Musculo-skeletal modelling of the shoulder

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Contents

- **Muscle dynamics**
  - **muscle dynamics in the optimisation**
  - **muscle model**
- **Inverse-dynamics summary**
- **Forward dynamic modelling**
  - **input/output**
  - **advantages of forward dynamics**
  - **calculating the input**
  - **integration methods**
- **Examples**
  - **prosthesis placement**
  - **computer assisted surgery**
- **Summary**

1 Introduction

1.1 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
  - coordination
  - energy usage
  - muscle and joint forces
- Computer-assisted surgery
  - optimisation of treatment for specific patient

1.2 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**
- **Interpretable results**
  - **can we relate model output to patient function?**
- **Fast model, user-friendly interface**
  - **for use in the clinical setting**

1.3 Specific requirements of a shoulder model

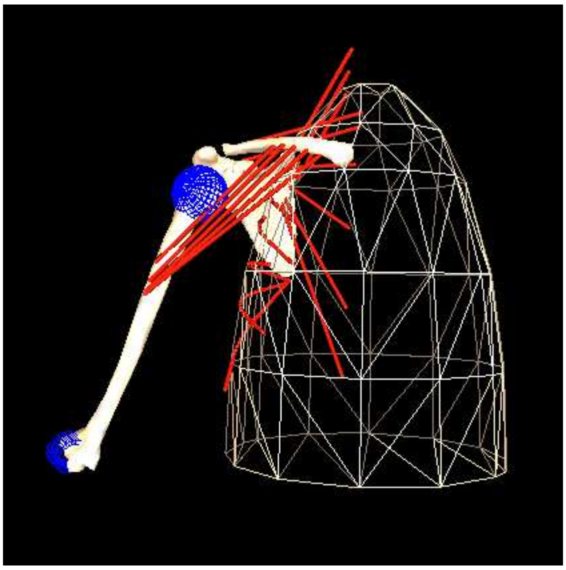
Segments

- **thorax, scapula, clavicle, humerus, ulna, radius, hand**

Degrees of freedom

thorax	**6**
sterno-clavicular joint	**3**
acromio-clavicular joint	**3**
gleno-humeral joint	**3**
humero-ulnar	**1**
radio-ulnar	**1**
wrist	**3**
scapulo-thoracic gliding plane	**-2**
conoid ligament	**-1**
Total	**17**

1.4 Example of a shoulder model



SIMM representation of the Delft Shoulder Model

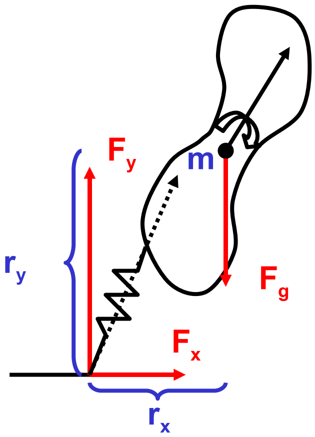
Full description in van der Helm (1994)

2 Equations of motion

2.1 Newton-Euler method

Free body diagram in 2D:

$$
\begin{aligned}
F_x - m\ddot{x}_x &= 0 \qquad (1)\\
F_y - m\ddot{x}_y - mg &= 0 \qquad (2)\\
F_x r_y - F_y r_x - I\ddot{\theta} &= 0 \qquad (3)
\end{aligned}
$$



This method results in a large set of algebraic equations and is cumbersome and time-consuming for multi-body systems.

Discussed in Zajac et al. (2002).

2.2 Lagrange method

The Lagrange method allows us to express the equations of motion in terms of generalised coordinates (degrees of freedom), using a minimum number of equations.

The system Lagrangian, L, is given by

$$L = T - V \tag{4}$$

where T is the kinetic energy, and V the potential energy.

Equations of motion are:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \left(\frac{\partial L}{\partial q_i}\right) = M_i \tag{5}$$

where M_i are the generalised moments.

This method results in a minimal set of ordinary differential equations (ODE) which can be numerically integrated.

2.3 TMT method

TMT is a combination of Newton-Euler and Lagrange.

