – motion results from applied loads

Summary of Degrees of Freedom and Constraints

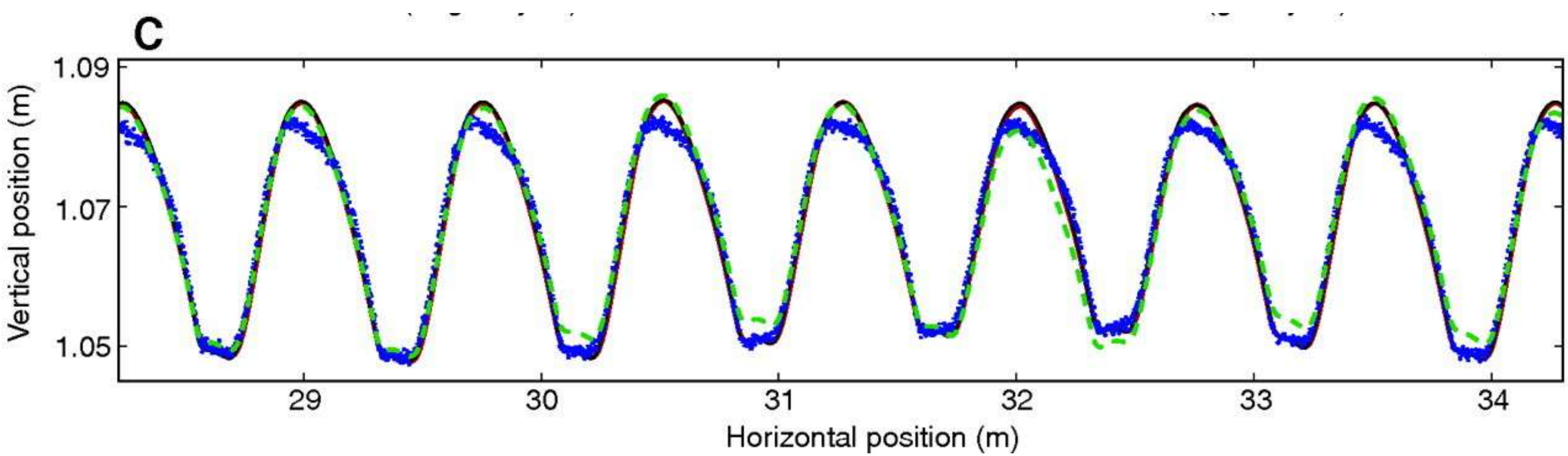
- No of DoF > No of Constraints = Mechanism (Dynamics)
- No of DoF = No of Constraints = Determinate structure (Statics)
- No of DoF < No of constraints = Indeterminate structure (stress analysis)

Dynamics – Newton's Laws

Relationships between force and acceleration

- I: If the vector sum of all the forces is zero, then there can be no resulting acceleration
- II: The acceleration of a body is proportional to the applied force and in the same direction
- **Force = mass * acceleration**

