

Programme Symposium

- Kinematics and kinematic models
 - DirkJan Veeger
- Biomechanical models
 - Ed Chadwick, Case Western Reserve University, Cleveland
- The upper extremity lab
 - Jaap Harlaar

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Goals

Biomechanical models should allow:

- Analysis of clinical problems
 - diagnosis of disorders
 - improvement of current treatments
 - development of new treatments
- Insight into human function
 - muscle function and coordination
 - energy usage
 - muscle and joint forces

Requirements

To achieve these goals, we need:

- Large-scale, 3D, comprehensive model
 - necessary to answer specific clinical questions
 - essential if validation is to be achieved
- Modification should be possible/easy
 - Speculative/Informed changes to anatomy
- Interpretable results
 - can we relate model output to patient function?

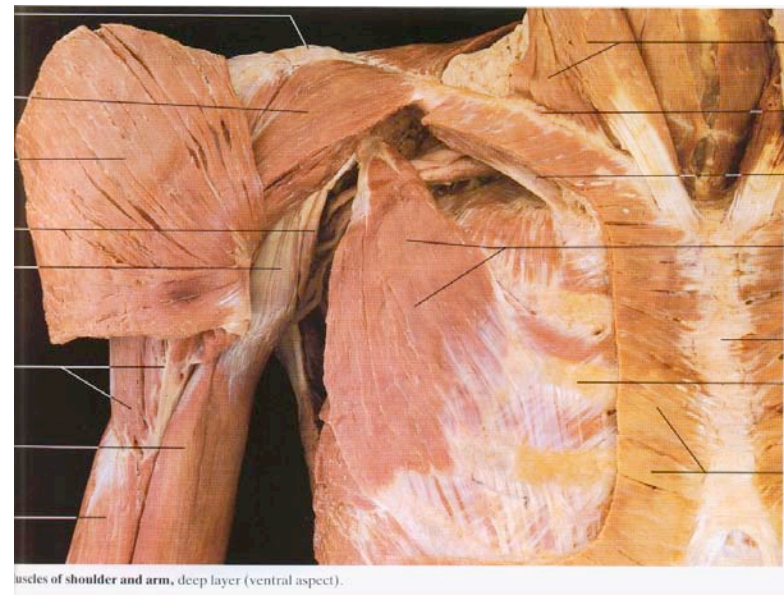
Constructing a model

- Anatomical reconstruction
 - Function follows from spatial orientation of segments and muscles
 - Accurate (3D), flexible, but complex
- Moment arm analyses
 - Tendon excursion
 - Image measurements
 - Simple (no muscle wrapping)
 - Restricted

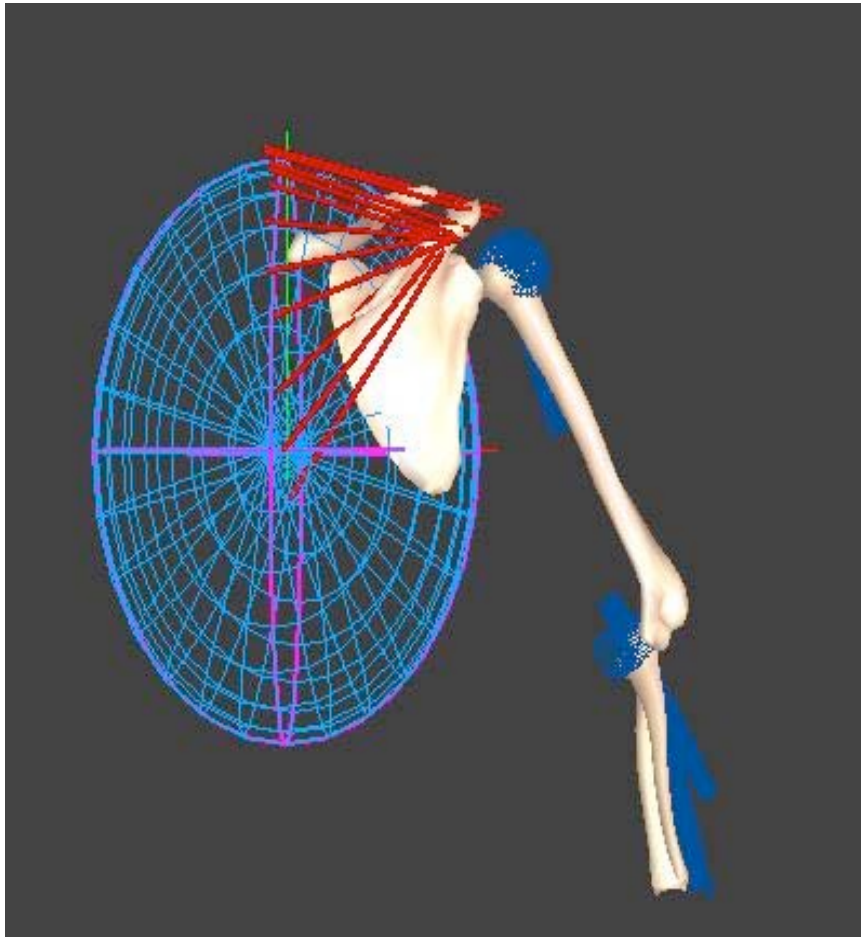
Model Parameters

Cadaver measurements:

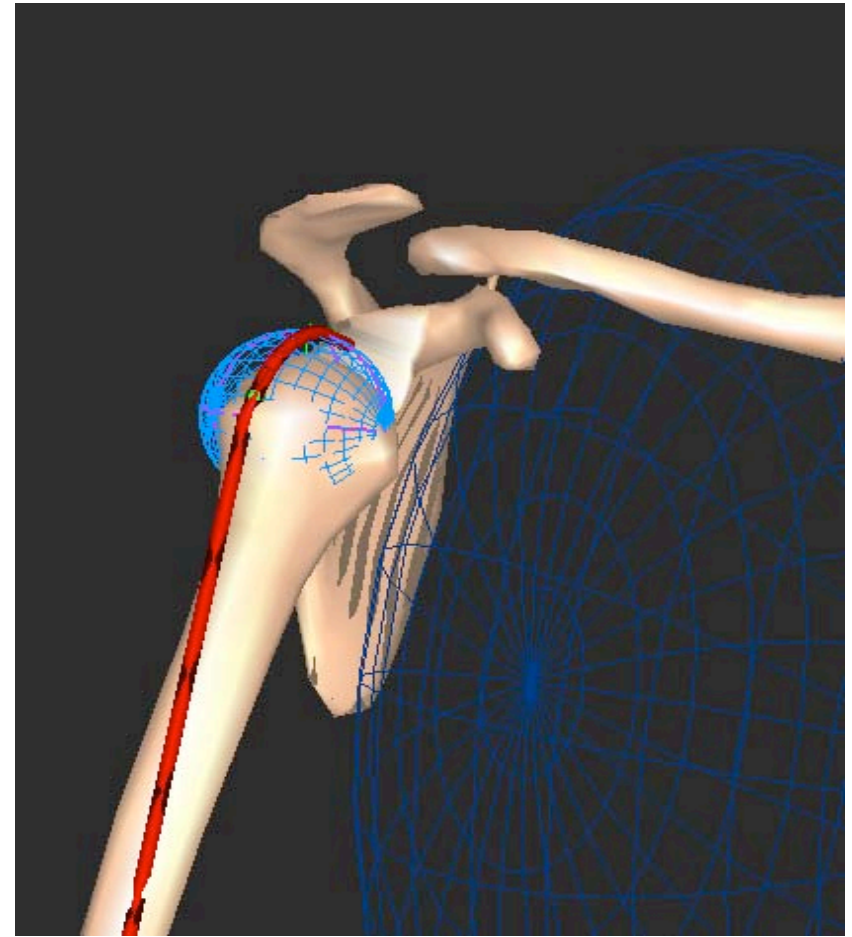
- Bony contours (joint surfaces, wrapping surfaces)
- Tendon and ligament attachments
- Muscle parameters (PCSA, fibre length, pennation angle, tendon length)



Muscle Modelling



Muscles can be represented by multiple elements



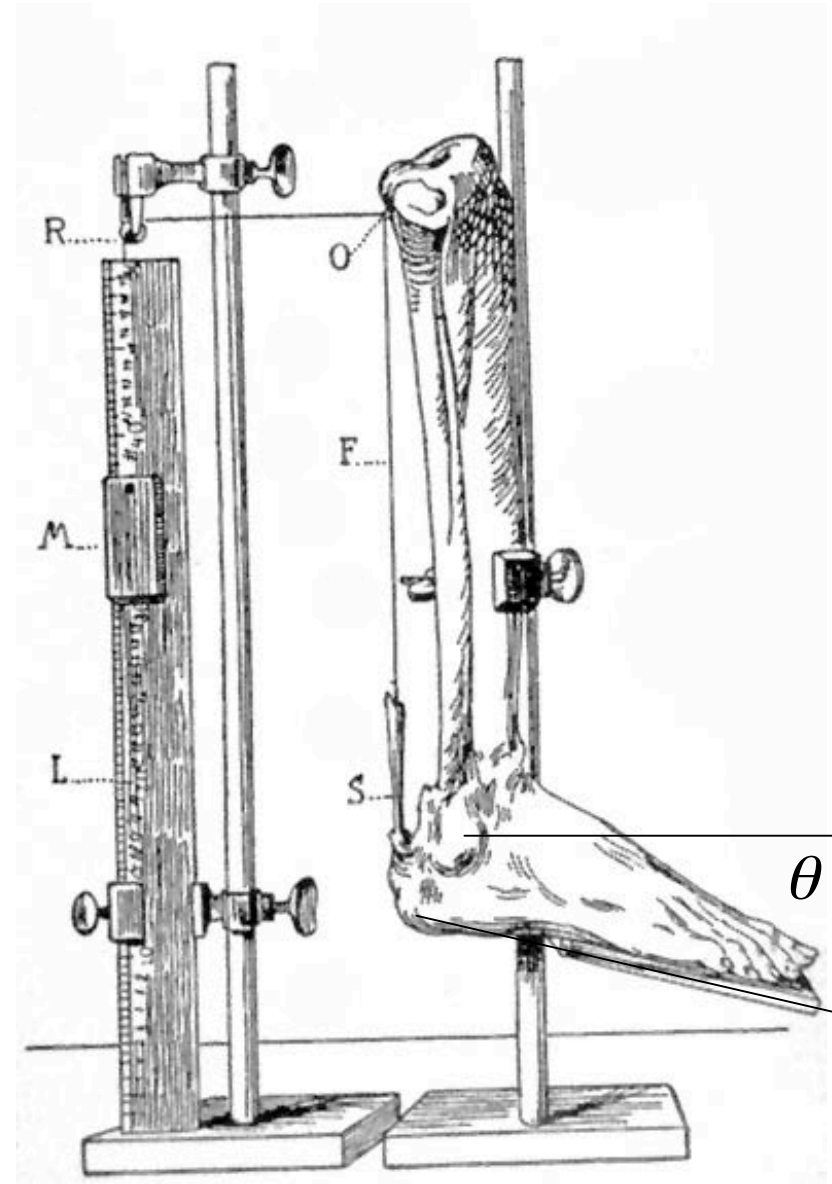
Muscles elements wrap around geometrical structures

Tendon excursion

Moment arms calculated from:

$$\frac{dL_i}{d\theta} = r_i$$

dL : tendon excursion
 $d\theta$: joint angle change
 r : moment arm

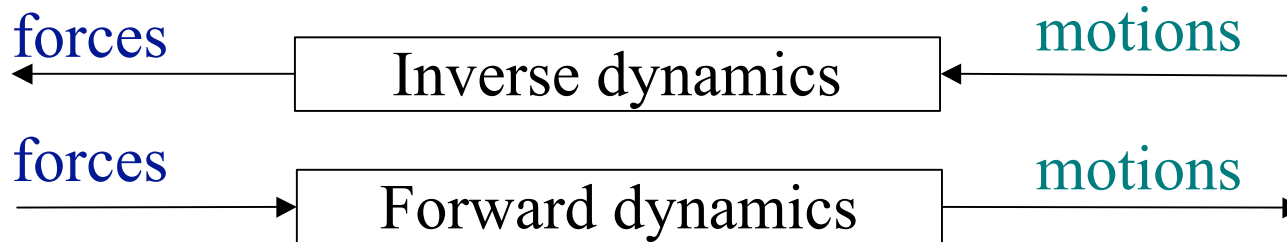


Upper Limb Models

- Shoulder
 - Hogfors et al. 1987, Karlsson and Peterson 1992, van der Helm 1994, Charlton 2000, Blana 2004
- Elbow
 - An 1989, Amis 1980, Nicol 1977, Chadwick 2000
- Wrist
 - Buchanan 1993, Loren 1996, Murray 2002
- Hand/finger
 - Dennerlein 1998, Fowler 2000, Sancho-Bru 2001

NB Not a complete list!

