Movement analysis with stereophotogrammetry: anatomical landmarks calibration

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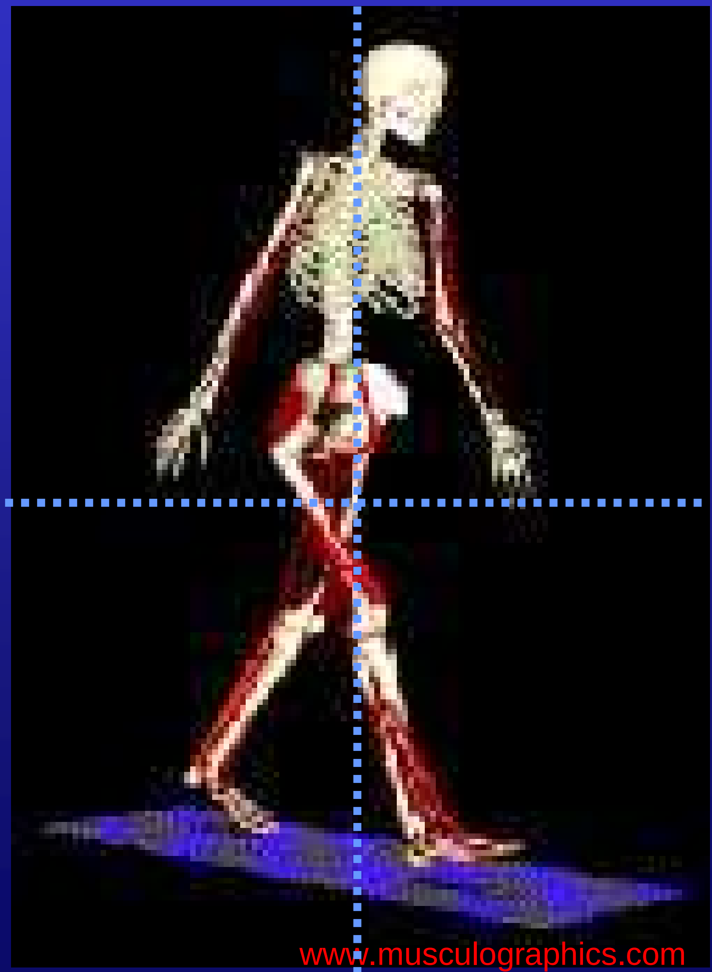
the geometry of the Euclidean 3-dimensional space

as a function of time

looking at the space around us
and describe it with numbers

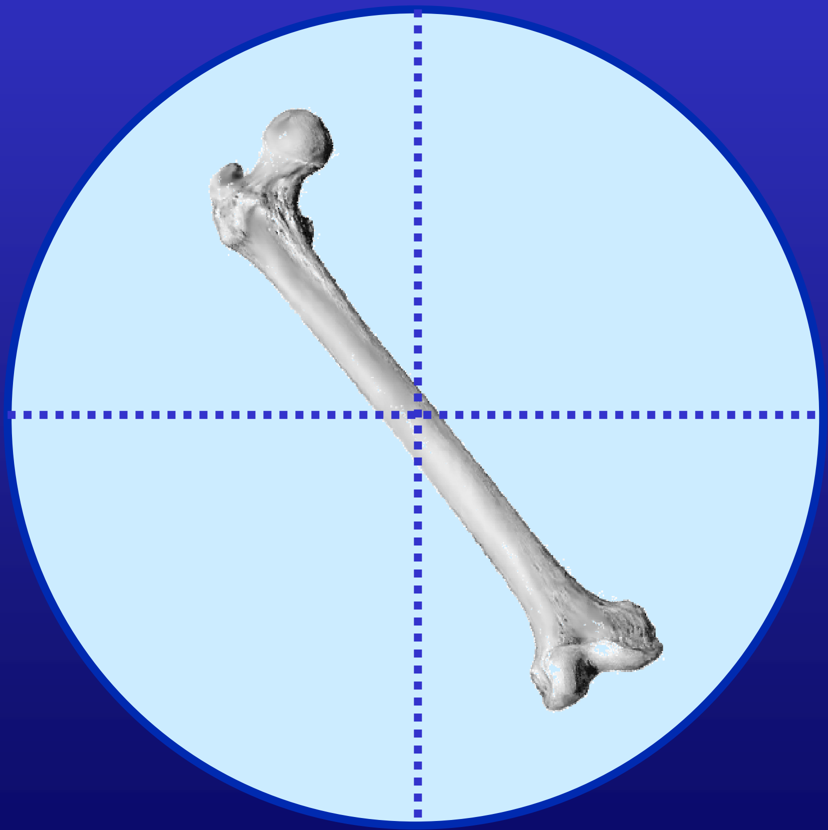
to be able to reproduce it exactly as it was
when observed, even if it may have changed meanwhile

this is the complicated reality we want to frame into a numerical structure



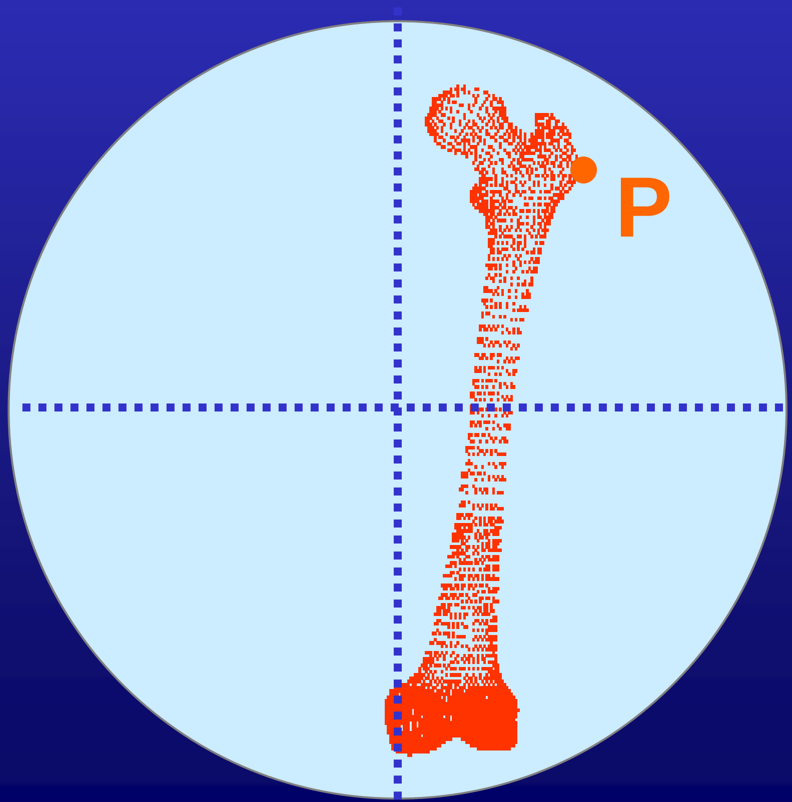
$$t = \bar{t}$$

let's focus on a single bone



a body may be thought of as made of particles

we represent a particle using the dimensionless geometric entity (model)
point



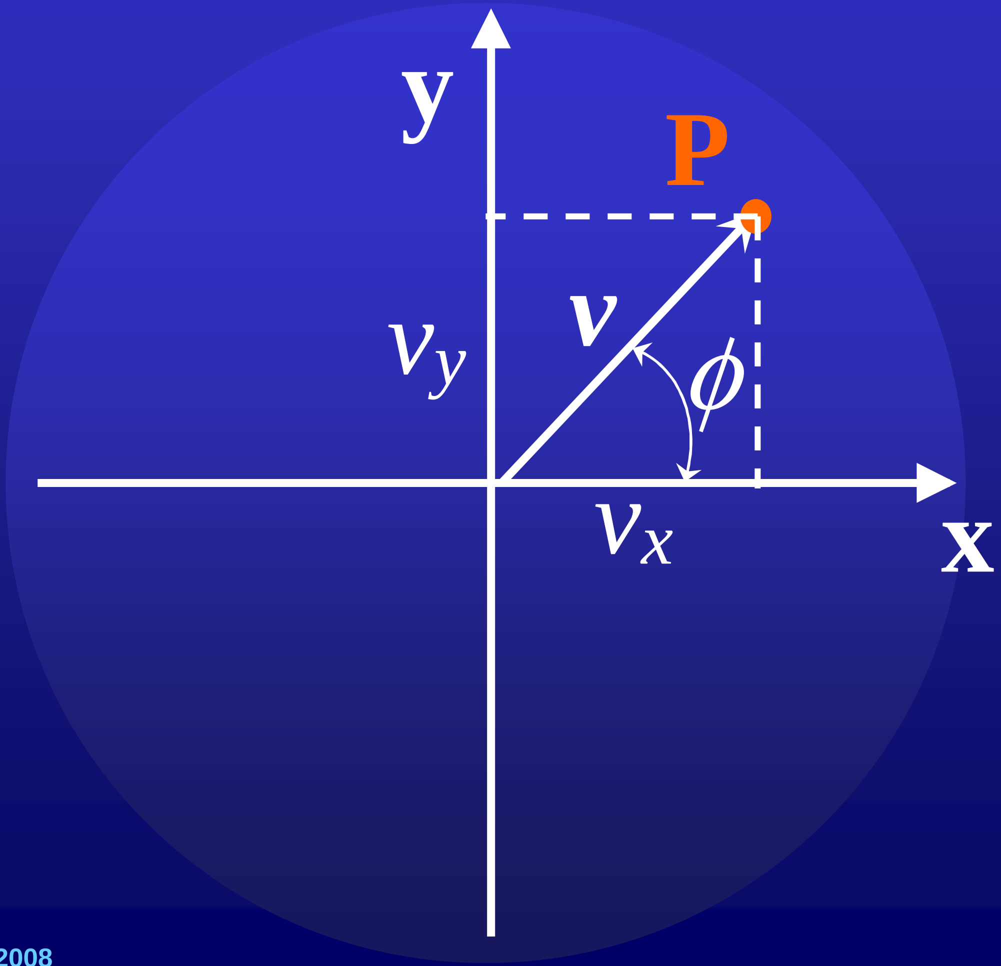
point which lies on a known plane

described with numbers

$$\boldsymbol{v} = \begin{vmatrix} v_x & v_y \end{vmatrix}$$

$$\begin{cases} v_x = v\cos\phi \\ v_y = v\sin\phi \end{cases}$$

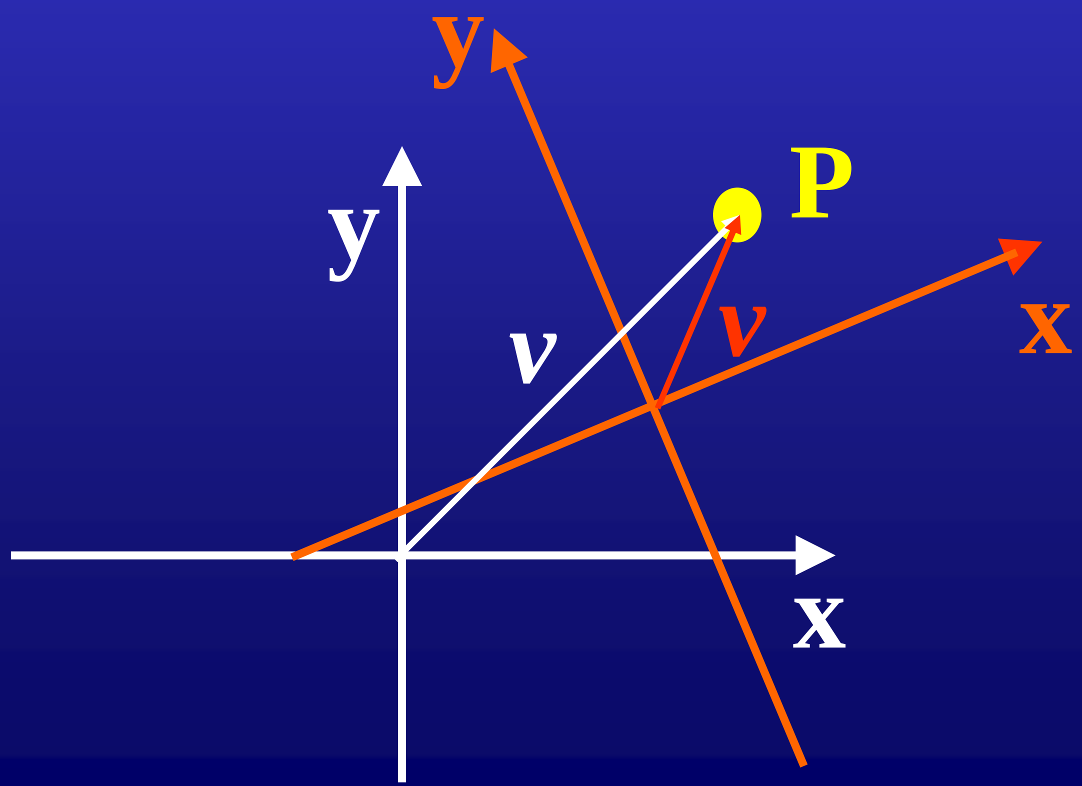
$$v = \sqrt{\left(v_x^{\ 2} + v_y^{\ 2}\right)}$$



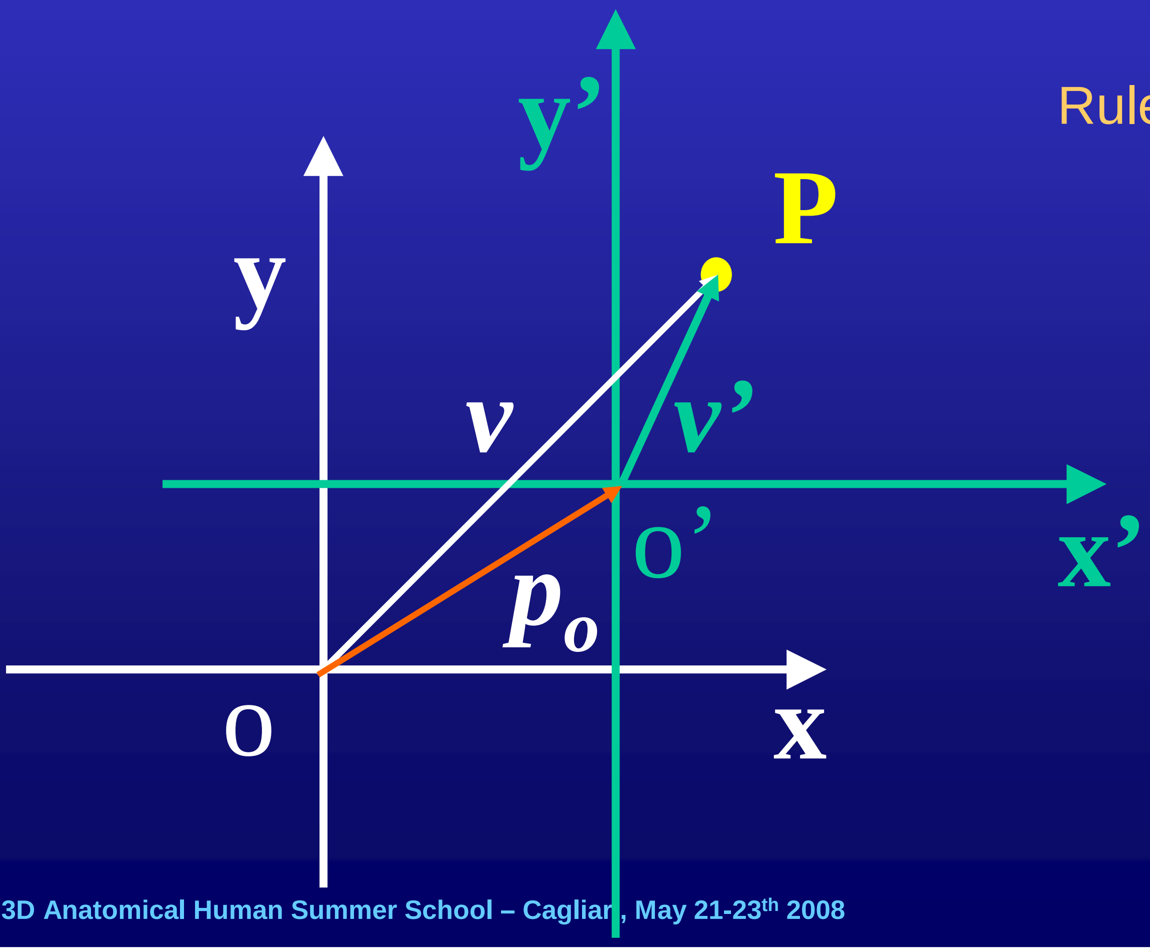
what happens if we change perspective?

The numerical description of the position of P changes

Can we set a relationship between ***v*** and ***v***?



change of perspective
by simply sliding (translating) the cross-wire

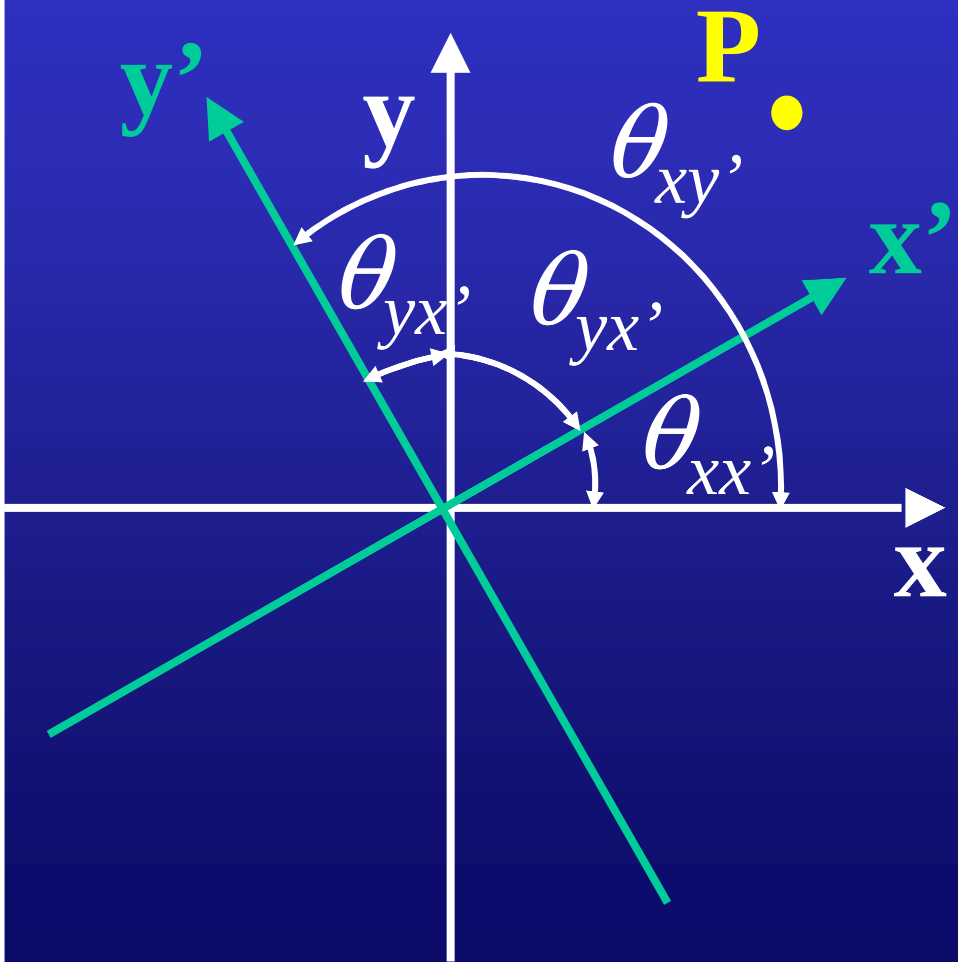


Rule for coordinate transformation

$$\begin{cases} v_x = p_{ox} + v_{x'} \\ v_y = p_{oy} + v_{y'} \end{cases}$$

$$\mathbf{v} = \mathbf{p}_o + \mathbf{v}'$$

rule for coordinate transformation



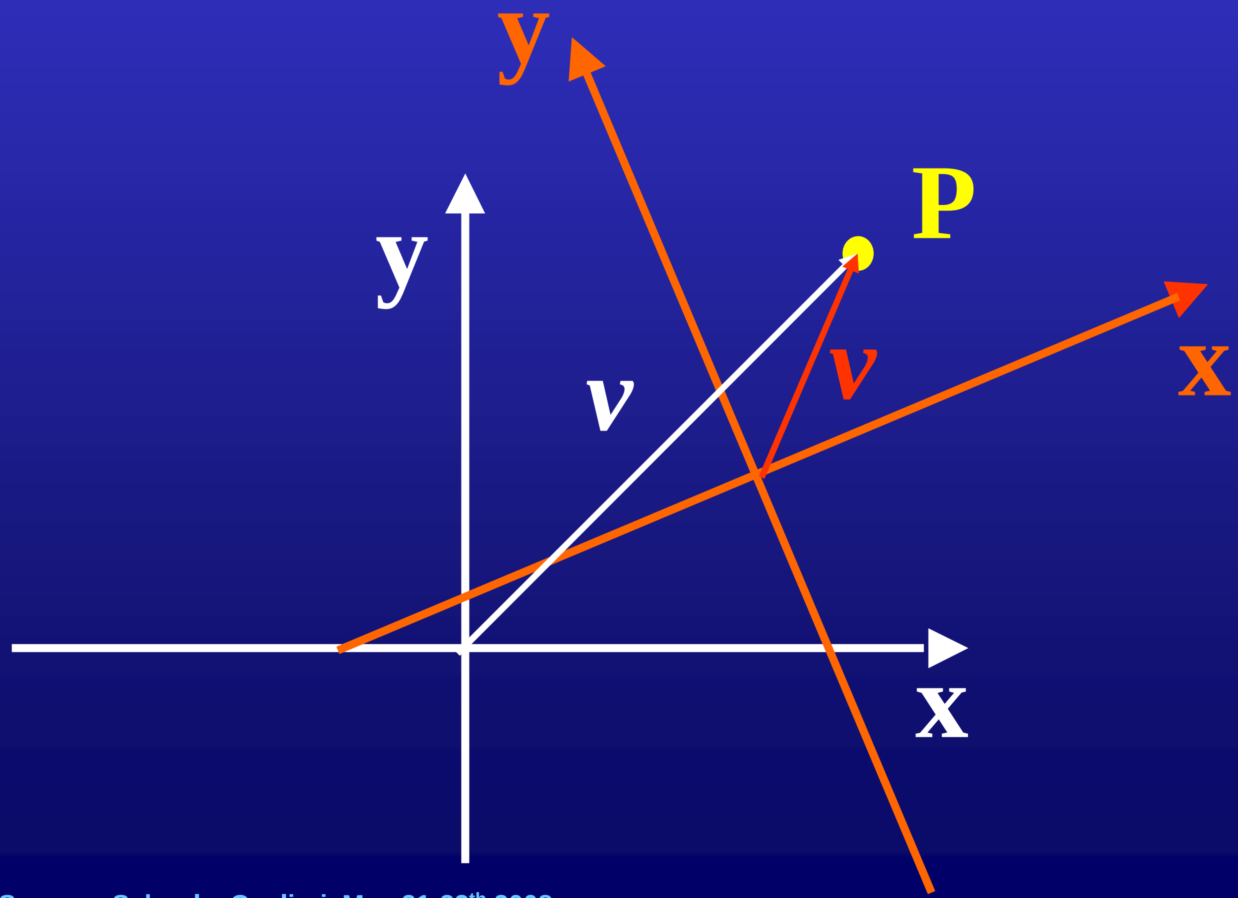
$$\begin{cases} v_x = v_{x'} \cos\theta_{x'x} + v_{y'} \cos\theta_{y'x} \\ v_y = v_{x'} \cos\theta_{x'y} + v_{y'} \cos\theta_{y'y} \end{cases}$$

$$\begin{vmatrix} v_x \\ v_y \end{vmatrix} = \begin{vmatrix} \cos\theta_{x'x} & \cos\theta_{y'x} \\ \cos\theta_{x'y} & \cos\theta_{y'y} \end{vmatrix} \begin{vmatrix} v_{x'} \\ v_{y'} \end{vmatrix}$$

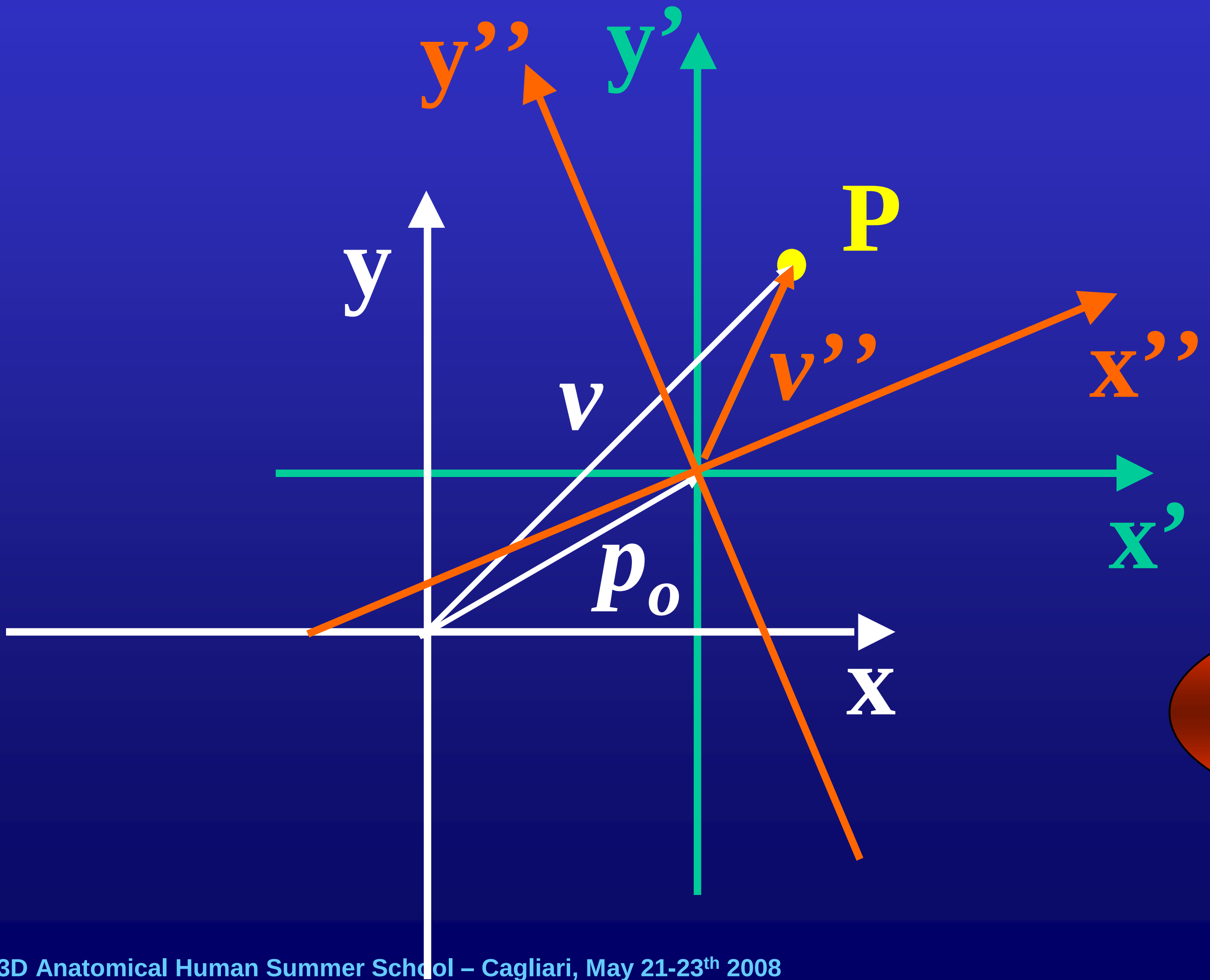
$$\boldsymbol{v} = \boldsymbol{A}\boldsymbol{v}'$$

general change of perspective

What is the relationship between ***v*** and ***v***?