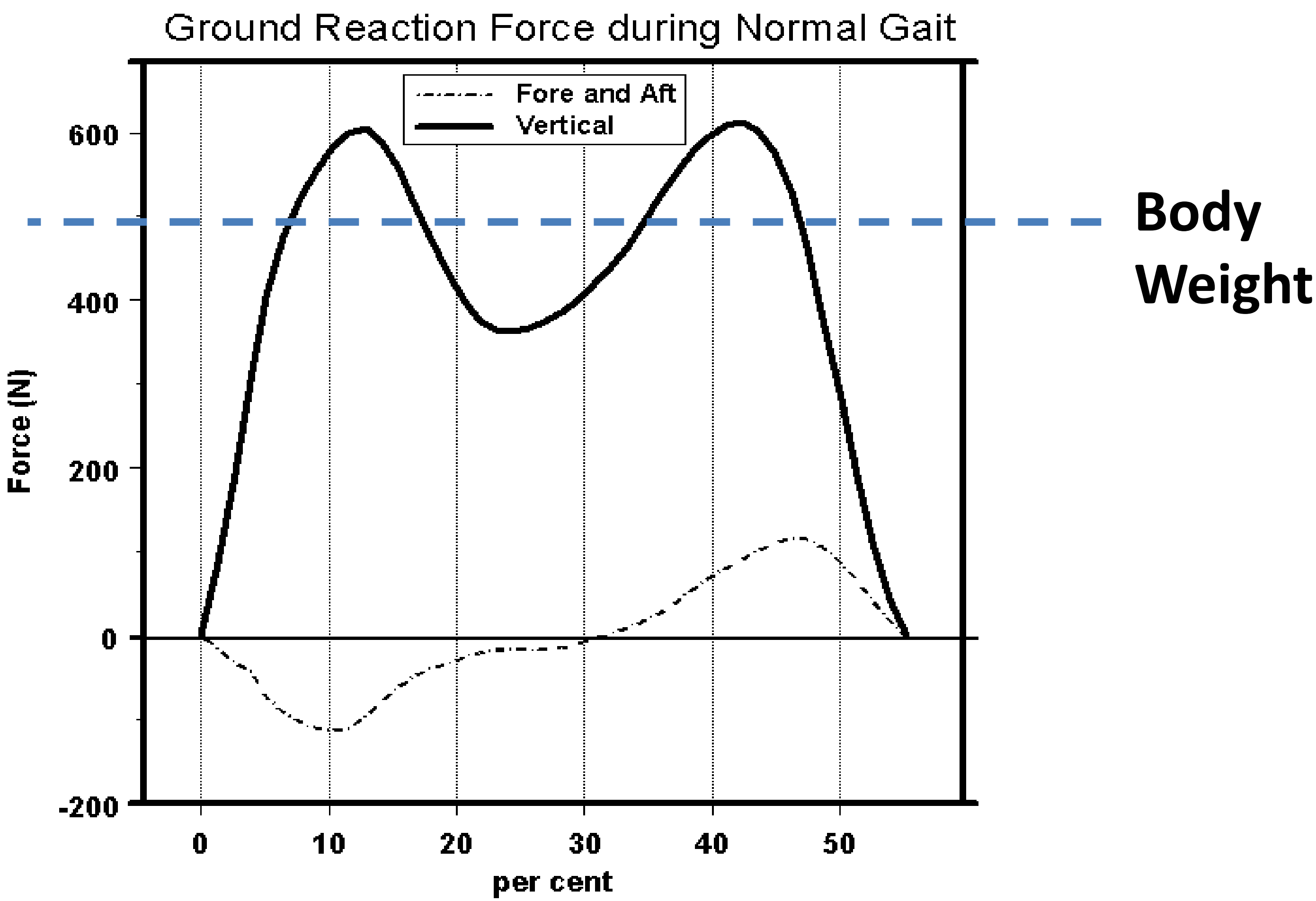
Dynamics – consider gait



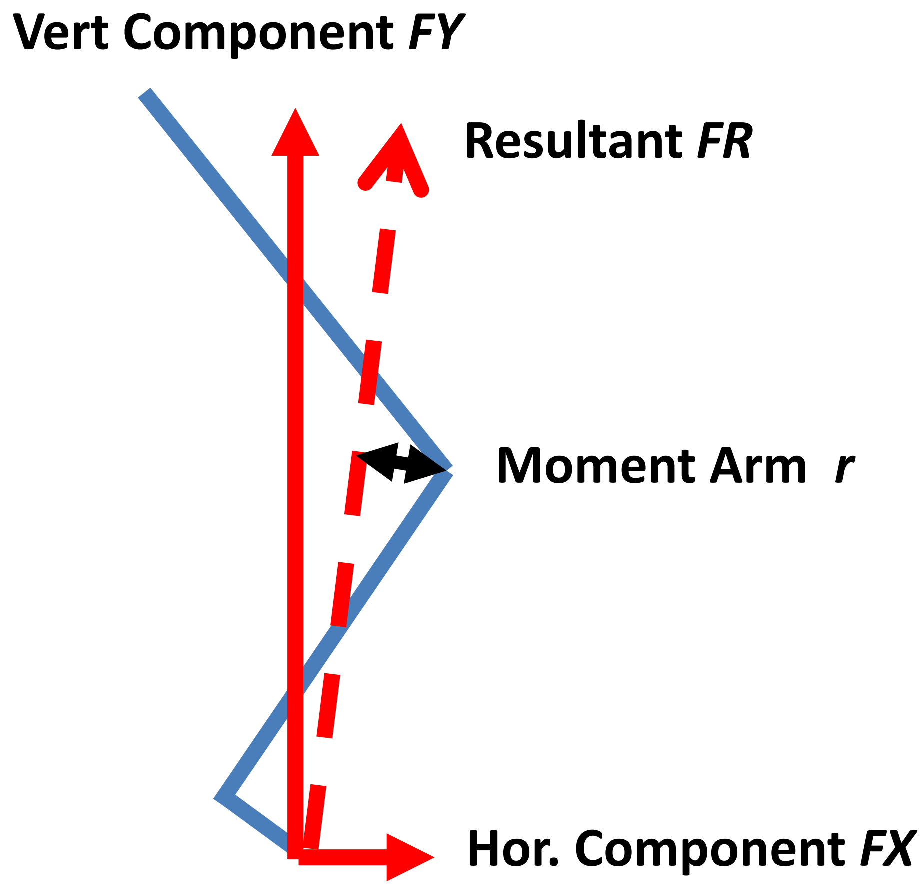
Vertical displacement of centre of mass

According to Newton's Second Law of Motion:
Vertical force = mass * acceleration

Force resulting from acceleration in gait

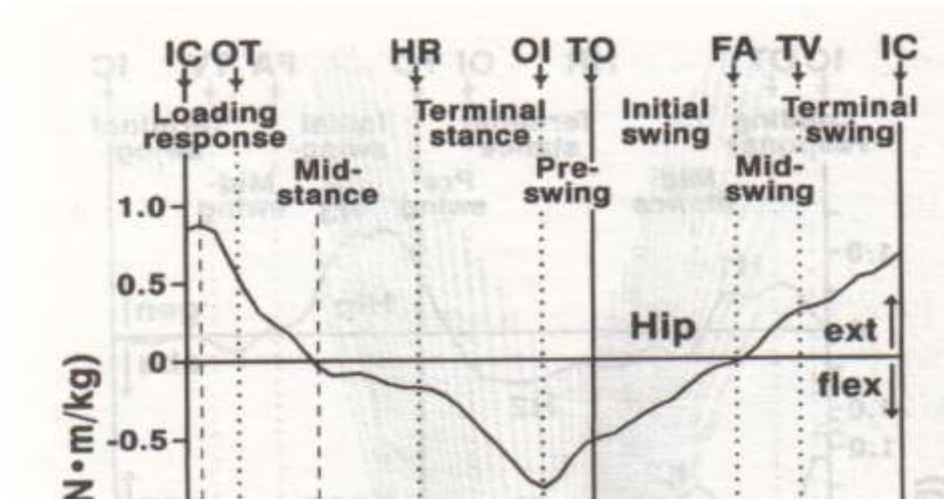


Moments at Joints during gait

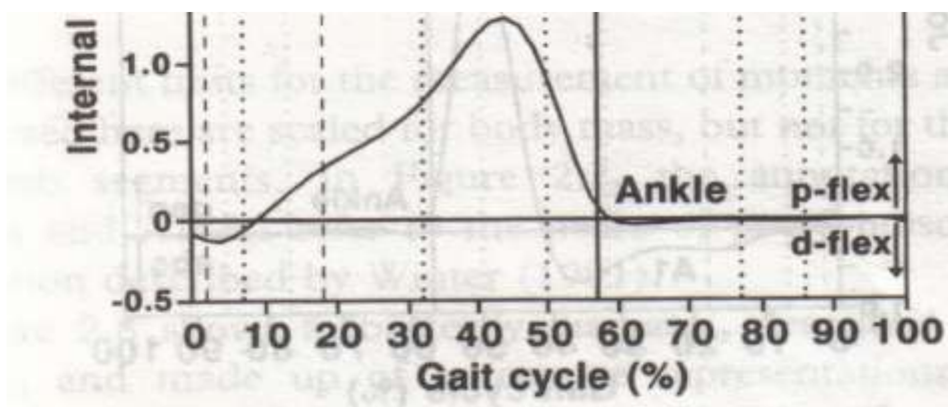


Moment at Knee = *FR* *r*

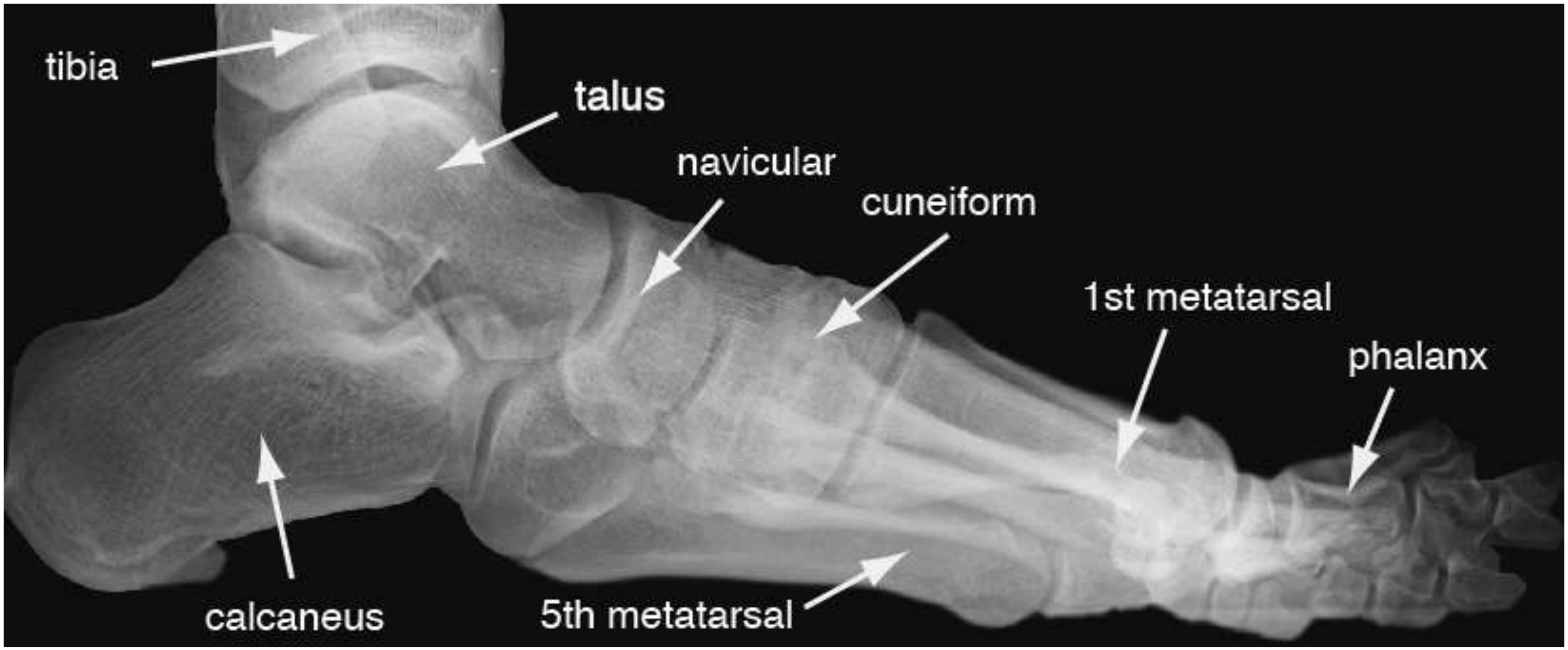
Moments at Lower Limb during Gait



N.B It is these moments which lead to the muscle and joint forces



An example of using biomechanical analysis – A Foot Model



An on-going study with Mr Peter Briggs

