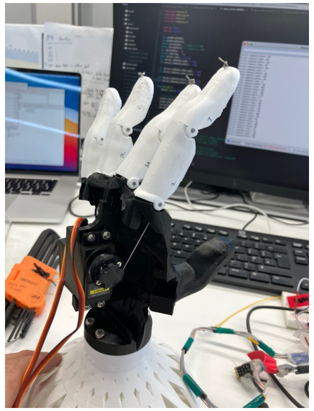
# WORKSHOP 6
# Human-Machine Interfacing and Mechatronics for Myoelectric Prosthetics

**Goal:** Explore from designing a bionic limb, assembling it, and implement a control system to control using sEMG

### 1st Day
### Build your bionic limb

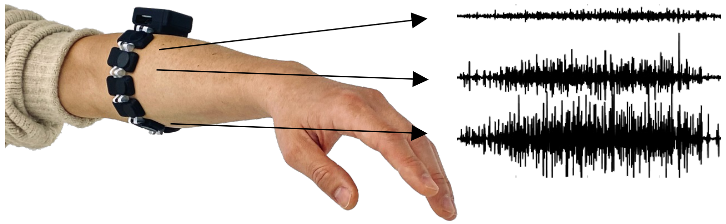
Fusion 360



**Lecture content (~20 min):**
- Generics on Bionic Limb reconstruction

**Task (~1h 30 min):**
- CAD (get an idea on how to design a bionic limb)
- Assemble simplified limb
- Actuate the hand by a code command

### 2nd Day
### Muscle interfacing technics



**Lecture content (~30 min):**
- Fundamental signal for motor control
- Interfacing with the Nervous system
- Feature extraction
- Data driven prosthesis control

**Task (~1h 30 min):**
- Implement an algorithm to create a 2DOF regressor

### 3rd Day
### Integration into online bionic limb control

**Task1 (~45min):**
- Online interfacing by using a neural interface device
- Exploration on different gestures and labels

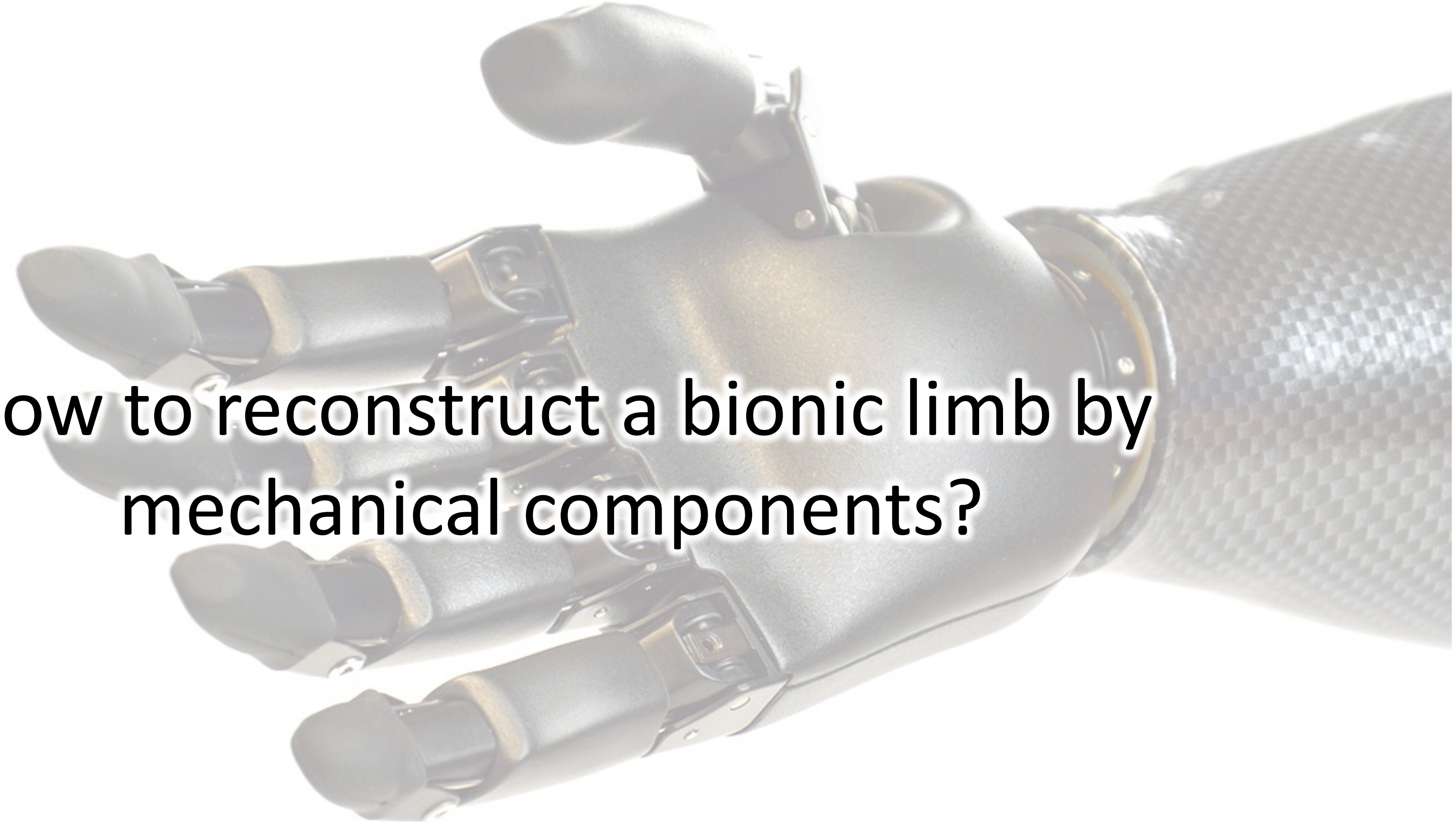
**Task2 (~45min):**
- Connect to a bionic hand and control by using your own muscle signals

