INPUT PARAMETERS FOR MODELS I

Lecture Overview

- Equations of motion
- Estimation of muscle forces
- Required model parameters
- Body segment inertial parameters
- Muscle moment arms and length
- Osteometric scaling
- Moment arm equations
- Muscle length equations
- Derivative information
- Inverse and direct dynamics

EQUATIONS OF MOTION

Equation for **Inverse Dynamics**

$$T = M(\theta).\ddot{\theta} + v(\theta,\dot{\theta}) + G(\theta)$$

Re-arrange equation for **Direct Dynamics**

$$\ddot{\theta} = M(\theta)^{-1}.(T - v(\theta,\dot{\theta}) - G(\theta))$$

Where

T - vector of joint moments (n x 1)
$M(\theta)$ - inertia matrix (n x n)
$v(\theta,\dot{\theta})$ - vector of centrifugal/Coriolis terms (n x 1)
$G(\theta)$ - vector of gravity terms
and n is the number of joints in the system

Solution Requires

- Body Segment Inertial Parameters
- Segment Kinematics (complete for inverse dynamics)
- Segment Kinematics (partial for direct dynamics)

EQUATIONS OF MOTION

If model is driven by forces produced by muscle model then

$$\boldsymbol{T} = \boldsymbol{R}(\theta).\boldsymbol{F_M}$$

Where

$\boldsymbol{R}(\theta)$ - matrix of muscle moment arms (musculoskeletal geometry)

$\boldsymbol{F_M}$ - vector of muscle forces, as estimated by the muscle model.

$$[\ \ddot{\theta} = M(\theta)^{-1}.(T - v(\theta,\dot{\theta}) - G(\theta))\ ]$$

Solution Requires

- Muscle Moment Arms
- Muscle Forces

ESTIMATION OF MUSCLE FORCES

The force produced by the muscle model (F_m) can be described using the following function

$$F_m = a_f . F_{max} . F_1(L_f) . F_2(V_f)$$

Where

a_f - normalized degree of activation of muscle fibers.

F_{max} - maximum isometric force muscle can produce

$F_1(L_f)$ - normalized force length relationship of muscle,

$F_2(V_f)$ normalized force-velocity relationship of muscle.

Generally the muscle model takes care of the estimation of muscle state during simulation, but the model still requires parameters.

ESTIMATION OF MUSCLE FORCES

$$F_m = a_f . F_{max} . F_1(L_f) . F_2(V_f)$$

Solution Requires

- Relationship to estimate Muscle-Tendon Lengths
- Maximum Muscle Force
- Parameters for Force-Length Curve
- Parameters for Force-Velocity Curve
- Parameters which describe Activation Dynamics

REQUIRED MODEL PARAMETERS

To run a direct dynamics muscle model driven simulation model of human movement requires

- Body Segment Inertial Parameters√
- Segment Kinematics (complete for inverse dynamics)√
- Segment Kinematics (partial for direct dynamics)√
- Muscle Moment Arms√
- Muscle-Tendon Lengths√
- Maximum Muscle Force
- Parameters for Force-Length Curve
- Parameters for Force-Velocity Curve
- Parameters which describe Activation Dynamics

BODY SEGMENT INERTIAL PARAMETERS

Anthropometry - measurement of the human body; in biomechanics these are mostly concerned with segment mass, center of mass, moment of inertia (these properties of a rigid body are often referred to as inertial properties). Anthropometry *can include just general* measurements of dimensions of body segments.

Techniques for determining body segment inertial parameters can be classified into four groups:-

1. **Simple Statistical Model**

2. **Complex Statistical Model**

3. **Imaging techniques**

4. **Geometric Solid Models**

BODY SEGMENT INERTIAL PARAMETERS

1. Simple Statistical Model

For example based on cadaver data of Dempster (1955), where segment mass is given as percentage of total body mass.

SEGMENT	Fraction of Whole Body Mass
UPPER ARM	0.028
FOREARM	0.016
HAND	0.006
THIGH	0.100
LOWER LEG	0.0465
FOOT	0.0145
HEAD & NECK	0.081
TRUNK	0.497

BODY SEGMENT INERTIAL PARAMETERS

2. Complex Statistical Model

For example Hinrichs (1985) developed multi-variable regression equations for the determination of segment moment of inertia values about transverse and longitudinal axes, using data from cadaver dissections.

For example for the thigh

$$I_T = (80.589.\boldsymbol{L} + 381.74.\boldsymbol{B} - 6525.7)*0.001$$

Where

L - the length of the thigh (in centimeters)
B – breadth of knee (in centimeters)

BODY SEGMENT INERTIAL PARAMETERS

3. Imaging techniques

It is possible to measure the inertial properties of segments using a variety of imaging techniques.

