Multibody dynamic approaches in modelling and analysis of biomechanical systems for human motion and injury assessment

by

Jorge Ambrósio and Miguel Tavares da Silva
IDMEC/IST, Technical University of Lisbon, Portugal

Motivation

Many complex systems have their dynamics characterized by large overall motion, large relative rotations between their components, complex interactions with surrounding systems.

Lecture Objectives

Present multibody based formulations able to handle complex systems of practical interest.

Modelling of the human body for the study of human motion tasks: on the use of inverse dynamics..

Biomechanical models in crash analysis: on the use of forward dynamics

Selected Challenges

Lecture Objectives

Present multibody based formulations able to handle complex systems of practical interest.

Modelling of the human body for the study of human motion tasks: on the use of inverse dynamics..

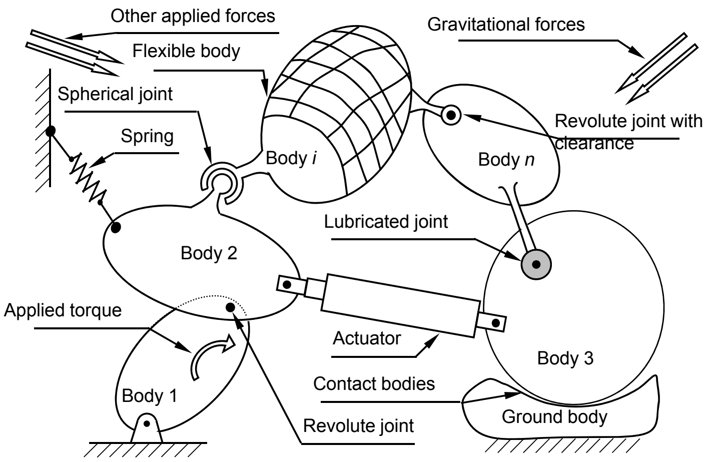
Biomechanical models in crash analysis: on the use of forward dynamics

Selected Challenges.

Multibody Dynamics

Generic **MB** equations of motion

$$\mathbf{M}\,\ddot{\mathbf{q}} = \mathbf{g}$$



nb bodies

$\mathbf{M}$-mass and inertias matrix

$\ddot{\mathbf{q}}$ - acceleration vector

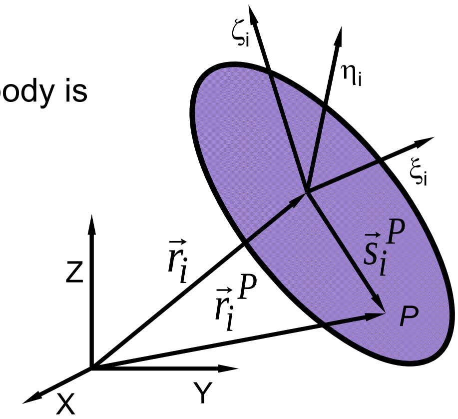
$\mathbf{g}$ – load vector

nc kinematic constraints: $\boldsymbol{\Phi}\left(\mathbf{q},t\right)=\mathbf{0}$

Multibody Dynamics

The position and orientation of a single body is described by the Cartesian coordinates

$$\mathbf{q}_i = \begin{bmatrix}\mathbf{r}^T & \mathbf{p}^T\end{bmatrix}_i^T$$



Several alternatives can be used to describe the rotational coordinates:

- Euler angles
- Bryant angles
- Euler parameters
- etc.

The position of a point P in the rigid body is

$$\mathbf{r}_i^P = \mathbf{r}_i + \mathbf{s}_i^P \equiv \mathbf{r}_i + \mathbf{A}_i\,\mathbf{s}_i'^P$$

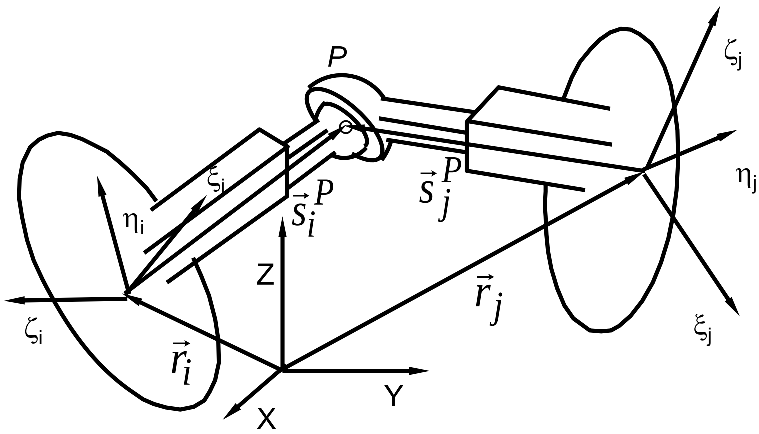
The form of the transformation matrix depends on the rotational coordinates used

Multibody Dynamics

Spherical joint

The spherical joint is defined as two bodies sharing a common point

$$\Phi^{(s,3)} \equiv \mathbf{r}_i + \mathbf{A}_i \mathbf{s}_i'^P - \mathbf{r}_j - \mathbf{A}_j \mathbf{s}_j'^P = \mathbf{0}$$



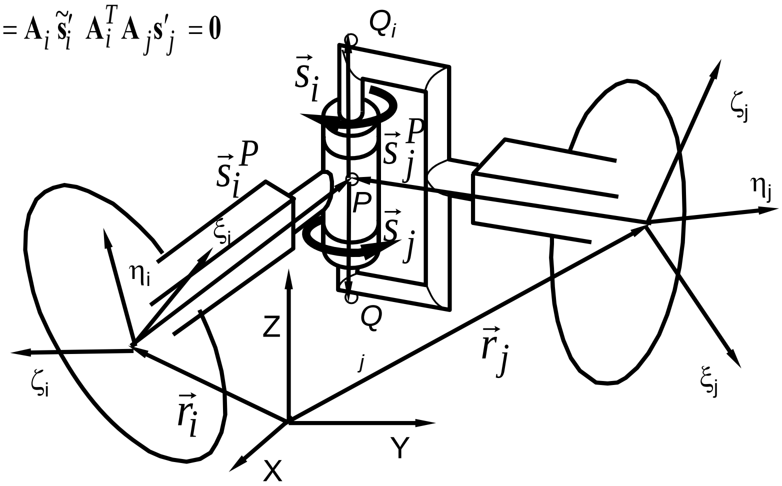
Multibody Dynamics

Revolute joint

The revolute joint is defined by adding to the spherical joint the constraint of parallelism between two vectors:

$$\Phi^{(s,3)} \equiv \mathbf{r}_i + \mathbf{A}_i \mathbf{s}_i'^P - \mathbf{r}_j - \mathbf{A}_j \mathbf{s}_j'^P = \mathbf{0}$$

$$\Phi^{(p1,2)} \equiv \tilde{\mathbf{s}}_i \, \mathbf{s}_j = \mathbf{A}_i \tilde{\mathbf{s}}_i' \, \mathbf{A}_i^T \mathbf{A}_j \mathbf{s}_j' = \mathbf{0}$$

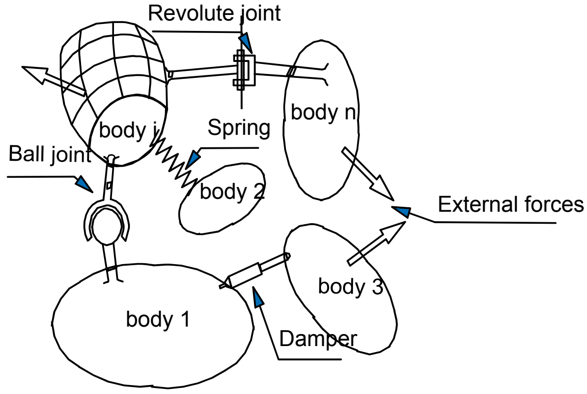


Multibody Dynamics - Forward

Velocity and acceleration constraints;
D-Jacobian matrix

$$\dot{\boldsymbol{\Phi}}(\mathbf{q},t) \equiv \mathbf{D}\dot{\mathbf{q}} = \boldsymbol{\nu}$$

$$\ddot{\boldsymbol{\Phi}}(\mathbf{q},\dot{\mathbf{q}},t) \equiv \mathbf{D}\ddot{\mathbf{q}} = \ddot{\gamma}$$



Including the equivalent reaction forces on the r.h.s.

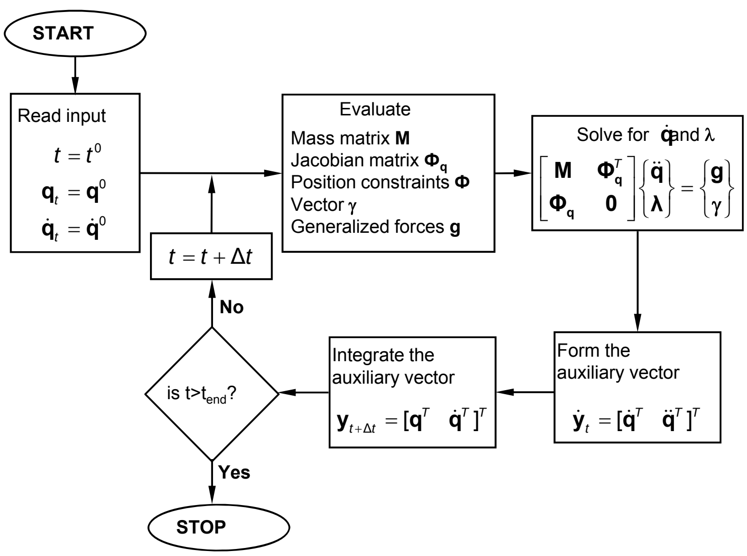
$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{g} - \mathbf{D}^T\boldsymbol{\lambda}$$

Resulting system of equations

$$\begin{bmatrix} \mathbf{M} & \mathbf{D}^T \\ \mathbf{D} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{g} \\ \boldsymbol{\gamma} \end{bmatrix}$$

Forward Dynamics

Flowchart of forward dynamic analysis



Generally variable time/step integration algorithms are used

Lecture Objectives

Present multibody based formulations able to handle complex systems of practical interest.

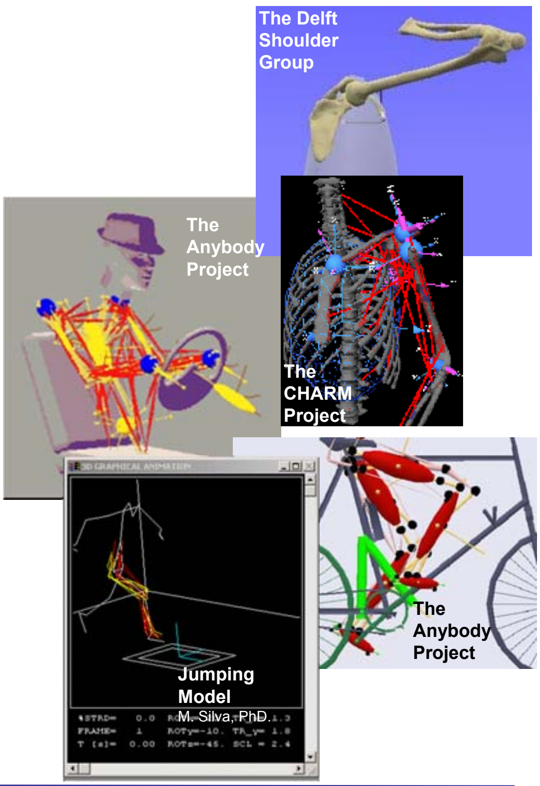
Modelling of the human body for the study of human motion tasks: on the use of inverse dynamics.

Biomechanical models in crash analysis: on the use of forward dynamics

Selected Challenges.

Biomechanical Models

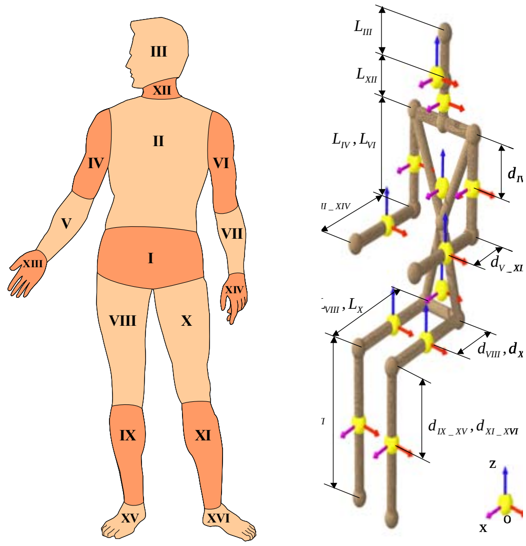
- First models appear in the 60's: use only a small set of rigid elements (3).
- 2D models.
- Not able to calculate internal loads.
- In the 70's the number of segments was gradually increased.
- Some models were 3D.
- First models capable of estimate the redundant muscle forces through linear optimization methods (simplex).
- During the 80's there was a generalization on the use of 3D models.
- During the 90's until today, increase in the quantity, quality and complexity of the models: interdisciplinary.



