Identification of Joint Impedance

tools for understanding the human motion system, treatment selection and evaluation

Lecture 12 SIPE 2010
Case Studies

Erwin de Vlugt, PhD
Delft-Leiden Research Connection

TU Delft
Delft University of Technology

DELFT LABORATORY for
NEUROMUSCULAR CONTROL

Frans van der Helm, Erwin de Vlugt, Alfred Schouten, Herman van der Kooij, David Abbink, Riender Happee, Winfred Mugge, Alistair Vardy, Judith Visser, Stijn van Eesbeek

Mission: development of SIPE technology to analyze the human neuromuscular control system

Laboratory for Kinematics and Neuromechanics

Hans Arendzen, Jurriaan de Groot, Carel Meskers, Frans Steenbrink, Erwin de Vlugt, Asbjorn Klomp, Hanneke van der Krogt, Andrea Maier, Bob van Hilten, Rob Nelissen

Mission: application and validation of SIPE technology in the clinical practice to improve efficacy of intervention
Robots for System Identification

- Mechanical energy transfer to the biological system
- Measurement of forces and movement
Robots for System Identification

- Natural tasks
- Perturbations
- Closed loop
- Interpretable parameters
System Identification & Parameter Estimation (SI-PE)

Physical System

Identification (SI)

Parameterization (PE)

System Behavior

Physical Properties

input

output

minimal a priori knowledge required

A priori knowledge required
Three case studies

1. Linear SIPE: intrinsic and reflexive properties of the shoulder (1DOF)

2. Linear SIPE: … but now for 3DOF (shoulder, elbow, wrist)

3. Nonlinear PE: intrinsic and reflexive torque of the ankle in stroke
Linear systems: Frequency domain analysis of mass-damper-spring

\[ H(s) = \frac{1}{Ms^2 + Bs + K} \]

\[ s = 2\pi f \]

- H is causal
- H is an admittance

\[ \omega_0 = \sqrt{\frac{K}{M}} \]

\[ \beta = \frac{B}{2\sqrt{KM}} \]
Optimal Admittance Control

- Simulations indicate that contribution of reflexes decrease with frequency of torque input.

Fig. 5. Magnitudes of $H_{CL}(f)$ for NB noise type 1 with different values of $f_h$ (solid curves), and for $H_c(f) = 0$, i.e. only intrinsic feedback (dashed curves). The filled areas denote the frequency range between $f_l$ and $f_h$.
Short Intro to Optimal Admittance Control

Joint Admittance
- is the dynamic relationship between joint angle and joint torque
- the result of visco-elasticity and torque generated by reflexes
- important for posture maintenance

Research Questions
- does admittance depend on the dynamic properties of external load, e.g. damping?
- how does admittance change with joint angle?
Case 1: 1DOF shoulder joint control
Procedures

- External damping $B_E$: 0 – 400 Ns/m
- External mass $M_E$: 0.6 – 10 kg
- Unpredictable force disturbances
  - 40 s (0.1-20 Hz)
- Grip displacements $\approx$ 3 mm (SD)
- EMG of four shoulder muscles
- $n=5$ (healthy)
Force perturbations: closed loop
Force perturbations: closed loop
SI Results: Frequency Response Functions

damper off
damper on
Parameter Estimation (PE)

Hold position

$D$

$F_{\text{hand}}$

$X_{\text{hand}}$

Linear Endpoint Model

FRF Estimation

Parameter Fit

FRF Simulation
PE Results: stretch reflex estimates

De Vlugt et al. 2002
Results: optimized stretch reflex
Reflexive Admittance Control: no environment

Admittance $H_{\text{TOT}}(f) = H_{\text{ARM}}(f)$

Gain [m/N]

$J_x = 100\%$

Phase [deg]

Frequency [Hz]

$K_p = 1000$
Reflexive Admittance Control: with External Damper

Admittance $H_{TOT}(f)$

- **Gain [m/N]**
  - $J_x = 100\%$
  - $K_p = 1000$, $B_E = 100$

- **Phase [deg]**
  - Frequency [Hz]
Case 2: SIPE in the 3DOF Shoulder
2DOF FRFs

Data model
## PE Result: intrinsic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mean (S.D.))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>$m_{hand}$ [kg]</td>
<td>1.96 (0.295)</td>
</tr>
<tr>
<td>$m_{fore}$ [kg]</td>
<td>1.13 (0.240)</td>
</tr>
<tr>
<td>$m_{hand}$ [kg]</td>
<td>0.496 (0.0976)</td>
</tr>
<tr>
<td>$B_h$ [N s/m]</td>
<td>167 (74.9)</td>
</tr>
<tr>
<td>$K_h$ [kN/m]</td>
<td>7.39 (3.09)</td>
</tr>
<tr>
<td>$T_{ds}$ [ms]</td>
<td>30.4 (2.48)</td>
</tr>
<tr>
<td>$T_{de}$ [ms]</td>
<td>33.4 (2.61)</td>
</tr>
<tr>
<td>$T_{dw}$ [ms]</td>
<td>40.4 (3.00)</td>
</tr>
<tr>
<td>$f_{act,s}$ [Hz]</td>
<td>1.98 (0.0842)</td>
</tr>
<tr>
<td>$f_{act,e}$ [Hz]</td>
<td>2.26 (0.136)</td>
</tr>
<tr>
<td>$f_{act,w}$ [Hz]</td>
<td>2.11 (0.175)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Subject.
Stiffness Ellipses

Admittance Ellipses [m/N]

0.1 Hz

0.4 Hz

1.3 Hz

2 Hz

5 Hz

Left  Central  Right

reflexes turned off / turned on

data model
Case 3: Nonlinear case: Ramp-hold
Ankle rotation in stroke

De Vlugt et al. 2010
Nonlinear case: Ramp-hold Ankle rotation

- stroke (n = 19)

Goal:
- estimate passive visco-elasticity and stretch reflex dynamics and compare to Ashworth Scale
Direct Physical Parameterization

Cross-bridge kinetics (Nonlinear damper)

Minimize Difference by Adjusting Model Parameters

Contractile Force

Tissue elasticity (Nonlinear spring)

Predicted Torque

Measured Torque (output)

Imposed Motion by Manipulator (input)
No Identification, Direct Parameterization

direct parameterization of a nonlinear model in time domain

Parameters:
- inertia
- tissue viscosity
- tissue elasticity
- activation dynamics
- contractile dynamics
Main Result

- Detailed parameterization possible:
  - Accurate (VAF > 90%)
  - Valid (low parameter SEM)

- Viscosity decreased with movement velocity

- Passive stiffness correlated to Ashworth Scale
Challenges: SIPE during movement

- **Time Varying Joint Admittance**
  - Wavelets and subspace techniques
  - Collaboration between the fac. of 3ME (DCSC, BMechE) and Aerospace Eng.
Summary

- Linear behavior: frequency domain can be used and provides direct qualitative information about the human joint dynamics.

- Nonlinear behavior: time domain analysis by direct parameterization of a physical nonlinear model of the human joint.

- Towards Time Varying System Identification…
Delft University of Technology

Graduate Student Master Projects

- Master Projects at NMC Lab involves a mixture of SIPE, physiology and clinical issues

- Many (international) opportunities for Graduate Students
  - internship (stage), preferably outside the Netherlands
  - fundamental projects: TUD
  - clinical projects: LUMC, Erasmus MC, VUMC