Inverse vs. Forward Dynamics



Inverse dynamics

- Efficient optimisation
- Assumptions about kinematics

Forward dynamics

- No assumptions about kinematics
- Intuitive
- Expensive optimisation

Inverse Dynamics



- Length
- Diameter
- Mass
- Centre of mass
- Moment of inertia
- Joint rotation centre
- Muscle attachments
- Muscle wrapping
- PCSA

Upper limb modelling

When modelling the upper limb, there are additional constraints to consider:

- Closed-chain mechanism of the shoulder girdle
- Scapula is constrained to move against thorax
 - Scapulo-thoracic gliding plane
 - Limits degrees of freedom of the shoulder girdle
- Conoid is a stiff ligament
 - Couples rotations of the clavicle to scapula rotations
 - Further reduces degrees of freedom of the shoulder girdle

Requirements

Degrees of freedom:

Thorax	6
Sterno-clavicular joint	3
Acromio-clavicular joint	3
Gleno-humeral joint	3
Humero-ulnar joint	1
Radio-ulnar joint	1
Wrist	3
Scapulo-thoracic gliding plane	-2
Conoid ligament	-1
Total	17

Model Input

Input motion can be kinematically incompatible with model geometry due to closed-chain mechanism.

- length of clavicle
- roundness of thorax
- length of conoid
- size of scapula

Two possible solutions

- scale model to match subject
- adjust input angles to fit model

Input adjustment

Minimise differences from measured

$$J = \sum_{i=1}^6 (\theta_{i,opt} - \theta_{i,meas})^2$$

Subject to the following constraints

- Scapula remains on thorax
- Length of conoid ligament is constant

The Load-Sharing Problem

Many more muscles than degrees of freedom

- System is indeterminate
- The 'load-sharing problem'

Minimise J , where J is one of the following:

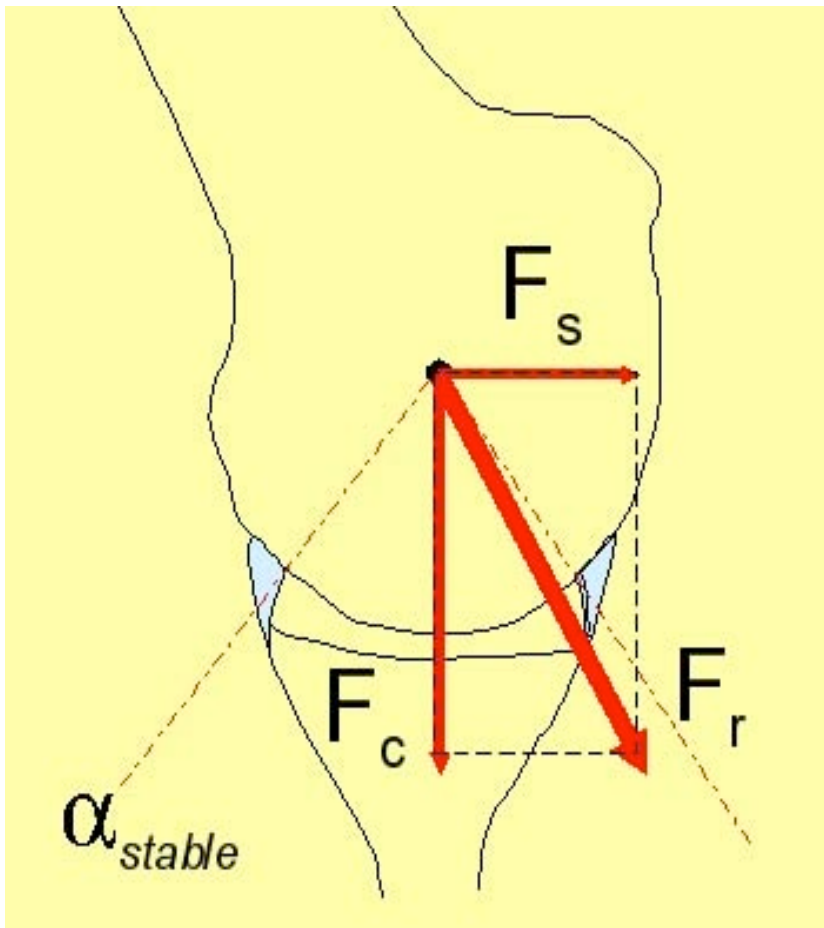
- sum of squared muscle forces
- sum of squared muscle stresses
- maximum muscle stress
- fatigue
- energy consumption
- others...

Constraining the Optimisation

In addition to the moment balance, there are several other constraints on the optimisation:

- Muscle forces must be non-negative
- Gleno-humeral joint stability must be maintained
- Contact force between thorax and scapula must be compressive
- Muscles can only generate force within a certain range of lengths and velocities
- Muscle dynamics prevent sudden changes in force and activation

Gleno-humeral stability



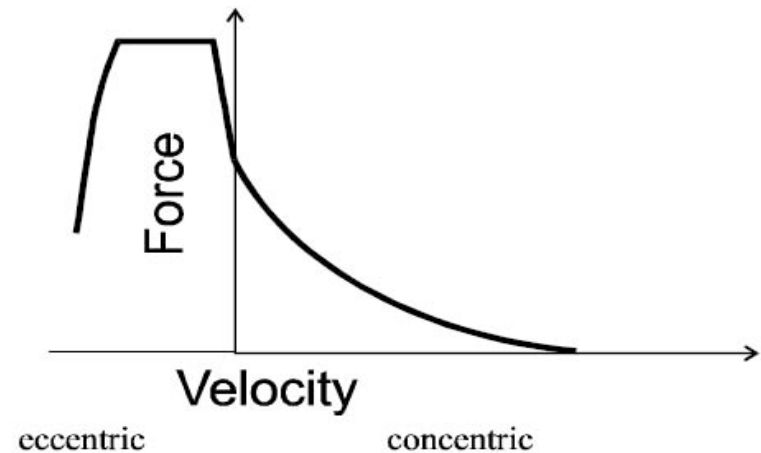
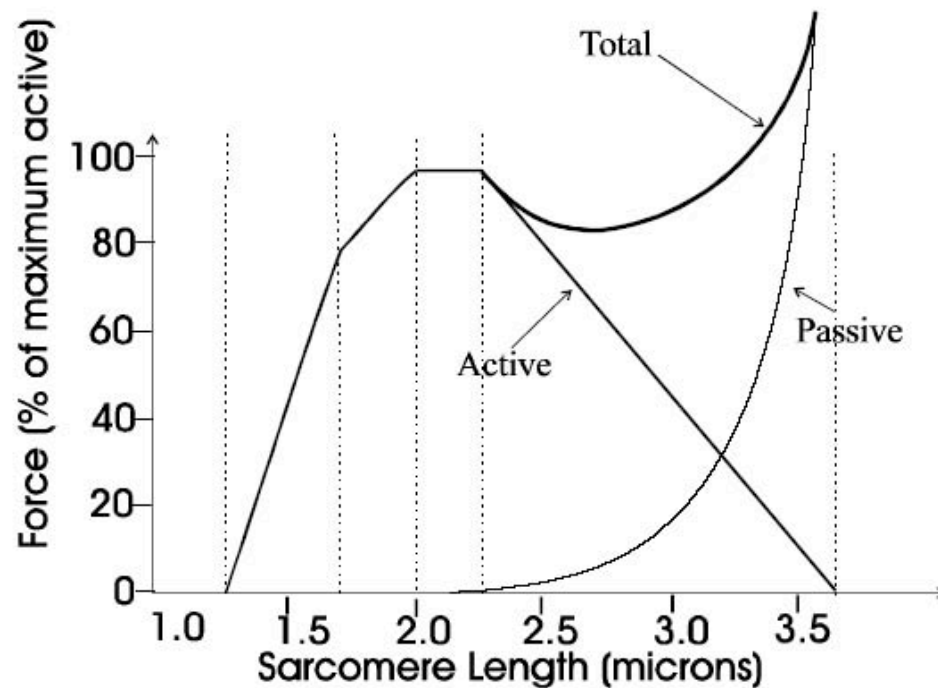
Gleno-humeral joint stability:
Joint reaction force must point
into the glenoid

Scapulo-thoracic gliding plane

- Contact force between thorax and scapula must be compressive
- Ensures correct activation of serratus anterior and rhomboids
- Prevents scapular winging (shown)



Force-length and velocity relations



Muscles can only generate force within a certain range of lengths and velocities

Muscle Dynamics

- Muscle dynamics also influence the optimisation:
 - Excitation → Activation → Contraction
(e) (a) (F)
- The dynamics constrain the results of the optimisation to produce physiologically realistic muscle forces
 - Instantaneous changes in force prevented

