Human Body Modeling with ANSYS Software

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Overview

This talk is motivated by the following observations:

1. Our understanding, and thus our ability to mathematically describe, the human body is to the point where one can assemble human body models as “boundary conditions” for biomedical simulations.

2. Improvements in ease-of-use and stability of multiphysics modeling tools.

3. Computational capabilities are continually increasing.
Types of Human Body Models

Human Body Modeling

- CFD, FEA, and emag models coupled to lumped parameter representations of the human body

Parametric System Level

- DOE for HBM
- Fully automated process

Application areas:
- Coronary stents
- Peripheral stents
- Artificial organs

Application areas:
- Transdermal
- Inhalers
- Oral
- Intrathecal

Application areas:
- Medical imaging
- Cardiology
- Drug delivery
- Cancer treatments
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Material properties
Can typically assume density and viscosity at average hematocrit and high shear.

\[ \rho = 1.05 \text{ g/cm}^3 \]
\[ \mu = 0.035 \text{ g/cm-s} \]

Inflow conditions
Literature a good source for inflow data*

Resting Condition
\[ Q_{\text{tot}} = 6.8 \text{ L/min, 75 bpm}^{**} \]

Exercising Condition
\[ Q_{\text{tot}} = 12.8 \text{ L/min, 117 bpm}^{**} \]

Patient-Specific Blood Flow

Material properties
Can take a blood sample and measure the patients hematocrit, protein content, etc.

\[ \rho \text{ vs } H^* \]
\[ \mu \text{ vs } \gamma^{**} \]

Inflow conditions
Taken from on-line measurements***

Geometry (courtesy Materialise Inc.)

* Hinghofer-Szalkay, ?? (1986)
** Cho & Kensey, Biorheology (1991)
*** Huntsman et al., Circulation (1983)
My Flow Patterns

speed

wall shear

pressure
Outflow Conditions For Aortic Flows

One complicating factor in aortic flow modeling is the application of accurate outflow boundary conditions.

Specialized conditions are required because the flow split at a bifurcation is controlled by downstream organ demand, not the bifurcation geometry.

Without a specialized condition, an analyst will not have a proper understanding of the baseline flow patterns and how an implanted device affects those patterns.

Flow Rate Reqs for Human Organ Circuits

1Rhodes & Tanner, Med Physiology (1995)
Create a detailed geometric model of the entire cardiovascular system, extending from the heart to the capillaries. The problems with this approach are obvious:

- Large geometric model required to capture full geometric details
- Accuracy of the geometry will be at question, esp. below 0.5 mm
Modeling Options for Outflow BCs

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- Large geometric model required to capture full geometric details
- Accuracy of the geometry will be at question, esp. below 0.5 mm

Use a lumped parameter approach to alleviate the need for detailed geometry at all length scales.

- The image to the right is an electrical circuit model of the human circulatory system, extending from the heart to the small arteries.
- Each box contains a lumped parameter representation of an artery section.

Electrical Circuit Model of the Human Cardiovascular System*

* Westerhof et al., J Biomech (1969)
The circuit on the lower left can be used to model the flow rate and pressure losses in each artery section. This circuit is referred to as a 3-element Windkessel.

- **Resistance term** – accounts for downstream flow resistance (primarily in the capillary beds)
- **Compliance term** – accounts for artery expansion/contraction (primarily in the large arteries)
- **Inertance term** – accounts for inertial effects (primarily in the large arteries)
The Westhof Circuit in Simploter
Impedance Comparison

Westerhof Model

Simplorer Model
(Inverted L Network)

Fig. 3. Input impedance of the entire systemic arterial tree with
different segment representations, elastic tapering, and adjusted
radii. Total peripheral resistance is 1420 g cm \(^{-2} \) sec \(^{-1}\) in all cases.
(Each successive graph gives effect of improvement while retaining
previous additions).
Insert FLUENT into the Simploter HBM
Validation
- Flow Past a Symmetric Bifurcation

The Windkessel boundary condition was applied to an idealized representation of the abdominal aorta. Transient values for the inlet flow rate and outlet pressures were culled from a literature source*. The geometry and boundary conditions were symmetric in this case. As seen in the figure on the right, there was excellent agreement between published and computational results for the outlet pressure.