A simple biomechanical model of the plantar aponeurosis

- A two dimensional model to explore basic biomechanics
- Assumptions
  - Single ray without intermediate joint
  - Dimensions and moment arms estimated from planar radiograph

  Identify degrees of freedom and equilibrium conditions

  Look at toe off, forefoot or metatarsal head unsupported

  Identify muscle actions required

Developing a model of the foot – how many degrees of freedom?

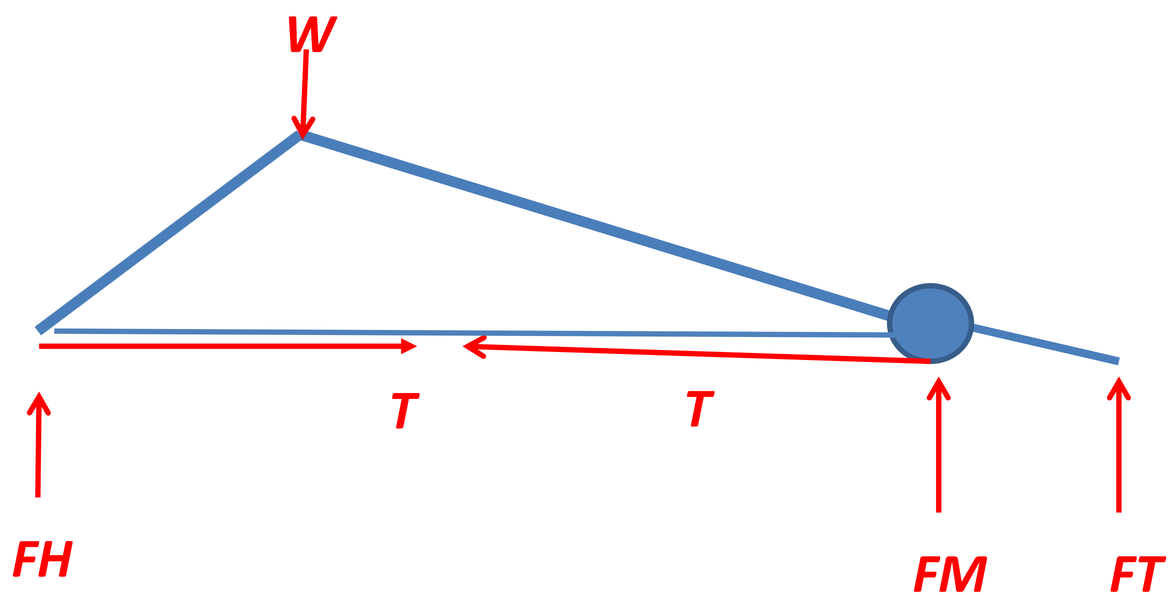
Simplest Model – rigid body in 2D space – 3 degrees of freedom
Equilibrium requires 3 forces

Hicks (1954) Model – Arch constrained by ligamentous structure attached to metatarsal

