Ecoles Polytechniques Fédérales de Lausanne
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How Softness Contributes to Human Dexterity


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Why human dexterity

Humans exhibit outstanding dexterity

Science
 source of dexterity

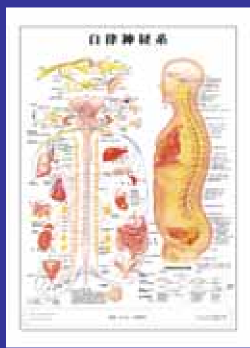
Engineering
 dexterous hands

Background (1/3)

Humans exhibit outstanding dexterity

What's the sources of dexterity
- brain-nerve system
- binocular eyes
- tactile receptors
- else?

Background (2/3)



Brain-nerve system

 delay in signal transmission (30 – 50 ms)

Why humans can manipulate objects despite of delay?

Background (3/3)

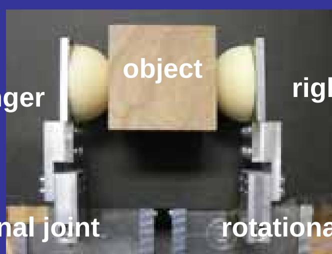
Human finger
 soft fingertip
 hard fingernail on the reverse side

Differs from animals

Does this structure contribute to dexterity?

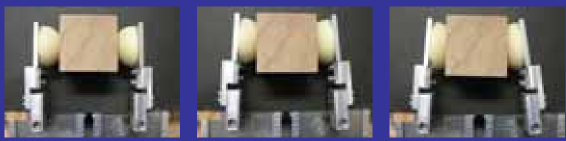
Observations (1/4)

Ability of a pair of 1-DOF fingers with hemispherical soft tips and hard back plates



Observations (2/4)

move two fingertips inward

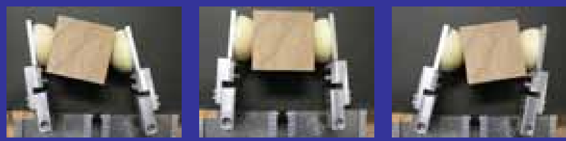


small deformation (grasping force) → large deformation (grasping force)

Can control grasping force

Observations (3/4)

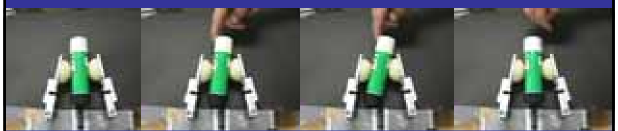
rotate two fingertips in the same direction



Can control object posture

Observations (4/4)

Fix two fingers and apply external force to pinched object



Object rotates without slip

Findings from observations

A pair of 1-DOF fingers with soft tips

can control grasping force and object posture independently

against Arimoto et al.'s claim

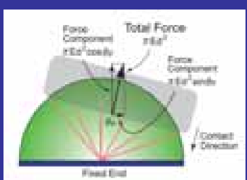
grasped object can rotate even if the two fingers are fixed

Model compatible with the observations

Modeling (1/7)

Arimoto et al.

A pair of 1 DOF fingers cannot control object posture

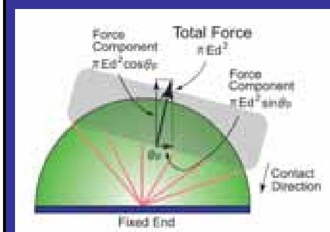


Discrepancy between the observation and the claim

Based on radially distributed model

Modeling (2/7)

Radially distributed model



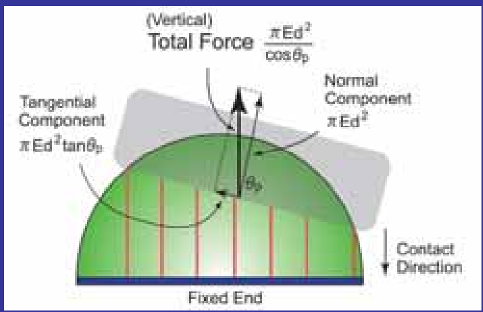
Contact force passes the center of hemisphere