change of perspective in two steps: translate and rotate it the cross-wire

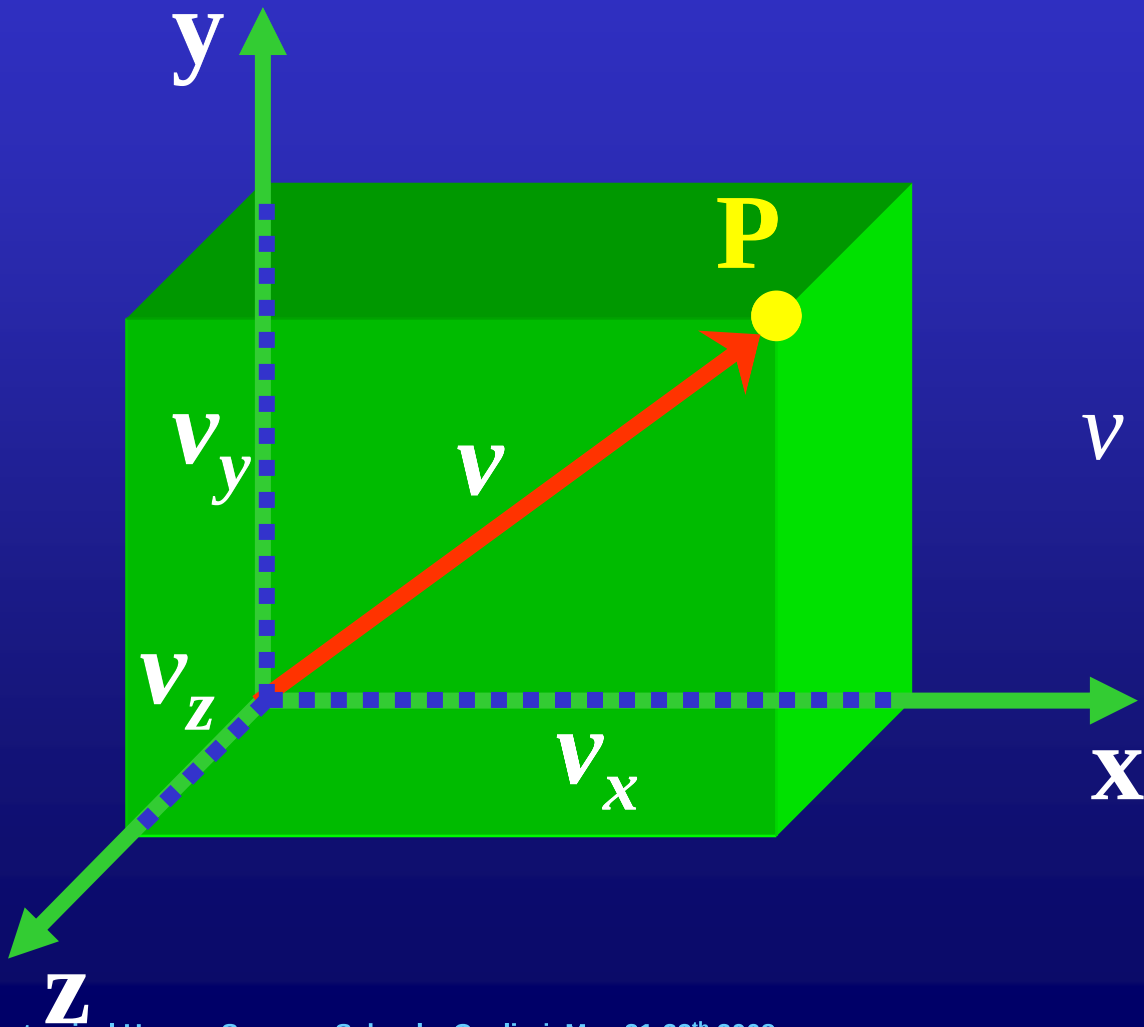


$$v = p_o + v'$$

$$v' = Av''$$

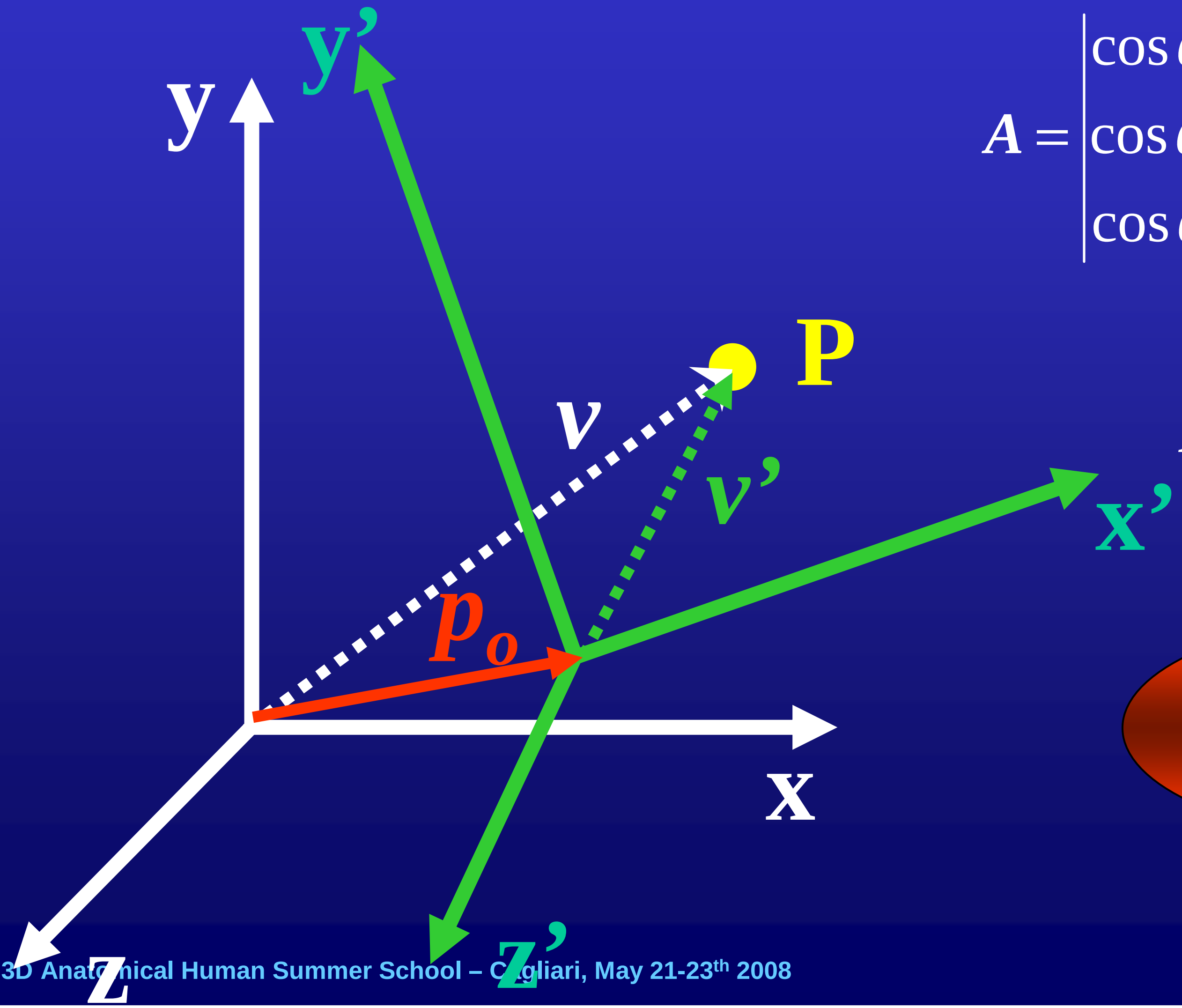
$$v = p_o + Av''$$

a point in the three-dimensional space



$$v = \begin{vmatrix} v_x & v_y & v_z \end{vmatrix}$$

change of perspective
in the three-dimensional space

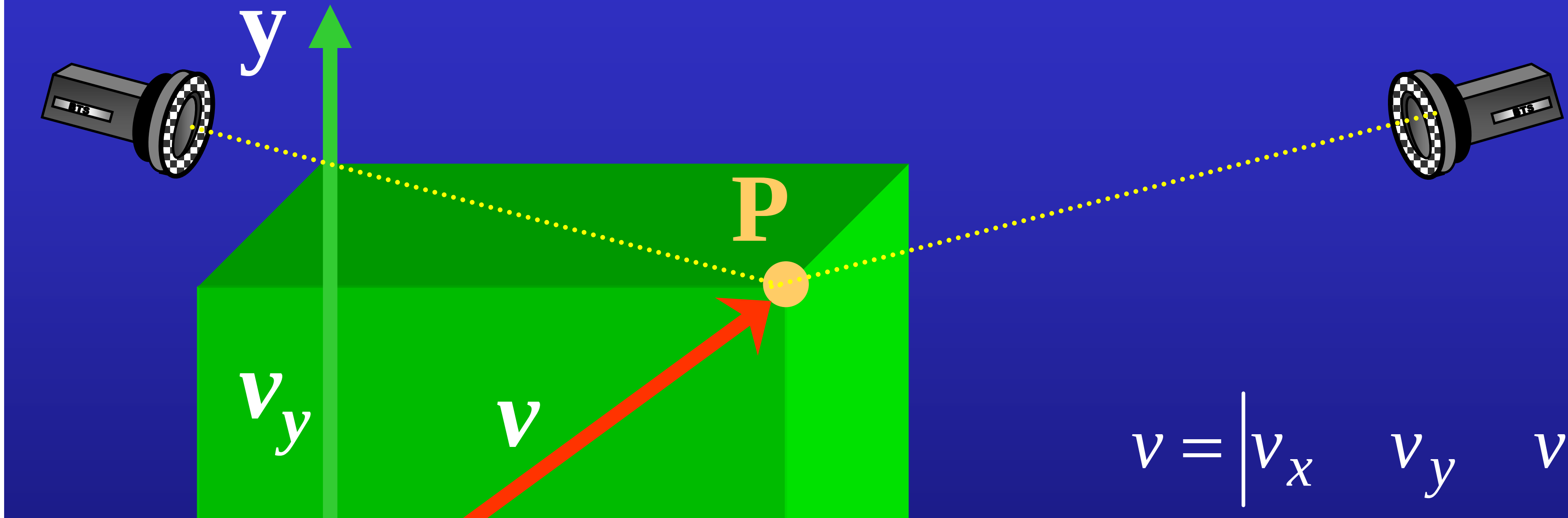


$$A = \begin{vmatrix} \cos\theta_{x'x} & \cos\theta_{y'x} & \cos\theta_{z'x} \\ \cos\theta_{x'y} & \cos\theta_{y'y} & \cos\theta_{z'y} \\ \cos\theta_{x'z} & \cos\theta_{z'z} & \cos\theta_{z'z} \end{vmatrix}$$

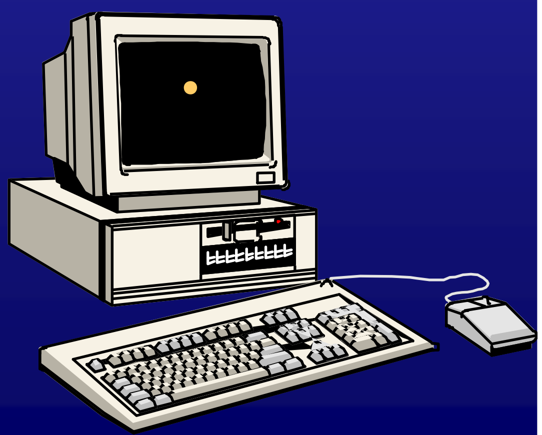
$$\boldsymbol{p}_o = \begin{vmatrix} p_{ox} & p_{oy} & p_{oz} \end{vmatrix}$$

$$\boldsymbol{v} = \boldsymbol{p}_o + \boldsymbol{A}\boldsymbol{v}'$$

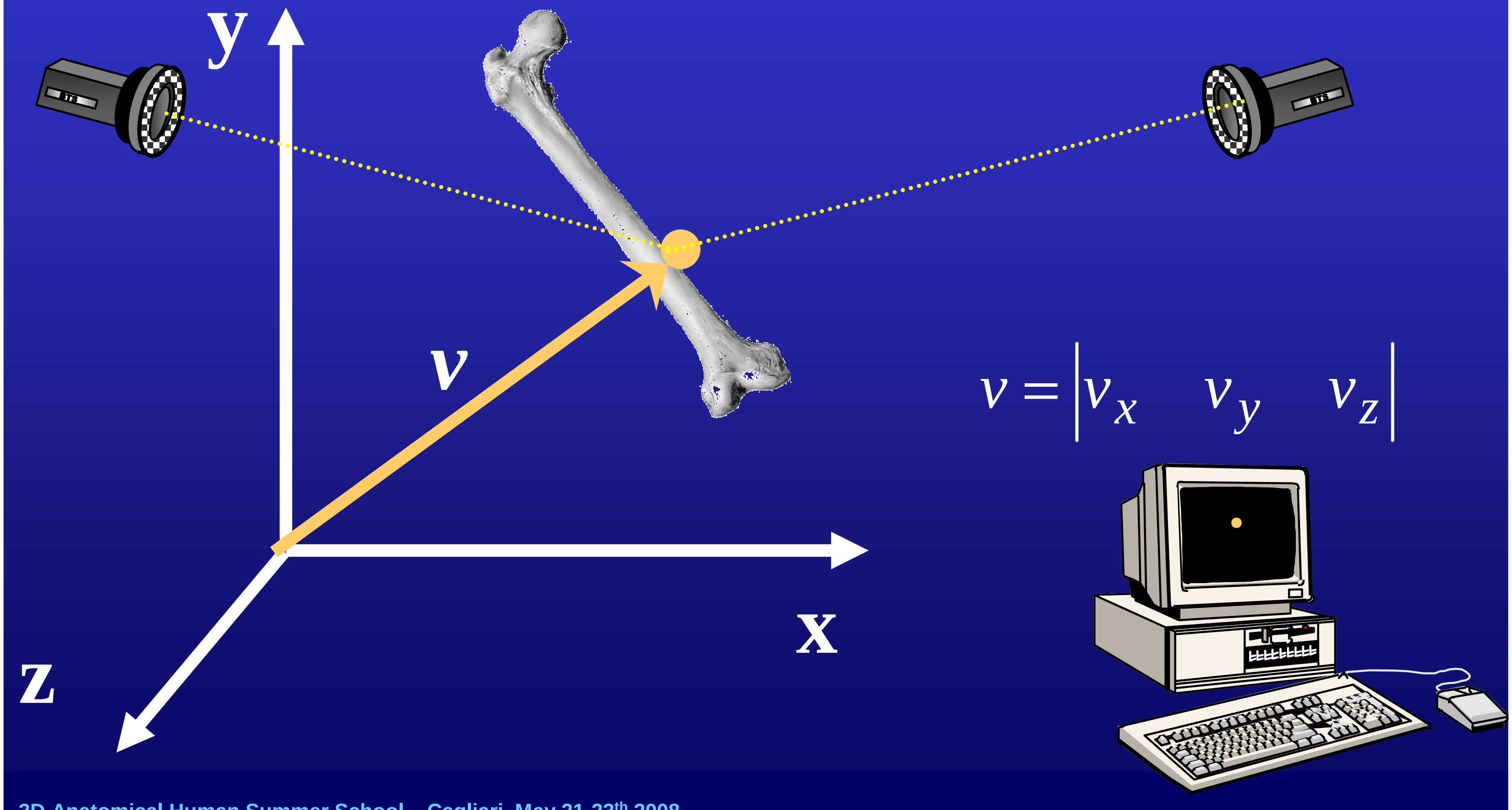
we are using stereophotogrammetry



$$v = \begin{vmatrix} v_x & v_y & v_z \end{vmatrix}$$



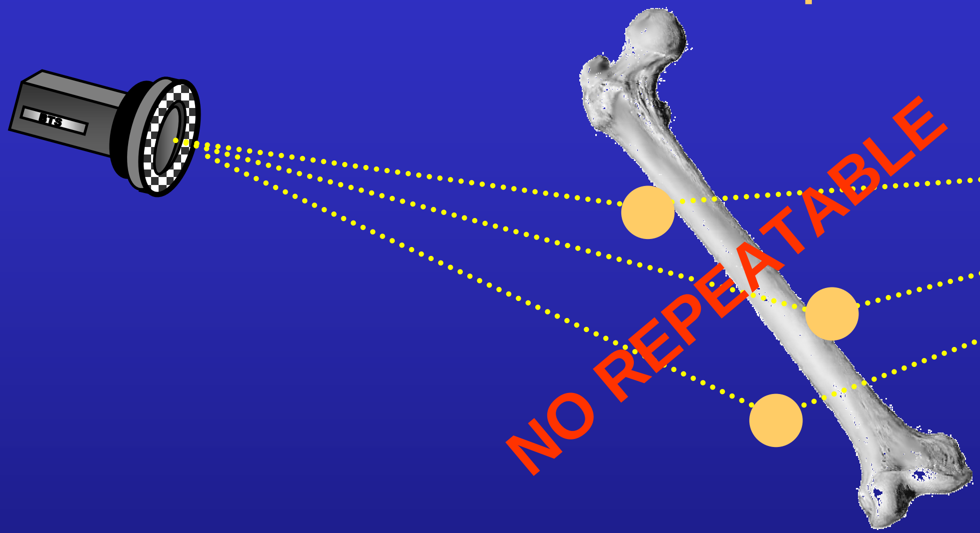
markers over a body segment



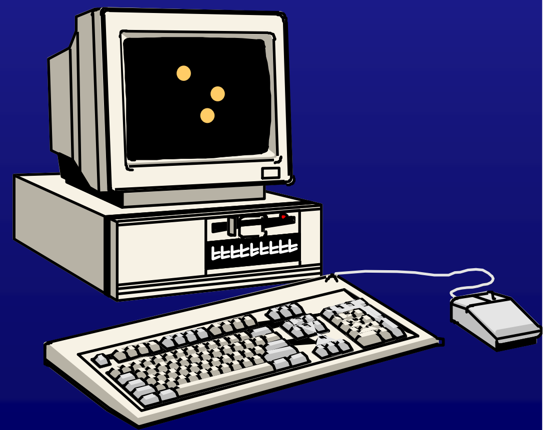
$$v = \begin{vmatrix} v_x & v_y & v_z \end{vmatrix}$$

markers over a body segment:

requirements

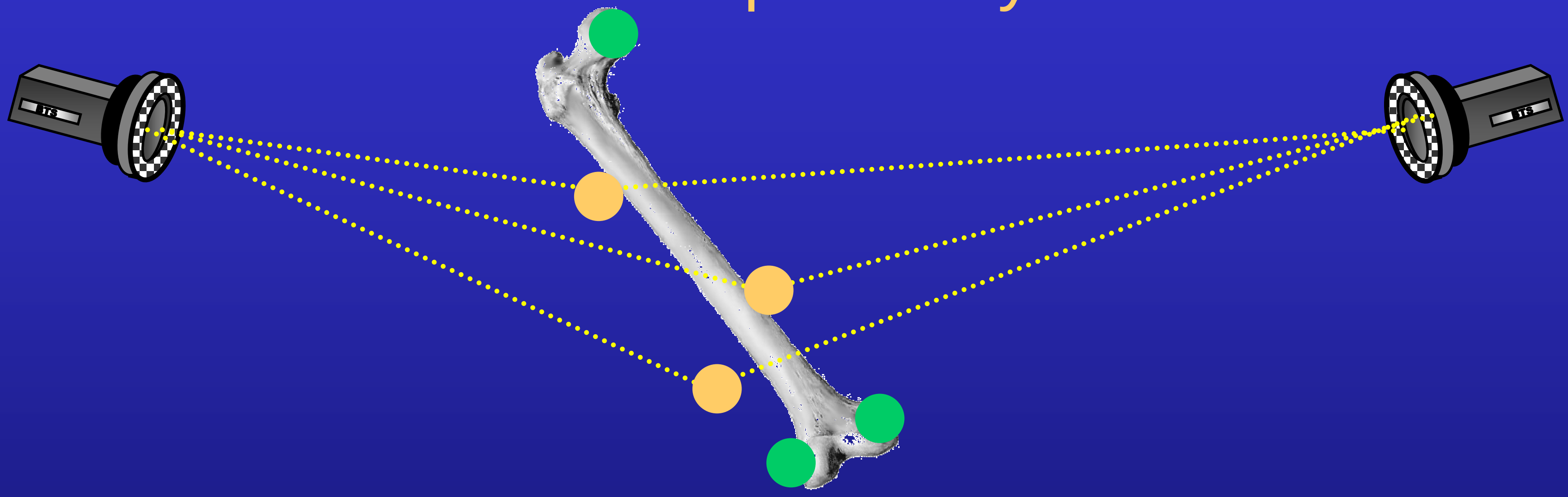


- ✓ visible to the cameras
- ✓ fast, easy and safe mounting
- ✓ minimal disturbance to the subject
- ✓ applicability over prostheses, orthoses
- ✓ spread in space

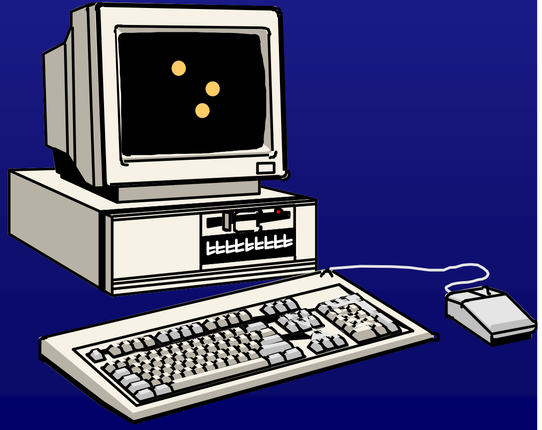


body segment representation:

repeatibility

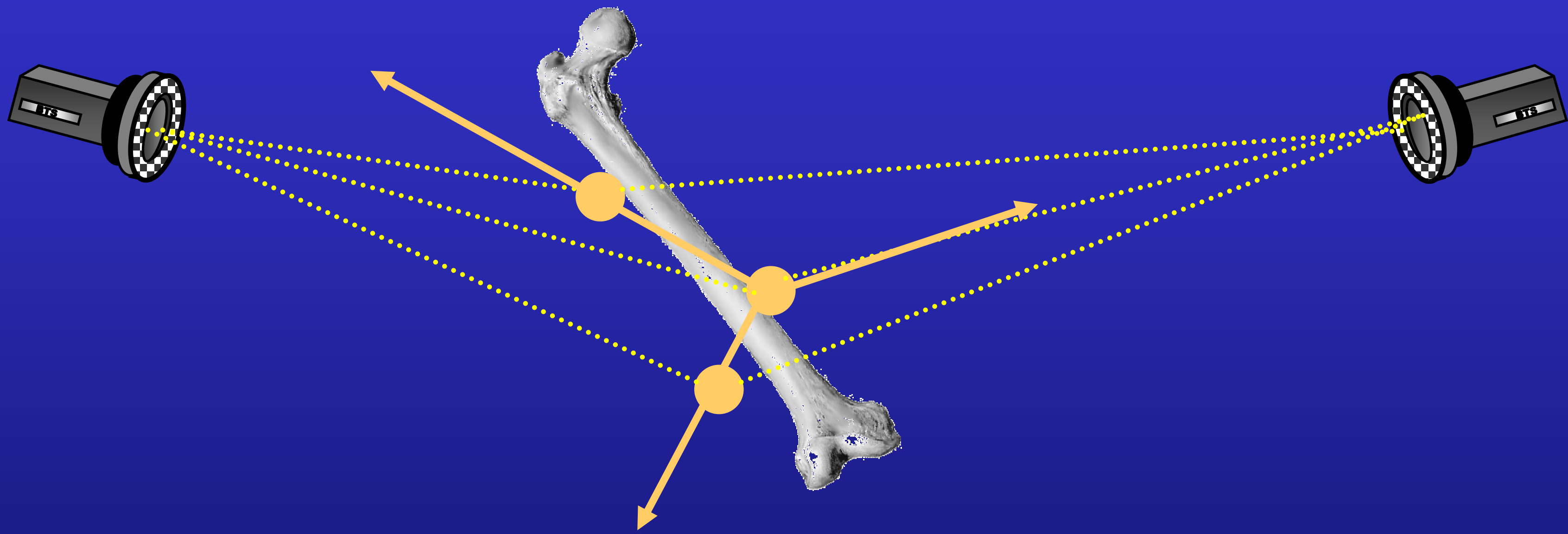


✓ points related to the anatomy
✓ joint axes location
✓ inertia properties (CoM, axes of inertia)

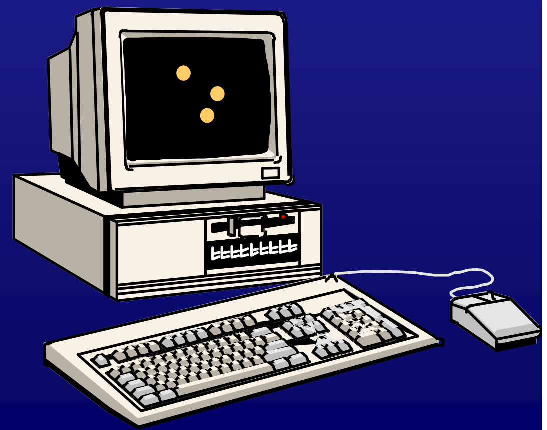


body segment representation:

Bone-embedded Frames

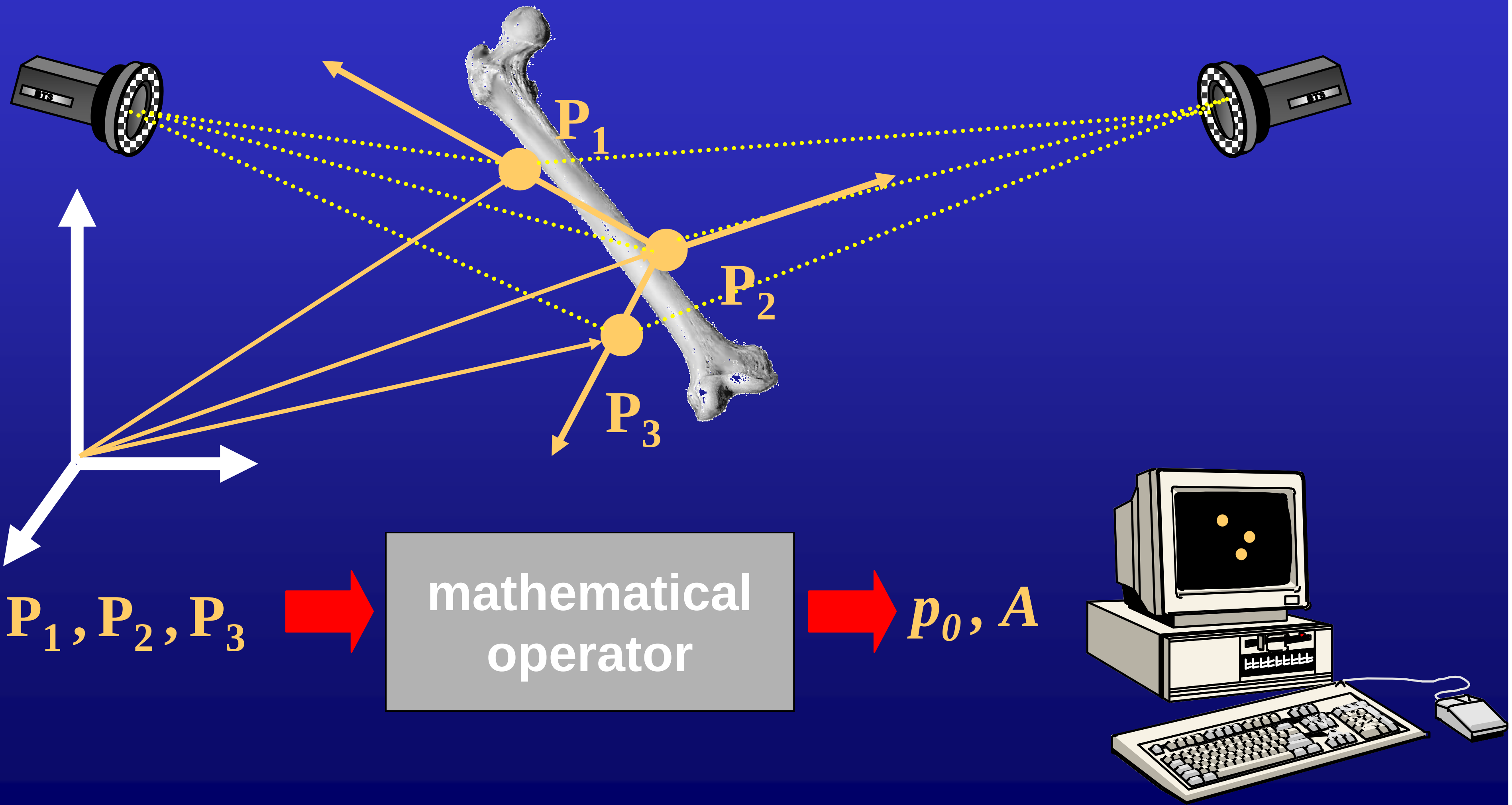


Bone-embedded Technical Frame (BTF)



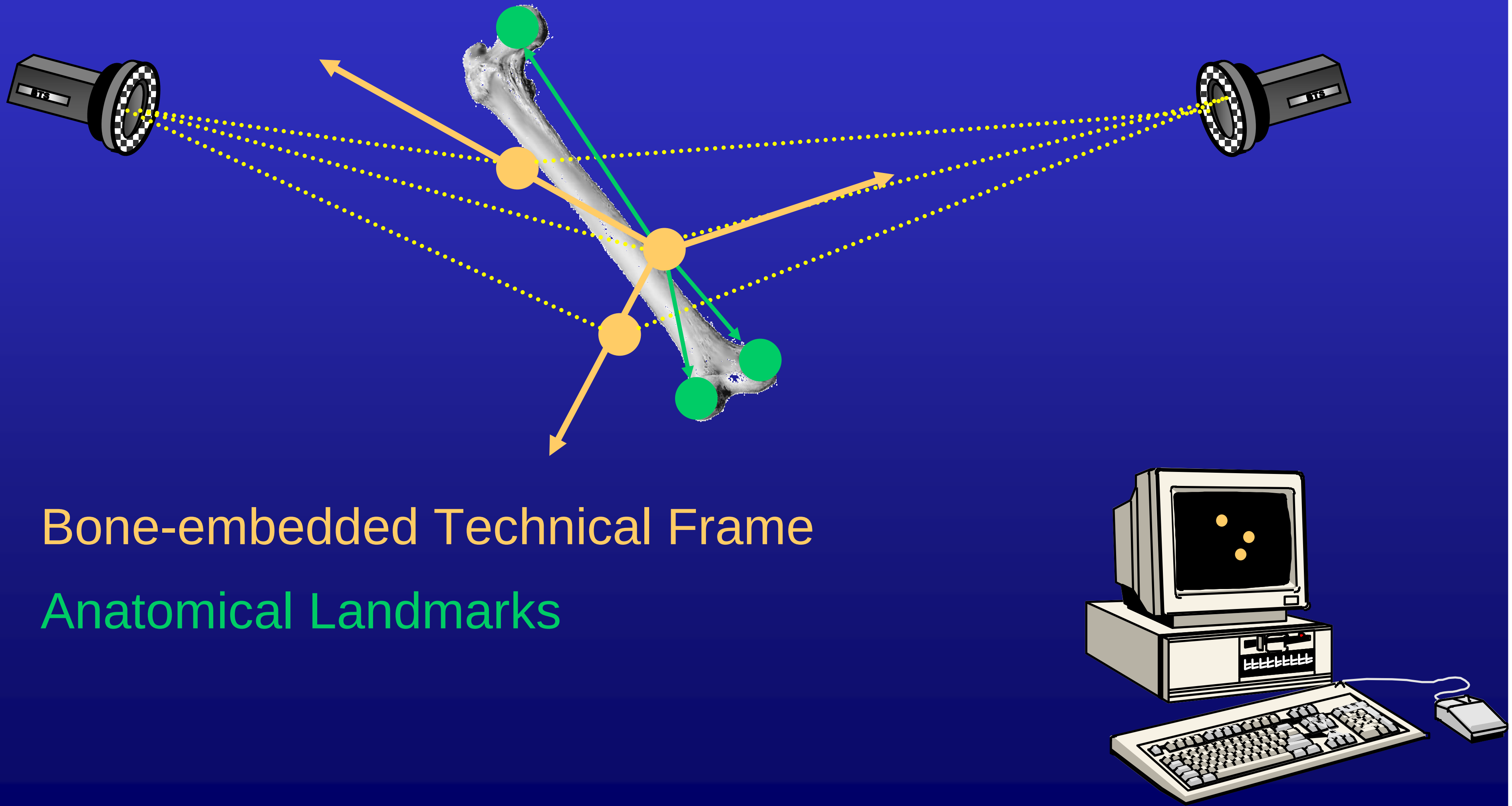
body segment representation:

Bone-embedded Frames



body segment representation:

Bone-embedded Frames

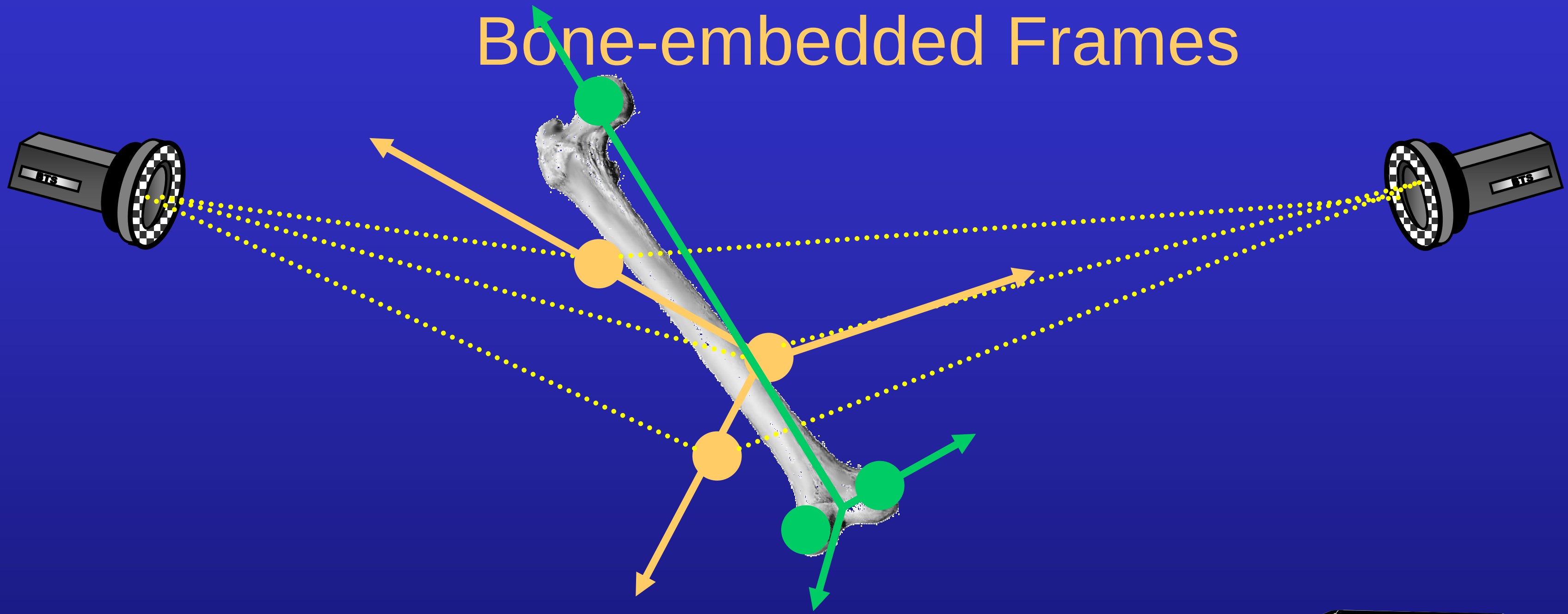


Bone-embedded Technical Frame

Anatomical Landmarks

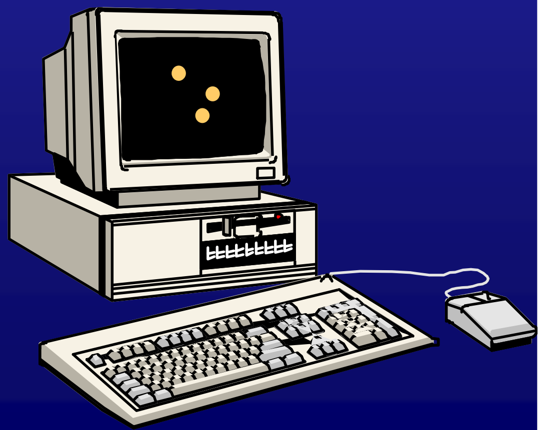
body segment representation:

Bone-embedded Frames



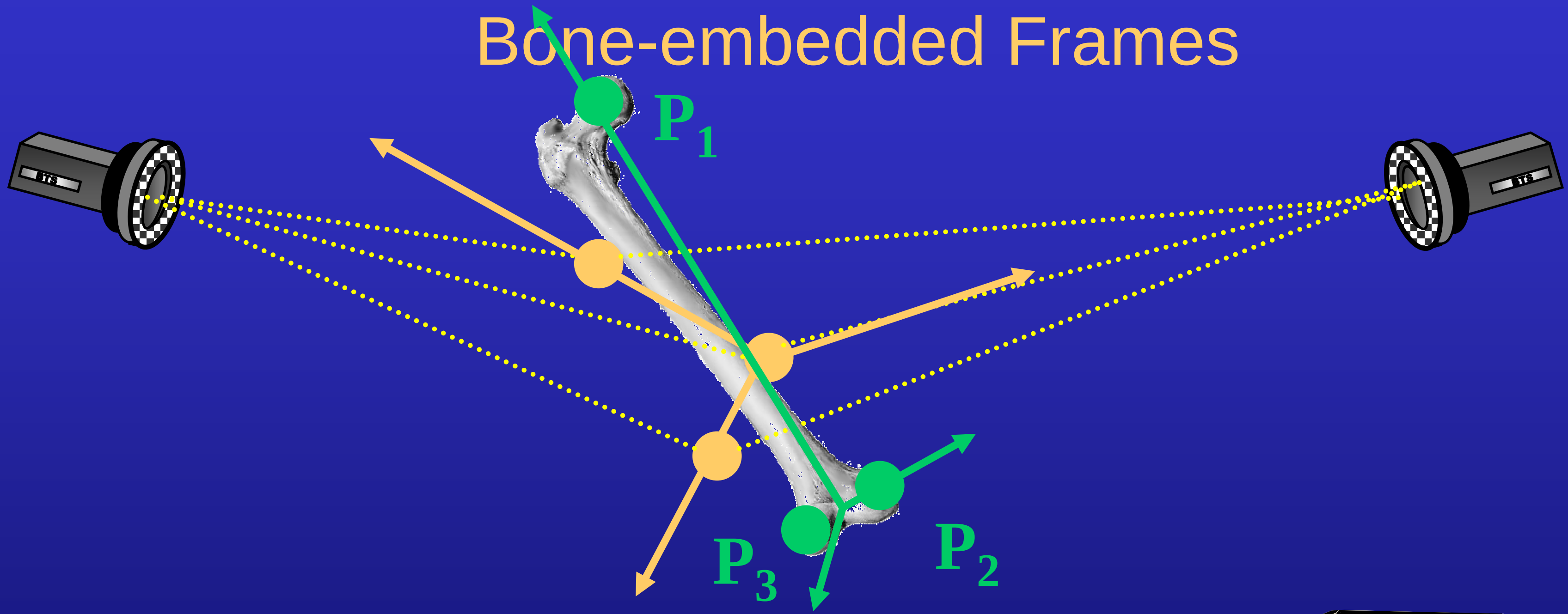
Bone-embedded Technical Frame

Bone-embedded Anatomical Frame (BAF)

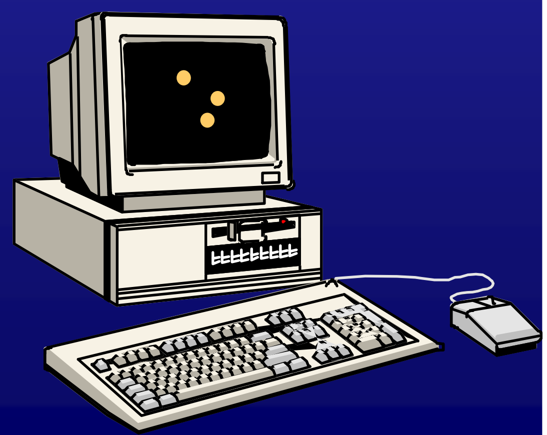


body segment representation:

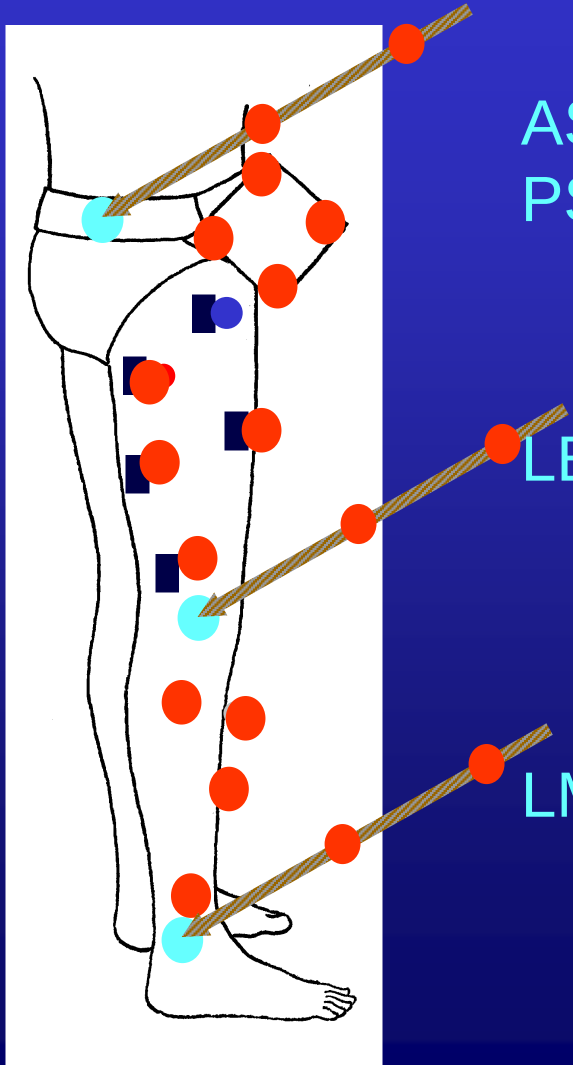
Bone-embedded Frames



P_1, P_2, P_3 → **mathematical operator** → p_0, A



anatomical landmark calibration

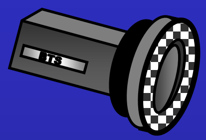


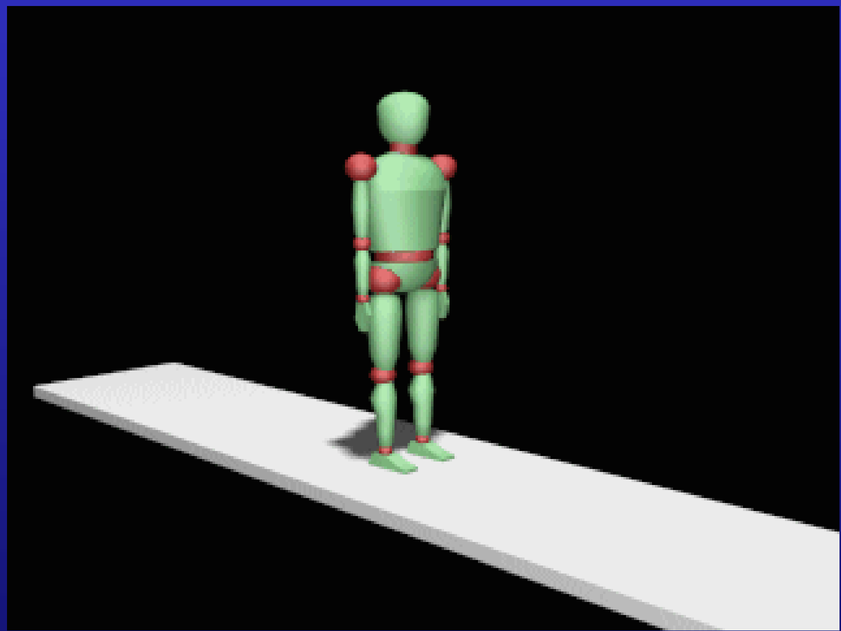
ASIS
PSIS

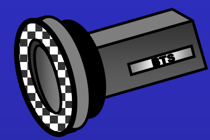
LE, ME, GT

LM, MM, TT, HF

now the scene is in motion



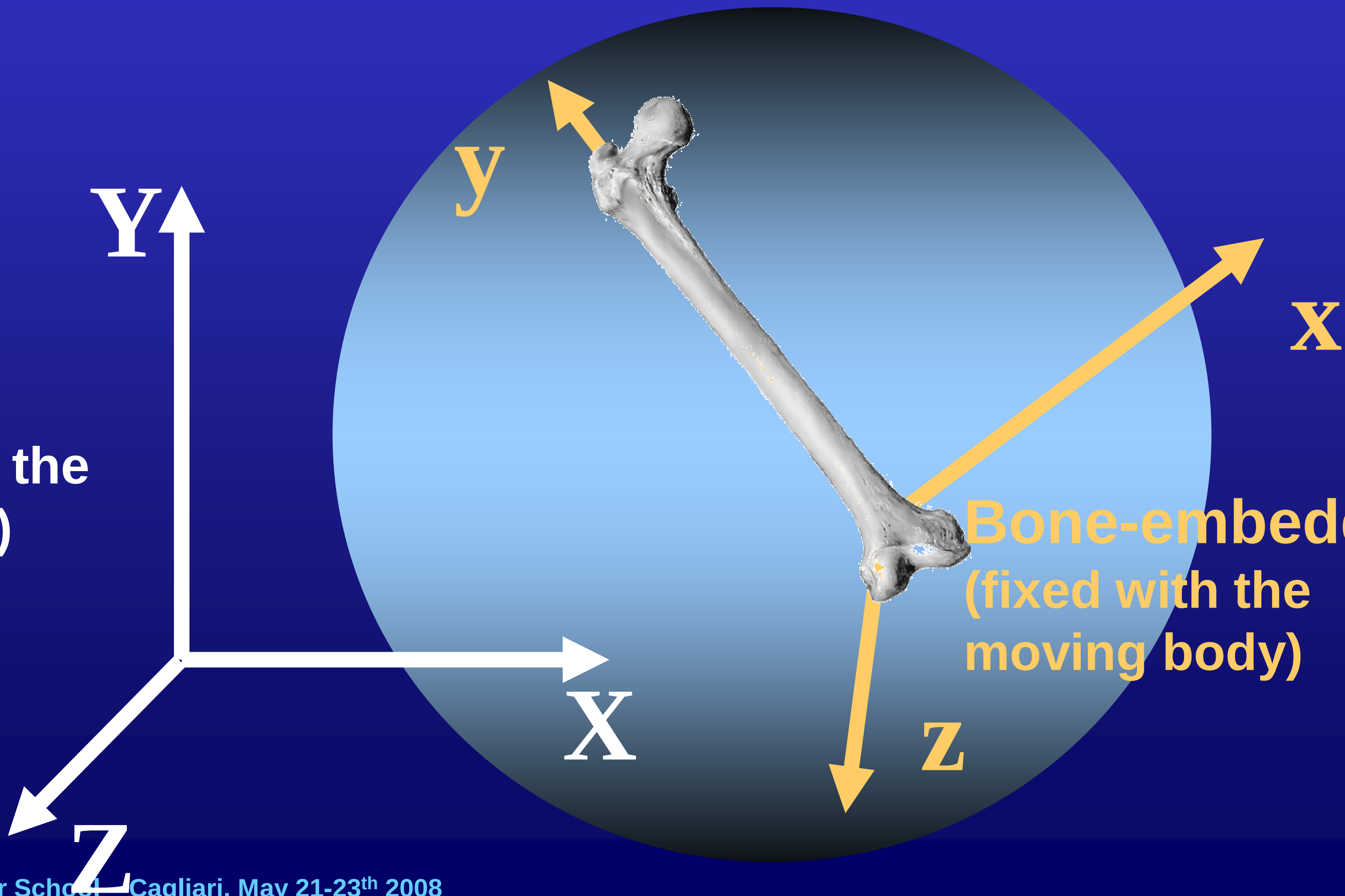




in every instant of time

we use two systems of axes

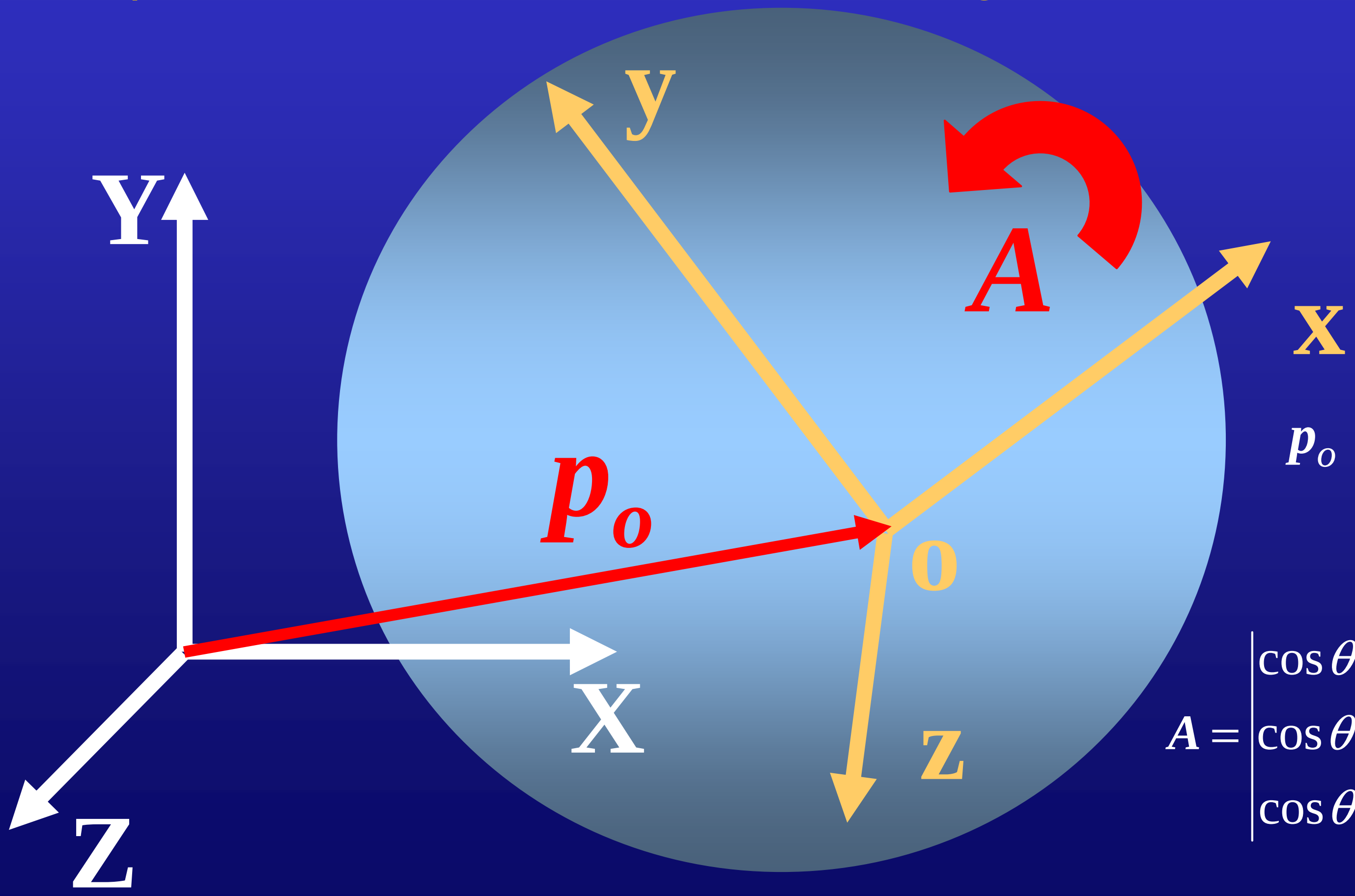
global
(fixed with the laboratory)



Bone-embedded
(fixed with the moving body)

movement reconstruction

position and orientation of the moving BF relative to the global frame



position vector

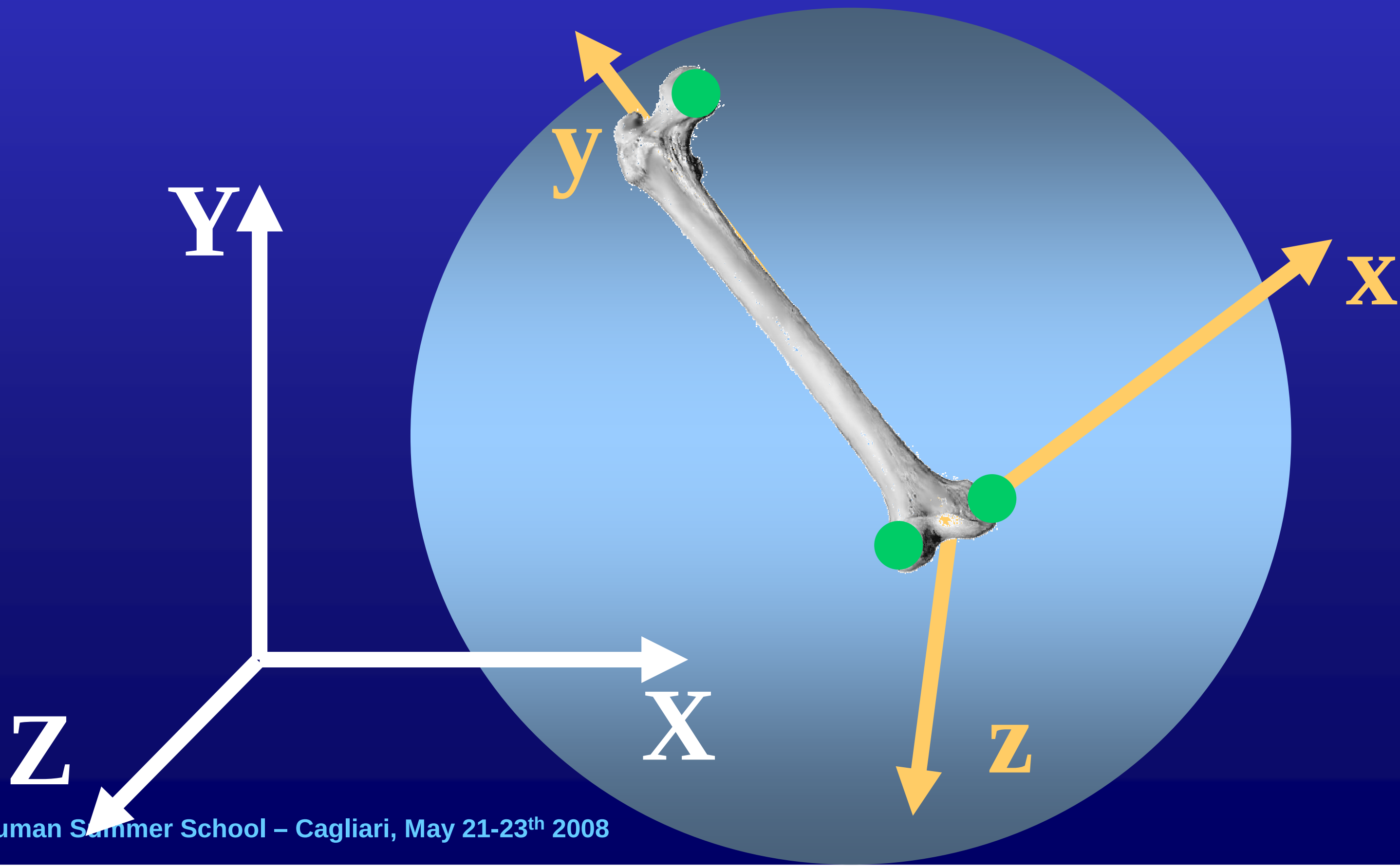
$$\boldsymbol{p}_o = \begin{vmatrix} p_{ox} & p_{oy} & p_{oz} \end{vmatrix}$$

orientation matrix

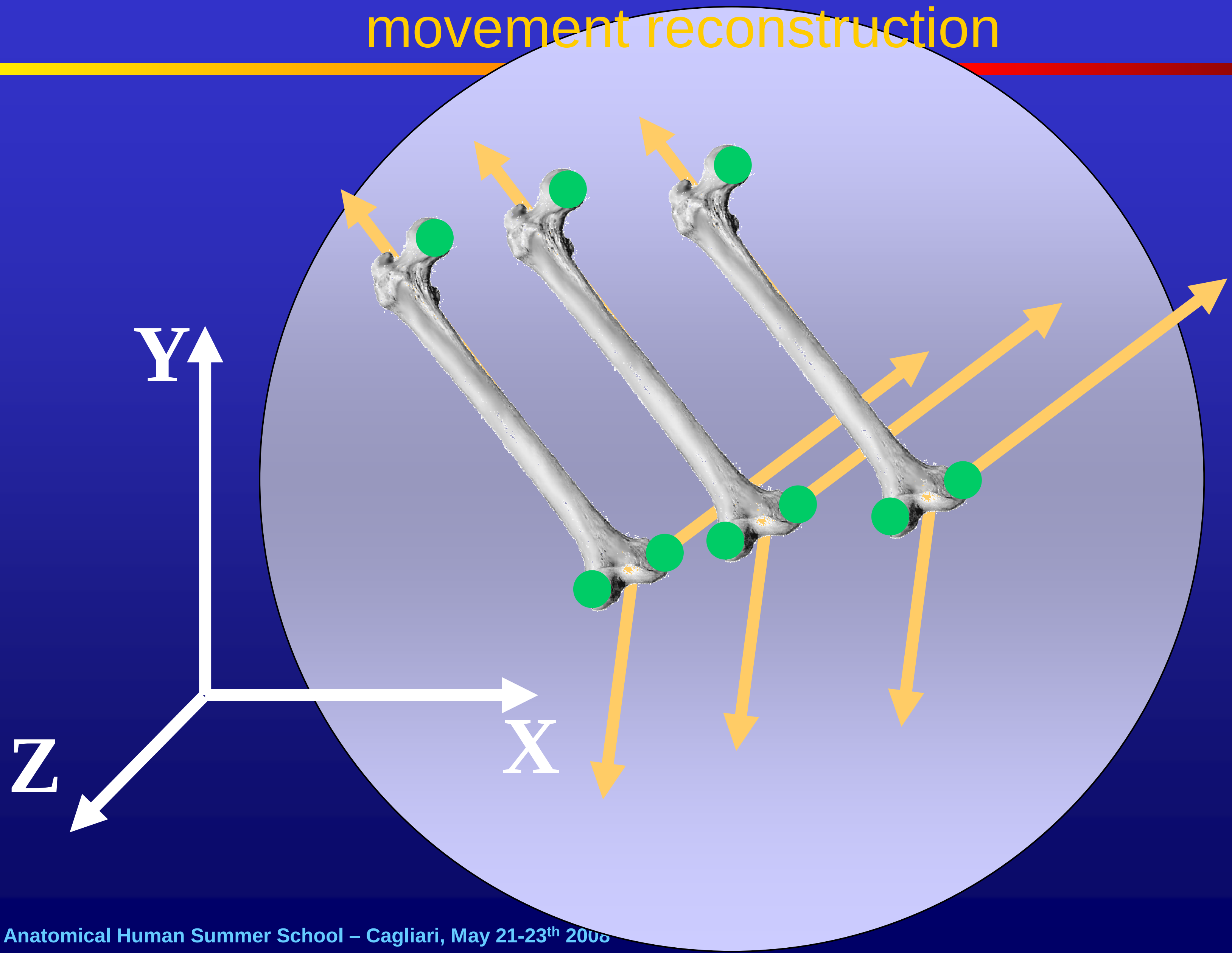
$$\boldsymbol{A} = \begin{vmatrix} \cos\theta_{x'x} & \cos\theta_{y'x} & \cos\theta_{z'x} \\ \cos\theta_{x'y} & \cos\theta_{y'y} & \cos\theta_{z'y} \\ \cos\theta_{x'z} & \cos\theta_{z'z} & \cos\theta_{z'z} \end{vmatrix}$$

in each sampled instant of time:

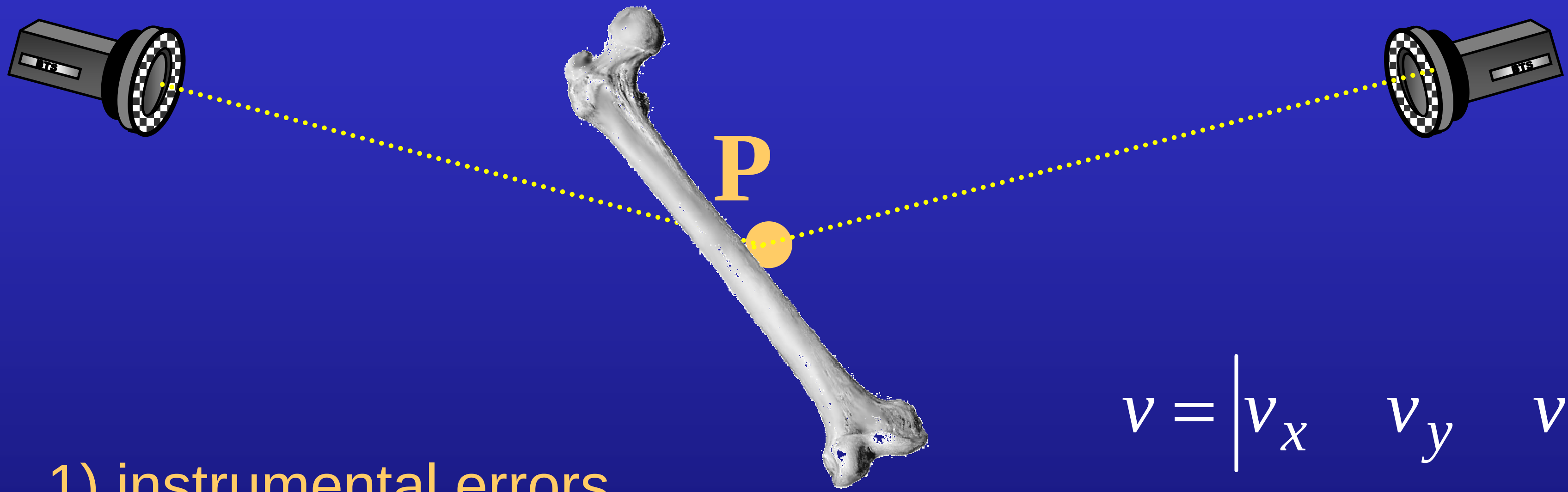
1. locate the BF relative to the global set of axes and
2. locate the body points in the BF in the global set of axes