Inverse Dynamic Optimisation

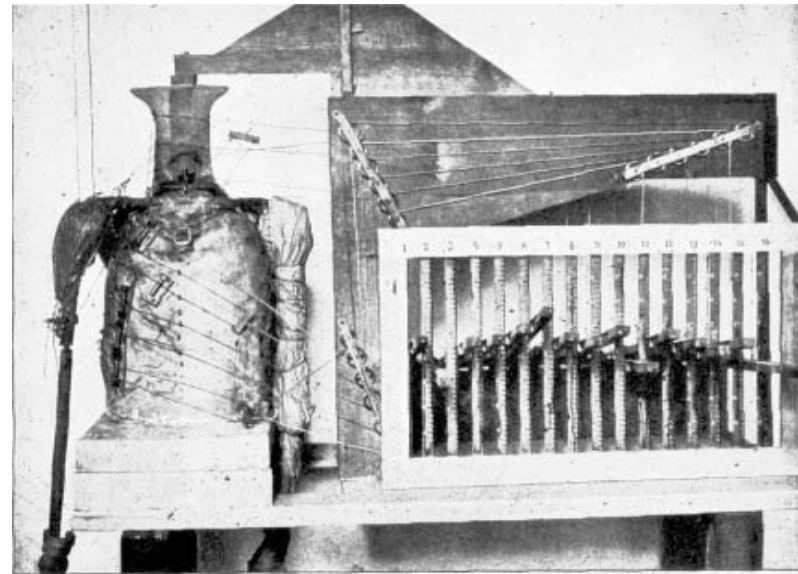
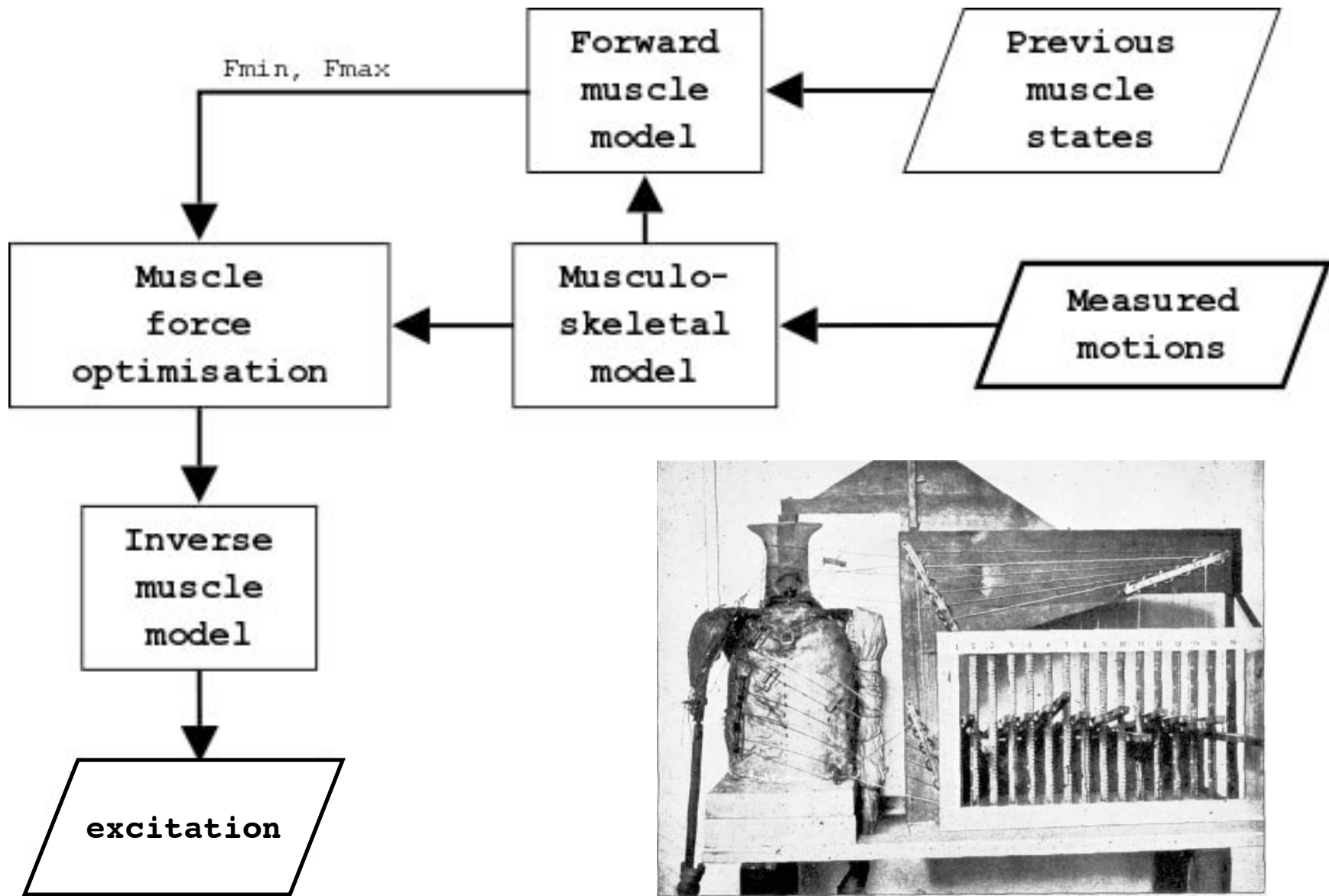
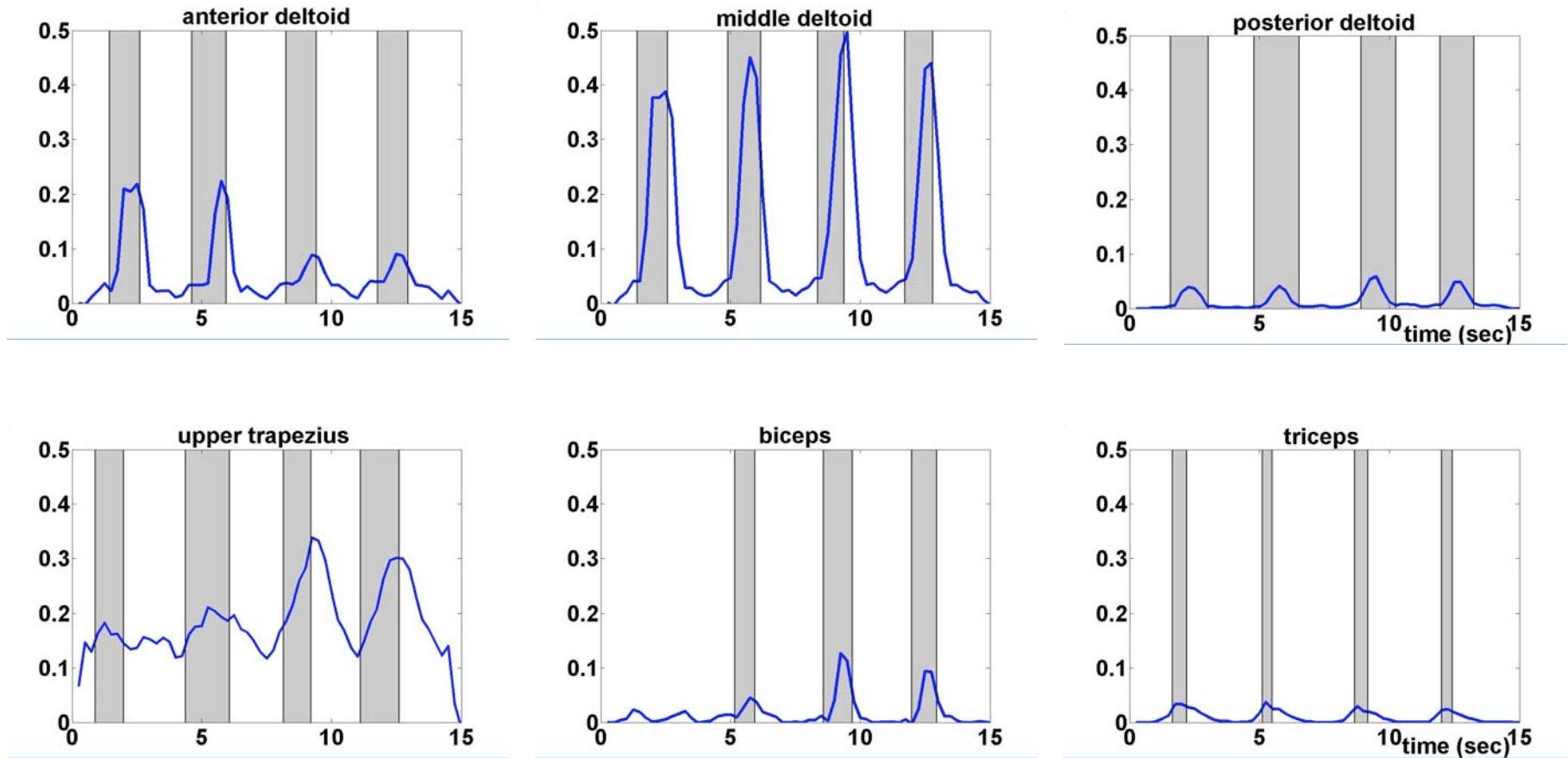


Fig. 1. Vorderansicht des bewegungsmechanischen Modelles.

Validation

Predicted muscle activation patterns are compared with recorded EMG



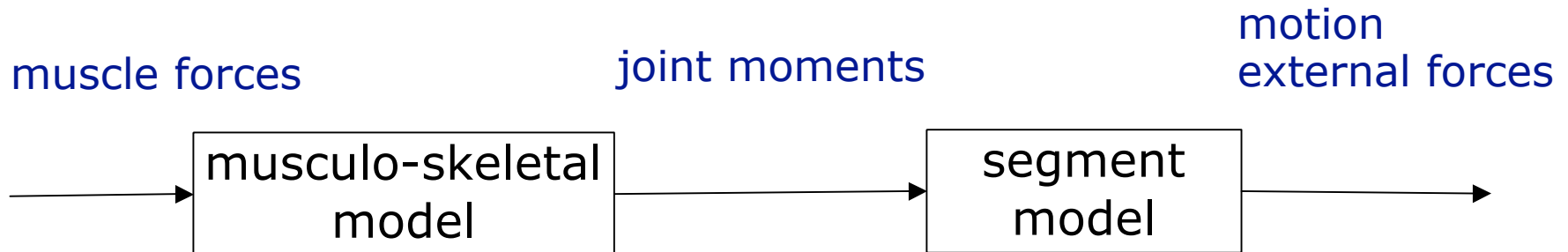
Inverse Dynamics Summary

So far, we have seen

- Model input: closed-chain mechanism
- Optimisation: efficiency, cost function
- Gleno-humeral stability, scapulo-thoracic contact
- Muscle dynamics
- Validation

Forward dynamics →

Forward Dynamics



- Joint rotation centre
- Muscle attachments
- Muscle wrapping
- PCSA

- Length
- Diameter
- Mass
- Centre of mass
- Moment of inertia

Rationale

Forward-dynamic models have some advantages:

- No *a priori* assumptions about kinematics
- output (motions) easy to visualise and relate to function
- modelling of stiff structures such as ligaments possible

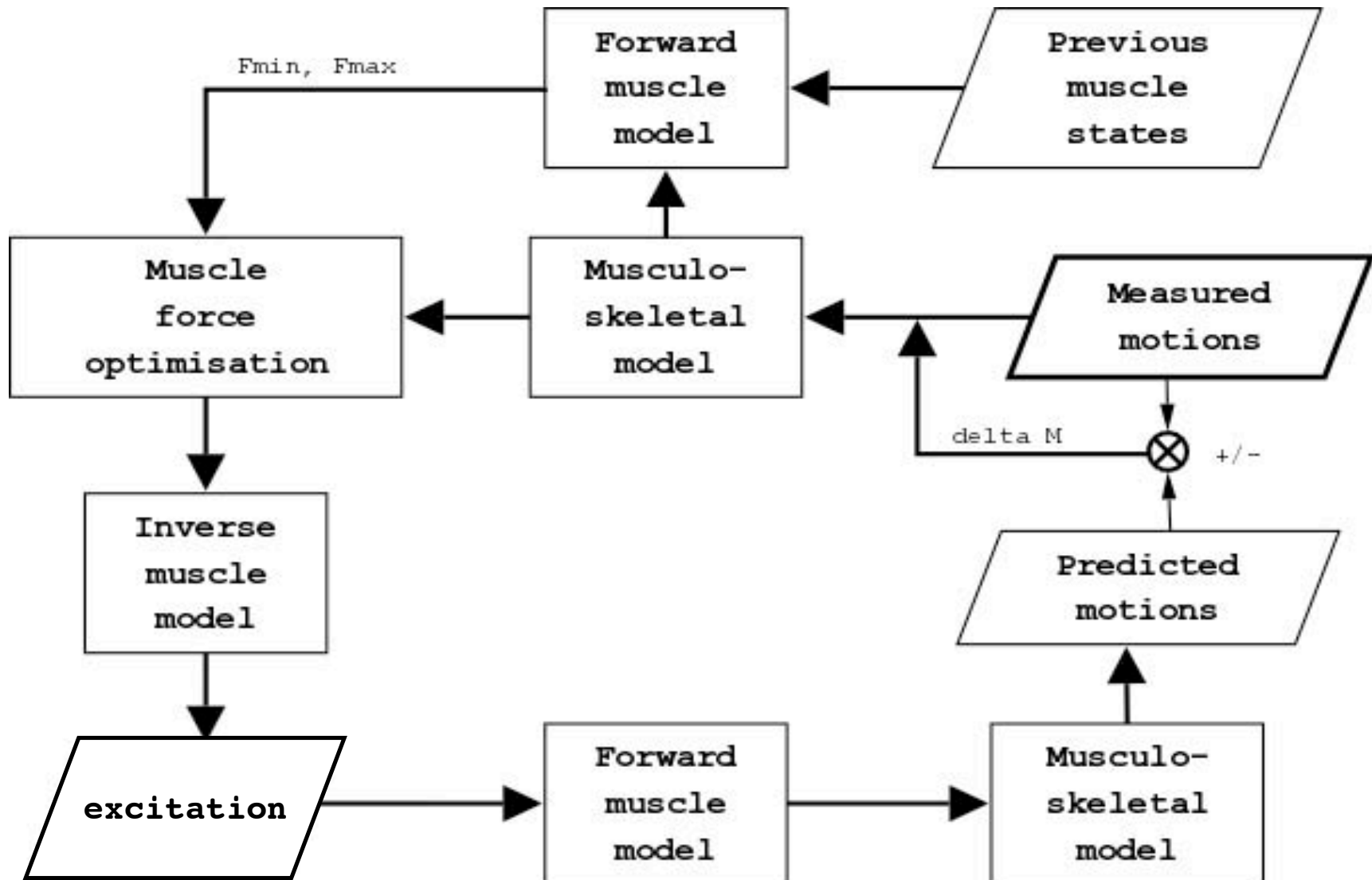
But one big disadvantage:

- optimisation requires repeated integration of the system and is thus computationally very expensive
- not suitable for large-scale models

Inputs

- How can we reach a solution in a reasonable time?
- 'Hybrid' model:
 - combined inverse/forward dynamics
 - inverse-dynamic optimisation to calculate inputs for forward-dynamic model

IFDOC



Forward Dynamics Summary

- Same model as inverse
 - Just different inputs and outputs
 - Different assumptions
- Full optimisation time-consuming
 - Hybrid models

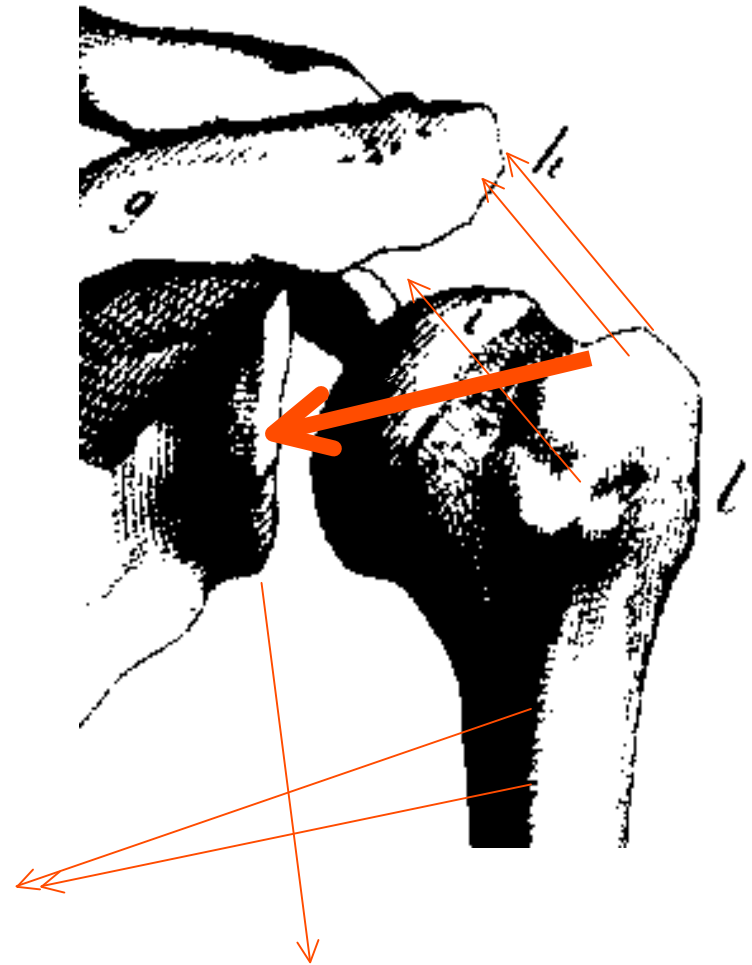
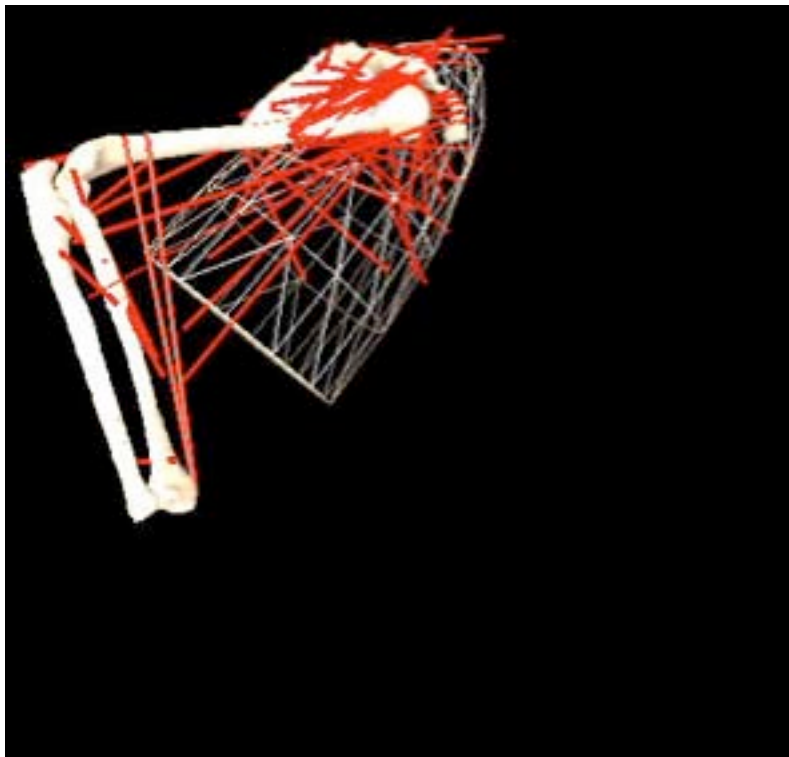
Applications →

Examples

1. Joint loading in wheelchair propulsion
 - Simple inverse-dynamics analysis
2. Tendon transfer
 - What is the best transfer for massive rotator cuff tear?
 - Inverse dynamics + “Monte Carlo”
3. Design of an upper limb FES system controller
 - Restoration of function in C5/C6 SCI
 - Inverse and forward models

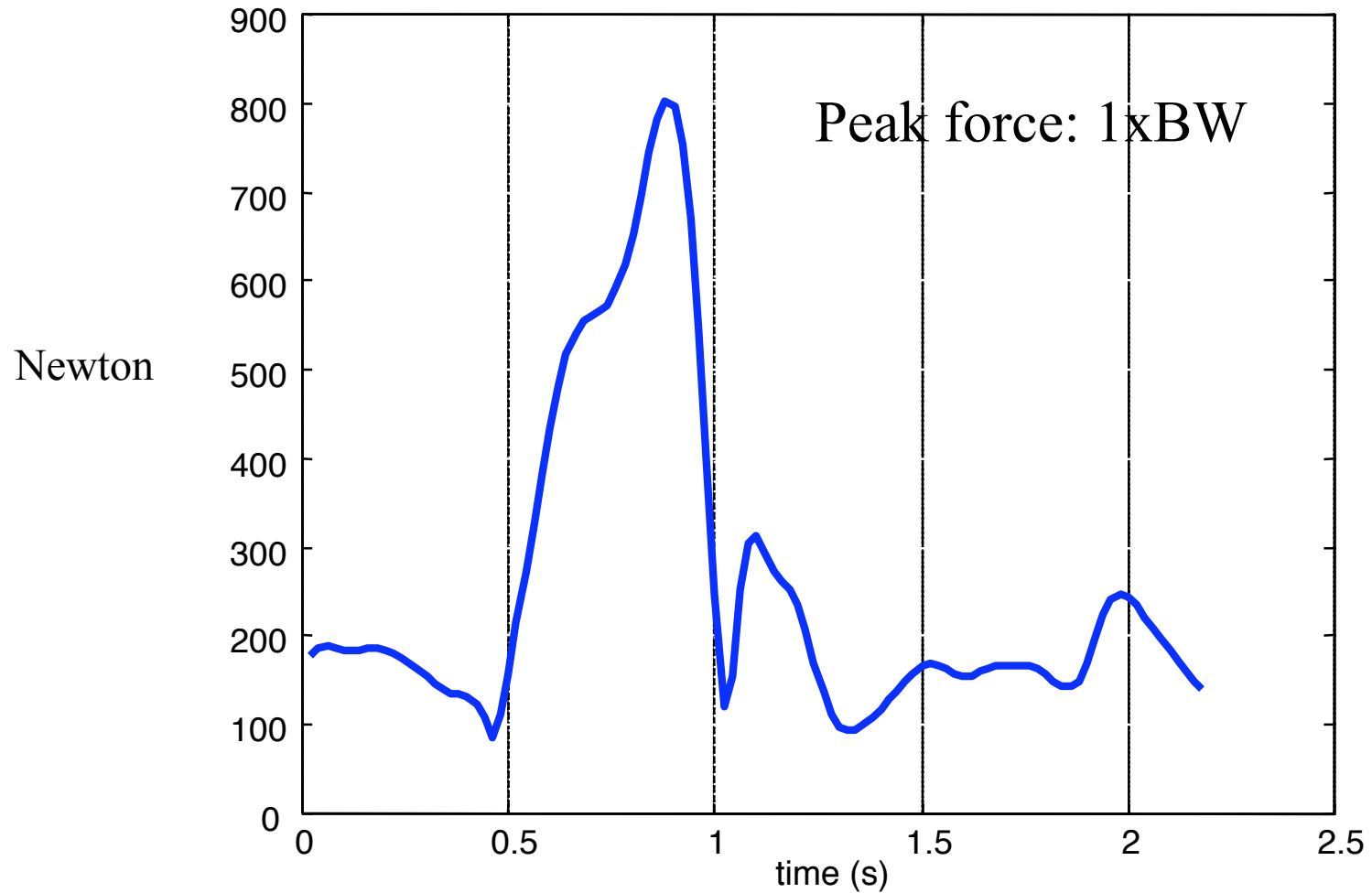
Joint loading

What is the loading on the gleno-humeral joint during wheelchair propulsion?