Two fingertips cause non-zero moment around the object

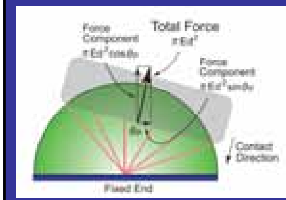
The 3rd DOF to cancel out the moment

Modeling (3/7)

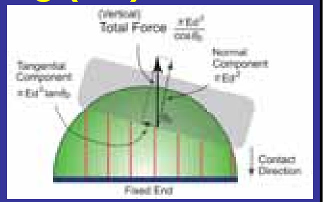
Parallel distributed model



Modeling (4/7)



radial



parallel

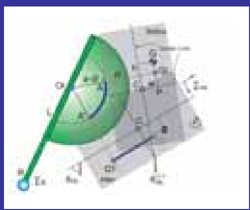
$$F_{\mathrm{radial}} = \pi E d^2$$

$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

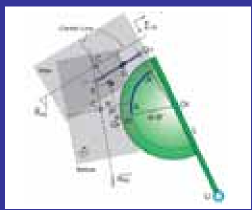
Force depends on object posture

Modeling (5/7)

Rolling constraints



left fingertip

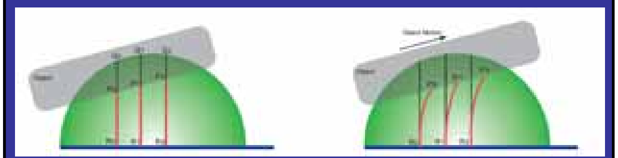


right fingertip

Object posture is unique (the object cannot rotate) when two fingers are fixed

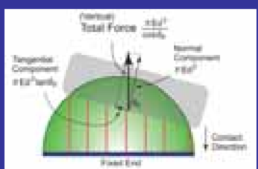
Modeling (6/7)

Parallel distributed model
with **tangential deformation**



$$F_{\mathrm{tangent}} = 2\pi E d d_{\mathrm{t}}$$

Modeling (7/7)

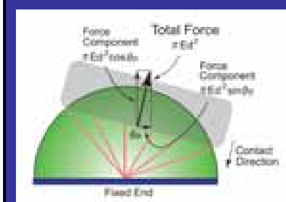


$$U_{\mathrm{parallel}}(d, d_{\mathrm{t}}, \theta_{\mathrm{p}}) = U_{\mathrm{perp}}(d, \theta_{\mathrm{p}}) + U_{\mathrm{tangent}}(d, d_{\mathrm{t}}, \theta_{\mathrm{p}})$$

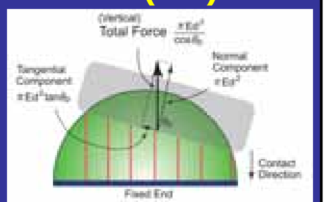
$$U_{\mathrm{perp}}(d, \theta_{\mathrm{p}}) = \frac{\pi E d^3}{3\cos^2\theta_{\mathrm{p}}}$$ normal

$$U_{\mathrm{tangent}}(d, d_{\mathrm{t}}, \theta_{\mathrm{p}}) = \pi E\{d^2 d_{\mathrm{t}} \tan\theta_{\mathrm{p}} + d d_{\mathrm{t}}^2\}$$ tangential

Model verification (1/2)



radial



parallel

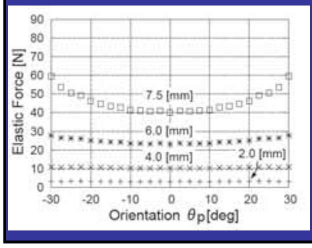
$$F_{\mathrm{radial}} = \pi E d^2$$

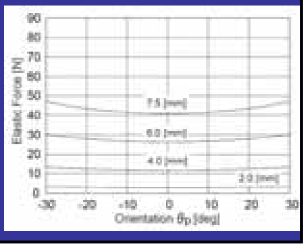
$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

