APPROACHING HUMAN HAND DEXTERITY THROUGH HIGHLY BIOMIMETIC DESIGN

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Yale University
Magician's Hand Manipulation Tricks

Magician Peter Pitchford

http://www.magicbymanipulation.com/
Why Anthropomorphic Robotic Hands?

By choosing five-fingered robotic hand design, researchers want to easily transfer knowledge of dexterous hand movements from human to robot.
Using Brain to Control Anthropomorphic Robotic Hands

Cortical homunculus shows how human brain sees the body from the inside

Introduction

(Principles of Neural Science, 4th Edition)
Autonomous Control of Anthropomorphic Robotic Hands

Movement Control Lab, University of Washington (Mordatch et al., 2014)

Introduction
Tele-manipulation: A Practical Way to Extract Hand Dexterity from Brain
The Anatomically Corrected Test-Bed (ACT) Hand

Mimics:
- Bone structure
- Tendon routings
- Joint DOFs
- Muscles
  - 6 motors the fingers
  - 8 motors for thumb
  - 4 motors for wrist

Introduction
Thumb Flexion Motion of The ACT Hand
Important Biomechanical Features Need to Be Mimicked

Introduction

http://www.wisegeek.org/
The Conventional Mechanical Joint Used inside The ACT Hand

Typical mechanizing process
The Common Mechanical Analogy of The CMC Joint

Introduction

The trapezium bone (cam)

The first metacarpal bone (follower)
The Common Mechanical Analogy of The CMC Joint

Introduction
The Shapes Of The Bones Decide The Basic Kinematics of The Human Hand

Trapezium bone of the human thumb

Unfixed joint axes (Crisco et al., 2015)
Our Approach

Our highly biomimetic design truthfully matches kinematics of the human hand

(Xu and Todorov, 2016)
Outline

- Introduction
- **Important Hand Biomechanics**
- Design & Prototype
- Perspective on Broader Impacts & Future Work
Human Hand Anatomy

Bones    Ligaments    Tendon and muscles    Blood vessel & nerves    Skin

Important Hand Biomechanics
Bones

- Contains 27 bones with 8 small wrist bones
- Four fingers and one thumb
- The scaffold for the soft tissues
- Trapezium bone is crucial for thumb opposition
Articular Surfaces Decides Basic Kinematics and Distributes Stress Better

Amy L. Ladd (2010)

Halilaj et al. (2013)

Important Hand Biomechanics
Joint ligaments

- The collateral joint ligaments – prevent abnormal sideways bending
- The volar plate -- prevents hyperextension
- Stabilize the finger joints by forming the joint capsule
- The joint capsule shapes the ROM of the finger

Important Hand Biomechanics
Biological Joint Requires Less Parts

Human thumb
(Cam-follower CMC joint with 2 parts)

Thumb of the ACT Hand
(Linkage CMC Joint with 3 parts)

Important Hand Biomechanics

Human Hand Anatomy

Bones  Ligaments  Tendon and muscles  Blood vessel & nerves  Skin

Important Hand Biomechanics
The Extensor & Flexor Tendons -- The Transmission System

- The transmission system of human hand
- Finger straightens – pull the extensor tendons
- Finger bends – pull the flexor tendons
- Contain built-in mechanical advantages.

Important Hand Biomechanics
The Gliding Mechanism of The Extensor Hood

- A thin web-structure
- Capable of changing shapes during different finger movements
- Smartly regulating joint torques during finger extension and flexion motions.

Important Hand Biomechanics
The Bulging Process of The Tendon Sheaths

Tendon sheaths (The pulleys)

Flexor tendon

Flexor tendon sheaths

Schematic showing the bulging effect

Important Hand Biomechanics
Summary of The Important Hand Biomechanics

- **Biological finger joint**
  - **Bones**
    - Demines the basic kinematics of finger movements
  - **Joint ligaments**
    - Contributing to built-in compliance and shapes the ROM of each finger joint

- **Biomechanical transmission**
  - **Gliding mechanism of the extensor hood**
    - Regulating both extension and flexion torques at finger joints
  - **Bulging Tendon Sheaths**
    - Regulating flexion torques at finger joints
Outline

- Introduction
- Important Hand Biomechanics
- Design & Prototype
- Perspective on Broader Impacts & Future Work
Design & Prototype

- Artificial joint
- Biomimetic transmission
- Whole hand integration
Design And Prototyping Process of the Artificial Joint

(Xu et. Al., 2011)
System Identification of The Artificial MCP Joint

- Two thicknesses of the silicon rubber sleeve:
  - Thin – 1.5 mm
  - Thick – 2.0 mm

