Musculoskeletal modelling: Basic principles, different models and methods, sensitivity analysis, levels of validation

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Basic principles

❑ Joint equilibrium

– Inverse dynamics (inter-segmental wrench)

– Muscular and articular geometry

« Net » joint force = Σ musculo-tendon forces (about lines of action)
+ Σ ligament forces (about lines of action)
+ Σ contact forces (about lines of action)

« Net » joint moment = Σ [lever arms × musculo-tendon forces (about lines of action)]
~~*+ Σ [lever arms × ligament forces (about lines of action)]*~~
~~*+ Σ [lever arms × contact forces (about lines of action)]*~~

- *Remark #1: muscular redundancy*
- *Remark #2: joint axes where the moments of joint reactions are assumed negligible*
- *Remark #3: 2-step computation*

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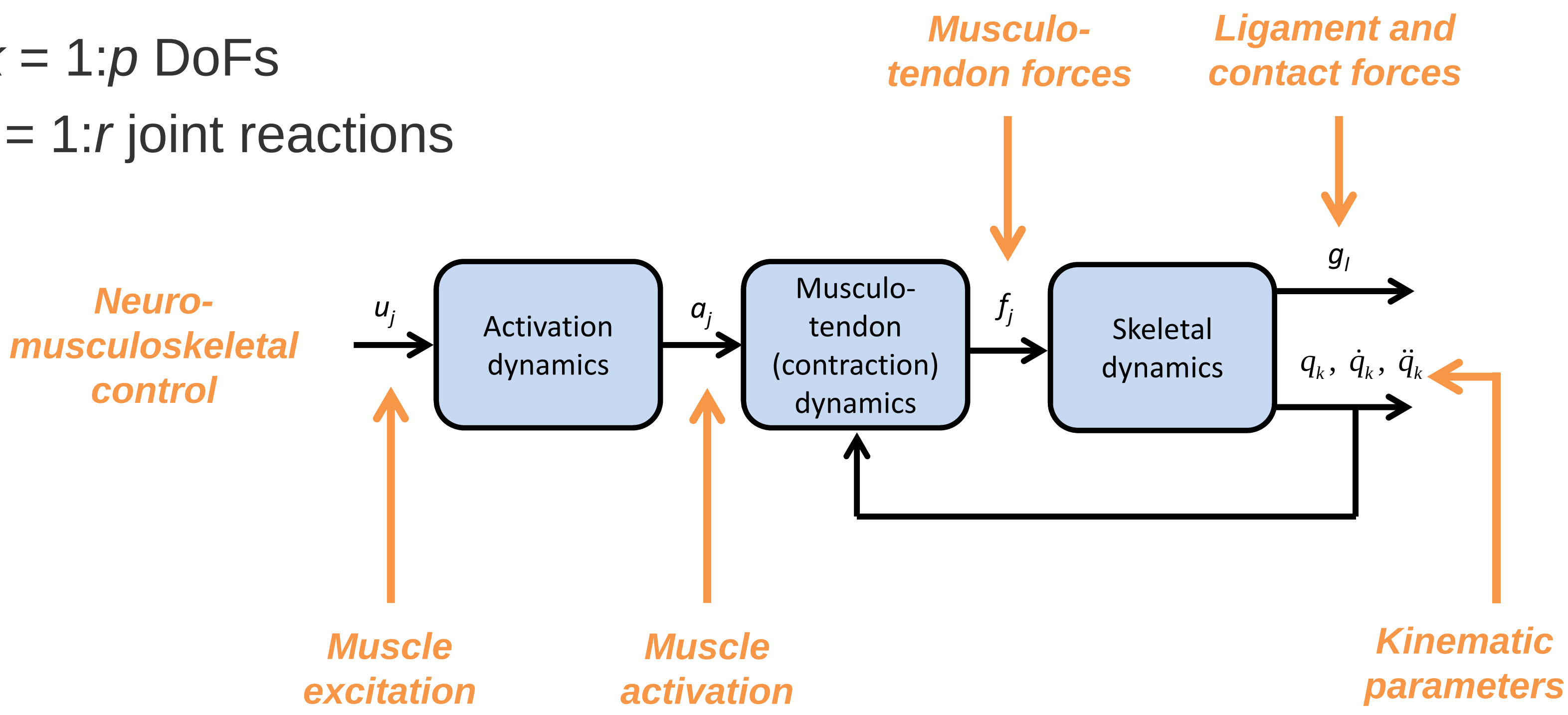
Basic principles