Iliac RCR parameters

\[ R_D = 3.22 \text{ mm Hg-s/cc} \]
\[ R = 0.55 \text{ mm Hg-s/cc} \]
\[ C = 0.001 \text{ cc/mm Hg} \]

Outlet pressure from SI[mplorerr compared well with the results of Taylor

* Wan et al. (preprint)
A Non-Symmetric Case

velocity

pressure
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AnyBody for Implant Loads

AnyBody provides a detailed description of the loads and joint forces occurring in the human body in daily activity. ANSYS Mechanical can import loads from Anybody, providing critical information for testing orthopaedic implants and the like.
Orthopaedic Workflow

Activities of daily living

Musculoskeletal Simulation

FEA loads for activities of daily living

Finite Element Analysis

Optimization

Medical images

CAD/Mesh

Orthopaedic Workflow

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Functional Patient-Specific Modeling

- Activities of daily living
- Boundary conditions
- Patient information
- FE-model
Unique Open Body Model Library
Daily Activity Analysis
Dynamic Physiologic Loads
In vivo validation
- Hip forces

Thielen et al. 2009
A Hip Simulator

Slide Track Patterns

- Slide tracks represent the relative motion of the ball and cup

Slide tracks on the head are determined by mounting pens to fixed points on the cup and vice versa for slide tracks on the cup.
Variation in Slide Track Patterns

Increasingly complex track patterns
Model Inputs

Geometry
- Femur and implant provided in STL format
- Acetabular cup was created in ANSYS Mechanical

- Kinematic joint conditions provided by AnyBody:

Walking

<table>
<thead>
<tr>
<th>Angle in Degrees</th>
<th>Time (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-27</td>
<td>-2.84</td>
</tr>
<tr>
<td>-17</td>
<td>3.84</td>
</tr>
<tr>
<td>-13</td>
<td>4.84</td>
</tr>
</tbody>
</table>

Cycling

<table>
<thead>
<tr>
<th>Flexion</th>
<th>Abduction</th>
<th>Ext. Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>
Implementation

Geometry
• Head, cup (rigid), and stem

Material properties
• Default material properties used for all parts

Boundary Conditions
• Angular data entered as displacement BC’s for the cup in tabular format

Solver
• ANSYS Mechanical 12.1 transient solver
• Rigid-flexible contact maintained between the head and the cup

Post-processing
• Slide tracks are calculated using an APDL script which is inserted as a command object
Creating Slide Tracks using APDL

Choose location of the “pen”
Get the node number for the pen location
Track the node during the transient cycle
Report \((x,y,z)\) vs time for the node at the end of simulation
Use point locations to create keypoints
Join keypoints to form a spline
Display the spline with initial geometry to see the slide tracks
Slide Tracks on the Cup - Walking Profile

Side of cup

Top of cup
Slide Tracks on the Cup - Cycling Profile

Side of cup

Top of cup
Slide Tracks on the Cup
- Walking Forces

Slide track with time-step locations

Force vs time data

- MediolateralForce
- ProximoDistalForce
- AnteroPosteriorForce
Slide Tracks on the Cup - Walking Forces

Slide track with time-step locations

Force vs time data

- MediolateralForce
- ProximoDistalForce
- AnteroPosteriorForce
Slide Tracks on the Cup - Kinematics

Side of cup

Top of cup
Archard’s Law defines the effect of sliding distance \( (v) \) and contact pressure \( (\sigma) \) on the per cycle wear depth \( (w) \):

\[
w(\phi, \theta) = \int_{cycle} k \times \sigma(\phi, \theta, t) \times v(\phi, \theta, t) dt
\]

Which can be approximated as:

\[
w = \sum_{cycle} k_w \times \sigma \times S
\]

- \( k_w \) is the wear coef. (which is material and surface dependent) = 1.066E-6
- \( \sigma \) is the contact stress, and
- \( S \) is the sliding distance
Cumulative Wear (after 1 cycle)

walking

wear depth reported in (mm)

cycling
Validation - Clinical Data


![Graph 1](image1.png)

**Fig. 2** Relationship between the rate of volumetric wear and femoral head radius

![Graph 2](image2.png)

**Fig. 3** Relationship between the rate of linear wear (penetration) and femoral head radius
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Pharmacokinetic (PK) Modeling

- PK models utilize a compartmentalized approach to model drug distribution in the body over time. The compartments represent organs and other drug depots.

- PK models simulate drug/chemical:
  - Absorption
  - Distribution
  - Metabolism
  - Excretion

- Coupling the PK model to the drug delivery model enables the designer to further refine the delivery system to work together with the human body, understand dependence on patient variability, disease state, etc.
Transdermal Delivery Model

The system consists of a cylindrical patch applied to the skin. The drug reservoir (in the patch) contains a mixture of drug and permeation enhancer. Diffusion is the only mode of transport out of the patch and through the skin. The far boundary of the skin is the inlet to the microcirculation, which acts as a drug sink.