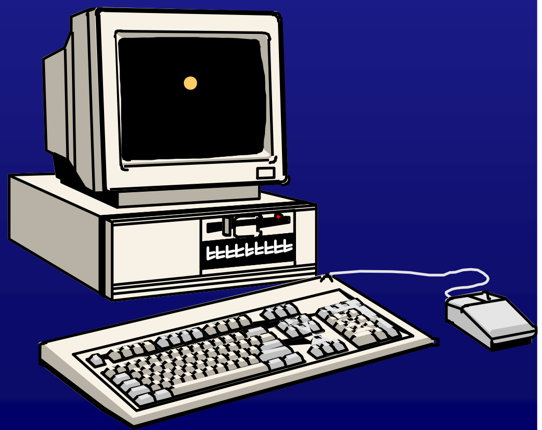
movement reconstruction



sources of errors



$$v = \begin{vmatrix} v_x & v_y & v_z \end{vmatrix}$$



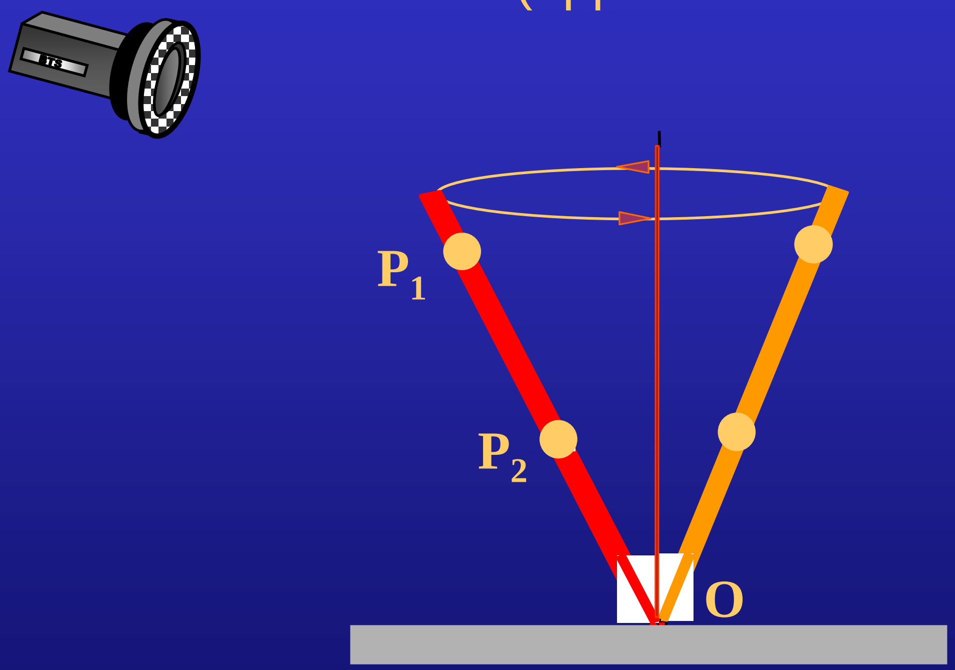
1) instrumental errors

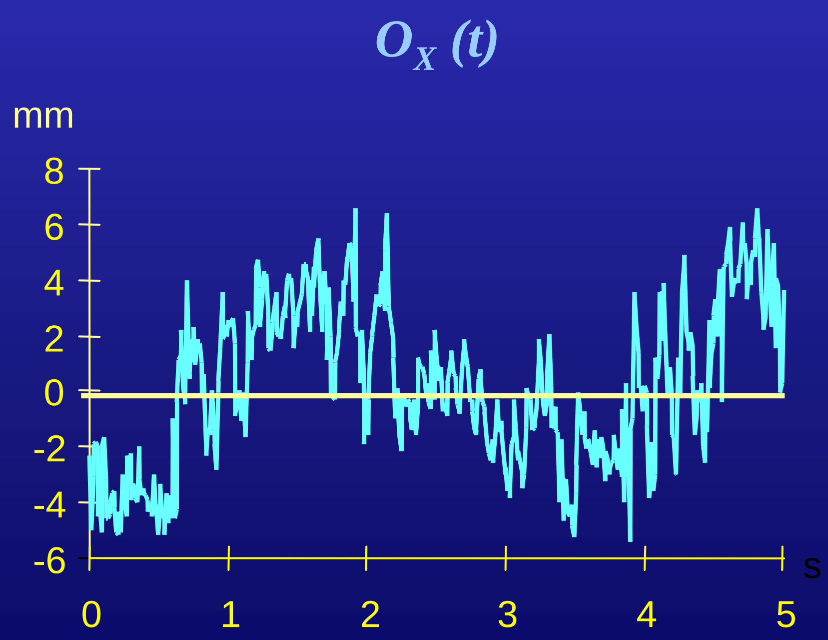
2) skin movement artifacts

3) anatomical landmark mislocation

1) instrumental errors

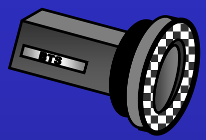
(apparent marker movement)

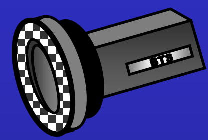




Della Croce et al., Med. & Biol. Eng. & Comp., 2000

compensation of instrumental errors



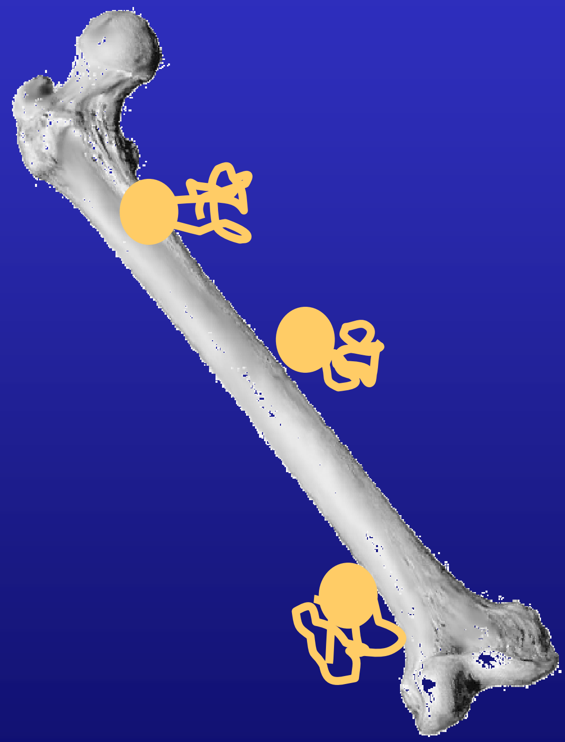


increase the number of cameras

improve camera location

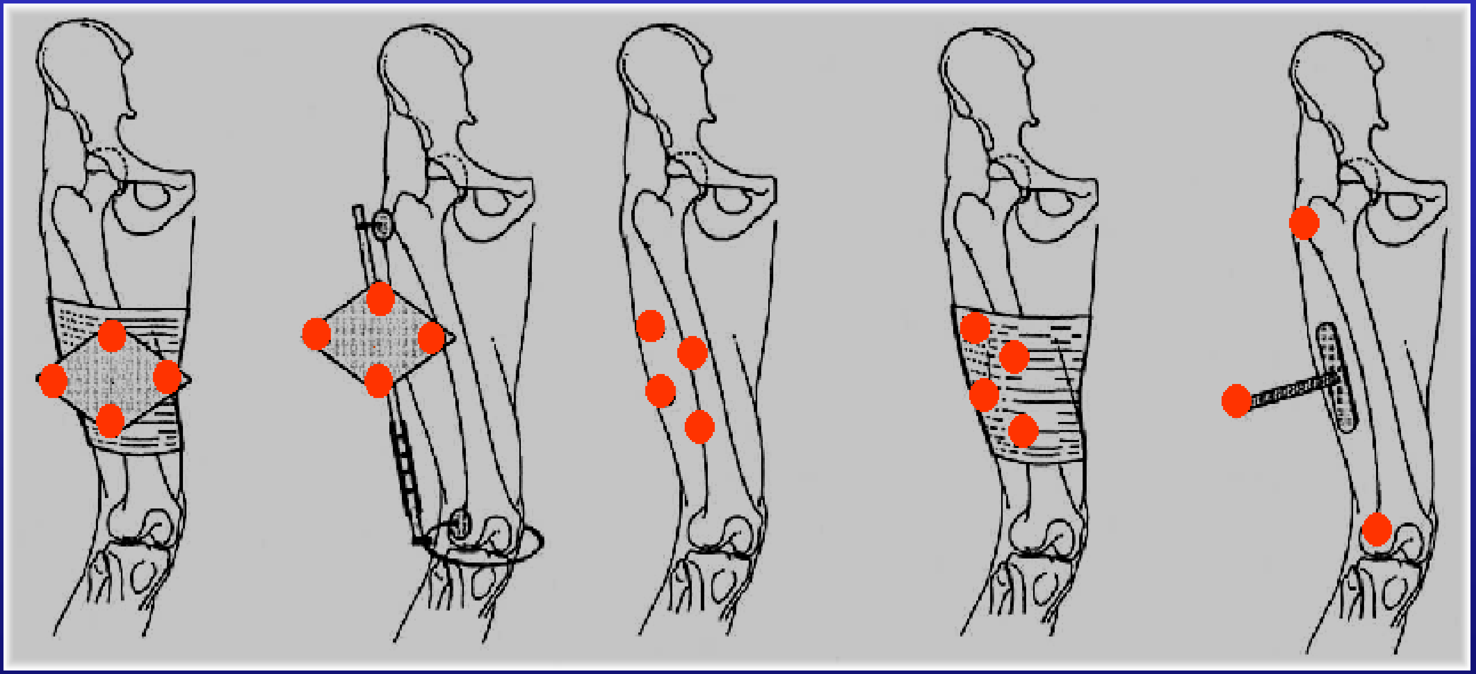
good marker maintenance

2) skin movement artifacts



(actual marker movement)

skin markers



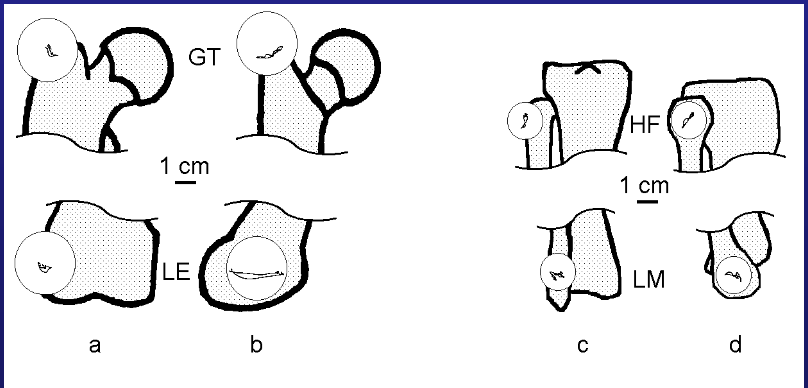
how to measure skin movement artifacts

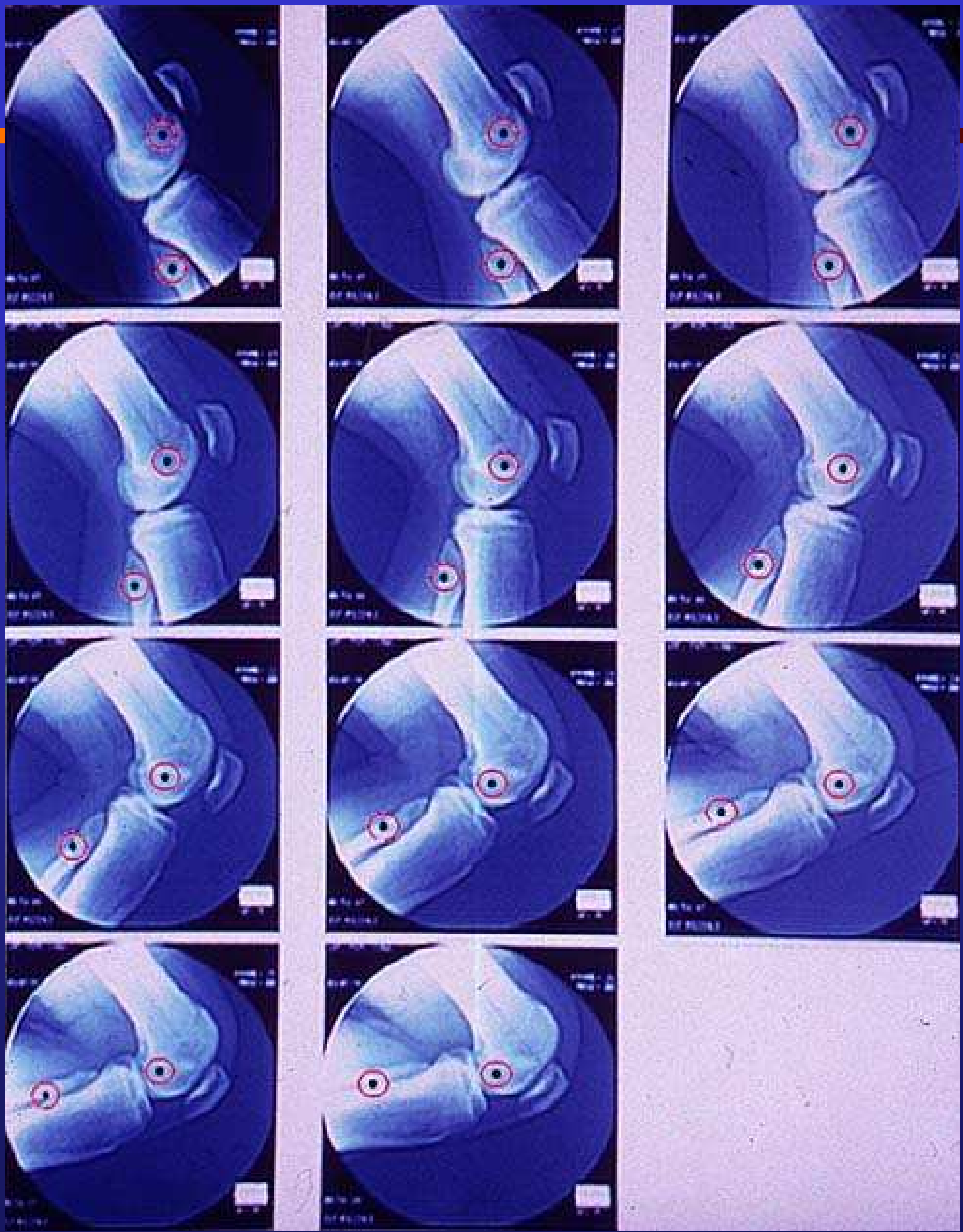
Fluoroscopy,

GT, LE, HF, LM

voluntary flexion

6 frames/sec

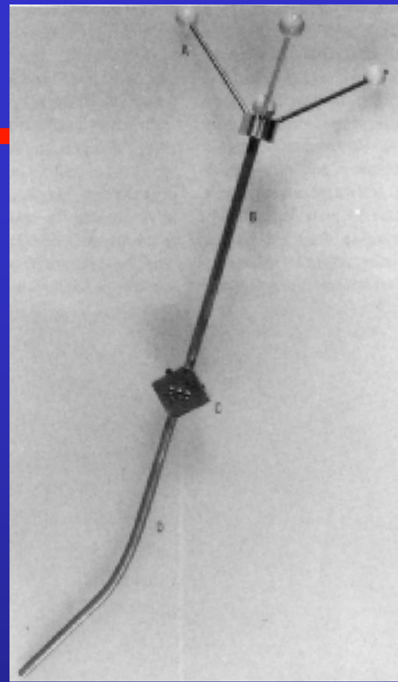




Angeloni et al., ESB 1992

how to measure skin movement artifacts

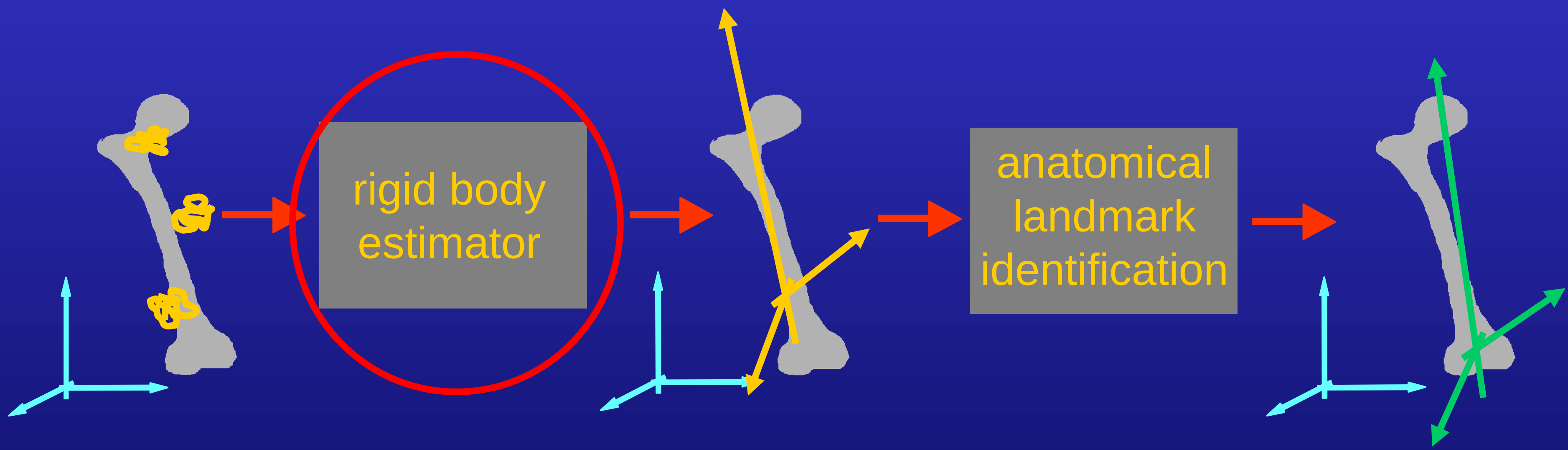
intracortical pins



- **60° flexion => 5.0° Ab/Ad and 9.4° Int/Ext** ***Lafortune and Cavanagh, Journal of Biomechanics 1992***
- **60° flexion => 3.4° Ab/Ad and 10.6° Int/Ext** ***Ishii et al., ClinOrtRelRes 1997***

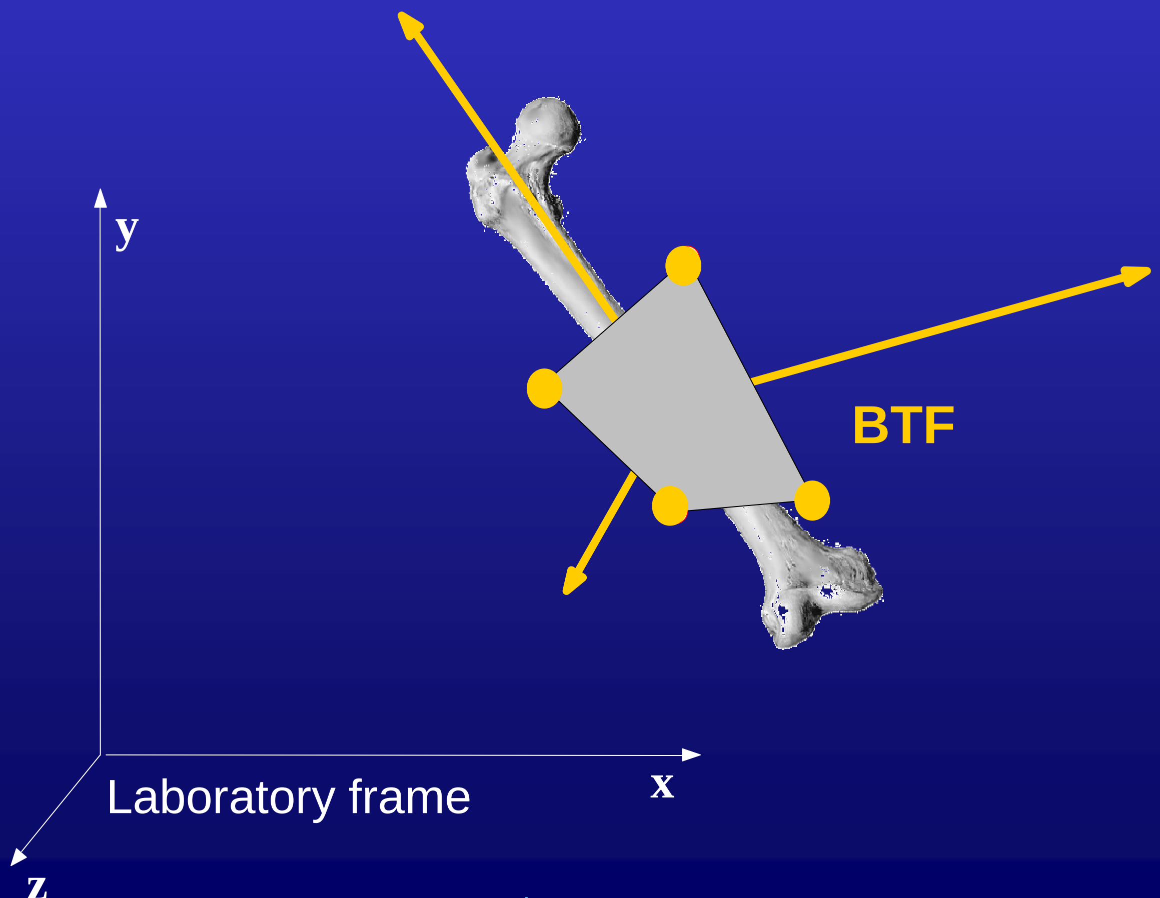
percutaneous_pins vs 11diff.arrays, tib/fib, 7 subj, gait ***Manal et al., GaitPost 2000***

the challenge



rigid body model calibration

in a given instant of time



Spoor and Veldpaus, 1980

Veldpaus et al., 1988

Söderkvist and Wedin, 1993

Challis, 1994

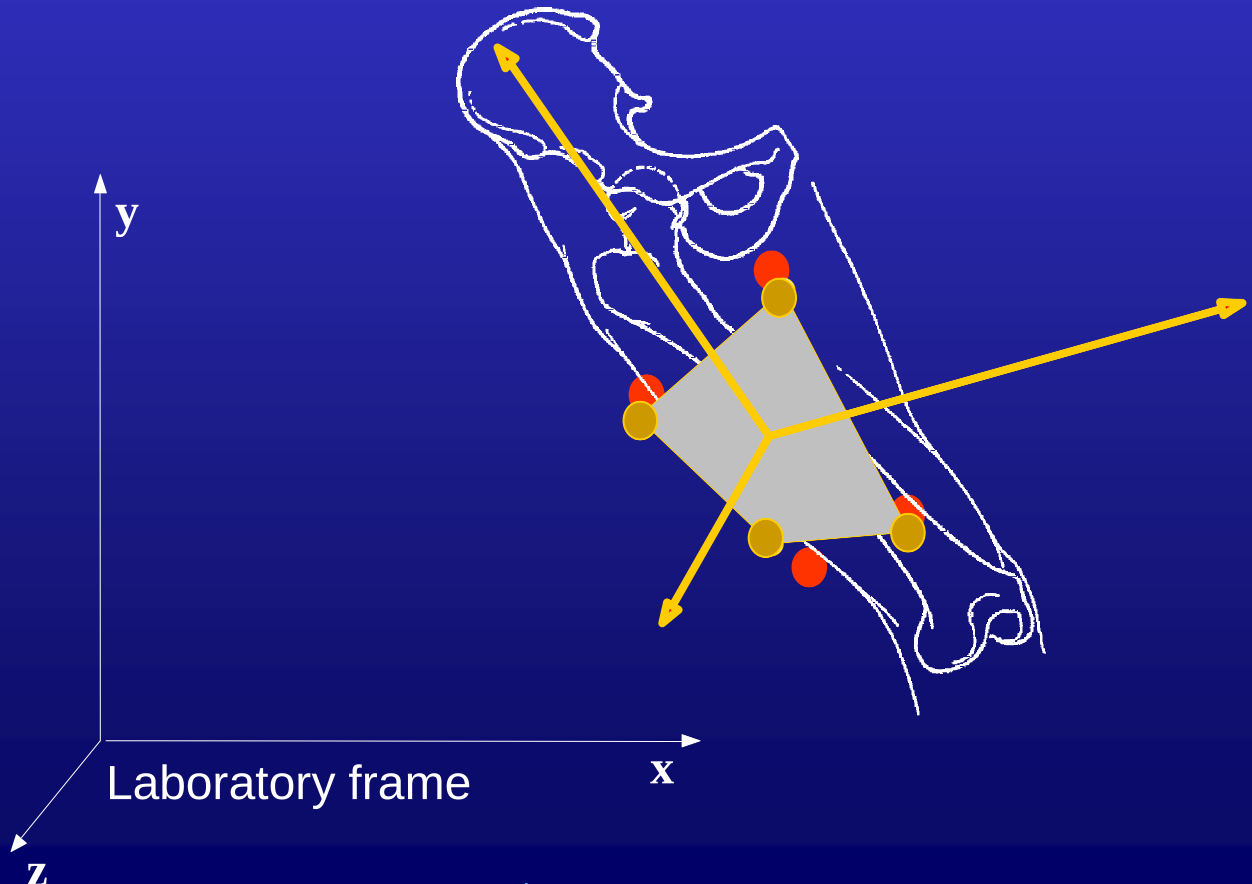
Challis, 1995

Cheze et al., 1995

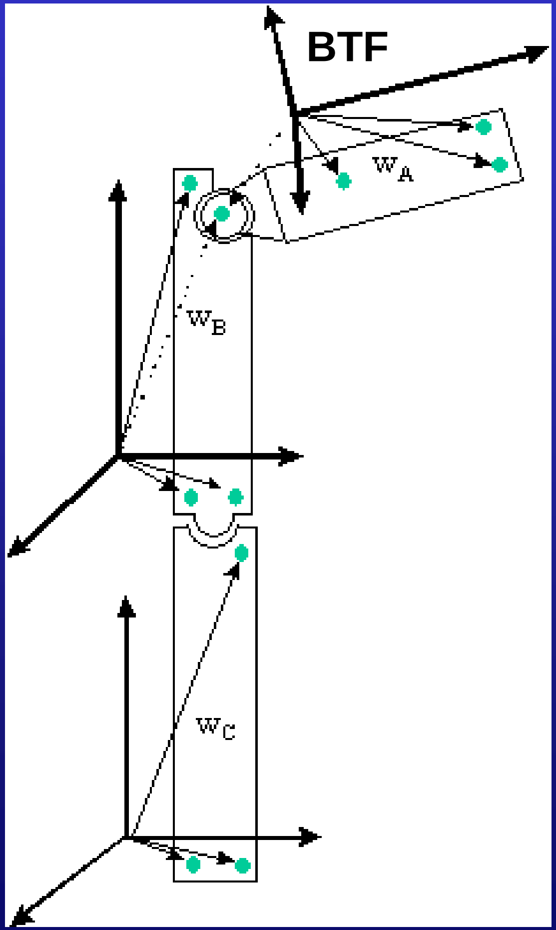
Cappozzo et al., 1997

fitting the rigid body model calibration to the markers in each sampled instant of time

during the movement



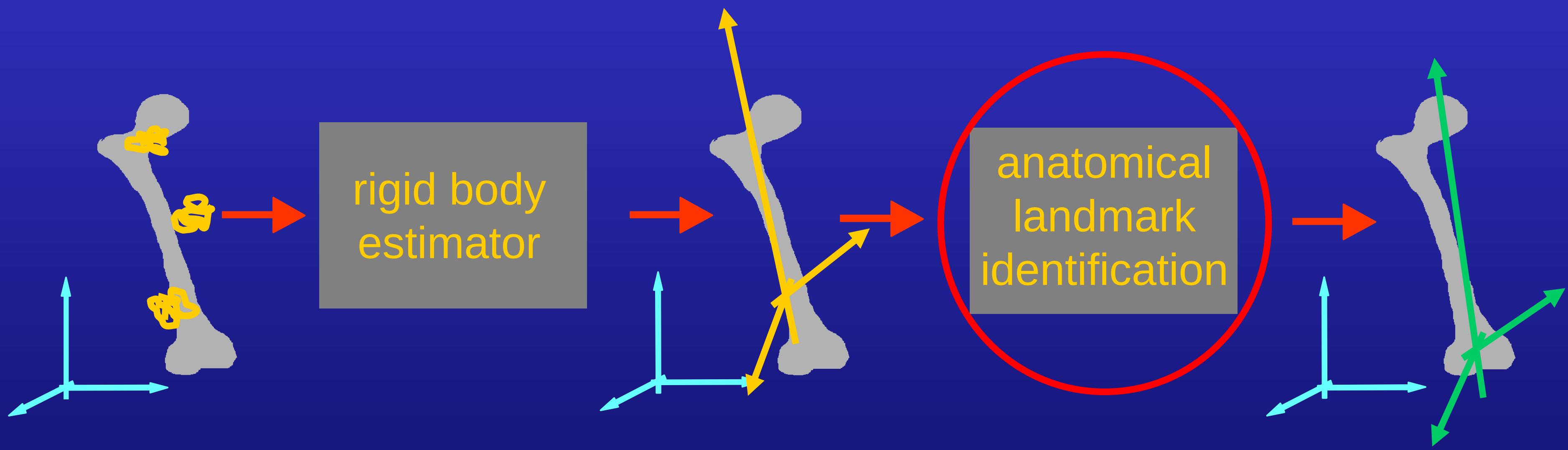
anatomical landmark calibration



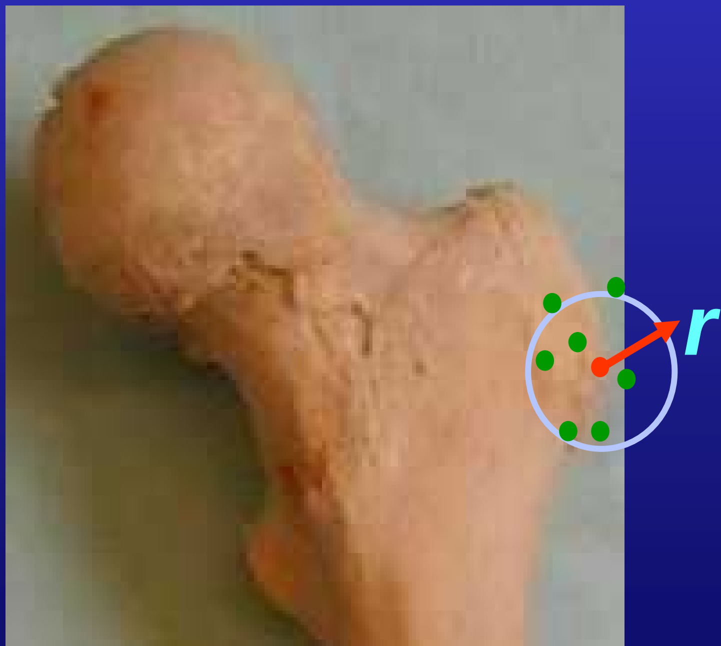
BTF bone-embedded technical frame

w_i anatomical landmark position vectors

3) anatomical landmark mislocation



palpable anatomical landmarks precision



[mm]	landmark	INTRA-OPERATOR	INTER-OPERATOR
		r	*r*
PELVIS	ASIS	12	15
	PSIS	13	25
FEMUR	GT	18	18
	ME	10	15
	LE	10	19
TIBIA and FIBULA	TT	5	12
	HF	6	12
	MM	7	15
	LM	9	17
FOOT	CA	10	16
	FM	8	22

Della Croce et al., Medical & Biol. Eng. & Comp., 1999

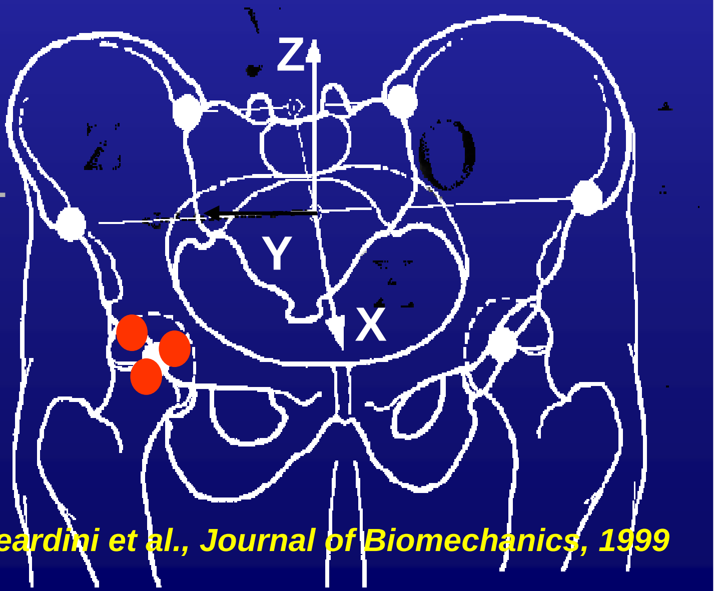
Identification of the hip joint center location

