Mechanism Synthesis for Modeling Human Movement

(Synthesis of spatial mechanisms for the modelling of human joints)

Vincenzo Parenti-Castelli and Nicola Sancisi

Department of Mechanical Engineering - University of Bologna, Italy
GRAB: Group of Robotics and Articular Biomechanics

Workshop on 21st Century kinematics
11- 12 August 2012, Chicago, Illinois, USA

GRAB - Group of Robotics and Articular Biomechanics

Vincenzo Parenti-Castelli

Research Group, GRAB-DIEM:
- **Nicola Sancisi**
- **Benedetta Baldisserri**
- **(Raffaele Di Gregorio)**
- **(Riccardo Franci)**
- **(Andrea Ottoboni)**
- **Diego Zannoli**
- **Margherita Forlani**

- **Alberto Leardini, IOR** (Istituto Ortopedico Rizzoli)

- **University of Bologna** (UoB), Bologna (**1088**)
  - about 120000 students
  - Engeneering: 12000 students
  - Mechanical Engineering Department
    - full professors: 20
    - associate professors: 25
    - assistant professors: 30
    - research assistants: 20
    - PhD students 60

Fields of interest:

- **Teory of mechanisms and machines**
  - kinematics and dynamics of open and closed chains
  - singularities
  - joint clearance
  - compliant mechanisms
  - electroactive polymers (EAP)
- **Biomechanics**
  - Articular prostheses (**internal** prostheses)
  - Prosthetic arms (**external** prostheses)
  - Orthoses

- Institutions:
  - Department of Mechanical Engineering – **DIEM**, Bologna
  - Rizzoli Orhopaedic Institute (**IOR**), Bologna
  - Oxford Orthopaedic Engineering Centre (**OOEE**), University of Oxford
  - INAIL Prostetic Center (**IPC**) , Budrio, Bologna,

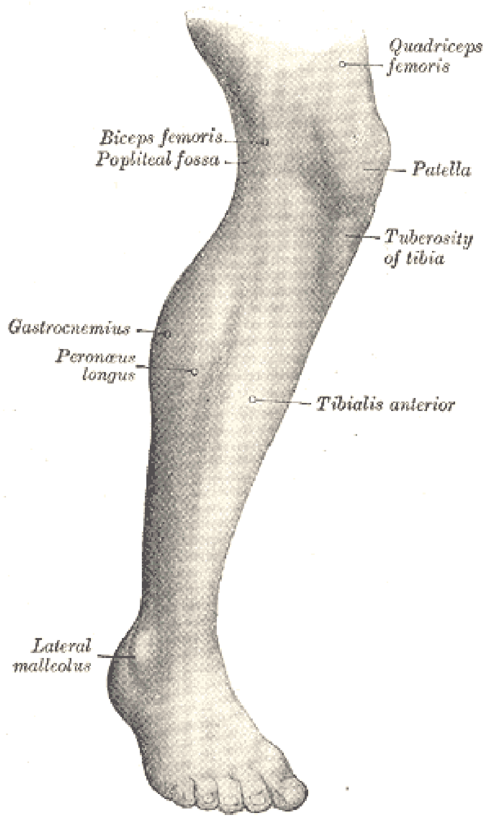
- People:
  - **DIEM**: **Di Gregorio**, Corazza, Venanzi, Cocconcelli, **Ottoboni**, Chebbi**,** Vertechy, Carricato, Troncossi, Paganelli, Corazza, **Sancisi**, **Franci**, Conconi, Caminati, **Baldisserri**
  - **IOR**: Catani, Leardini, Giannini, ….
  - **OOEE:** O'Connor, Feikes, ….

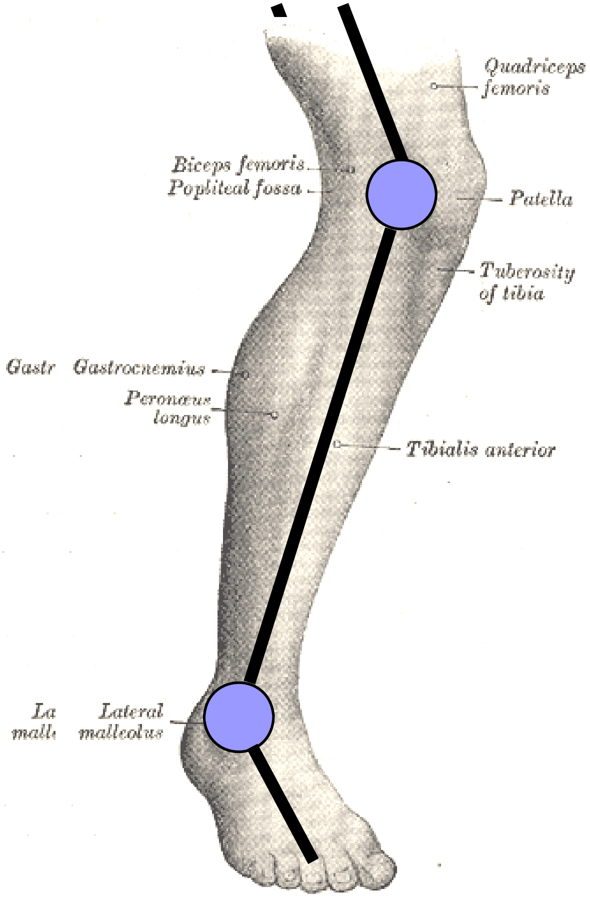
JOINT MODELLING

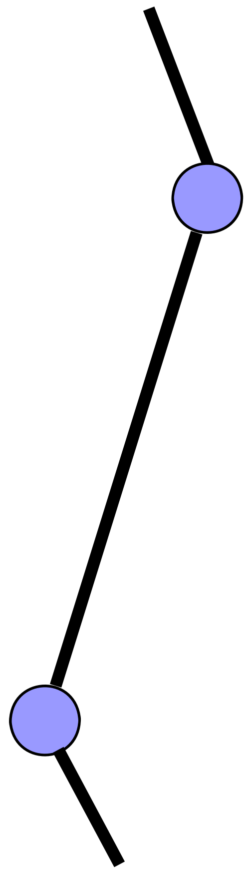
Motivations and applications:

- Definition of surgical and diagnostic procedures for joint disorders caused by injuries and/or diseases
- Assessment of the role of the joint biological structures in the joint characteristics in normal and pathological condition
- Prosthesis and orthosis design

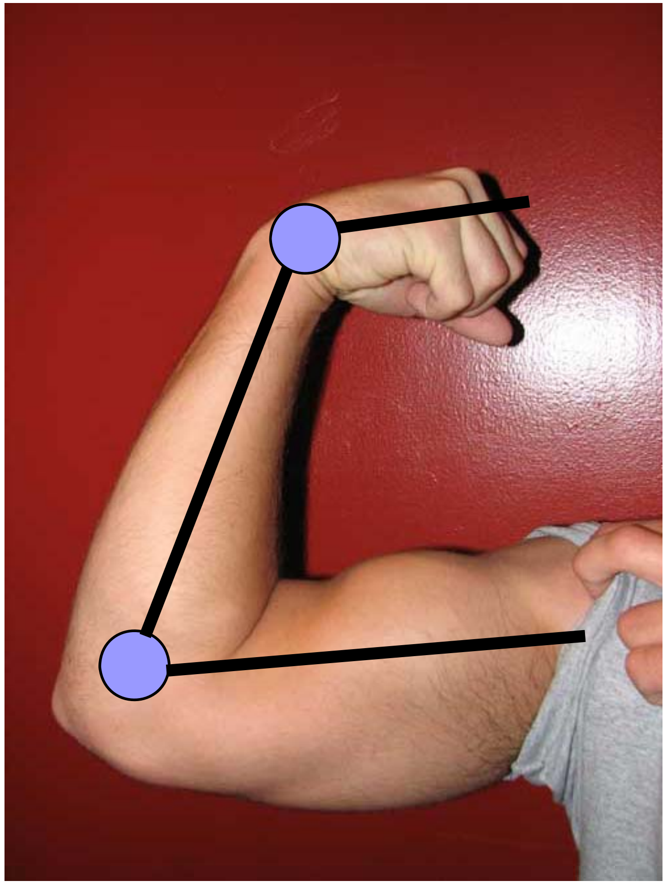
Simple Kinematic model - 1

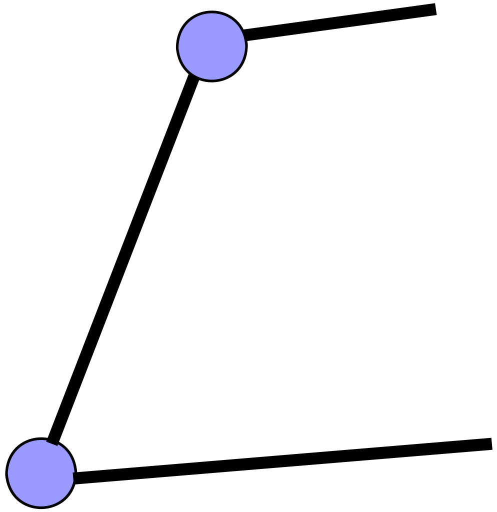






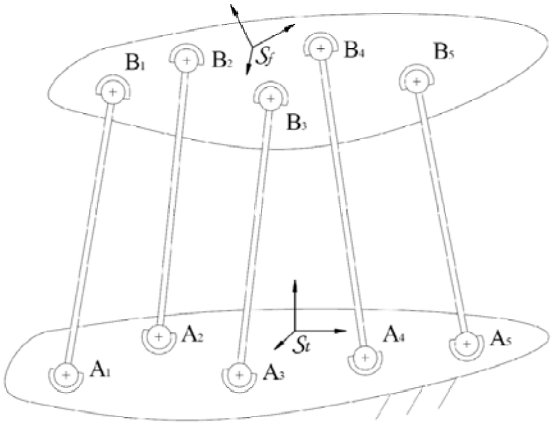
Simple Kinematic model - 2



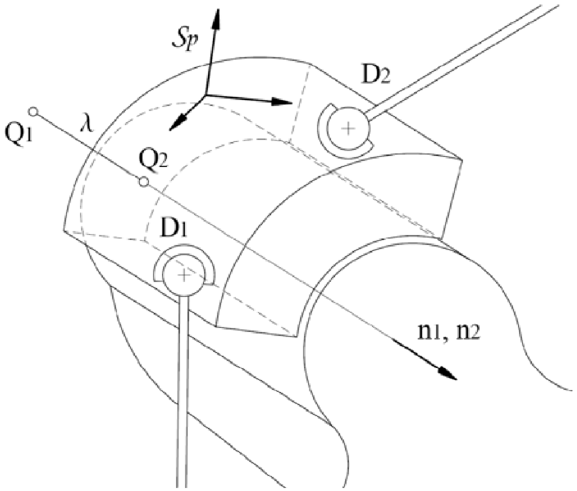


Complex Kinematic models : knee (model M1)

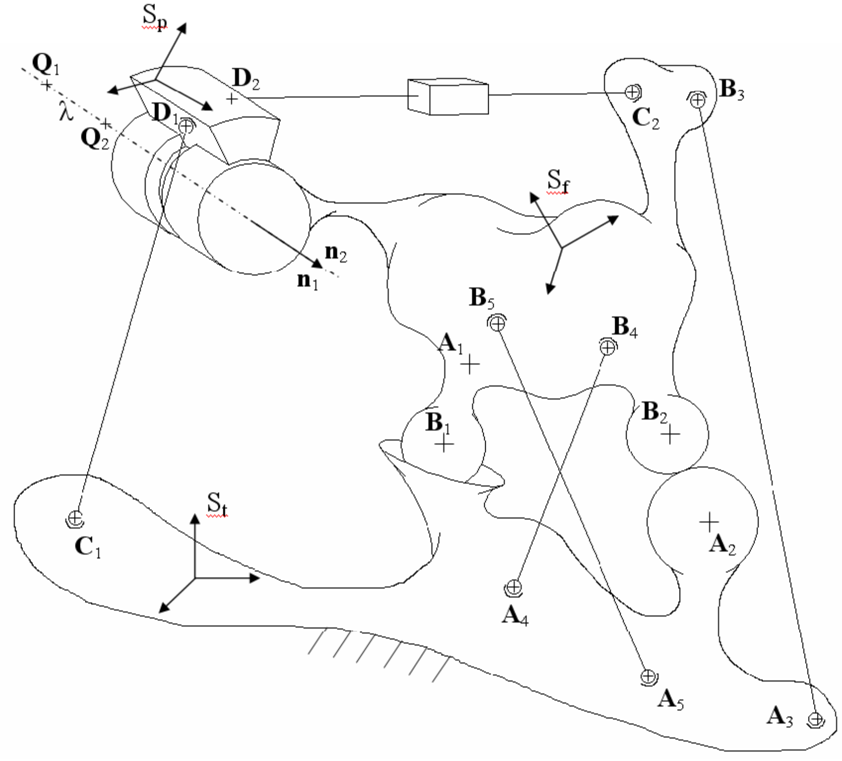
- **TF model**



- **PF model**



- **Knee model**



SUMMARY

- Introduction
  - Passive motion of diarthrodial joints
  - Joint modelling
  - Previous approaches for the modelling of diarthrodial joints
- The new approach (synthesis of equivalent mechanisms)
- Application to the knee, the ankle and the lower leg
- Results
- Conclusions

THE PASSIVE MOTION OF DIARTHRODIAL JOINTS

The motion of the joint under virtually unloaded condition

Importance:

- Deeper understanding of the joint kinematics
- Deeper understanding of the stabilizing role of articular components

Characteristics:

- Complex and repeatable spatial motion
- Guided by few structures at a time (isometric fibres and articular contacts)

n-DoF Motion → n-DoF (parallel) mechanism

For instance, for the knee and the ankle n=1

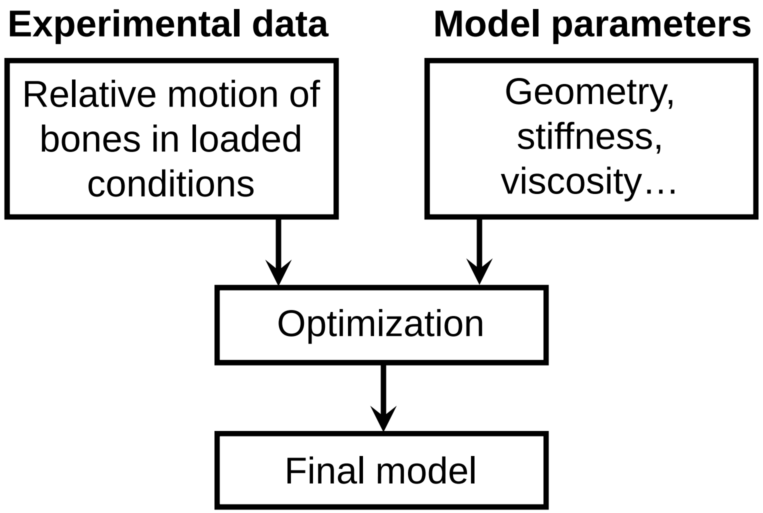
1-DoF Motion → 1-DoF (parallel) mechanism

JOINT MODELLING

Two approaches for joint modelling:

- **Simultaneous approach**: dynamic models with viscoelastic structures of a single specific task
- **Kinematic approach**: kinematic models with rigid bodies (equivalent mechanisms) of the passive motion

SIMULTANEOUS APPROACH



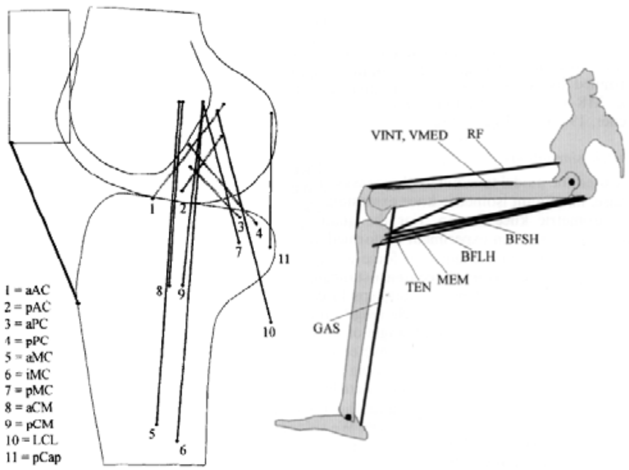
A single optimization problem is solved and model parameters are identified on the given task.

Advantages

- All structures of the joint are involved (both passive and active)
- Suitable to simulate the dynamic behaviour of the joint

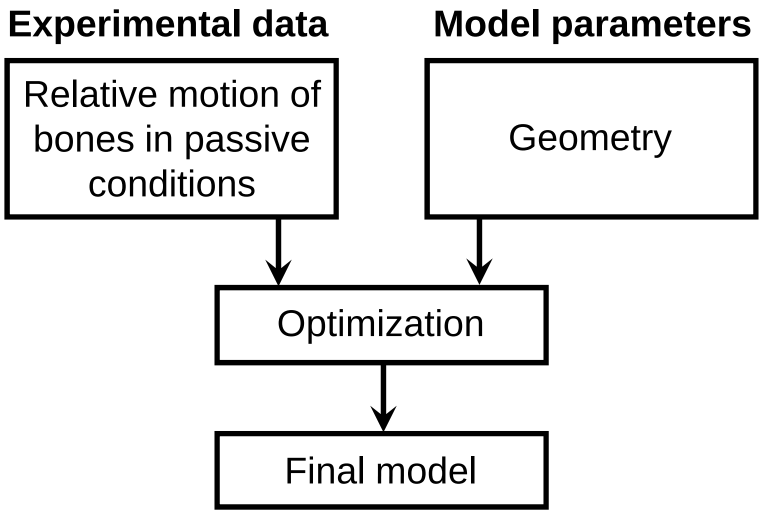
Disadvantages

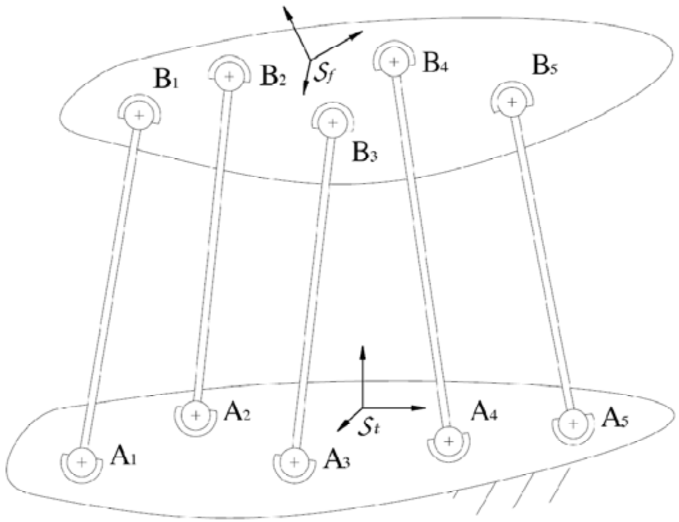
- Computational demanding
- The restraining function of joint structures is lost: model elements and parameters have a subtle relation with the anatomy
- Model results fit the experimental results of the given task only
- Outcomes of the models are difficult to interpret and the model itself is less useful to surgeons and to prosthesis designers



KB Shelburne, MG Pandy (1997). *A musculoskeletal model of the knee for evaluating ligament forces during isometric contraptions.* JBiomech 30(2): 163-176.

KINEMATIC APPROACH





A single optimization problem is solved and model parameters are identified on the passive motion.

Advantages

- Good accuracy in passive motion simulation
- Function of the structures that influence the passive motion is correctly replicated
- Computationally simple

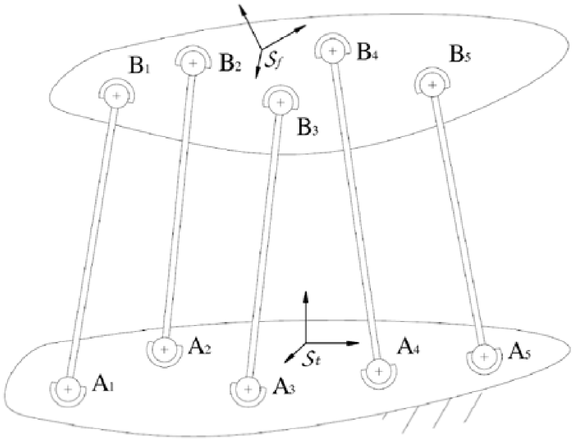
Disadvantages

- Only a few structures of the joint are modelled
- Model results fit the experimental passive motion only

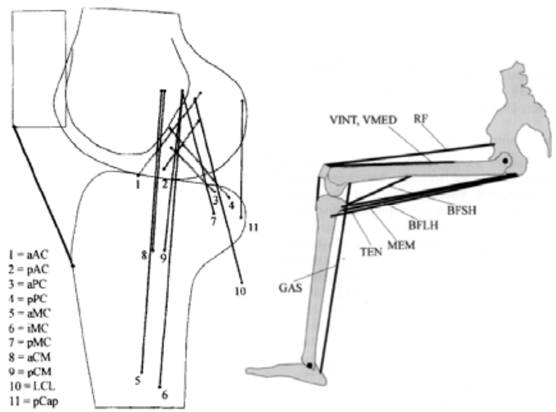
- Propose a new procedure with the final object

To consider all the anatomical structures of a joint (both the passive and the active ones) making their role evident in the kinematic and kinetostatic-dynamic behaviour of the joint itself.