Biomechanical Models

Kinematic Structure:

- Whole body model.
  – Partial models can also be used.
- The **kinematic structure** includes:
  – Definition of the **anatomical segments** and **rigid bodies**.
  – Definition of **joints** and **degrees-of-freedom**.
  – Definition of the **topology of the system**.
- Anthropometric definition of **anatomical segment lengths**.



Anatomical Segments

Anthropometrics and Topology

3D Biomechanical Model for Inverse Dynamics Analysis.

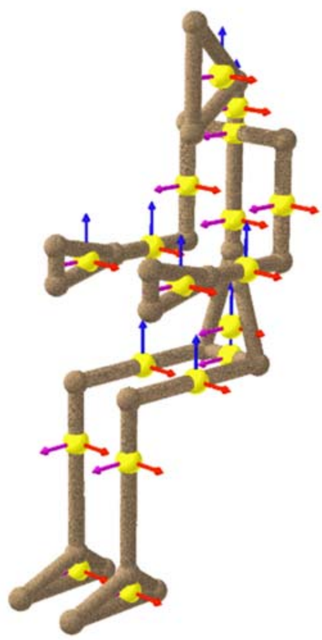
Biomechanical Models

Mass and Inertial Characteristics:

- The biomechanical model also includes:
  – Definition of the **mass** of the anatomical segments.
  – Definition of the **inertia** of the anatomical segments.
  – Definition of the **centre-of-mass location** of each segment.

Complementary Characteristics:

- Joint resistance characteristics (passive, dissipative terms).
- Muscles data:
  – Origin, insertion and via points.
  – CSA, max isometric force, length, etc.



3D Biomechanical Model for Inverse Dynamics Analysis.

Biomechanical Models

Databases and Scaling Factors

- **Biomechanical and anthropometric databases** are created to include individuals with different percentile, gender, ATDs, etc.

- **Scaling factors** are used to adjust database information to model's specific dimensions aiming to an increased biofidelity.

$$\chi_{L_i} = \frac{L_i^{n^{th}}}{L_i^{50^{th}}}$$ • Length SF.

$$\chi_{m_i} = \frac{m_i^{n^{th}}}{m_i^{50^{th}}}$$ • Mass SF.

$$\chi_{I_i} = \chi_{m_i} \cdot \chi_{L_i}^2$$ • Inertia SF.

```
-----------------------------------------------------------------
OCCUPANT NR.        DESCRIPTION
     1              50TH PERCENTILE, AIRCREWMEMBER
     2              PART 572        , DUMMY
     3              ULISSES         , APOLLO´s DUMMY
     4              USER DEFINED
     5              USER DEFINED
-----------------------------------------------------------------
DESCRIPTION              OCCUPANT#1  OCCUPANT#2  OCCUPANT#3

SEG. LENGHT(in)
LOWER_TORSO               .9440E+01  .1050E+02  .1080E+02
UPPER_TORSO               .1310E+02  .1150E+02  .1160E+02
HEAD                      .8500E+01  .8350E+01  .8350E+01
UPPER_ARM                 .1160E+02  .1130E+02  .1130E+02
LOWER_ARM                 .1480E+02  .1330E+02  .1330E+02
UPPER_LEG                 .1710E+02  .1650E+02  .1650E+02
LOWER_LEG                 .1840E+02  .1800E+02  .1800E+02
NECK                      .5100E+01  .4880E+01  .4880E+01
-----------------------------------------------------------------
CM.LOCATION(in)
LOWER_TORSO               .2500E+01  .4170E+01  .4670E+01
UPPER_TORSO               .7600E+01  .6550E+01  .6550E+01
HEAD                      .5570E+01  .5050E+01  .6330E+01
.
.
.
```

Biomechanical Database with Anthropometric and Kinematic Data

Biomechanical Models

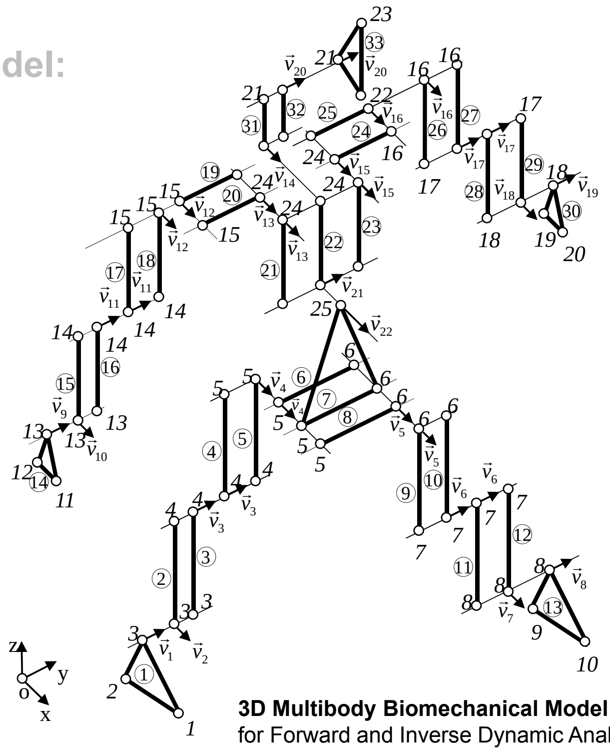
Whole-body biomechanical model:

Applications:

- Forward and inverse DA.
- General purpose model.
- Calculation of muscle forces.

Characteristics:

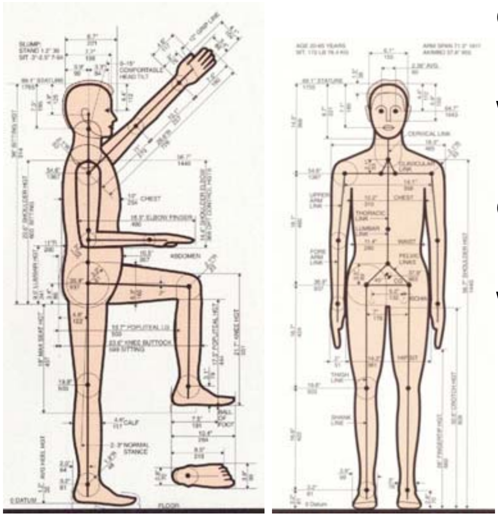
- Three dimensional.
- 33 Rigid bodies.
- 26 Revolute joints.
- 6 Universal joints.
- 1 Base body joint.
- 44 Degrees-of-freedom.



3D Multibody Biomechanical Model for Forward and Inverse Dynamic Analysis (*M. Silva, PhD Thesis, 2003*)

Biomechanical Models

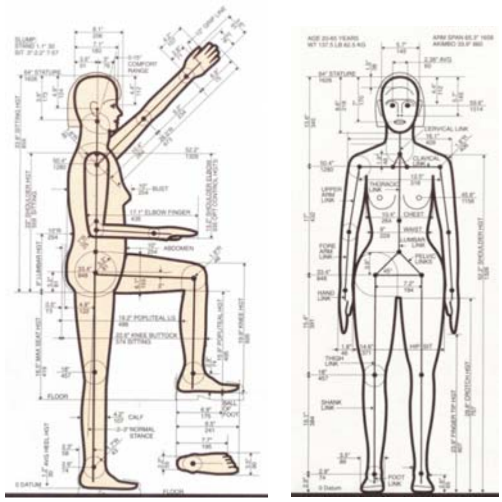
Anthropometric Dimensions* – 50th Percentile – Age (0 - 65)



Anthropometric Dimensions
Adult 18/65 years, Male – 50th Percentile

Gender: Male
Height: 175.5 cm
Weight: 78.4 kg

Gender: Female
Height: 162.6 cm
Weight: 62.5 kg



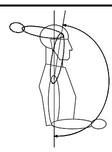
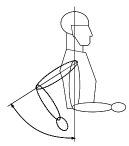
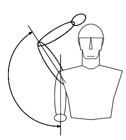
Anthropometric Dimensions
Adult 18/65 years, Female – 50th Percentile

(*) From **http://www.tumbleforms.com/**
"The Measure of Man and Woman: Human Factors in Design",
Alvin R. Tilley, Henry Dreyfuss Associates, Whitney Library of Design, New York, 1993.

Biomechanical Models

Joints Range of Motion (ROM):

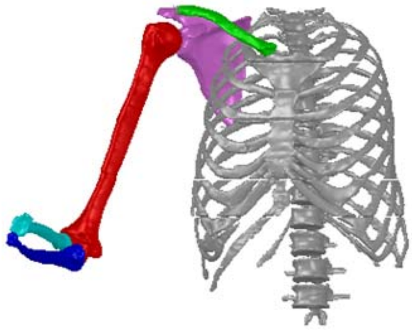
- The range of motion of the anatomical joints is fundamental in **forward dynamic analysis**, i.e., when the objective is to **simulate** the biomechanical response of the human body to a given external solicitation.
- Example for the case of the **shoulder joint** is presented.
- In such circumstances an **articular joint model** must be applied to **model joint resistance and ROM**.

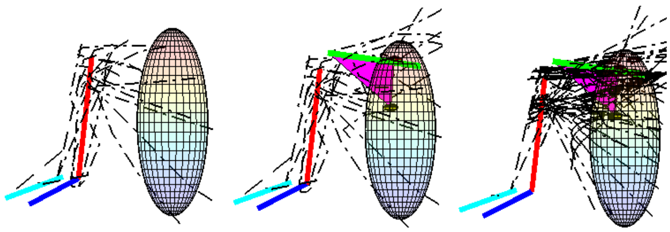
Joint Name	Motion Name	Representation	Rotation [deg]
	Flexion		180
Shoulder	Hyperextension		58
	Abduction		130

Data: 50th percentile male.

Biomechanical Models

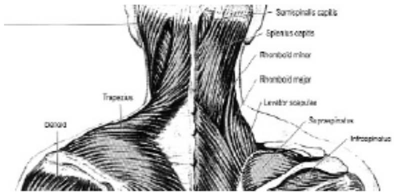
Shoulder models:

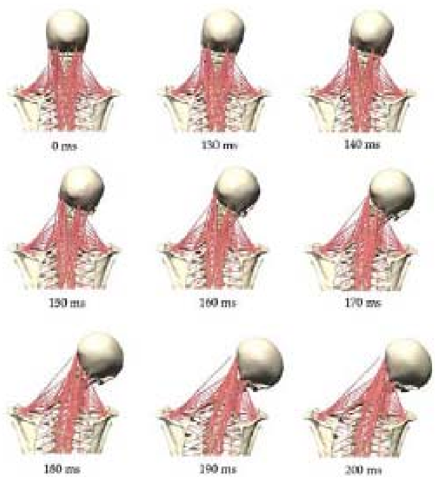




C. Quental at al., Multibody System Dynamics, 2012

Spine models:

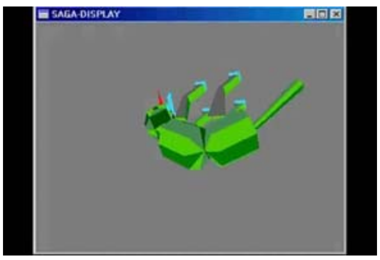


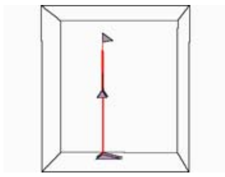


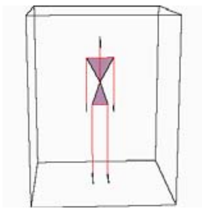
Volkan Esat PhD Thesis, Loughborough Univ, 2006

Biomechanics: Human Body Motion

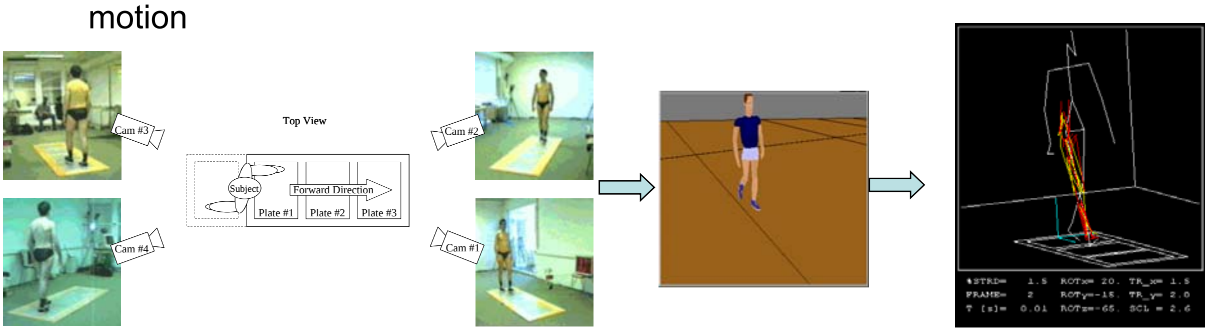
Forward dynamic analysis of human motion







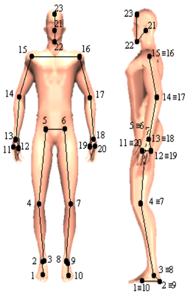
Inverse dynamic analysis of human motion



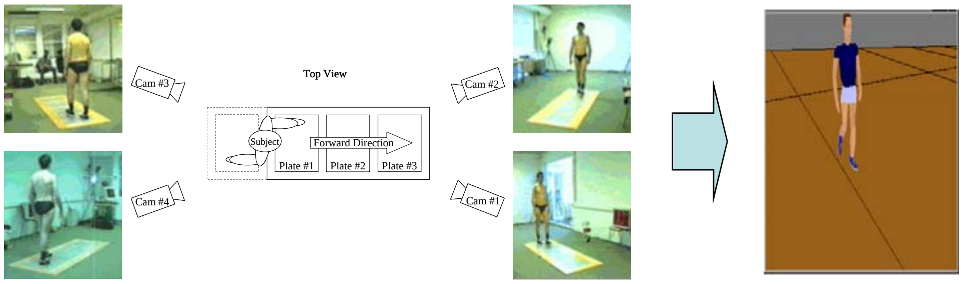
Biomechanical Model: Kinematic Input

Cartesian coordinates of a set of anatomical points:

- 23 anatomical points located at the joints and extremities.
- Motion capture using 4 synchronized 60 Hz video cameras.