Examine if force depends on object posture

Model verification (2/2)

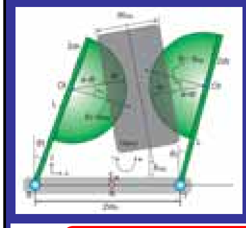
parallel model





Experiment

Simulation (1/3)



dynamic simulation based on Lagrange formulation

kinetic and potential energies

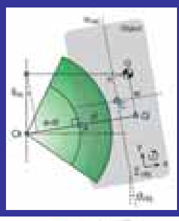
object

left fingertip   right fingertip

$$T = \frac{1}{2}m_{\mathrm{obj}}(\dot{x}_{\mathrm{obj}}^2 + \dot{y}_{\mathrm{obj}}^2) + \frac{1}{2}I_{\mathrm{obj}}\dot{\theta}_{\mathrm{obj}}^2 + \frac{1}{2}I_{\mathrm{finger}}\dot{\theta}_1^2 + \frac{1}{2}I_{\mathrm{finger}}\dot{\theta}_2^2$$

$$U = U_{\mathrm{parallel}}(d_{\mathrm{n}1}, d_{\mathrm{t}1}, \theta_1 - \theta_{\mathrm{obj}}) + U_{\mathrm{parallel}}(d_{\mathrm{n}2}, d_{\mathrm{t}2}, \theta_2 + \theta_{\mathrm{obj}}) + m_{\mathrm{obj}}g y_{\mathrm{obj}}$$

Simulation (2/3)



normal constraints (holonomic)

$$C_1^{\mathrm{H}} \triangleq -(x_{\mathrm{obj}} - O_{1x})C_{\mathrm{obj}} - (y_{\mathrm{obj}} - O_{1y})S_{\mathrm{obj}} - (a - d_{\mathrm{n}1}) + \frac{W_{\mathrm{obj}}}{2} = 0$$

rolling constraints (non-holonomic)

$$C_1^{\mathrm{N}} \triangleq G\dot{Q}_1 + a(\dot{\theta}_1 - \dot{\theta}_{\mathrm{obj}}) + \dot{d}_{1\mathrm{t}} = 0$$

Simulation (3/3)

Lagrangean $\mathcal{L} = T - U + \lambda_1^{\mathrm{H}}C_1^{\mathrm{H}} + \lambda_2^{\mathrm{H}}C_2^{\mathrm{H}}$

holonomic

non-holonomic

object

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{x}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial x_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{x}_{\mathrm{obj}}}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{y}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial y_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{y}_{\mathrm{obj}}}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial \theta_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{\theta}_{\mathrm{obj}}}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

fingers

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_1} - \frac{\partial \mathcal{L}}{\partial \theta_1} = \frac{\partial}{\partial \dot{\theta}_1}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_2} - \frac{\partial \mathcal{L}}{\partial \theta_2} = \frac{\partial}{\partial \dot{\theta}_2}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

fingertips

normal

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{d}_1} - \frac{\partial \mathcal{L}}{\partial d_{\mathrm{n}1}} = \frac{\partial}{\partial \dot{d}_1}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

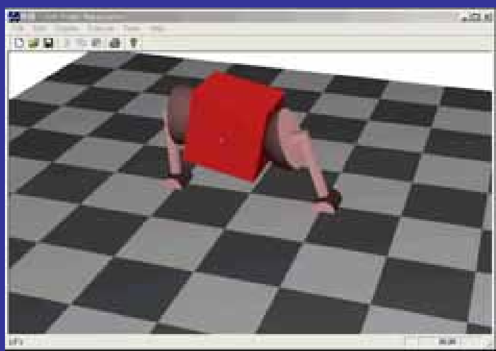
$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{d}_2} - \frac{\partial \mathcal{L}}{\partial d_{\mathrm{n}2}} = \frac{\partial}{\partial \dot{d}_2}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