Kinematic approach



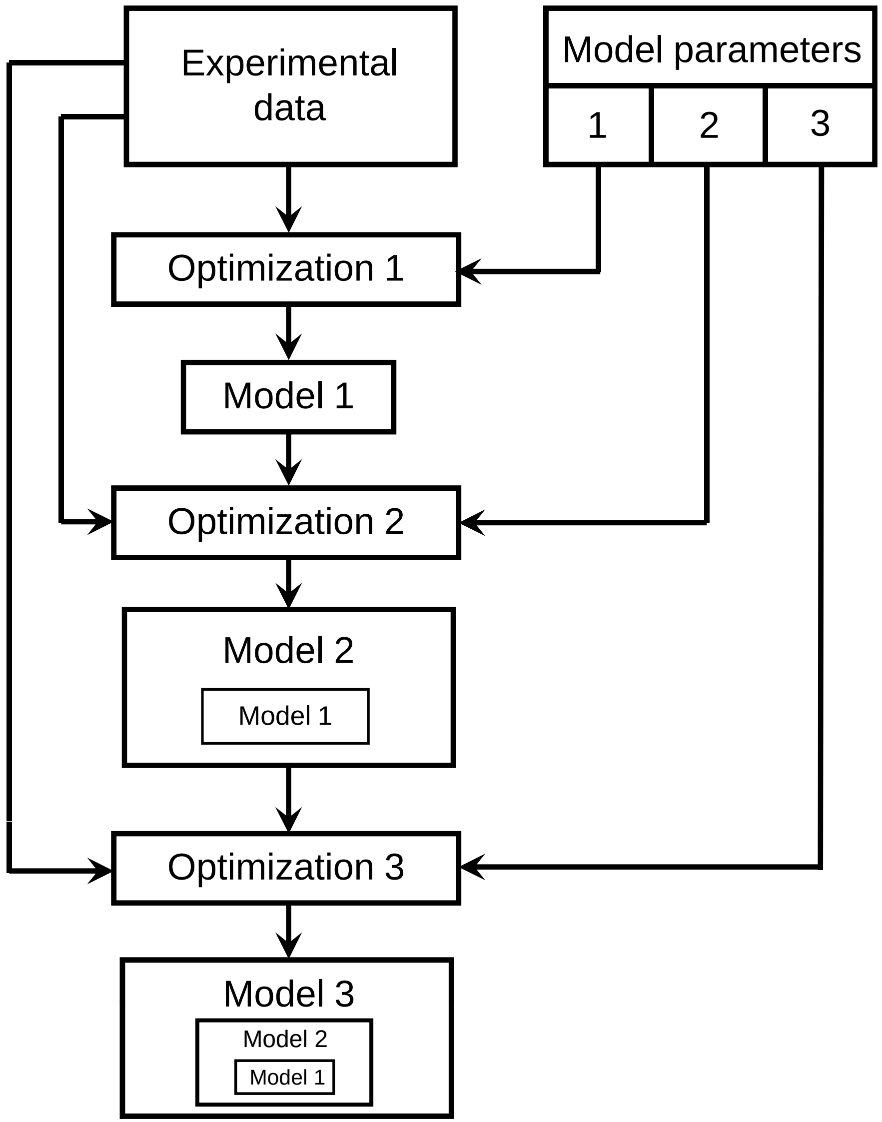
Sequential approach



A NEW PROCEDURE HAS TO BE DEVISED

SEQUENTIAL APPROACH

A sequence of more and more sophisticated, i.e. generalized, models. The final model is obtained by means of three intermediate steps.



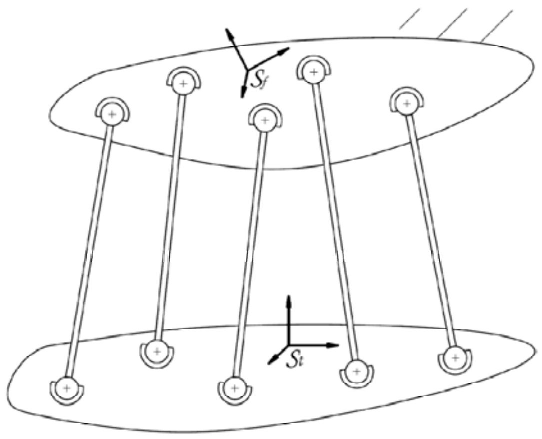
Rules:

- Once a parameter has been identified at a particular step, it is not changed at the following steps
- Parameters identified at each step must be chosen so that they do not alter the results obtained at the previous steps

Advantages:

- The two rules guarantee that the results obtained at each step do not change those already obtained at previous steps
- At each step it is therefore possible to identify the role of the added structures

SEQUENTIAL APPROACH



Step 1 – Passive motion model

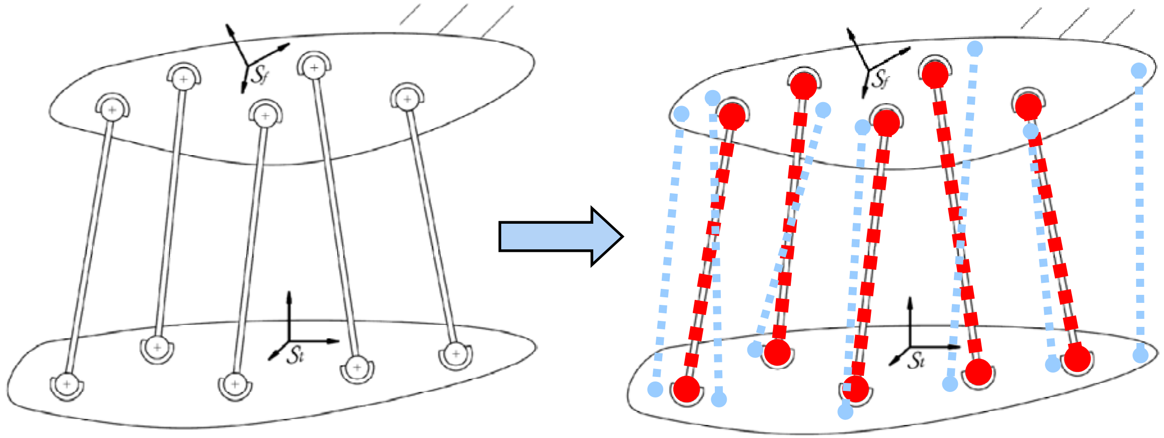
Features:

• It refers to the joint's main anatomical structures which are involved during the motion of the joint under virtually unloaded conditions

• Three dimensional rigid body mechanism

• Geometric parameters identified by an optimization process based on in vitro/vivo measurements

SEQUENTIAL APPROACH



Step 1 – Passive motion model (M1) **Step 2 – Stiffness model (M2)**

Features:

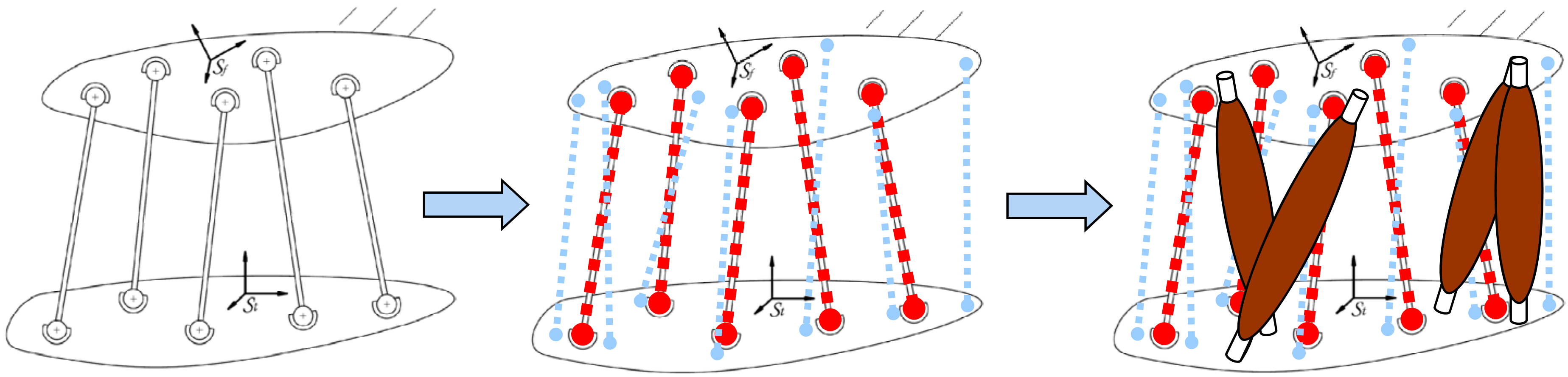
• The model comprises the M1 model with the addition of the remaining passive structures

• All the passive structures involved (both those of the M1 model and those added at this step) are now considered as elastic or viscoelastic structures

• The model's geometric and structural parameters are identified by an optimization procedure based on in vivo measurements (static loads)

• The identification procedure is performed by satisfying the rules of the sequential approach

SEQUENTIAL APPROACH

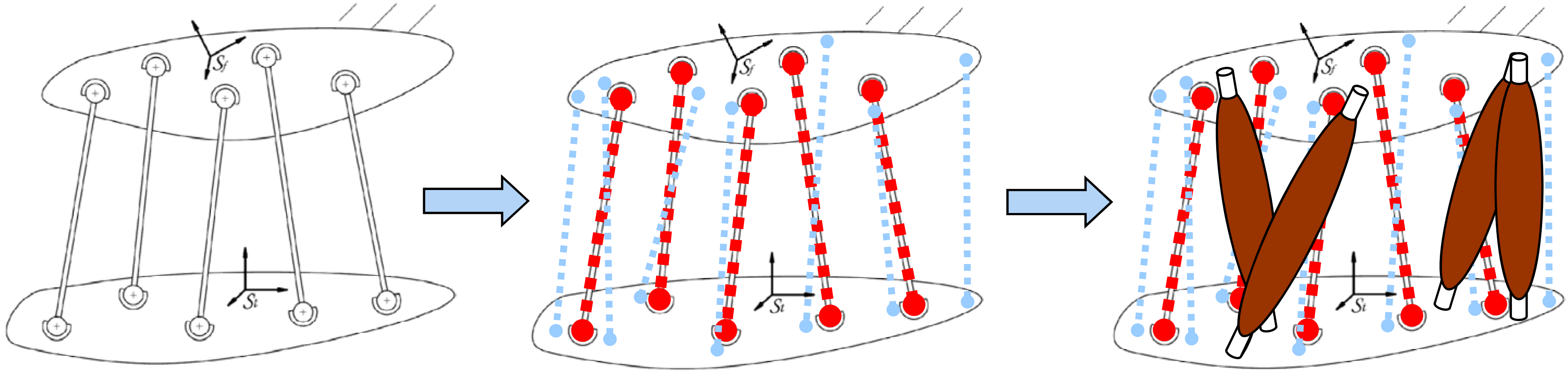


Step 1 – Passive motion model (M1) **Step 2 – Stiffness model (M2)** **Step 3 – Dynamic model (M3)**

Features:

- The M3 model comprises the M2 model with the addition of all the active joint structures, i.e. mainly all muscles involved in the motion of the joint
- Dynamic loads and tasks are considered (inertia)
- An optimization procedure makes it possible to identify the remaining geometrical and structural parameters of the model

SEQUENTIAL APPROACH



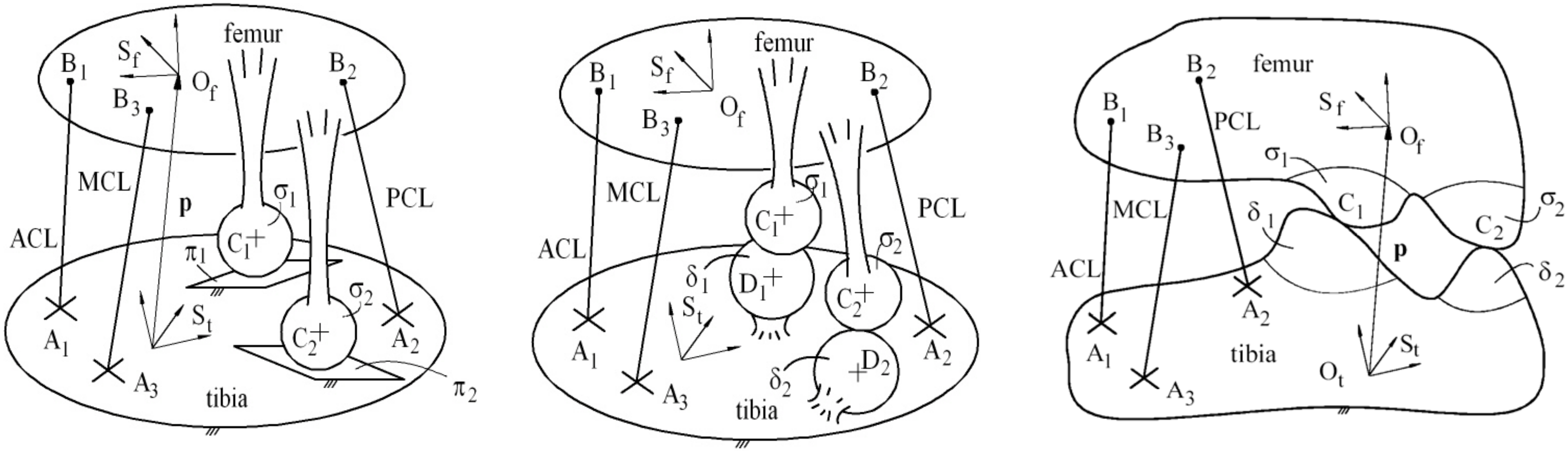
Step 1 – Passive motion model (M1) **Step 2 – Stiffness model (M2)** **Step 3 – Dynamic model (M3)**

Each model has its own advantages and disadvantages:

• M1 is simple and computationally not too much expensive but provides a limited amount of information

• M3 is computationally demanding but provides all the information related to the behaviour of the joint.

KNEE EQUIVALENT MECHANISMS



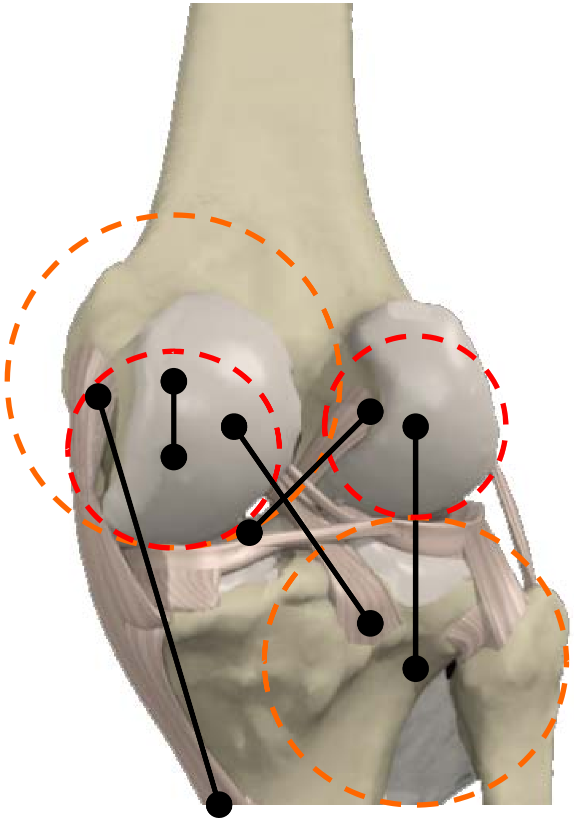
The mechanisms proposed in the literature replicate only the relative motion of the femur-tibia articulation

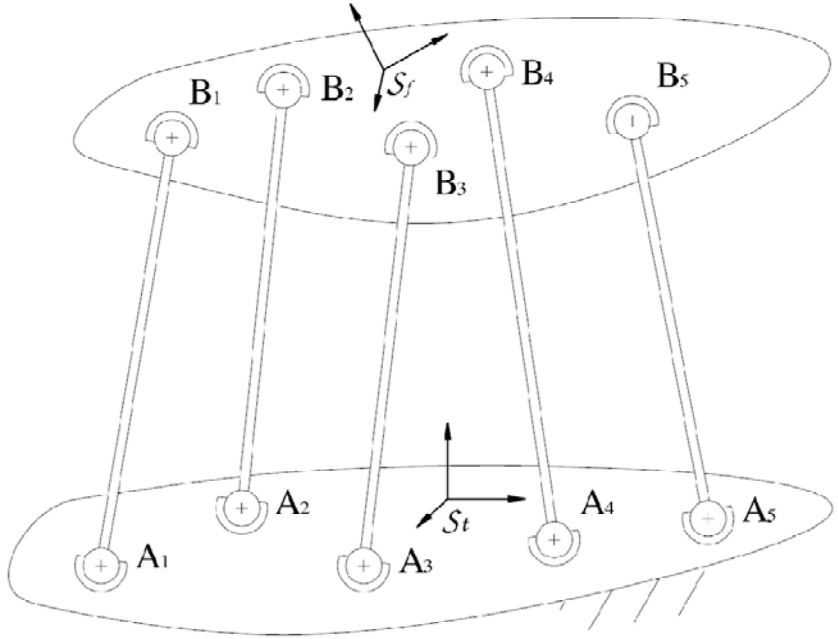
It is not possible to use these mechanisms for studying loading conditions

A complete knee mechanism is defined that comprises the patella too

APPLICATION TO THE KNEE (MODEL M1)

- **Tibio-femural joint model**



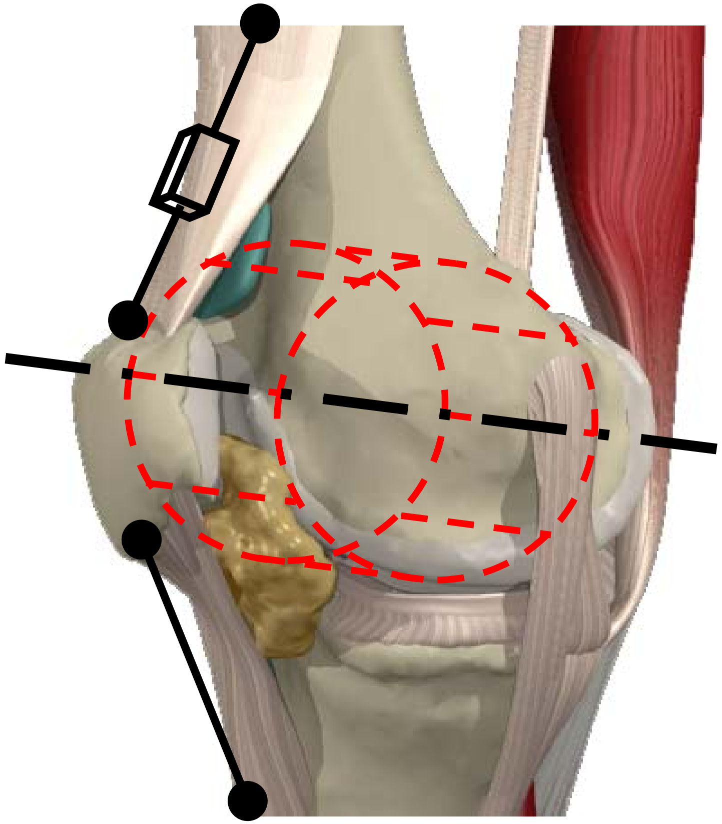


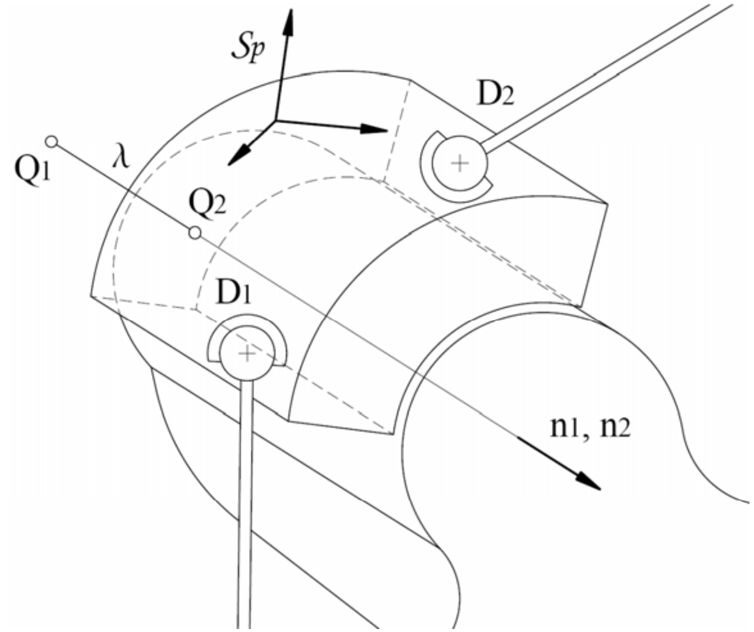
- Isometric fibres of ACL, PCL, MCL
- Spherical approximation of the condyles

5-5 fully parallel mechanism

APPLICATION TO THE KNEE (MODEL M1)