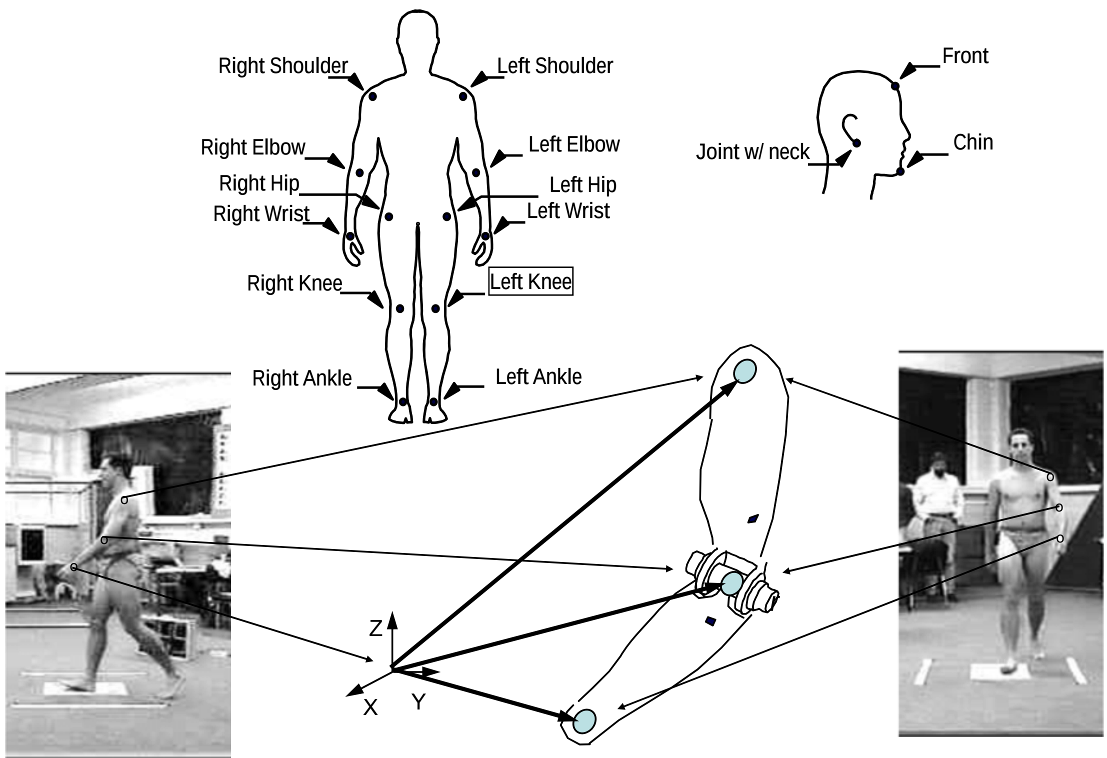


Sequence of anatomical points



- 3D reconstruction of point coordinates using DLT.
- Noise reduction using low-pass filtering techniques.
- Calculation of kinematic consistent positions for the model.
- Calculation of velocities and accelerations using splines.

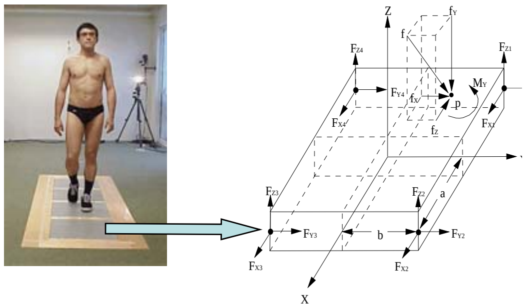
Dynamic Analysis: Anatomical points



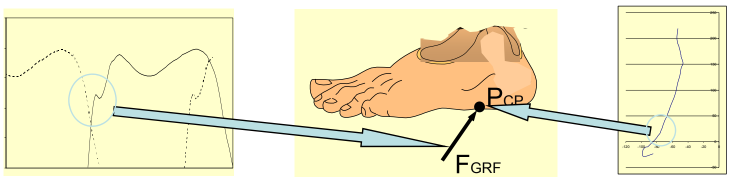
Biomechanical Model: Dynamic Input Data

Measuring the external applied forces:

- Three force plates are used, synchronized with the video cameras.
- The information collected needs to be filtered to reduce noise.



Obtain the ground reaction forces and the center-of-pressure curves.

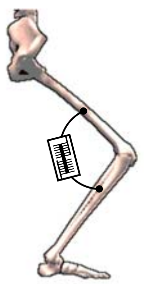


Biomechanical Model: Joint Actuators

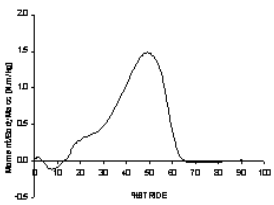
Used to drive the model through the analysis:

- To each d.o.f. of the model is associated a joint rotational actuator.
- Joint Actuators are constraint equations.
- The number of constraint equations and coordinates are equal, i.e., an unique solution for the inverse problem can be obtained.
- To each driver equation is associated a Lagrange Multiplier.

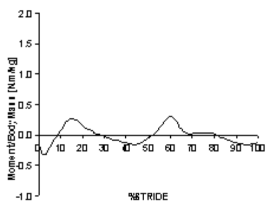
Net moments-of-force at the joints are obtained from the Lagrange Multipliers as solution of the equations of motion of the system.



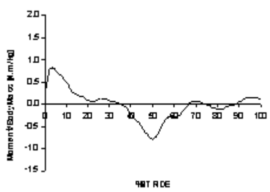
Joint Rotational Actuator



Ankle Moment



Knee Moment



Hip Moment

Redundant Muscle Forces

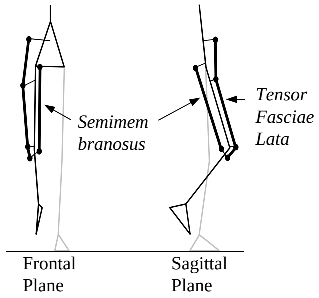
Used to simulate muscle action:

- Defined with 2 or more points depending on muscle complexity:
  - *Semimembranosus* (2 points);
  - *Tensor Fasciae Lata* (4 points).
- To each muscle actuator a Lagrange Multiplier is associated.

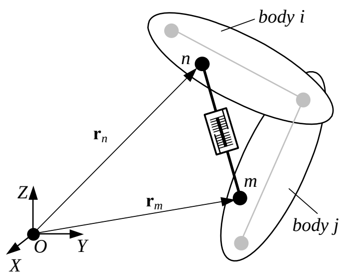
Muscle actuators are kinematic constraints equations of scalar product type:

$$\Phi^{(MA,1)}(\mathbf{q},t) = (\mathbf{r}_m - \mathbf{r}_n)^T(\mathbf{r}_m - \mathbf{r}_n) - L_{nm}^2(t) = 0$$

Constrain the distance between two points to change according to a specified length change history.



Simple/Complex muscle paths



Muscle actuator defined between bodies i and j

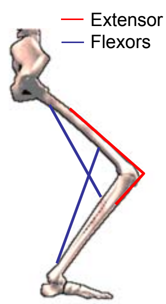
Redundant Muscle Forces

In complex biomechanical systems, almost every joint is crossed by several muscles or muscle groups:

- **Different activation patterns** can generate forces that produce the **same net moments-of-force**.
- Results in a same posture or movement.

'The redundant problem in biomechanics':

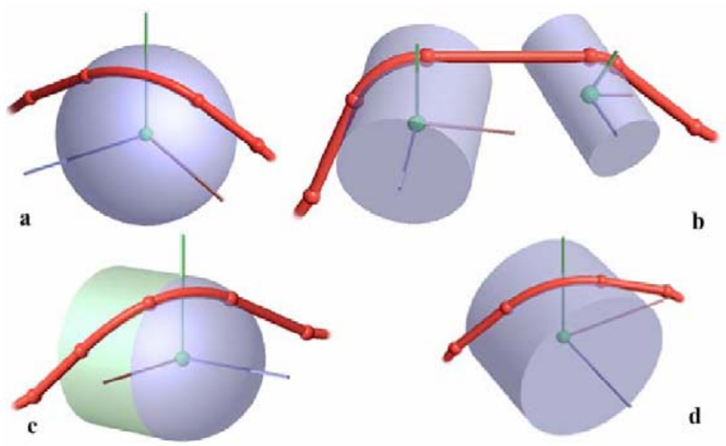
- Mathematically results from the fact that the number of load-transmitting elements at a joint exceeds the number of available equilibrium equations.
- An unique solution can not be obtained.
- **Optimization techniques are used** to choose from an infinite set of solutions the one that minimizes some physiological criteria described by a proper cost-function..



Example of redundant muscle forces

Muscle Paths

The muscle path is defined by via points and obstacles.



Source:
Garner, B. A., Pandy, G. (2000), Comp. Meth. Biomech. Biomed. Eng. , 3, 1-30

Redundant Muscle Forces

Activation Dynamics:

Generates a muscle tissue state that transforms the neural signal into activation of the contractile apparatus.

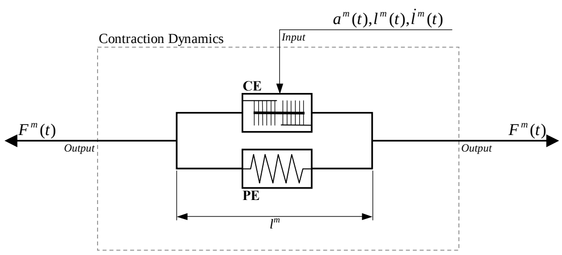
Contraction Dynamics:

Transforms the muscle activation in muscle force.

A Hill type muscle model is used to simulate contraction dynamics.

Hill Contractile Element (CE).

Passive Elastic Element (PE).



Hill type muscle model

Redundant Muscle Forces

Total Muscle Force:

$F_m = F_{CE} + F_{PE}$

Force Contractile Element:

$$F_{CE}^m(a^m(t), l^m(t), \dot{l}^m(t)) = \frac{F_l^m(l^m(t)) F_{\dot{l}}^m(\dot{l}^m(t))}{F_0^m} a^m(t)$$

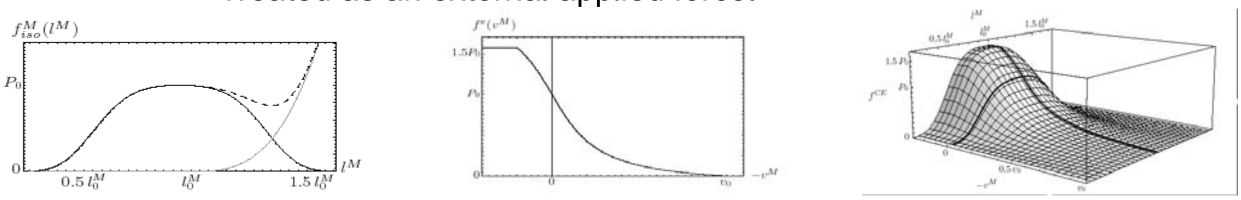
F_l and $F_{\dot{l}}$ represent the length and velocity dependency of the CE.