- Effect of external weights:
  - Unloaded
  - Loaded – 7.5g mass

- 120 manual perturbations at ~1 Hz
  - 2 Human
  - 4 Artificial

- Motion capture system at 480 Hz using a 7-camera system
Modeling of The Artificial MCP Joint

\[ \ddot{\theta} = -k - b \dot{\theta} + a_0 + a_1 \cos(\theta) + a_2 \sin(\theta) + c_1 \psi + c_2 \theta^2 + c_3 \dot{\theta}^2 \]

Where \[ \psi(t) = \int \tanh(\dot{\theta}(\tau))d\tau \]

<table>
<thead>
<tr>
<th>MCP joint of the index finger</th>
<th>Stiffness K (Nm/rad)</th>
<th>Damping B (Nms/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human joint</td>
<td>0.50 (averaged between -0.2 to 1 radians)</td>
<td>0.0142 (SD = 0.23)</td>
</tr>
<tr>
<td>Artificial joint</td>
<td>0.534 +/- 0.025 (95% confidence interval)</td>
<td>0.024 +/- 0.0003 (R^2 = 0.87)</td>
</tr>
</tbody>
</table>
Design of The Biomimetic Index Finger

Artificial Finger Joint

(Xu et. Al., 2012)
Design & Prototype

- Artificial joint
- Biomimetic transmission
- Whole hand integration
Crocheted Extensor Mechanism

- Compliant textile
- Withstand high tensile forces
- Can be made into any shape

Henderson and Taimina, (2001)
Testing The Mechanical Properties of The Crocheted Extensor Mechanism

(Xu et. Al., 2016)
Results of The Tensile Test

- 15N/mm found in the human wrist extensor.

Table 3.1: Comparison of mechanical properties between different crocheted conditions.

<table>
<thead>
<tr>
<th>Samples (n = number of the samples)</th>
<th>Ultimate load (N) Mean ± SD</th>
<th>Linear stiffness (N/mm)² Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single string (n=3)</td>
<td>109.3 ± 4.2</td>
<td>17.6 ± 4.6</td>
</tr>
<tr>
<td>Single crocheted chain (n=3)</td>
<td>249.5 ± 9.5</td>
<td>57.7 ± 7.9</td>
</tr>
<tr>
<td>Double crocheted chain (n=3)</td>
<td>292.2 ± 14.8</td>
<td>62.3 ± 13.8</td>
</tr>
<tr>
<td>Triple crocheted chain (n=3)</td>
<td>440.7 ± 150.4</td>
<td>61.8 ± 20.1</td>
</tr>
<tr>
<td>Type 1-branching (n=6)</td>
<td>260.1 ± 20.0</td>
<td>59.2 ± 14.0</td>
</tr>
<tr>
<td>Type 2-branching-middle (n =3)</td>
<td>277.4 ± 22.2</td>
<td>60.5 ± 13.3</td>
</tr>
<tr>
<td>Type 2-branching-side (n=6)</td>
<td>277.6 ± 15.6</td>
<td>56.2 ± 10.6</td>
</tr>
</tbody>
</table>

²Linear stiffness values of the crocheted samples are calculated from the linear region of the curves.

(Xu et. Al., 2016)
The Crocheted Extensor Hood On The ACT Hand

Biomimetic Transmission
Improved Design of The Extensor Hood & Tendon Sheaths

Biomimetic Transmission
Design & Prototype

- Artificial joint
- Biomimetic transmission
- Whole hand integration
Whole Hand Integration – Actuators

Table 7.1: The specifications of the Dynamixel servos.

<table>
<thead>
<tr>
<th>Dynamixel Servo Model</th>
<th>AX-12A</th>
<th>MX-12W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working voltage (V)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>No load speed (RPM)</td>
<td>59</td>
<td>470</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>254/1</td>
<td>32/1</td>
</tr>
<tr>
<td>Resolution (°)</td>
<td>0.29</td>
<td>0.088</td>
</tr>
<tr>
<td>Range of Motion (°)</td>
<td>300</td>
<td>360</td>
</tr>
<tr>
<td>Communication Speed</td>
<td>7343bps 1Mbps</td>
<td>8000 bps - 4.5 Mbps</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>55</td>
<td>54.6</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>32 × 40 × 50</td>
<td>32 × 40 × 50</td>
</tr>
</tbody>
</table>

(Xu and Todorov, 2015)
Whole Hand Integration – Data Glove

The string potentiometer unit
Evaluation
Outline

- Introduction
- Important Hand Biomechanics
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Hand Dexterity Is A Personal Property

“Regardless of the degree of training, not all musicians are capable of the same finger movements” (Watson, 2006)

Robotics -- Telemanipulation

Due to the one-to-one mapping of the kinematics, the telemanipulation process will also feature reduced cognitive load & easy programming.
Medical Research -- Scaffolds

Important biomechanical data can be physically preserved and then used to generate artificial scaffolds for limb regeneration research.
Future – Artificial Limb

by Scott McNutt
Future Work: 3-axis Fingertip Force Sensor

(Xu et al., 2014)