- **Patello-femural joint model**

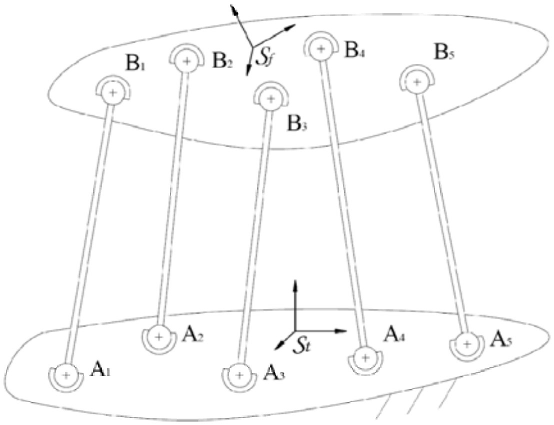




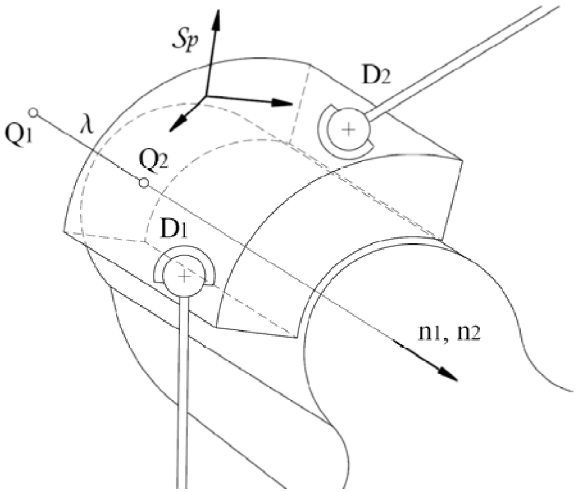
- Cylindrical approximation of the trochlea and of the anterior femur condyles
- Isometric fibre of the patellar ligament
- SPS group for the modelling of the quadriceps

APPLICATION TO THE KNEE (MODEL M1)

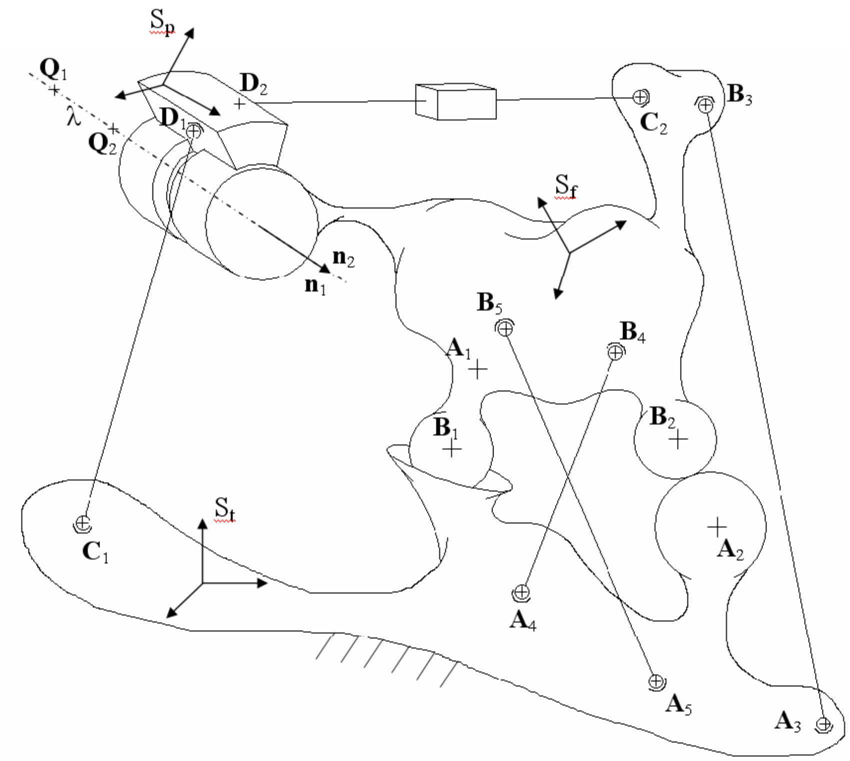
- **TF model**



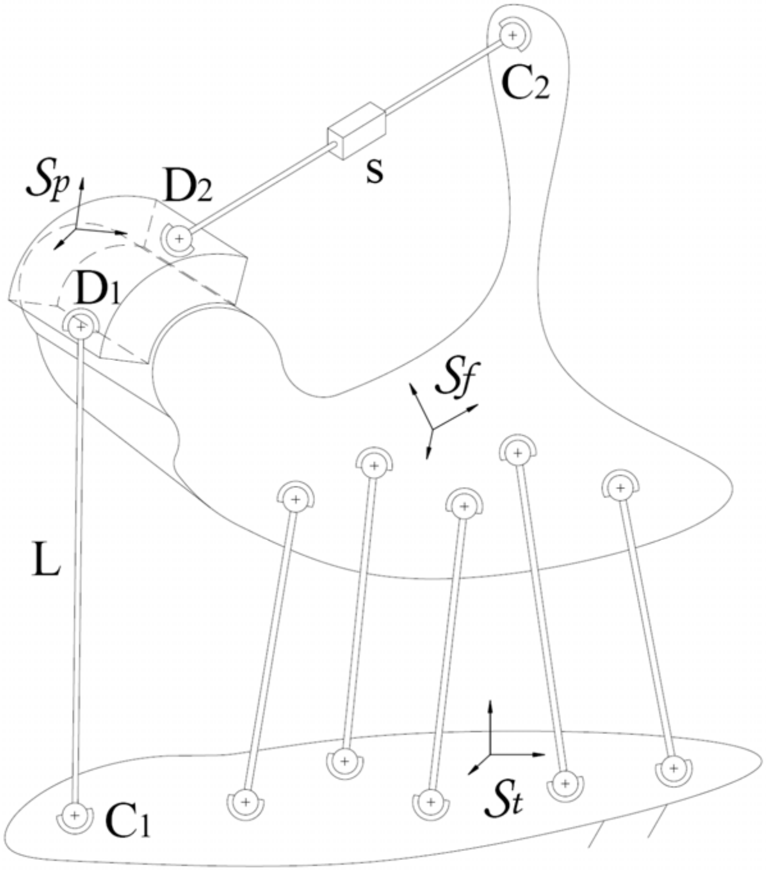
- **PF model**



- **Knee model**



PROPOSED MODEL



- two sub-chain partially decoupled
- closure equations:

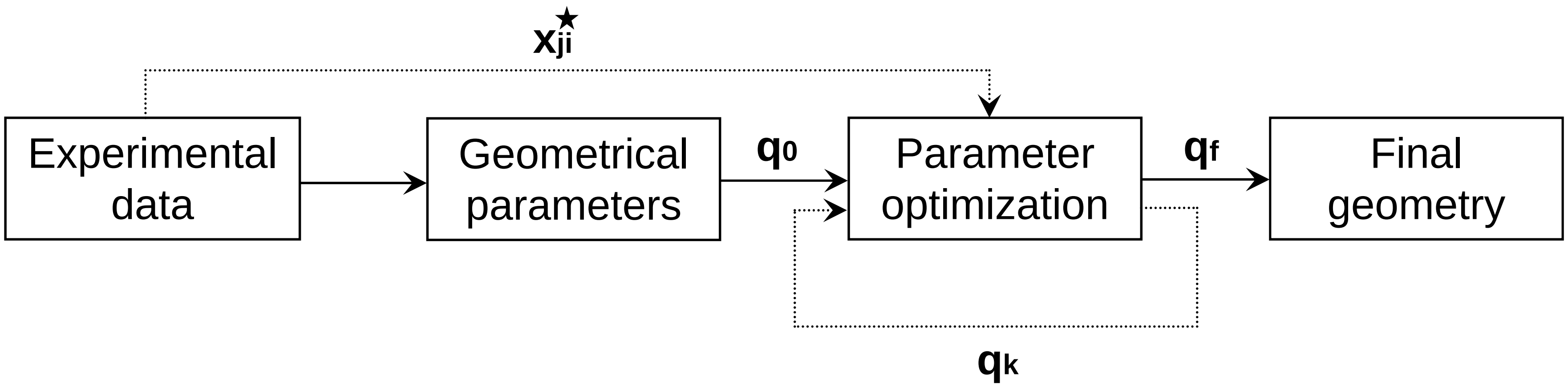
$$\|\mathbf{A}_i - R_{tf}\mathbf{B}_i - \mathbf{P}_{tf}\| = L_i, \quad (i = 1, \ldots, 5)$$

$$R_{fp}\mathbf{n}_2 = \mathbf{n}_1$$
$$R_{fp}\mathbf{Q}_2 + \mathbf{P}_{fp} = \lambda\mathbf{n}_1 + \mathbf{Q}_1$$
$$\|R_{tf}\left(R_{fp}\mathbf{D}_1 + \mathbf{P}_{fp}\right) + \mathbf{P}_{tf} - \mathbf{C}_1\| = L$$

- geometrical parameters:
  - 35 for sub-chain FT
  - 16 for sub-chain FR

PARAMETER OPTIMIZATION

Synthesis procedure:



Parameter optimization:

$$f = \sum_{j=1}^{n_x} \sum_{i=1}^{n} \frac{\left(x_{ji} - x_{ji}^{\star}\right)^2}{x_{jd}^2} \quad \text{if closure succeed}$$

$$f = X \quad \text{otherwise}$$

- bounded optimization
- n control points, n_x motion components
- discontinuous objective function
- genetic algorithms + quasi-Newton

RESULTS

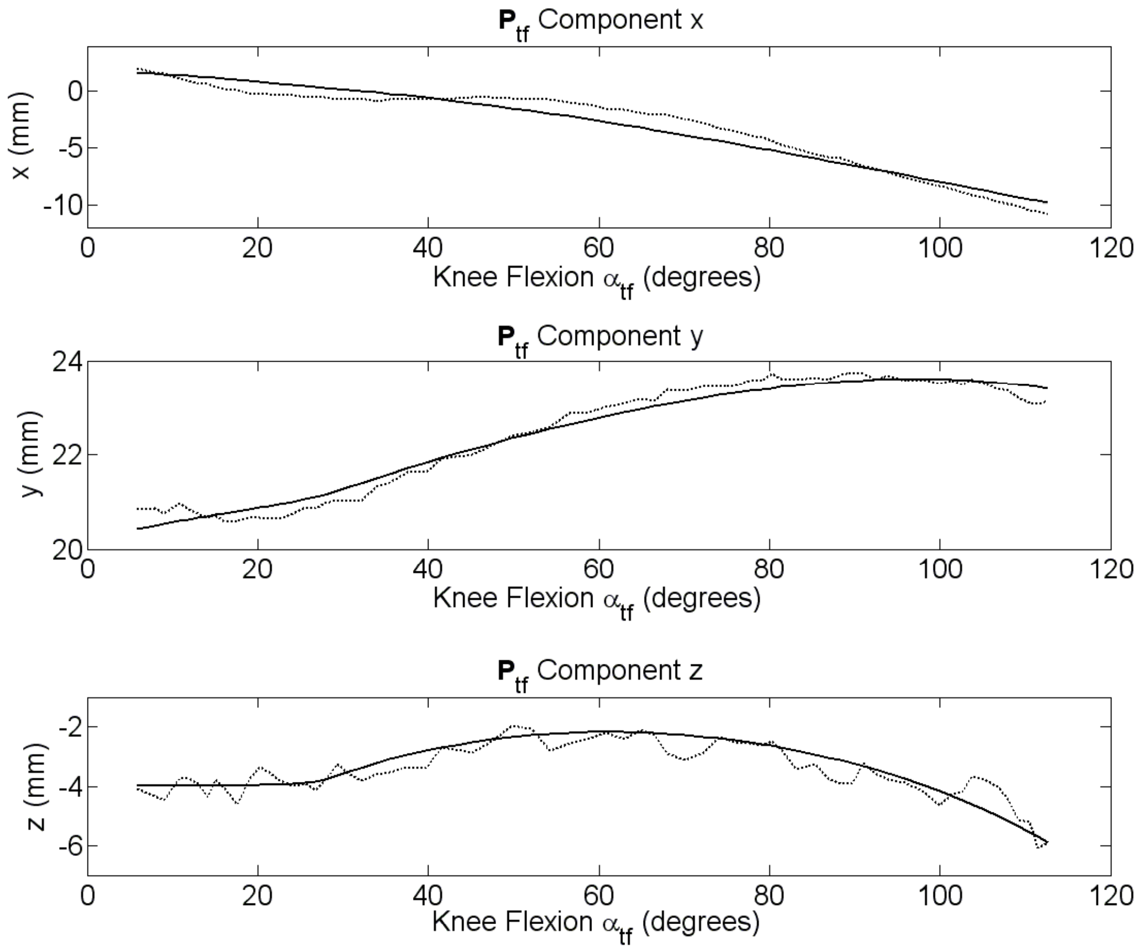
Original

Optimized

Small differences between the original and the optimized models → Consistency of the geometric and kinematic hypotheses of the model

RESULTS

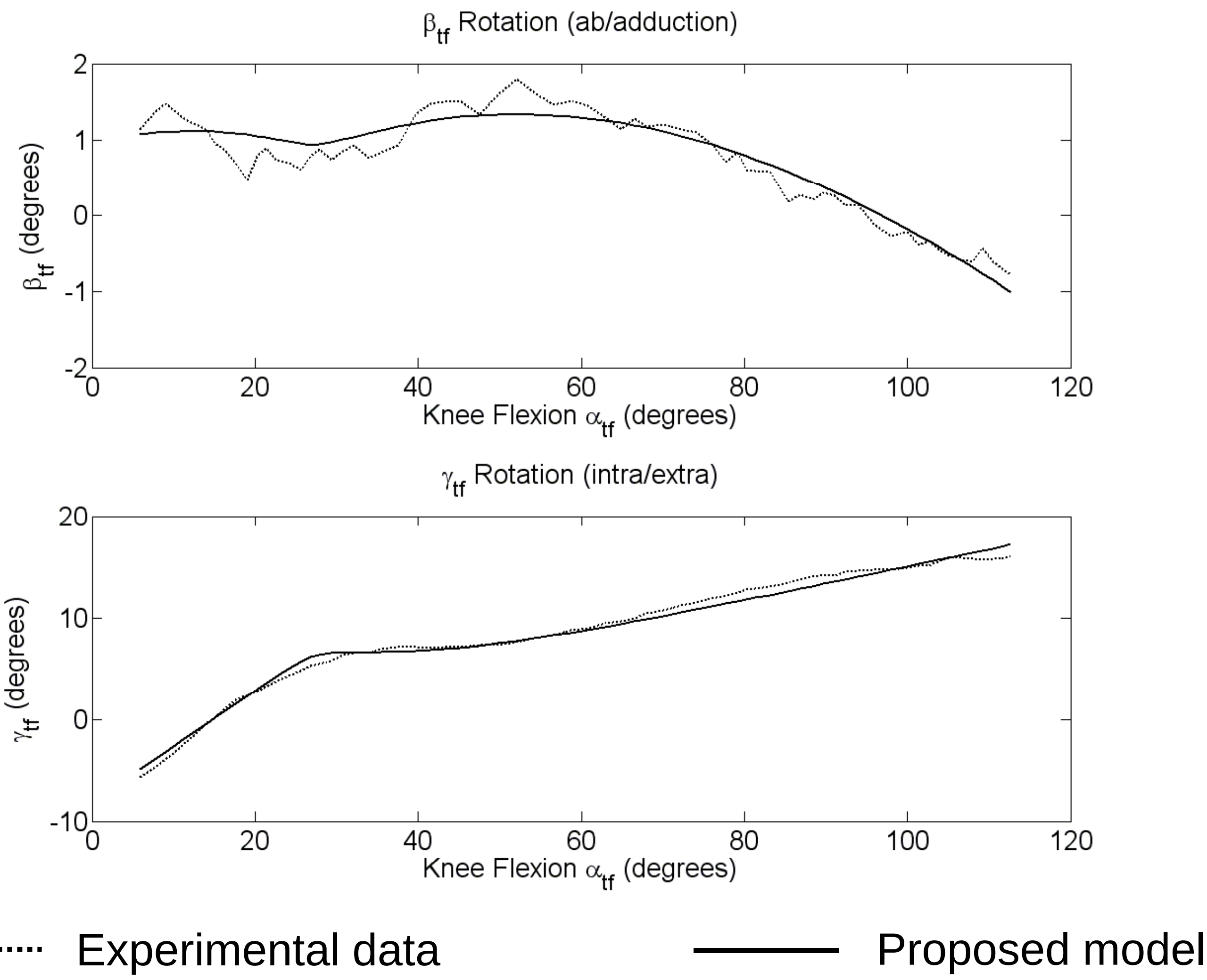
- **Relative position Femur-Tibia in passive flexion**