Force Passive Elastic Element:

Does not depend on de activation.

Does not carry load until muscle is stretched past its resting length.

Treated as an external applied force.



Redundant Muscle Forces

Optimization tools are used to find, from all the possible solutions the one that minimize a prescribed objective function.

Mathematically, the Static Optimization Problem is stated as

$$\text{minimize} \quad F_0(u_i)$$

$$\text{subject to:} \begin{cases} f_j(u_i) = 0 & j = 1, \dots, n_{ec} \\ f_j(u_i) \geq 0 & j = (n_{ec}+1), \dots, n_{tc} \\ u_i^{lower} \leq u_i \leq u_i^{upper} & i = 1, \dots, n_{sv} \end{cases}$$

The minimization of **cost functions simulate the physiological criteria** adopted by the central nervous system when deciding which muscles to recruit as well as the level of activation that produce the adequate motion or posture.

Redundant Muscle Forces

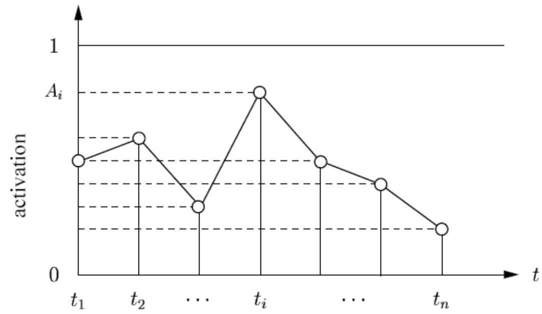
Force Contractile Element:

$$F_{CE}^{m}(a^{m}(t), l^{m}(t), \dot{l}^{m}(t)) = \frac{F_{l}^{m}(l^{m}(t)) F_{\dot{l}}^{m}(\dot{l}^{m}(t))}{F_{0}^{m}} a^{m}(t)$$

Activation profile

$$a(t) = A_i + (t - t_i)\frac{A_{i+1} - A_i}{t_{i+1} - t_i}, \quad i = 0, \dots n; \quad t \in [t_i, t_{i+1})$$

A_i are the design variables



Number of design Variables = Number of Muscles X Number of frames

Redundant Muscle Forces

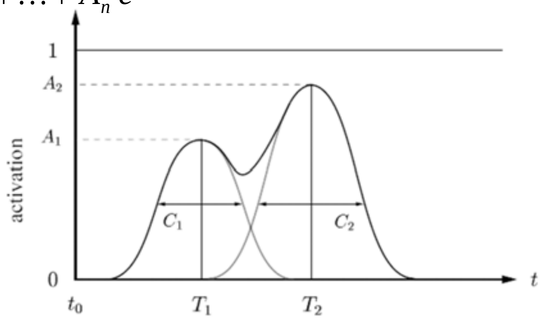
Force Contractile Element:

$$F_{CE}^{m}(a^{m}(t), l^{m}(t), \dot{l}^{m}(t)) = \frac{F_{l}^{m}(l^{m}(t)) F_{\dot{l}}^{m}(\dot{l}^{m}(t))}{F_{0}^{m}} a^{m}(t)$$

Activation profile

$$a(t) = A_1 e^{-C_1(t-T_1)^2} + A_2 e^{-C_2(t-T_1)^2} + \dots + A_n e^{-C_n(t-T_1)^2}$$

A_i, C_i and T_i are the design variables



Number of Design Variables = Number of Muscles X Number of Exp. Functions

Redundant Muscle Forces

In gait analyses, the following cost functions are used:

Minimization of the sum of the square of the muscle forces:

$$F_0 = \sum_{m=1}^{n_{ma}} \left(F_{CE}^{m}\right)^2 = \sum_{m=1}^{n_{ma}} \left(\frac{F_l^{\,m} F_l^{\,m}}{F_0^{\,m}} a^m \right)^2$$

Minimization of the sum of the cube of the muscle stress:

$$F_0 = \sum_{m=1}^{n_{ma}} \left(\sigma_{CE}^{m}\right)^3 = \sum_{m=1}^{n_{ma}} \left(\overline{\sigma} \frac{F_l^{\,m} F_l^{\,m}}{F_0^{\,m\,2}} a^m \right)^3$$

The constraints that state variables fulfill are the equations of motion:

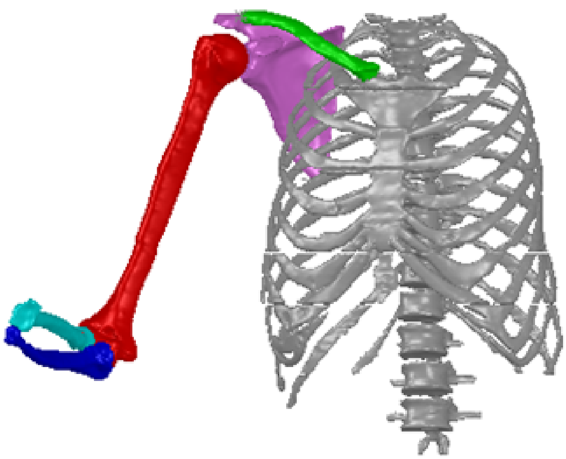
$$\mathbf{f} = \begin{Bmatrix} f_1 \\ \vdots \\ f_{n_{tc}} \end{Bmatrix} = \Phi_{\mathbf{q}} \boldsymbol{\lambda} + \left(\mathbf{M}\ddot{\mathbf{q}} - \mathbf{g} \right) = \mathbf{0}$$

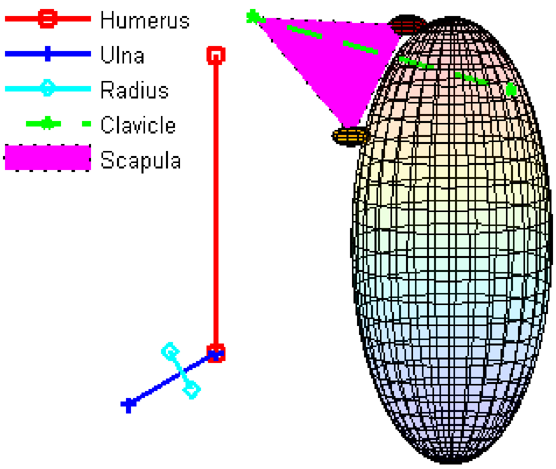
Gradients are already calculated!

$$\nabla_{\boldsymbol{\lambda}} \mathbf{f} = \frac{\partial \mathbf{f}}{\partial \boldsymbol{\lambda}} = \Phi_{\mathbf{q}}$$

Methods

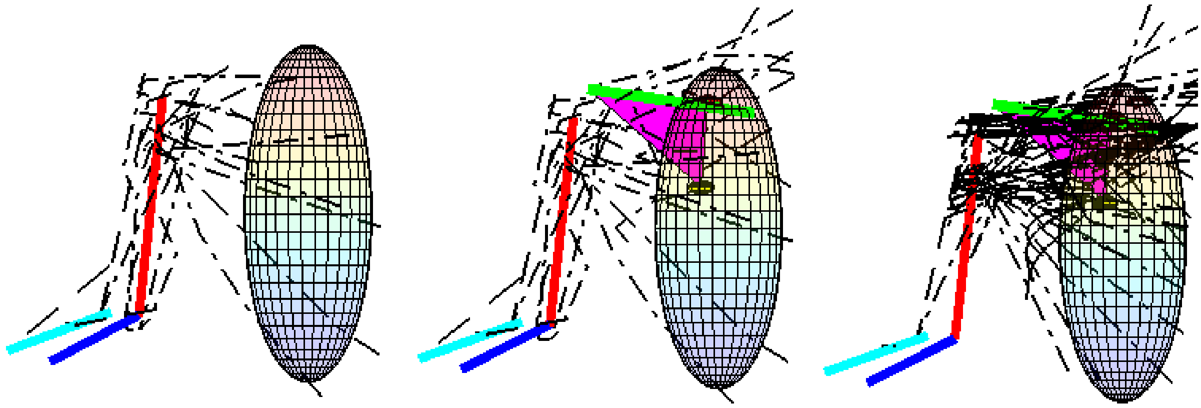
- Multibody system
  - Skeletal model
  - Musculoskeletal model
- Inverse dynamics
  - Motion
  - Optimization problem





Muscle modeling

- Multibody system
  - Skeletal model
  - Musculoskeletal model
- Inverse dynamics
  - Motion
  - Optimization problem



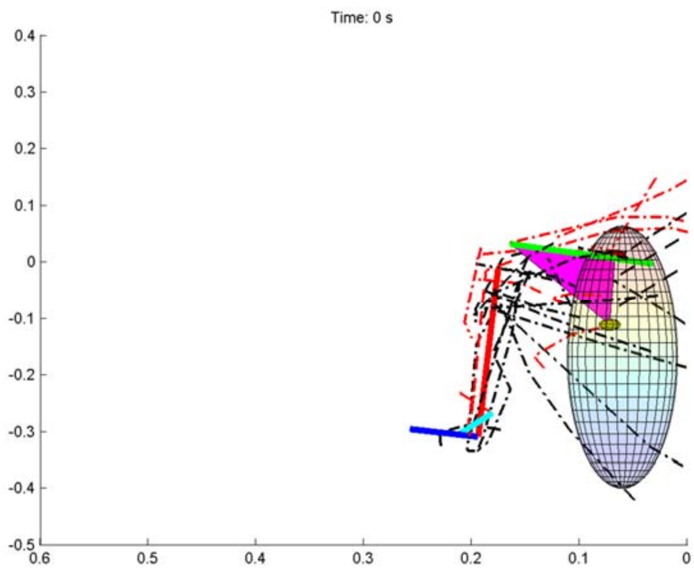
Model 1 –
15 muscles - 24 segments

Model 2 –
21 muscles - 37 segments

Model 3 –
21 muscles - 127 segments

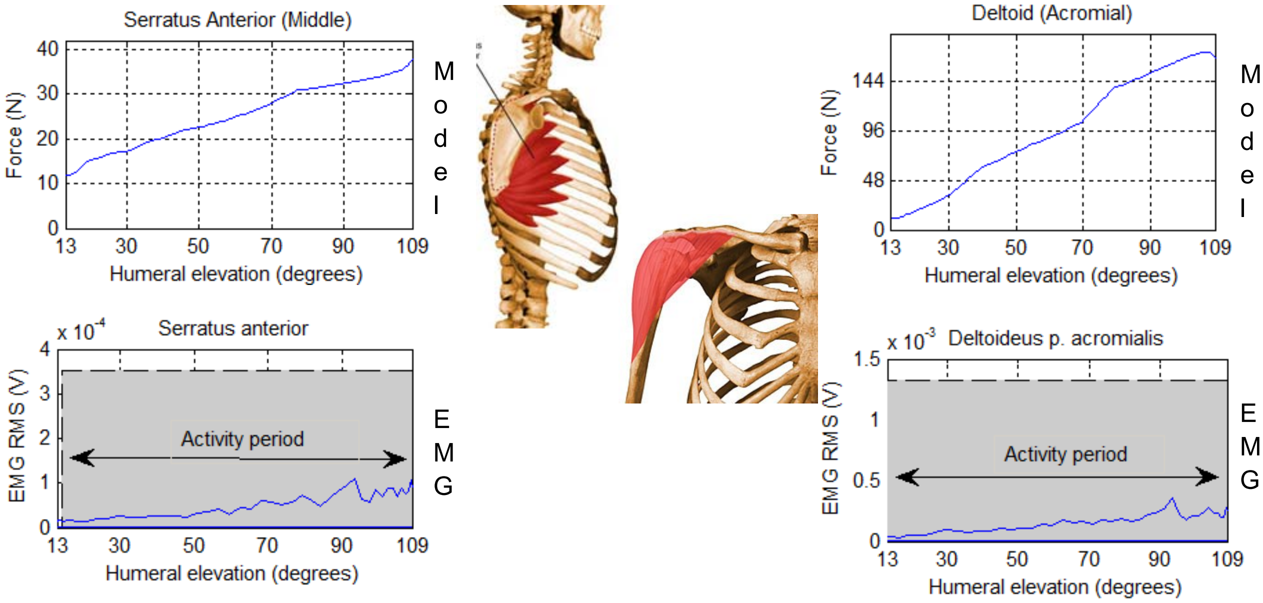
Results
Abduction

- Motion
- Muscles forces
  - Medial deltoid
  - Serratus anterior
  - Rotator cuff muscles
- GH joint reaction force



- Active muscle
- Non-active muscle

Results
Abduction



Rotates the glenoid upwardly during abduction and Stabilizes the scapula

Main abductor, specially between 30º and 120º of amplitude

Application Case: Normal Gait

Normal cadence stride.