Start with the Newton-Euler equation:

$$\sum(f_i - M_{ij}.\ddot{x}_j) = 0 \tag{6}$$

Transfer function, T_i, describes output vector, x_i, in terms of generalised coordinates, q_j:

$$x_i = T_i(q_j) \tag{7}$$

Differentiation of (7) w.r.t. time gives:

$$\dot{x}_i = \frac{\partial T_i}{\partial q_j}.\dot{q}_j = T_{i,j}.\dot{q}_j \tag{8}$$

and again:

$$\ddot{x}_i = \frac{\partial T_{i,j}}{\partial q_k}.\dot{q}_j.\dot{q}_k + T_{i,j}.\ddot{q}_j = T_{i,jk}.\dot{q}_j.\dot{q}_k + T_{i,j}.\ddot{q}_j \tag{9}$$

Substitution of (9) into (6) gives:

$$\sum f_i - M_{ij}\left(T_{i,jk}.\dot{q}_j.\dot{q}_k + T_{i,j}.\ddot{q}_j\right) = 0 \tag{10}$$

Premultipying by $T_{i,j}^T$ and rearranging gives:

$$T_{i,j}^T.M_{ij}.T_{i,j}.\ddot{q}_j = T_{i,j}^T.\sum f_i - T_{i,j}^T.M_{ij}.T_{i,jk}.\dot{q}_j.\dot{q}_k \tag{11}$$

Simplifying,

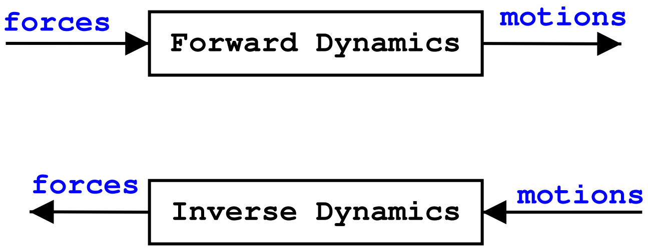
$$\ddot{q} = f(t, \dot{q}) \tag{12}$$

which are the equations of motion in terms of an ODE.

- **simple derivation of equations of motion**
- **number of equations = number of DoF**
- **suitable for numerical methods (see 6.4)**

Described by van Soest et al. (1992) and Jonker (1984).

2.4 Inverse or forward dynamics?



Inverse dynamics:

+ efficient optimisation

- assumptions about kinematics

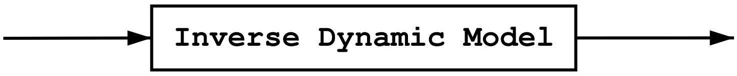
Forward dynamics:

+ no assumtions about kinematics

- optimisation very expensive

3 Inverse-dynamic modelling

3.1 Input/Output



input

recorded motions
external loads

output

muscle lengths
moment arms
net moments
muscle forces
joint forces
muscle powers

3.2 Model input

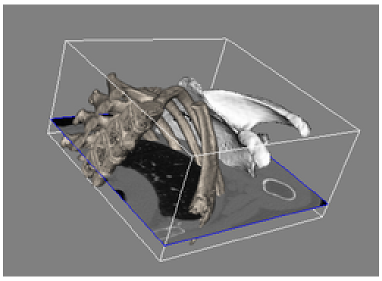
Input motion can be kinematically incompatible with model geometry due to closed-chain mechanism.

Ideally,

⇒ scale model to subject geometry

Best solution but difficult:

- **clavicle length**
- **scapula dimensions**
- **conoid length**
- **thorax dimensions**



Work in progress! click here to see automatic segmentation
More information at: http://visualisation.tudelft.nl/

Workaround:

⇒ adjust input angles to satisfy constraints

Minimise J, where

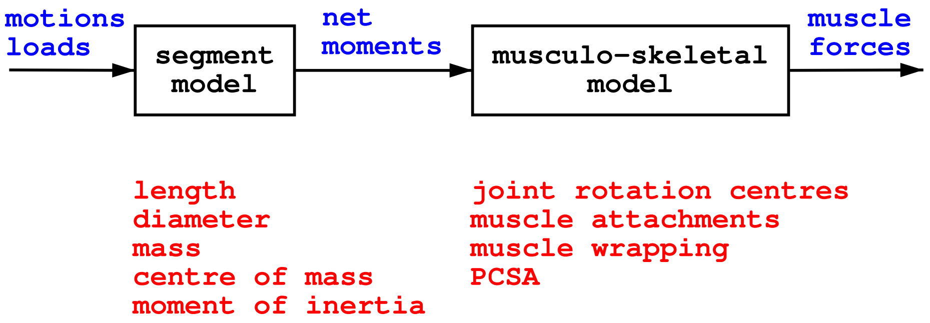
$$J = \sum_{i=1}^{6} (\theta_{i_{measured}} - \theta_{i_{optimised}})^2 \tag{13}$$

where θ_{1-6} are the angles of the clavicle and scapula

subject to the following constraints:

- **scapula remains on thorax**
- **conoid length constant**

3.3 Stages of inverse-dynamic modelling



3.4 The load-sharing problem

Many more muscles than degrees of freedom

⇒ System is indeterminate (the 'load-sharing problem')

⇒ Optimisation: minimise some performance criterion, 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...**

See Tsirakos et al. (1997) for a discussion of different cost functions.

3.5 Constraining the optimisation

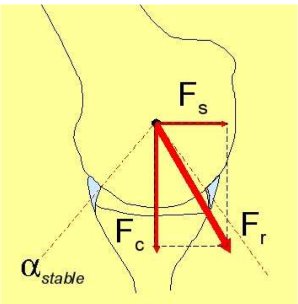
In addition to the moment balance, there are four other constraints on the optimisation:

The first is obvious:

- **muscle forces must be non-negative**

The next applies specifically to the gleno-humeral joint:

- **GH joint stability must be ensured**

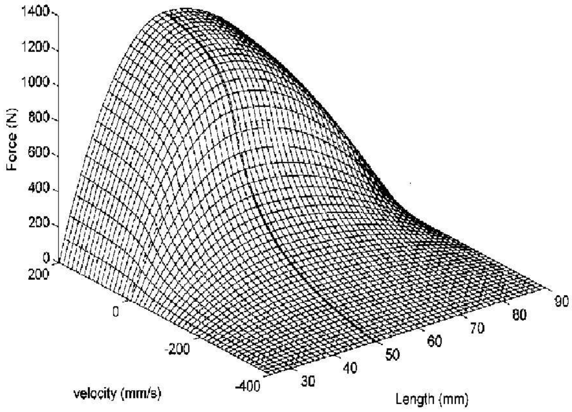


The next applies to the scapulo-thoracic gliding plane:

- **contact force between thorax and scapula must be negative (compression)**

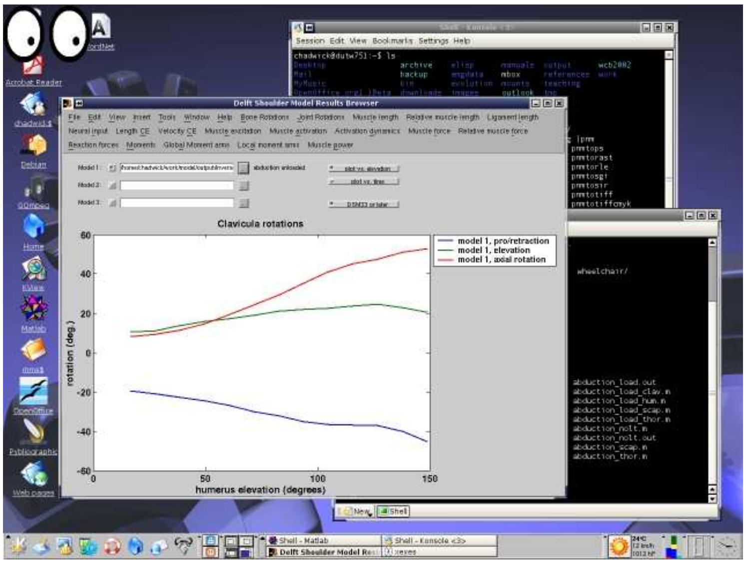
Finally,

- **muscles can only generate force within a certain range of lengths and velocities**



4 Examples of inverse dynamics

4.1 Matlab results viewer



```
chadwick@dutw751:~$ ls
Desktop                 archive    elisp      manuals  output      wcb2002
Mail                    backup     engdata    mbox     references  work
MyMusic                 bin        evolution  mounts   teaching
OpenOffice.org1.1Beta   downloads  images     outlook  tmp
```

```
lpmm
pnmtops
pnmtorast
pnmtorle
pnmtosgi
pnmtosir
pnmtotiff
pnmtotiffcmyk
```