Reaction force in glenoid

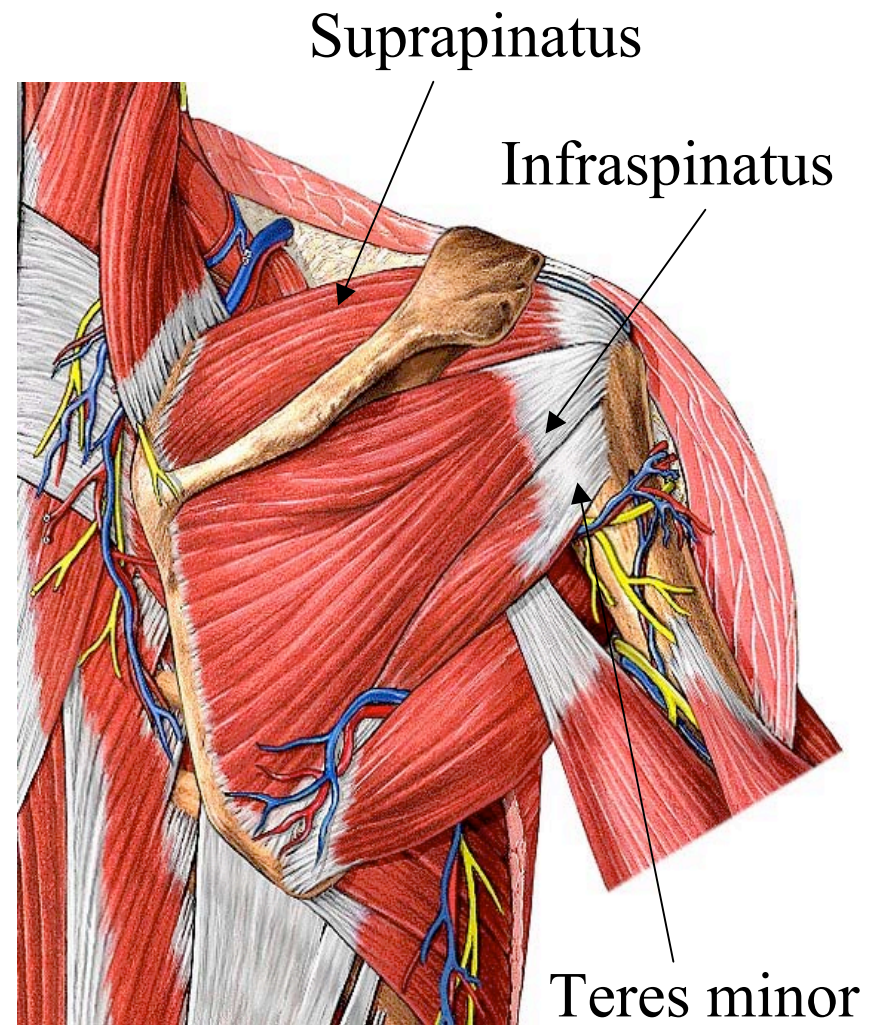
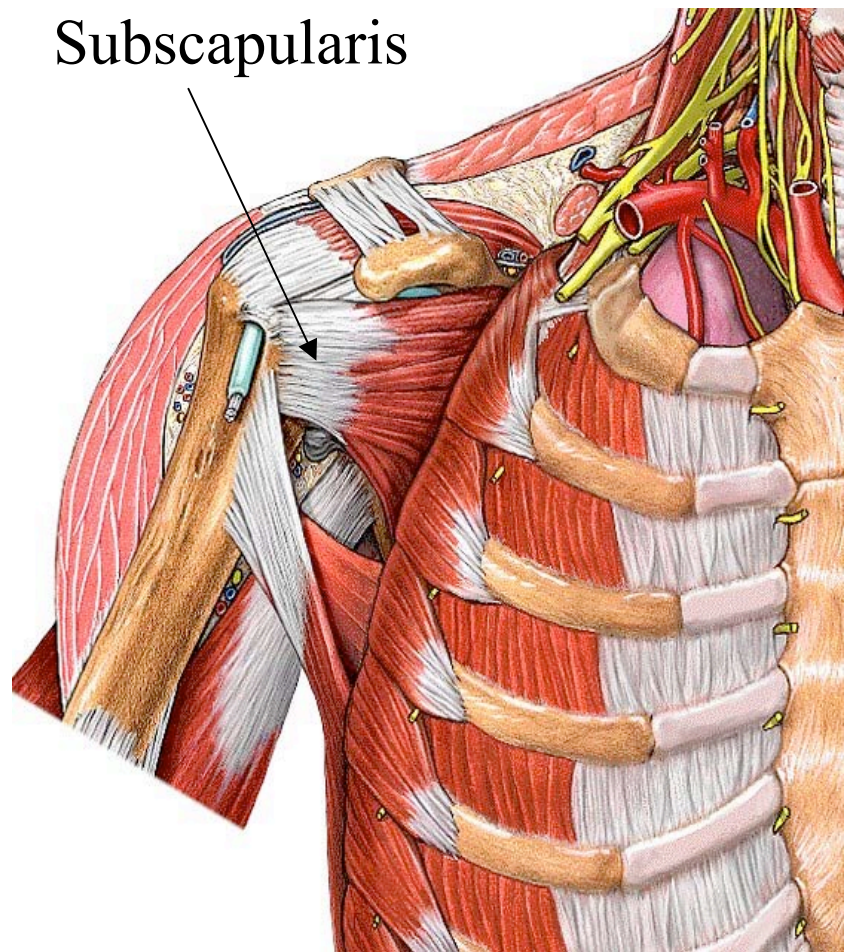
Contact force in GH-joint



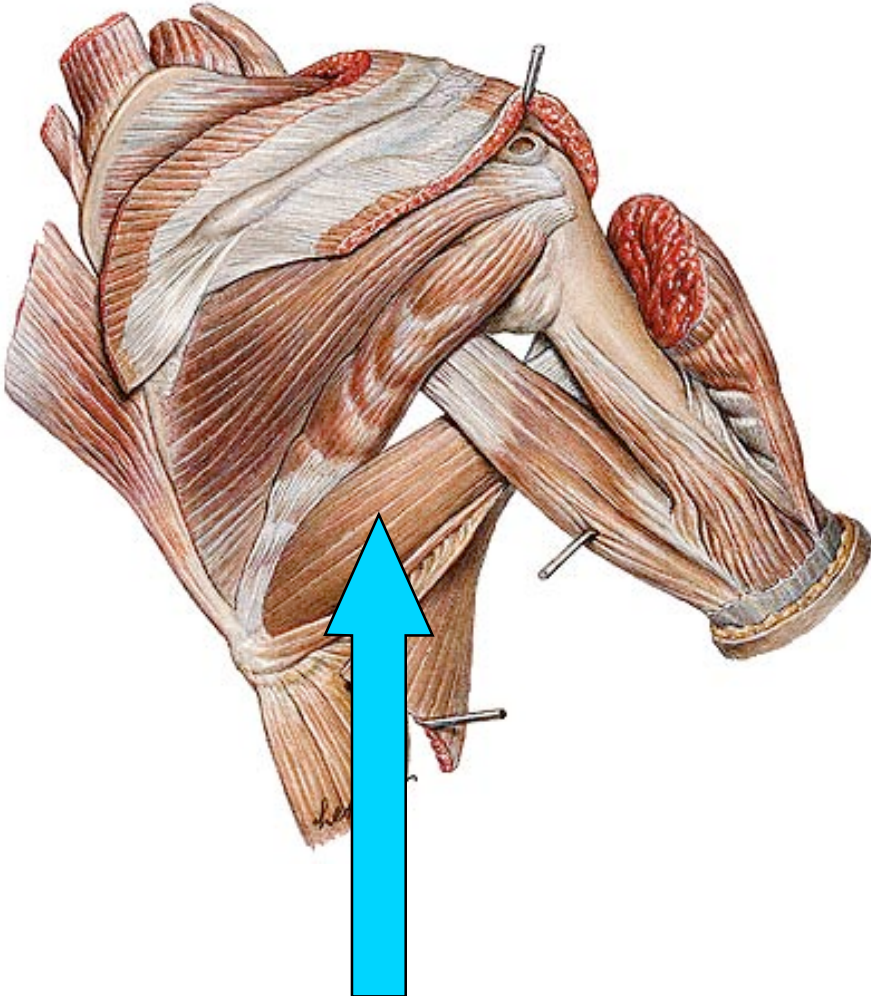
Tendon Transfer

- Transfer of latissimus dorsi or teres major to rotator cuff for massive rotator cuff tear
- What is the optimum transfer?
 - Muscle: latissimus dorsi or teres major?
 - Insertion: Superior/Inferior? Anterior/Posterior?
- Method: Simulation of all possibilities
- Outcome: Successful simulation
 - Percentage of tasks able to be completed