❑ System dynamics

– j = 1:m muscles
– k = 1:p DoFs
– l = 1:r joint reactions



Cheze et al. 2015

Models

- Activation dynamics
  - Non-linearity

$$a_j = \left(e^{A \cdot u_j} - 1\right) / \left(e^{A} - 1\right)$$

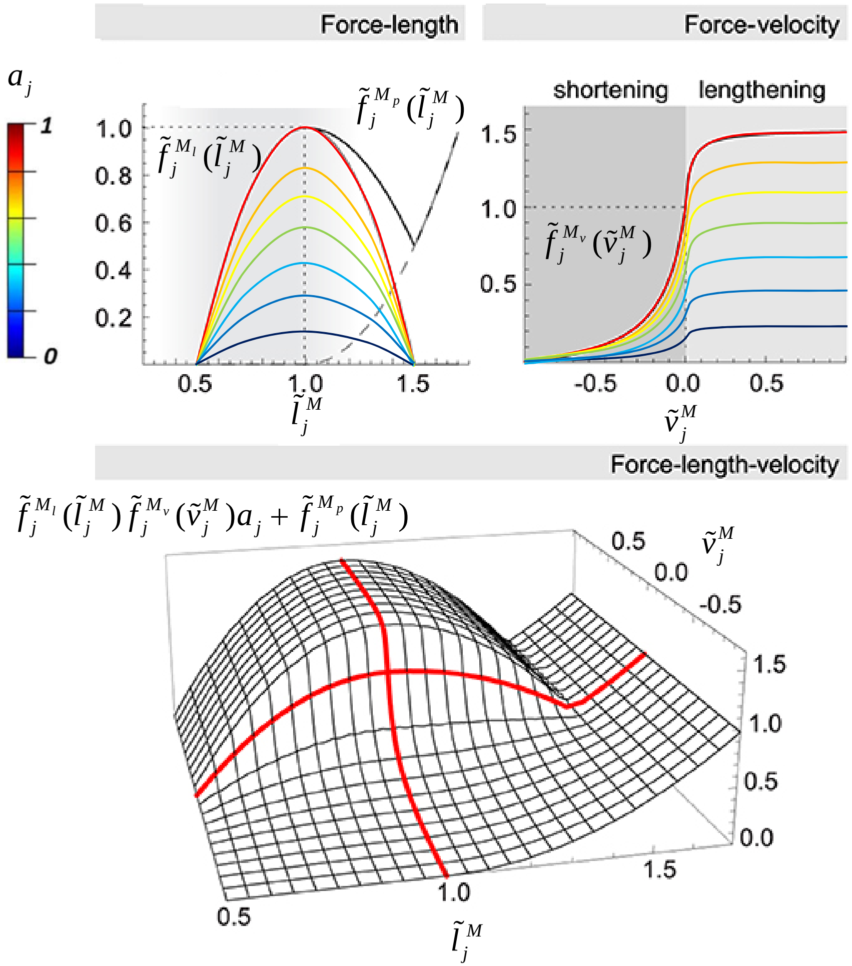
Lloyd and Besier 2003

Models

- Activation dynamics
  - Non-linearity

$$a_j = \left(e^{A \cdot u_j} - 1\right) / \left(e^{A} - 1\right)$$

- Contraction dynamics
  - Hill-type muscle
    - *Force-length*
    - *Force-velocity*
    - *Passive*
  - Tendon



Models

❑ Skeletal dynamics

– Recursive Newton-Euler

- *m muscles, p DoFs, r joint reactions*
- *i = 1:n joint*

$$\begin{pmatrix} \mathbf{M}_1 \bullet \mathbf{e}_1 \\ \vdots \\ \mathbf{M}_n \bullet \mathbf{e}_p \end{pmatrix} = \begin{bmatrix} \mathbf{L}_1^f & \cdots & \mathbf{L}_m^f \end{bmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_m \end{pmatrix}$$

« Net » joint moments — ***DoF axes*** — ***Lever arms*** — ***Musculo-tendon forces***

Fraysse et al. 2009
Cleather et al. 2011

- *Remark #1: non-invertible (m > p)*
- *Remark #2: multiple joints (bi-articular muscles)*

Models

❑ Skeletal dynamics

– Recursive Newton-Euler

- *m muscles, p DoFs, r joint reactions*
- *i = 1:n joint*

$$\begin{pmatrix} \mathbf{M}_1 \bullet \mathbf{e}_1 \\ \vdots \\ \mathbf{M}_n \bullet \mathbf{e}_p \end{pmatrix} = \begin{bmatrix} \mathbf{L}_1^f & \cdots & \mathbf{L}_m^f \end{bmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_m \end{pmatrix}$$