**Wrap up and Q&A (30min)**

Imperial College London

# Generic on mechatronic design of prostheses

**Jumpei Kashiwakura**
Department of Bioengineering
Imperial Collage London

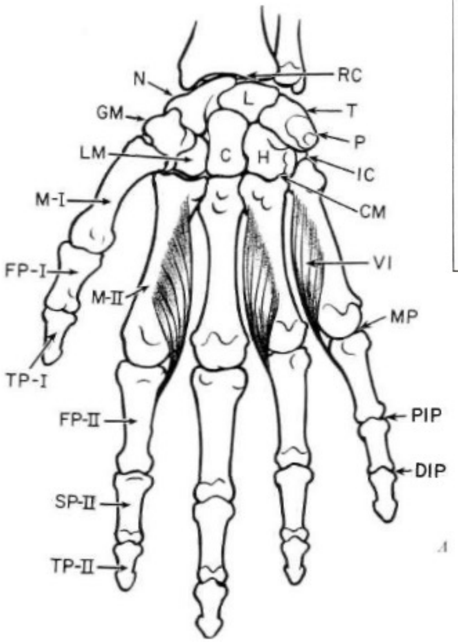


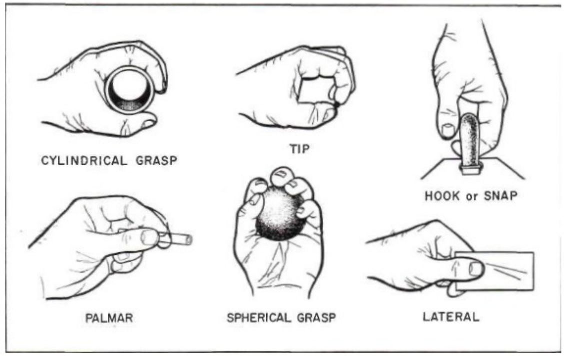
# How to reconstruct a bionic limb by mechanical components?

# Human’s natural limbs

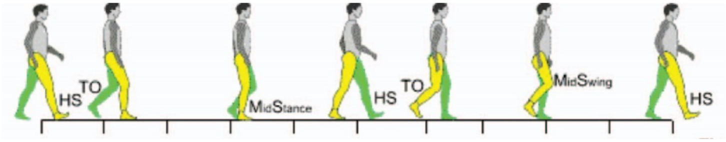
❖ Limb anatomy

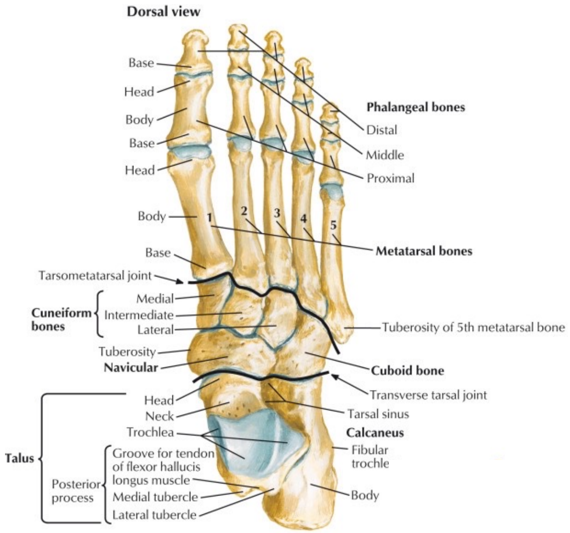
Upper limb




Lower limb




Natural limbs achieve complicated, rapid and high power while robust movements by numbers of bones, muscles, and DOF (>20)

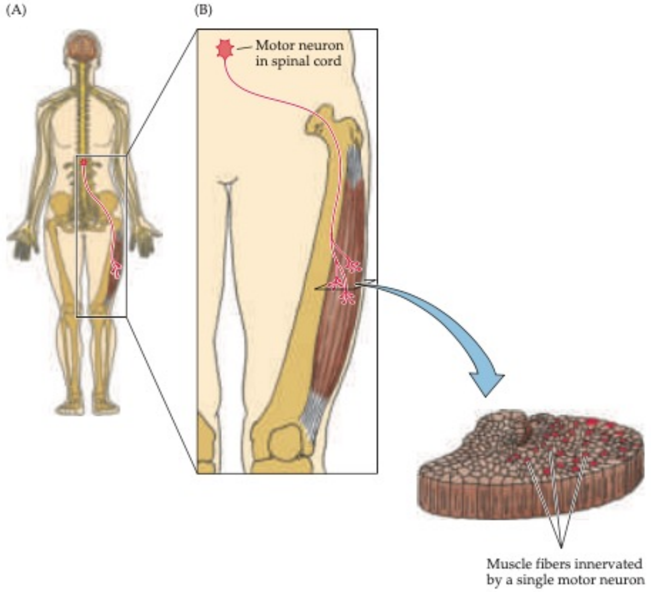
Taylor et al. 1955
Atlas of human anatomy, Elsevier