Martin et al. (1989) used MRI to calculate the inertial parameters of eight baboon cadaver arm segments, they also measured the inertial parameters directly so could assess accuracy of this method.

Parameter	Mean Difference	Standard Deviation
Volume	6.3	5.0
Density	0.0	3.1
Mass	6.7	2.8
C of M. location	-2.4	8.2
Mom. of I (T)	4.4	3.0

BODY SEGMENT INERTIAL PARAMETERS

4. **Geometric Solid Modeling**

Within this class of techniques all segments are modeled as a series of geometric solids. The dimensions of these shapes are obtained by taking measurements on the subjects, for example:

truncated cones $\Rightarrow$ length and perimeters

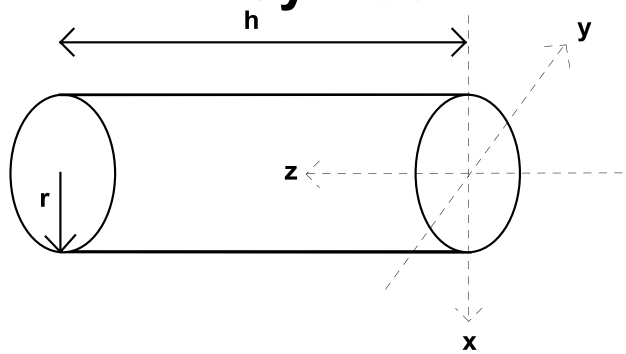
stadium solids lengths $\Rightarrow$ perimeters and widths.

Density values for these solids are taken from the cadaver data, and is normally assumed to be uniform throughout a given segment.

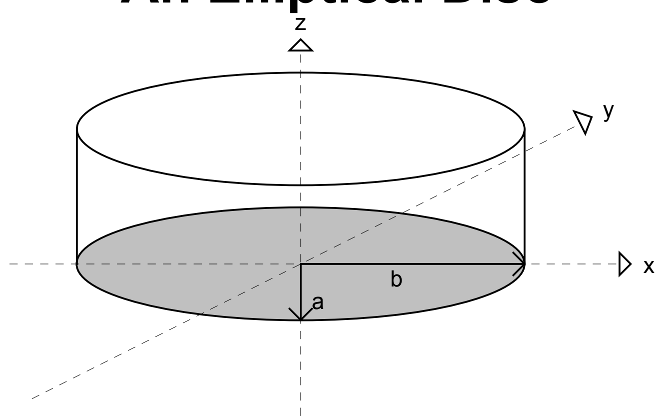
BODY SEGMENT INERTIAL PARAMETERS

Examples of three commonly used shapes in geometric solid models

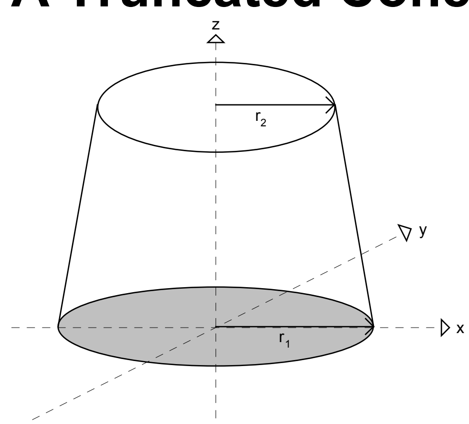
A Cylinder



An Elliptical Disc



A Truncated Cone



BODY SEGMENT INERTIAL PARAMETERS

Reference: Hatze, H. (1980): A mathematical model for the computational determination of parameter values of anthropomorphic segments. ***Journal of Biomechanics*** 13, 833-843.

BODY PART	Hatze (1980)
Foot	103 Unequal Trapezoindal Plates
Shank	10 Elliptical Cylinders
Thigh	1 Ellipto-parabolic section 10 Elliptical Cylinders
Hand	1 Prism 1 Hollow Half-cylinder 1 Arched Rectangular Cuboid
Forearm	10 Elliptical Cylinders
Upper Arm	1 Hemisphere 10 Elliptical Cylinders
Trunk	Lower 10 Complex plates Buttocks 2 Elliptical Parabolas Upper Unequal Semi-ellipses, with parabolas removed
Head	1 Elliptical Cylinder 1 General Body of Revolution
#Segments	17
#Measures	242

BODY SEGMENT INERTIAL PARAMETERS

Models rely to some extent on these inertial parameters, estimates report that moments of inertia cannot be determined to within 10% of true value, mass and location of center of mass 5%. This is probably not significant if the model is not subject specific, if it is subject specific then it may be important; to date this importance has not been identified.