– 2-step computation for joint reactions

$$\begin{Bmatrix} \mathbf{F}_i \\ \mathbf{M}_i \end{Bmatrix} - \begin{Bmatrix} \sum f_j \mathbf{u}_j \\ \sum (\mathbf{M}_i \bullet \mathbf{e}_k) \mathbf{e}_k \end{Bmatrix} = \begin{bmatrix} \mathbf{u}_1 & \cdots & \mathbf{u}_r \\ \mathbf{L}_1^g & \cdots & \mathbf{L}_r^g \end{bmatrix} \begin{pmatrix} g_1 \\ \vdots \\ g_r \end{pmatrix}$$

Cheze et al. 2015

« Net » joint forces, moments — *Lines of action* — *Lever arms* — *Ligament and contact forces*

- *Remark: invertible (r = 6*n-p)*

Models

❑ Skeletal dynamics

– Lagrange

- *m muscles, p DoFs, n joints*
- *r = 6*n-p joint constraints*

Jacobian of constraints **Lagrange multipliers**

$$\begin{pmatrix} \frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_1}\right) - \frac{\partial E}{\partial q_1} - \frac{\partial P}{\partial \dot{q}_1} \\ \vdots \\ \frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_{p+r}}\right) - \frac{\partial E}{\partial q_{p+r}} - \frac{\partial P}{\partial \dot{q}_{p+r}} \end{pmatrix} = \begin{bmatrix} \mathbf{L}_1^f & \cdots & \mathbf{L}_m^f \end{bmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_m \end{pmatrix} + \begin{bmatrix} \frac{\partial \boldsymbol{\Phi}}{\partial \mathbf{q}} \end{bmatrix}^T \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_r \end{pmatrix}$$

Kinetic energy **Kinematic parameters** **Power of external forces**

Erdemir et al. 2007
Moissenet et al. 2014
Cheze et al. 2015

- *Remark #1: appropriate for forward dynamics*
- *Remark #2: 1-step computation for joint reaction*

Models

- Skeletal dynamics
  - Lagrange
    - *m muscles, n joints*
    - *r penalty-based reactions*

Penalty stiffness   *Penalty constraints*

$$\begin{pmatrix} \frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_1}\right) - \frac{\partial E}{\partial q_1} - \frac{\partial P}{\partial \dot{q}_1} \\ \vdots \\ \frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_{6*n}}\right) - \frac{\partial E}{\partial q_{6*n}} - \frac{\partial P}{\partial \dot{q}_{6*n}} \end{pmatrix} = \begin{bmatrix} \mathbf{L}_1^f & \cdots & \mathbf{L}_m^f \end{bmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_m \end{pmatrix} + \begin{bmatrix} \frac{\partial \mathbf{\Phi}}{\partial \mathbf{q}} \end{bmatrix}^T \begin{pmatrix} K_1 \Phi_1 \\ \vdots \\ K_r \Phi_r \end{pmatrix}$$

6 DoFs per joints

Shelburne et al. 2005
Guess et al. 2011
Lenhart et al. 2015

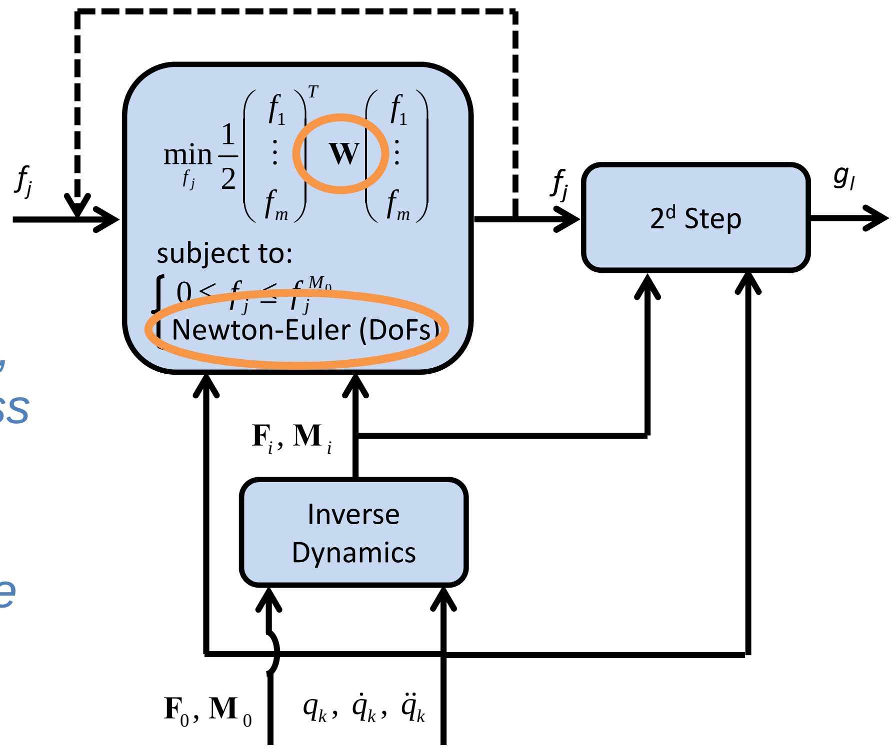
- *Remark: appropriate for forward dynamics with deformable joints*