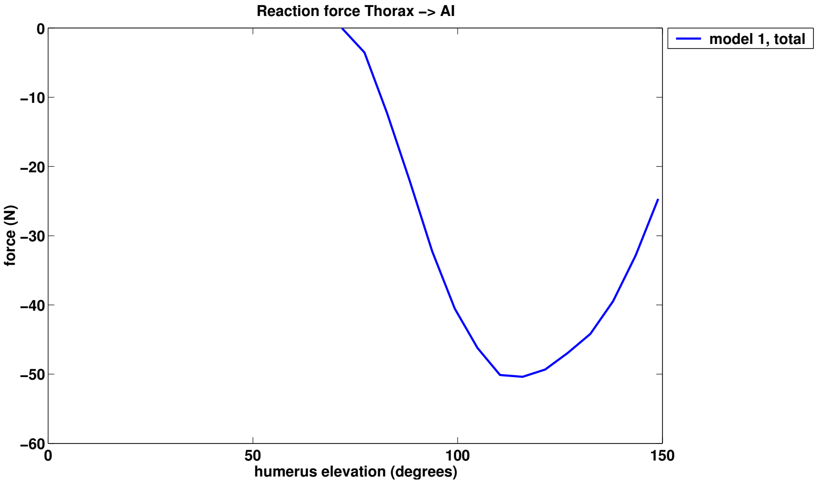
```
wheelchair/

abduction_load.out
abduction_load_clav.m
abduction_load_hum.m
abduction_load_scap.m
abduction_load_thor.m
abduction_nolt.m
abduction_nolt.out
abduction_scap.m
abduction_thor.m
```

⇒ (5)

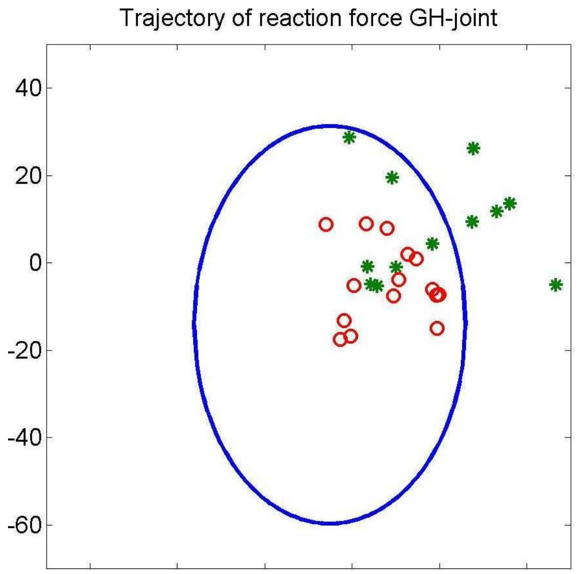
4.2 Effects of constraints: scapulo-thoracic contact

Anteflexion of the humerus:



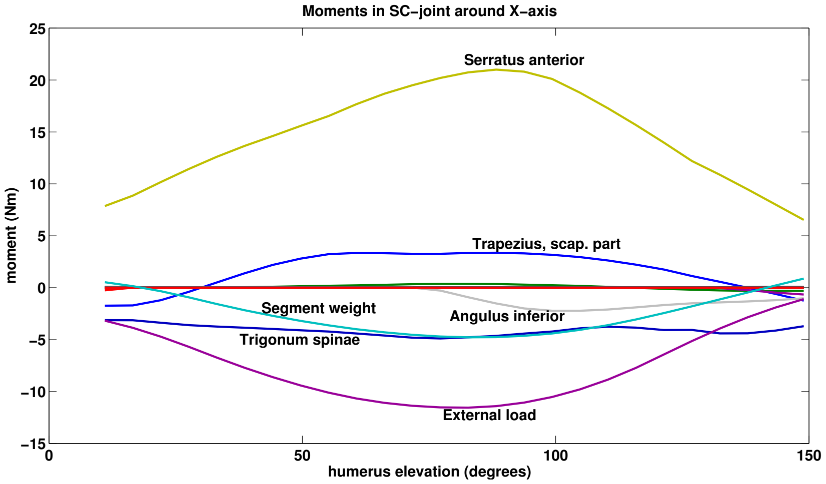
Force between AI and thorax is zero at beginning of movement, showing that the scapulo-thoracic constraint is active to keep the scapula against the thorax.