Major Cadaver Studies

Author(s)	*Cadavers*	*Age (Years)*	*Body Mass (kg)*	*Stature (m)*
Dempster (1955)	8 male	52 - 83	49 - 72	1.59-1.86
Clauser et al. (1969)	13 male	28 - 74	54 - 88	1.62-1.85
Chandler et al. (1975)	6 male	45 - 65	51 - 89	1.64-1.81

MUSCLE MOMENT ARMS AND LENGTH

Two ways in which these can be determined in vivo

- Based on musculo-skeletal geometry
- Using equations describing relationship between joint angle muscle length/moment arm

If the musculo-skeletal geometry is known then the line of action of the muscle can be estimated from the known origin and insertion of the muscles and the locations of the bones.

There are a variety of sources of geometry data, for example

- Brand et al. (1982) - provided the averaged scaled locations of the origins and insertions of 47 muscles
- White et al. (1989) - provided data suitable for osteometric scaling for 40 muscles of the lower limb
- Johnson et al. (1996) – the major muscles of shoulder

OSTEOMETRIC SCALING

Osteometric scaling - the extrapolation from dry bone specimen landmarks to another specimen, normally a live subject.

- The locations of the origins and insertions of muscles and ligaments are often inaccessible on a live subject. This information can be obtained from the results of cadaver dissection, and then applied to a live subject.

- Some form of scaling is appropriate as the physical dimensions of the bones of the cadaver and the subject are likely to be different. Osteometric scaling permits this.

OSTEOMETRIC SCALING

The following procedures have been adopted for using cadaver data for a live subject:

1. **No Scaling** - e.g. Amis et al. (1987). Dubious procedure (see Lew and Lewis, 1977).

2. **Uniform Scaling** - where all the dimensions of the bone are scaled in the same proportions e.g. Crowninshield and Pope (1975).

3. **Homogeneous Scaling** - scaling along prescribed principal axes (e.g. Morrison, 1970).

4. **Non-homogeneous scaling** - scaling is performed along arbitrary axes, this method involves non-homogeneous scaling based on finite-element principles (Lewis et al., 1980). Requires eight common landmarks on subject and cadaver specimen.

OSTEOMETRIC SCALING

Example

Lew and Lewis (1977) presented data of the locations of six bony landmarks on two human tibias, selected so that the "geometry differences between the bones were as large as possible." (page 174).

1. tubercle of Gerdy
2. lateral malleolus
2. posterior cruciate attachment
4. middle of tibial spines
5. center of lateral condylar surface
6. tubercle on soleal line

Point Excluded/ Predicted	Absolute Relative Differences (m)		
	x	y	z
1	0.016	0.004	0.008
2	0.072	0.022	0.052
3	0.028	0.010	0.010
4	0.009	0.008	0.009
5	0.025	0.003	0.000
6	0.015	0.007	0.009
Mean	0.027	0.009	0.015

MOMENT ARM EQUATIONS

There are a variety of these equations including

Elbow Joint – e.g. Pigeon et al. (1996)

Knee and Hip Joints – e.g. Visser et al. (1990)

Ankle – e.g. Voigt et al.(1995)

These measurements can be made on cadavers (e.g. Visser et al., 1990), or made in vivo for example using MRI (e.g. Spoor and Van Leeuwen, 1992).

Equation inputs are joint angle, and some normalized length (e.g. limb length).

MUSCLE LENGTH EQUATIONS

There are a variety of these equations including

Elbow Joint – e.g. Pigeon et al. (1996)

Knee and Hip Joints – e.g. Hawkins and Hull, (1990)

Ankle – e.g. Grieve et al. (1978)

Again these measurements can be made on cadavers (e.g. Grieve et al., 1978), or made in vivo for example using MRI (e.g. Spoor and Van Leeuwen, 1992).

Equation inputs are joint angle, and some normalized length (e.g. limb length).