tangential

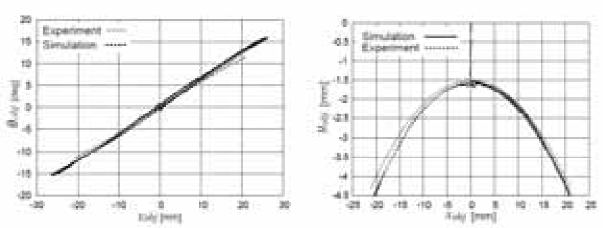
$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{d}_{1\mathrm{t}}} - \frac{\partial \mathcal{L}}{\partial d_{\mathrm{t}1}} = \frac{\partial}{\partial \dot{d}_{1\mathrm{t}}}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathcal{L}}{\partial \dot{d}_{2\mathrm{t}}} - \frac{\partial \mathcal{L}}{\partial d_{\mathrm{t}2}} = \frac{\partial}{\partial \dot{d}_{2\mathrm{t}}}\{\lambda_1^{\mathrm{N}}C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}}C_2^{\mathrm{N}}\}$$

Simulation (3/3)



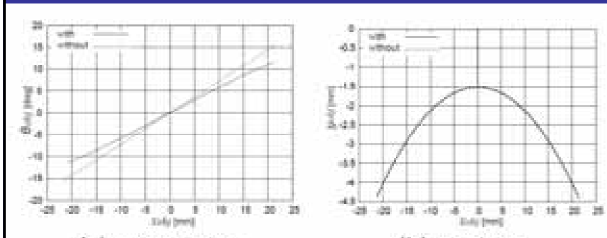
Comparison (1/2)



(a) orientation (b) position

simulation vs experiment

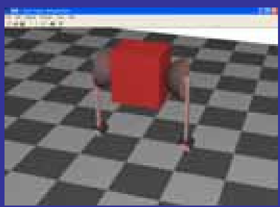
Comparison (2/2)



(a) orientation (b) position

with / without tangential deformation

Response to external force

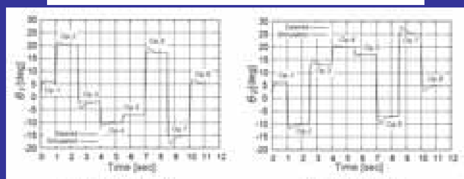


Object rotates without slip as observation

Robust against external force

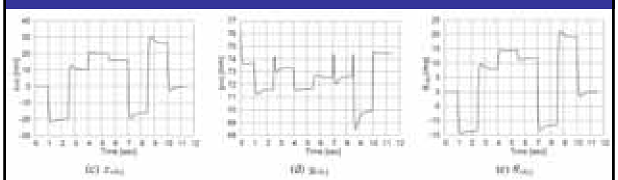
Finger joint angle control (1/2)

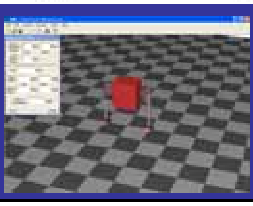
initial state	both fingers grasp an object in parallel
motion 1	$(\theta_1^d, \theta_2^d) = (6\,\text{deg}, 6\,\text{deg})$
motion 2	$(\theta_1^d, \theta_2^d) = (20\,\text{deg}, -10\,\text{deg})$
motion 3	$(\theta_1^d, \theta_2^d) = (-2\,\text{deg}, 13\,\text{deg})$
motion 4	$(\theta_1^d, \theta_2^d) = (-10\,\text{deg}, 20\,\text{deg})$
motion 5	$(\theta_1^d, \theta_2^d) = (-7\,\text{deg}, 17\,\text{deg})$
motion 6	$(\theta_1^d, \theta_2^d) = (17\,\text{deg}, -7\,\text{deg})$
motion 7	$(\theta_1^d, \theta_2^d) = (-15\,\text{deg}, 25\,\text{deg})$
motion 8	$(\theta_1^d, \theta_2^d) = (5\,\text{deg}, 5\,\text{deg})$