5 degrees of freedom + 1 constraint (aponeurosis) = 4 dof

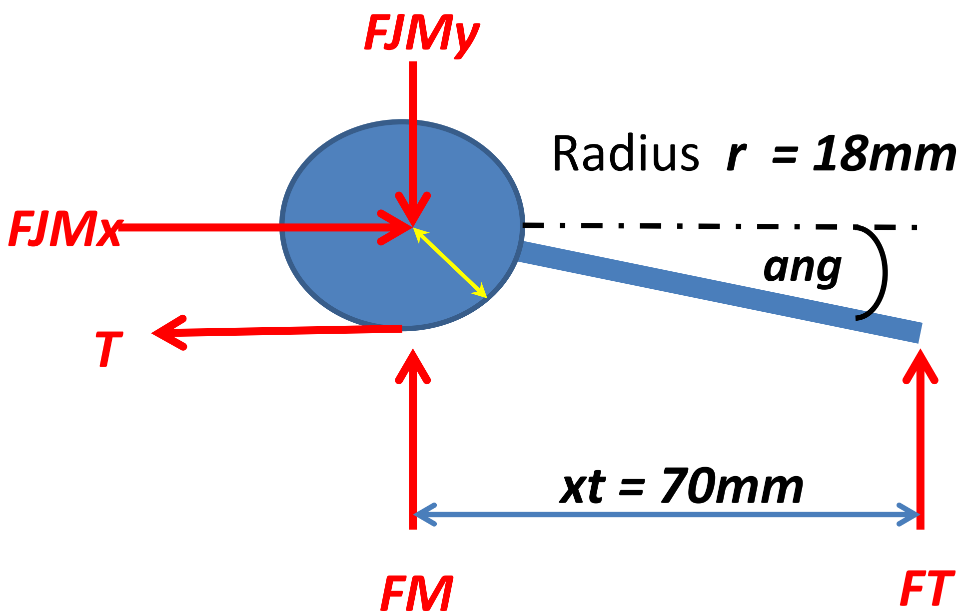
Equilibrium requires 4 external forces + 1 internal tension

N.B. This is a MECHANISM



Kinematics – How does mechanism move? – Reverse Windlass

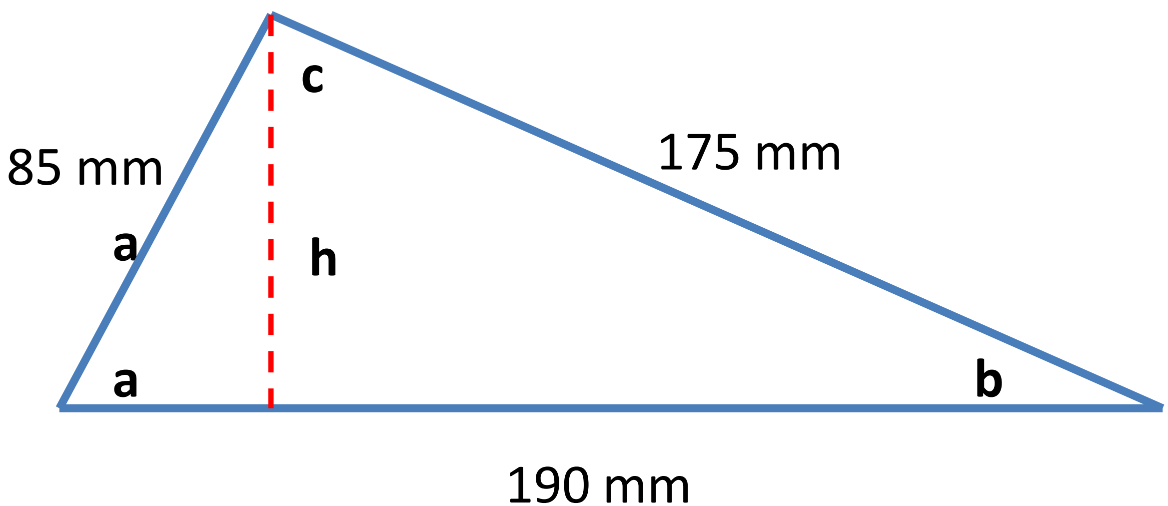
Mechanism and Dimensions at Metatarsal Head



Change in length = ***r * ang***

N.B Radius is small – change of length small!!

Basic Geometry and Kinematics
Change of arch height (*h*) caused by shortening of aponeurosis