4.3 Effects of constraints: gleno-humeral stability



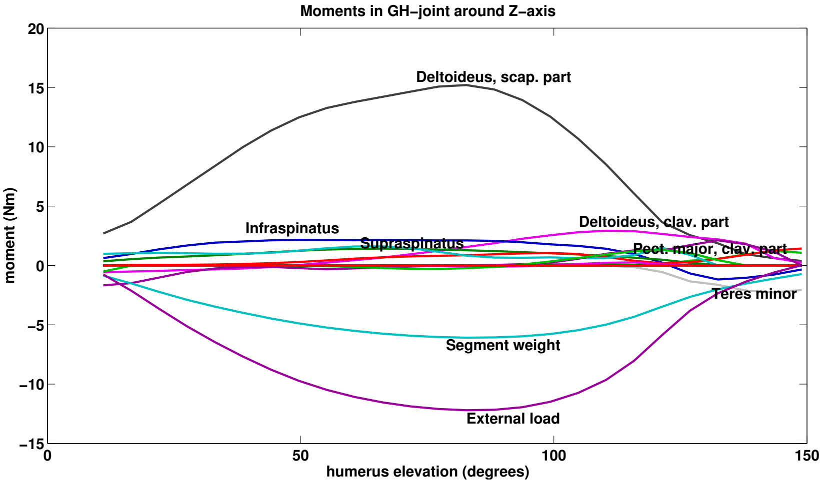
position of JRF in glenoid: green without rotator cuff

4.4 Moment balance: SCx during loaded anteflexion (2kg)



moments in the sagittal plane

4.5 Moment balance: GHz during loaded abduction (2kg)



moments in the frontal plane

4.6 Gleno-humeral joint forces

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

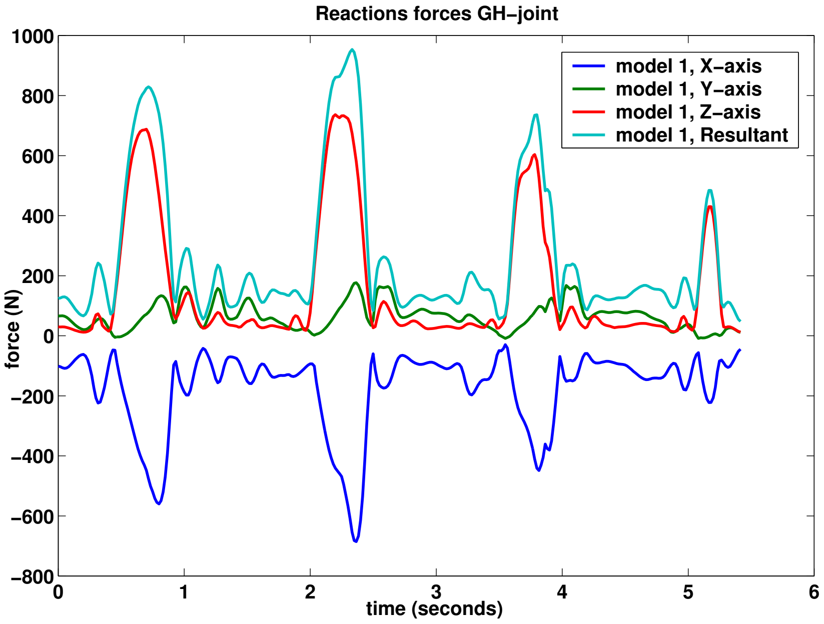
Context: Motions are known (measured from volunteers), muscle and joint forces only required.

Tool: Inverse-dynamic model.

Application: Understanding shoulder pain in wheelchair users.