Experimental data — Proposed model

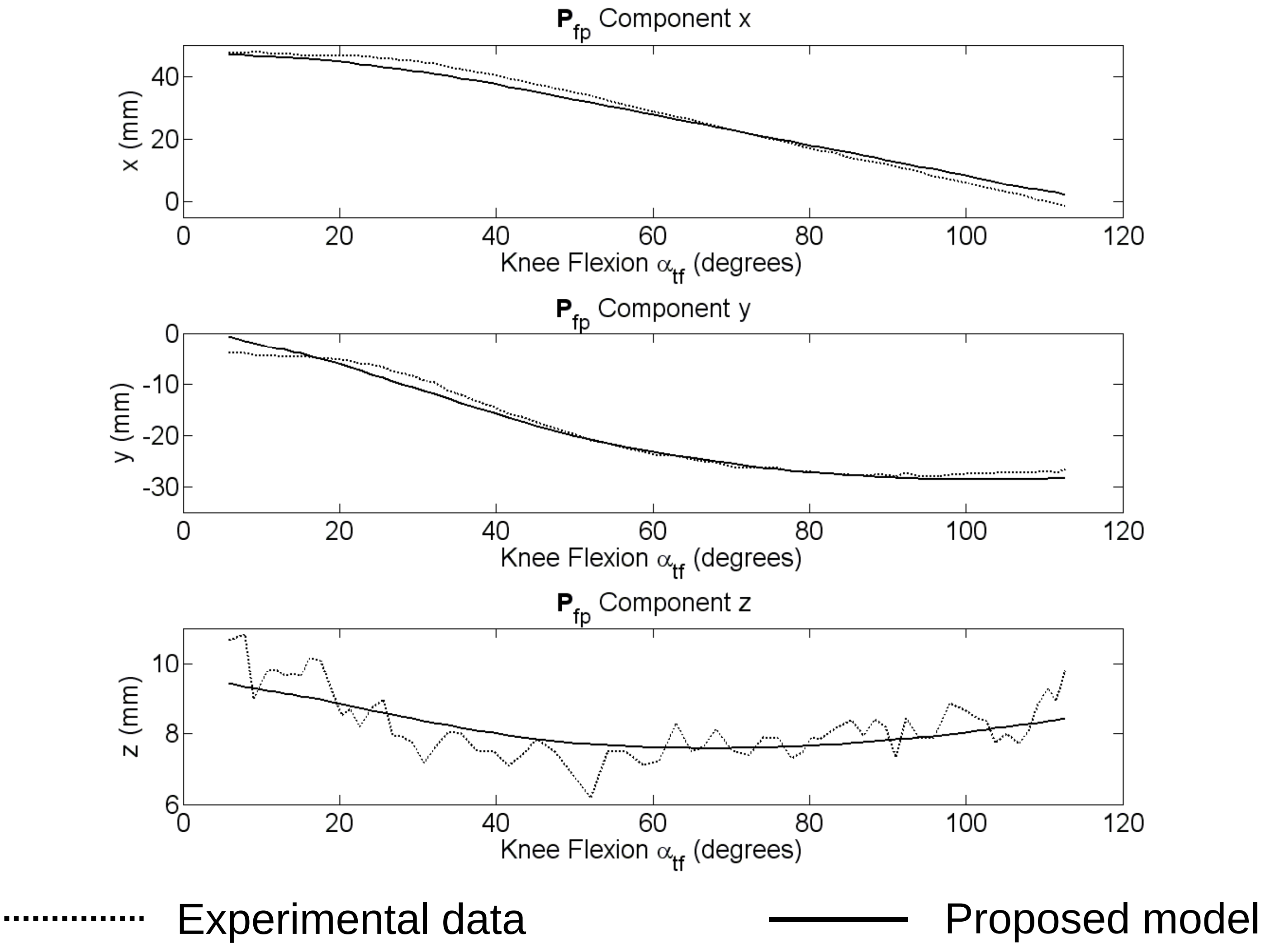
RESULTS

- **Relative orientation Femur-Tibia in passive flexion**



RESULTS

- **Relative position Femur-Patella in passive flexion**



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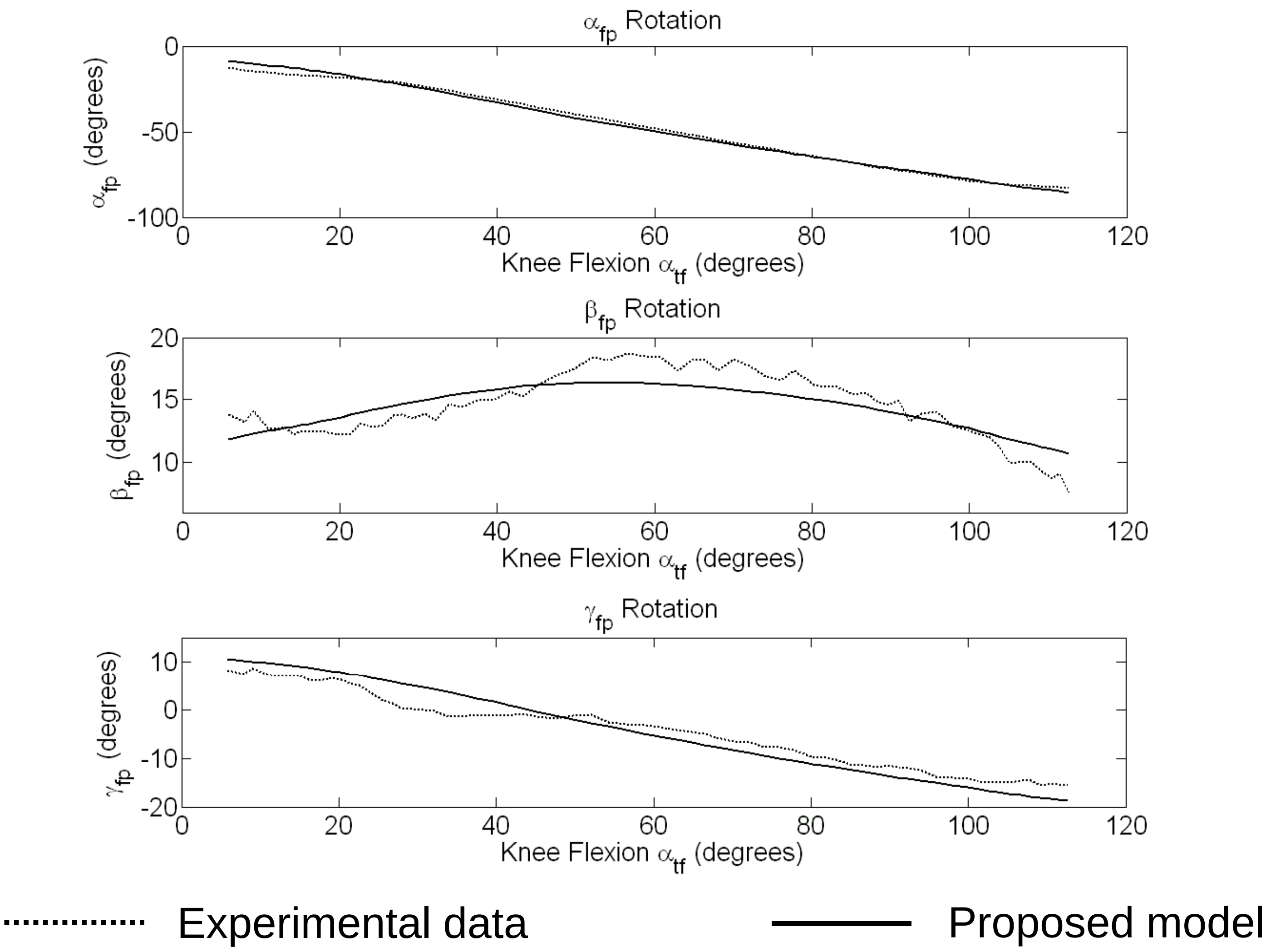
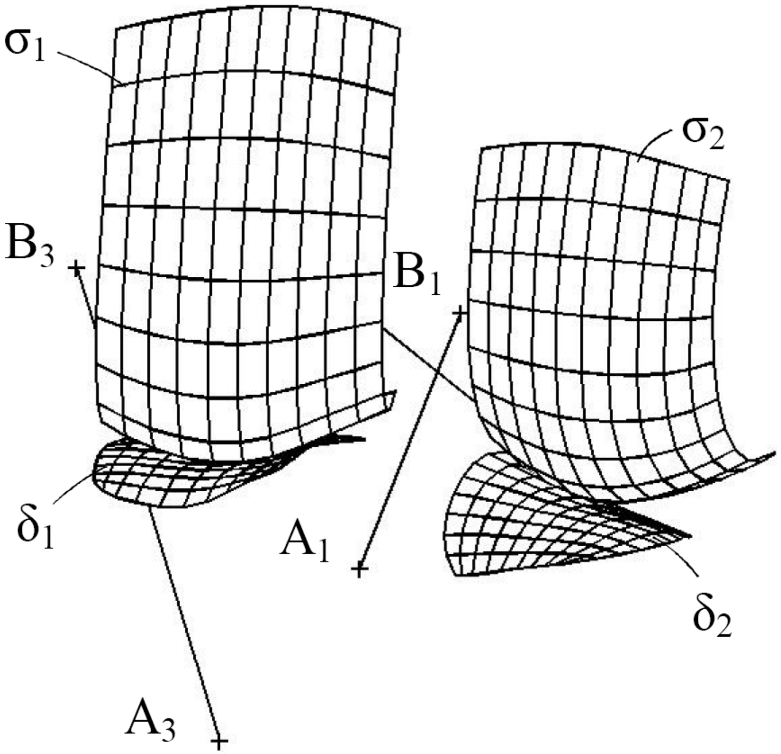
Group of Robotics and Articular Biomechanics

RESULTS

- **Relative orientation Femur-Patella in passive flexion**



Synthesis of new surfaces for knee prostheses:

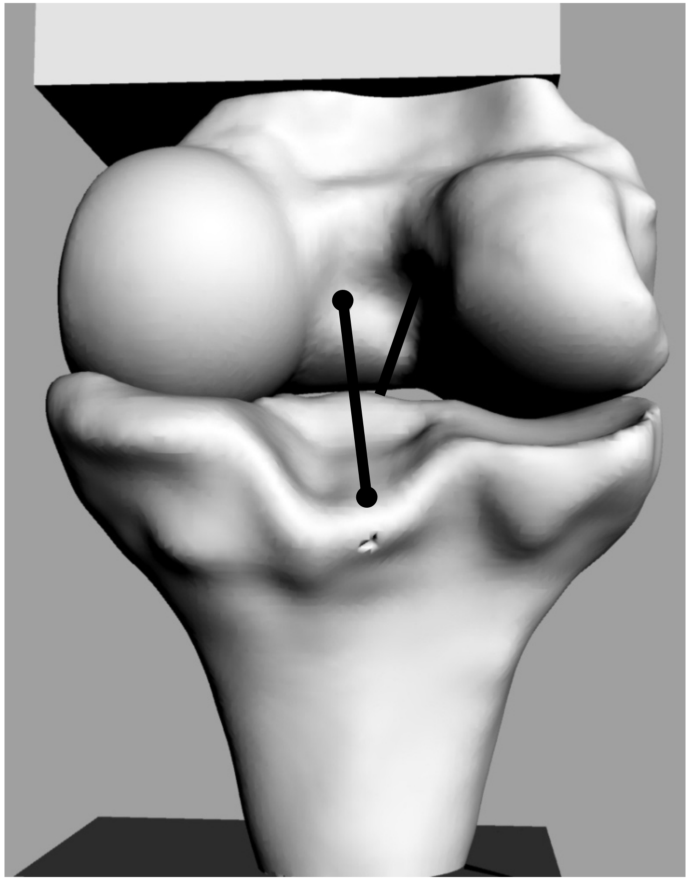


Ottoboni, Parenti-Castelli, and Leardini, AIMETA 2005
Ottoboni, Sancisi, Parenti-Castelli, Leardini, I-MECH submitted, 2009

New Design of Prostheses for Human knee Joint

Knee prosthesis design

Anterior view



Posterior view

- Patents:

Parenti Castelli Vincenzo
Title: Orthopaedic Device and procedure to Realize such a device
International application number PCT/IB2006/003787
US application number: 12/159,747
Atty Docket. No. BUG3-43935
LA FILING Date: 12/28/2006
Priority date: 12/28/2005

Parenti Castelli Vincenzo, Nicola Sancisi, Fabio Catani, Alberto Leardini,
"Dispositivo ortopedico perfezionato"
Riferimenti Bugnion: Ns Rif. 61.U2164.12.IT.27
61.I3257.12.IT.19 TP/gl
Vs Rif. Bologna, 13 maggio 2009
DOMANDA DI BREVETTO N. BO2009A000291

APPLICATION TO THE ANKLE (MODEL M1)

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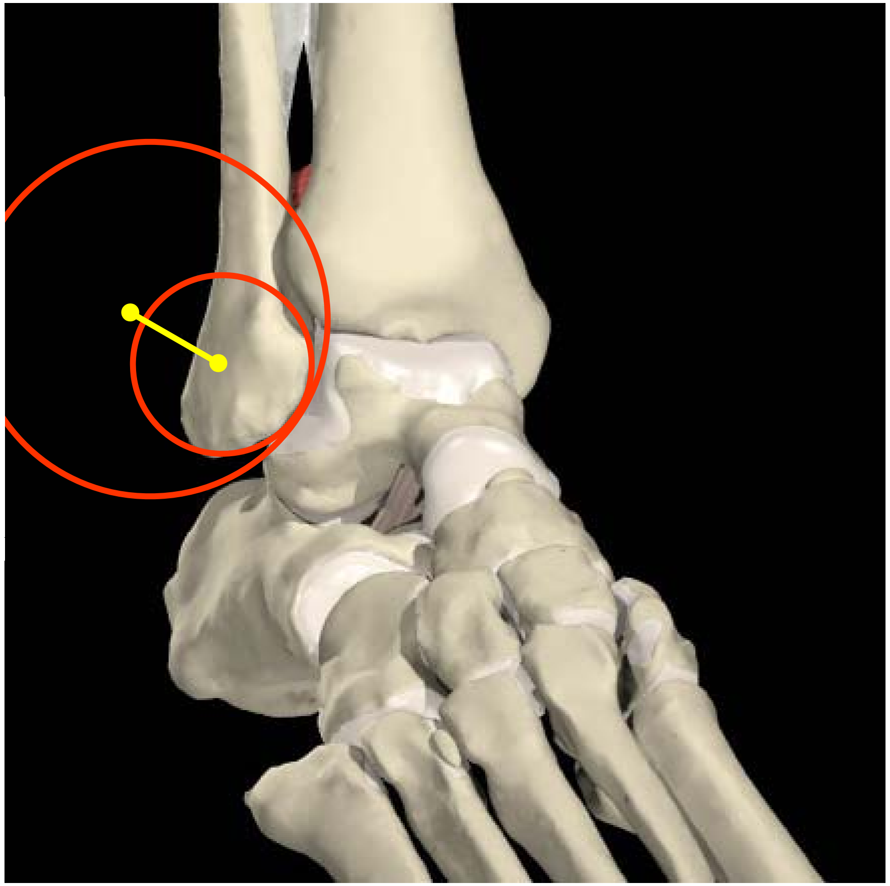
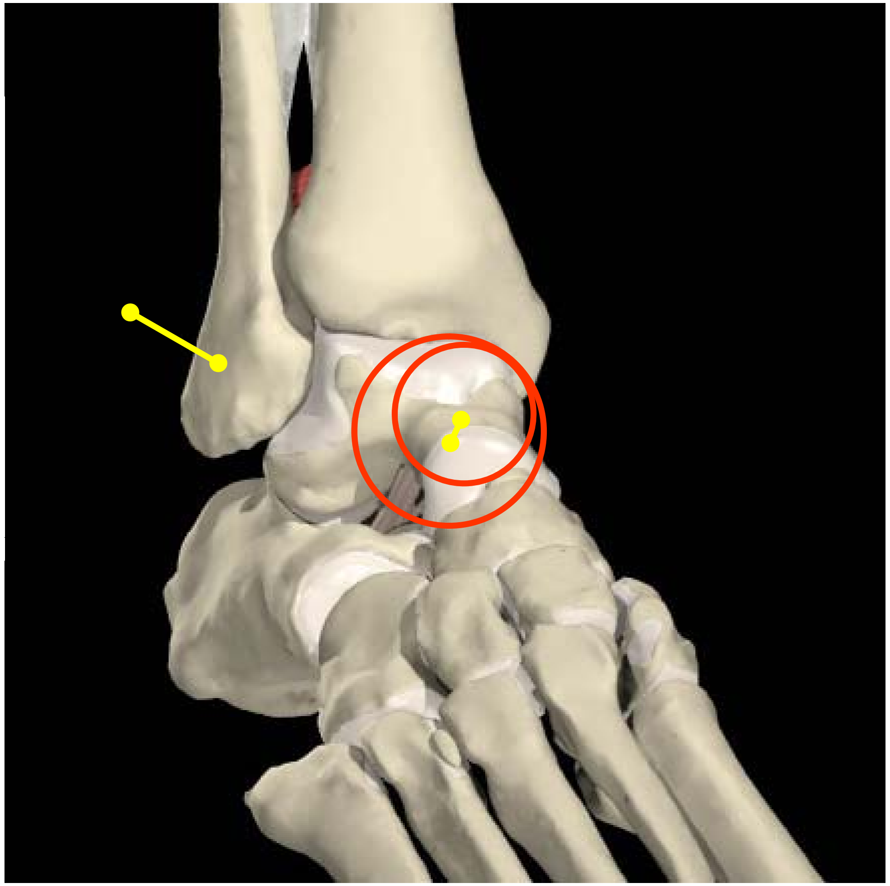


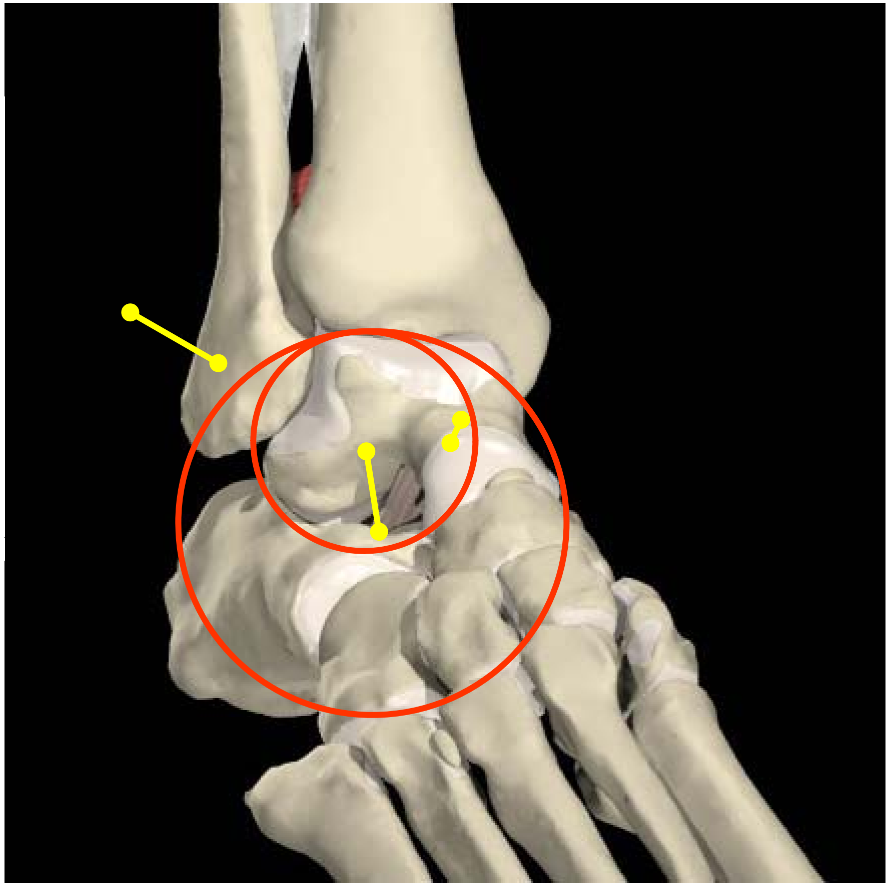
Spherical approximation of the lateral malleolus

APPLICATION TO THE ANKLE (MODEL M1)



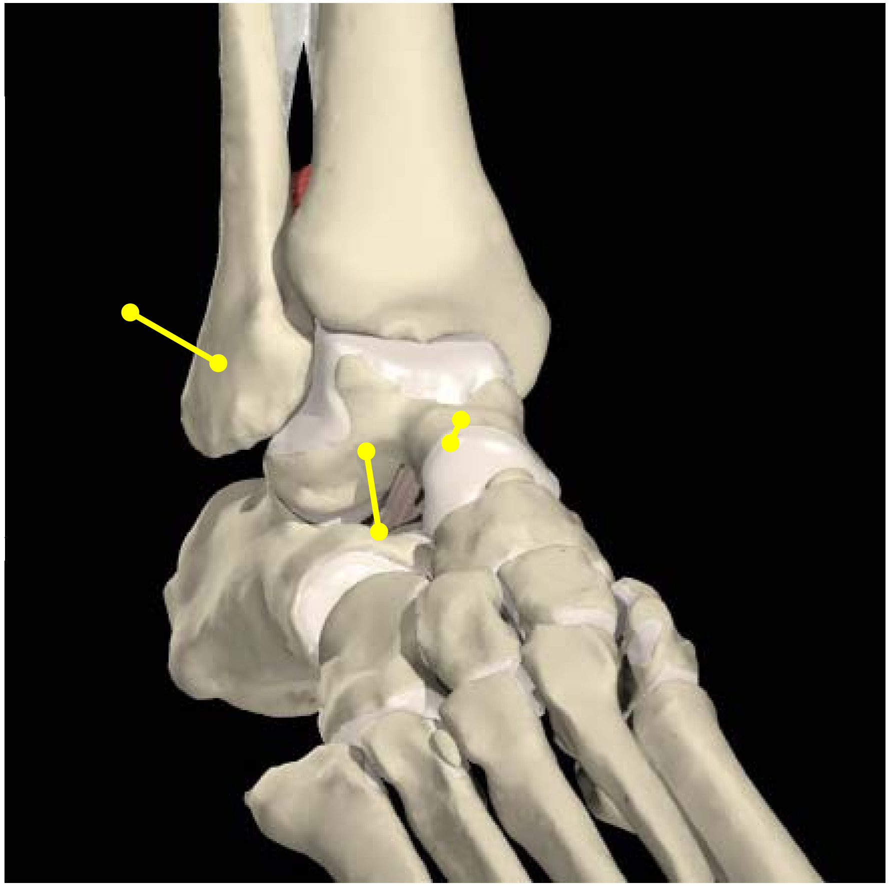
Spherical approximation of the medial malleolus

APPLICATION TO THE ANKLE (MODEL M1)



Spherical approximation of internal region of the inferior surface of the distal tibia articulates with the talus surface

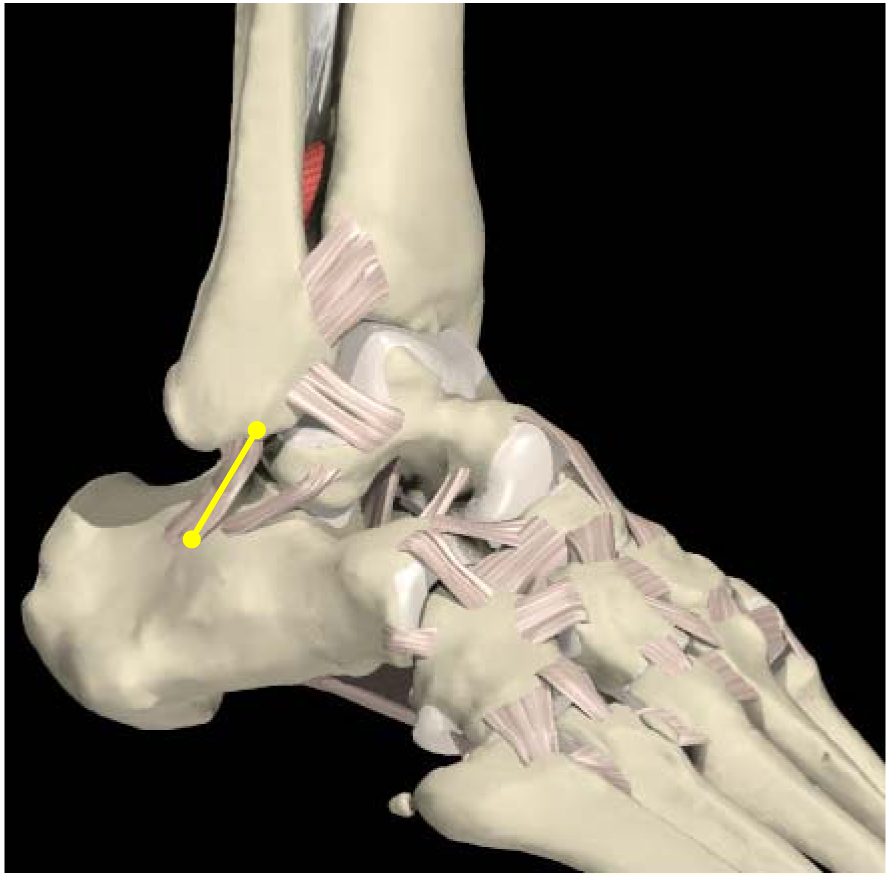
APPLICATION TO THE ANKLE (MODEL M1)