Methods

❑ Static optimisation

– Minimisation of musculo-tendon forces

- *Remark #1: weighting by, e.g., physiological cross section area*
- *Remark #2: joint modelled as hinge or spherical*



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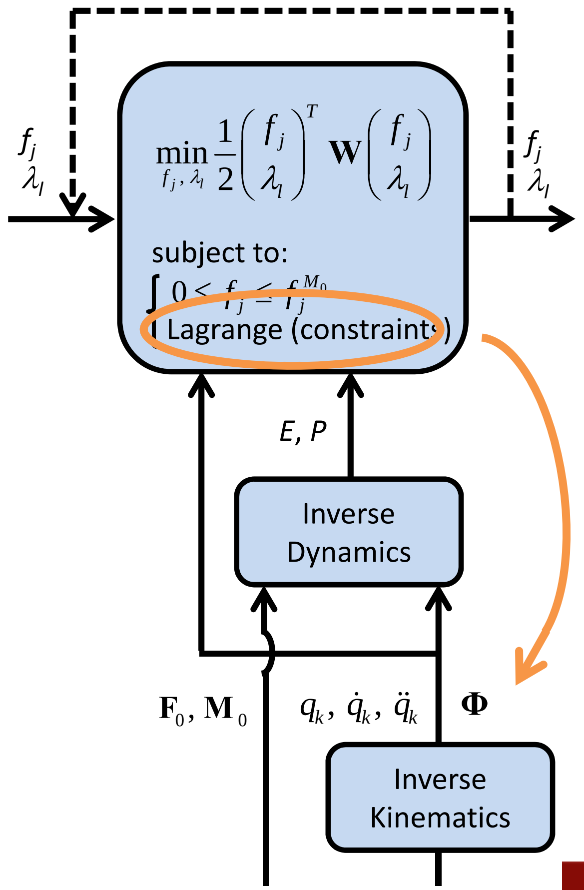
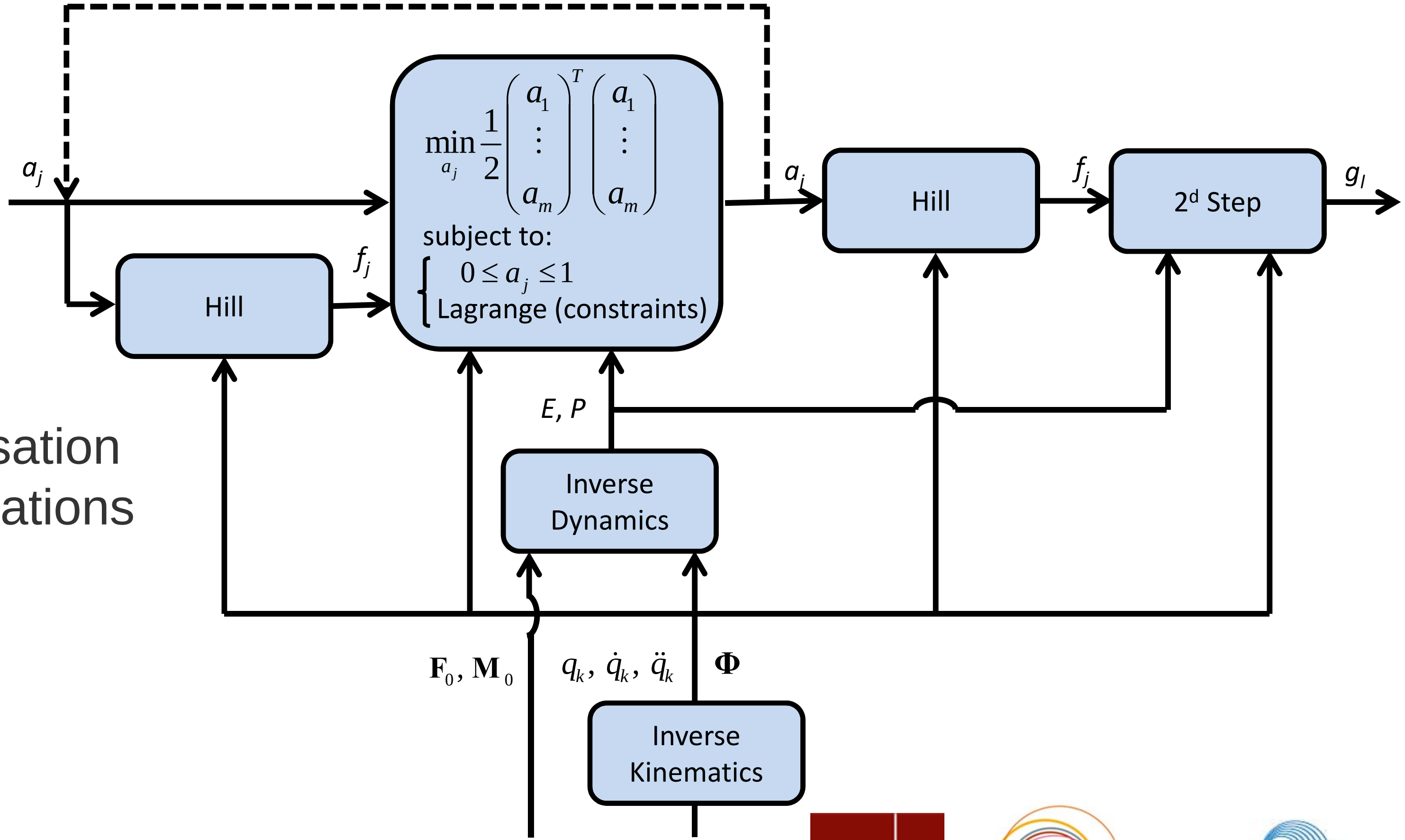
Methods