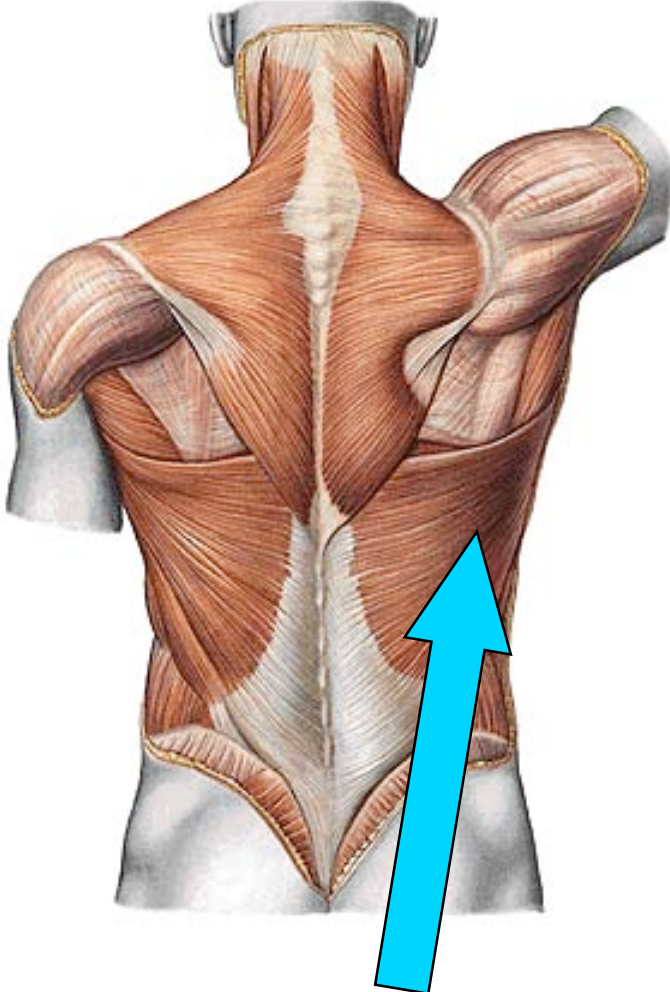
Rotator Cuff Muscles



Tendon transfer

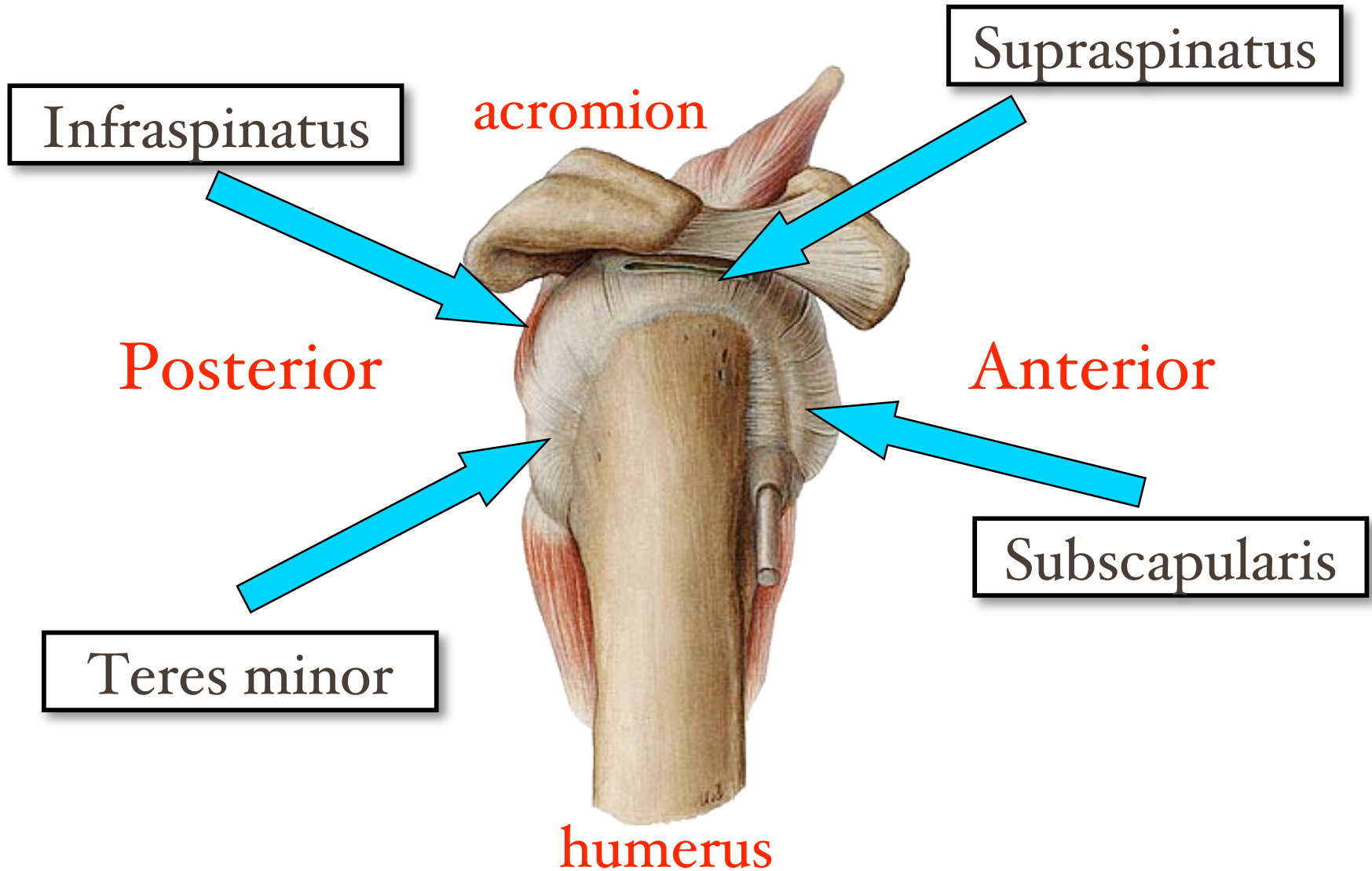


Teres Major (TM)

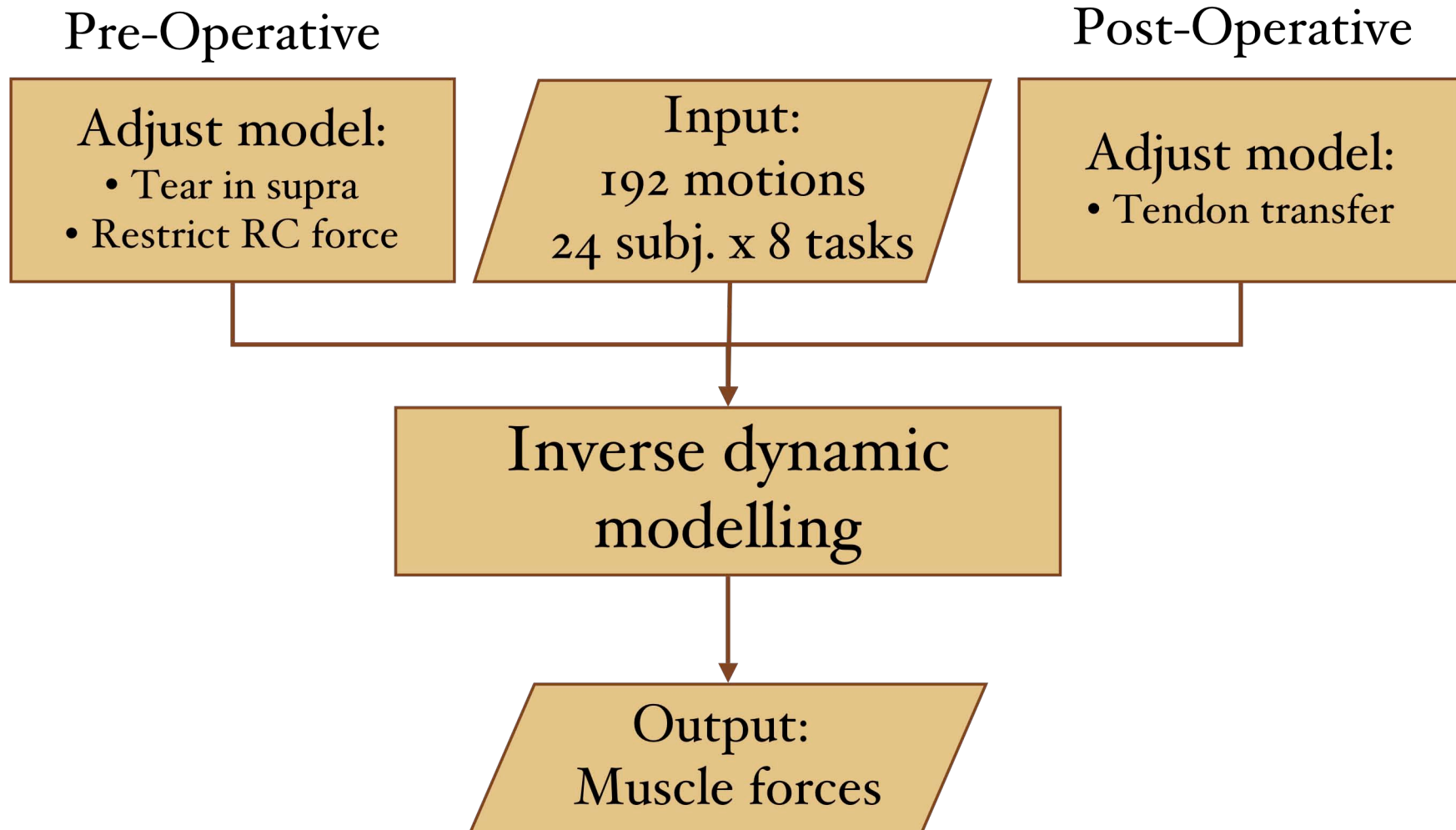


Latissimus Dorsi (LD)