Antfolk et al. 2013

# Natural limb organs

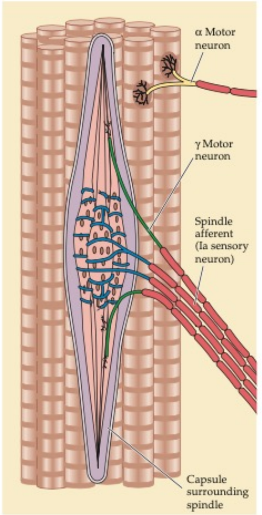
## ❖ Muscle

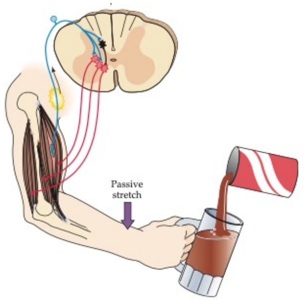
Single motor neuron to muscle fibers




Muscle spindle

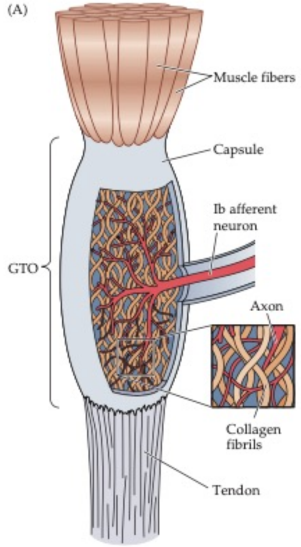
Motor and sensory neurons in a spindle (Proprioception)



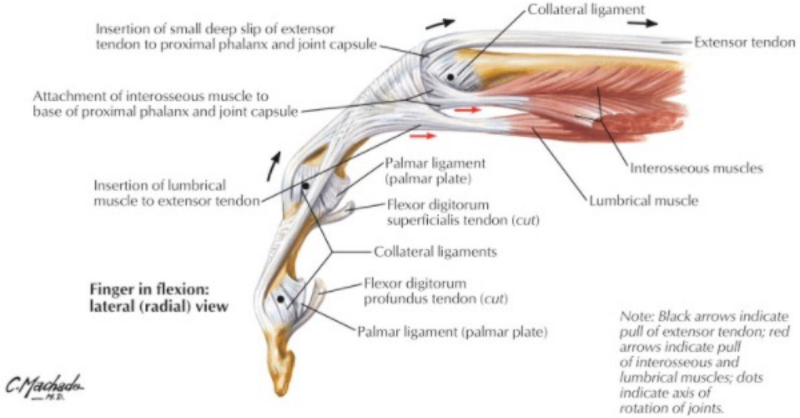

Golgi tendon organ

Junction of muscle and tendon (Proprioception)




## ❖ Tendons and ligaments

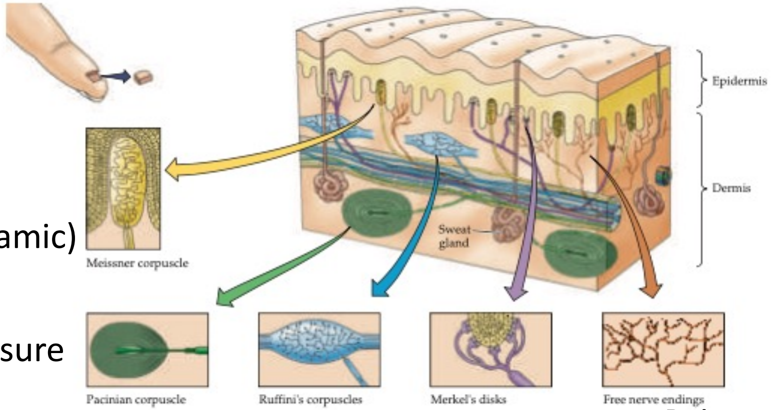
Movements achieved by the pull of tendons from muscle




## ❖ Somatic Sensory Receptors

Function

Touch, pressure(dynamic)




Deep pressure

Stretch

Touch, pressure(static)

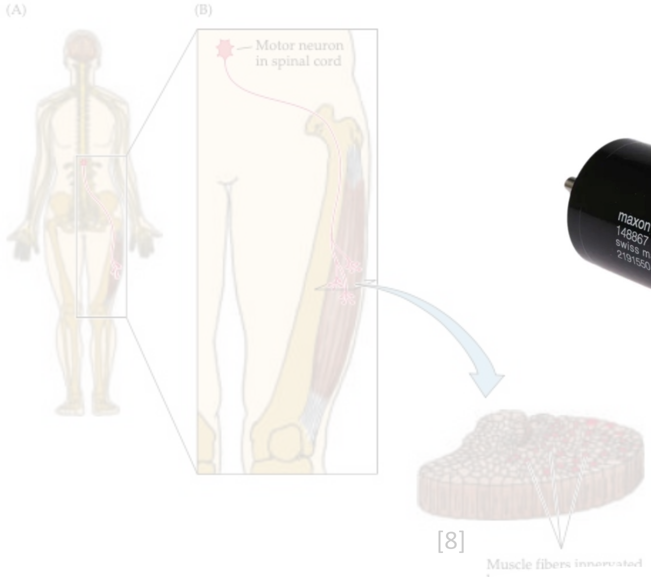
Pain, temperature

Neuroscience, Sunderland, Massachusetts U.S.A.