DERIVATIVE INFORMATION

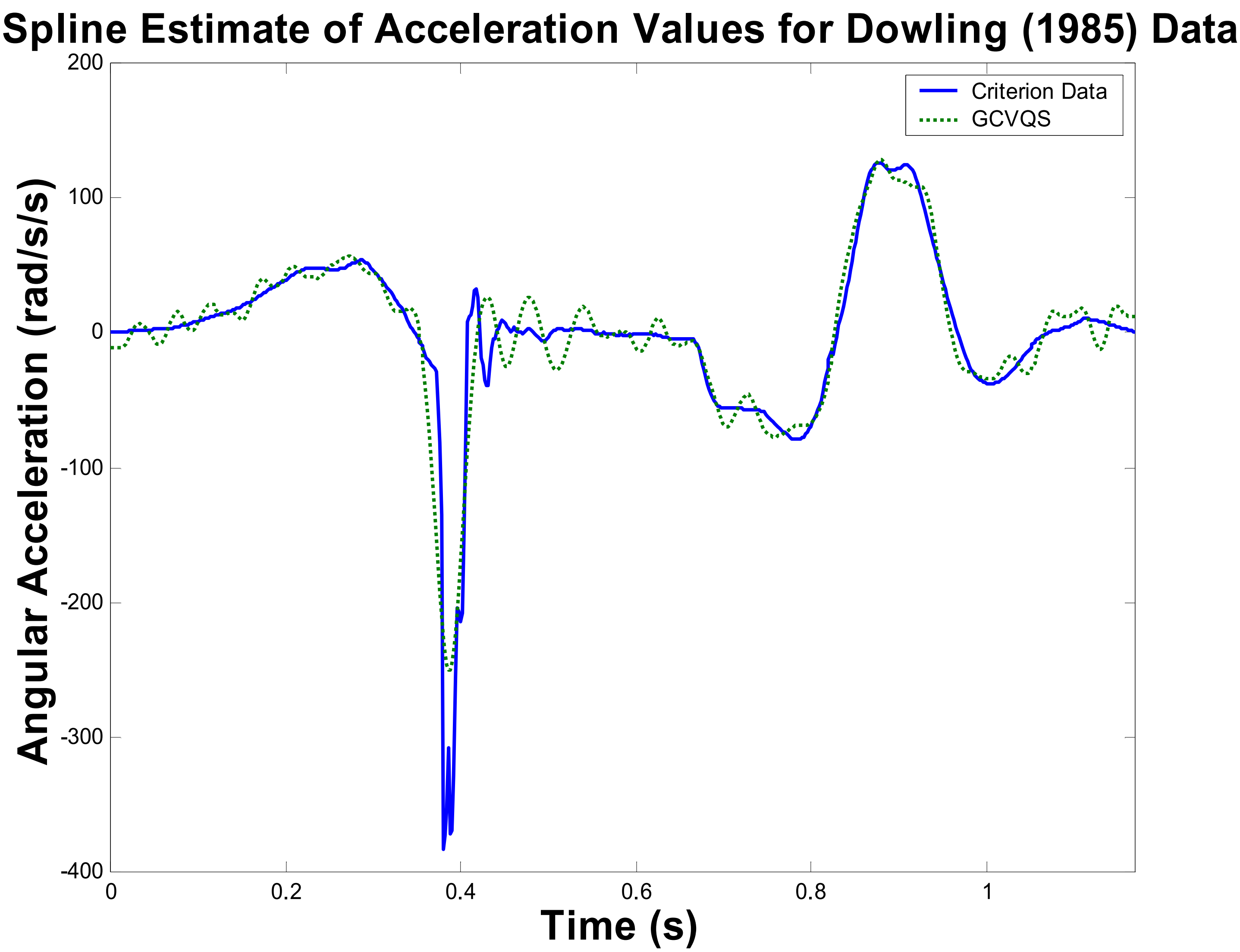
To perform inverse dynamics requires the acceleration of the segments centers of mass, and the angular acceleration of the segments. To perform direct dynamics these variables become parameters because they are needed as part of the initial conditions for the solution of the ordinary differential equations which define the equations of motion of the system under study.

- Sampled movement signals are generally contaminated with white noise.

- A low-pass filter will remove the high frequency noise, but cannot remove all of it because in the lower frequencies the movement signal also exists.

DERIVATIVE INFORMATION

The data of Dowling (1985) was processed with the generalized cross validated quintic spline of Woltring (1986), it shows how poor acceleration estimates can be.



DERIVATIVE INFORMATION

As accurate derivative information is so difficult to determine, the following should be considered

- Using best processing techniques to get as accurate derivatives as possible.
- Use a range of starting values which encompass your assumed error and see the influence on output.
- Analyze a movement which starts from stationary.

INVERSE AND DIRECT DYNAMICS

- Some models are driven using inverse dynamics information.

- Both sets of equations are derived from same mechanical principles so results should be equivalent. (Never assume you can drive a direct dynamics model with inverse dynamics data and get the same results.)

- There are different error sources associated with numerical differentiation, and numerical integration, so results are never quite the same.

- Numerical differentiation is very sensitive to sample noise.

- Numerical integration is very sensitive to sample interval.

Reference - Risher et al. (1997) The use of inverse dynamics solutions in direct dynamics simulations. ***Journal of Biomechanical Engineering*** 119, 417-422.

REVIEW QUESTIONS

1) What methods are available for determining body segment inertial parameters? Why might errors in their determination have a greater influence for inverse dynamics than direct dynamics?

2) What is osteometric scaling? How can it be used in the modeling of human movement?

3) How can the lengths and moment arms of muscle-tendon complexes be determined? Which of these methods is to be preferred?

4) What measures should be taken if trying to drive a direct dynamic model with data derived from an inverse dynamics analysis?