	Δx			Δy			Δz		
METHOD	Func.	Bell	Davis	Func.	Bell	Davis	Func.	Bell	Davis
MEAN [mm]	4	-7	-12	3	-19	8	-2	5	17
SD [mm]	6	6	17	6	10	10	4	10	10

Func. ➡ Cappozzo, Human Movement Science, 1984

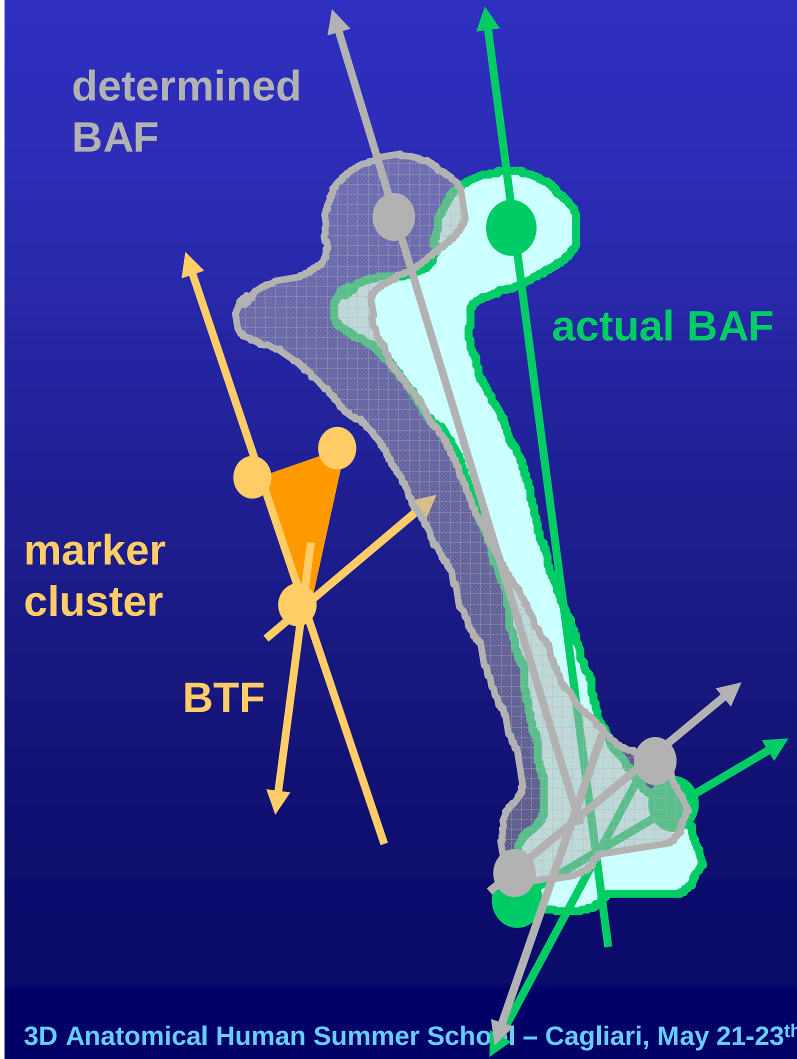
Bell ➡ Bell et al., Journal of Biomechanics, 1990

Davis ➡ Davis et al., Human Movement Science, 1991



Leardini et al., Journal of Biomechanics, 1999

anatomical reference frame precision

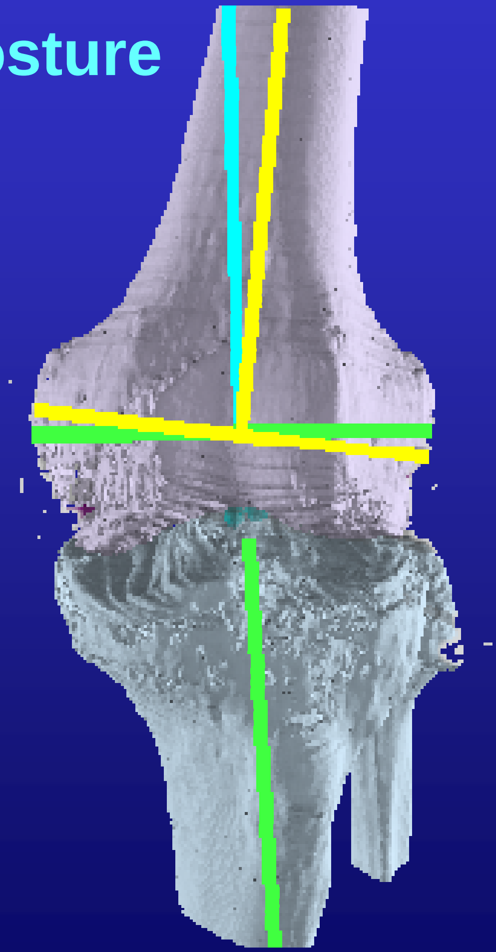


r [deg]		INTRA-OPERATOR	INTER-OPERATOR
PELVIS	A-P	2.3	5.2
	V	2.6	3.7
	M-L	3.7	4.1
FEMUR	A-P	0.9	2.5
	V	4.7	5.1
	M-L	0.9	3.0
TIBIA and	A-P	1.4	4.2
FIBULA	V	3.5	9.4
	M-L	0.3	2.6
FOOT	A-P	2.7	5.9
	V	2.3	9.2
	M-L	1.8	5.1

Della Croce et al., Medical & Biol. Eng. & Comp., 1999

joint kinematics precision

upright posture

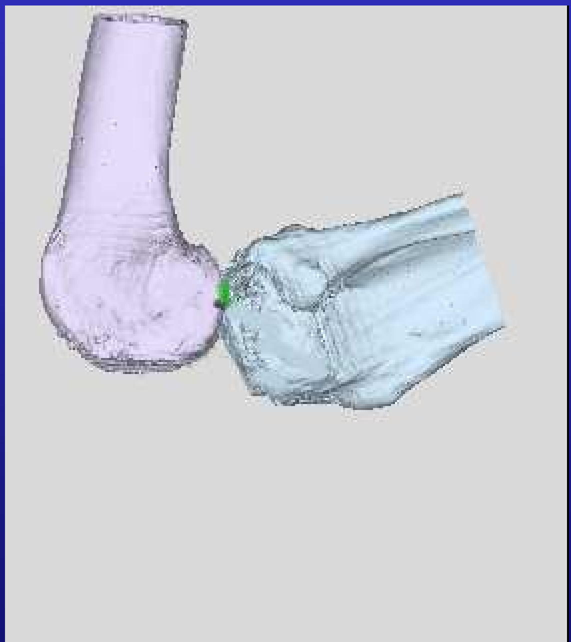


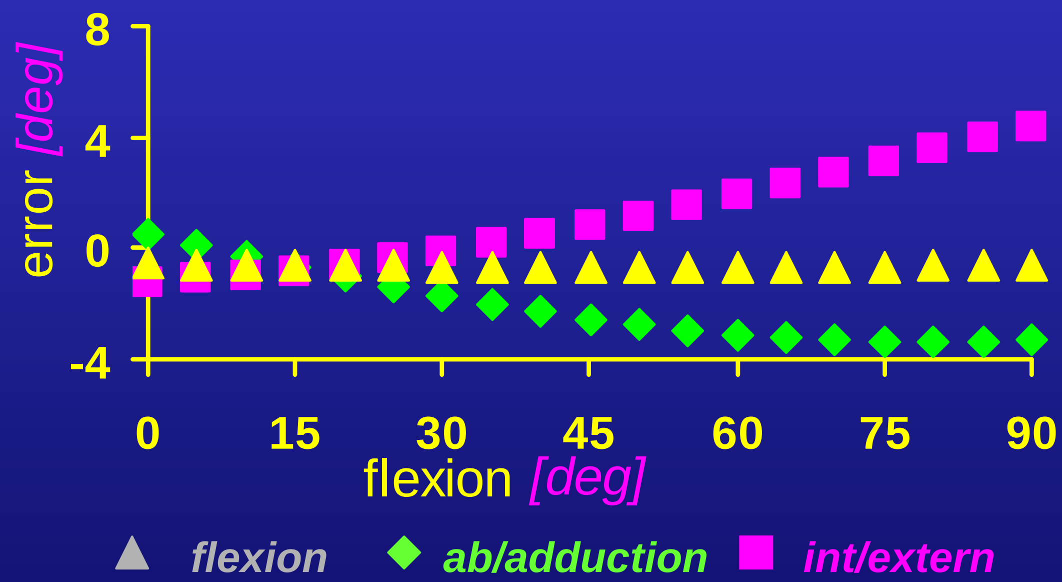
r [deg]		INTRA-OPERATOR	INTER-OPERATOR
HIP	Fl/ex	3.9	5.0
	Int/ext	5.3	10.4
	Ab/add	2.5	5.2
KNEE	Fl/ex	1.0	3.7
	Int/ext	5.8	10.4
	Ab/add	1.7	5.2
ANKLE	Fl/ex	1.6	3.3
	Int/ext	3.9	10.3
	Ab/add	3.5	10.9

Della Croce et al., Medical & Biol. Eng. & Comp., 1999

joint kinematics precision

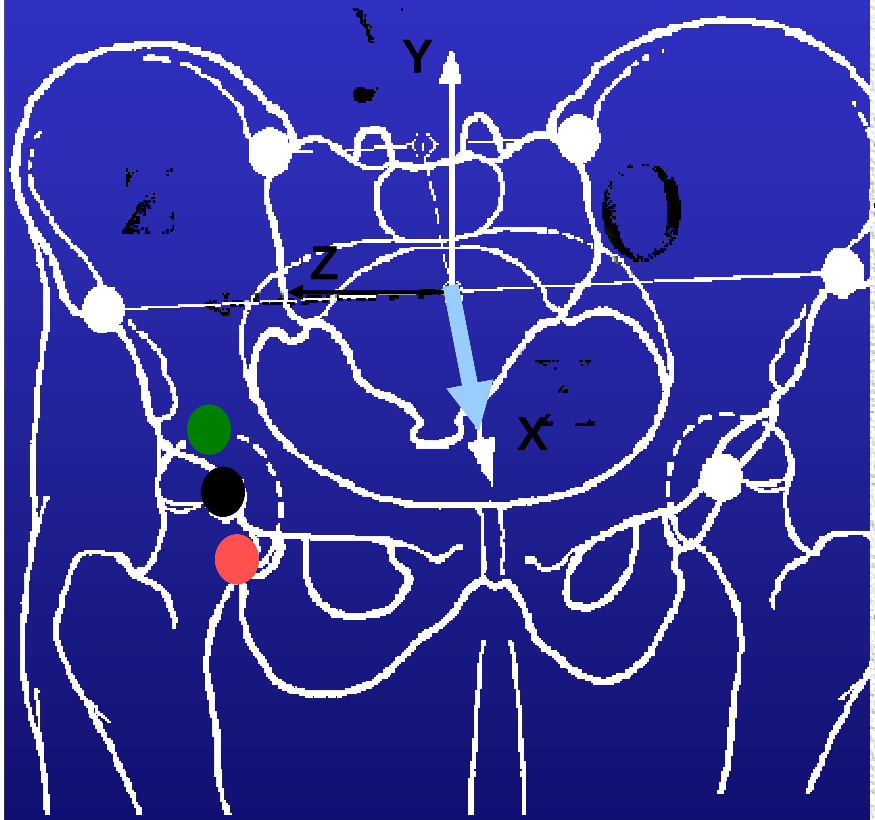
flexion-extension

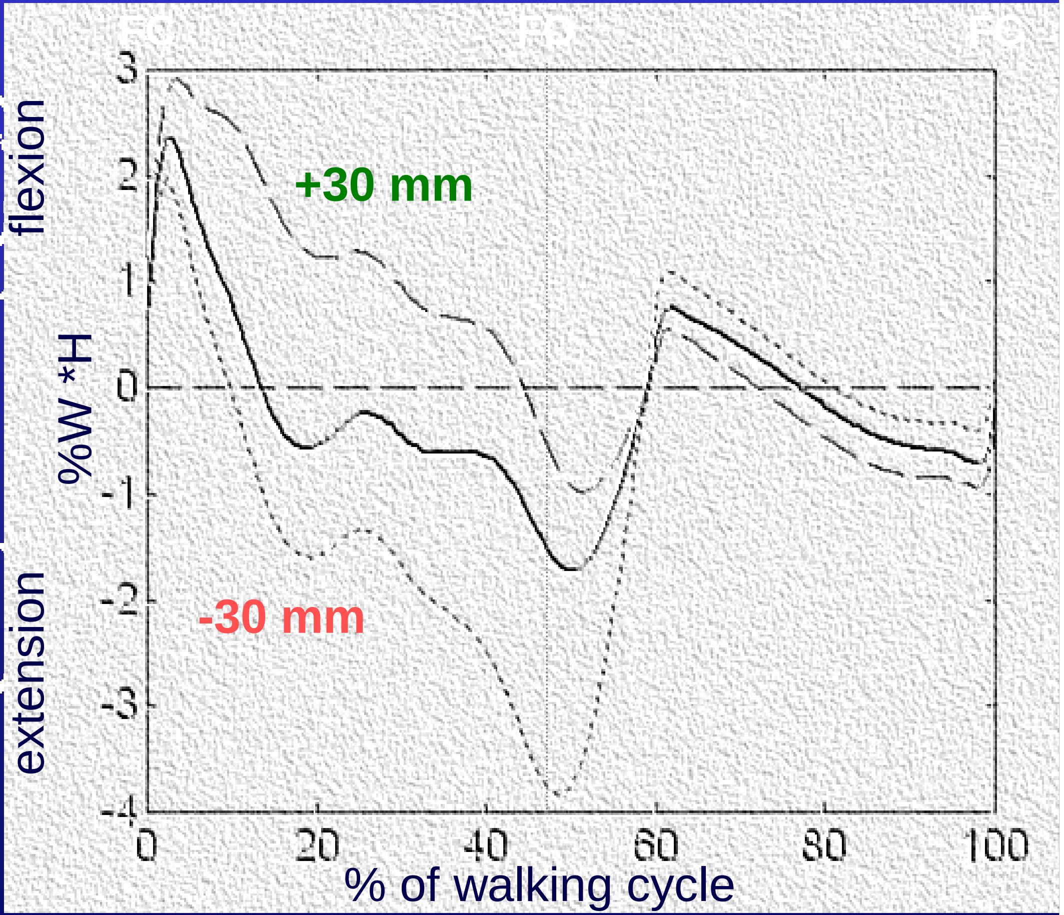




Della Croce et al., Medical & Biol. Eng. & Comp., 1999

FLEXION-EXTENSION MUSCULAR MOMENT AT THE HIP

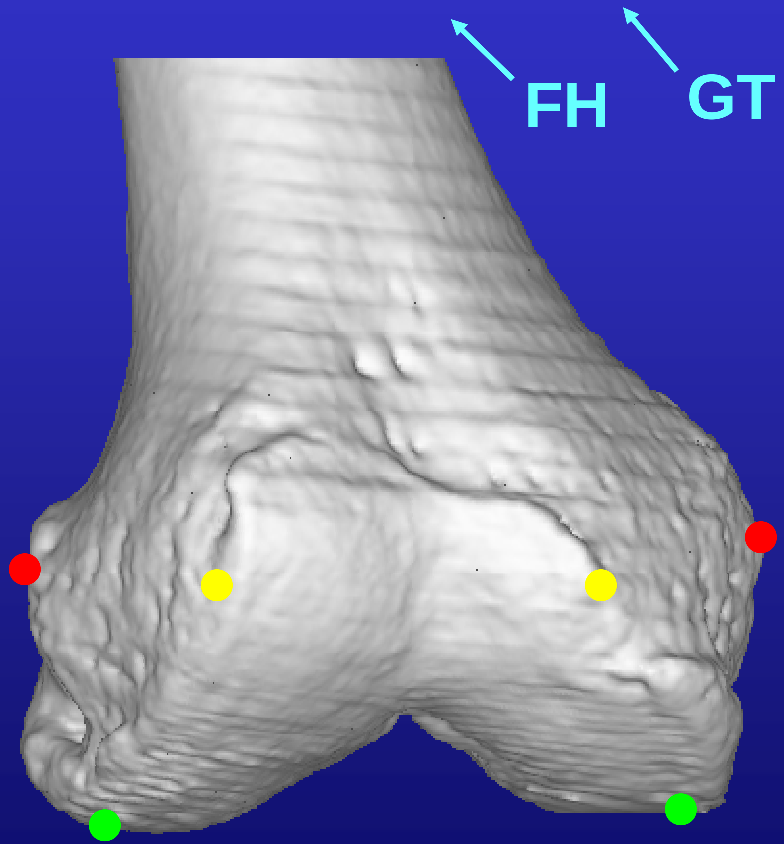




Stagni et al., Journal of Biomechanics, 2000

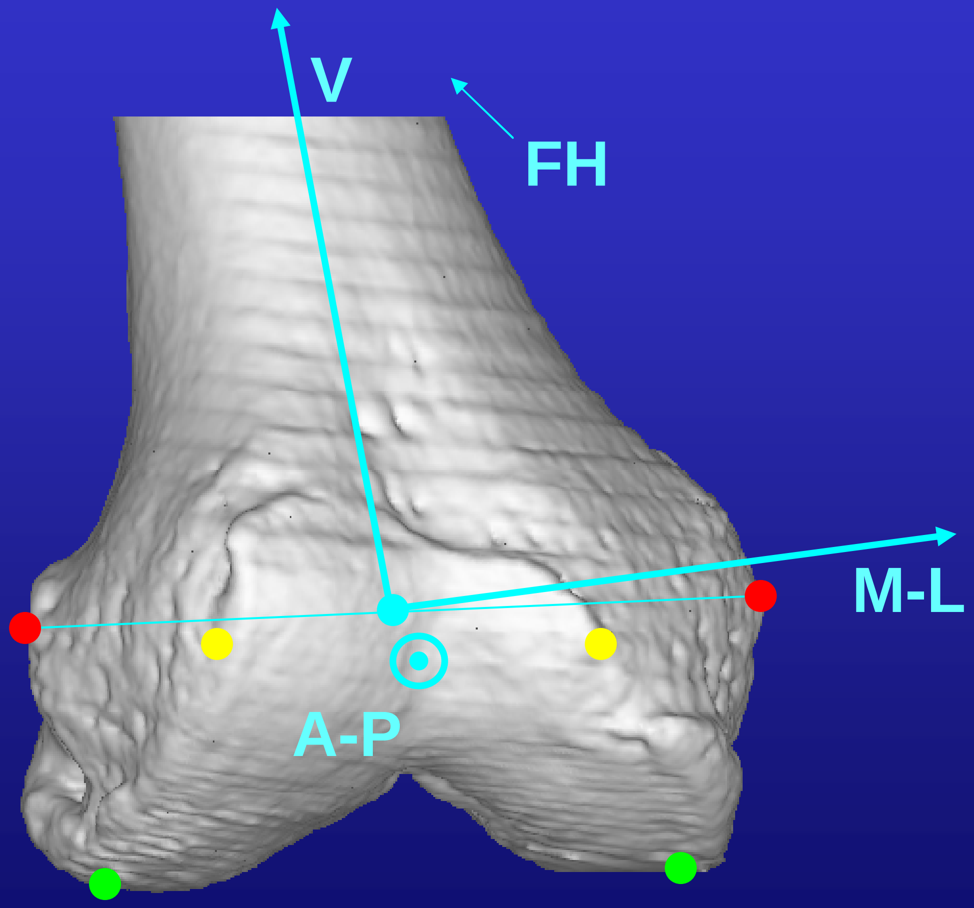
additional anatomical landmarks

- LE and ME
- LC and MC
- LP and MP



Bone-embedded Anatomical Frame (BAF)

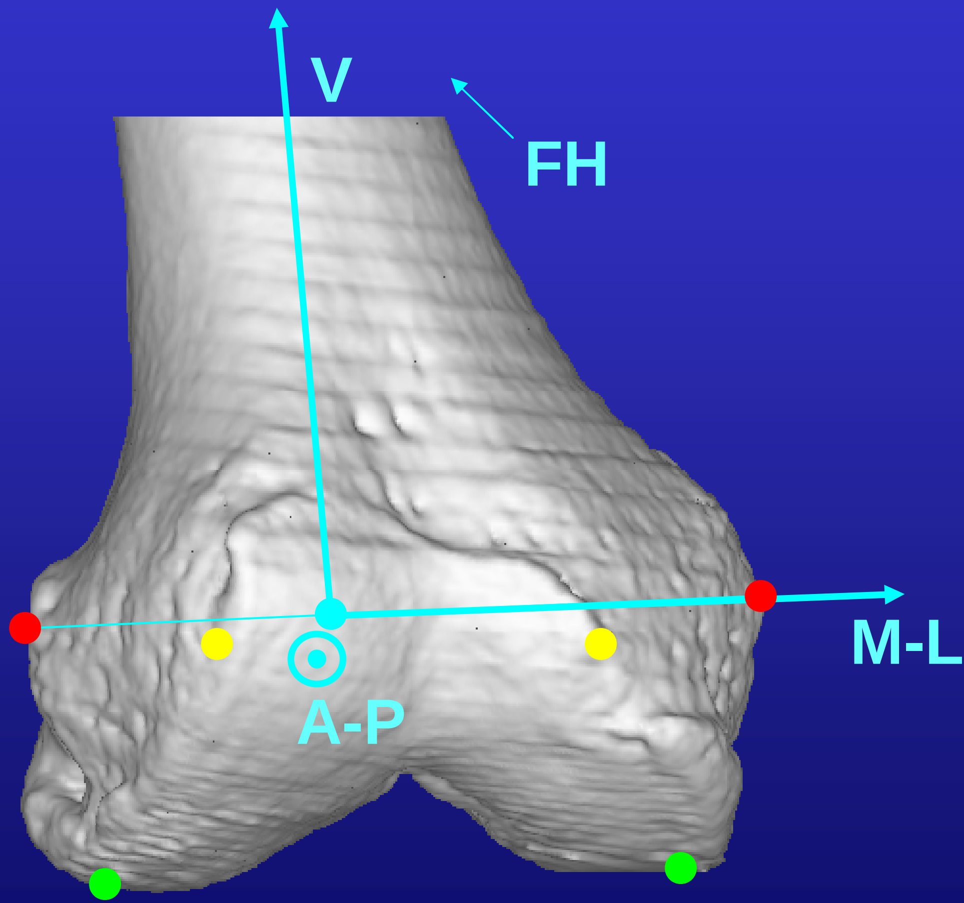
- LE and ME
- LC and MC
- LP and MP



(BAF1)

additional BAF (2)

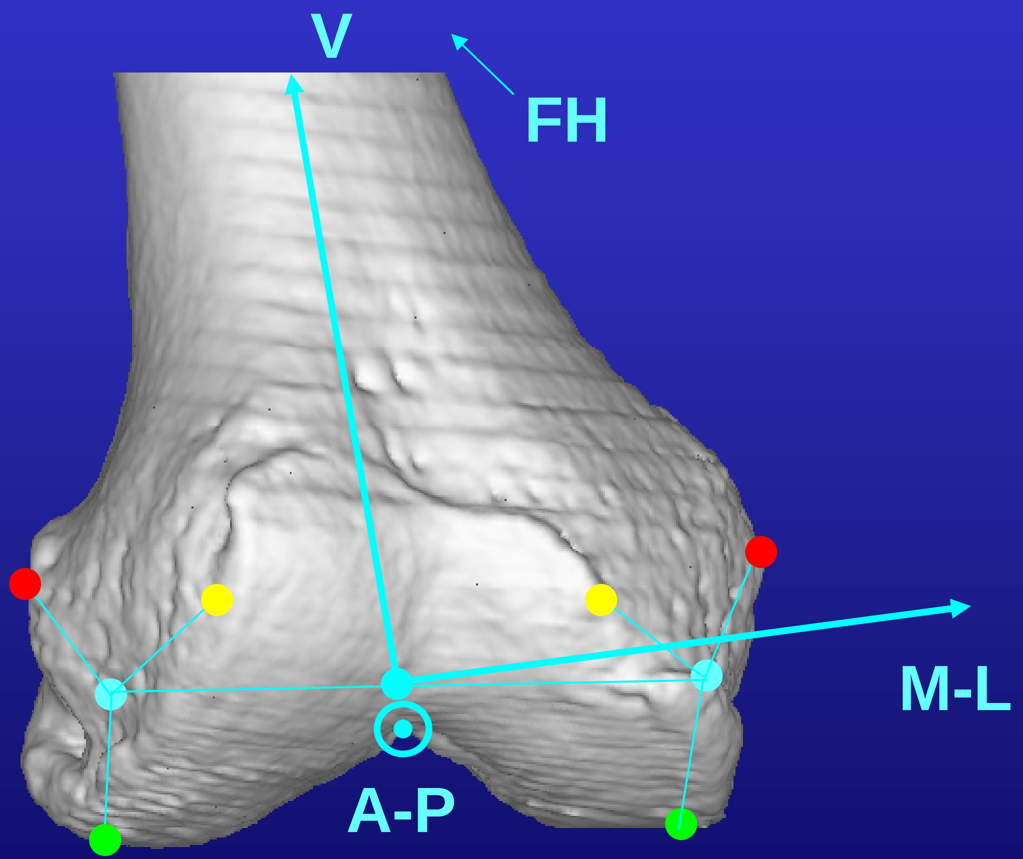
- LE and ME
- LC and MC
- LP and MP



(BAF1)
(BAF2)

additional BAF (3)

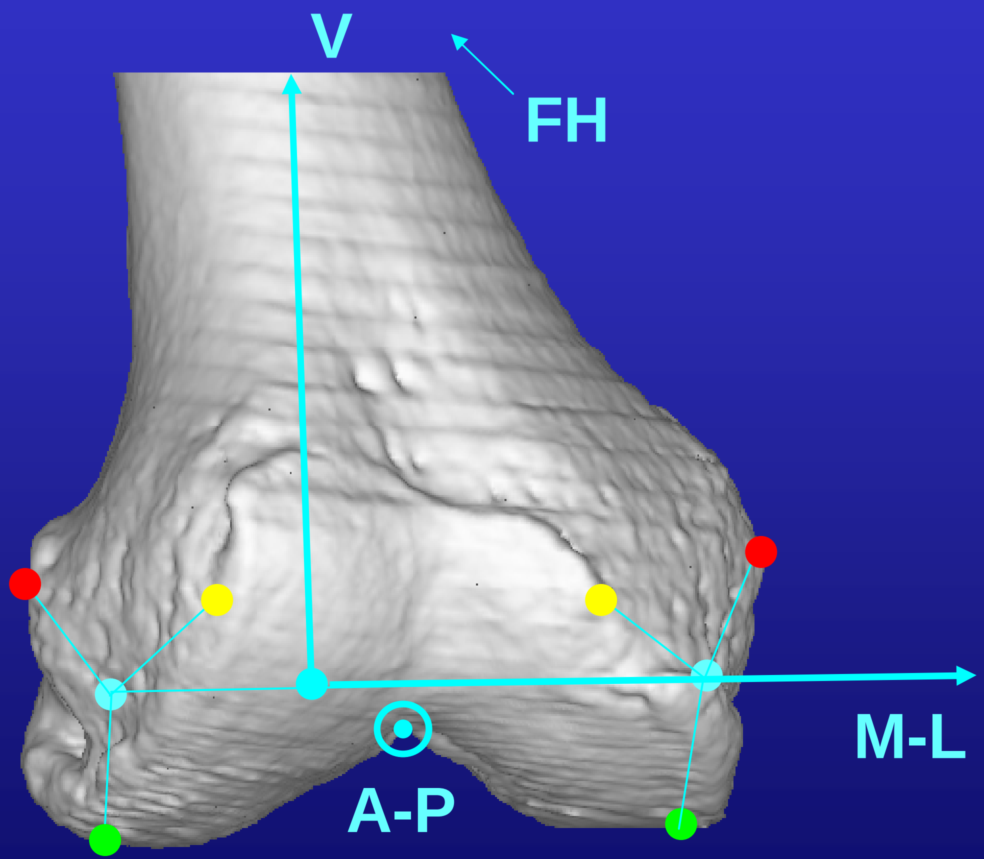
- LE and ME
- LC and MC
- LP and MP



(BAF1)
(BAF2)
(BAF3)

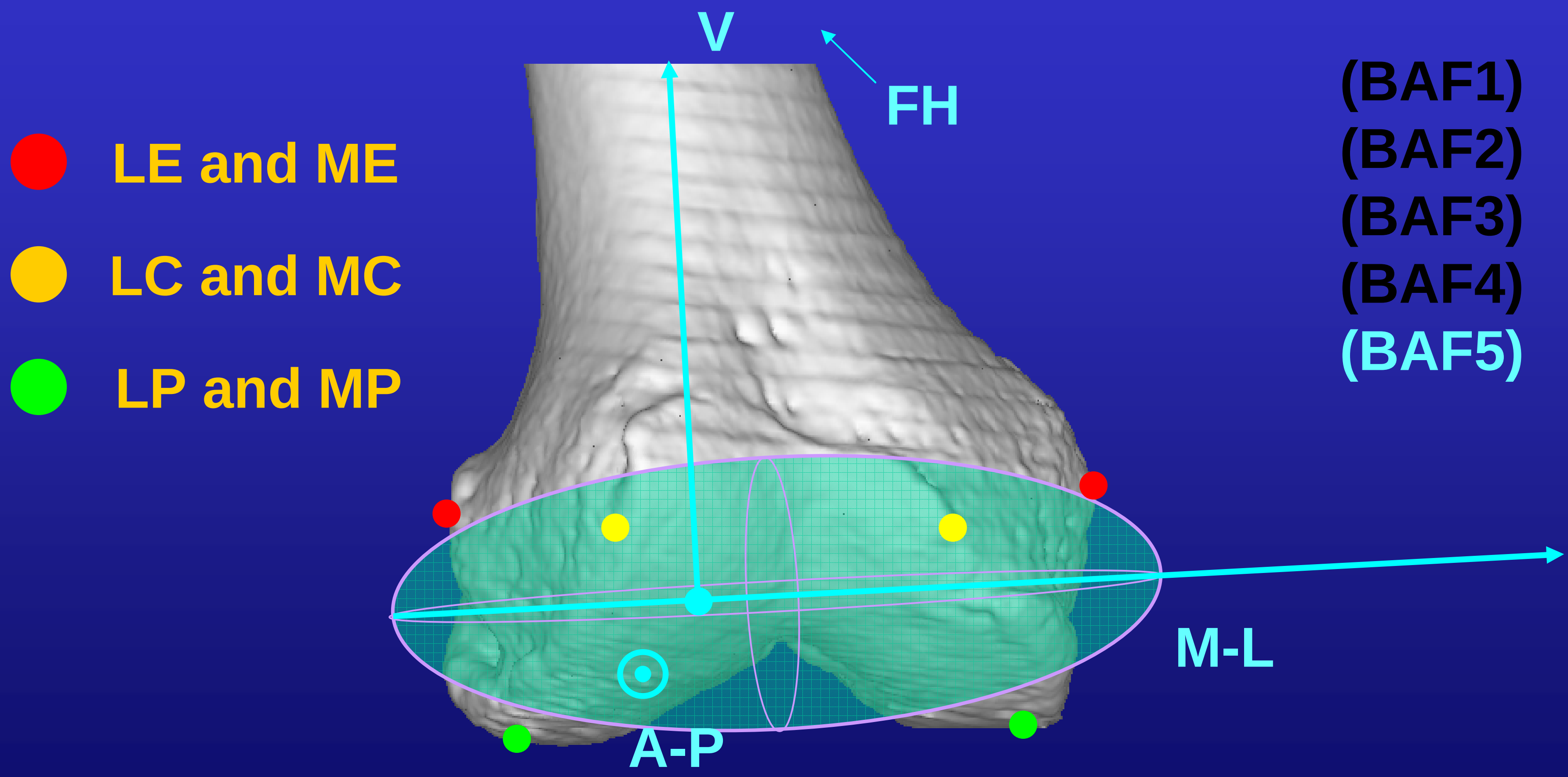
additional BAF (4)