# Natural limb organs

❖ Muscle

Single motor neuron to muscle fibers



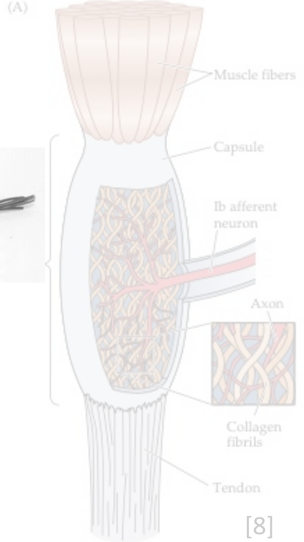

Muscle spindle

# Actuators

[8] [8]

Golgi tendon organ

Junction of muscle and tendon (Proprioception)



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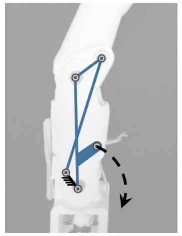
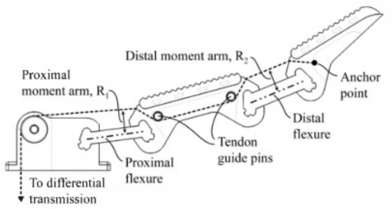
❖ Tend

Mov

# Torque transmission



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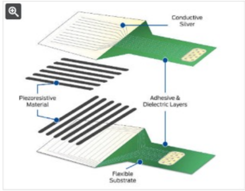
❖ Som ors

# Sensory devices

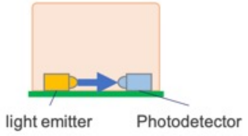
Function

Touch, pressu

Deep p







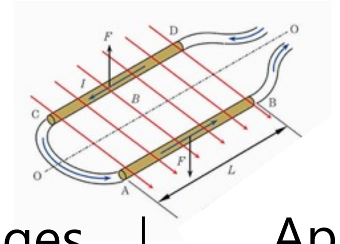

Pain, temperature

[7] Atlas of human anatomy, Elsevier [8] Neuroscience, Sunderland, Massachusetts U.S.A.

# Mechatronics details - Actuator 1/3

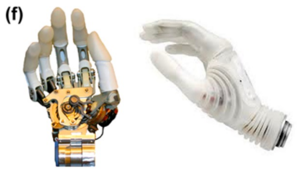
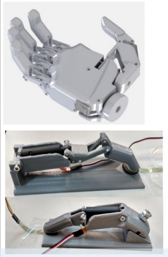
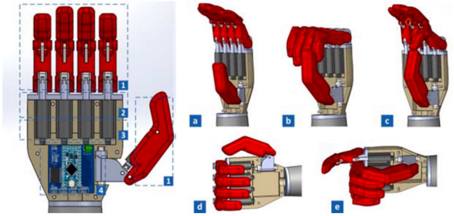
❖ Actuator

➢ **Motor**, Pneumatic, Others



Faraday's Law

$$F = BIL$$

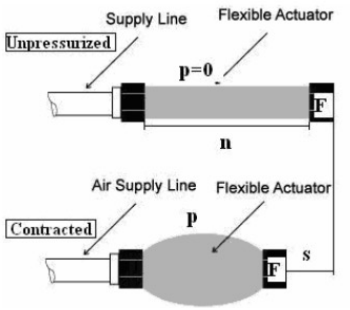
| Motor type | Advantages/Disadvantages | Application examples |
|---|---|---|
| DC/EC  | ✓ Small<br>✓ Various gear head combination<br>✓ High accuracy<br>✗ Need motor controller |   |
| Servo motor  | ✓ Cheap<br>✓ Easy to use (PWM)<br>✓ Assembled with gears<br>✗ Few varieties of torque<br>✗ Spacial<br>✗ Low accuracy |   |
| Linear actuator  | ✓ Direct force activation<br>✓ Easy to use (PWM)<br>✗ Cost ineffective<br>✗ Low accuracy |   |

**Widely used, cheap, various types depends on the needs**

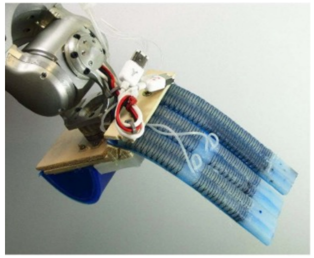
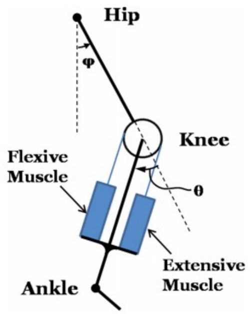
Michelangelo, Ottobock, Ossur, PROPRIO foot, Hero arm, Open bionics
HACKBerry, HACKBerry, Grau et al. 2019, Calderon-Cordova et al. 2017

# Mechatronics details - Actuator 2/3

- ❖ Actuator
- ➢ Motor, **<u>Pneumatic</u>**, Others




The inflatable tube decreases it's length (proportional to the compressed air), result in linear force

| Working fluid | Advantages/Disadvantages | Application examples |
|---|---|---|
| Air<br><br>Pneumatic air muscles (PAMs) | ✓ High compliant<br>(safe for human interaction)<br>✓ Light weight<br>✓ High power<br>✗ Non-linear activation<br>✗ Low accuracy |  <br> <br> |

*Liquid is less commonly used for prosthetic devices

**High robustness but low accuracy in position control**

PETRE et al. 2009, Deimel et al. 2013, Groenewegen et al. 2014, Waycaster et al. 2011

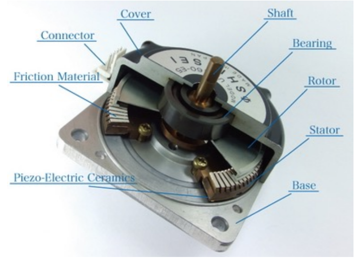
# Mechatronics details - Actuator 3/3

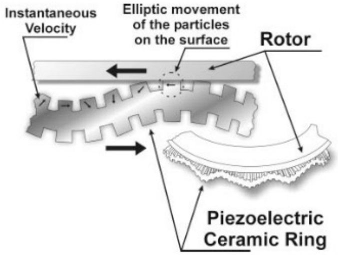
❖ Actuator

➢ Motor, Pneumatic, **Others**

| Actuator | Advantages /Disadvantages | Application examples |
|---|---|---|

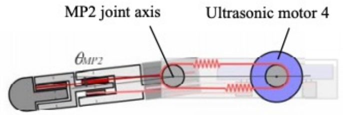
## Ultrasonic actuator




Actuates by a propagation wave in an elastic ring

✓ Small sized
✓ High power density
✓ Silent functioning
✗ Low durability
✗ High cost