(a) right finger joint (b) left finger joint

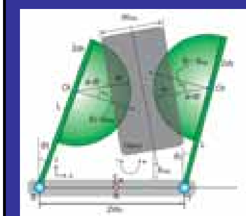
Finger joint angle control (2/2)





Object motion is stabilized without any feedback of object information

Radial vs parallel models



Sum of two fingertip potential energies around equilibrium point with two joints fixed

Radial model --- saddle point

Parallel model --- local minimum
no continuous feedback needed

Rigid vs. soft fingertips

rigid fingertips

soft fingertips

stable grasping	A pair of 1-DOF fingers (2DOF)	A single 1-DOF finger (1DOF)
stable grasping & posture control	1 DOF and 2-DOF fingers (3DOF)	A pair of 1-DOF fingers (2DOF)

Discussion (1/2)

- Parallel distributed model
  - with tangential deformation
  - meets observations
- Experimental model verification
  - force magnitude depends on
  - object posture
- Dynamics of manipulation process
  - simulation and experiment
  - validate parallel model

Discussion (2/2)

- Finger joint angle control
  - object motion is stabilized
  - without object information
- Response to external force
  - meets observations
  - robust against external force

Fingertip model

Is our theory applicable to human manipulation?

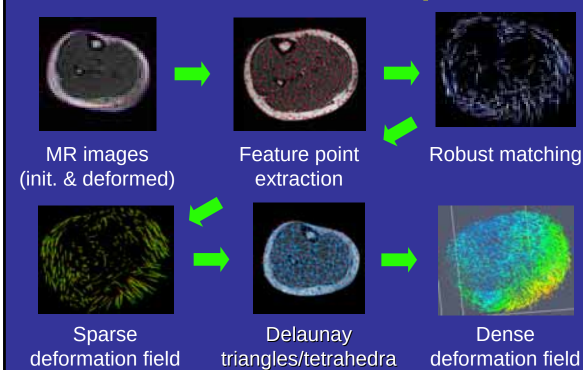
Need to measure **inner deformation** of fingertips

Inner deformation

Compute deformation field from MR images before and after deformation

Estimate non-uniform physical parameters from deformation field

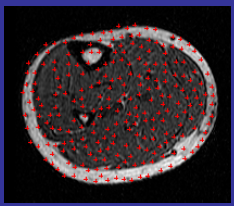
Deformation field computation



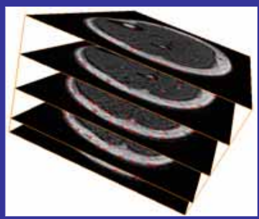
Extracting feature points

3D Harris operator

$$\mathbf{M} = \begin{pmatrix} I_x^2 & I_xI_y & I_xI_z \\ I_xI_y & I_y^2 & I_yI_z \\ I_xI_z & I_yI_z & I_z^2 \end{pmatrix}$$



Feature points in one slice



Feature points distributed in layered slices

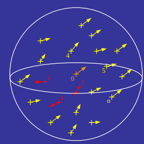
Robust matching

Candidate generation

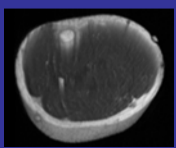
Obtain a set of many-to-many candidate matches using correlation score

Consistency check

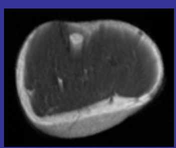
Eliminate false matches so that candidate matches be globally consistent based on energy function



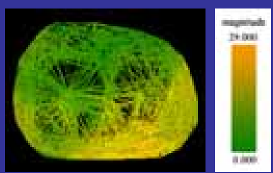
Result



Initial volume (human calf)



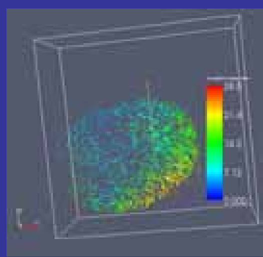
deformed volume



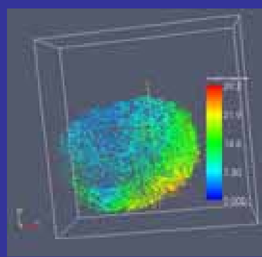
Deformation magnitude at the node of FE model