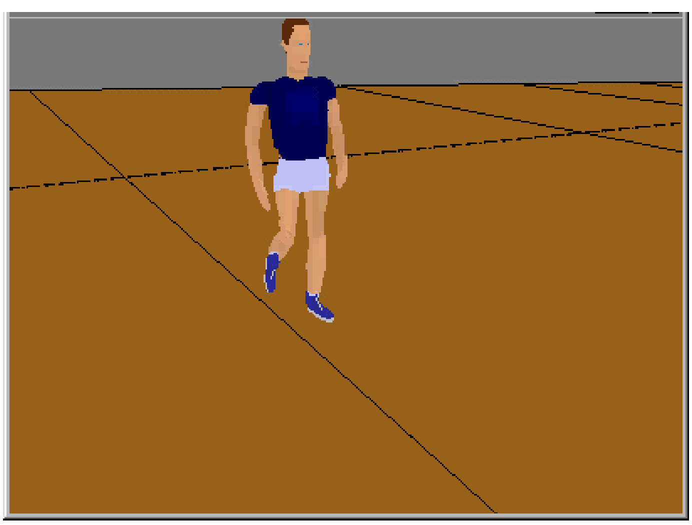
Subject:

- 25 years old male;
- 70.0 Kg;
- 1.70 m;
- Wearing running shoes.

Walking cadence of 111 steps pm.

Four 60Hz cameras.

Three force plates.

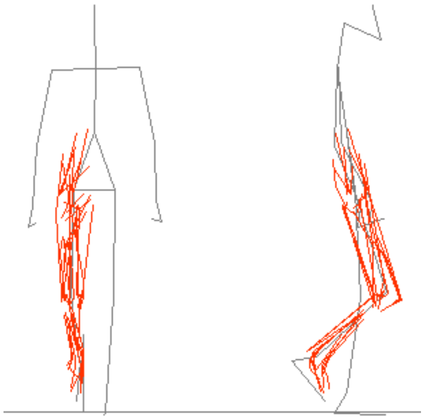


Redundant Muscle Forces

Contains information on muscles of the locomotion apparatus.

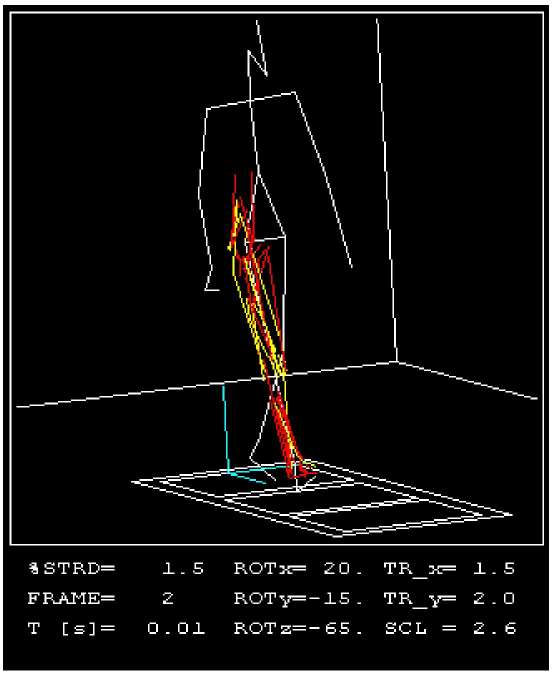
35 muscles per leg (Carhart and Yamaguchi, 2001)

Graphical Representation



Muscle Name	Muscle Name
Adductor Brevis	*Peroneus Brevis*
Adductor Longus	*Peroneus Longus*
Adductor Magnus	*Peroneus Tertius*
Biceps Femoris (long head)	*Piriformis*
Biceps Femoris (short head)	*Psoas*
Extensor Digitorum Longus	*Quadratus Femoris*
Extensor Hallucis Longus	*Rectus Femoris*
Flexor Digitorum Longus	*Sartorius*
Flexor Hallucis Longus	*Semimembranosus*
Gastrocnemius (lateral head)	*Semitendinosus*
Gastrocnemius (medial head)	*Soleus*
Gemellus (inferior and superior)	*Tensor Fasciae Lata*
Gluteus Maximus	*Tibialis Anterior*
Gluteus Medius	*Tibialis Posterior*
Gluteus Minimus	*Vastus Intermedius*
Gracilis	*Vastus Lateralis*
Iliacus	*Vastus Medialis*
Pectineus	

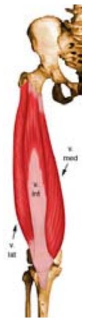
Redundant Muscle Forces



Visualization of the muscle apparatus.

Semimembranosus

Tensor Fasciae Lata



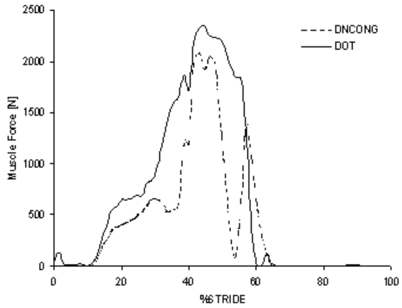
Vastae Family

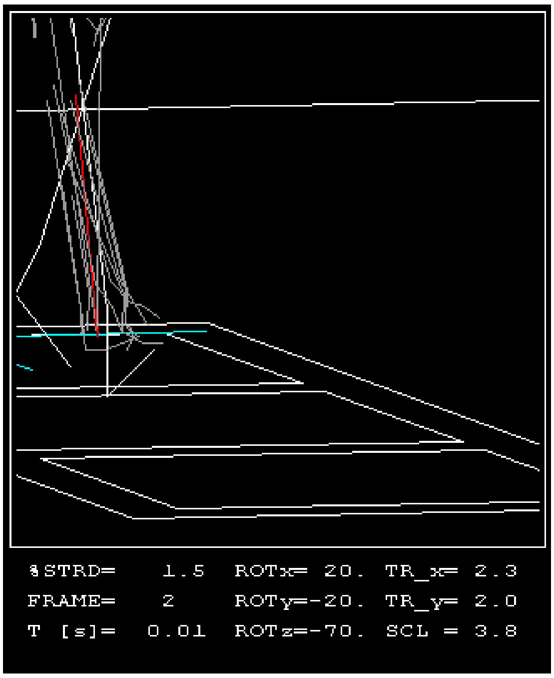
Gastrocnemius

Gluteus Medius

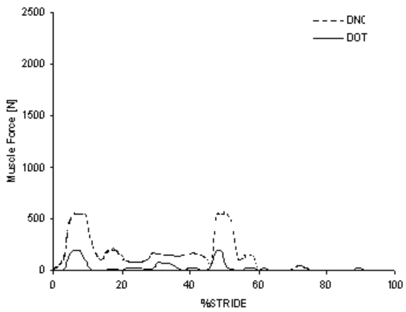
Soleus

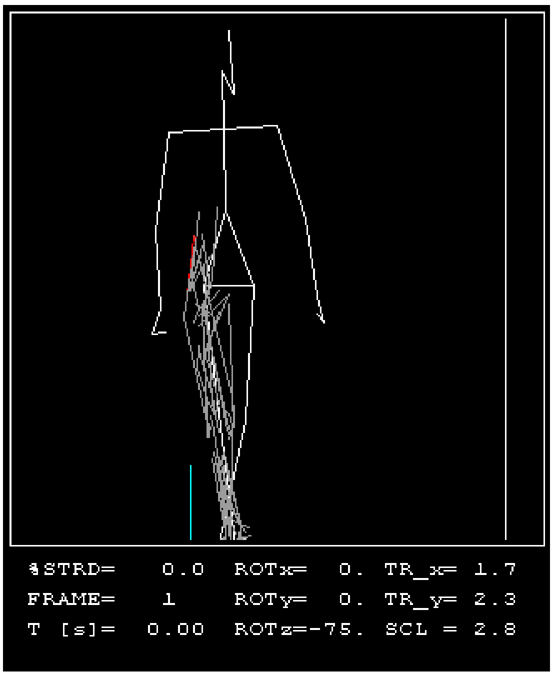
Redundant Muscle Forces





Redundant Muscle Forces





Lecture Objectives

Present multibody based formulations able to handle complex systems of practical interest.

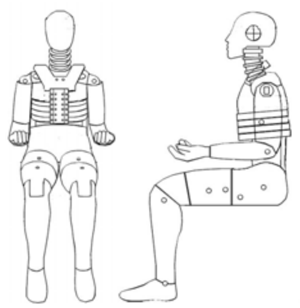
Modelling of the human body for the study of human motion tasks: on the use of inverse dynamics.

Biomechanical models in crash analysis: on the use of forward dynamics

Selected Challenges..

Vehicle Crashworthiness: Injury

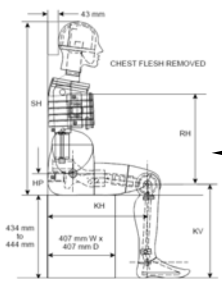
Dummies in Regulations



Front impact dummies

In regulation ←

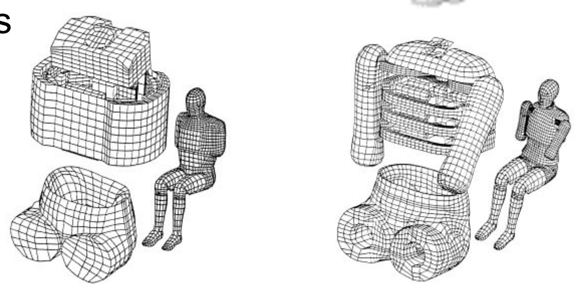
Multibody →



Side impact dummies

In regulation ←

Finite element →



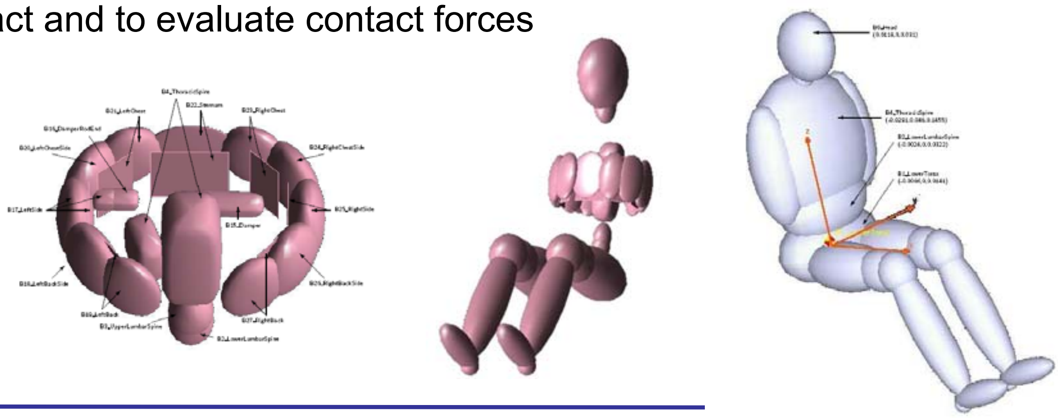
Vehicle MB Model for Crash Analysis

Occupant Biomechanics - US DOT SID

All the mechanical components of the US DOT SID are modeled.

It is important to model Dummies rather than 'real human' because these are in fact measuring devices.