- LE and ME
- LC and MC
- LP and MP

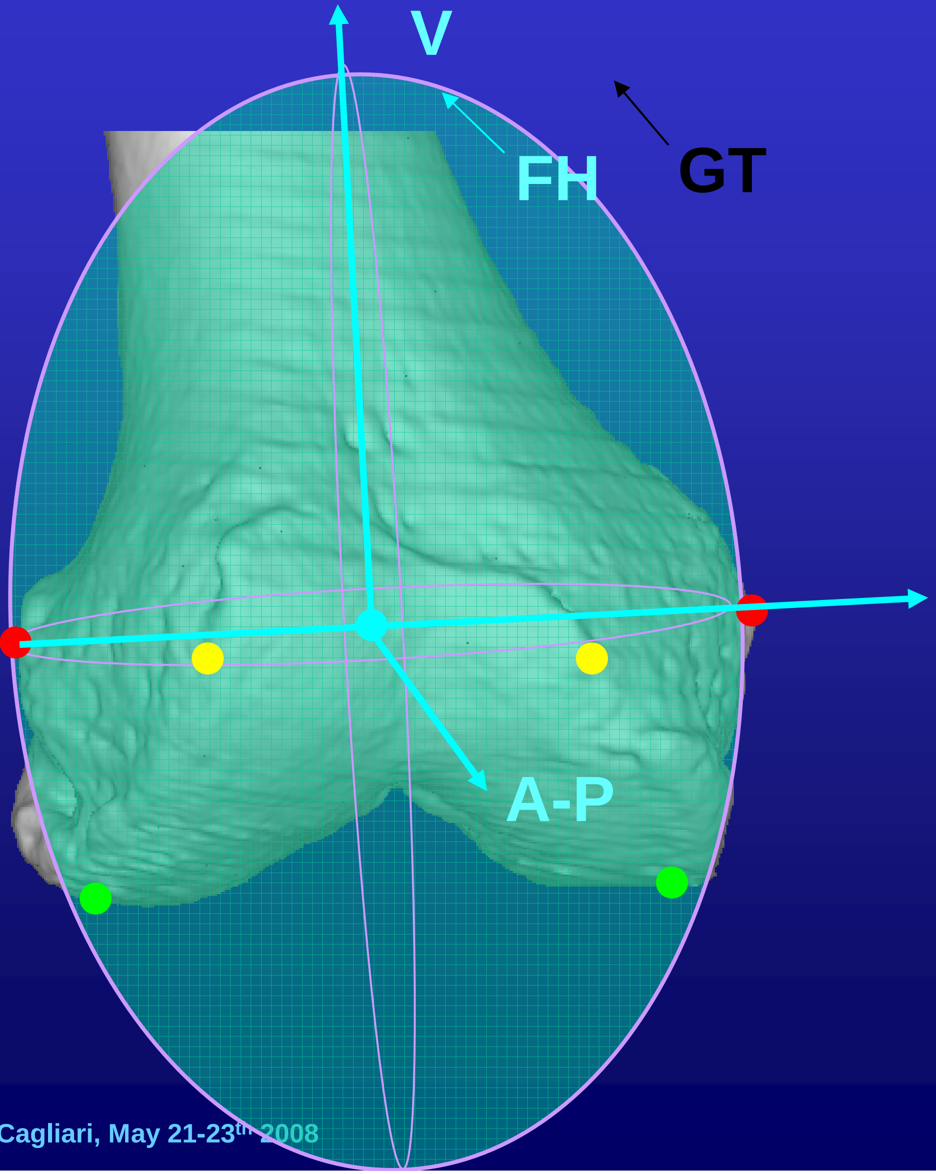


(BAF1)
(BAF2)
(BAF3)
(BAF4)

additional BAF (5)



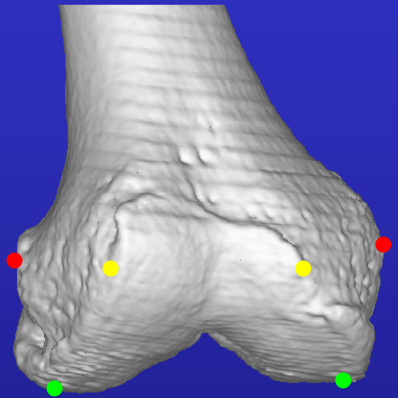
additional BAF (6)

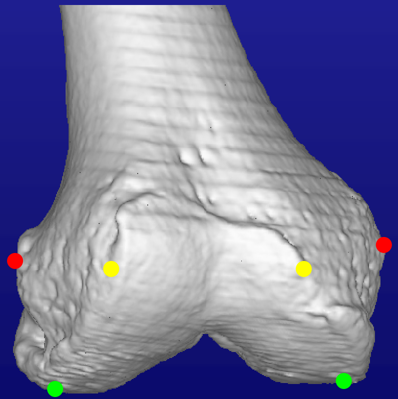


- LE and ME
- LC and MC
- LP and MP

(BAF1)
(BAF2)
(BAF3)
(BAF4)
(BAF5)
(BAF6)

additional BAF (7)





SVD

(BAF1)
(BAF2)
(BAF3)
(BAF4)
(BAF5)
(BAF6)
(BAF7)

$$ {}^{\bar{a}}\mathbf{X} = \begin{bmatrix} {}^{\bar{a}}\mathbf{x}_{GT} & {}^{\bar{a}}\mathbf{x}_{LE} & {}^{\bar{a}}\mathbf{x}_{ME} & {}^{\bar{a}}\mathbf{x}_{LP} & {}^{\bar{a}}\mathbf{x}_{MP} & {}^{\bar{a}}\mathbf{x}_{LC} & {}^{\bar{a}}\mathbf{x}_{MC} & {}^{\bar{a}}\mathbf{x}_{FH} \end{bmatrix} $$

results

%	A-P	V	M-L
BAF2	-190.9	0.5	-4.3
BAF3	15.5	25	9.5
BAF4	-65.1	25.1	9
BAF5	-140	21.5	7.7
BAF6	31.2	8.3	17.6
BAF7	22.7	76.9	-162

recent advances

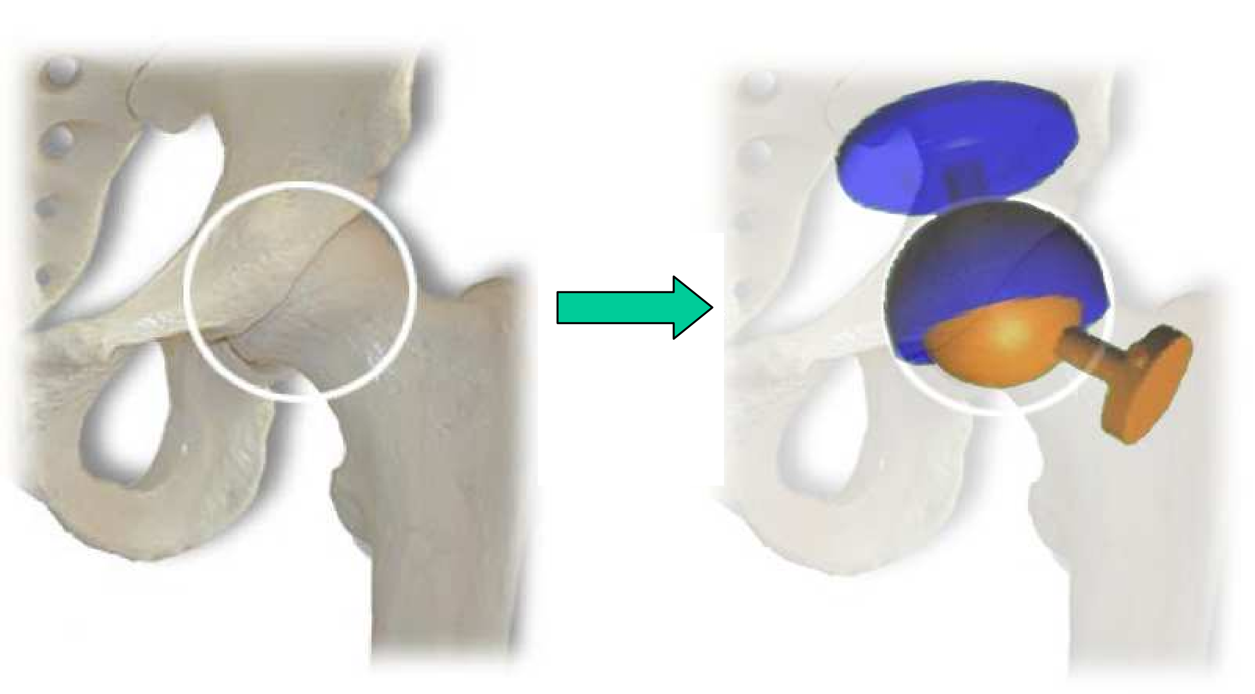
- optimization of functional methods for joint modelling
- augmented anatomical landmark identification

provided in part by

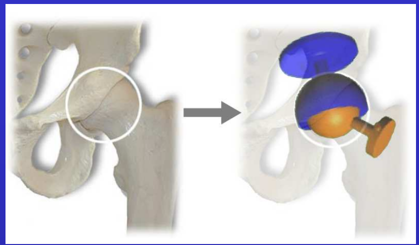
Department of Human Movement and Sport Sciences
University Institute for Movement Science
Rome, Italy

optimization of functional methods for joint modelling

hip : spherical joint



optimization of functional methods for joint modelling



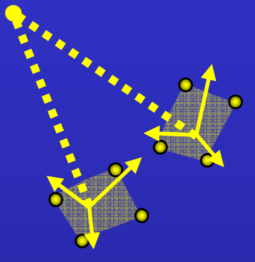
functional approach

HJC:
relative rotation center between pelvis and femur

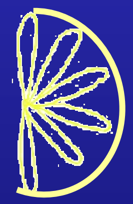
optimization of functional methods for joint modelling

hip : spherical joint

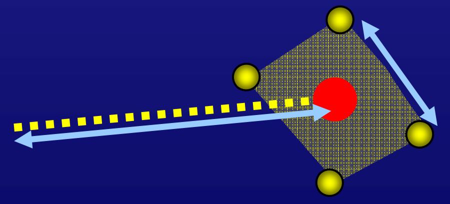
- best algorithm



- more suitable movement



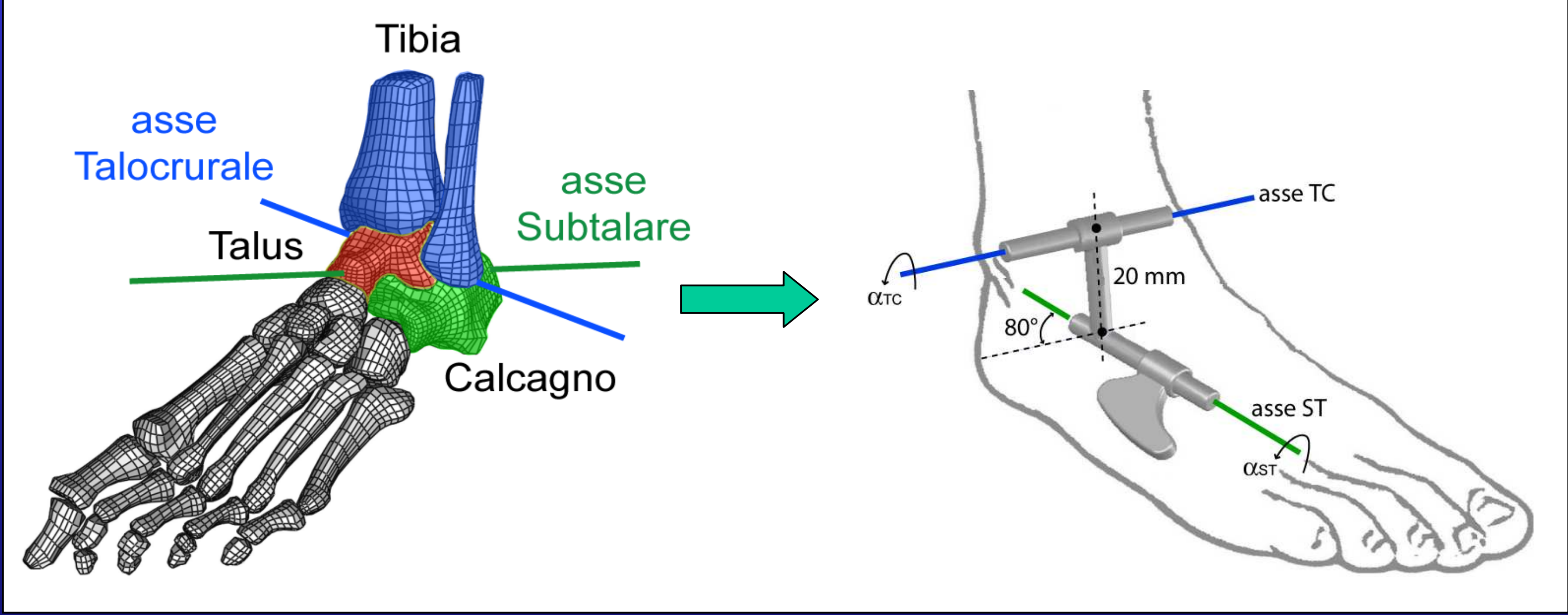
- criteria for marker cluster design



Cereatti et al. (2004)
Camomilla et al. (2006)

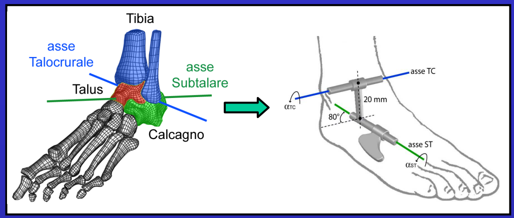
optimization of functional methods for joint modelling

ankle : universal joint



2 degrees of freedom → 3 angular rotations
3 linear displacements

optimization of functional methods for joint modelling



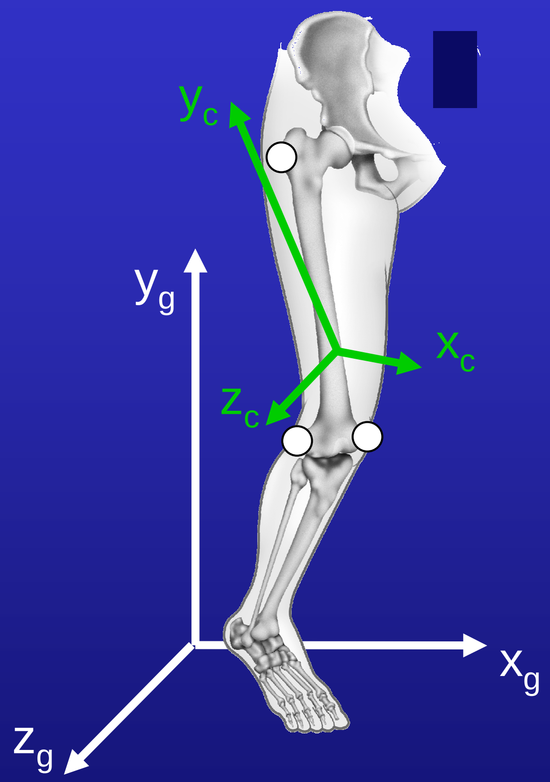
functional approach

axes positions and orientations

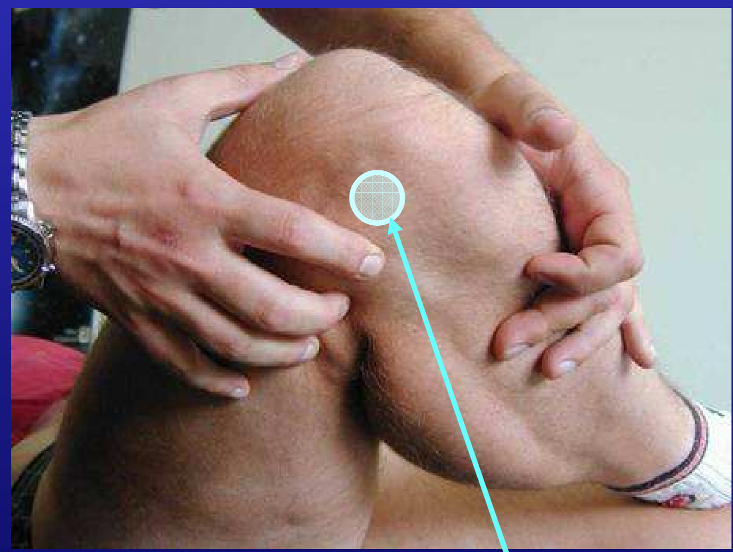
recent advances

- optimization of functional methods for joint modelling
- anatomical landmark identification

anatomical calibration: traditional approach



superficial anatomical landmarks
are identified by palpation



lateral epicondyle

$${}^{c}\mathbf{a}_i = \left[{}^{c}a_{xi} \quad {}^{c}a_{yi} \quad {}^{c}a_{zi}\right],\ \mathrm{i} = 1,\ldots,\mathrm{r}$$

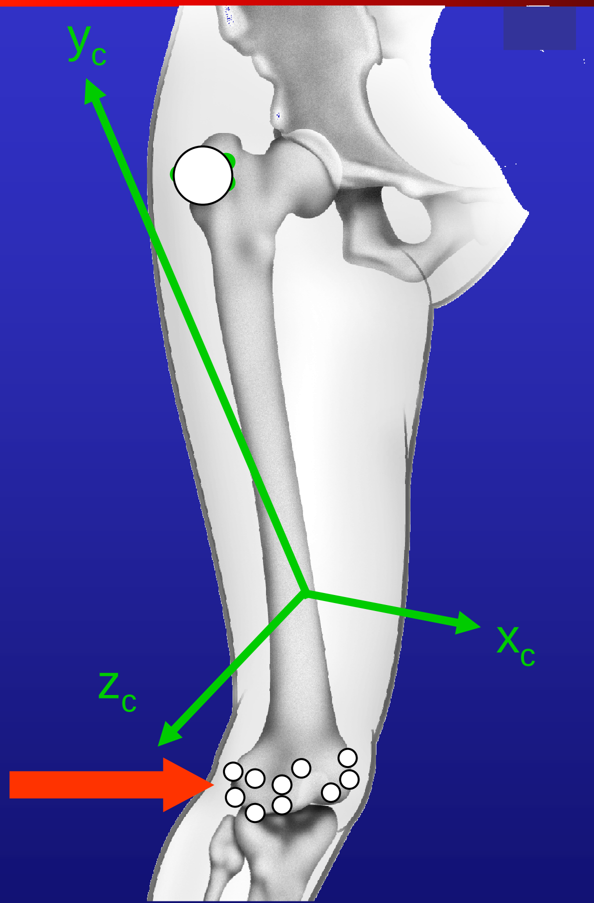
anatomical calibration: traditional approach

- selected anatomical landmarks

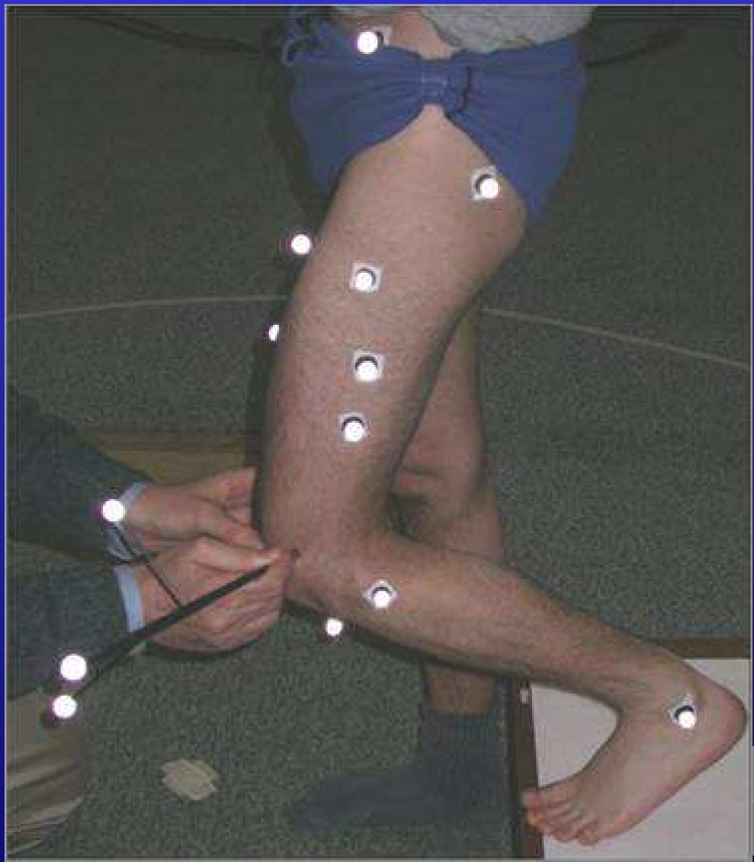
$$ {}^{c}\mathbf{a}_{i'} = \begin{bmatrix} {}^{c}a_{xi'} & {}^{c}a_{yi'} & {}^{c}a_{zi'} \end{bmatrix}, \ \mathrm{i} = \mathrm{i}' $$

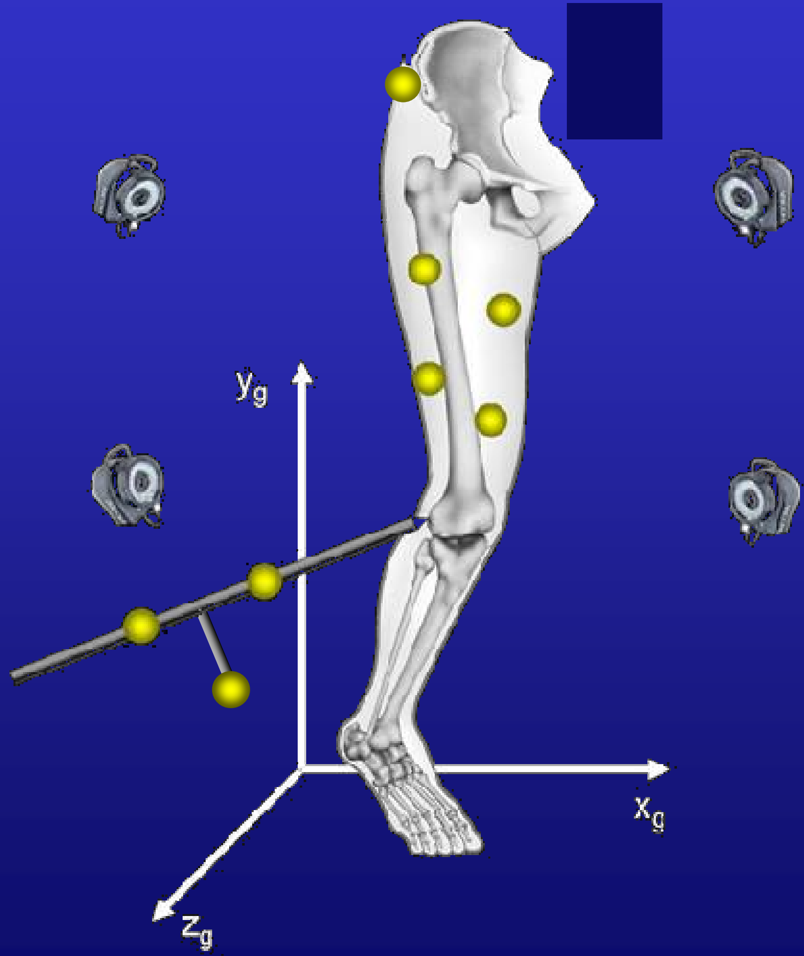
- unlabelled points
  selected in areas of the bone covered by a thin layer of soft tissues, so that the skin surface may be considered to coincide with the bone surface

$$ {}^{c}u_{i} = \begin{bmatrix} {}^{c}u_{xi} & {}^{c}u_{yi} & {}^{c}u_{zi} \end{bmatrix}, \ \mathrm{i} = 1,\ldots,\mathrm{r} $$



anatomical calibration: novel approach





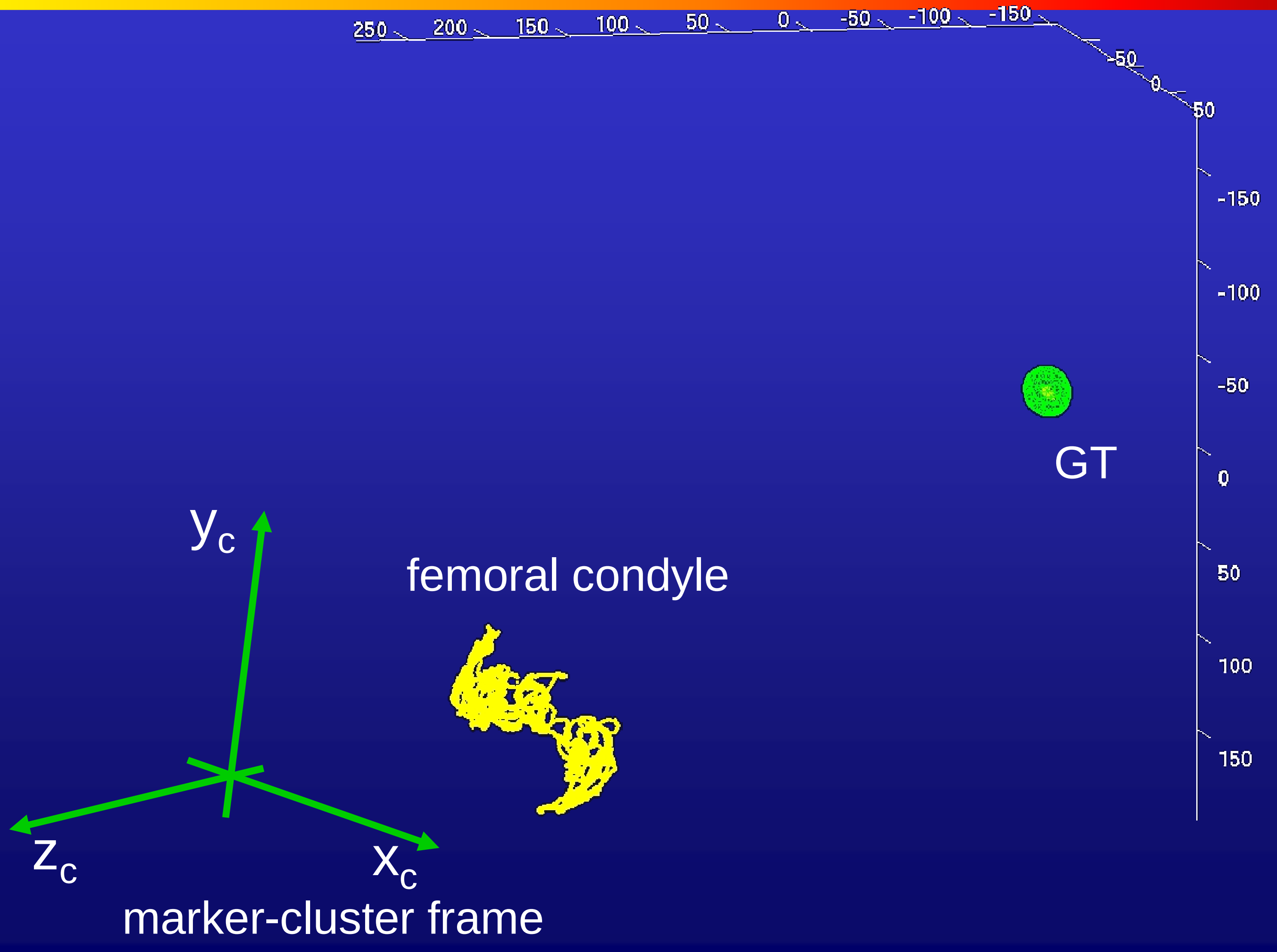
$$ {}^{g}\mathbf{u}_i = \begin{bmatrix} {}^{g}u_{xi} & {}^{g}u_{yi} & {}^{g}u_{zi} \end{bmatrix}, \quad i = 1,\ldots,r $$