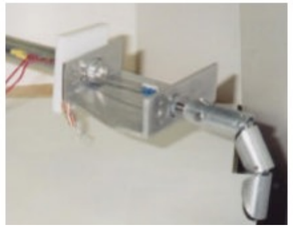


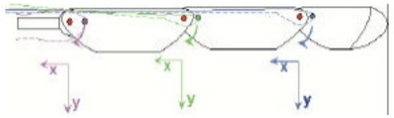

(a) Top view

## Shape Memory Alloy

Changes mechanical displacement through thermo-elastic transformation by heat

✓ Good strength-weight ratio
✓ Can be used in a form of wire
✗ High temperature required ($55℃ \ to \ 100℃$)
✗ Low operating frequency
✗ Nonlinear

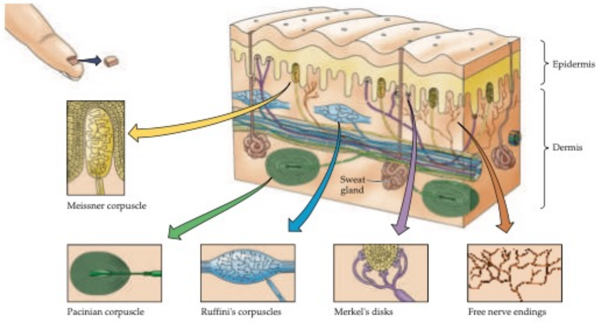




**Unique features but barriers remain to apply for prostheses**

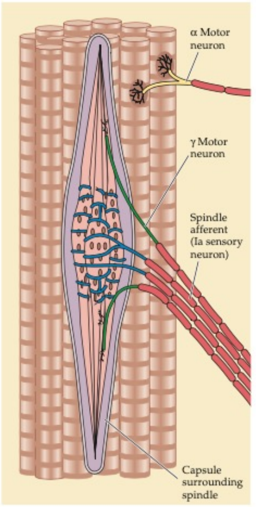
Yamano et al. 2005, DeLaurentis et al. 2000

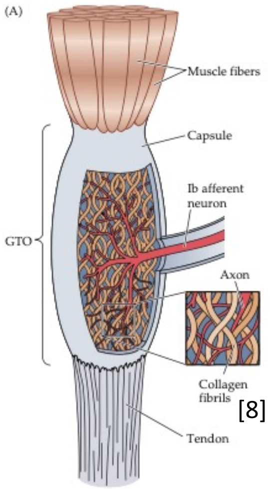
- ❖ Somatic Sensory Receptors




[8]

- ❖ Muscle spindle and Golgi tendon organ



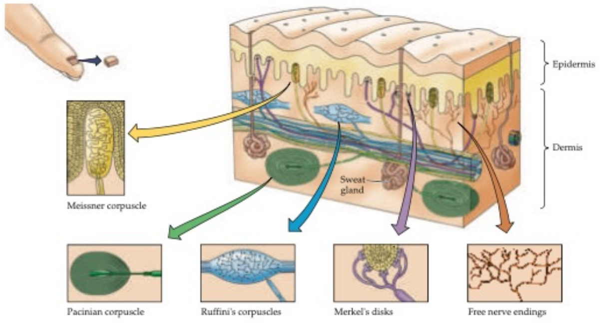

[8]

- ❑ Sensations from natural organs

- Touch
- Pressure (static, dynamic)
- Stretch
- Pain
- Temperature
- Proprioception

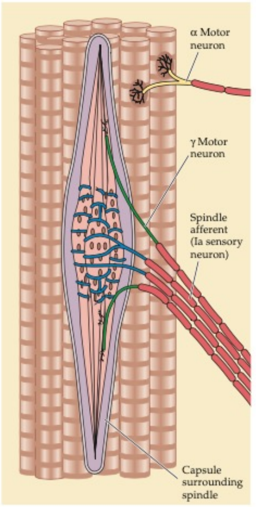
# Mechatronics details - Sensors

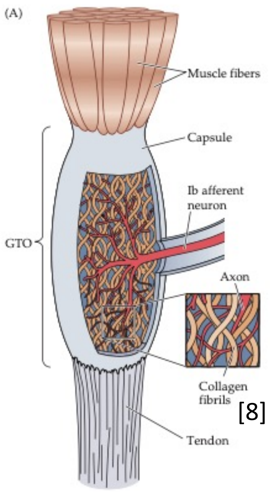
❖ Somatic Sensory Receptors




[8]

❖ Muscle spindle and Golgi tendon organ

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❑ Sensations from natural organs

❑ Substitute to mechatronic device

- **<u>Touch</u>**
- **<u>Pressure (static, dynamic)</u>**

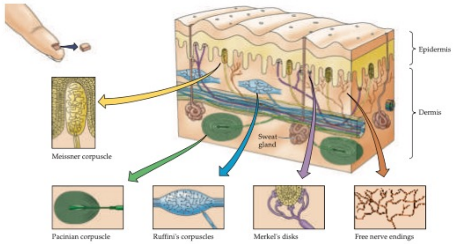
Tactile sensor

- Stretch
- Pain
- Temperature
- **<u>Proprioception</u>**

Joint angle sensor

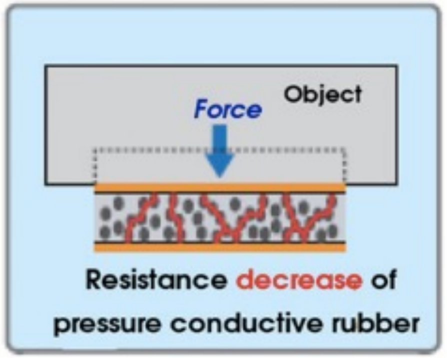
Tactile and proprioception are the
main sensations required in everyday life [23][24]