Initial angles

a = 67 deg

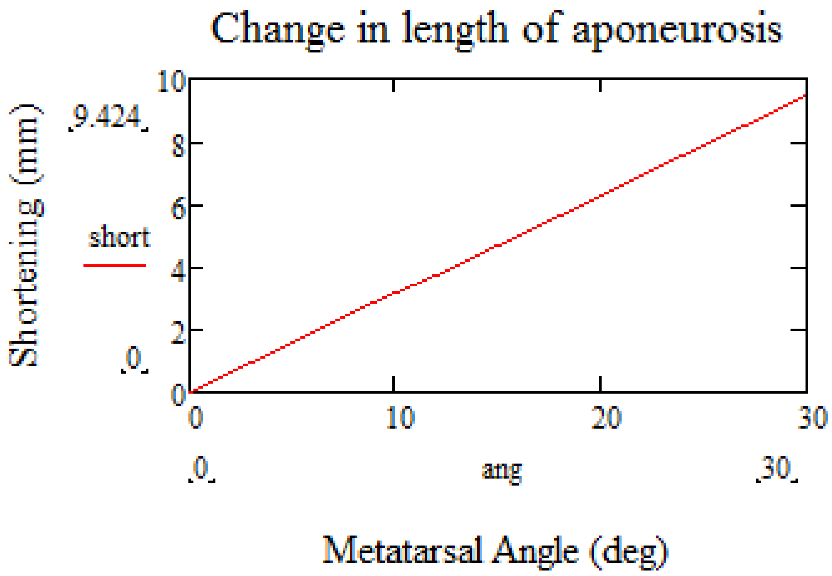
b = 26 deg

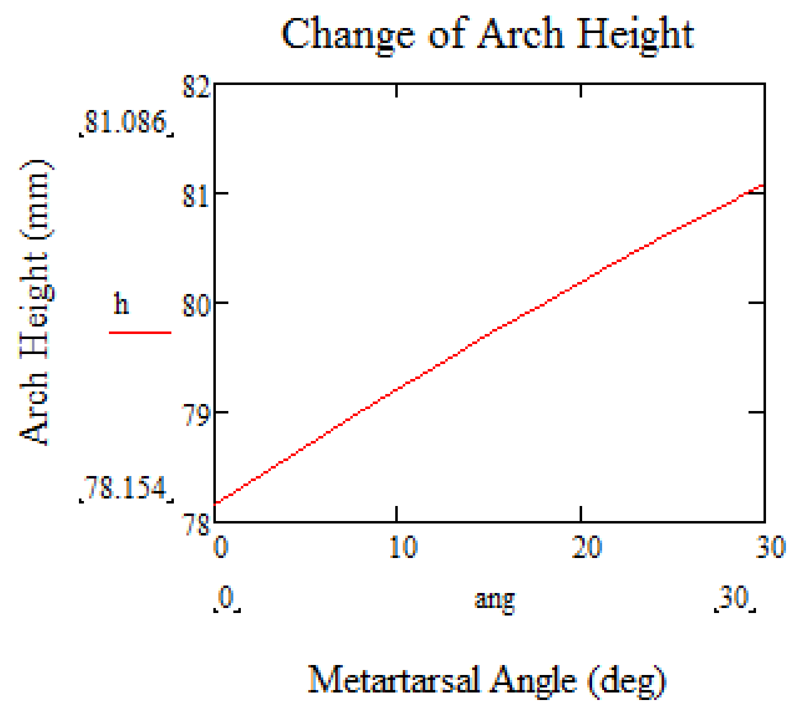
c = 87 deg

Initial arch height = 78mm

Kinematics

Change of arch height with shortening of aponeurosis



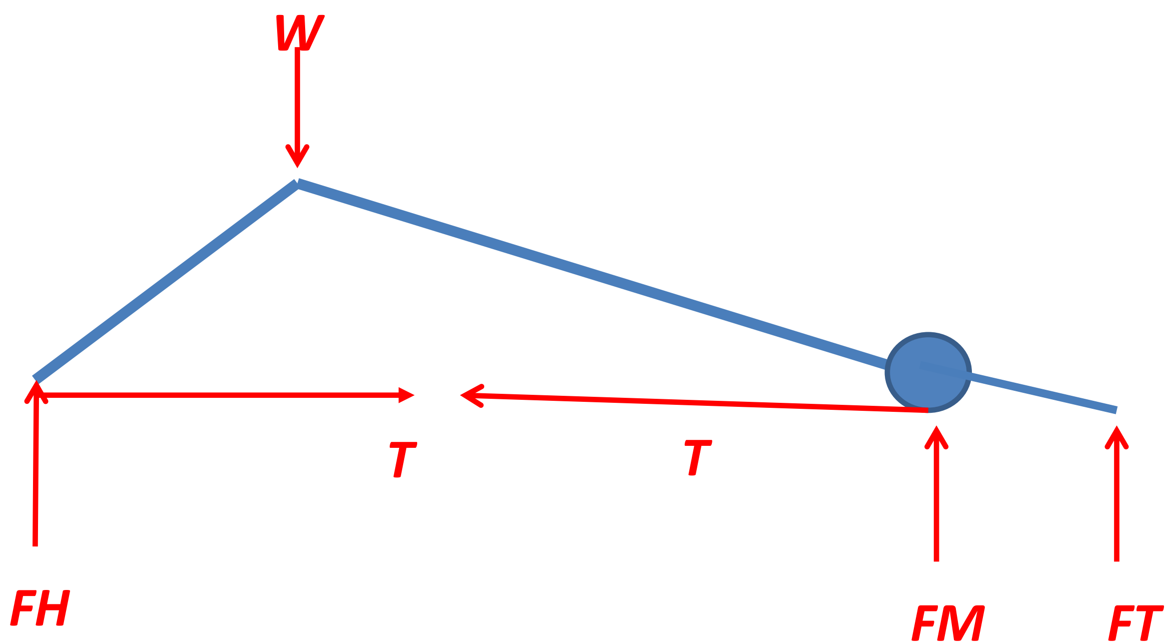


Change in Arch Height

3 mm for 30 deg rotation!