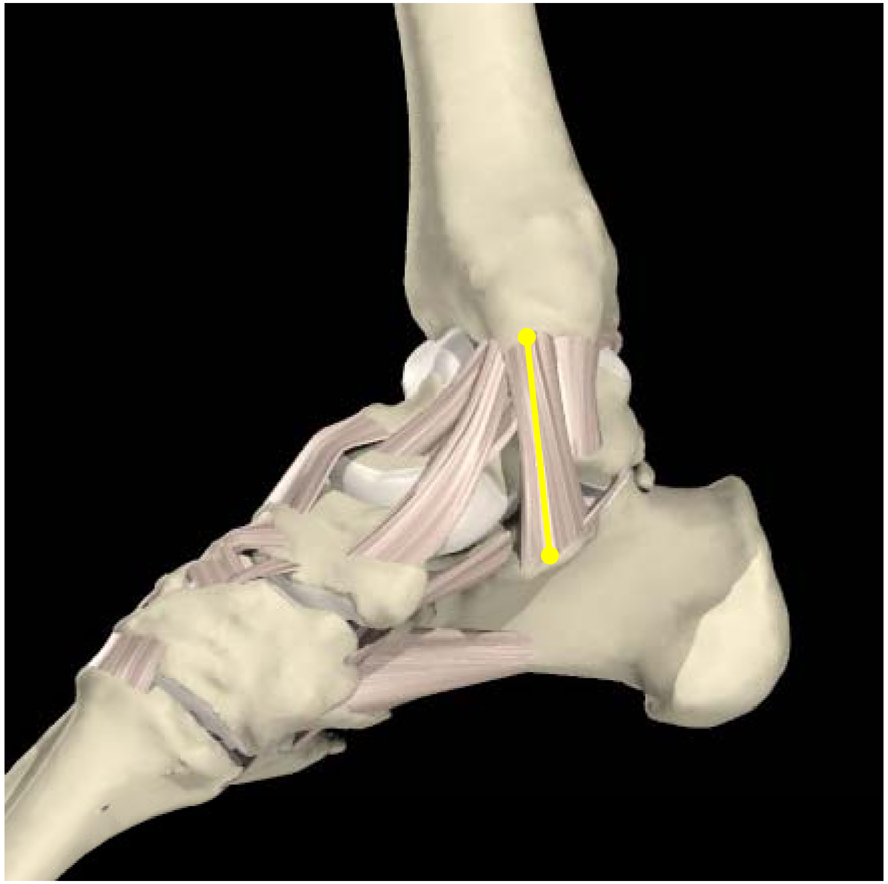


Distance between the centers of the spherical pairs is constant

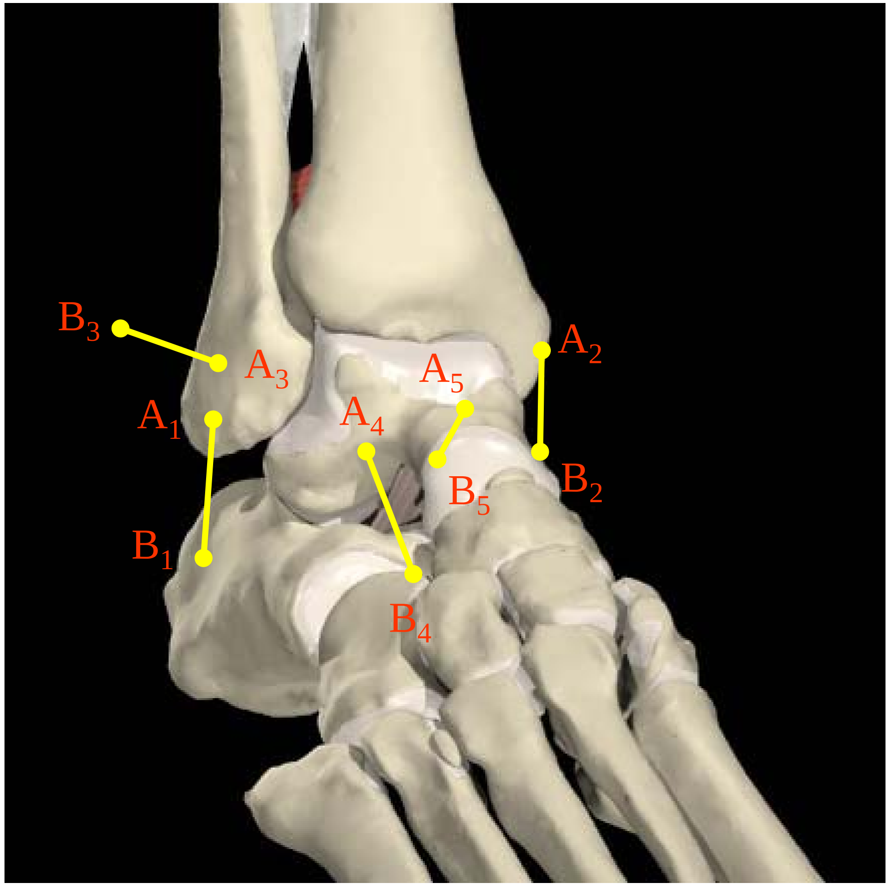
APPLICATION TO THE ANKLE (MODEL M1)

Isometric fibers of ligaments

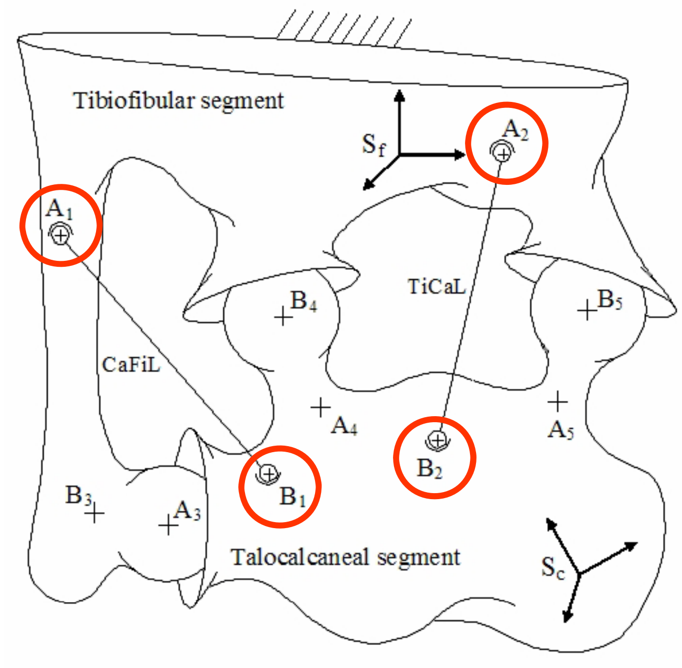

Calcaneofibular ligament


Tibiocalcaneal ligament

APPLICATION TO THE ANKLE (MODEL M1)

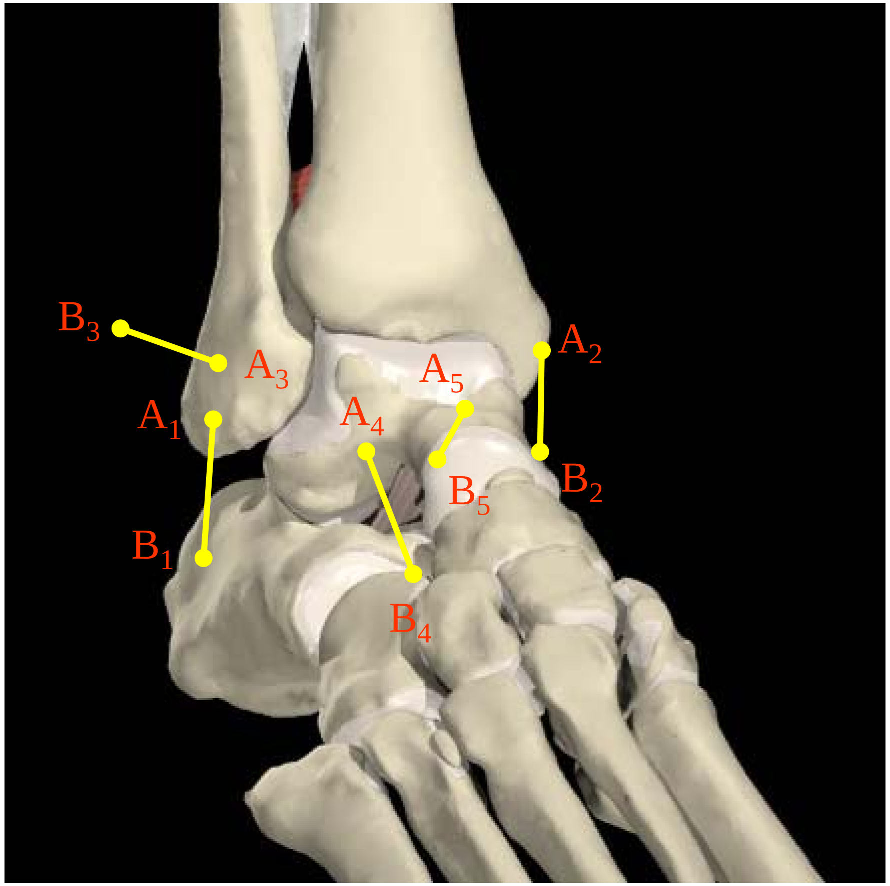


1-DoF parallel mechanism

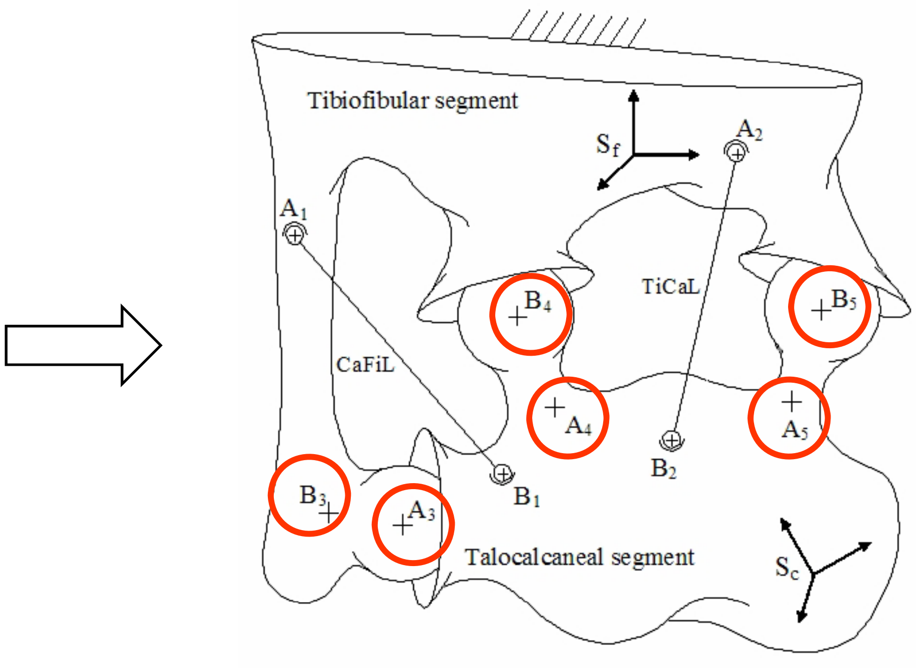


- insertion points of two isometric fibers of the two ligaments

APPLICATION TO THE ANKLE (MODEL M1)

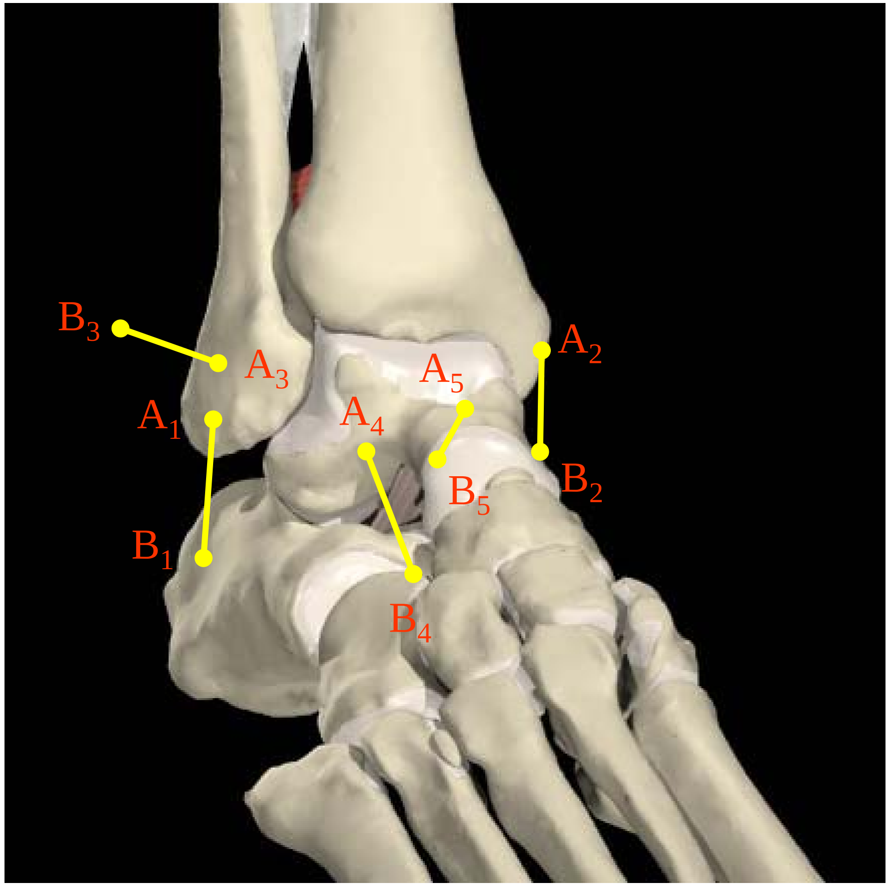


1-DoF parallel mechanism

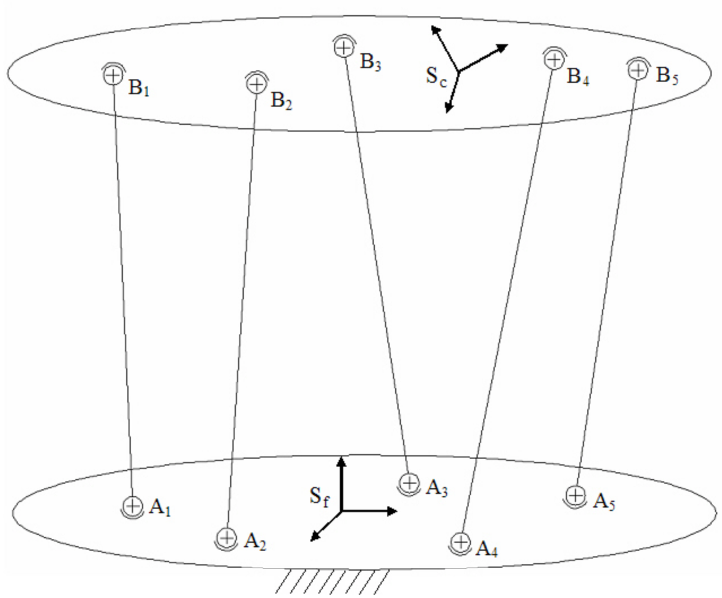


- centers of the spherical surfaces of the three sphere-to-sphere contact points

APPLICATION TO THE ANKLE (MODEL M1)



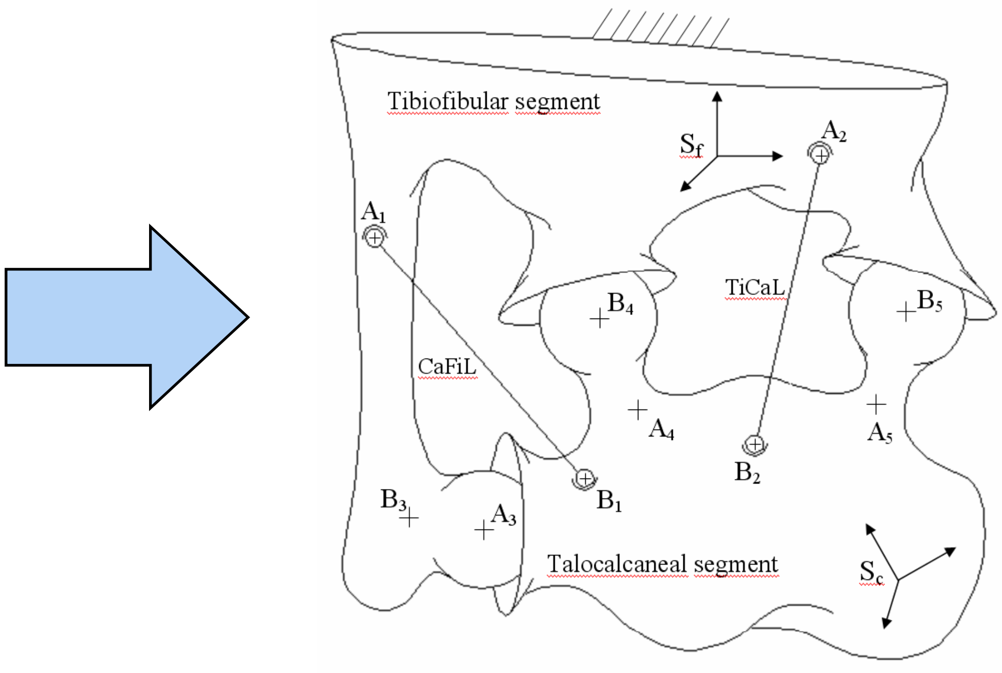
1-DoF parallel mechanism



5-5 fully parallel mechanism

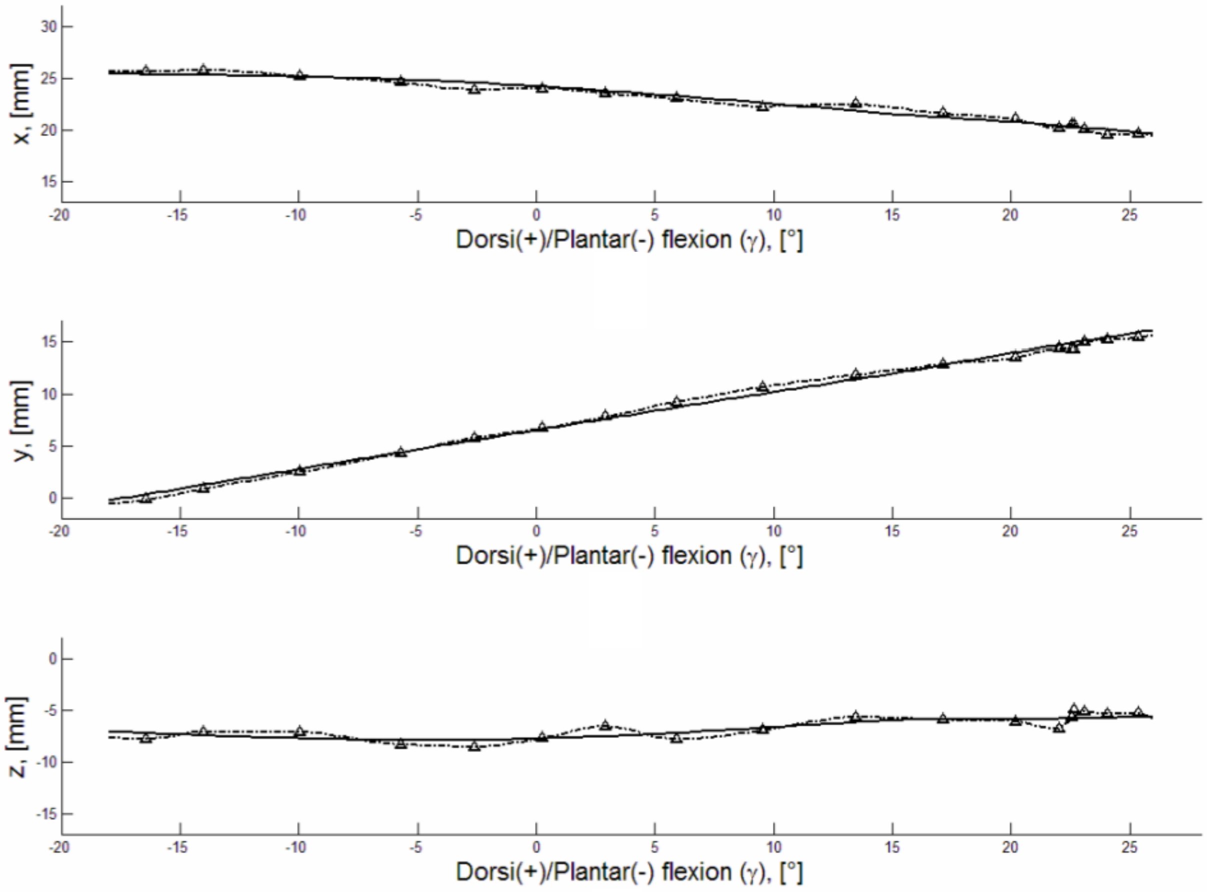
APPLICATION TO THE ANKLE (MODEL M1)

INSERIRE IMMAGINI RICCARDO



RESULTS

- **Relative position Tibia-Talus in passive flexion**



- · - · - Experimental data ——— Proposed model

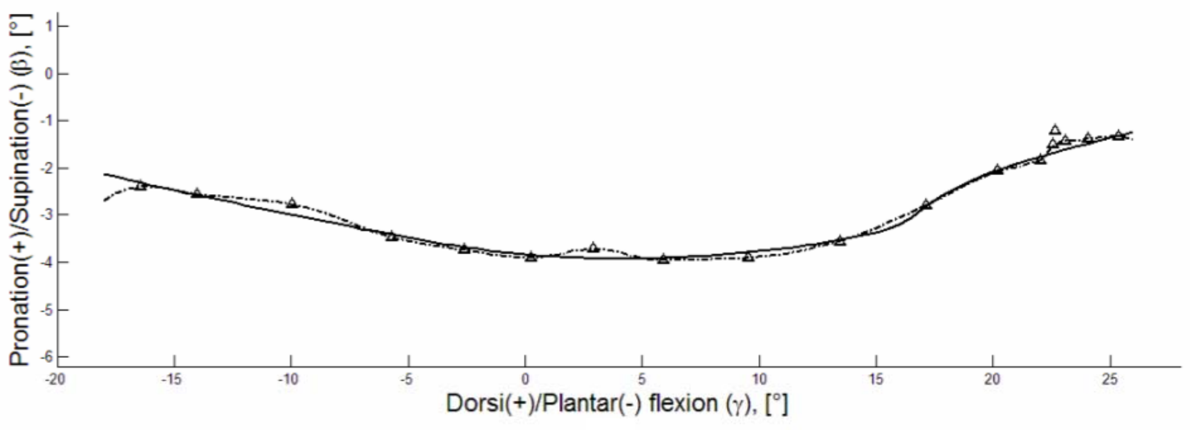
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