# Mechatronics details – Sensors – Tactile sensor types 1/4



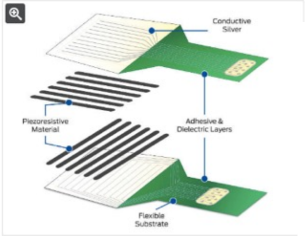

## ❖ Piezoresestive effect sensors

Sensing the change in electrical resistance during the mechanical deformation process




- ✓ Commonly used
- ✓ Simple to manufacture
- ✗ Non-linear response
- ✗ Fragile
- ✗ Permanent deformation

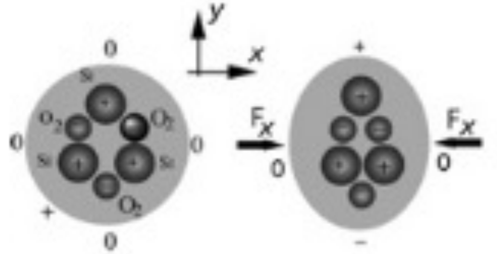
Tekscan





## ❖ Piezoelectric effect sensors

Sensing the electrical charge generation in the crystalline material in response to applied force/pressure

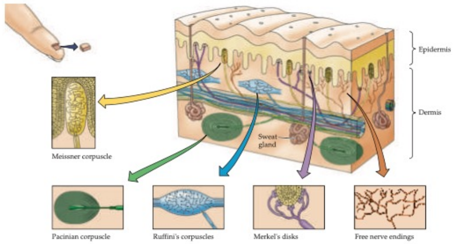



An applied force causes the change in the arrangement of Si+ and O2-

- ✓ High bandwidth
- ✗ Temperature dependence
- ✗ Dynamic sensing only

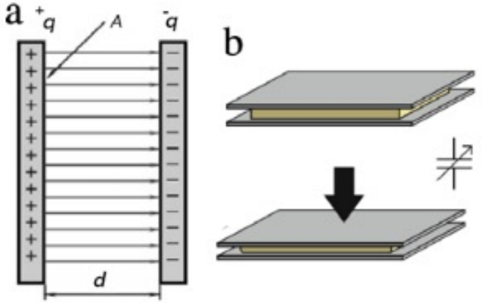
Kappassov et al. 2015

# Mechatronics details – Sensors – Tactile sensor types 2/4

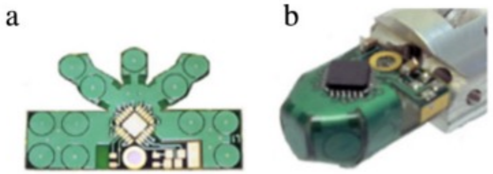


❖ Capacitive sensors

Sensing the capacitance changes when the gap between the two conductive plates changes

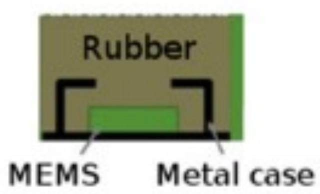



✓ Commonly used
✓ Flexible
✗ Influenced by electro-magnetic noise
✗ Sensitive to temperature
✗ Non-linear response

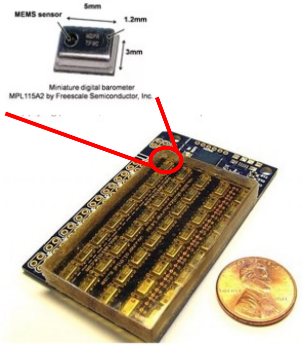


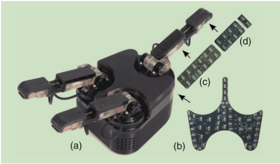

❖ Barometric sensors

Sensing the pressure of the silicon or fluid by using pressure transducers casted inside the structure



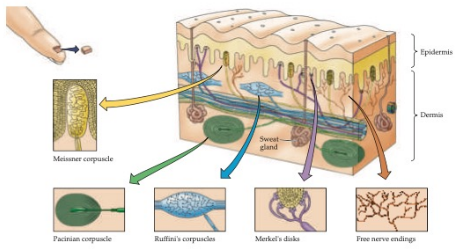

✓ High sensitivity
✓ High bandwidth
✗ Low spatial resolution
✗ Temperature dependency