- Static optimisation
  - Minimisation of musculo-tendon forces
  - Minimisation of musculo-tendon, ligament and contact forces



Methods

- Static optimisation



– Minimisation of activations

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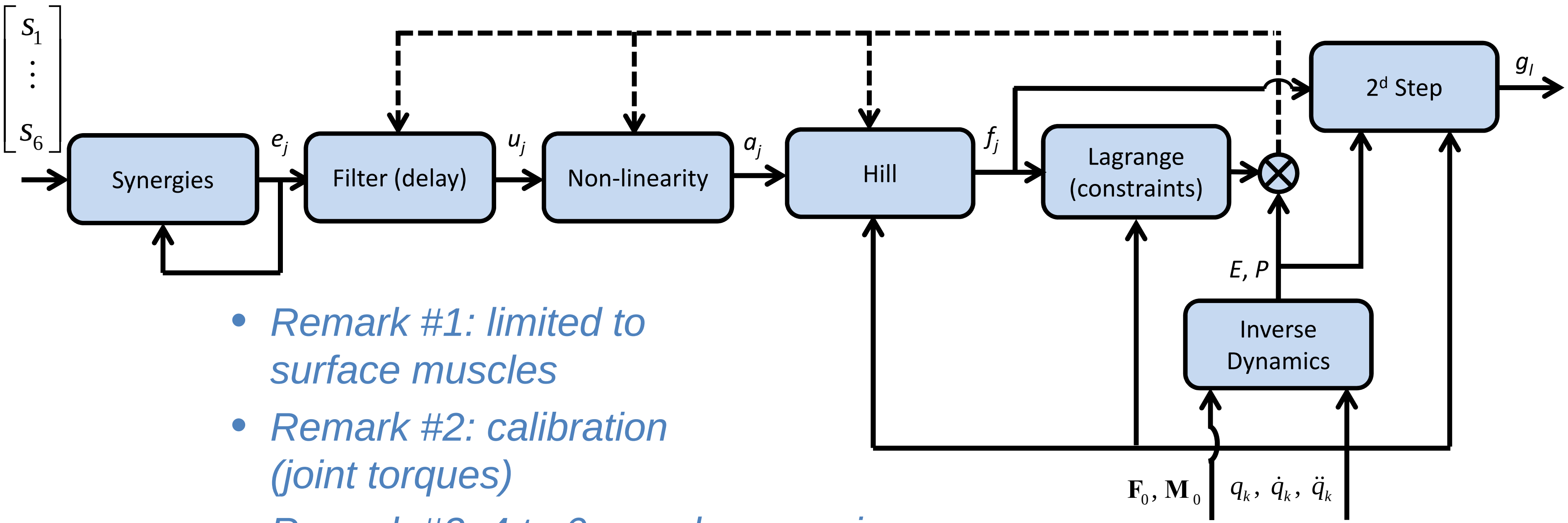
Methods