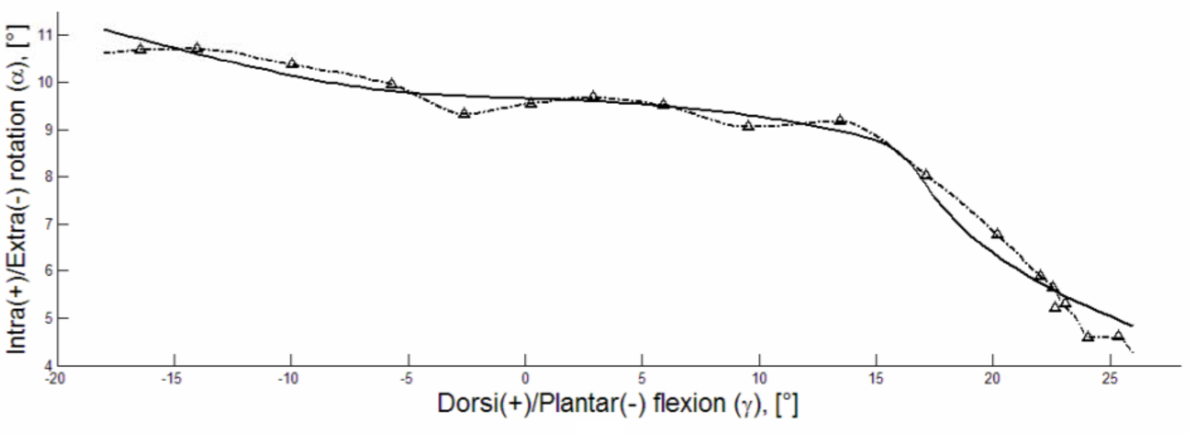
Group of Robotics and Articular Biomechanics

21ST CENTURY KINEMATICS

RESULTS

- **Relative orientation Tibia-Talus in passive flexion**





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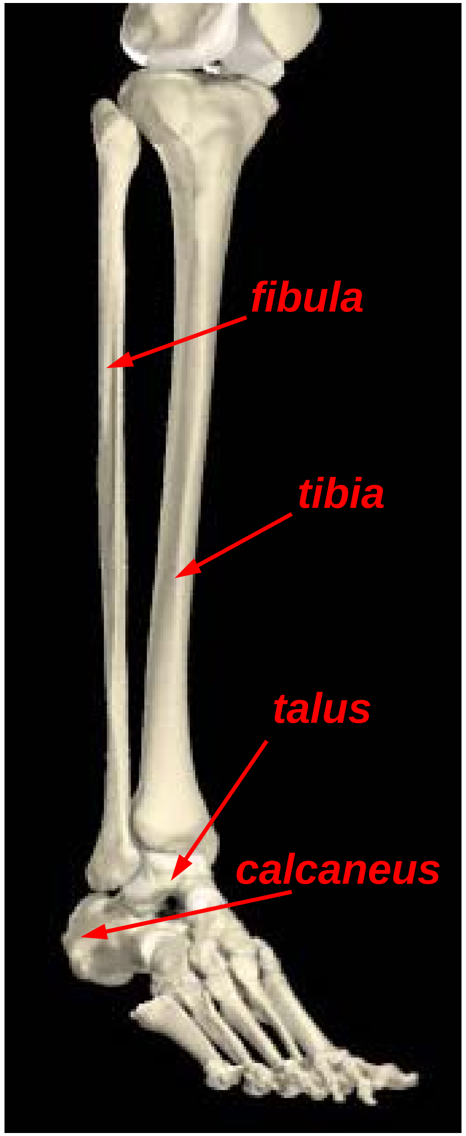
MODELLING THE TIBIA-FIBULA-ANKLE COMPLEX (TFC)

The TFC complex is composed by:

- tibia
- fibula
- talus
- calcaneus

Importance of modelling the TFC complex:

- first step for future developments of complete models of the entire human lower limb
- a better knowledge of the ankle complex
- investigation of the fibula role
- preplanning of surgical intervention and new prostheses design



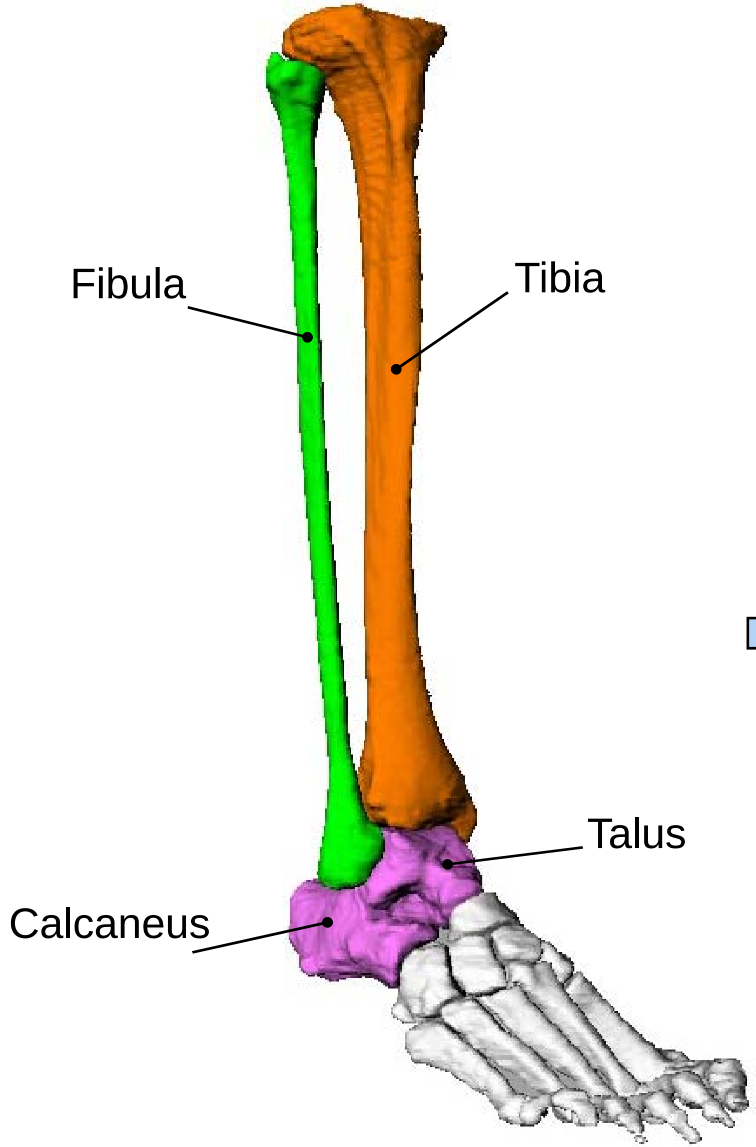
THE EQUIVALENT MECHANISM

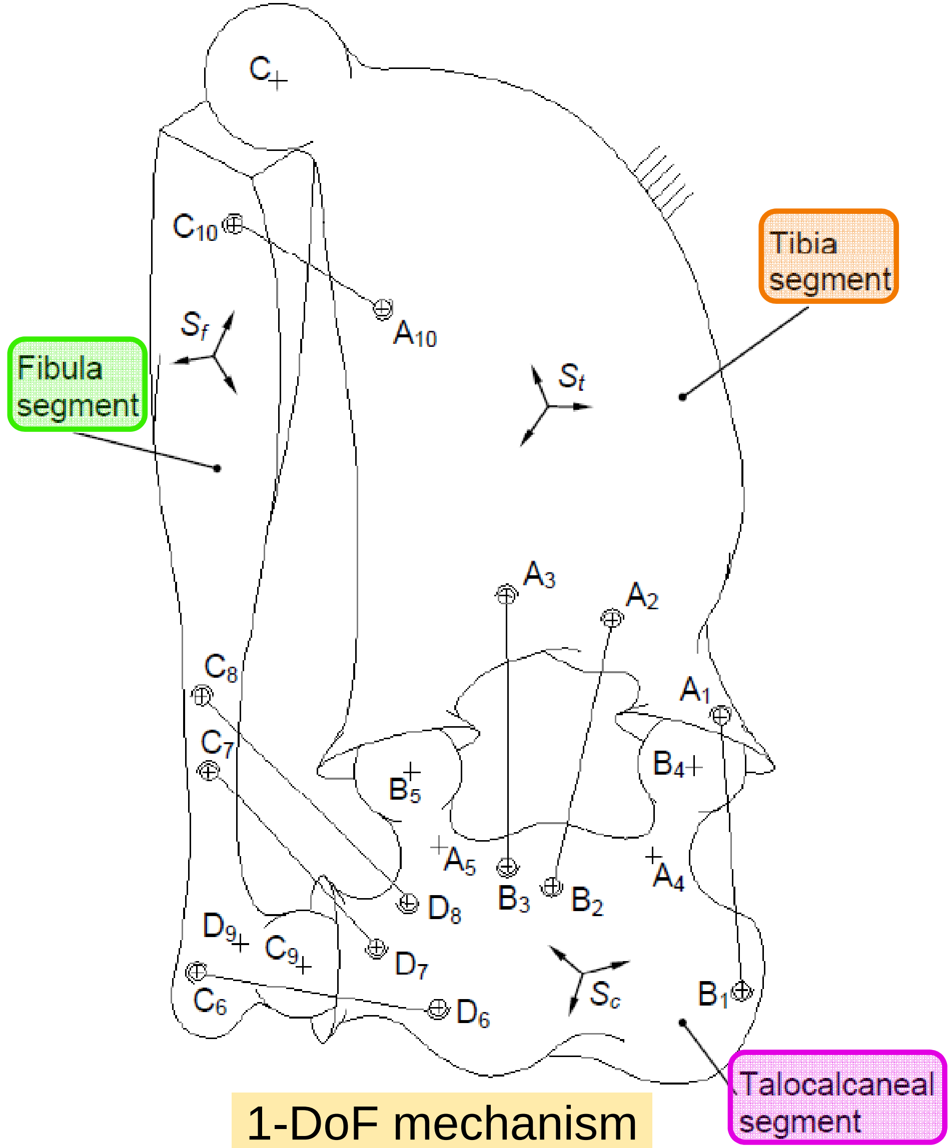
Assumptions

1. Close correspondence between articulation anatomical structures and mechanism elements

Anatomical structure		Mechanism element
• bones	↔	• rigid bodies
• ligament isometric fibres	↔	• rigid rods
• ligament-to-bone insertions	↔	• spherical pairs
• bone contact points	↔	• higher pairs which have 5-DoFs

THE PROPOSED EQUIVALENT MECHANISM





1-DoF mechanism

THE PROPOSED EQUIVALENT MECHANISM

The talocrural joint

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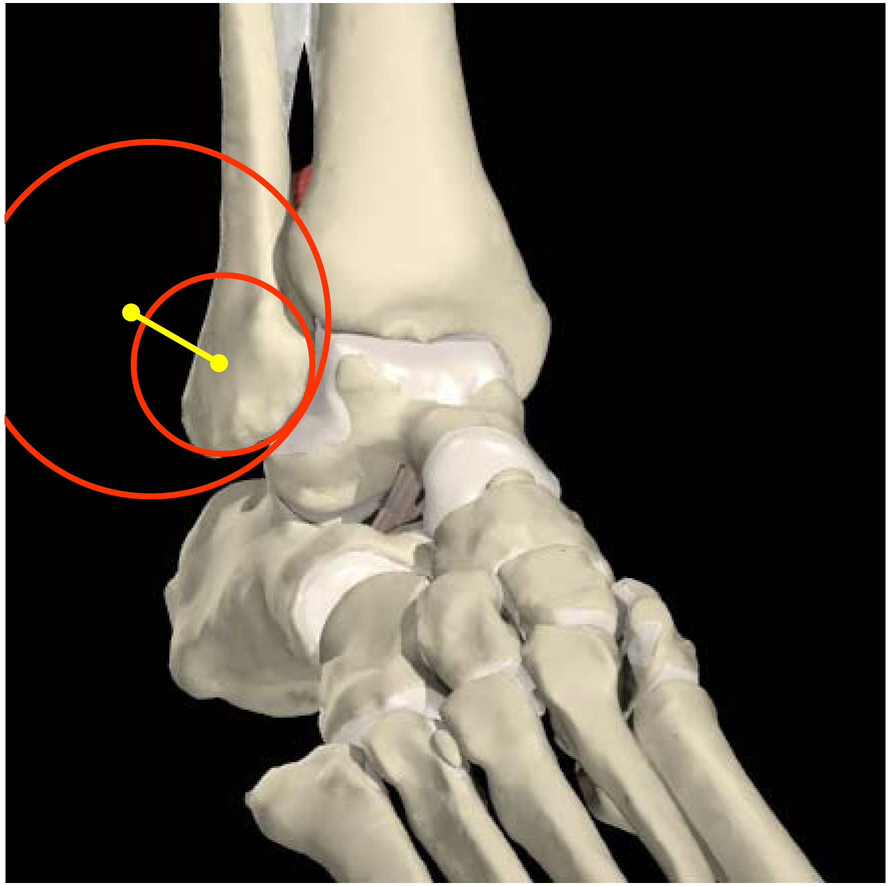
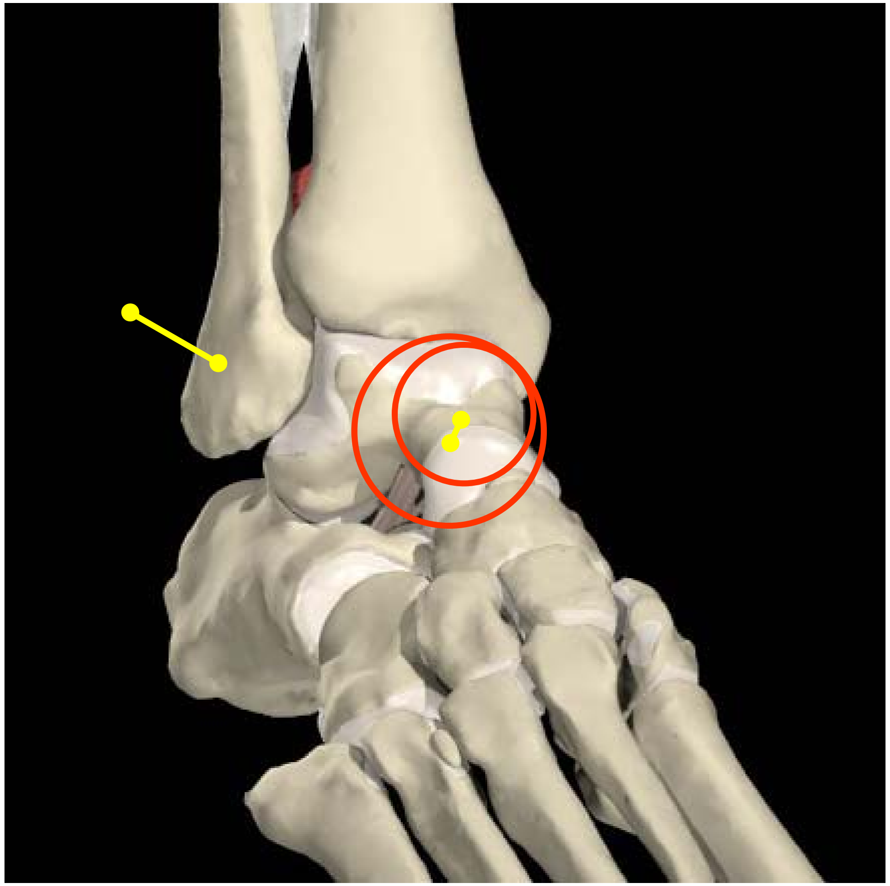
The talocrural joint



Spherical approximation of the lateral malleolus

THE PROPOSED EQUIVALENT MECHANISM

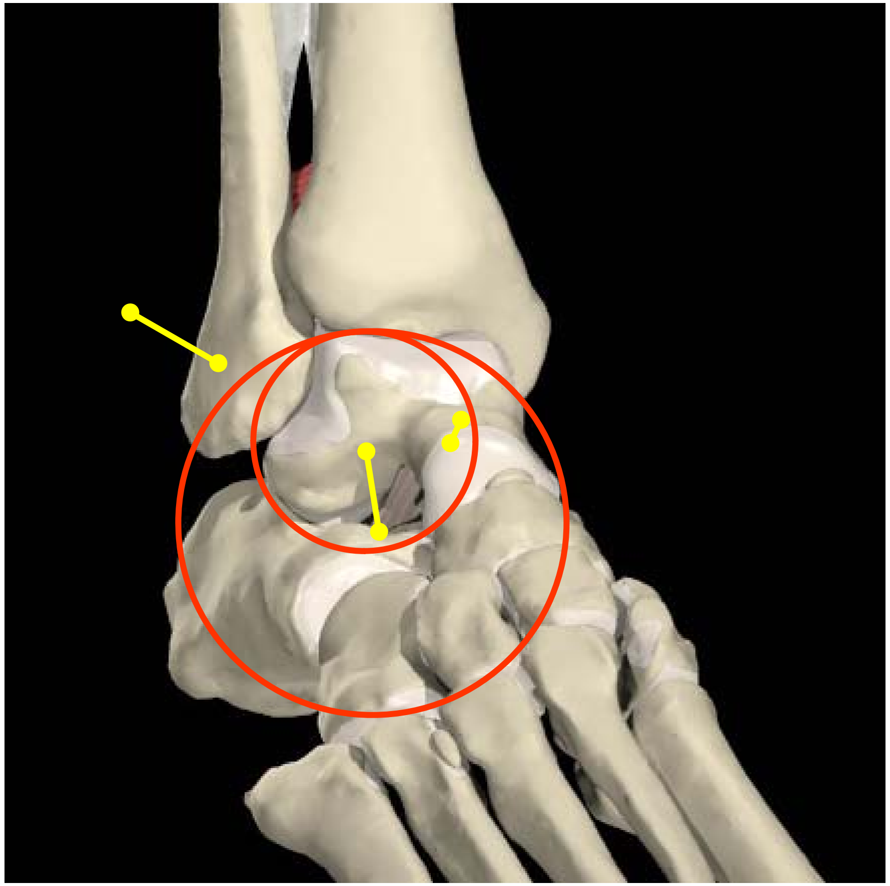
The talocrural joint



Spherical approximation of the medial malleolus

THE PROPOSED EQUIVALENT MECHANISM

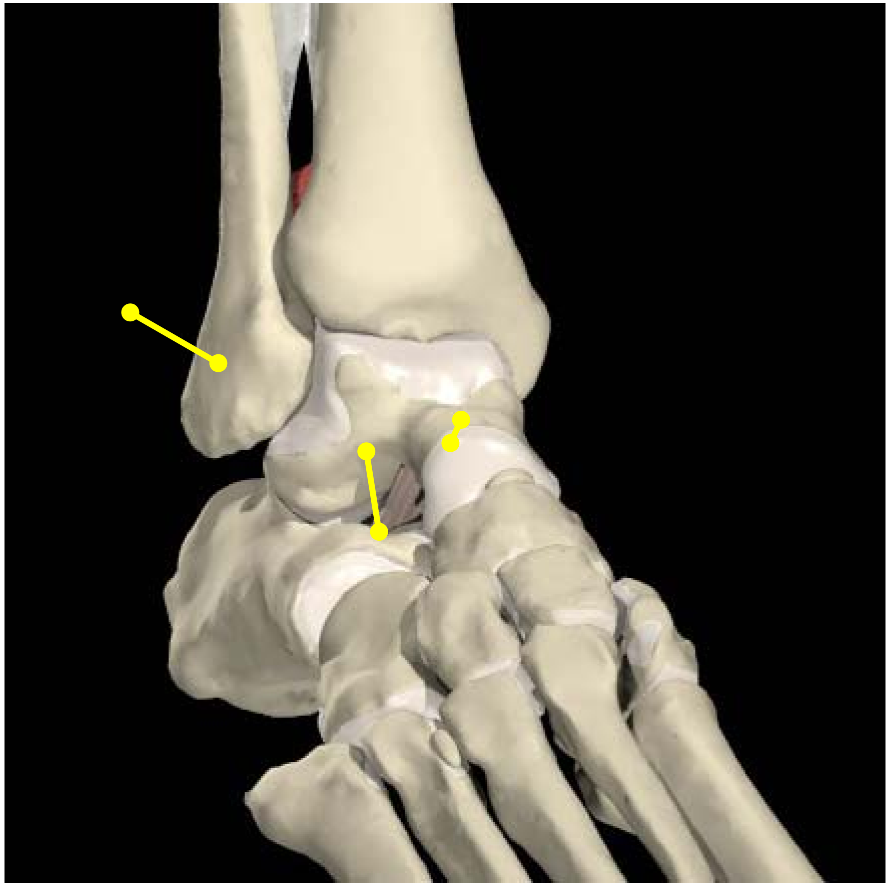
The talocrural joint



Spherical approximation of internal region of the inferior surface of the distal tibia articulate with the talus surface