Possible attachment sites

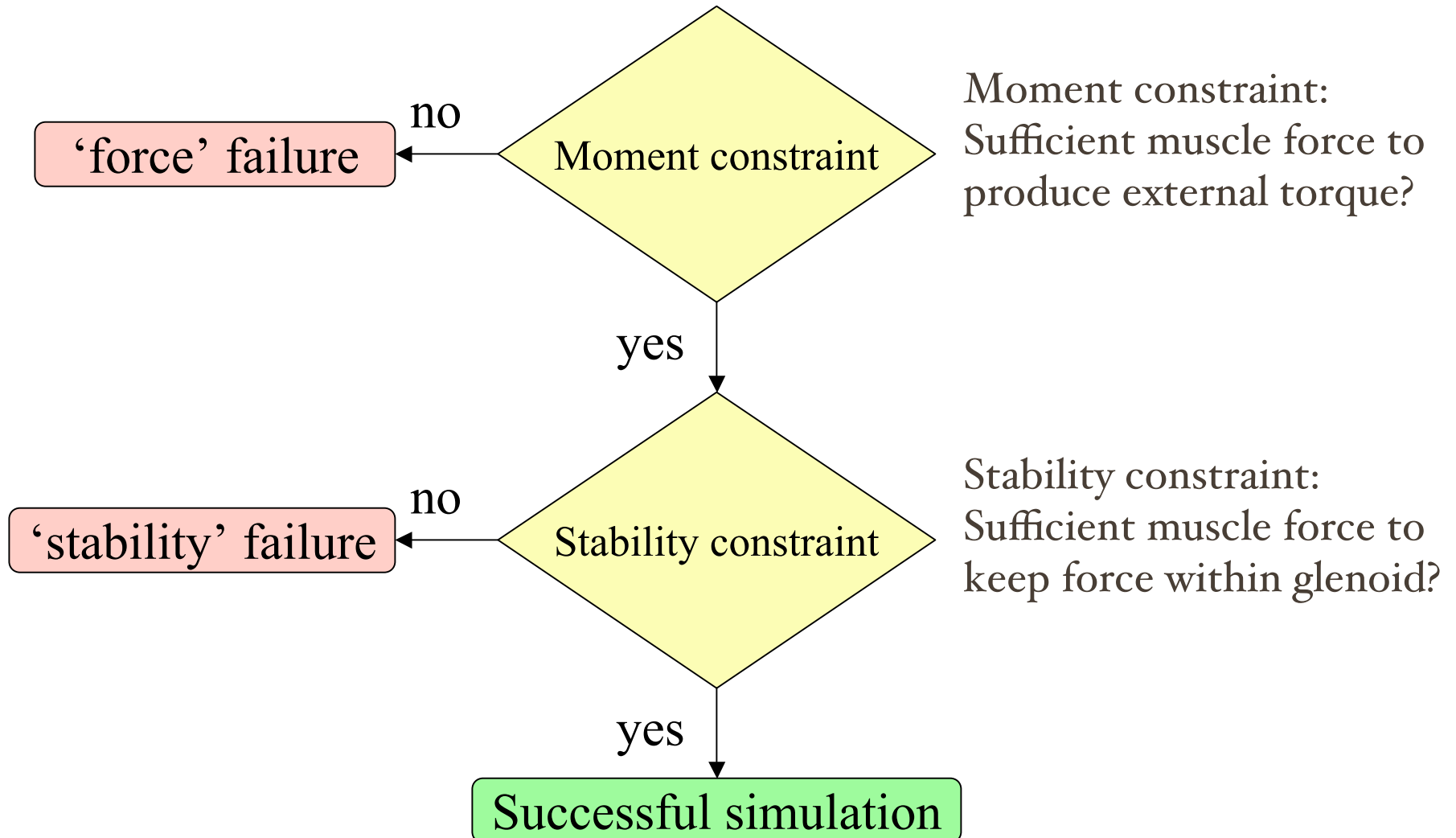


Simulation procedure

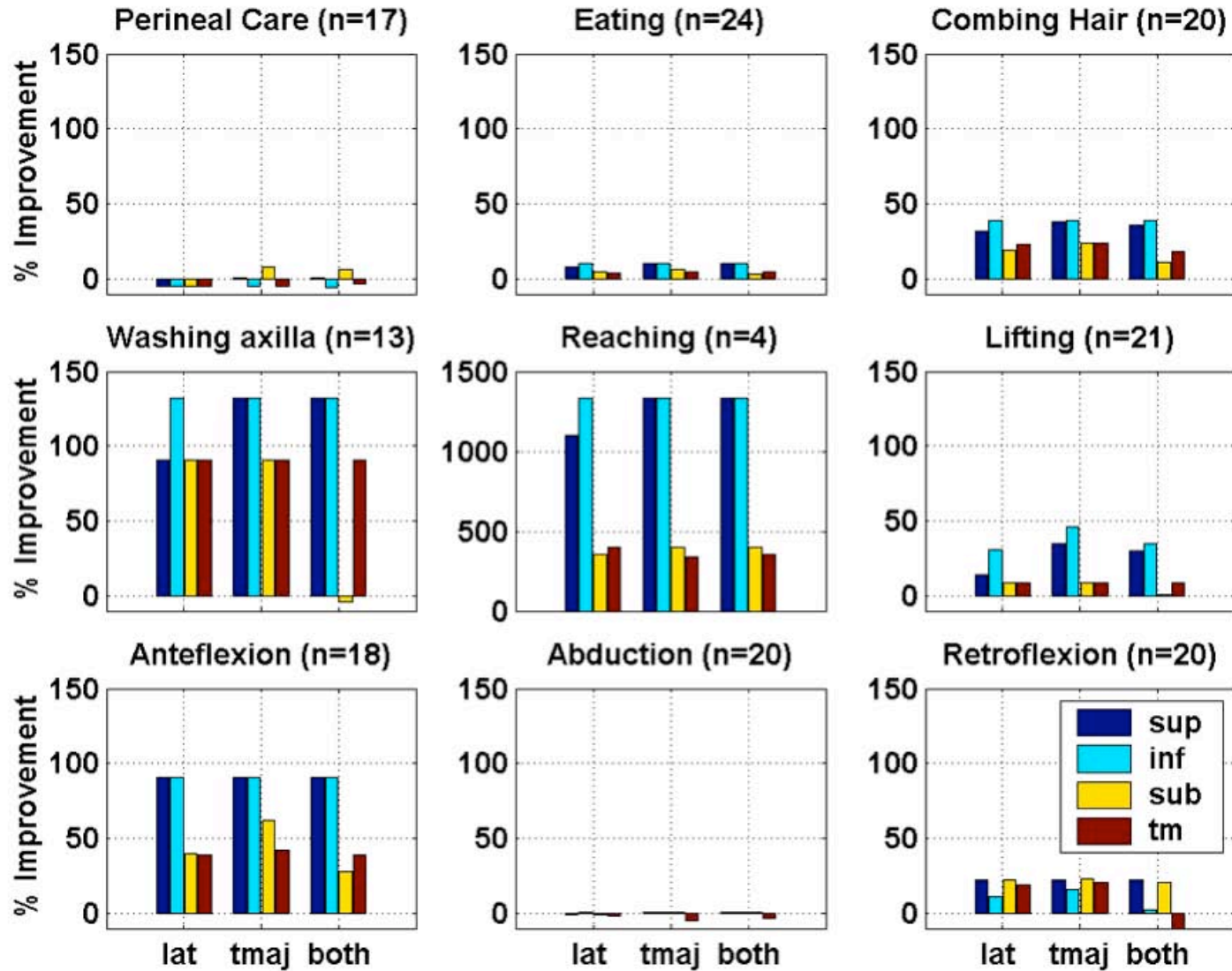


Optimisation procedure

Minimise sum of squared muscle stresses



Simulation outcomes

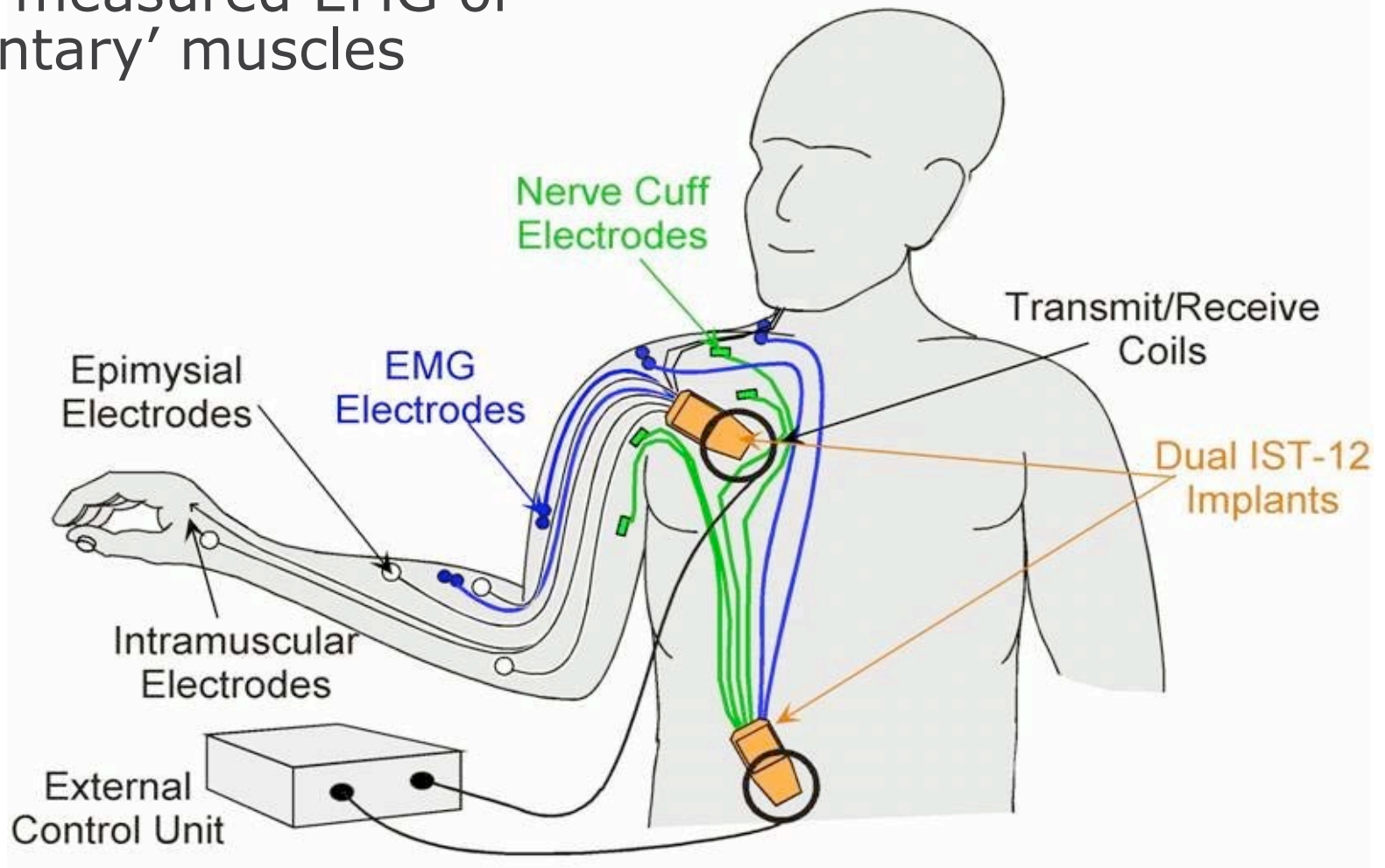


Conclusions

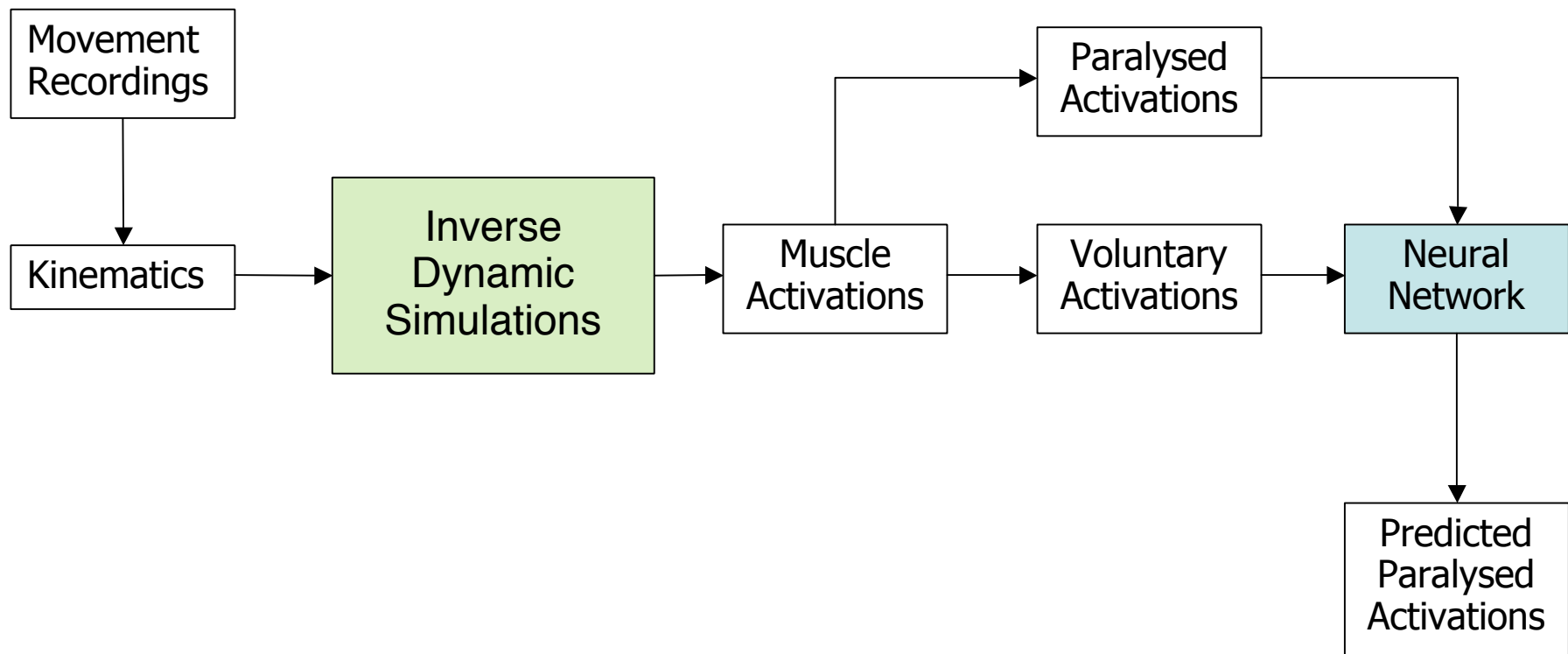
- All tendon transfers are effective
- Transfer to the supraspinatus mechanically the best option
 - Both teres major and latissimus
- What transfer to perform depends on:
 - Surgical conditions
 - Loss of function due to transfer
 - Teres major preferable over latissimus (adduction moment)