Veeger et al. (2002)

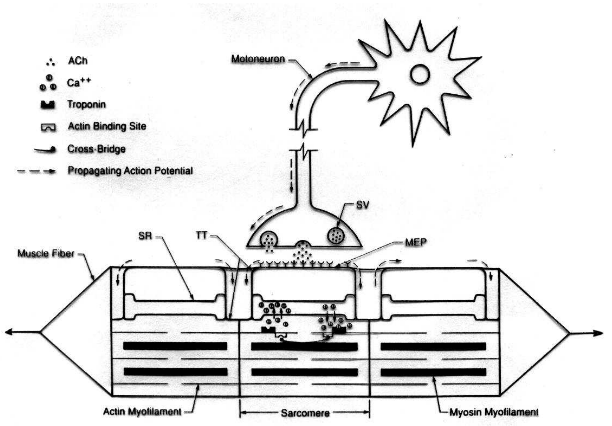
4.7 Gleno-humeral joint forces during wheelchair propulsion



5 Muscle dynamics

But

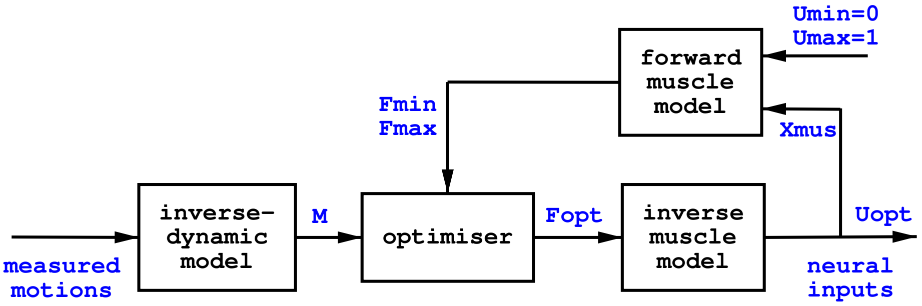
- **muscle force cannot change instantaneously**



⇒ include muscle dynamics in optimisation

5.1 Inverse-/Forward-Dynamic Optimisation (IFDO)

The frames of the motion are no longer time-independent with the inclusion of muscle dynamics, so the scheme becomes a little more complicated:

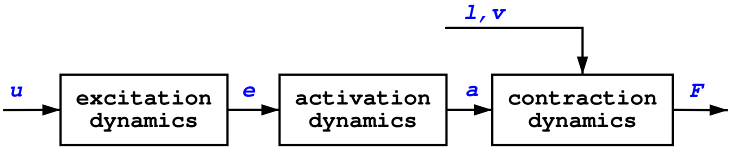


Fmin and Fmax are calculated by integration of the muscle states to the next time-step, and ensure physiologically feasible bounds for the optmisation.

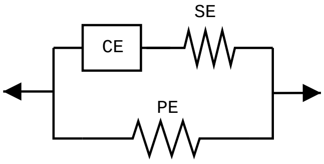
Happee and Van der Helm (1995)

5.2 Muscle model

Hill-type muscle model:



State variables:



- **excitation,** e: $\dot{e} = (u - e)/\tau_{ne}$
- **activation,** a: $\dot{a} = (e - a)/\tau_a$
- **length contractile element,** l_{ce}

Based on Winters and Stark (1985)

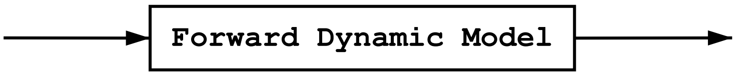
5.3 Inverse dynamics summary

So far we have seen:

- **model input: closed chain mechanism**
- **optimisation: efficiency, cost function**
- **GH stability, scapulo-thoracic contact**
- **examples: joint forces, moment balance**
- **muscle dynamics**

But, we would really like forward dynamics...

6 Forward dynamics



Forward Dynamic Model

input

neural activation

output

predicted motions
hand forces

muscle lengths
moment arms
net moments
muscle forces
joint forces
muscle powers

6.1 Why do we need this?

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**
- **computer-assisted surgery**

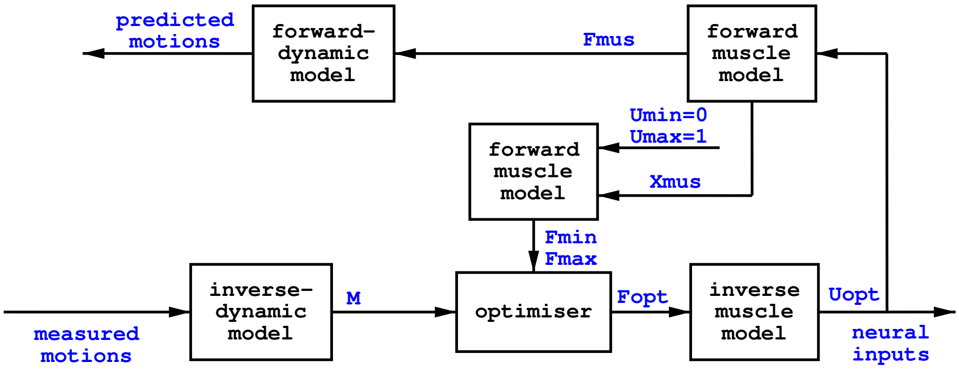
But one big disadvantage:

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

However, we already have a set of optimum inputs (5.1) so no further optimisation is necessary.