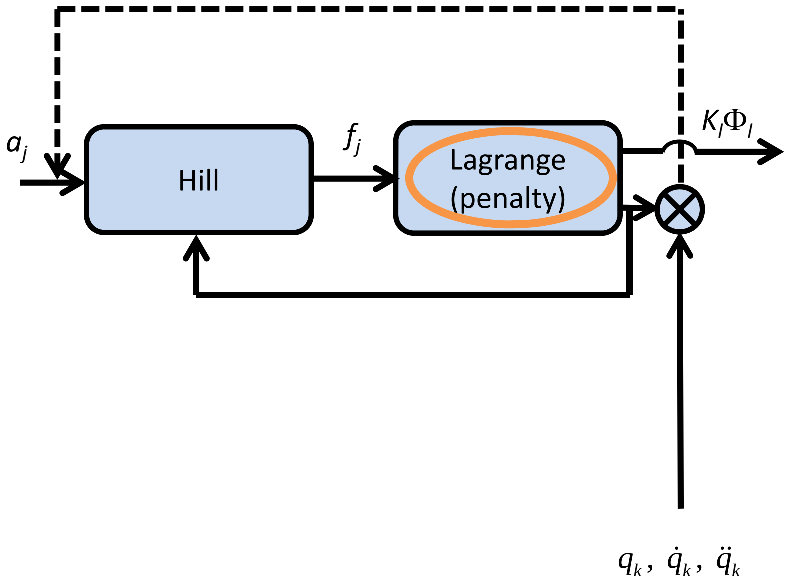
❑ EMG to force



- *Remark #1: limited to surface muscles*
- *Remark #2: calibration (joint torques)*
- *Remark #3: 4 to 6 muscle synergies for locomotion (non-negative matrix factorisation of the EMG)*

Methods

- Forward dynamics assisted data tracking
  - Tracking of kinematics
    - *Remark #1: additional minimisation (e.g., activations) and constraints*
    - *Remark #2: time integration, foot contact model (and deformable joints)*