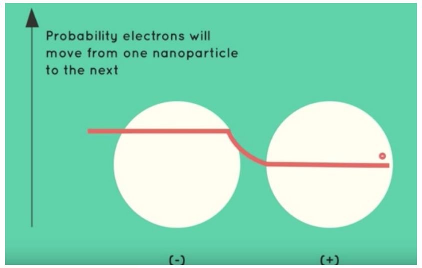
Tenzer et al. 2012

# Mechatronics details – Sensors – Tactile sensor types 3/4

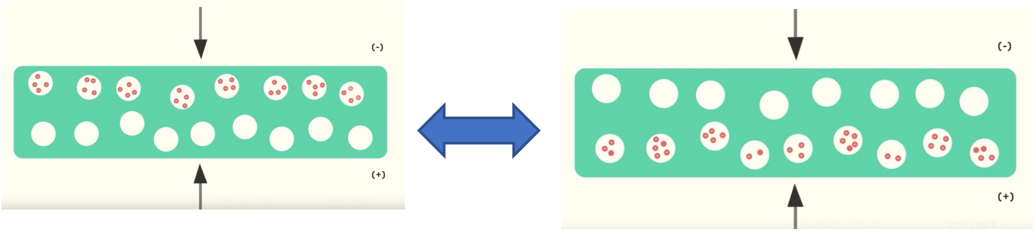


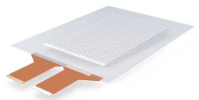
## ❖ Quantum tunnel effect sensor

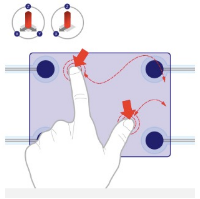
Sensing the change in the electrons that has appeared between the metal particles by quantum tunnel effect




- ✓ Linear response
- ✓ High dynamic range
- ✗ Complexity in manufacturing

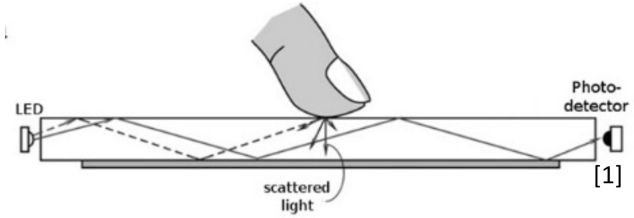




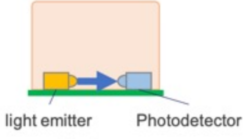
## ❖ Optical sensor

Using the optical optical reflection between light emitter and photodetector



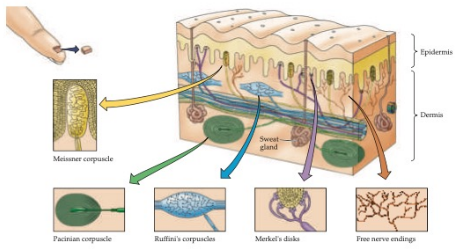

[1]

- ✓ High spatial resolution
- ✓ High sensitivity, repeatability
- ✗ Bulky
- ✗ High-power consumption




Touchence inc.

# Mechatronics details – Sensors – Tactile sensor types 4/4

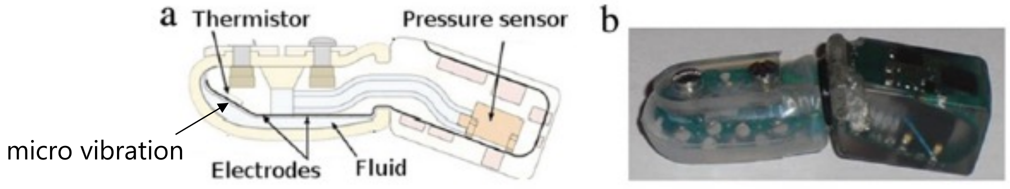


## ❖ Multimodal sensors

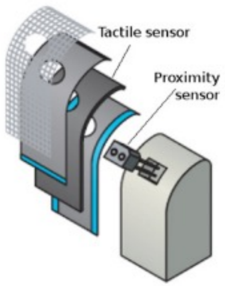
**Combined with several sensors**

✓ Achieves both compliant surface and tactile sensation
✓ Close to human sensation
✗ Tend to be complicated and complex

SynTouch



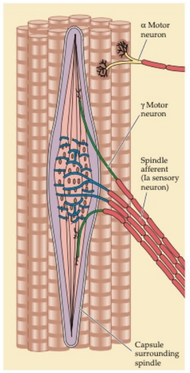

[25]

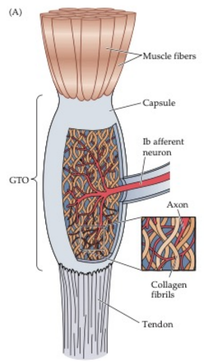



Detects both contact pressure and distance to an object

[25]

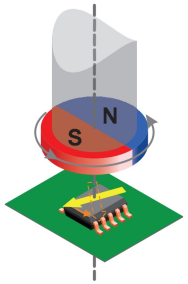
# Mechatronics details – Sensors – Proprioception



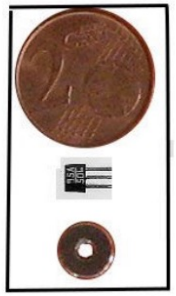



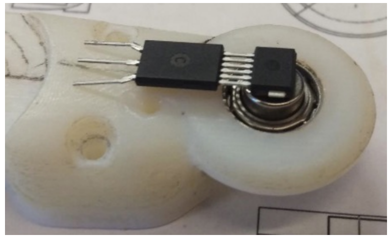

## ❖ Hall effect sensor

Outputs a voltage proportional to the magnitude of a magnetic field.
Consist of Hall Effect IC and permanent magnet.