The geometries of the mechanical components are used to detect contact and to evaluate contact forces

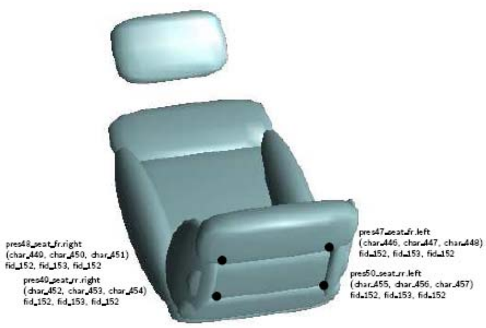


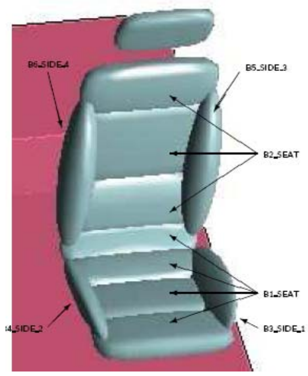
Vehicle MB Model for Crash Analysis

Occupant Biomechanics – Seat Model

The geometries of the seat components are used to detect contact and to evaluate contact forces

The compliance of the seat materials is used in the model, as well as in the proposed cushing models

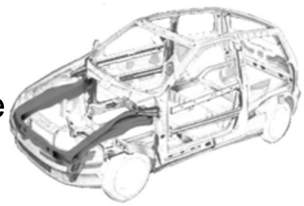


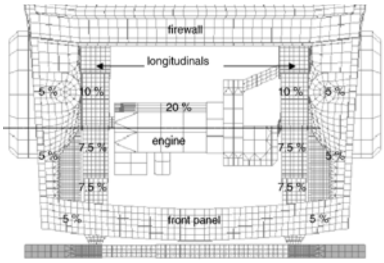


Vehicle MB Model for Crash Analysis

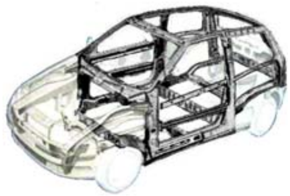
Vehicle energy absorbing structural components

Front impact protection structure





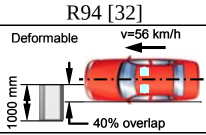
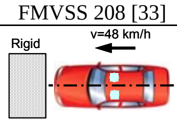
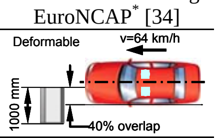
Side impact protection structure



Rollover protection structure

Vehicle MB Model for Crash Analysis

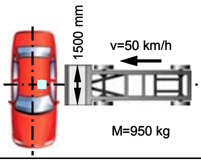
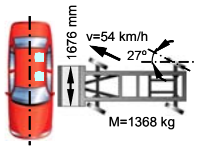
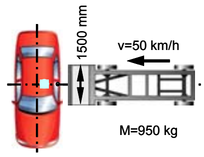
Front Impact Regulations

	European Regulation R94 [32]	US Regulation FMVSS 208 [33]	New Car Assess. Prog. EuroNCAP* [34]
Test Configuration			
Dummies	2 Hybrid III	2 Hybrid III	2 Hybrid III
Head Injury	HPC<1000 a_{3ms}<80 g	HIC_{36}<1000 HIC_{15}<700	a_{peak}<80g If a_{peak}>80 g, a_{3ms}<72 g and HIC_{36}<650
Neck Injury+	$N_{extension}$<57 Nm $N_{tension@60ms}$<1.1 kN $N_{shear@45ms}$<1.1 kN	N_{ij}<1.0	$N_{extension}$<42 Nm $N_{tension@0ms}$<2.7 kN $N_{shear@0ms}$<1.9 kN
Thorax Injury	CC< 50 mm VC< 1.0m/s	CC<76.2 mm a_{3ms}<60 g	CC<22 mm VC<0.5 m/s
Femur Injury+	$FFC_{@10ms}$<7.58 kN	FFC<10 kN	$FFC_{@10ms}$<3.8 kN
Knee Injury	Δd<15 mm		Δd<6 mm
Tibia Injury	TCFC<8 kN TI<1.3		TCFC<2 kN TI<0.4
Steering Wheel Displ.	Δx<100 mm Δy<80 mm		Δx<90 mm Δy<72 mm
Pedal Displacement			Δx<100 mm

*The EuroNCAP limits are presented for maximum score. The R94 limits lead to null score.
+The limits are bounded by a force corridor described in the regulation

Vehicle MB Model for Crash Analysis

Side Impact Regulations

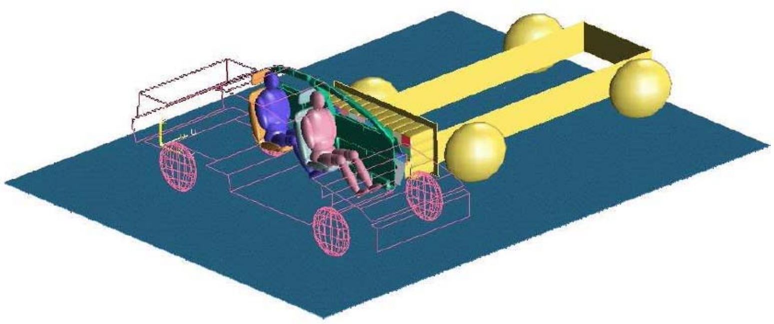
	European Regulation R95 [35]	US Regulation FMVSS 214 [36]	New Car Assess. Prog. EuroNCAP* [34]
Test Configuration			
Dummies	1 EuroSID	2 SID	1 EuroSID
Head Injury	HPC<1000		a_{peak}<80g If a_{peak}>80 g, a_{3ms}<72 g and HIC_{36}<650
Thorax Injury	VC< 1.0m/s RDC<42 mm	TTI<85 g	CC<22 mm VC<0.32 m/s
Pelvis Injury	PSPF < 6 kN	a_{peak}<130 g	PSPF<3 kN
Abdomen Injury	APF < 2.5 kN		APF< 1.0 kNm
Tibia Injury			TCFC<2 kN TI<0.4

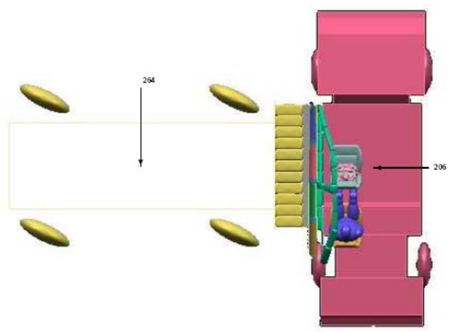
*The EuroNCAP limits are presented for maximum score. The R95 limits lead to null score.

Vehicle MB Model for Crash Analysis

Side Impact Primary Scenario: FMVSS 214

Model fully validated against experimental testing results

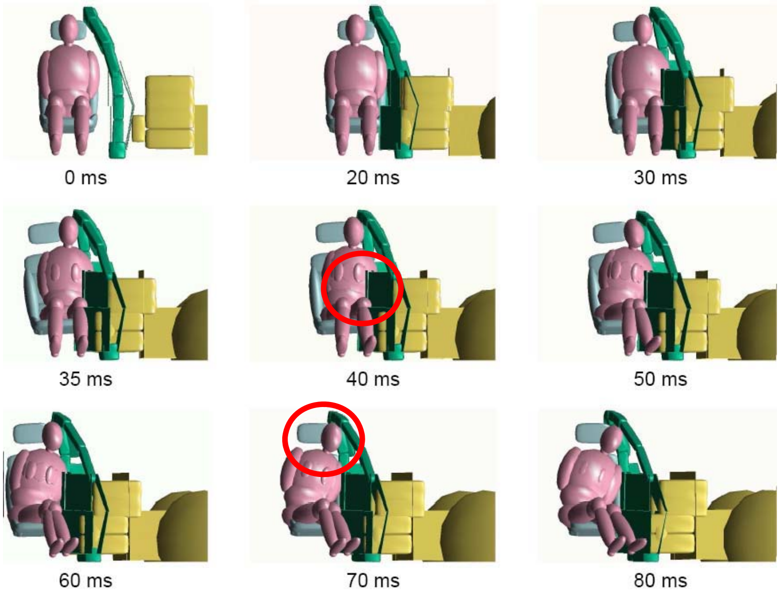




System ID	System Name
1	Floor (Reference Space)
2	S2_Car
3	S3_Left_Side
4	S4_BARRIER
5	S5_US_DOT_Side_Impact_Dummy
6	S6_SEAT
7	S7_US_DOT_Side_Impact_Dummy
8	S8_SEAT

Vehicle MB Model for Crash Analysis

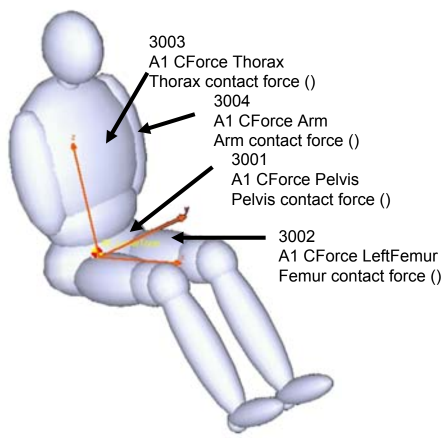
Side Impact Primary Scenario: original model

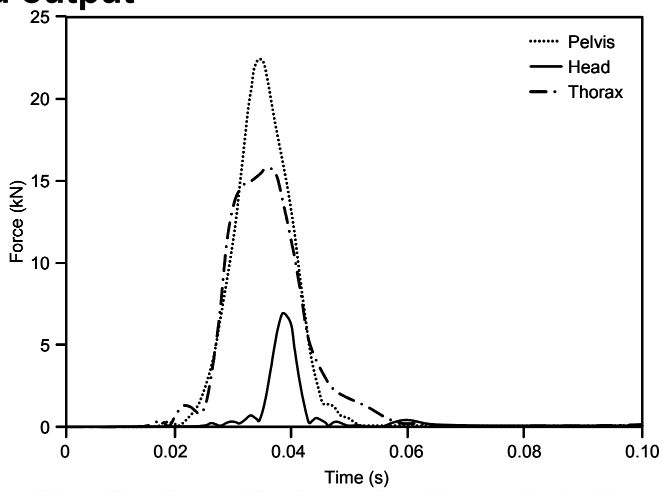


Vehicle MB Model for Crash Analysis

Side Impact Primary Scenario
Design evaluation – selected output

Occupant contact forces





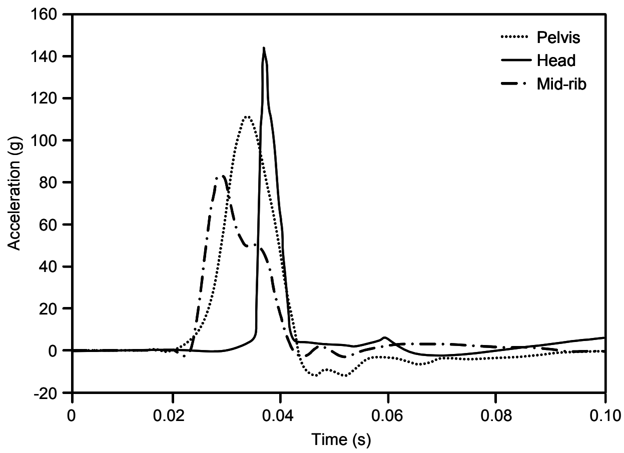
Note: The values considered are resultant force magnitude values.

Peak values:	Thorax CF +Arm CF	1.598158e+04 N
	Pelvis CF +Femur CF	2.247170e+04 N
	Head CF	6.9033E+03 N - 37.50 ms

Vehicle MB Model for Crash Analysis

Side Impact Primary Scenario
Design evaluation – selected output

Occupant accelerations – Injury criteria



Peak accelerations:

Head acc	1.4109E+03 m/s**2 - 36.10 ms
T1 acc	4.5788E+02 m/s**2 - 39.40 ms
T12 acc	8.8200E+02 m/s**2 - 34.40 ms
Mid rib acc	8.2132E+02 m/s**2 - 28.10 ms
Pelvis acc	1.0814E+03 m/s**2 - 33.10 ms

Injury criteria:

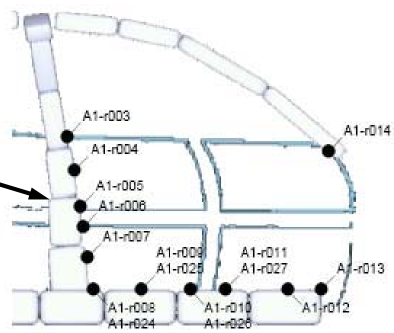
		limits
HIC36	492.96	(1000)
TTI	87.829	(85 g)
Chest deflection	3.7847E-02 m - 48.20 ms	(4.2e-2 m)
T12 peak resultant acc	8.9161E+02 m/s**2 - 34.40 ms	(8.0442e+2 m/s**2)
Pelvis peak lateral acc	1.0814E+03 m/s**2 - 33.10 ms	(1.2753e+3 m/s**2)

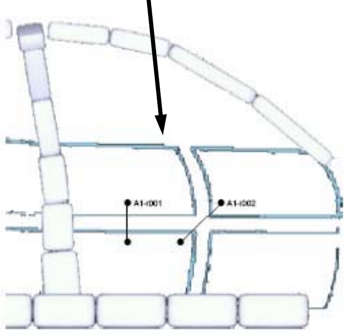
Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies
Alternative Designs