Rozumalski A, Schwartz MH. Gait & Posture 2004

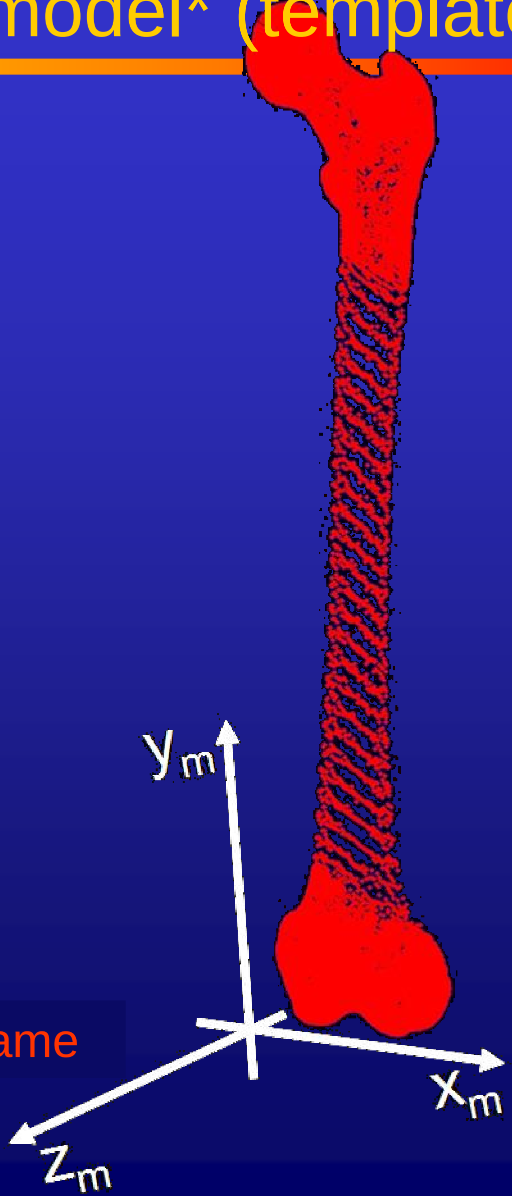
global position of unlabelled points of the bone surface

a wand carrying three non-aligned markers

points on the subject's bone surface as reconstructed using stereophotogrammetry



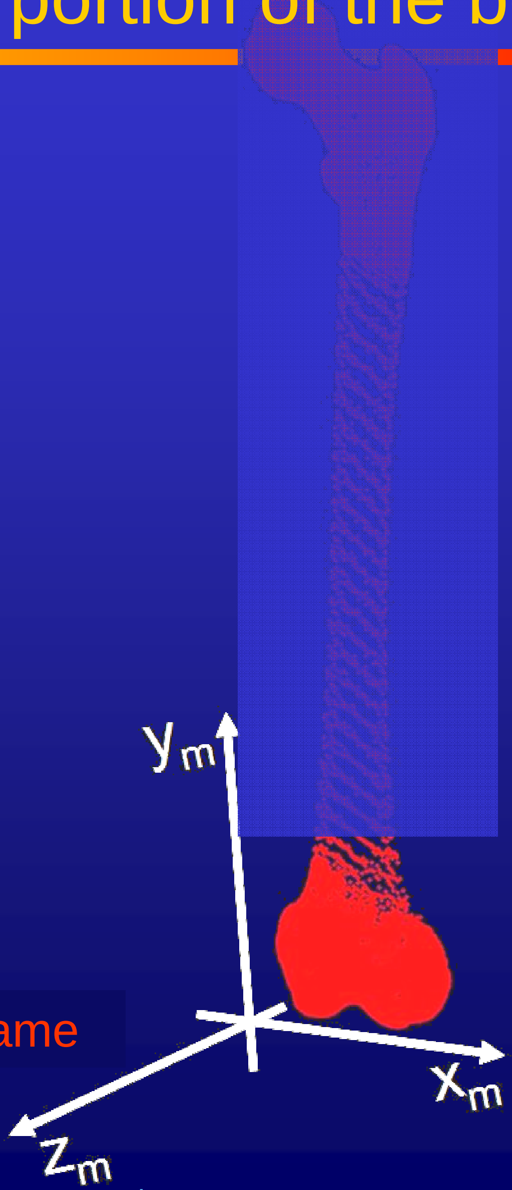
bone digital model* (template from database)



morphological frame

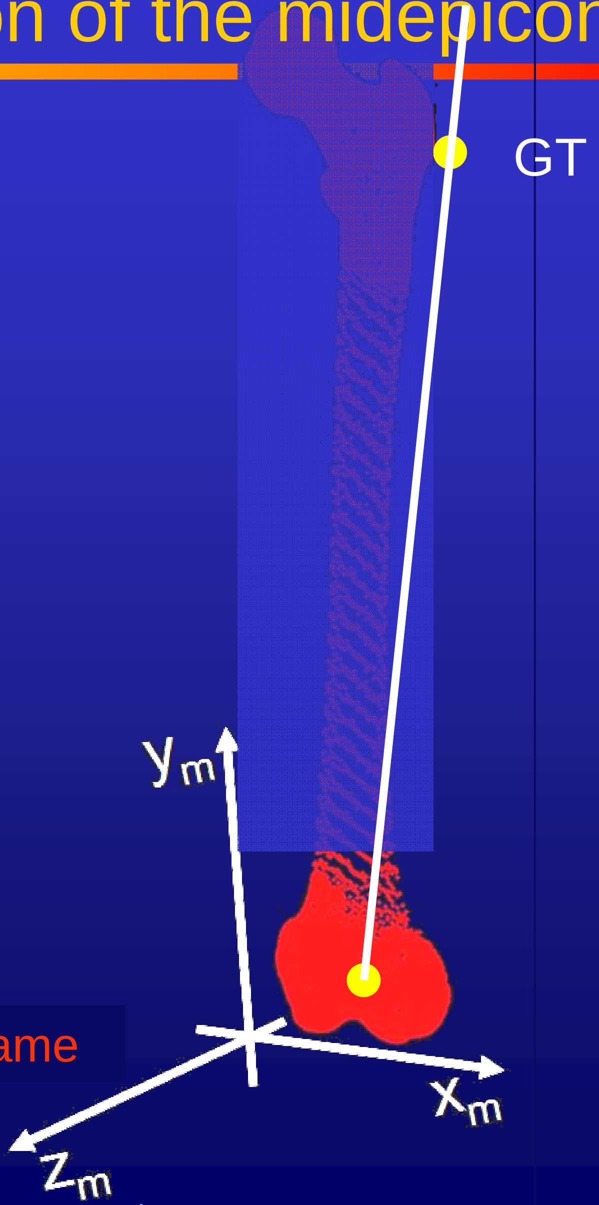
* Provided by
Laboratorio di Tecnologie
Biomediche at I.O.R - Bologna

the distal portion of the bone is isolated



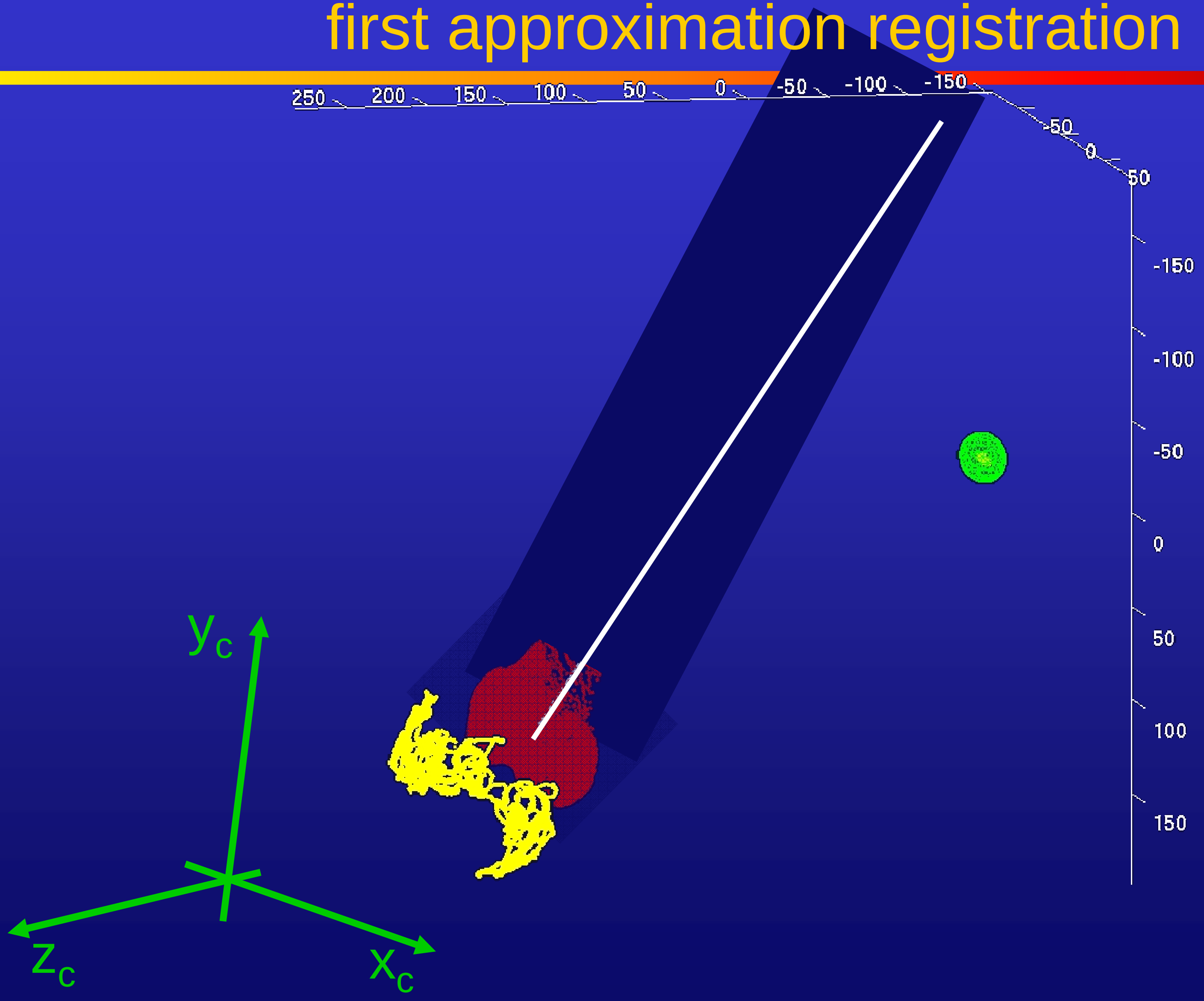
morphological frame

construction of the midepicondyle-GT line



morphological frame

first approximation registration



registration: iterative method

matching

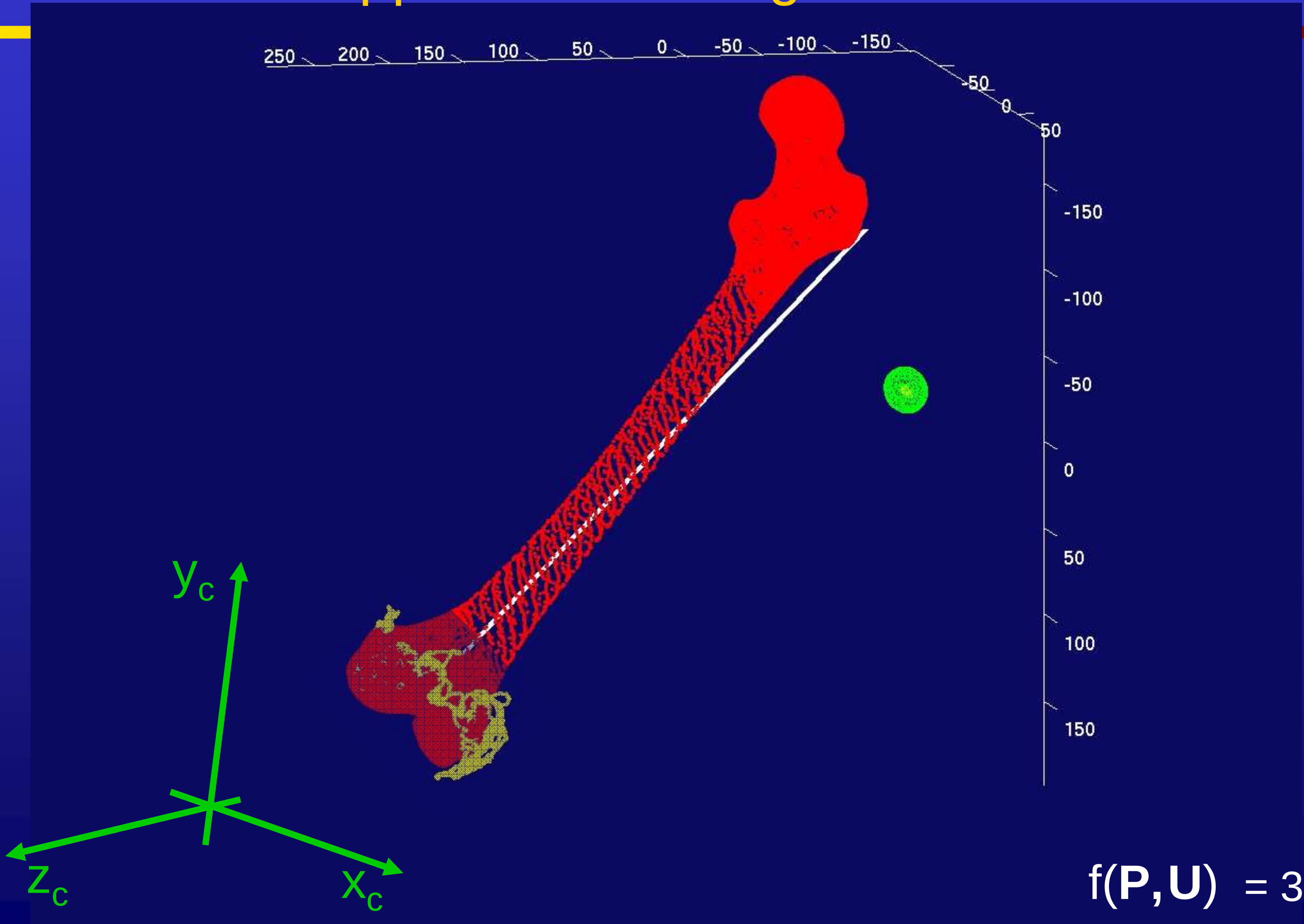
↓

Minimization of mean direct Hausdorff distance

Minimization was performed using a genetic algorithm

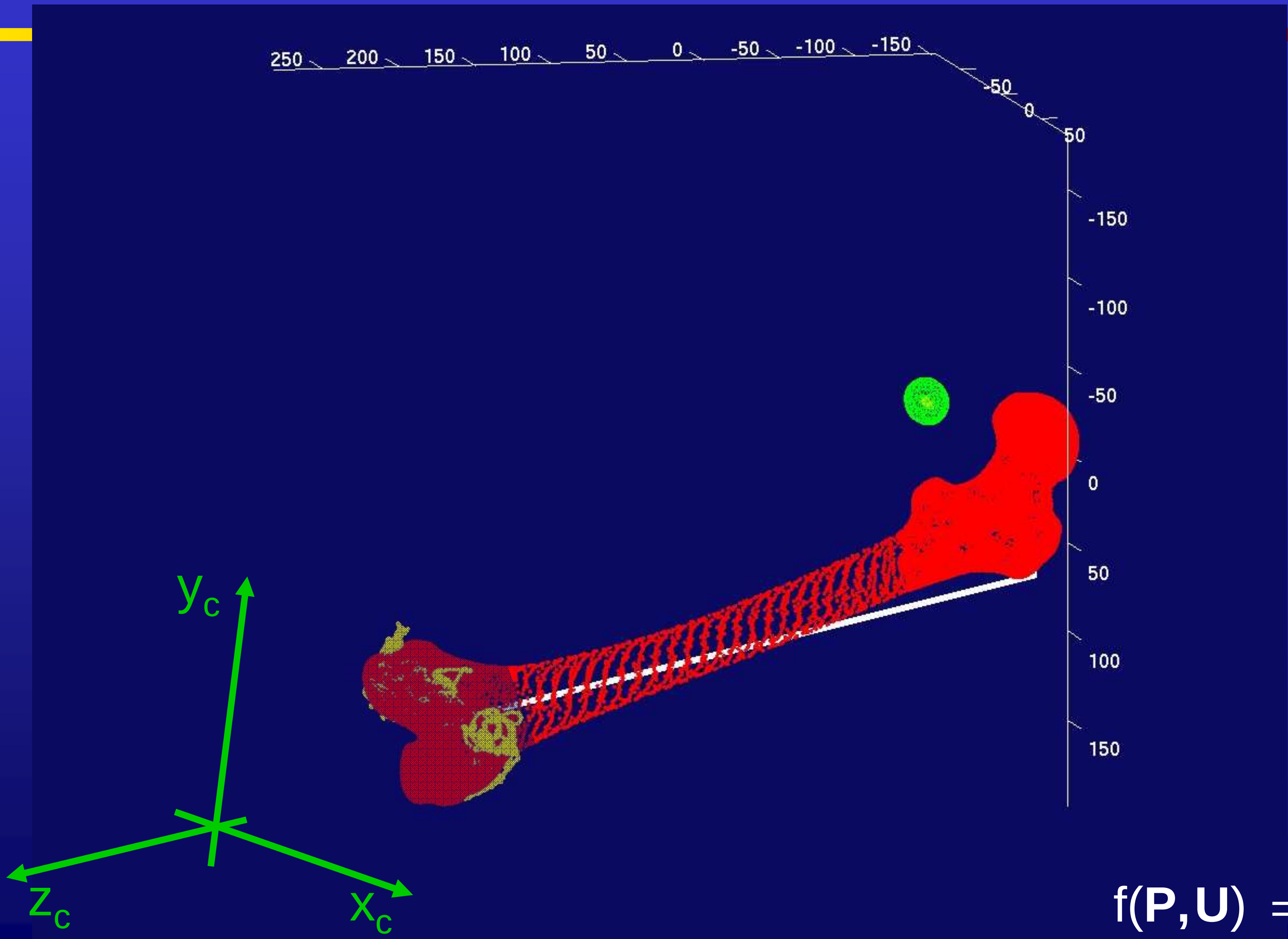
Michalewicz, Z. (1996). Genetic Algorithm + Data Structures = Evolution Programs. Springer-Verlag: New York