Points in initial volume	1000
Points in deformed volume	5000
Node numbers	771
Tetrahedrons	4344

Result



Deformation Field (10,000 points)

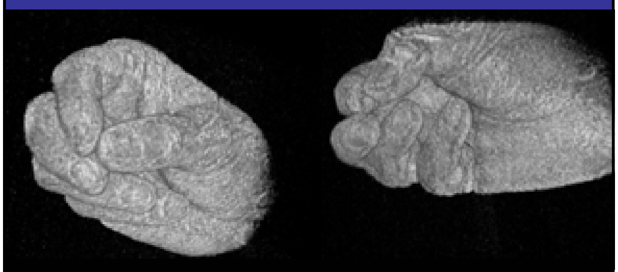


Deformation Field (30,000 points)

Ongoing Issues

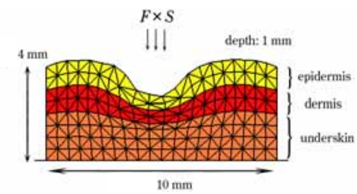
- **Measuring fingertip deformation during human manipulation**
- **Simulation of skin deformation**
- **Identification of physical parameters**

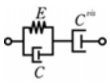
Measuring human fingertips



pinch motion **pen grasp**

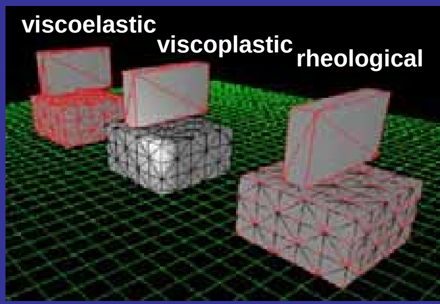
Simulating skin deformation



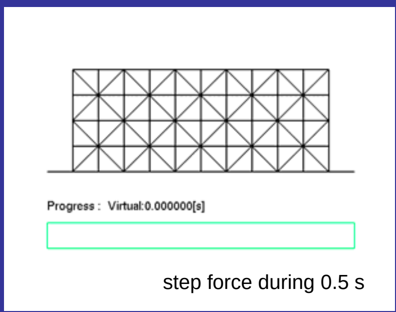


	Epidermis	Dermis	underskin
Young's modulus E	136000	80000	34000
Viscous modulus C	*	*	*
Viscous modulus C^{vis}	300000	300000	300000
Poisson's ratio	0.48	0.48	0.48

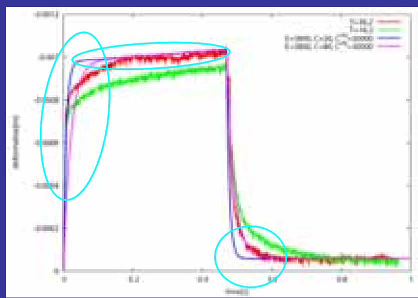
Elastic-plastic deformation



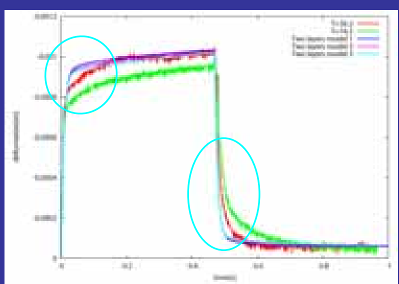
Simulating skin deformation



1-layered model

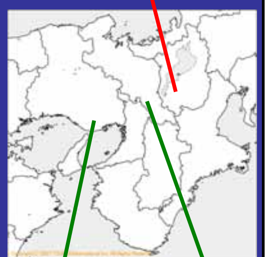


multi-layered model



20min from Kyoto
70min from Kobe
by local train

Kusatsu
aside of Lake Biwa



Kobe
ICRA2009

Kyoto

Thank you for your attention