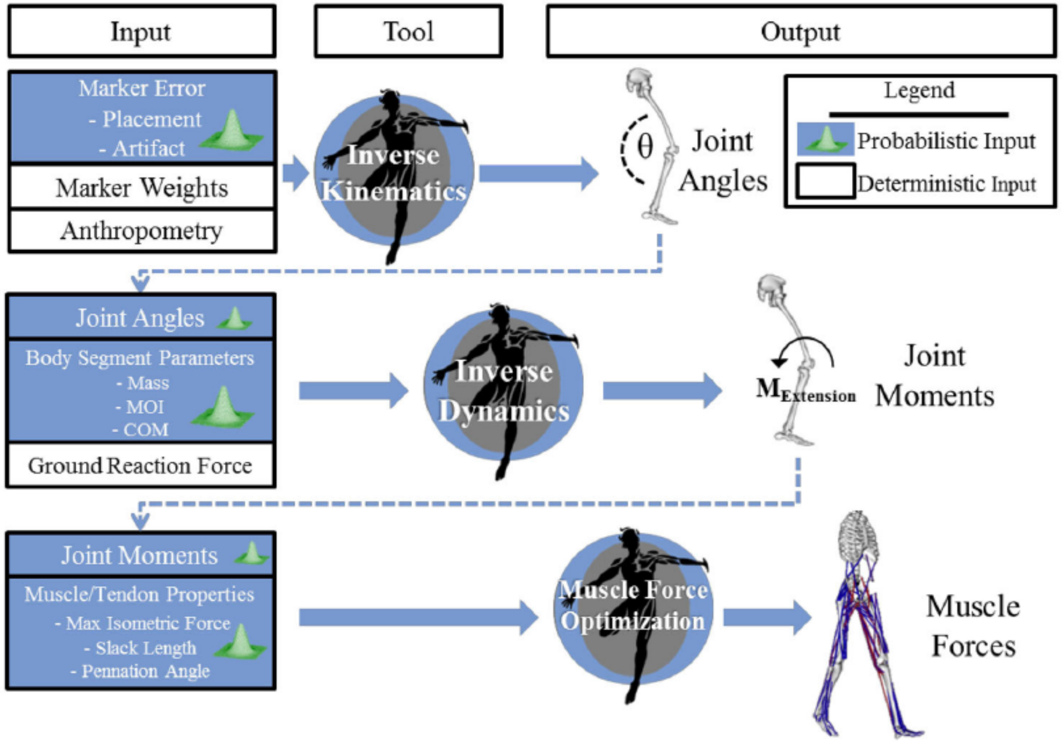
Sensitivity analysis

- Model parameters
  – Opensim / Anybody workflows

Carbone et al. 2012
Valente et al. 2014
Bosmans et al. 2015
Myers et al. 2015

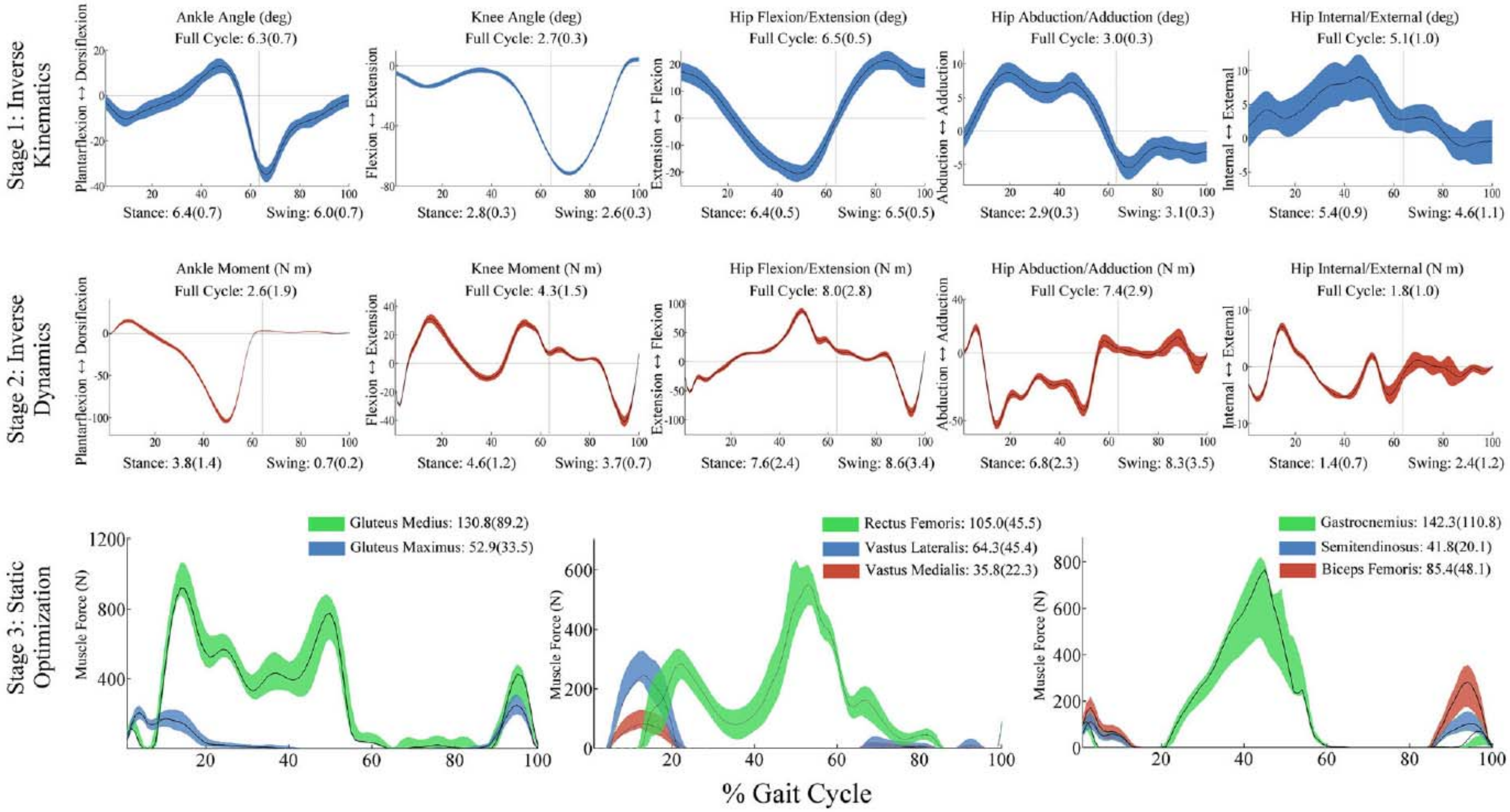
Sensitivity analysis

- Model parameters
  - Opensim / Anybody workflows
    - *From 7mm (LM) to 21mm (ASIS)*
    - *From 100g (foot) to 1kg (thigh)*
    - *From 45N (glutei) to 177N (vasti)*