FORCES AND EQUILIBRIUM

Free Body Diagram - External Equilibrium

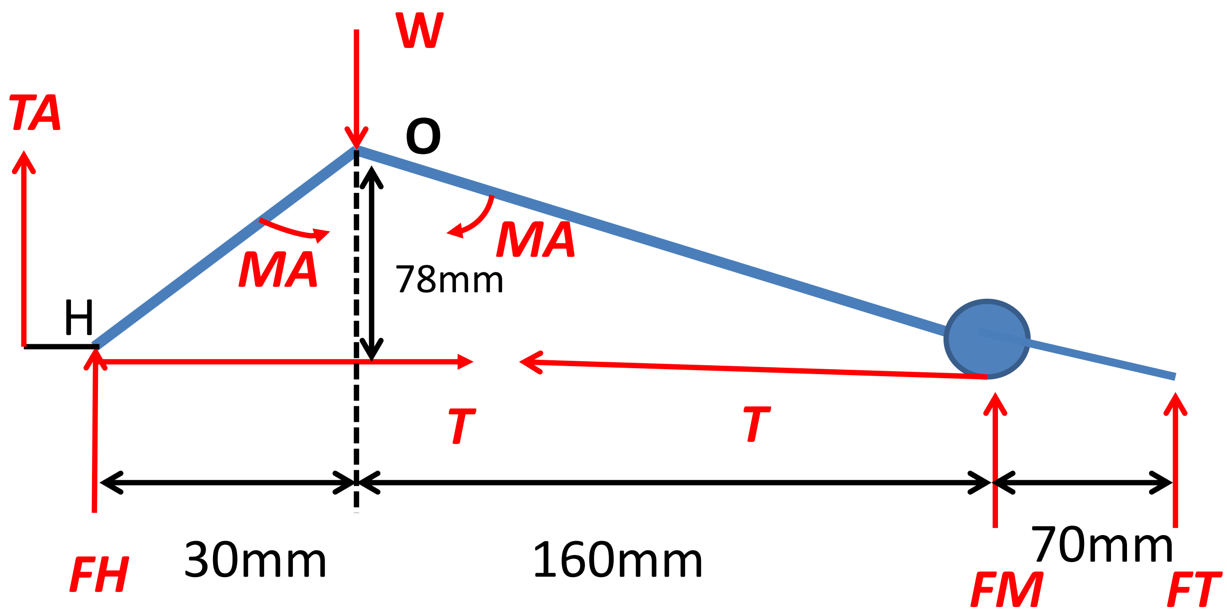


Initial Assumptions

Quiet Standing – no muscle activity

No friction – only vertical ground reaction forces

Equilibrium of level standing – 3 point support



External Equilibrium

Vertical: FH + FM + FT – W = 0

Moments about O: 0.23*FT + 0.16*FM – 0.03*FH-.05*TA = 0

External equilibrium appears indeterminate! BUT consider internal mechanics

Moments about O for OH: .078*T-.03*FH-.05*TA+MA = 0

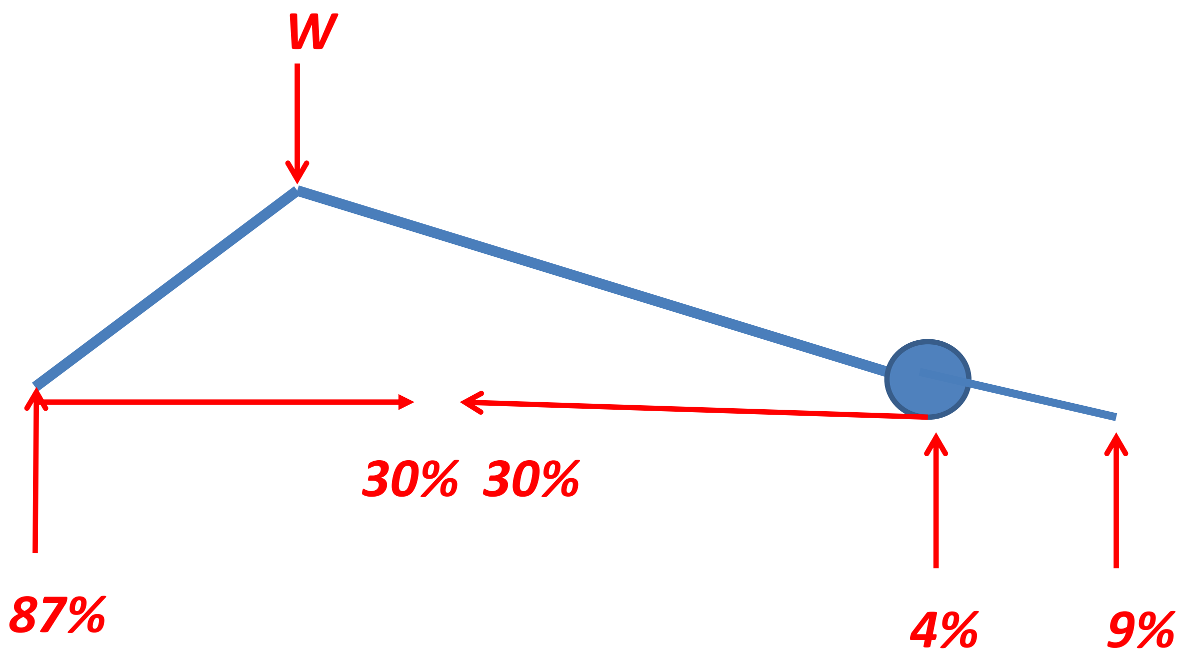
Moments for metatarsal: .07*FT-T*.018 = 0

We are dealing with a mechanism rather than a structure. Equilibrium possible with additional constraints – **heel, metatarsal heads and toe all supported**

Equilibrium of level standing – 3 point support

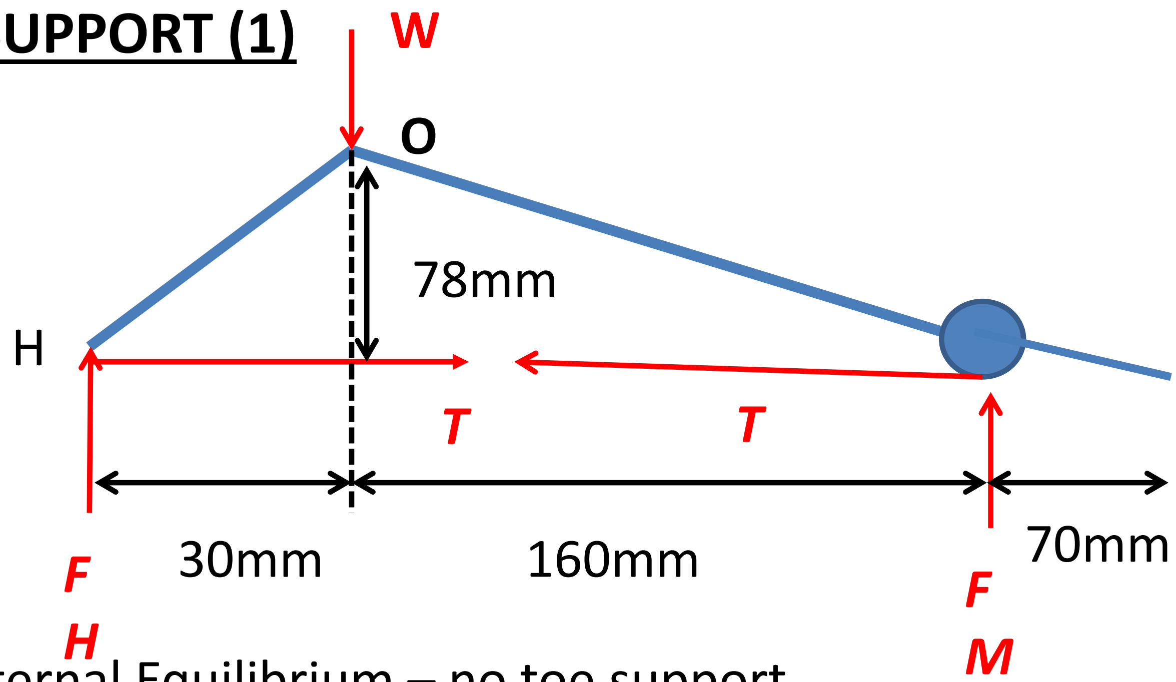
Assuming :– Tendo achilles zero tension and zero passive moment

Predicted load distribution – percentage of total supported load



N.B. Toe reaction force in equilibrium with aponeurosis force – moments at metatarsal head

NO TOE SUPPORT (1)