Controller for Implanted FES System

Control stimulation levels from measured EMG of 'voluntary' muscles

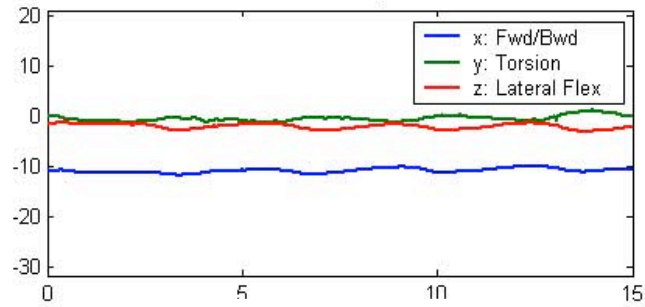


Design of FES Controller

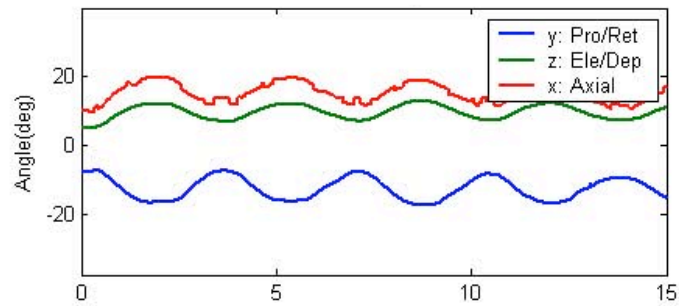


Model Input

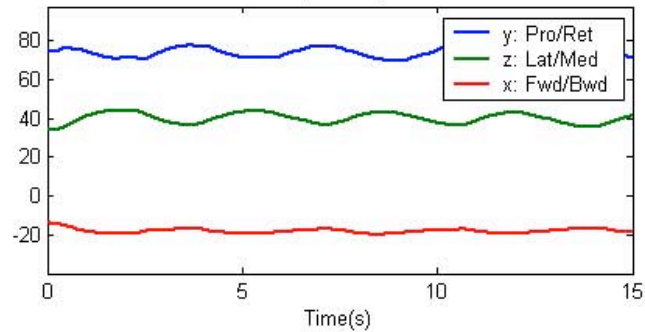
Thoracic Angles



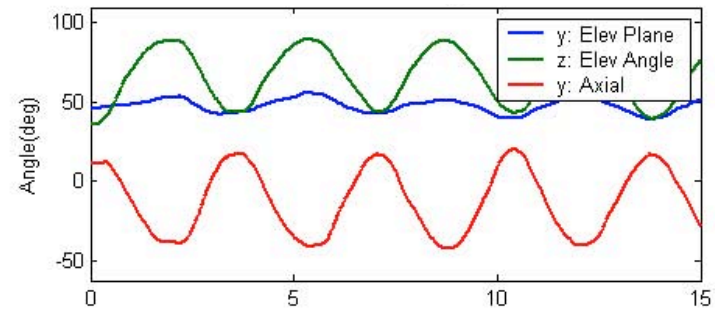
Clavicular Angles



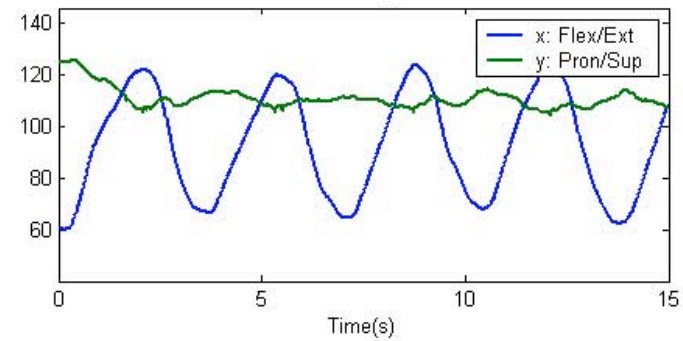
Scapular Angles



Glenohumeral Angles

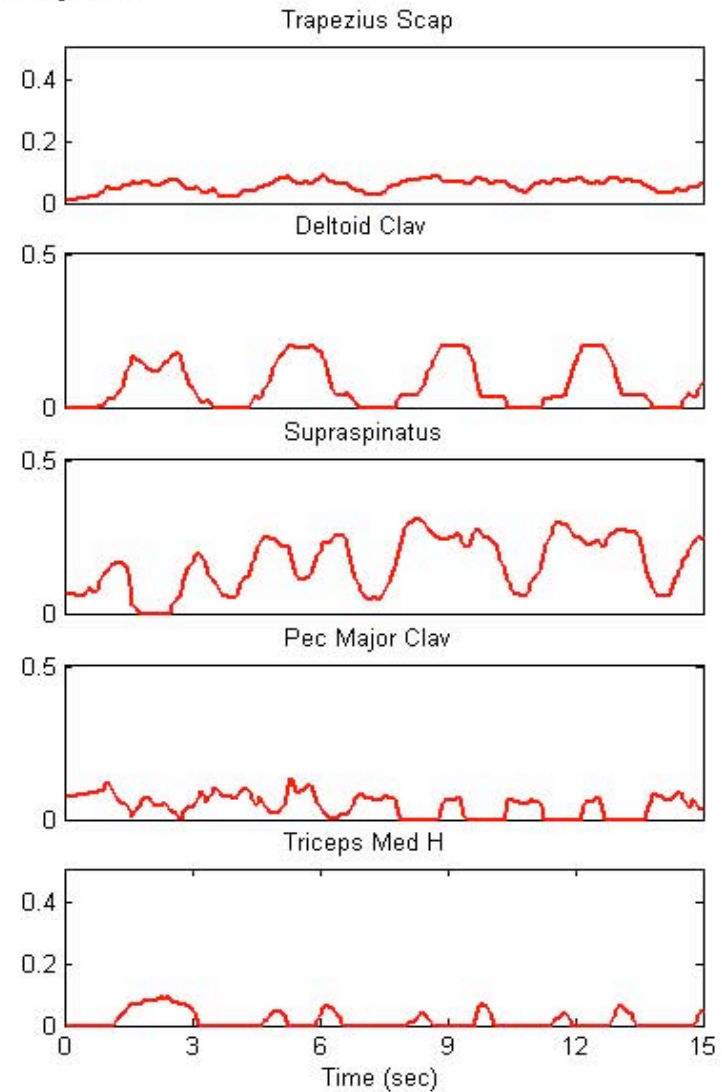
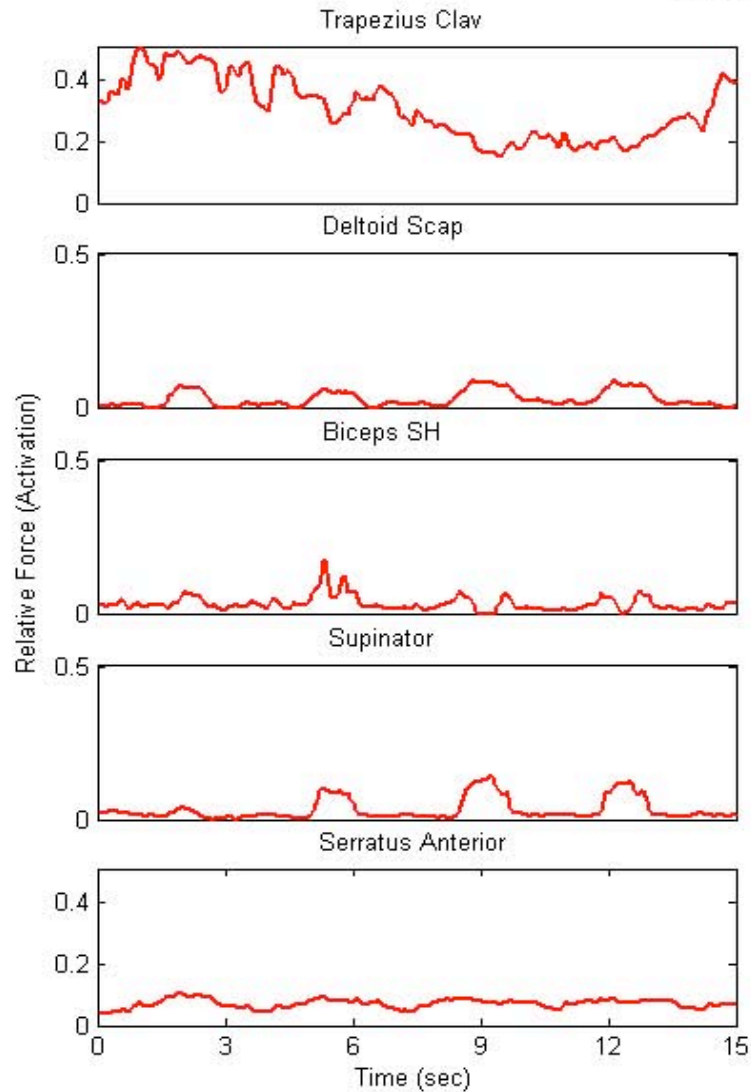


Elbow Angles



Model output

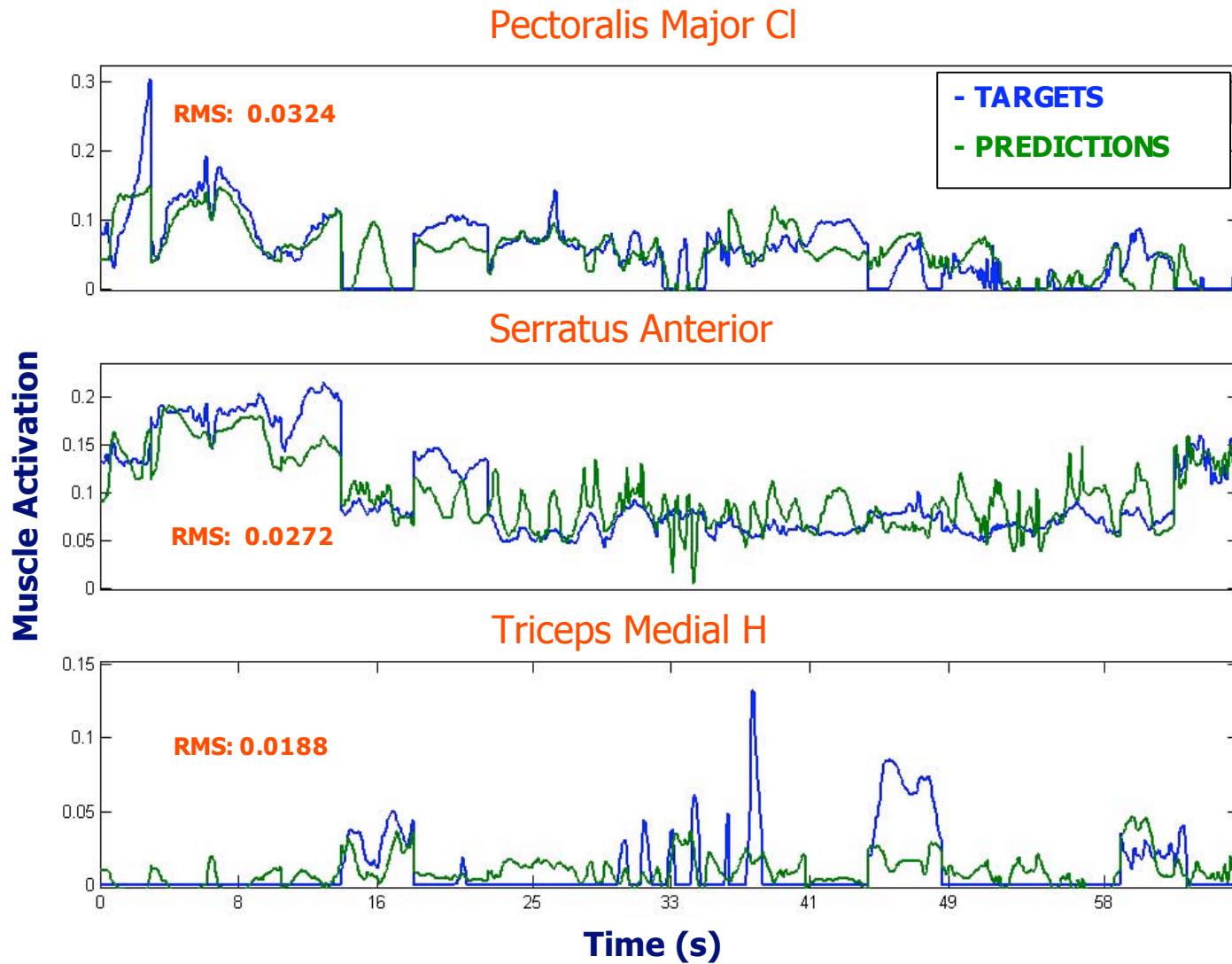
Muscle Activations - Eating Task



Control scheme

- Voluntary muscles chosen as input
- 'Paralysed' muscles chosen as output
- Train neural network to predict activation predicted in paralysed muscles (stimulation) from activation predicted in voluntary muscles (recording)

Controller training



Controller checking

- We used an **inverse-dynamic** model to predict the required muscle activation patterns
- We used a **neural network** to predict stimulation levels for paralysed muscles from EMG signals from voluntary muscles
 - Obviously some error inherent in this
- We can use a **forward-dynamic** model to check that the predicted stimulation patterns are sufficiently accurate
 - Safer than testing this on the patient

Summary

Things to consider when modelling the upper limb:

- General
 - Inverse or forward dynamics
 - Calculation of neural inputs for forward dynamics
 - Load-sharing problem
 - Constraints: e.g. muscle dynamics in optimisation
- Shoulder
 - DoF: closed-chain mechanism
 - Constraints: gleno-humeral stability, scapulo-thoracic gliding plane

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