Computersimulation mit einem digitalen Menschmodell: zur Prognose von Produkt- und Produktionsergonomie

Infoday Human Models, DYNAmore GmbH, 02.06.2016
Human movement taken to the extreme – Dean Potter†

Slack line: 30m long, 1000m above ground, Taft Point, Yosemite Valley, USA

neurons
100 millions – 1 billion

brain
clock speed ~100Hz

nerves
wire speed 0.5-120m/s

sensors
X millions
delay ~10ms

visual
tactile
auditory
vestibular
proprioceptive

information processing and storing

actuators
>600

muscles (skeletal, smooth, cardiac)
tendons, ligaments

actions resulting on different parameters

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Video source radX YouTube channel: https://youtu.be/KVaTsuf5Z0
Multi-scale nature of a biological system
From a millimetres to angstroms

Our research scale

Organism
Organ
Tissue
Cells
Molecules

large spatial scale small
Our viewpoint on natural systems
From single joint to complex movement generation: numerical models

Bones  Rigid bodies
Structure

Ligaments, Passive forces
cartilage, fat
Springs

Muscles  Active forces
Motors

Neurons  Reflexes, commands
Wires, CPU

\[
\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i
\]

\[
F_p = f(z, \dot{z})
\]
\[
\text{with } z = [q_1, \ldots, q_n, o_1, \ldots, o_m]^T
\]

\[
F_a = f(z, \dot{z}, u)
\]
\[
\text{with } u = [u_1, \ldots, u_k]^T
\]

\[
u = f(z, \dot{z}, "brain")
\]
**Multibody Dynamics of the skeletal system**

Bones as linked rigid bodies

Forward dynamics equation of motion

\[ \ddot{q} = M(q)^{-1} \left( f - C(q, \dot{q}) - G(q) \right) \]

where

\[ f = f_{\text{ext}} + f_{\text{aktiv}} + f_{\text{passiv}} \]

\[ = E(q, \dot{q}) + R_{\text{aktiv}}(q) L_{\text{aktiv}}(q, \dot{q}, u) + R_{\text{passiv}}(q) L_{\text{passiv}}(q, \dot{q}) \]

- \( q \) - generalized coordinate
- \( C(q, \dot{q}) \) - Coriolis and centrifugal forces
- \( G(q) \) - Gravitation
- \( M(q) \) - System matrix


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Soft tissue relative to bone movement

Muscle tissue and traveling shock waves

http://dx.doi.org/10.1016/s0021-9290(06)83091-5

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Soft tissue relative to bone movement

Wobbling masses

- ... facilitate short ground contact time
- ... allow for fast signal travelling along the body
- ... represent well adjusted inertia properties of the distal segments

\[ P_{k/x,\text{wob}}(t) = F_{k/x,\text{coup}}(t) \cdot \dot{X}_{k,\text{wob}}(t) \]
\[ P_{k/y,\text{wob}}(t) = F_{k/y,\text{coup}}(t) \cdot \dot{Y}_{k,\text{wob}}(t) \]
\[ P_{k/\varphi,\text{wob}}(t) = M_{k/z,\text{coup}}(t) \cdot \dot{\varphi}_{k,\text{wob}}(t) \]

\[ \Delta E_{k/j,\text{wob}} = \int_{t=0}^{90 \text{ ms}} P_{k/j,\text{wob}} \, dt \]


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Passive structures
Ligaments, cartilage, fat

Non-linear ligaments

Non-linear intervertebral discs

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Guenther et al., 2007, Rupp et al., 2015
Karajan et al., 2012
Active structures
Modified Hill-Type Muscle Model

Muscle-tendon unit with serial damping and eccentric force–velocity relation

**Force equilibrium:**

\[ F_{MTU} = F_{CE}(l_{CE}, i_{CE}, a) + F_{PEE}(l_{CE}) \]

\[ = F_{SEE}(l_{CE}, l_{MTU}) + F_{SDE}(l_{CE}, l_{CE}, l_{MTU}, a) \]

**Activation dynamics:**

\[ \dot{a}_i = f_a(a_i, l_{CE}^i, u_i) \]

**Contraction dynamics:**

\[ i_{CE}^i = f_v(l_{MTU}^i, v_{MTU}^i, l_{CE}^i, a_i) \]


http://dx.doi.org/10.1016/j.jbiomech.2014.02.009

Infoday Human Models, DYNAmore GmbH, 02.06.2016
Modified Hill-Type Muscle model
Available as open source code

Can be found online at http://dx.doi.org/10.1016/j.jbiomech.2014.02.009


Infoday Human Models, DYNAmore GmbH, 02.06.2016
Biological control of the muscle model
Neural control algorithm

Learning of target muscle lengths


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Biological control of the muscle model
Lambda and hybrid controllers

feedback control

feedforward and feedback control

Bayer et al. (2016) submitted
System dynamics perspective
Modular chart of the human motion modelling

Controller

- Brain "High level" controller
- Sub-cortical "Low level" controller
- Neural pathways
- Command

Control system and environment

- Sensors
- Noise
- Feedback
- Perturbation
- Skeleton dynamics
- Passive structures
- Physical state dependencies

Muscles

"Low level" controller
Biomechanical response of the human body to vibrational loads

Simulation studies
Seated vibrations as typical nowadays load

What we don’t know…

Questions:

1. Is muscular activity at spine level able to reduce internal loads in the intervertebral disc?
2. Is there any difference between static and dynamic cases?
3. Role other biological parts of the spine play?