External Equilibrium – no toe support

Vertical: FH + FM– W = 0

Moments about O: 0.16*FM – 0.03*FH = 0

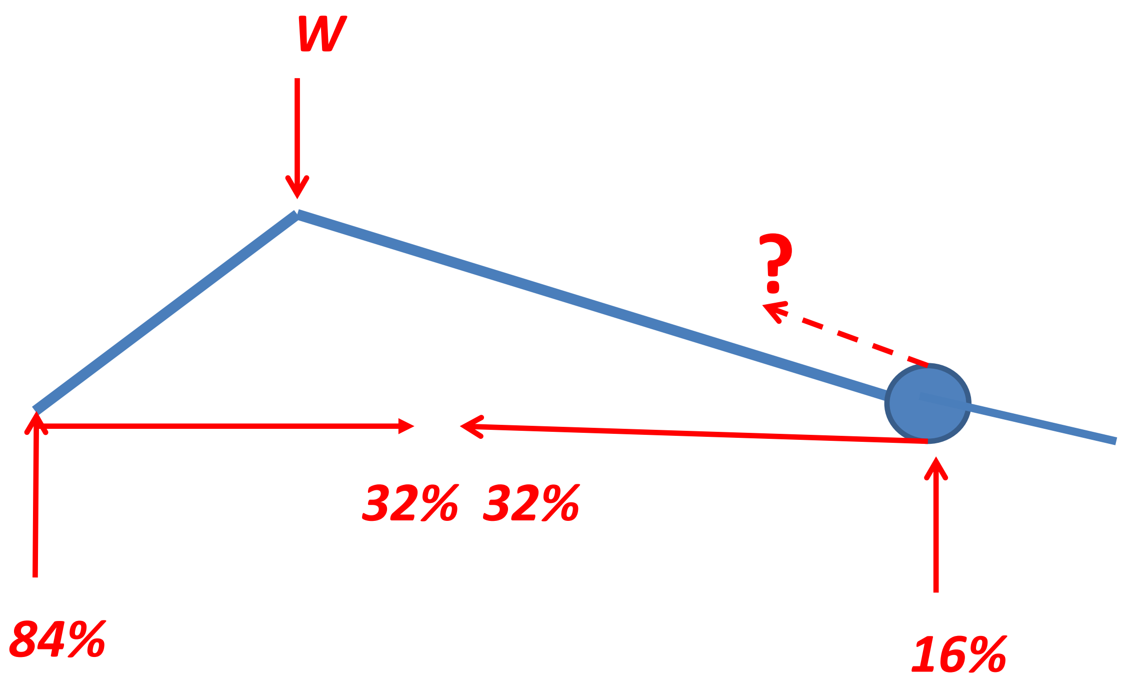
External equilibrium appears determinate! BUT consider internal mechanics

Moments about O for OH: .078*T-.03*FH = 0

Moments for metatarsal: NO EQUATION

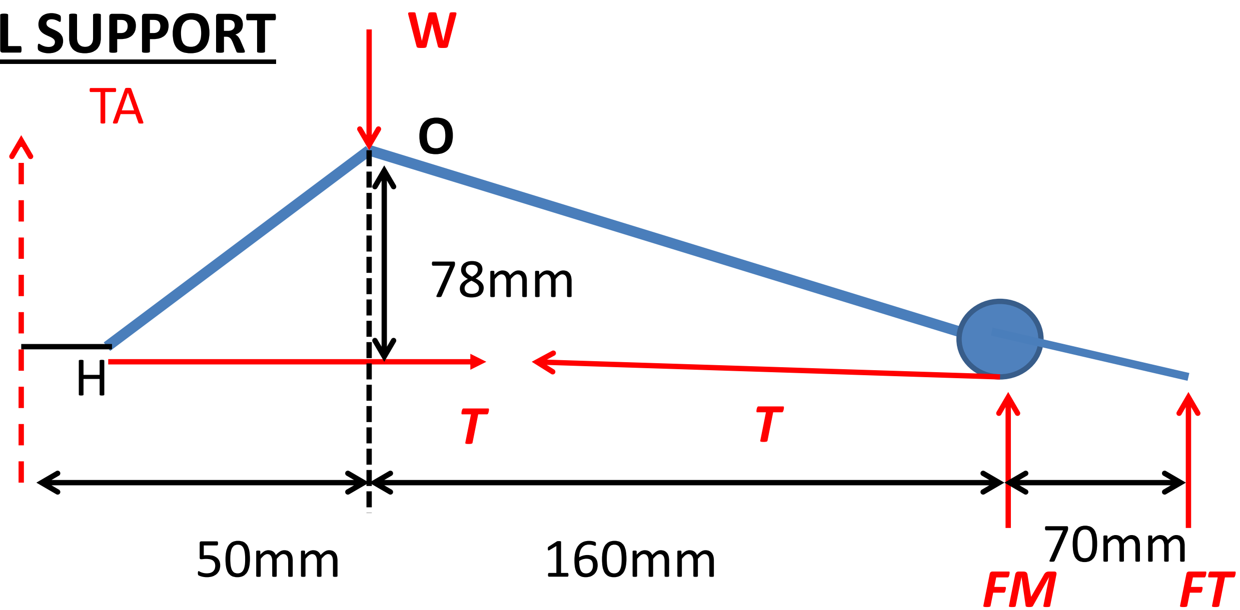
3 UNKNOWNS and 3 EQUATIONS - OK? NO – it's a mechanism!

NO TOE SUPPORT (2)



Equilibrium of arch is satisfied but metatarsal not in equilibrium!
Need extensor muscle?? – extensor hallucis longus.
N.B. This implies that a toe extensor is responsible for maintain arch equilibrium