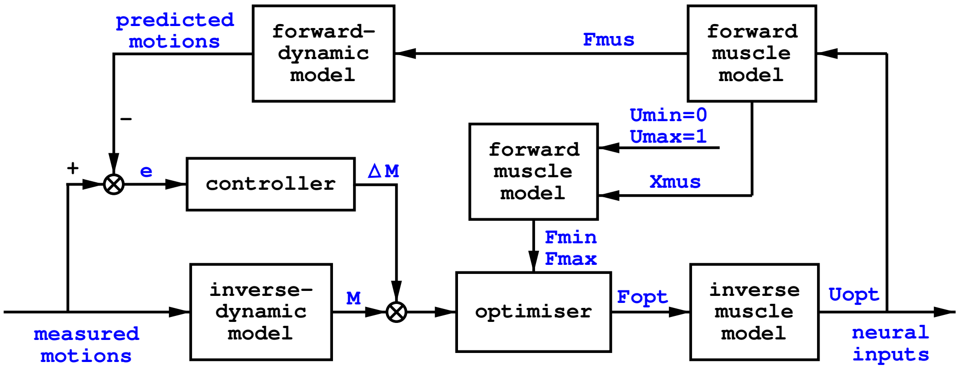
These inputs can be used to drive the FD model ⇒

6.2 Driving the FD model



- FD model should reproduce measured motions... but model can drift

6.3 Inverse-Forward Dynamic Optimisation with Controller



- forward muscle model ensures physiologically feasible solutions for muscle force optmisation
- controller ensures calculated neural inputs reproduce measured motions

6.4 Integration routines

Euler:

- **predictor method, constant step-size**
- **fast but not very accurate**

Adams-Moulton:

- **predictor-corrector method, variable step size**
- **accurate but slow**

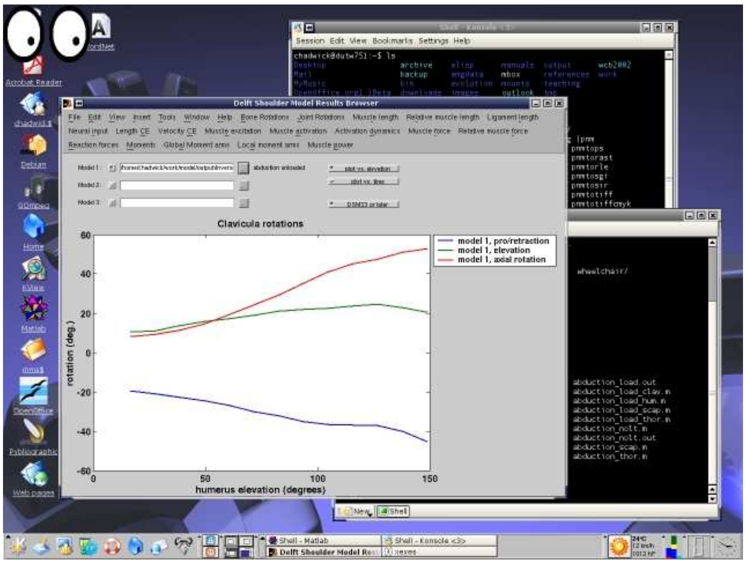
Runge-Kutta:

- **predictor method**
- **good combination of accuracy and speed**

Further reading: Lennox and Chadwick (1977) and Press et al. (1992).
See also: http://mathworld.wolfram.com/OrdinaryDifferentialEquation.html