Myers et al. 2015

Sensitivity analysis



Myers et al. 2015

Sensitivity analysis

- ❑ Model parameters
  - – Opensim / Anybody workflows
  - – Joint definition (personalisation)
    - *Position of joint centre*
    - *Orientation of joint axis*
    - *Position of contact points (knee)*

Heller et al. 2003
Lenaerts et al. 2008, 2009
Gerus et al. 2013
Martelli et al. 2015
Lener et al. 2015

- ❑ Model definition
  - – Number of DoFs
  - – Joint stiffness
  - – Level of muscular redundancy
  - – Optimisation (design variables, objective function, constraints)

Glitsch et al. 1997
Li et al. 1998
Xiao et al. 2008, 2010
Cleather et al. 2010, 2011
Dumas et al. 2012
Mokhtarzadeh et al. 2014
Moissenet et al. 2015, 2016

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Level of validation

- ❑ Challenging
- ❑ Guidelines
  - Model components
    - *Activation dynamics*
    - *Musculo-tendon (contraction) dynamics*
    - *Skeletal dynamics*
  - Simulation outputs
    - *Depending on the optimisation method*

Lund et al. 2012
Hicks et al. 2015

Level of validation

Musculoskeletal model test	Parameters and inputs tested *Parameters of the sensitivity analysis*	Validation best practices *In vivo data (e.g., pins, MRI, maximum voluntary force)*
Model kinematics: compute model kinematics through each joint's range of motion	Joint definitions (e.g., joint location, orientation, and type); body segment lengths	Joint ranges of motion match experimental data. Modeled joints reproduce experimental motion from bone pin, cadaver, or imaging data to within measurement error.
Muscle moment arms: compute muscle moment arms throughout the model's range of motion	Muscle geometry (attachment and via points, wrapping surfaces); **model kinematics**	Moment arms are within 2 SD of experimental data measured by tendon excursion or MRI.
Passive joint moments: calculate the net moment generated by muscles and other modeled forces (e.g., ligaments) throughout joint range of motion when muscles have zero activation	**Model kinematics**; muscle moment arms; muscle geometry; **muscle–tendon dynamics model** and its parameters, including passive force–length curve, *tendon slack length*, tendon stiffness, and maximum isometric force.	Passive moment curves are within 2 SD of experimental data.
Maximum net joint moments: calculate the net moment generated by muscles and other modeled forces (e.g., ligaments) throughout joint range of motion when agonist muscles have maximum activation input and all other muscles have zero activation	**Model kinematics**; **muscle moment arms**; muscle geometry; **muscle–tendon dynamics model** and all related parameters	Maximum moment curves are within 2 SD of experimental data. Joint moments generated by the model during submaximal activation should also be tested.

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Level of validation

Inverse simulation output	Dependencies	Validation best practices
Muscle forces and/or activations	Optimization criterion (e.g., minimize sum of squared activations); muscle moment arms; muscle force-generating capacity as a function of **path lengths and speeds; joint definitions** (e.g., degrees of freedom and other passive structures modeled)	On and off timings of muscle activity are within electromechanical (EMG-to-force) delay (∼100 ms) of experimental EMG. Muscle activity and EMG curves are qualitatively similar.
Joint reaction forces	**Kinematics; kinetics**; ***muscle forces***; *joint definitions*; segment inertial properties; *muscle geometry*	Forces are within 2 SD of experimental joint forces (e.g., instrumented implants) for similar motion.
Forward simulation output	**Dependencies**	**Validation best practices**
Contact forces and moments	Initial/current model state and either *constraint type* (e.g., weld or rolling without slipping) or compliant contact model parameters (e.g., geometry, stiffness, dissipation, friction)	Contact forces and moments are within 2 SD of experimental data (e.g., ground contact forces and moments) for similar motion.
Kinetics of joints and bodies	**Muscle–tendon forces**; contact forces; initial/current model state; joint definitions; segment lengths and inertial parameters; muscle geometry	Joint moments are within 2 SD of published or independent experimental data for similar motion.

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Thank you for your attention

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