NO HEEL SUPPORT



External Equilibrium

Vertical equilibrium: FM + FT – W = 0

Moments about O for OH: .078*T= 0 **!!!**

Moments for metatarsal: .07*FT- 0.018*T = 0

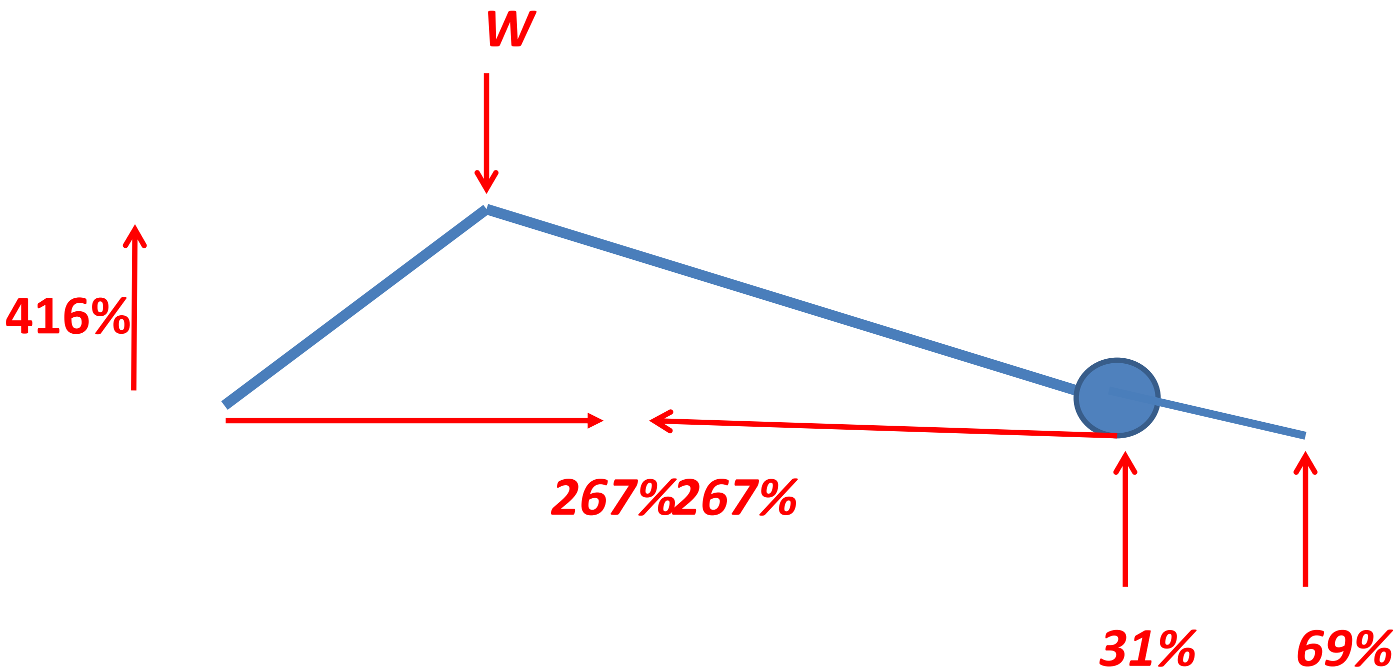
Predicting zero tension and, therefore, zero toe force, but then, from equation 2, FM = 0 i.e. not in equilibrium. Need Achilles Tendon!!

N.B. TA tension does not affect vertical equilibrium (reacted by ankle contact force) but produces a couple = TA* 0.05 (published moment arm).

NO HEEL SUPPORT - continued

External moments: 0.03*TA - 0.16* FM – 0.23*FT =

New moments equation for OH: 0.03*TA - 0.078*T = 0

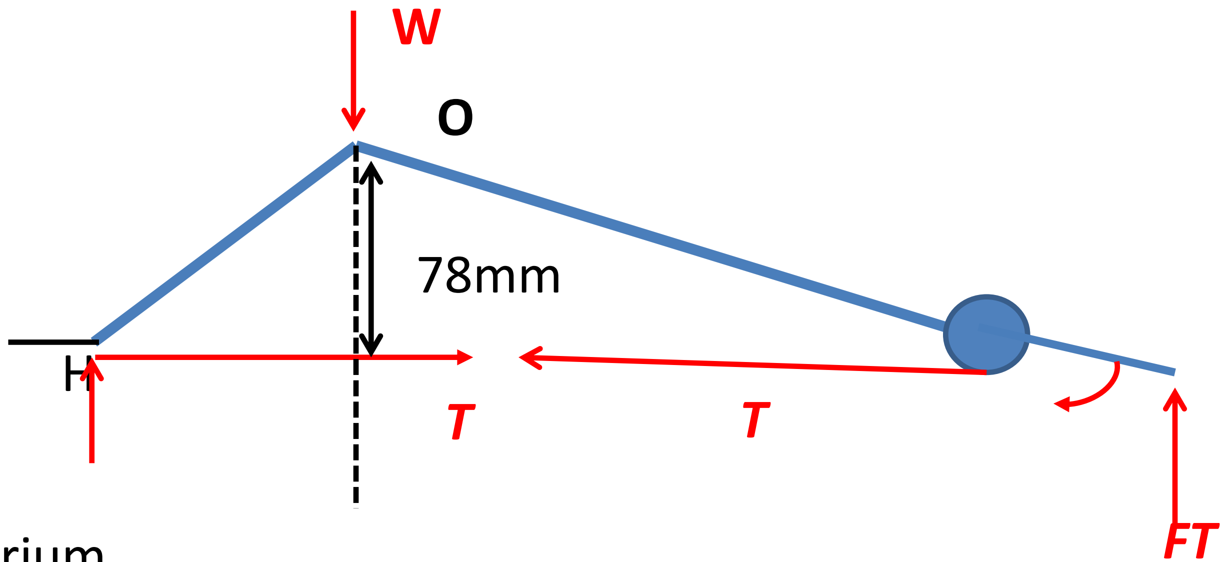


Predictions of TA and Aponeurosis forces are high – but see later!!

Force under toe appears vital to equilibrium - is that what happens?

Calcaneus acts as sesamoid between TA and aponeurosis

NO MET HEAD SUPPORT



Equilibrium

1. Vertical equilibrium: FH + FT – W = 0
2. Moments about O for foot: FH*.03 – FT*.23 = 0
3. Moments about O for OH: .078*T- FH*.03= 0
4. Moments for metatarsal: .07*FT- 0.018*T = 0

FH = 0.72*W and FT = 0.82*W

BUT: Equations 3 & 4 are in conflict – NO SOLUTION – this is an underconstrained mechanism!

A short toe flexor would be required for equilibrium

Biomechanics of Plantar Aponeurosis - Conclusions

- The Hicks Model represents a 4 dof mechanism
- Equilibrium of the mechanism requires 3 ground reaction forces for level standing – but no muscles
- Kinematics - The predicted arch lift is small (c 3mm) – probably impossible to measure reliably
- Any stance on two contact points requires muscle activity
- The toe mechanism is vital to arch stability
- The TA load at toe off is determined by muscle or passive loads which may transfer load from the toe end to the metatarsal head.
- Predicted loads seem broadly in agreement with one relevant published study.

Overall Comments

- This has been a small introduction to a big topic!
- Basic mechanics allows us to understand a vast amount about how joints and muscles function both in health or after injury or pathology
- In the next lecture, we'll look at a more advanced application in the design of a shoulder replacement