- Two boundary conditions are tested at the far wall:
  1. zero flux condition – which assumes the plasma is an infinite sink
  2. PK condition – to account for drug build-up in plasma
### Transdermal Model Details

**Axisymmetry is assumed**

**Drug and enhancer are modeled as user-defined scalars in FLUENT**

**A transient diffusion equation models transport through the skin and patch:**

\[
\frac{\partial c_i}{\partial t} = \nabla \cdot (D_i \nabla c_i)
\]

, where \(i = \text{drug}, \text{permeation enhancer}\)

- **The interfacial conditions at the patch-skin interface are continuity of flux and a partitioning (jump) condition:**

\[
D_{i,\text{patch}} \nabla c_{i,\text{patch}} = D_{i,\text{skin}} \nabla c_{i,\text{skin}}
\]

\[
c_{\text{drug,skin}} / c_{\text{drug,patch}} = K , \text{ where } K \text{ is the partition coefficient}
\]
The permeation enhancer increases the drug flux through the skin. The level of enhancement is typically a function of the local enhancer concentration. Two typical situations are:

\[ D_{\text{drug,skin}} = D_{\text{drug,0}} + \mu C_{\text{pe}} \]

\[ K_{\text{drug,skin}} = K_{\text{drug,0}} + \eta C_{\text{pe}} \]

The permeation enhancer increases the diffusivity of drug in the skin

The permeation enhancer increases drug solubility in the skin

-\( \mu \) increasing

-\( \eta \) increasing
Validation Case - Fentanyl Patch, No PK Model

Rim et al. examined the effect of enhancement type on drug flux. These plots compare FLUENT results to their experimental and computational results.

flux when $D_{drug} = f(C_{enhancer})$

flux when $K = f(C_{drug})$

Pharmacokinetic (PK) Analysis of a Fentanyl Patch

MOTIVATION: Understand/optimize patch performance by including the physiologic processing of drug.

- Patch model extensions:
  - BC between epidermis and dermal vasculature:
    \[-D \frac{\partial c}{\partial z} = P \cdot [c(t) - f_u \cdot C_p(t)]\]
  - The ODE's for the three compartment PK model are:

    **plasma:**
    \[\frac{dC_p}{dt} = \nu \cdot [c(t) - f_u \cdot C_p(t)] - [k_{el} + k_{12} + k_{13}] \cdot C_p(t) + k_{21} \rho_2 C_2(t) + k_{31} \rho_3 C_3(t)\]

    **well-perfused compartment:**
    \[\frac{dC_2}{dt} = k_{12} C_p(t) / \rho_2 - k_{21} C_2(t)\]

    **poorly perfused compartment:**
    \[\frac{dC_3}{dt} = k_{13} C_p(t) / \rho_3 - k_{31} C_3(t)\]
Pharmacokinetic (PK) Analysis of a Fentanyl Patch

**MOTIVATION:** Understand/optimize patch performance by including the physiologic processing of drug.

- Patch model extensions:
  - Peripheral compartment
  - Central compartment
  - Third compartment

**ODE's for the three compartment PK model:**

\[\frac{dC_1}{dt} = k_{21} C_2 - k_{12} C_1 + \rho_{pel} \cdot \frac{dC_1}{dC_1} \]

\[\frac{dC_2}{dt} = k_{12} C_1 - k_{31} C_2 + \rho_{pup} \cdot \frac{dC_2}{dC_2} \]

\[\frac{dC_3}{dt} = k_{31} C_2 - \rho_{plasma} \cdot \frac{dC_3}{dC_3} \]

\[C_p(t) = \int_{0}^{t} \frac{dC_3}{dC_3} dt\]

- Well-perfused compartment
- Poorly perfused compartment
- Plasma compartment
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Hyperthermia cancer treatment used to accelerate effects of chemotherapy

RF power applied to tumor using phased array antenna

- Eight strip dipole antennas connected in parallel pairs and printed on inner surface of cylindrical plastic shell
HFSS Model of RF Phased Array Applicator

Device operates at 138 MHz

- Element excitations optimized to concentrate power inside tumor
Electromagnetic power is a function of time:
- 28 W used to reach desired temperature and 9 W to maintain temperature

Transient analysis used to determine temperature rise inside tumor:
- Reaches 47° C in 6 minutes and is maintained there for 14 minutes
Closing Remarks

Coupling detailed simulations to lumped parameter models can provide more rigorous prediction of device performance.
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V&V is possible.
Closing Remarks

ANSYS provides flexible and open solutions that can be adapted to solve even the most challenging problems facing the biomedical engineers of today.

The ANSYS vision for this industry includes collaborating with other software vendors to enable one-way and/or cosimulation with the highest fidelity models available.