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 source 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

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
left finger
rotational joint
right finger
rotational joint
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)

\[ F_{\text{radial}} = \pi Ed^2 \]
\[ F_{\text{perp}} = \frac{\pi Ed^2}{\cos \theta_p} \]
Force depends on object posture

Modeling (5/7)
Rolling constraints

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

Modeling (6/7)
Parallel distributed model with tangential deformation

\[ F_{\text{tangent}} = 2\pi Edd_t \]

Modeling (7/7)

\[ U_{\text{parallel}}(d, \theta_1, \theta_p) = U_{\text{perp}}(d, \theta_p) + U_{\text{tangential}}(d, \theta_1, \theta_p) \]
\[ U_{\text{perp}}(d, \theta_p) = \frac{\pi Ed^2}{3 \cos \theta_p} \]
\[ U_{\text{tangential}}(d, \theta_1, \theta_p) = \pi E(d'd_1 \tan \theta_p + dd_t^2) \]

Model verification (1/2)

Examine if force depends on object posture
**Simulation (1/3)**

Dynamic simulation based on Lagrange formulation kinetic and potential energies

\[
T = \frac{1}{2} m_{\text{obj}} (\dot{x}_{0b}^2 + \dot{y}_{0b}^2) + \frac{1}{2} I_{\text{obj}} \dot{\theta}_{0b}^2 + \frac{1}{2} I_{\text{finger}} \dot{\theta}_f^2 + \frac{1}{2} I_{\text{finger}} \dot{\theta}_2^2
\]

\[
U = U_{\text{parallel}}(d_{11}, d_{41}, \theta_1, \theta_{0b}) + U_{\text{parallel}}(d_{12}, d_{42}, \theta_2, \theta_{0b}) + m_{\text{obj}} g h_{0b}
\]

**Simulation (2/3)**

Normal constraints (holonomic)

\[
C^h \equiv -(x_{0b} - O_x) \dot{y}_{0b} - (y_{0b} - O_y) \dot{x}_{0b} - (n - d_n) \frac{W_{\text{obj}}}{2} = 0
\]

Rolling constraints (non-holonomic)

\[
C^n \equiv \dot{Q}_1 + a(\theta_1 - \theta_{0b}) + d_n = 0
\]

**Simulation (3/3)**

Lagrangian

\[
\mathcal{L} = T - U + \lambda^T \epsilon^c + \lambda^T \epsilon^f
\]

Object

- Holonomic
- Non-holonomic

Fingers

- Normal
- Tangential

Fingertips

- Normal
- Tangential

Experiment

Parallel model
Comparison (1/2)

Simulation vs experiment

(a) orientation  (b) position

Comparison (2/2)

With / without tangential deformation

(a) orientation  (b) position

Response to external force

Object rotates without slip as observation
Robust against external force

Finger joint angle control (1/2)

Finger joint angle control (2/2)

Object motion is stabilized without any feedback of object information

Finger joint angle control (1/2)

Finger joint angle control (2/2)

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

<table>
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<tr>
<th>stable grasping</th>
<th>A pair of 1-DOF fingers (2DOF)</th>
<th>A single 1-DOF finger (1DOF)</th>
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</thead>
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<tr>
<td>stable grasping &amp; posture control</td>
<td>1 DOF and 2-DOF fingers (3DOF)</td>
<td>A pair of 1-DOF fingers (2DOF)</td>
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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

MR images $\Rightarrow$ Feature point extraction $\Rightarrow$ Robust matching

MR images (init. & deformed) $\Rightarrow$ Delaunay triangles/tetrahedra $\Rightarrow$ Dense deformation field
**Extracting feature points**

- 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

**Deformation Field**

- 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

Elastic-plastic deformation

viscoelastic
viscoplastic
rheological

Simulating skin deformation

1-layered model

20min from Kyoto
70min from Kobe
by local train

Kusatsu
aside of Lake Biwa

Kansai area

multi-layered model
Thank you for your attention