Door Locking

Door Stiffening



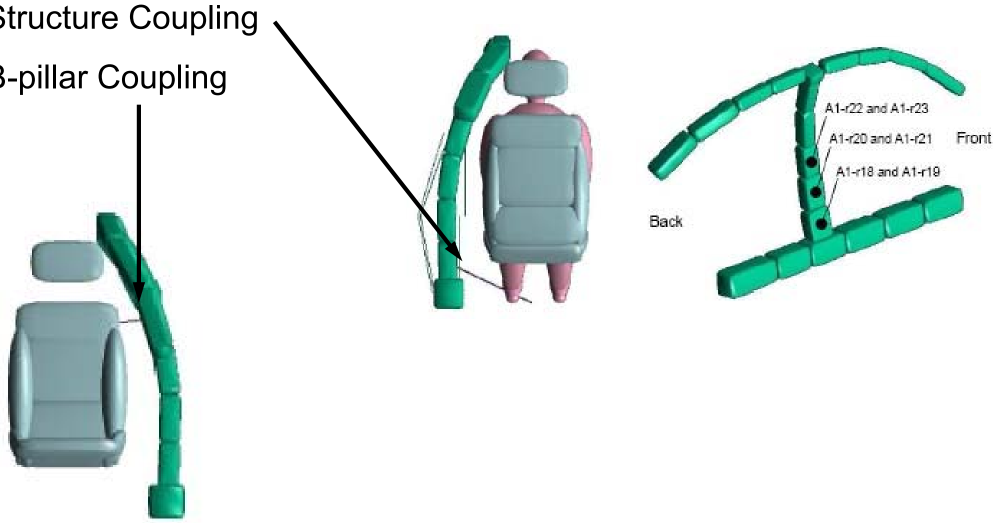


Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies
Alternative Designs

Seat to Structure Coupling

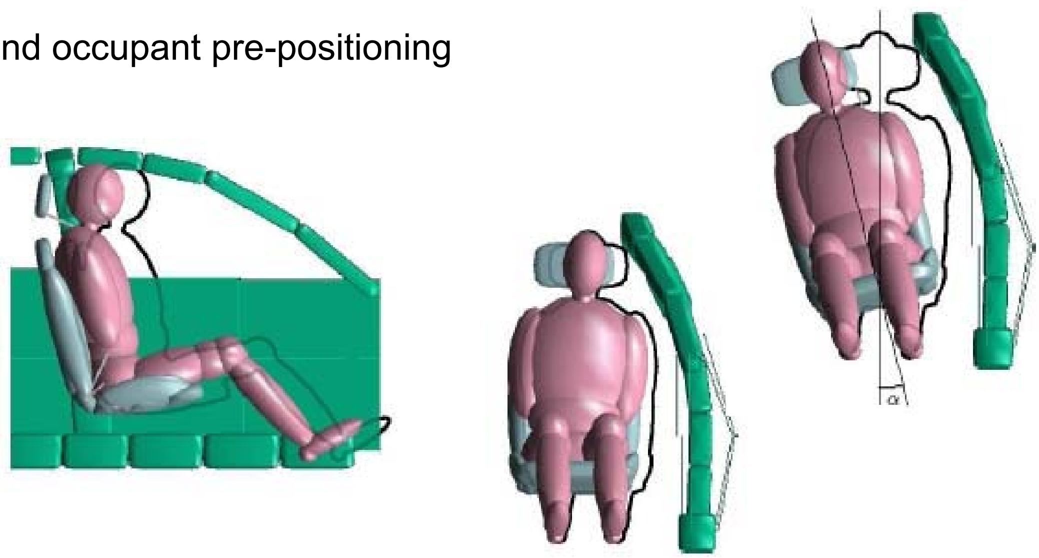
Seat to B-pillar Coupling



Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies
Alternative Designs

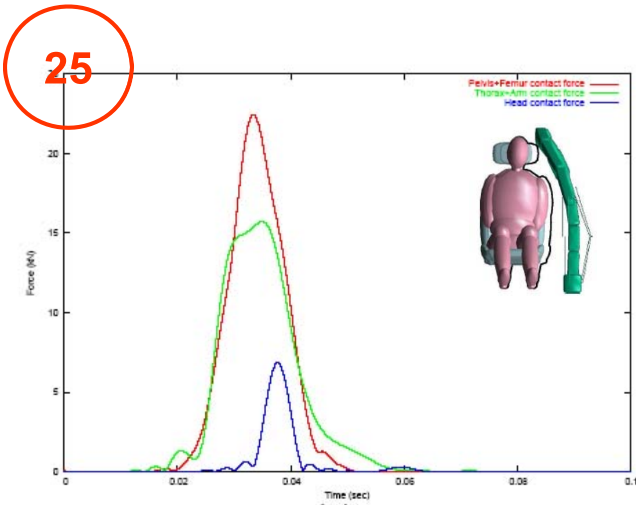
Seat and occupant pre-positioning



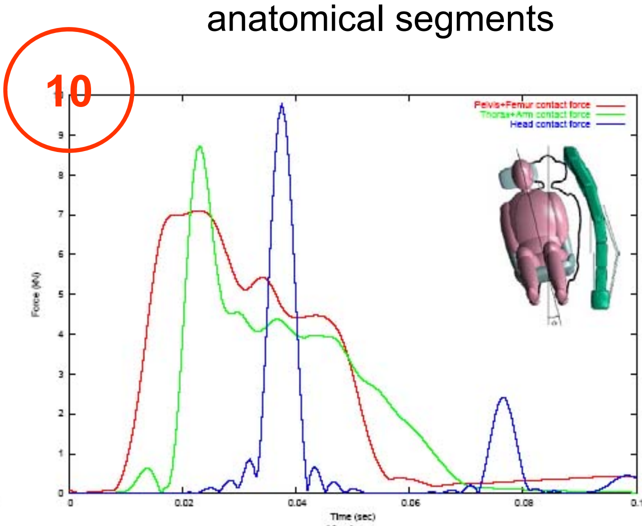
Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies
Design evaluation – selected output

Contact forces for different anatomical segments



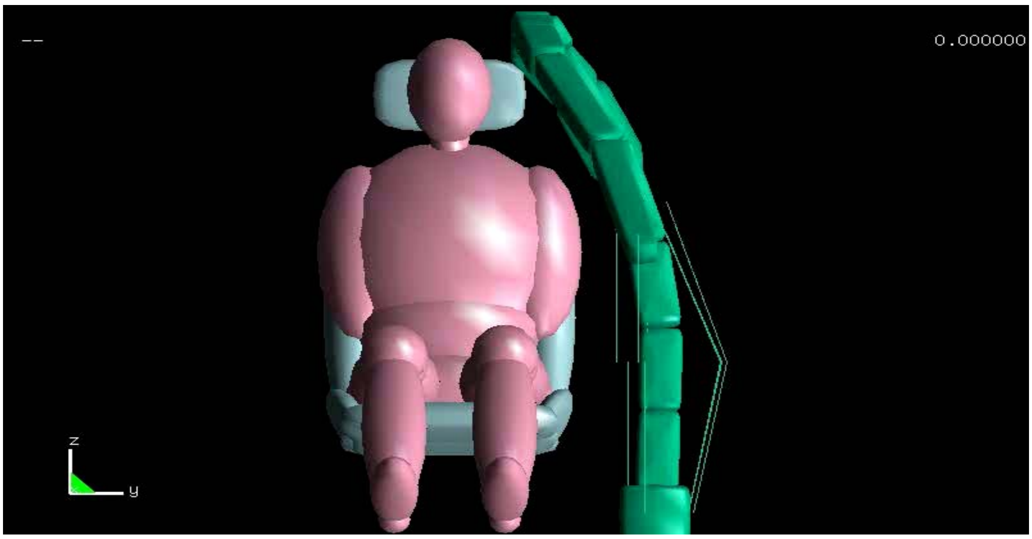
Initial



Modified

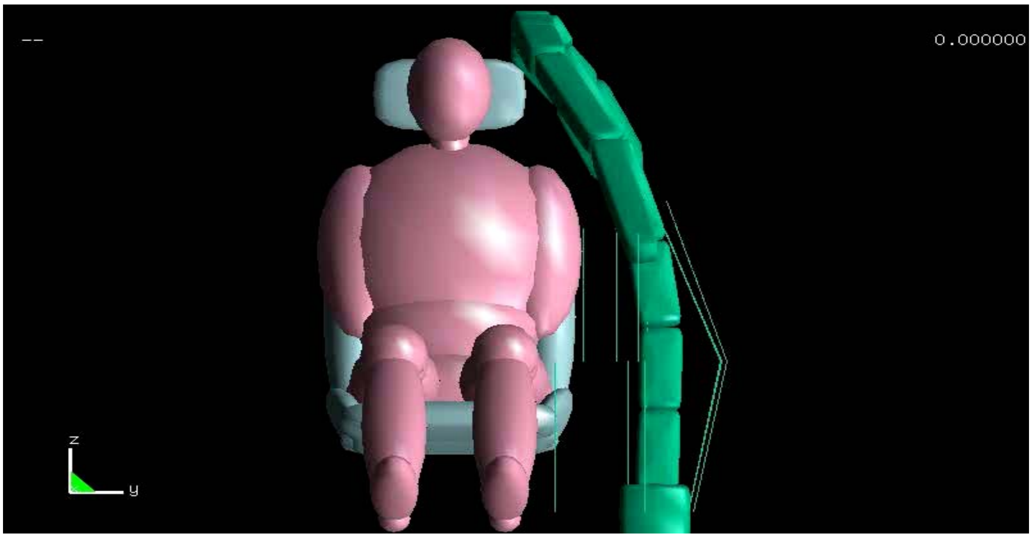
Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies: Original Design



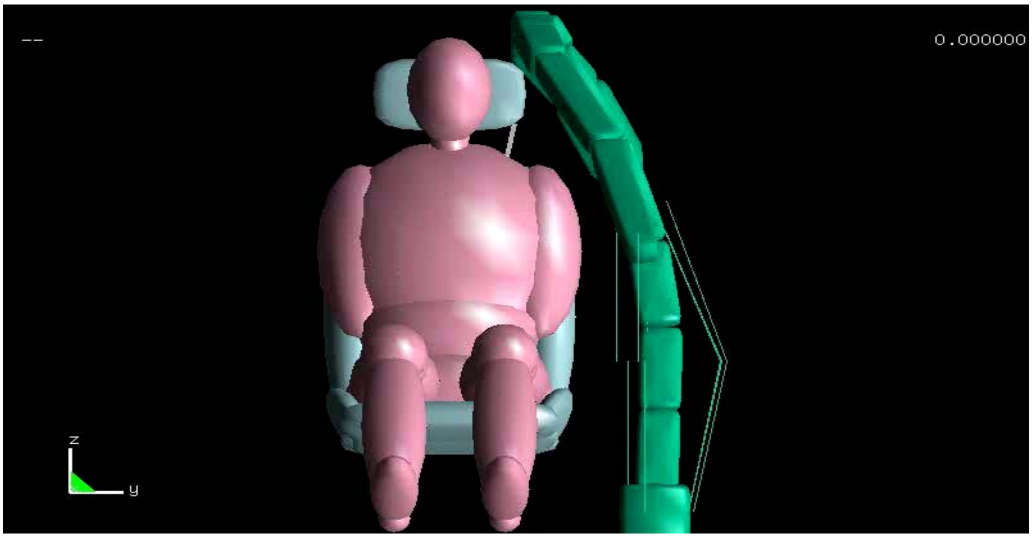
Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies: Improved Interior Cushing



Vehicle MB Model for Crash Analysis

Side Impact Protection Strategies: Seat Structure Coupling



Primary and Secondary Collisions

Train crash events depicted in two phases:

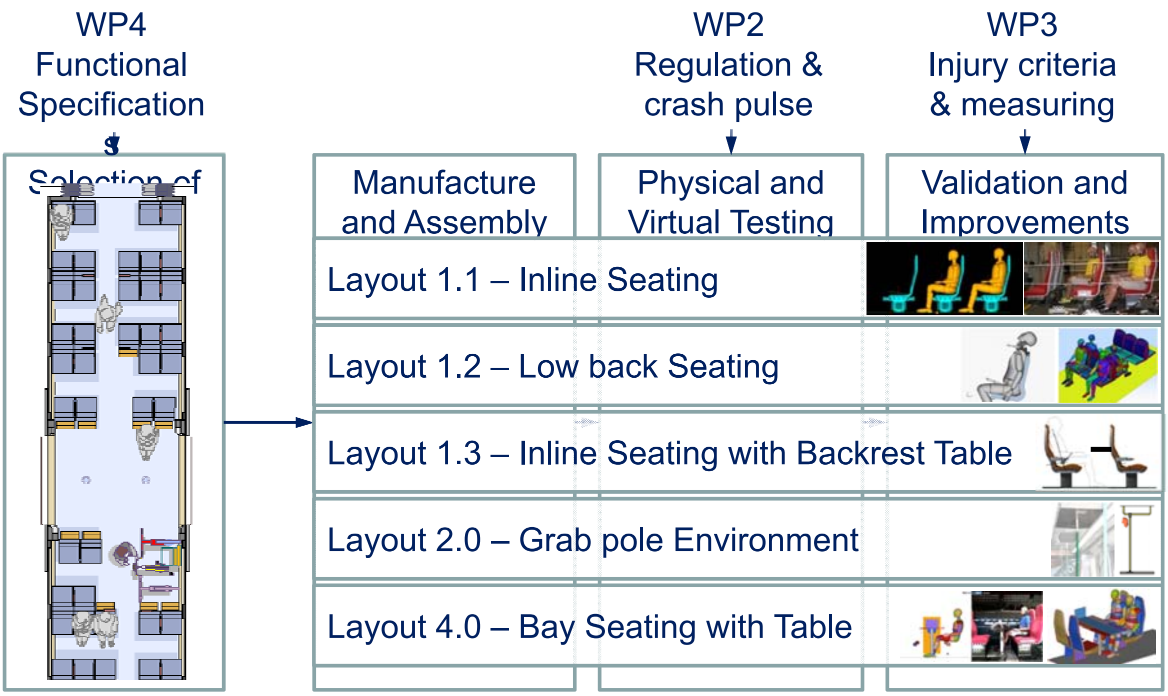
- primary collision,

  In this phase occupant compartment integrity and acceptable vehicle acceleration levels **are the most important design requirements to be considered.**