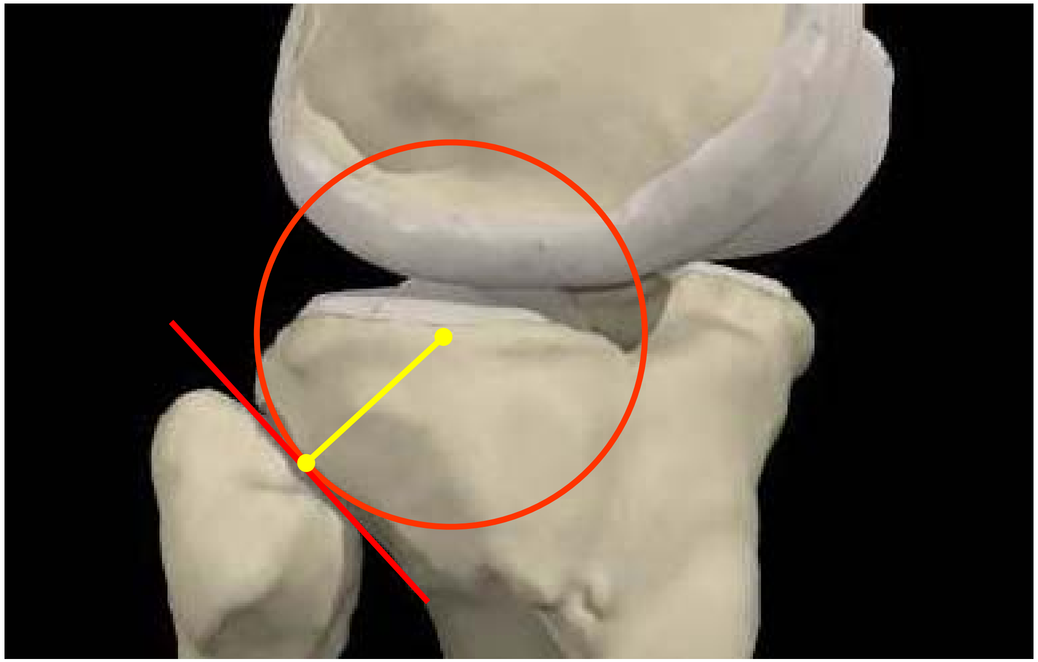
THE PROPOSED EQUIVALENT MECHANISM

The talocrural joint



THE PROPOSED EQUIVALENT MECHANISM

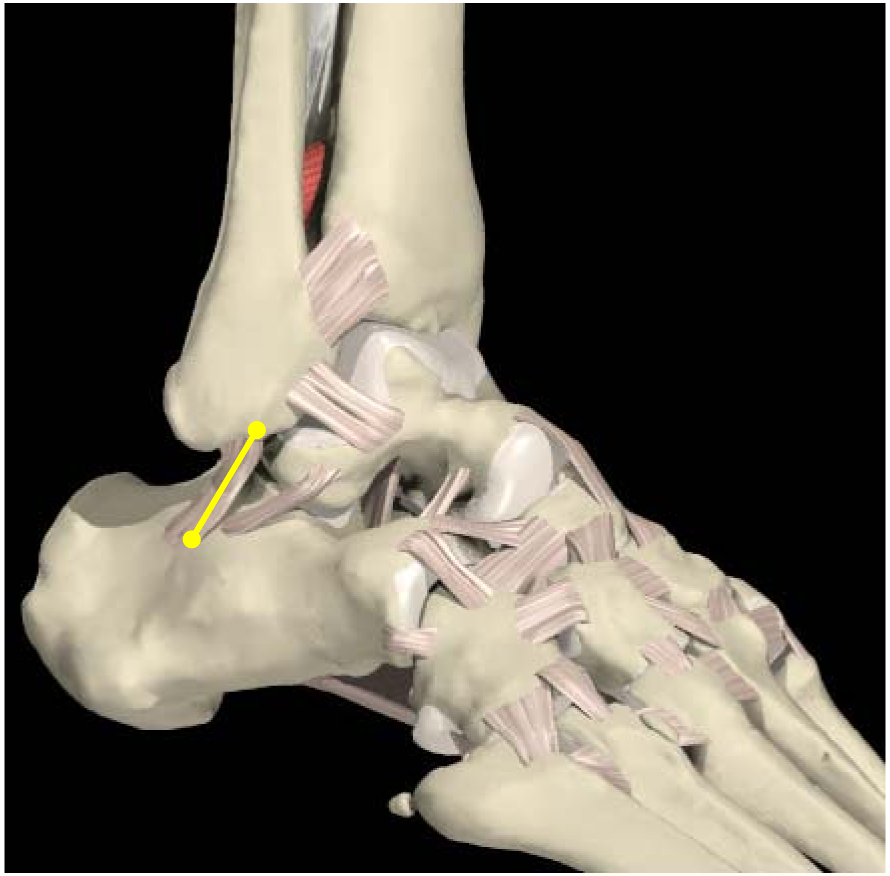
The proximal end of tibia and fibula



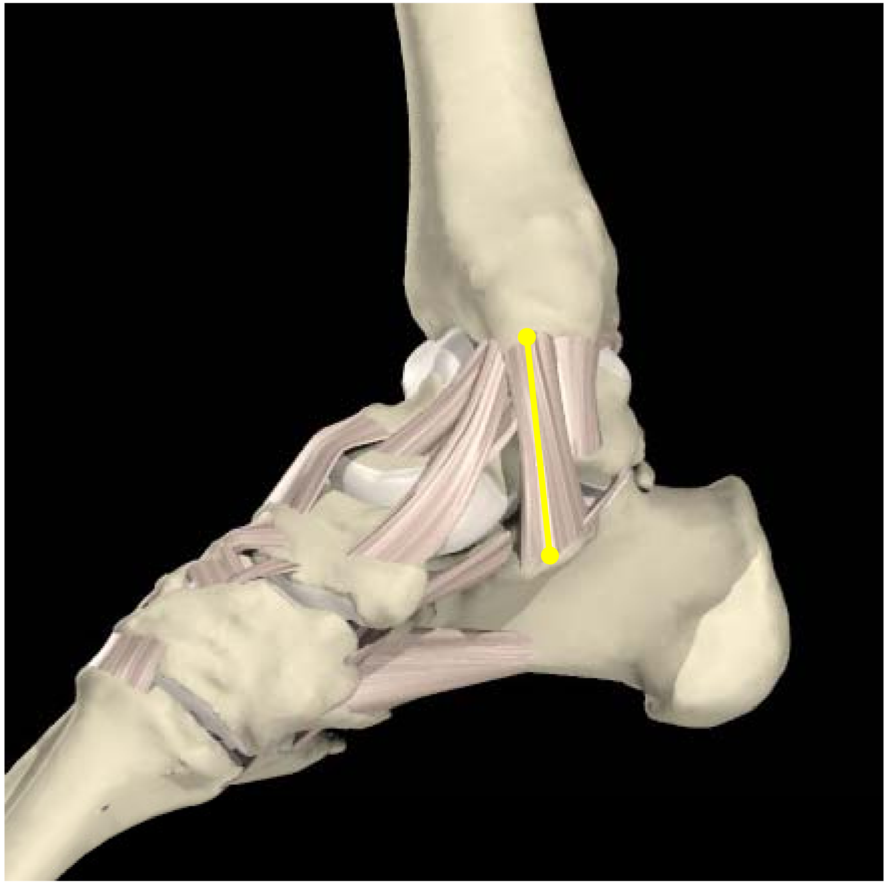
Plane-to-sphere approximation of the contact between tibia and fibula surfaces at the proximal end