Hypotheses

1. Static loads on the intervertebral disc increase with increased muscular activity of the trunk muscles.
2. Muscular activity is able to shift loads between biological parts in the spine in the dynamic load case.

Bayer et al. (2016) submitted
Biomechanical response of the human body
Full human multibody model description

13 Rigid Bodies (1.78 m, 68 kg)
- Feet, Shanks
- Thighs, Pelvis
- Waist, Head, Arm

Rupp et al., 2015

58 nonlinear ligaments in the lumbar spine
- ALL, PLL, LF, ISL, SSL

Panjabi et al., 1982
Pintar et al., 1992
Rupp et al., 2015

5 nonlinear, coupled IVDs

Properties taken from homogenized FE model
Karajan et al., 2013

252 Muscle-Tendon Units
- CE, SEE, PEE, SDE

Häufle et al., 2014

1 Neuronal controller

Combination of
- Open-loop control and
- Closed-loop control

Bayer et al., 2016
Kistemaker et al., 2016
Passive and active muscles influence comparison
2 models in a sitting posture, exposed to whole-body vibrations

Muscle-tendon units:
actively driven

Muscle control parameters:
\[ u^{\text{open}} - 2\% \ldots 6\% \]
\[ u^{\text{closed}} - k_p = 2 \]
Resulting stimulation
up to 13.5%

Muscle-tendon units:
passively driven

Muscle control parameters:
\[ u^{\text{open}} - \text{up to } 0.001\% \]
\[ u^{\text{closed}} - k_p = 0 \text{ result} \]
Resulting stimulation
up to 0.001%
Muscular activity reduces peak loads on the IVD
Internal load components in joint L4/5

**Model with passive muscles**

**Model with active muscles**

- **Muscle forces** are lower for passive model: 30N max vs 380N max
- **Ligament forces** are higher for passive model: 473N max vs 210N max

Bayer et al. (2016) submitted
Spine surgery and Personalized medicine

Simulation studies
Spinal fusion surgery and Personalised medicine
How to perform proper implantation?

preoperative  initial postoperative  8-year postoperative

Change of ...
...displacement, internal forces and moments?


Infoday Human Models, DYNAmore GmbH, 02.06.2016
Human model - lower extremity and spine
Same full human multibody model as above

Video source: HMSL YouTube channel: https://youtu.be/EanNZJPVwD0
Human model - lower extremity and spine
Loading of posterior ligaments: $F_{\text{total}}$

Unfused IVDs

Fused L4/5

~350N (+40%)

Controlled human movements

Simulation studies
Controlled human movements simulation
Active sitting down on a seat – full forward-dynamic motion simulation

Motion control with four supporting equilibrium points

<table>
<thead>
<tr>
<th>#</th>
<th>Position</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>Upright standing</td>
<td>0.00 s &lt;= t &lt; 0.10 s</td>
</tr>
<tr>
<td>P₂</td>
<td>Hip flexion</td>
<td>0.10 s &lt;= t &lt; 0.15 s</td>
</tr>
<tr>
<td>P₃</td>
<td>Knee flexion</td>
<td>0.15 s &lt;= t &lt; 0.55 s</td>
</tr>
<tr>
<td>P₄</td>
<td>Upright sitting</td>
<td>0.55 s &lt;= t</td>
</tr>
</tbody>
</table>

Bayer et al. (2016) submitted
Controlled human movements simulation
Quiet stance and walking in different conditions

... on earth.

... on the moon.


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Automotive engineering and Ergonomics

Simulation studies
Automotive engineering and Ergonomics
Active Human Body Model is needed

Human Movement Simulation Lab Research Topics

Biomechanics  Neuroscience  FEM  Mechanics of Materials

Infoday Human Models, DYNAmore GmbH, 02.06.2016  Video source AUTO BILD YouTube channel: [https://youtu.be/DHSeuaoZ-mI](https://youtu.be/DHSeuaoZ-mI)
Future concept cars – new way of driving

Autonomous stress free driving, Entertainment and Interaction, Time saving

Images courtesy of Daimler AG, Rinspeed Inc., Toyota Central R&D Labs. Inc.

Infoday Human Models, DYNAmore GmbH, 02.06.2016
Automotive engineering and Ergonomics
THUMS v3 with active muscle elements – steering maneuver simulation
Interdisciplinary coupling of different numerical methods
3D Continuum-Mechanical Model for Forward-Dynamics Simulations

Röhrle, O., Sprenger, M., Schmitt, S (submitted 2016) A Two-Muscle, Three-Dimensional, Continuum-Mechanical, Forward-Dynamics Simulation of the Upper Limb
Thank you for your attention!

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