- secondary collision,

  Design requirements must involve the aspects of interior layouts, acceptable severity levels and biomechanical response **to vehicle crash pulses.**

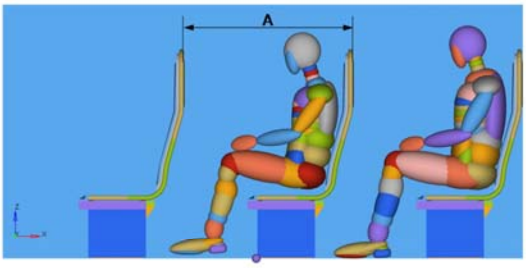
Railway Interior Scenarios

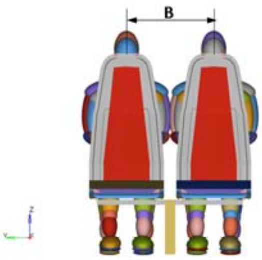


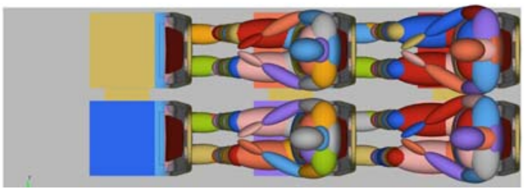
Model of the Inline Seating

A vehicle interior model is made by using multibody systems to represent the dummies and nonlinear finite elements for the seats.

The MADYMO multibody code is used for the model development.





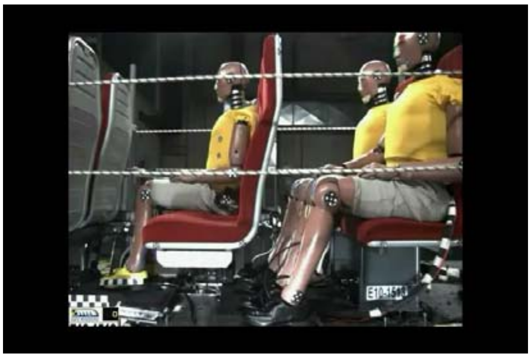


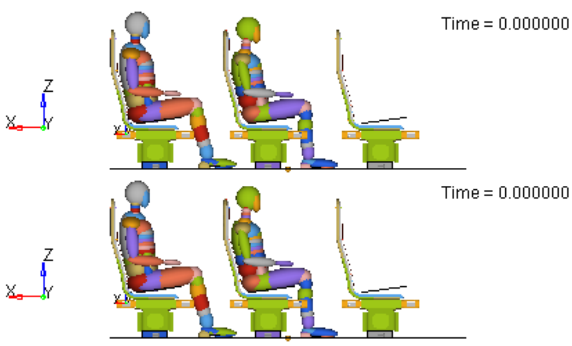
- Seat pitch (1st class)
  - A = 950 mm
- Horizontal distance between seats
  - B = 508mm
- Forward Dummies
  - Hybrid III 50%-ile
- Rear Dummies
  - Hybrid III 95%-ile

Performance of Validated Model

Inline seating: Physical testing and validation.

Reference Model

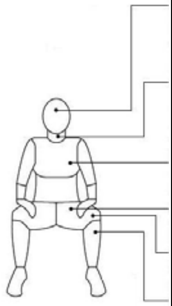




Experimental

Validated Model

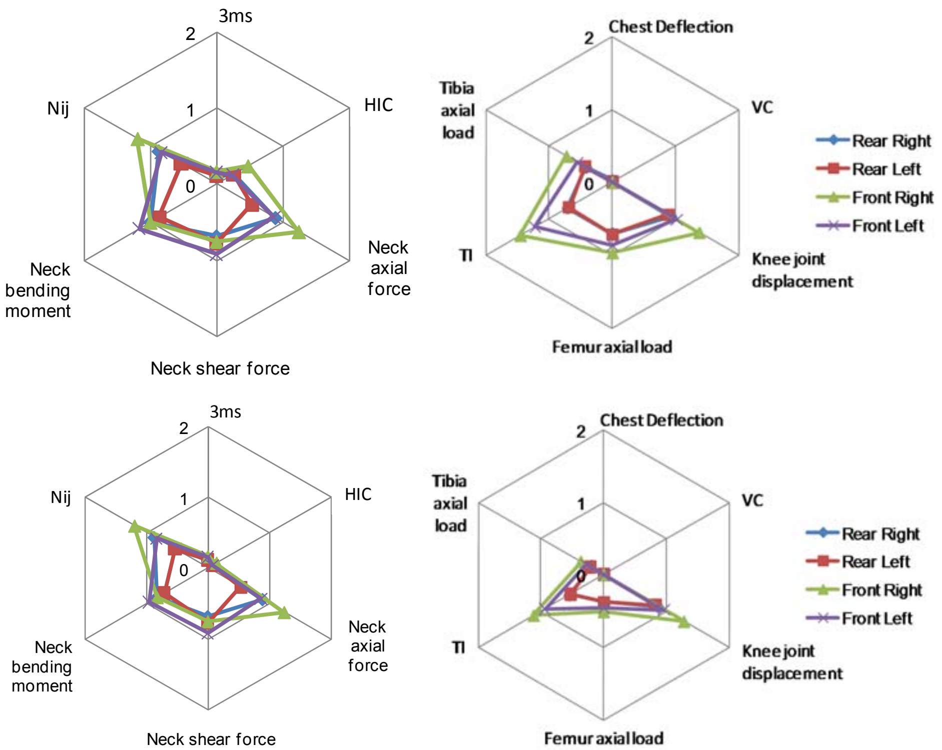
Performance of Validated Model



Body region	Injury criterion	MADYMO	Experimental	% Difference (MADYMO-Exp.)/Exp.
HEAD	Resultant Head Acceleration (3ms) (g)	50.8	57.2	-11
	HIC15	239.6	268.7	-11
UPPER NECK	Neck Shear Force (N)	1614	1300	24
	Neck Axial Force (N)	1030	850	21
	Neck Bending Moment (Nm)	41.0	46.2	-11
CHEST	Deflection of chest wall relative to spine (m)	0.0	0	0
	Localized Rib Viscous Criterion (m/s)	0.0	0	0
FEMUR	Femur uni-axial Load (right) (N)	2320	2450	-5
	Femur uni-axial Load (left) (N)	2901	2480	17
KNEE	Knee Joint Displacement (right) (mm)	11.1	4	178
	Knee Joint Displacement (left) (mm)	13.4	13.5	-1
TIBIA	Tibia Axial Load (right) (N)	-776	-450	72
	Tibia Axial Load (left) (N)	-696	-550	27
	Tibia Index (right)	0.70	0.09	678
	Tibia Index (left)	0.90	0.2	350

- The Head and femural injury indexes obtained in the virtual and physical testing are very close.
- The Tibia indexes show large differences, but, in any case, with values far from the injury threshold.
- The Hybrid III is known for having a unreliable biofidelity for the knee measures (and eventually for the tibial measures).

Injury Indexes (Dimensionless)



a) moderate limit

b) serious limit

Lecture Objectives

Present multibody based formulations able to handle complex systems of practical interest.

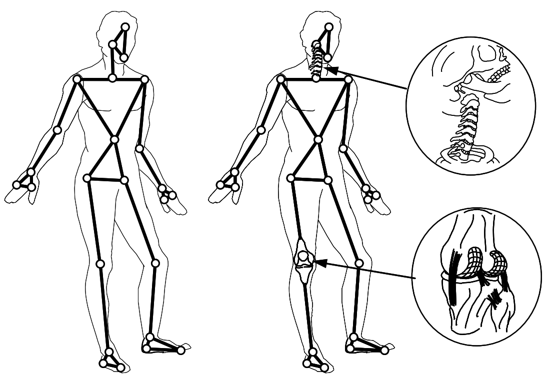
Modelling of the human body for the study of human motion tasks: on the use of inverse dynamics..

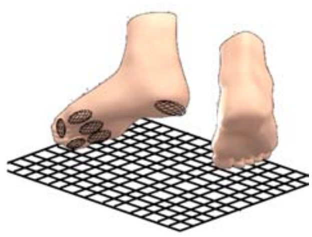
Biomechanical models in crash analysis: on the use of forward dynamics

Selected challenges.

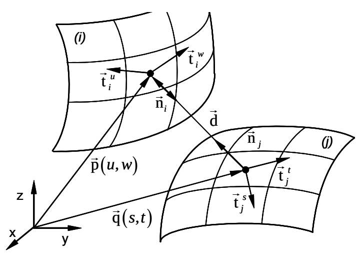
Selected Challenges: Biomechanics

Realistic contact models for anatomical joints and external contacts:





Implications on the evaluation of the internal forces of the human body (muscle forces and intersegment forces) and on the injury indexes.



Selected Challenges: Biomechanics

Indentification of the objective functions to characterise the human motion:

Minimal energy?

Maximum stability?

Minimal intersegment forces (pain)?

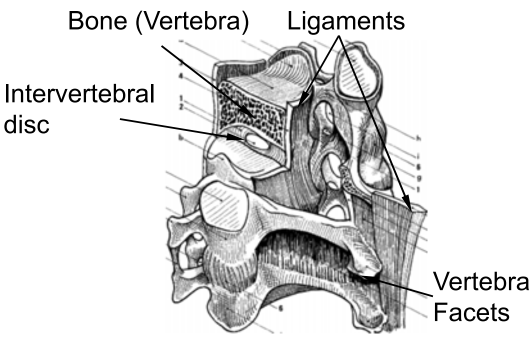
Multiple objective?

Other?

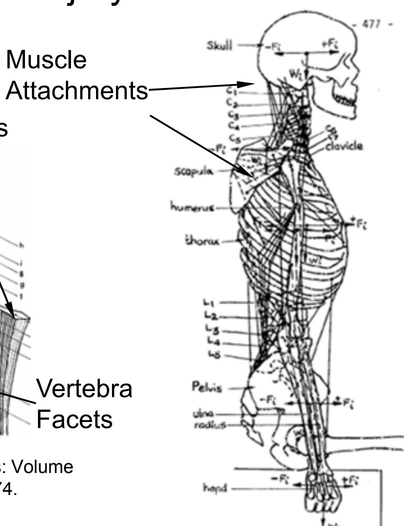
Implications on the evaluation of the internal forces of the human body (muscle forces and intersegment forces).

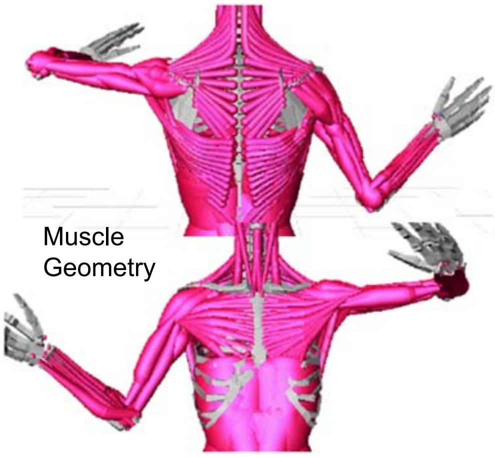
Selected Challenges: Biomechanics

Human biomechanical models including muscle voluntary contraction in injury biomechanics:



In: I.A. Kapandji, 'The Physiology of the Joints: Volume 3', Churchill Livingstone, Edinburgh, U.K., 1974.





In: Walter Murial, '3D Modeling of the Human Upper Limb Including the Biomechanics of Joints, Muscles and Soft Tissues, Ph.D. Thesis, Ecole Polytechnique Federal de Lausanne, Lausanne, Switzerland, 1999

In: A. Seireg and R. Arvikar, 'Biomechanical Analysis of the Muscoloskeletal Structure for Medicine and Sports', Hemisphere Pub. Corp., New York, New York, 1989

Implications on applicability of the model (omnidirectional) and on the evaluation of the injury indexes (kinematic modifiers)

Thank you for your attention