THE PROPOSED EQUIVALENT MECHANISM

Isometric fibres of ligaments



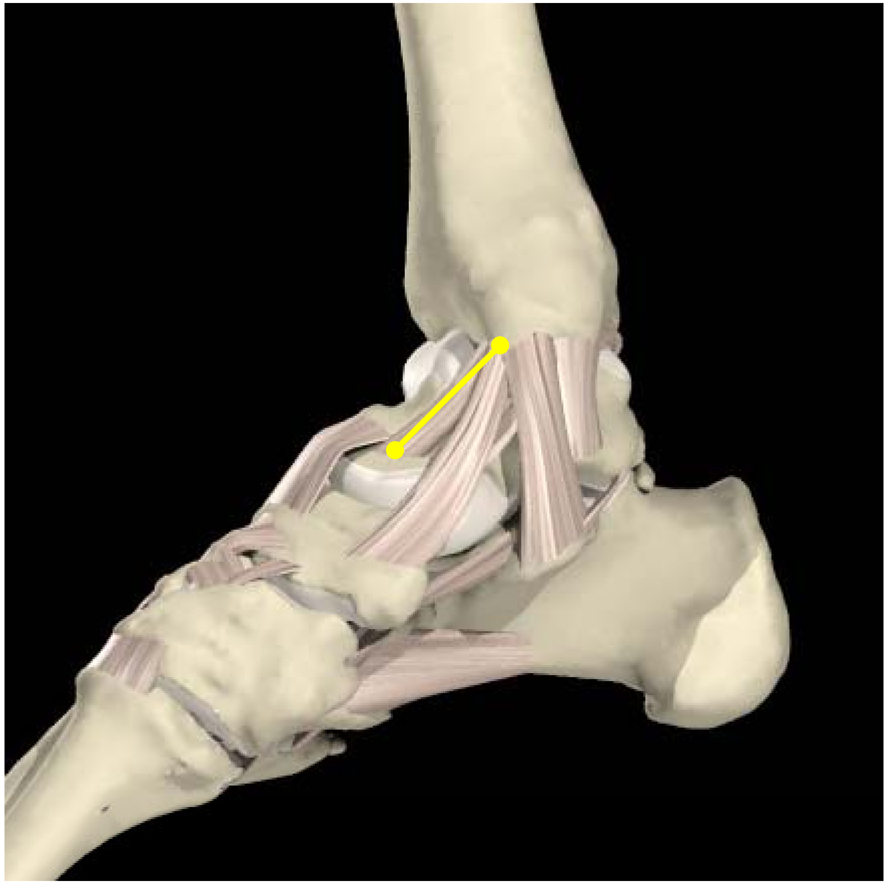
Calcaneofibular ligament



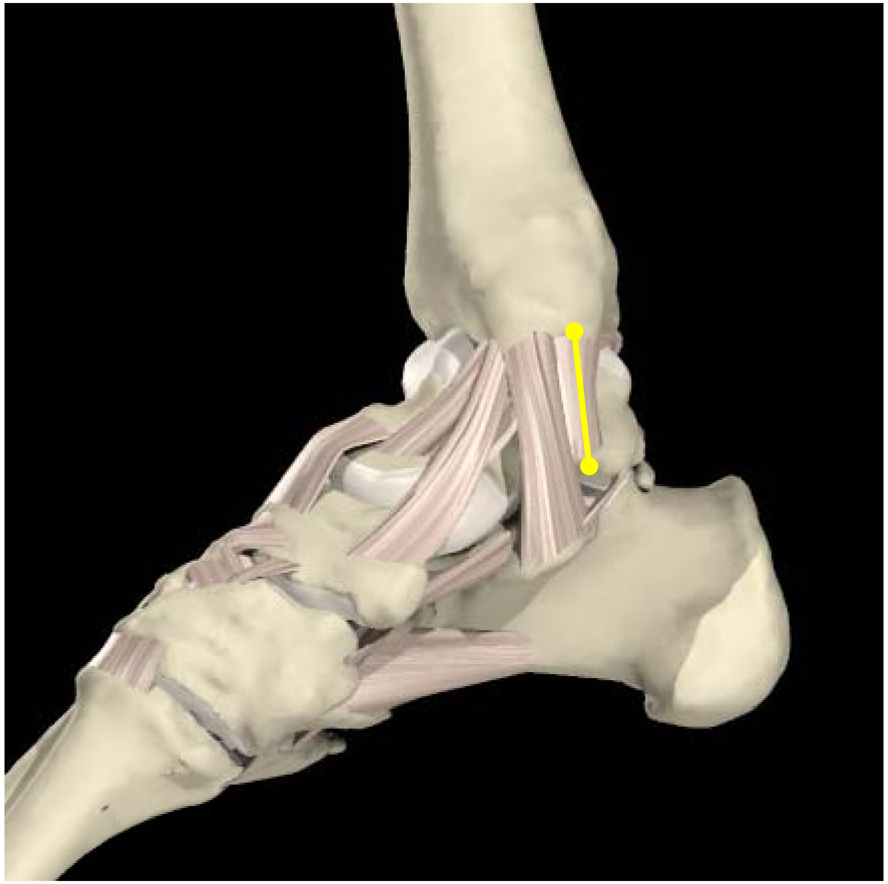
Tibiocalcaneal ligament

THE PROPOSED EQUIVALENT MECHANISM

Isometric fibres of ligaments



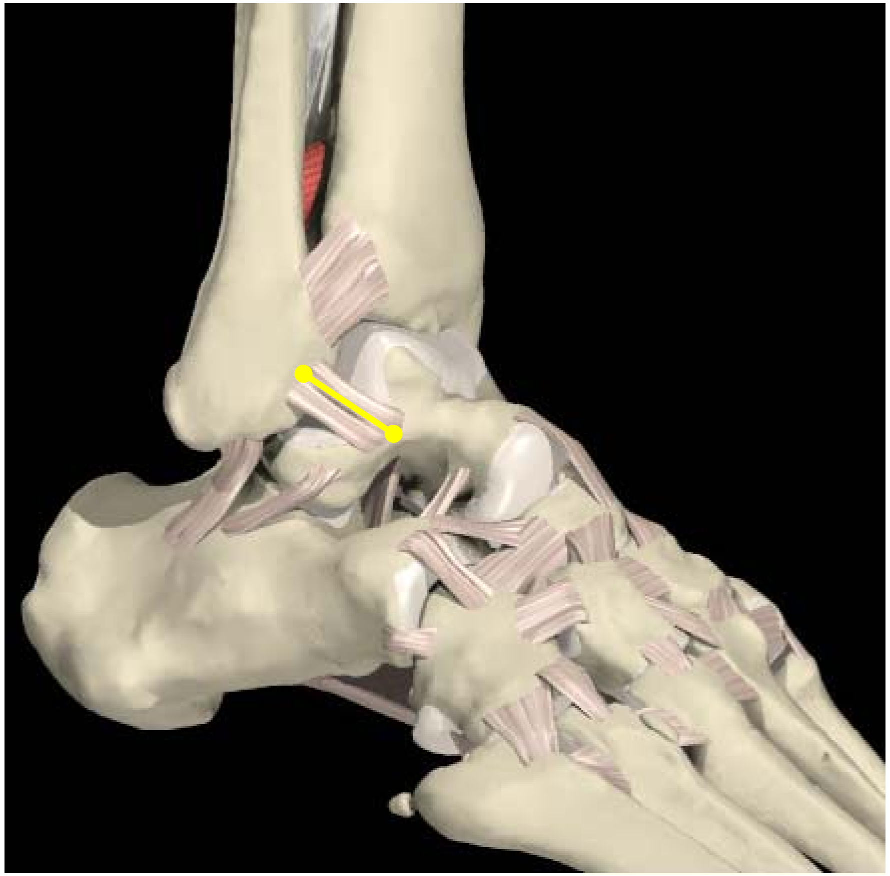
Ant-Tibiotalar ligament



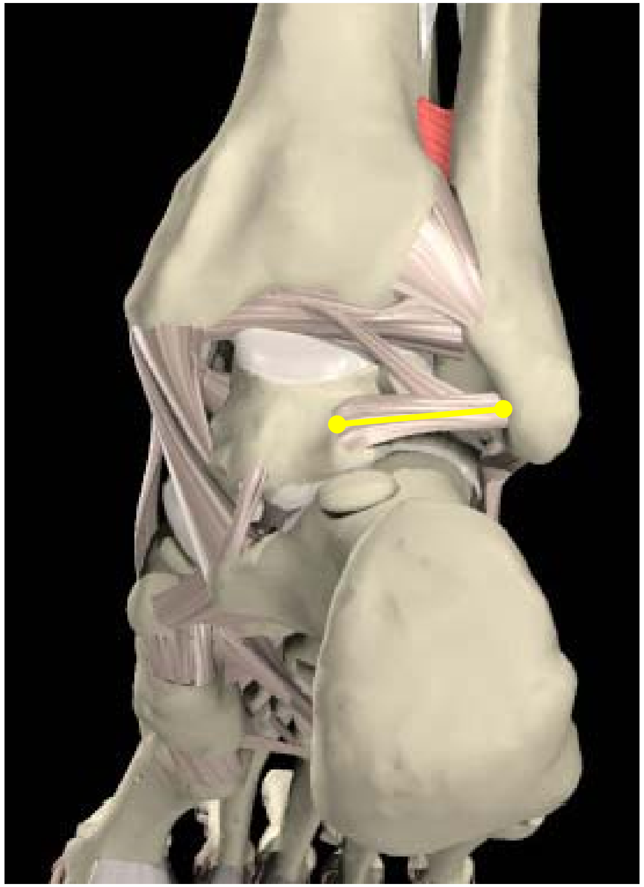
Post-Tibiotalar ligament

THE PROPOSED EQUIVALENT MECHANISM

Isometric fibres of ligaments



Ant-Talofibular ligament



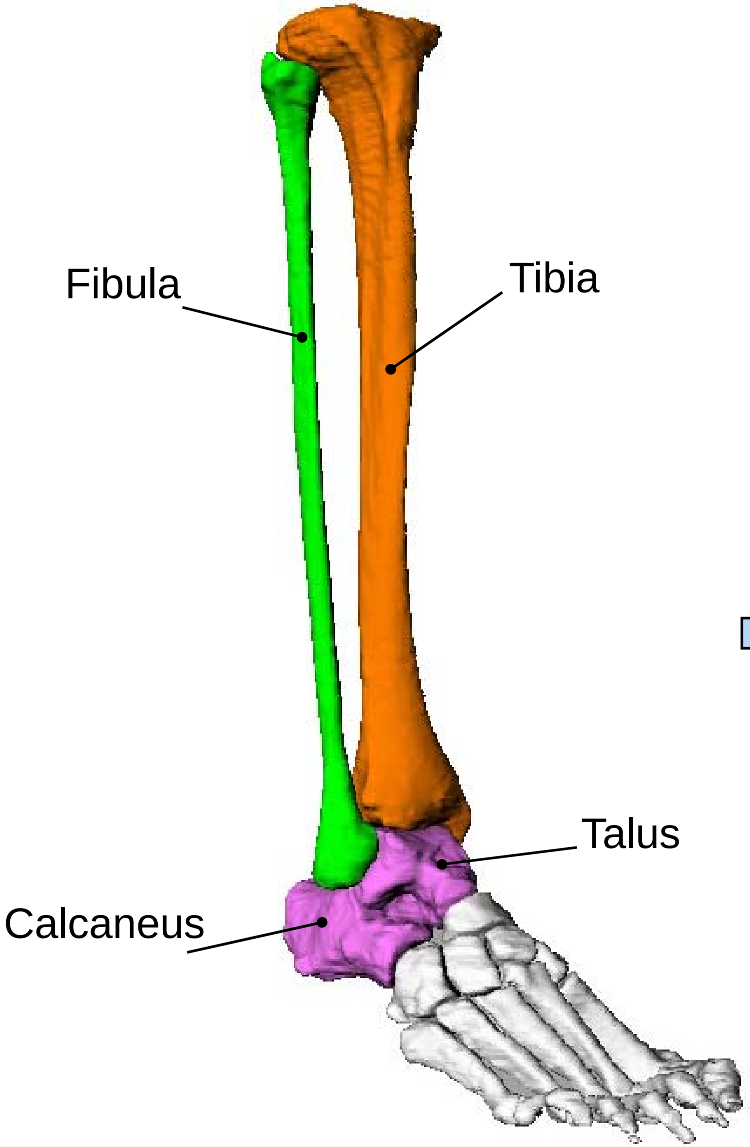
Post-Talofibular ligament

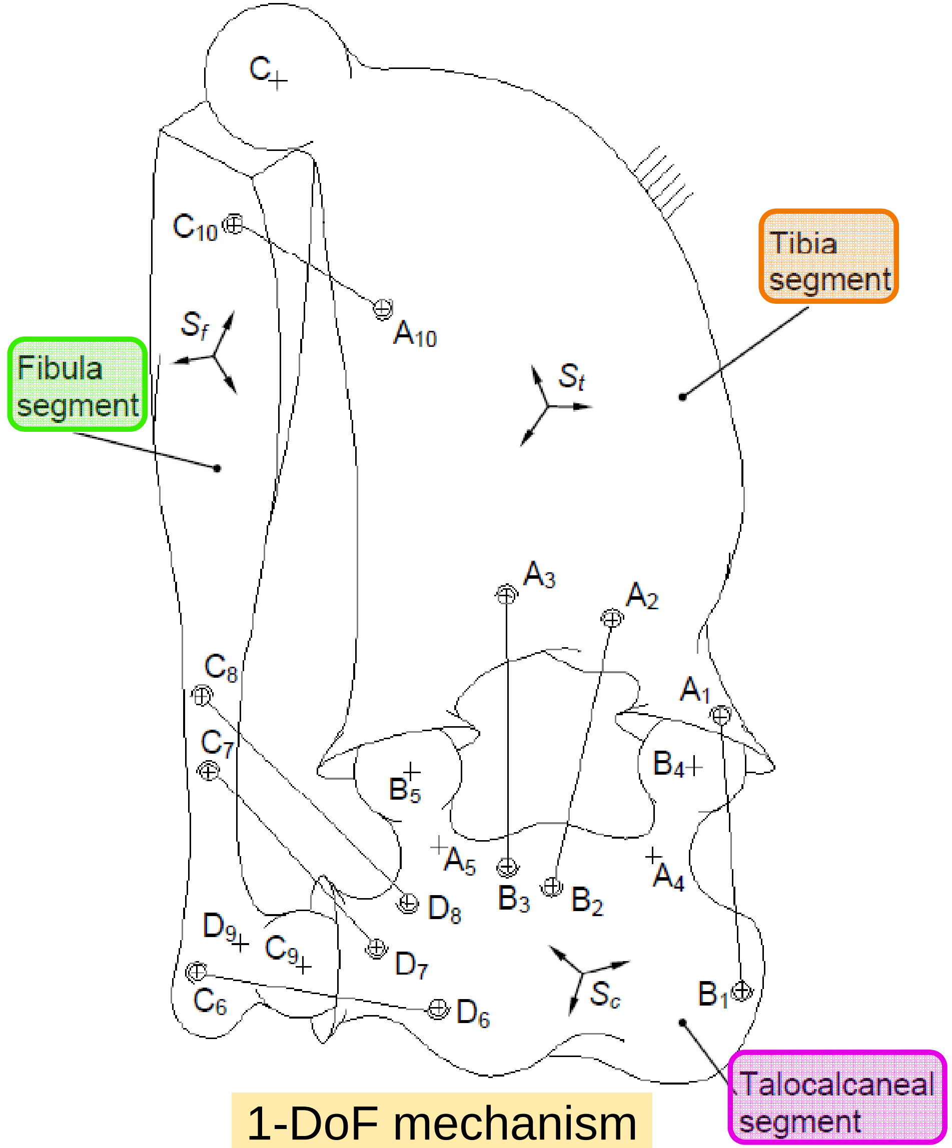
THE PROPOSED EQUIVALENT MECHANISM

Isometric fibres of ligaments

Interosseus membrane between
tibia and fibula

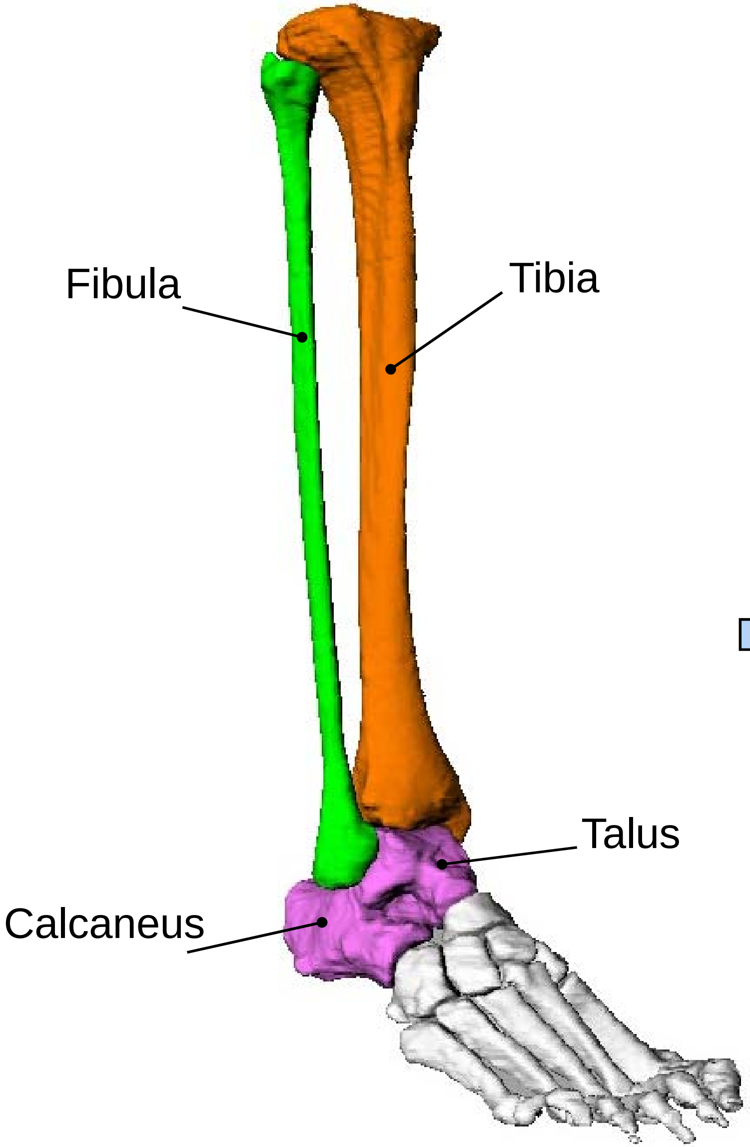
THE PROPOSED EQUIVALENT MECHANISM

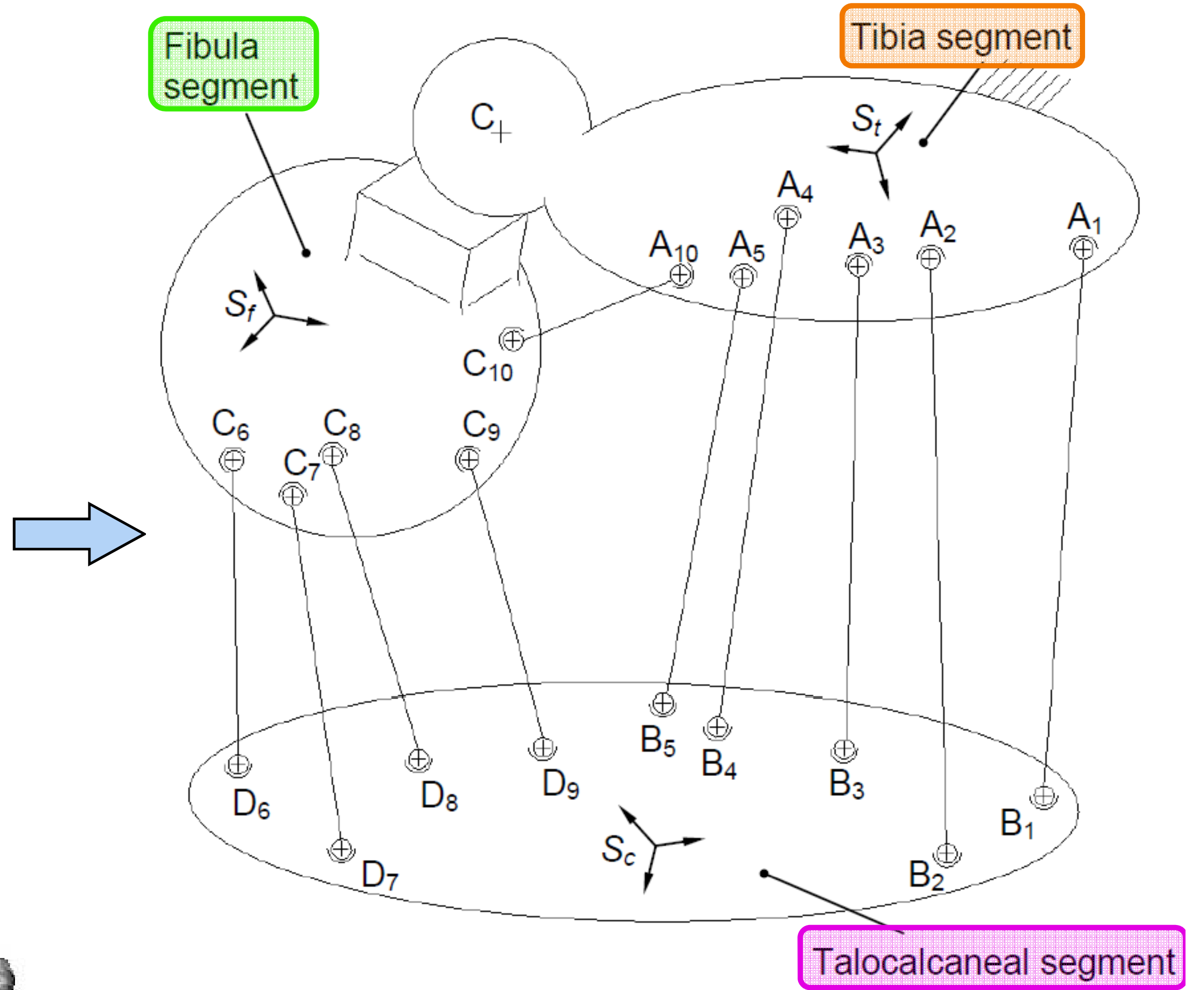




1-DoF mechanism

THE PROPOSED EQUIVALENT MECHANISM

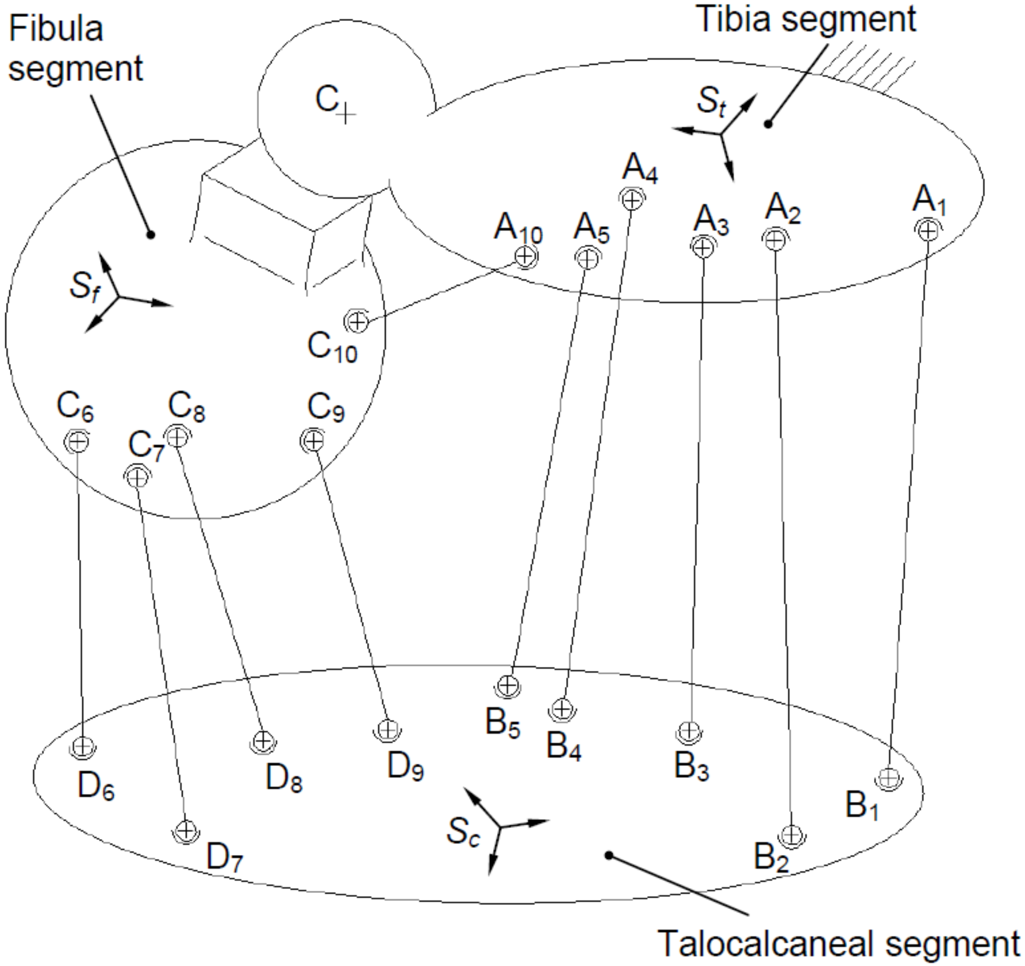




1-DoF mechanism

KINEMATIC MODEL

The 1-DoF equivalent mechanism



- **Closure equations:**

1. Rigid rods:

$$|| A_i - \mathbf{R}_{tc} B_i - p_{tc} ||^2 = L_i^2 \qquad (i = 1,\dots,5)$$
$$|| D_j - \mathbf{R}_{cf} C_j - p_{cf} ||^2 = L_j^2 \qquad (j = 6,\dots,9)$$
$$|| A_{10} - \mathbf{R}_{tf} C_{10} - p_{tf} ||^2 = L_{10}^2$$

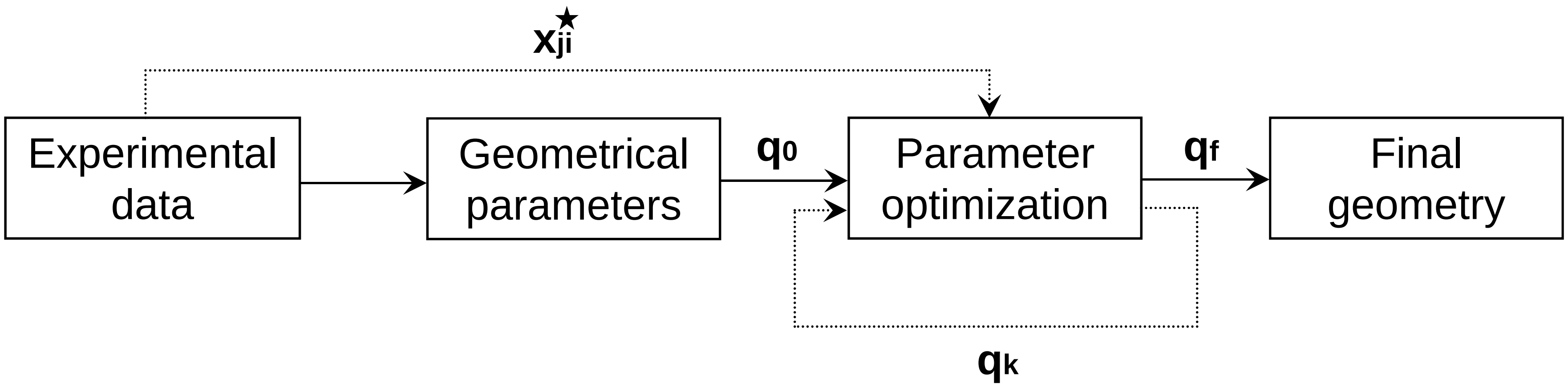
2. Plane-to-sphere contact higher pair:

$${}^tn\,(C - {}^tH) = 0$$
with
$${}^tn = \mathbf{R}_{tf}\, n$$
$${}^tH = \mathbf{R}_{tf}\; H + p_{tf}$$

- **78 geometrical parameters**

SYNTHESIS OF THE EQUIVALENT MECHANISM

Synthesis procedure:



Parameter optimization:

$$f = \sum_{j=1}^{11} \sum_{i=1}^{n} \frac{\left(x_{ji} - x^{\star}_{ji}\right)^2}{x^2_{jd}} \quad \text{if closure succeed}$$

$$f = X \quad \text{otherwise}$$

- bounded optimization
- discontinuous objective function
- genetic algorithms + quasi-Newton

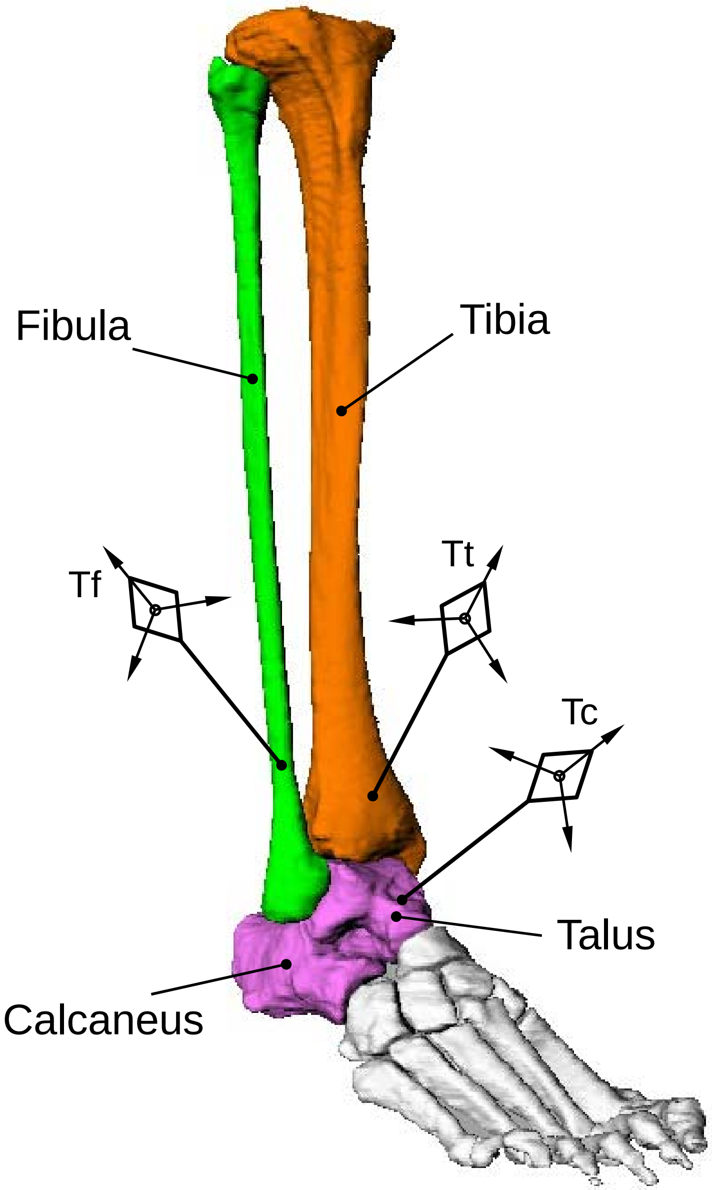
CASE STUDY

1. **Geometry of the bones**:
   - axial computer tomography (TAC)

2. **Geometry of the ligaments**:
   - points digitized with surgical navigation system
   - literature

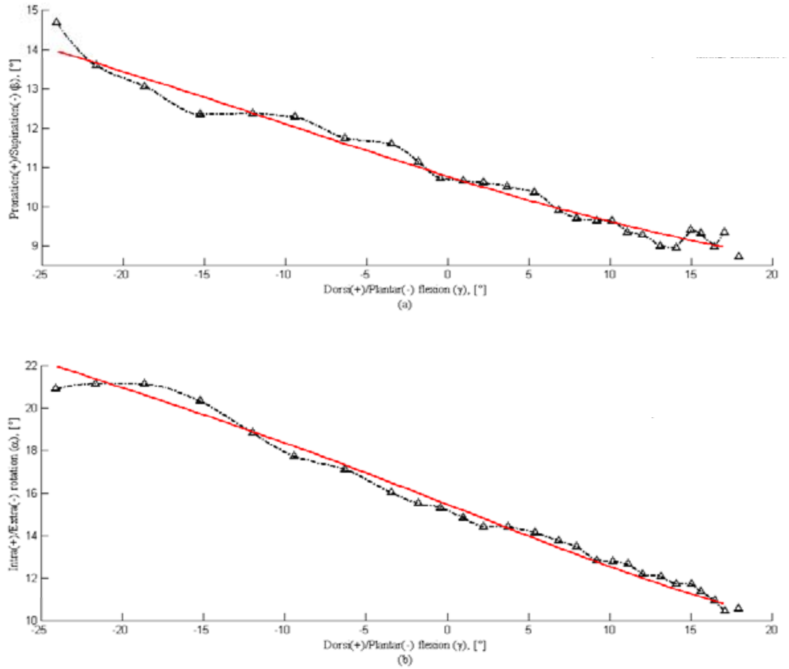
3. **Relative position** of the talocalcaneal segment and of the fibula segment with respect to the tibia segment:
   - recording with surgical navigation system

4. **Parameter optimization:**
   Objective Function includes only the results of the talocalcaneus and tibia kinematic analysis; **the point C_9** (the centre of the sphere that approximates the contact surface of the fibula in the lateral malleolus) is constrained to move inside an anatomical volume

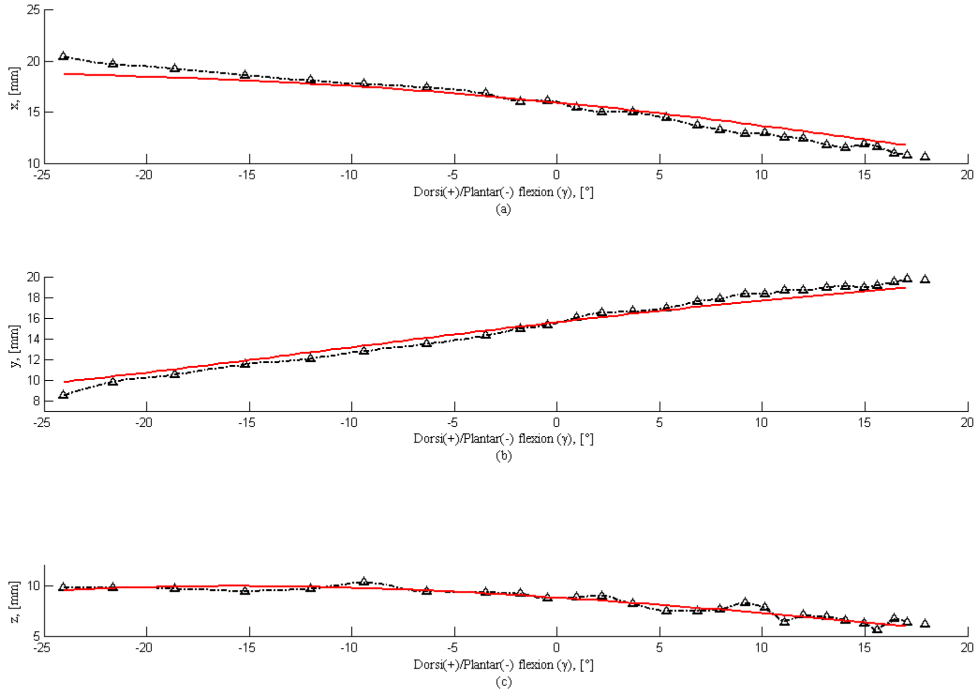


CASE STUDY

Orentation



Position



■ Experimental data

■ Equivalent mechanism

CONCLUSIONS

A sequential procedure for the modelling of human diarthrodial joints was presented.

The procedure relies upon some basic assumptions (rules) and provides, in three sequential steps, three different joint models (M1, M2 and M3 respectively) with increasing complexity that incorporate both more and more complex anatomical structures and different joint loading conditions.

It makes it possible:

- to preserve the restraining function of the joints’ anatomical structures
- to highlight the role that each individual joint structure plays in the joint

The results of the M1 model for the knee, the ankle and the lower leg are reported, and M2 model for the knee, showing the efficiency of the proposed procedure.

I thank you for your kind attention