first approximation registration



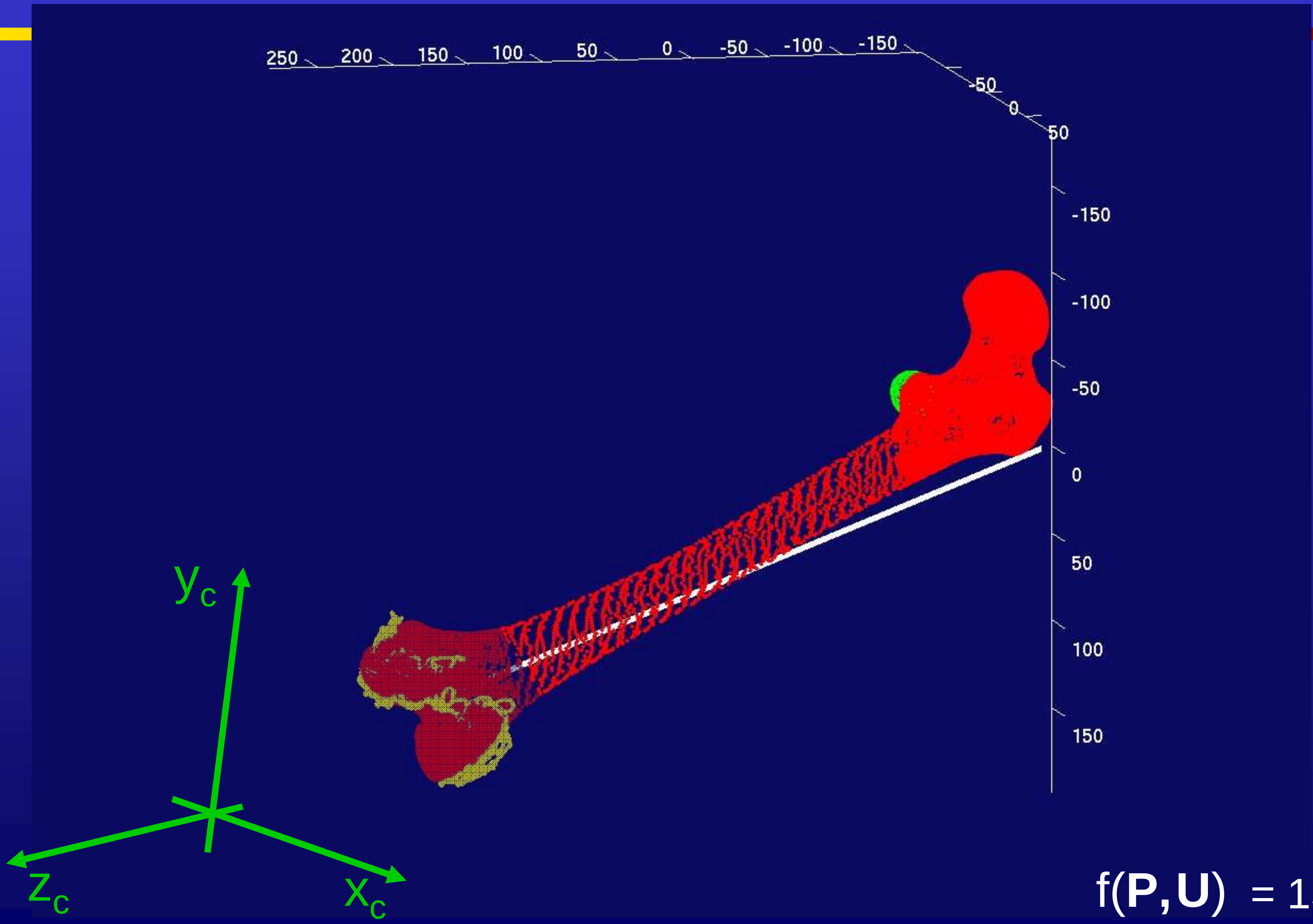
f(**P**,**U**) = 37788

iterations



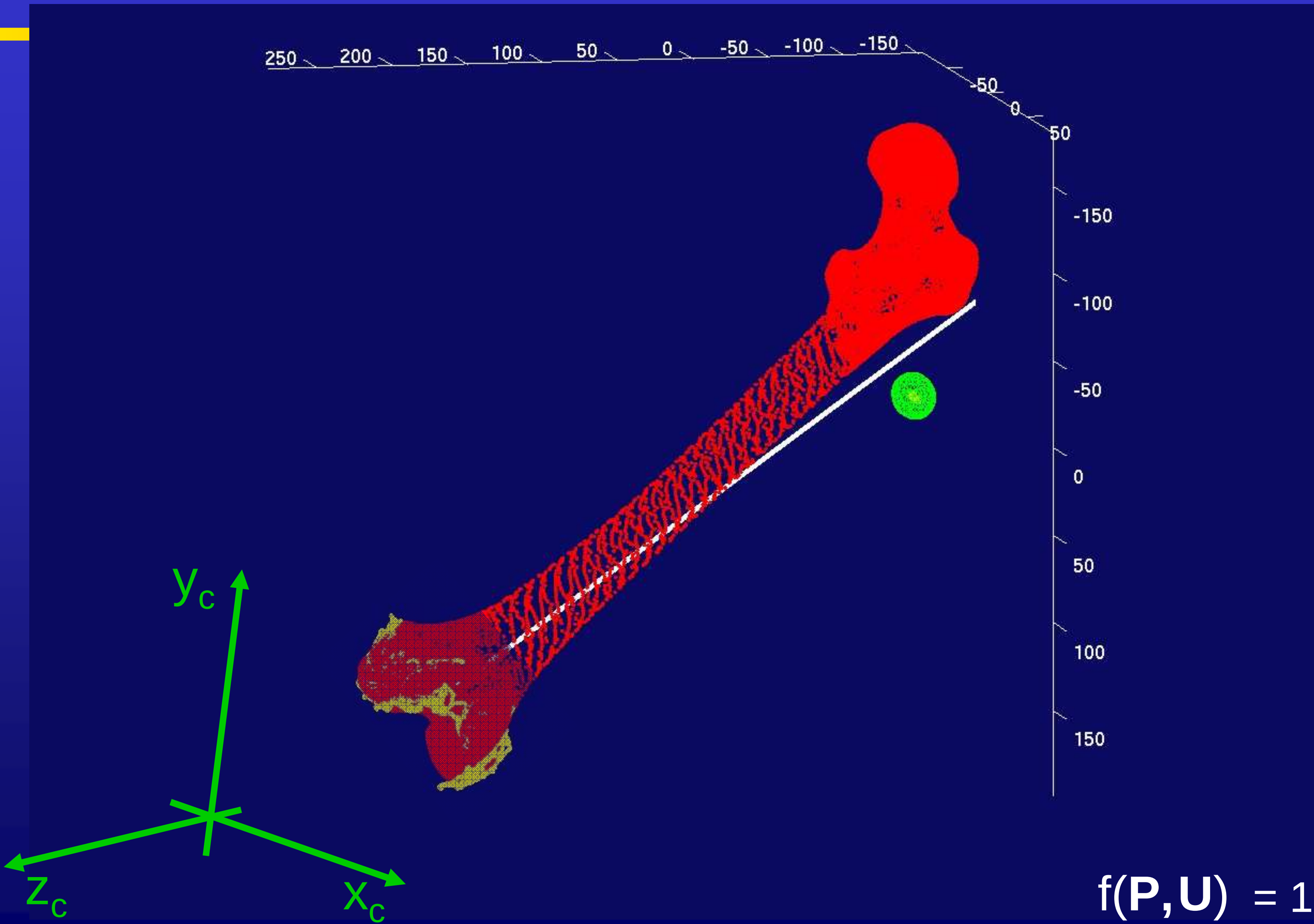
$f(\mathbf{P},\mathbf{U}) = 27528$

iterations



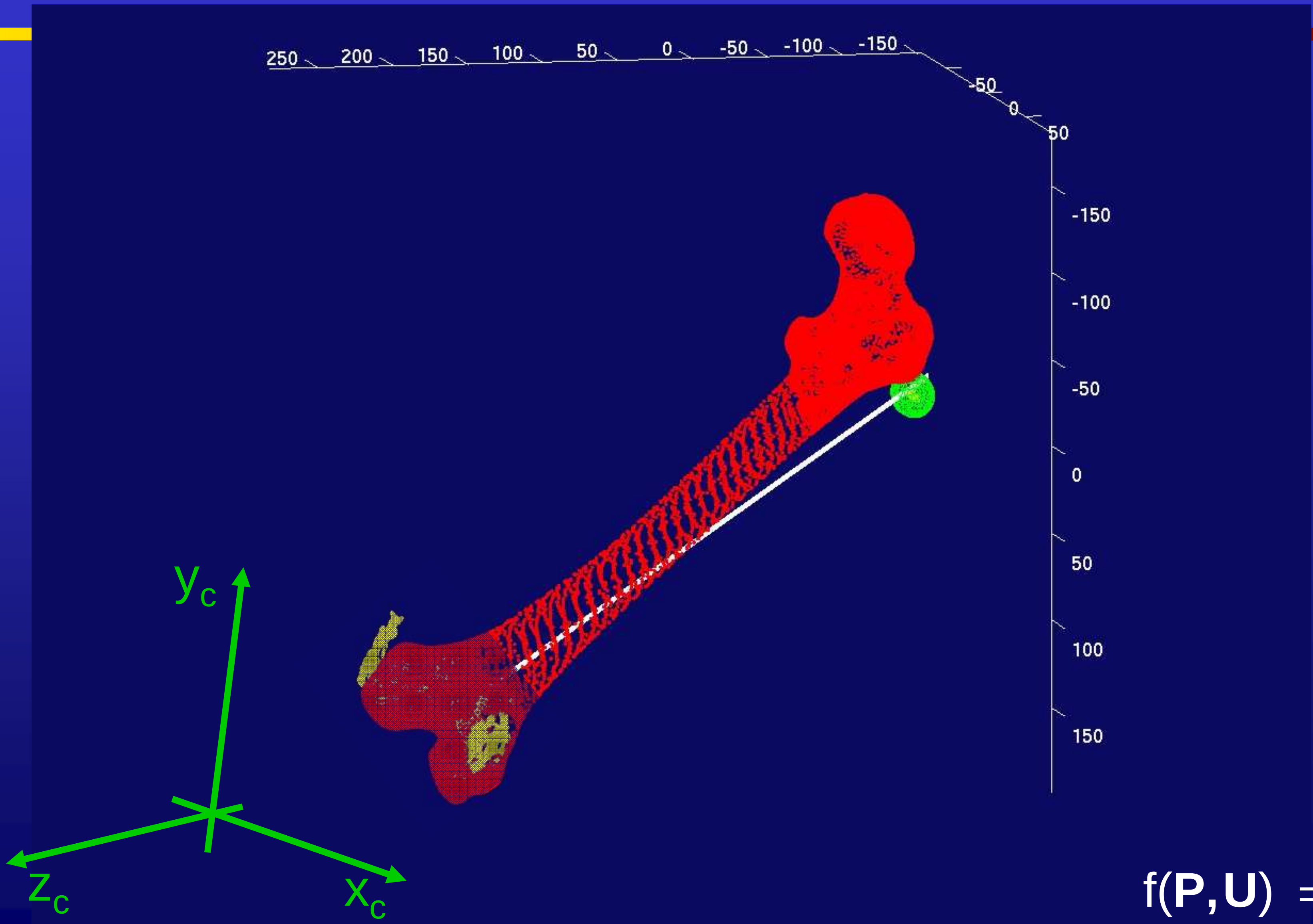
f(**P**,**U**) = 15698

iterations



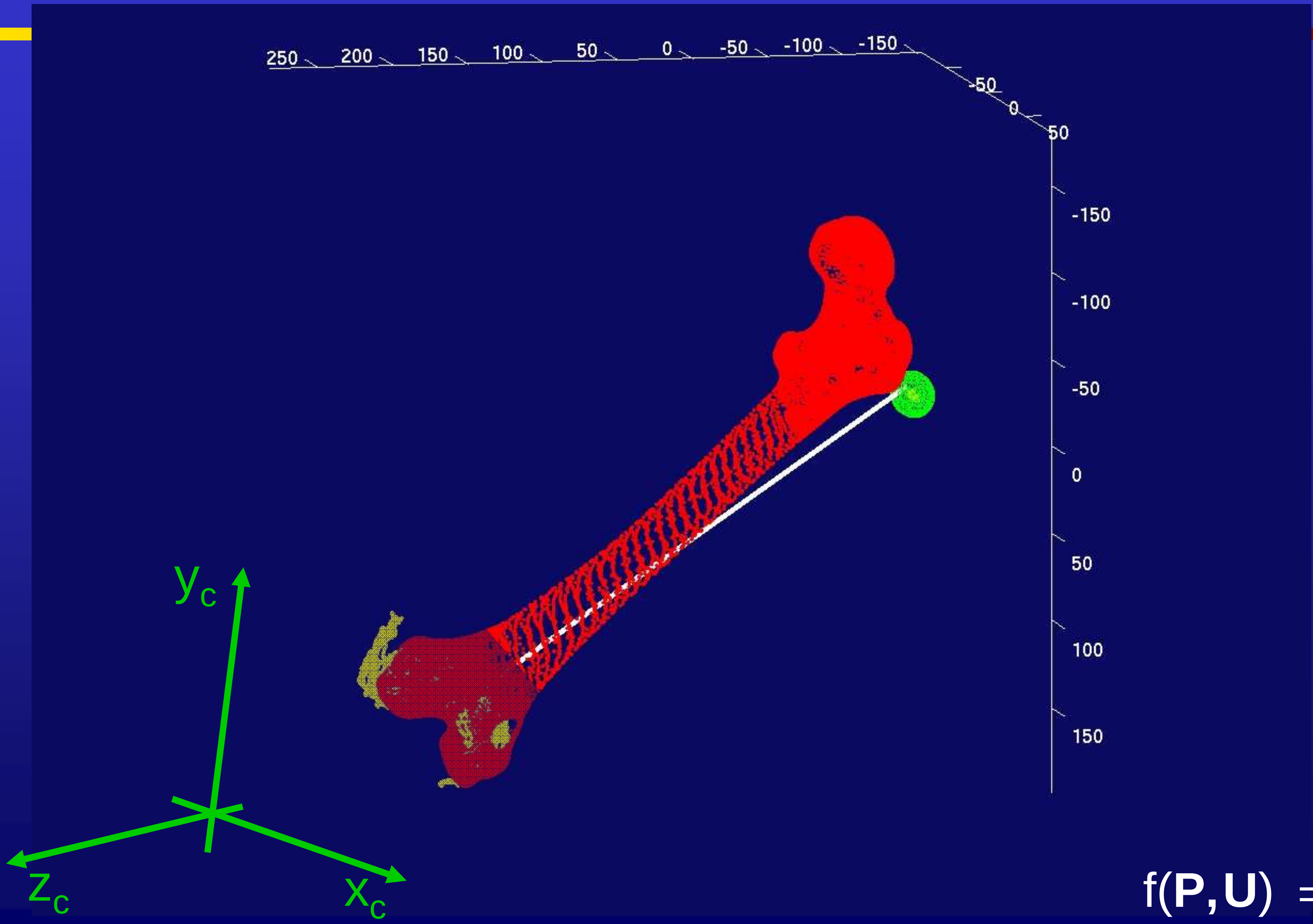
$f(\mathbf{P},\mathbf{U}) = 12307$

iterations



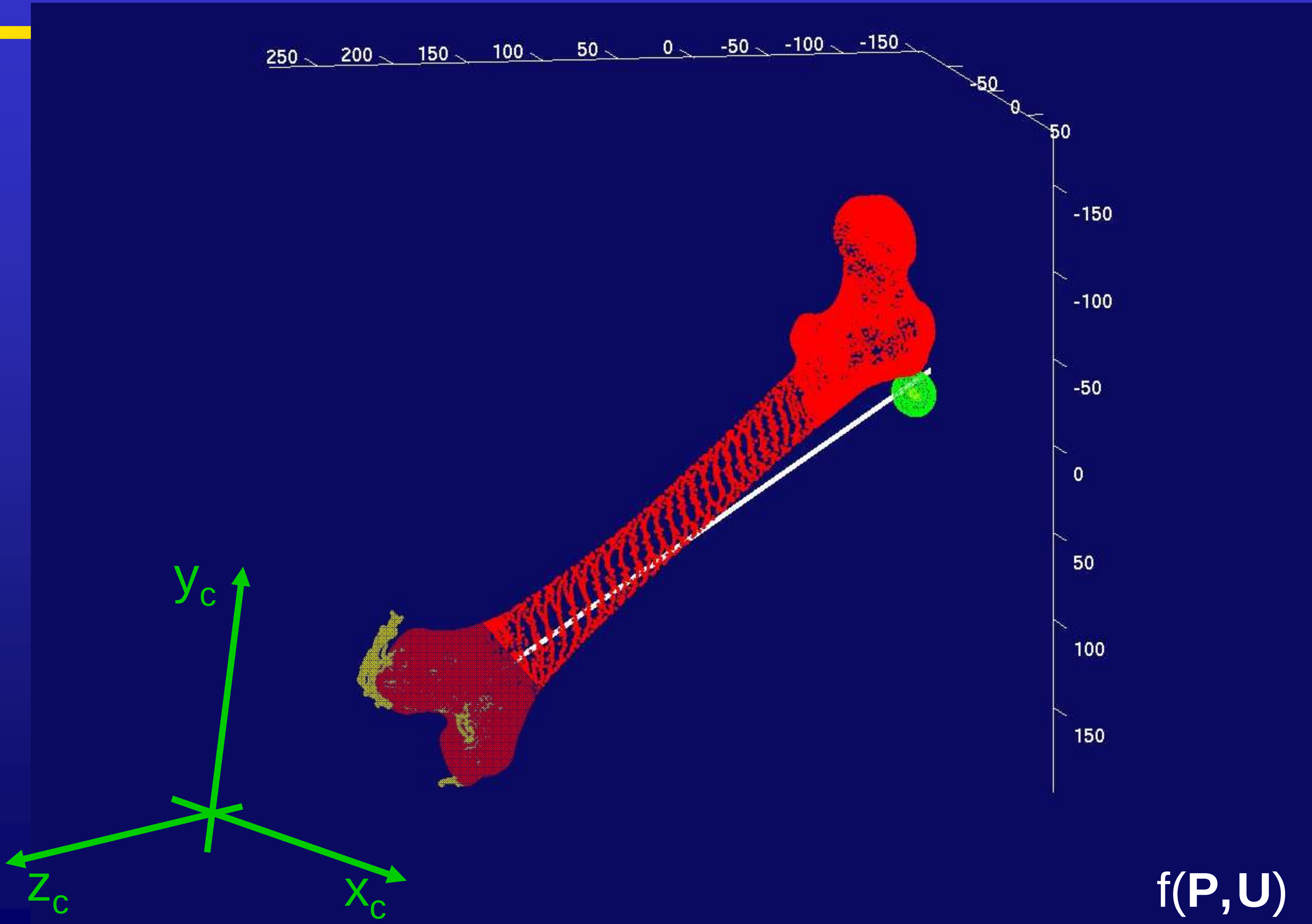
$f(\mathbf{P},\mathbf{U}) = 184$

iterations



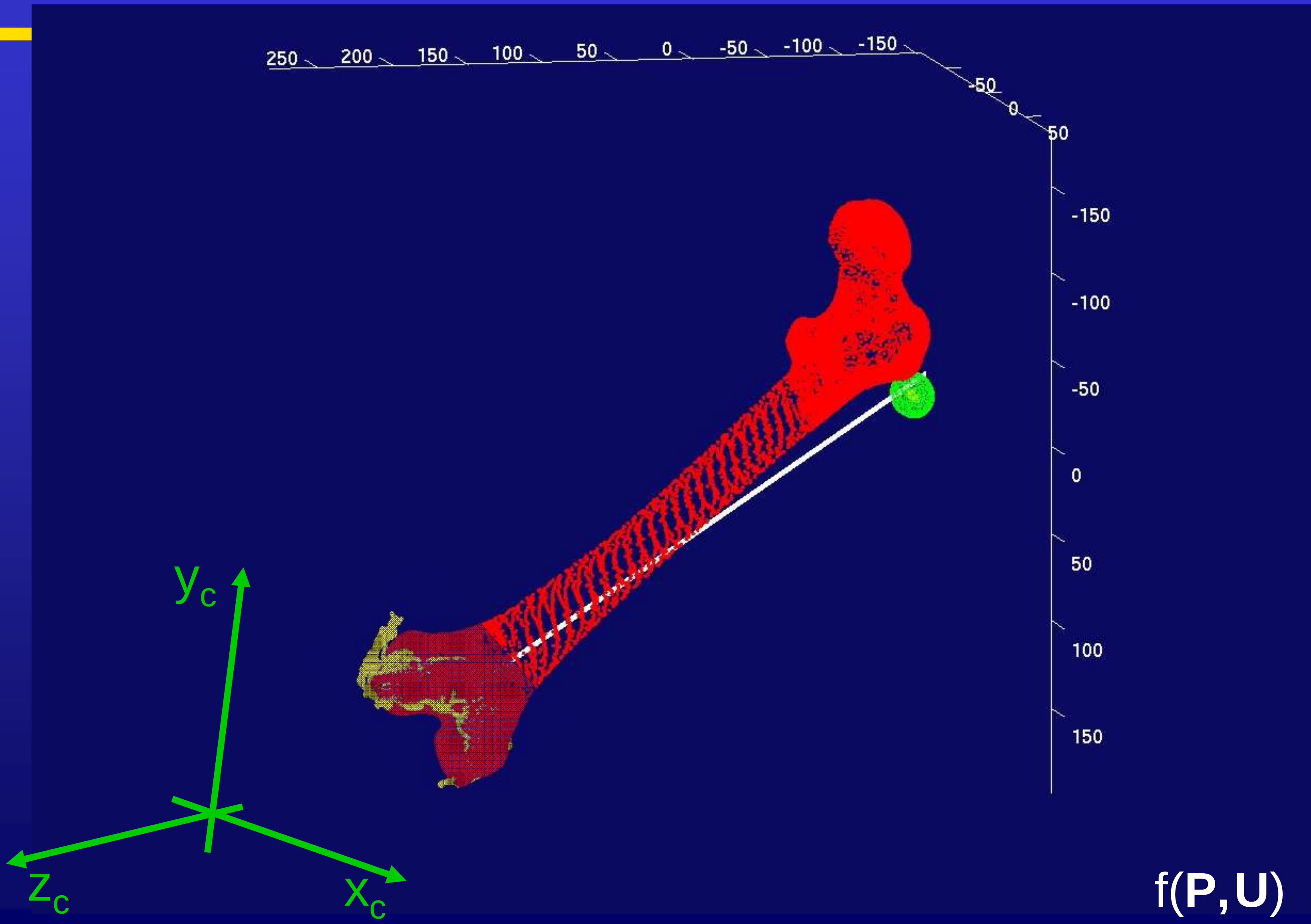
f(**P,U**) = 122

iterations



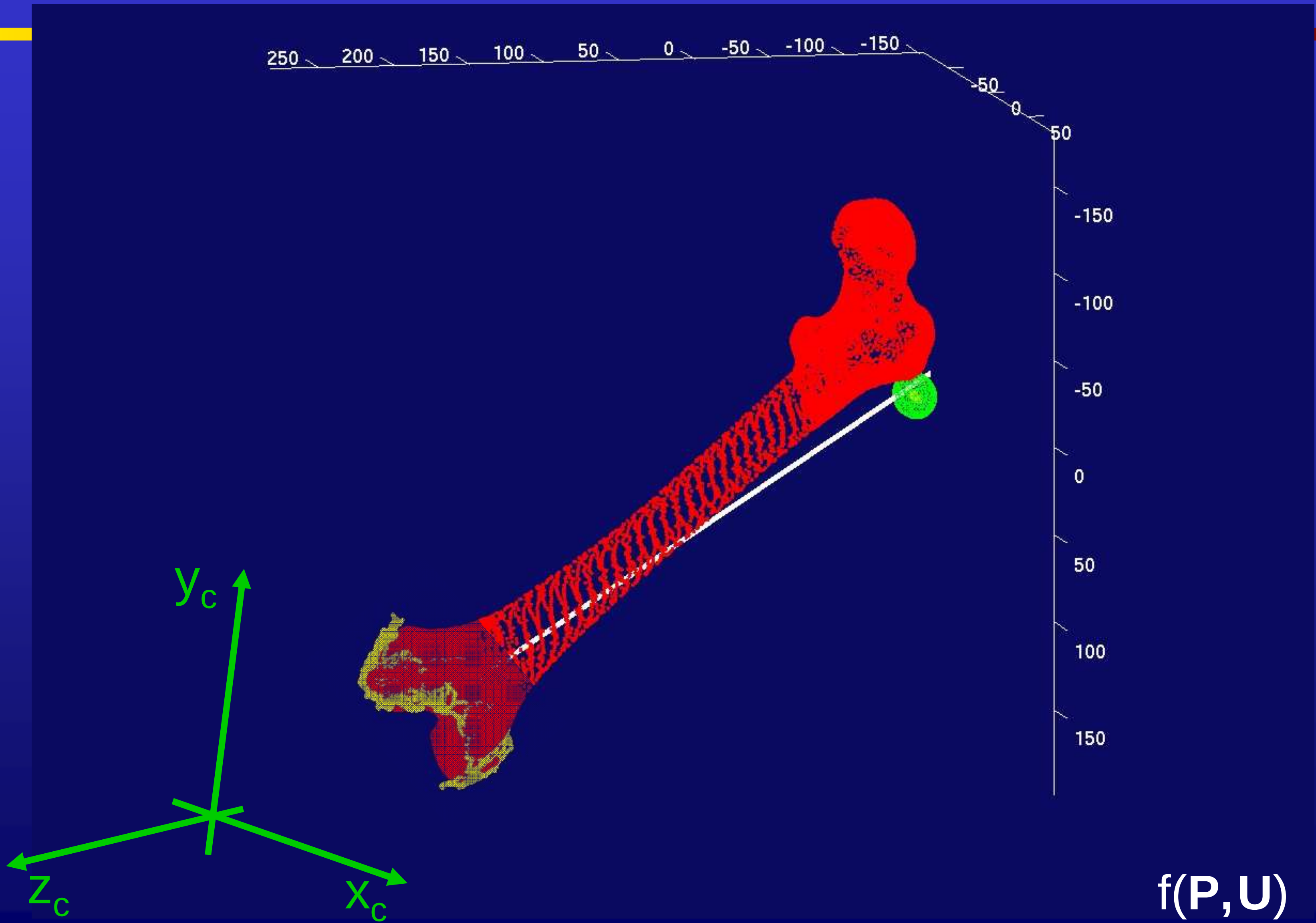
$f(\mathbf{P},\mathbf{U}) = 53$

iterations



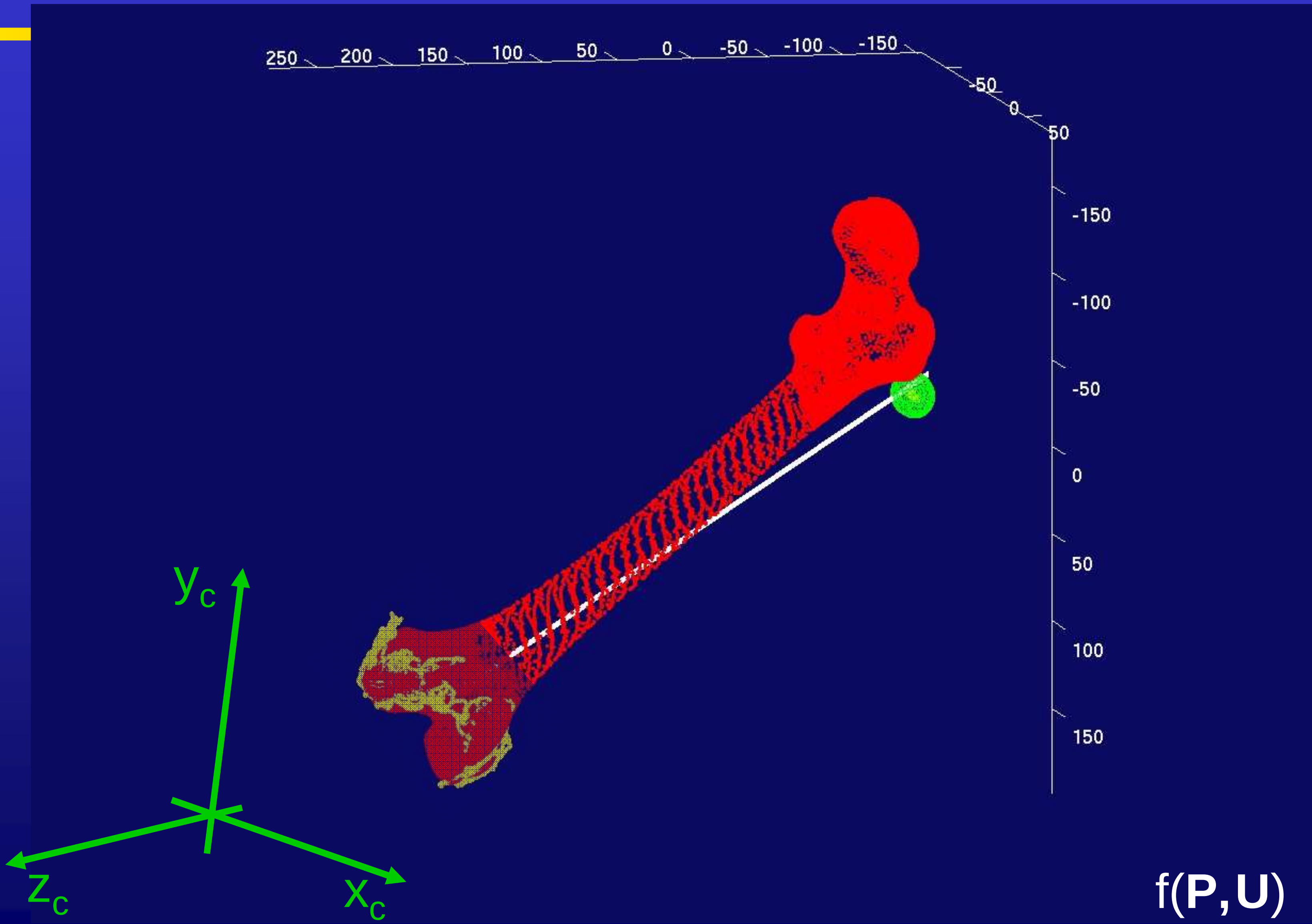
$f(\mathbf{P},\mathbf{U}) = 24$

iterations



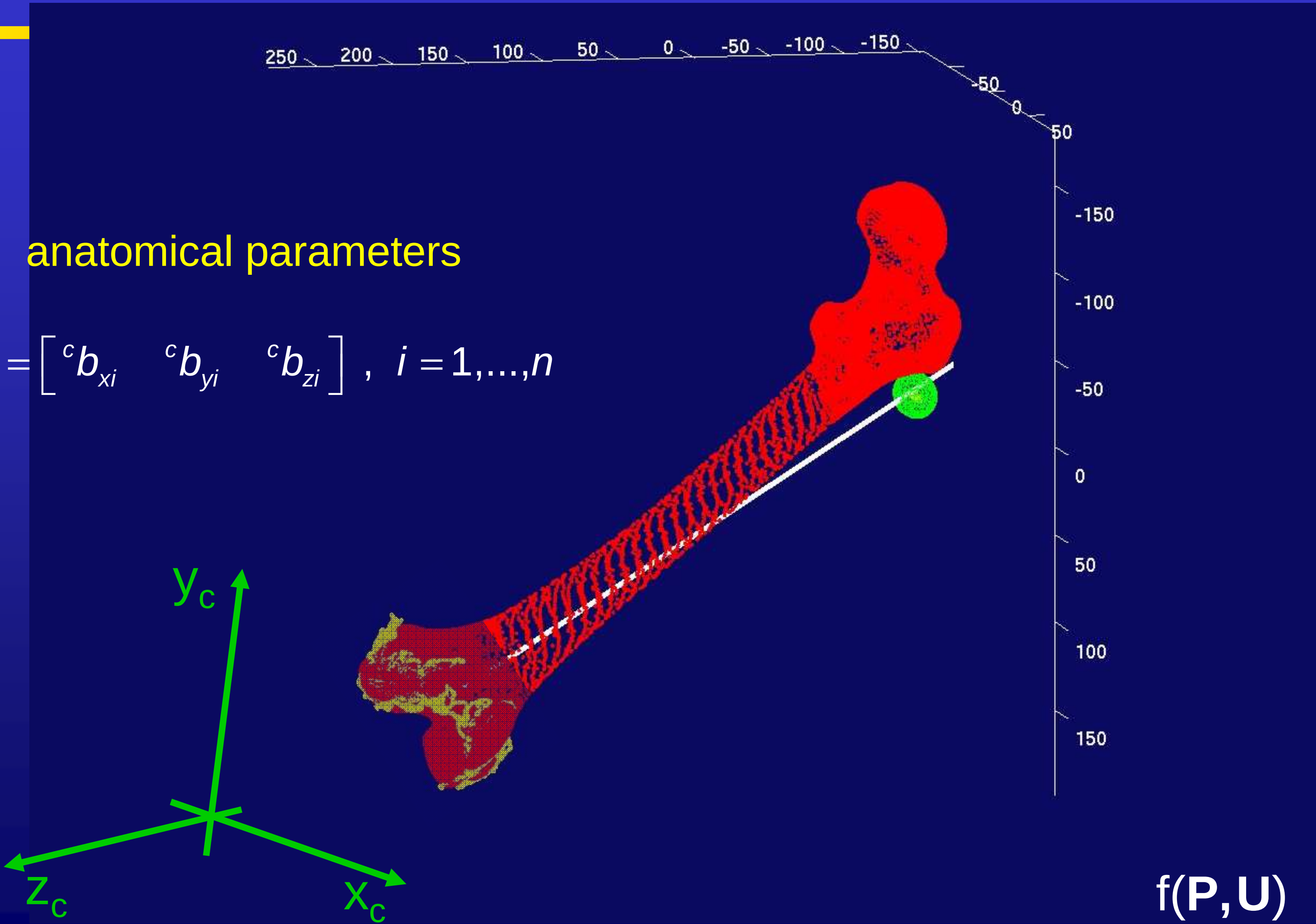
$f(\mathbf{P},\mathbf{U}) = 15$

iterations



$f(\mathbf{P},\mathbf{U}) = 12$

solution

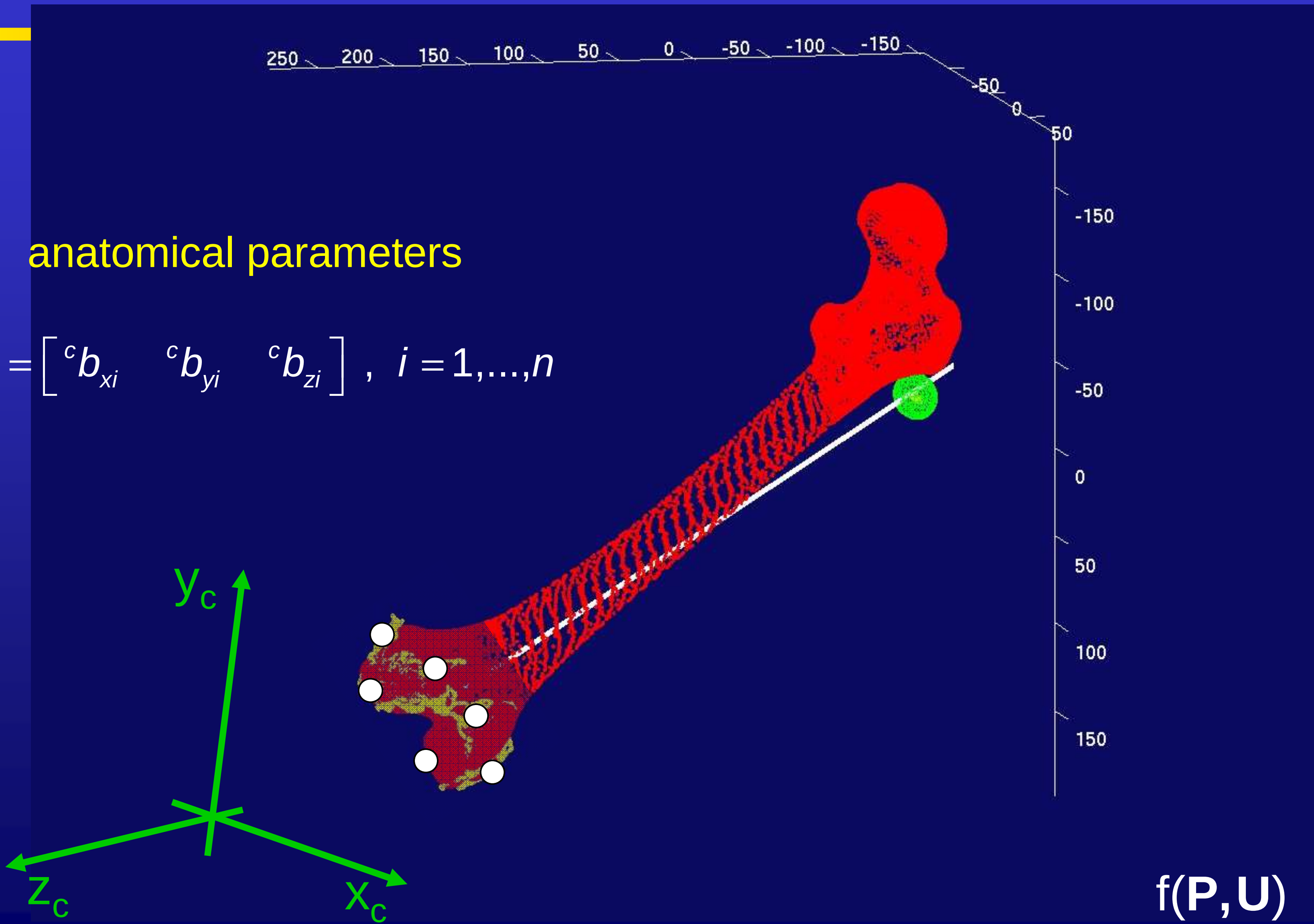


anatomical parameters

$$ {}^{c}\mathbf{b}_i = \begin{bmatrix} {}^{c}b_{xi} & {}^{c}b_{yi} & {}^{c}b_{zi} \end{bmatrix}, \quad i = 1,\ldots,n $$

$f(\mathbf{P},\mathbf{U}) = 10$

solution

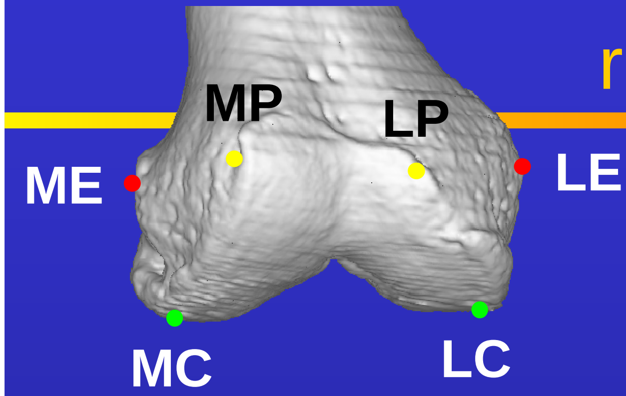


anatomical parameters

$$ {}^{c}\mathbf{b}_i = \left[{}^{c}b_{xi} \quad {}^{c}b_{yi} \quad {}^{c}b_{zi} \right], \quad i = 1,\dots,n $$

$f(\mathbf{P},\mathbf{U}) = 10$

repeatability assessment

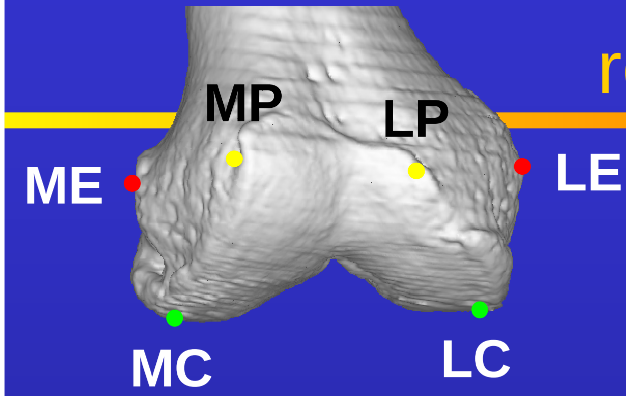


sd [mm]

landmark	LE	ME	LP	MP	LC	MC
Method # 3* Intra-operator	8	7	8	11	3	5
Method # 3* Inter-operator	19	15	15	19	13	14
Method # 4** Intra-operator	1	1	2	2	1	1
Method # 4** Inter-operator	4	5	4	4	4	3

** Della Croce U, Cappozzo A, Kerrigan C. Medical & Biol Engng & Comp 1999*
*** Donati et al (2007)*

repeatability assessment



sd [mm]

landmark	LE	ME	LP	MP	LC	MC
Method # 3* Intra-operator	8	7	8	11	3	5
Method # 3* Inter-operator	19	15	15	19	13	14
Method # 4** Intra-operator	1	1	2	2	1	1
Method # 4** inter-operator	4	5	4	4	4	3

Expert physiotherapists

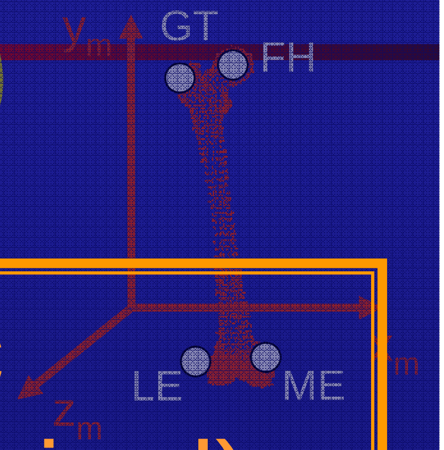
Bioengineers

Della Croce U, Cappozzo A, Kerrigan C. Medical & Biol Engng & Comp 1999

** *Donati et al (2007)*

anatomical calibration: method # 4

Morphology data: → High resolution non subject-specific data

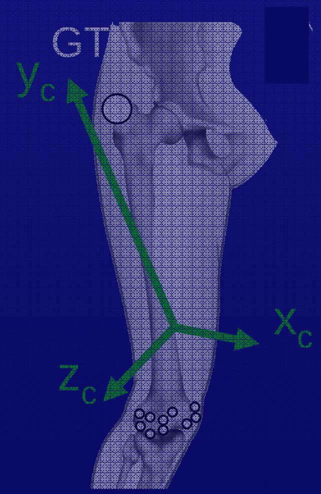


$$ {}^{m}\hat{\mathbf{a}}_i = \left[{}^{m}\hat{a}_{xi} \quad {}^{m}\hat{a}_{yi} \quad {}^{m}\hat{a}_{zi} \right],\ \mathrm{i} = 1,\ldots,\mathrm{r} $$

Precise and economic
(no skilled professional required)

$$ {}^{m}\hat{\mathbf{b}}_i = \left[{}^{m}\hat{b}_{xi} \quad {}^{m}\hat{b}_{yi} \quad {}^{m}\hat{b}_{zi} \right],\ \mathrm{i} = 1,\ldots,\mathrm{n} $$

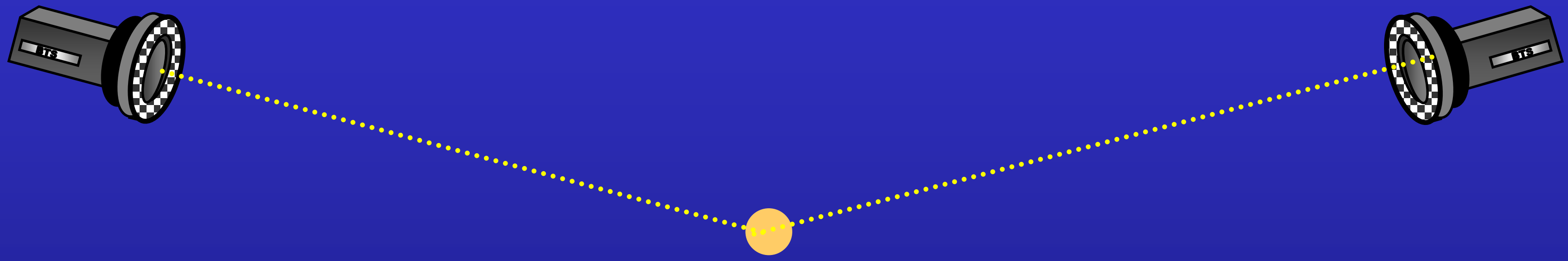
Registration data: → unlabelled and labelled points of the bone surface



$$ {}^{c}u_i = \left[{}^{c}u_{xi} \quad {}^{c}u_{yi} \quad {}^{c}u_{zi} \right],\ \mathrm{i} = 1,\ldots,\mathrm{r} $$

$$ {}^{c}\mathbf{a}_{i'} = \left[{}^{c}a_{xi'} \quad {}^{c}a_{yi'} \quad {}^{c}a_{zi'} \right],\ \mathrm{i} = \mathrm{i}' $$

conclusions



anatomical landmark mislocation can be reduced by:

- increasing the number of anatomical landmarks
- using the least sensitive BAF definition rules
- defining and determining anatomical landmark areas

Thank you