7 Examples of forward dynamics

7.1 Matlab results viewer



```
chadwick@dutw751:~$ ls
Desktop               archive    elisp      manuals  output      wcb2002
Mail                  backup     engdata    mbox     references  work
MyMusic               bin        evolution  mounts   teaching
OpenOffice.org1.1Beta downloads  images     outlook  tmp
```

```
lpnm
pnmtops
pnmtorast
pnmtorle
pnmtosgi
pnmtosir
pnmtotiff
pnmtotiffcmyk
```

```
wheelchair/
```

```
abduction_load.out
abduction_load_clav.m
abduction_load_hum.m
abduction_load_scap.m
abduction_load_thor.m
abduction_nolt.m
abduction_nolt.out
abduction_scap.m
abduction_thor.m
```

7.2 Prosthesis placement

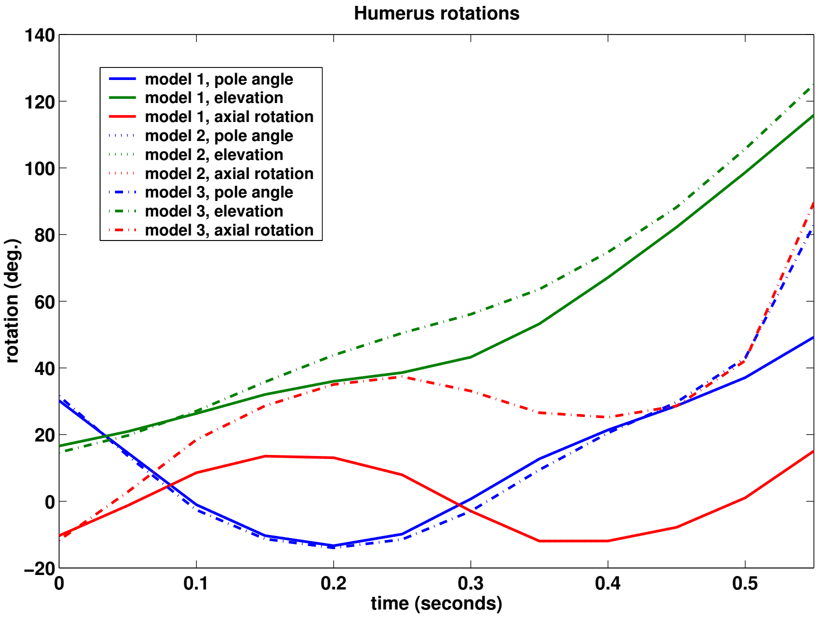
Question: How sensitive is shoulder function after arthroplasty to prosthesis placement?

Context: Unknown effect on post-operative motions, neural input known for standard motions (from healthy volunteers).

Tool: Forward-dynamic model (sensitivity analysis).

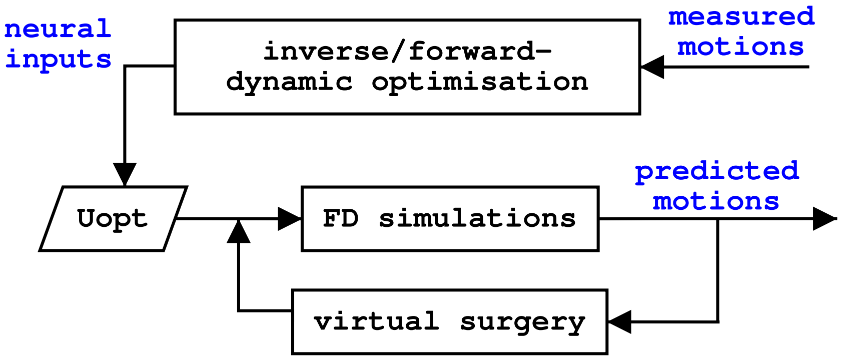
Application: Specifications for improved operative technique for prosthesis implantation.

7.2.1 Rotations of the humerus



chain line shows rotations of humerus with displaced joint rotation centre (1cm laterally)

7.3 Computer-assisted surgery



1. Run IFDOC to get neural inputs
    - using healthy motions
2. Carry out CAS using only FD model
    - no optimisation necessary → fast simulations

8 Summary

Things to consider when modelling the shoulder:

- **17 DoF, closed-chain mechanism (1.3, 3.2)**
- **Equations of motion: TMT method recommended (2.3)**
- **Load-sharing problem (3.4)**
- **Constraints: GH stability, gliding plane (3.5)**
- **Muscle dynamics in optimisation (5)**
- **Advantages of forward dynamics (6.1)**
- **Calculation of neural inputs for forward dynamics (6.3)**
- **But consider application when choosing model (4.6)**

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