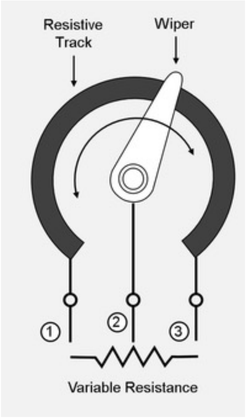

✓ Contact less
✓ Cheap
✓ Absolute position
✗ The magnet has to be placed close enough to the IC



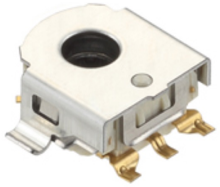


## ❖ Potentiometers

Outputs a voltage by the voltage divider




✓ Cheap
✓ Simple to use
✗ Additional friction to the joint
✗ Durability
✗ Large sized

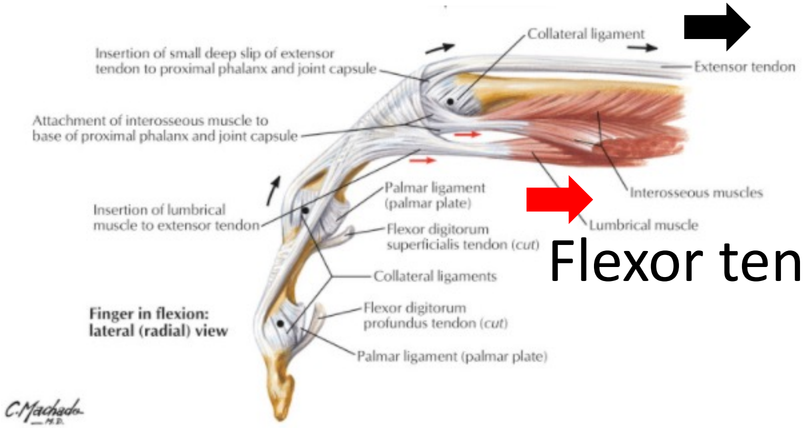


Powell et al. 2016

# Mechatronics details – Transmission of the torque

❖ Human limb activation

Extensor tendon



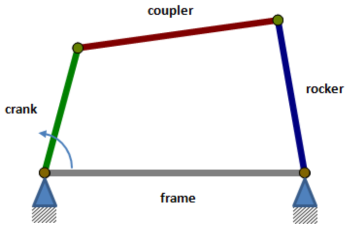

Flexor tendon

- ❑ Humans limbs are tendon driven by extensor and flexor tendons

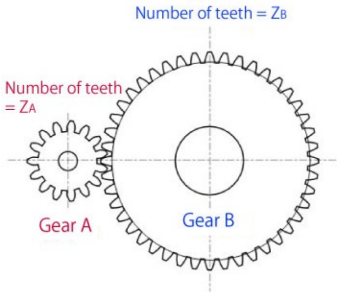
Various ways to achieve the joint movement by mechanical components

Tendon

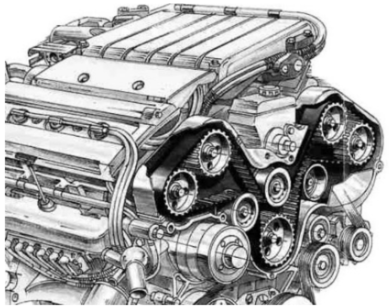

Linkage




Gear



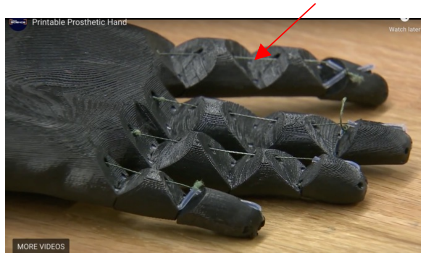

Timing belt



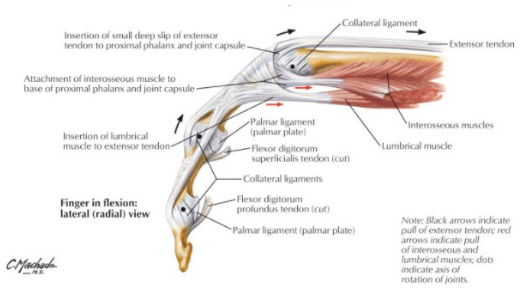
# Mechatronics details – Transmission of the torque 1/2

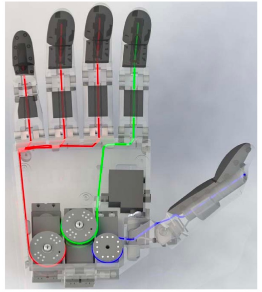
❖ Tendon driven

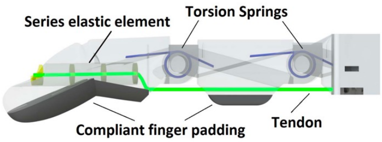
Tendon




✓ Allowance of flexible design
✓ Transmits force over a distance
✗ Complex design leads to high friction
✗ Maintenance
✗ Slack

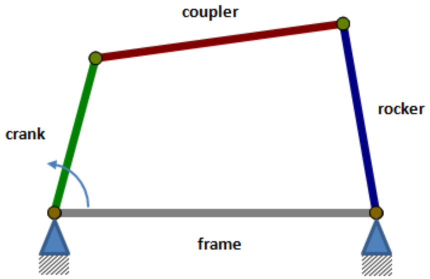





❖ Linkage

Four bar linkage




✓ Rigid torque transmission (low back lash)
✓ Kinematic calculation
✗ Large sizes
✗ Heavy, bulky

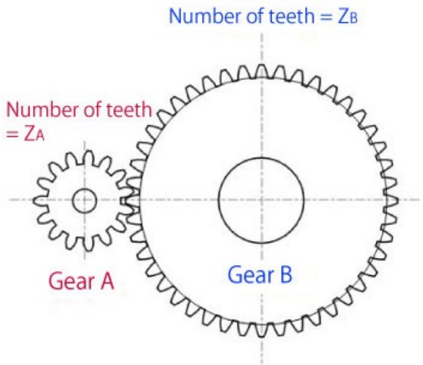
KINOVA

Universal Robots

Lalibert et al. 2010, Kappassov et al.2013, M.G. Catalano et al. 2014
KINOVA, Universal rotots

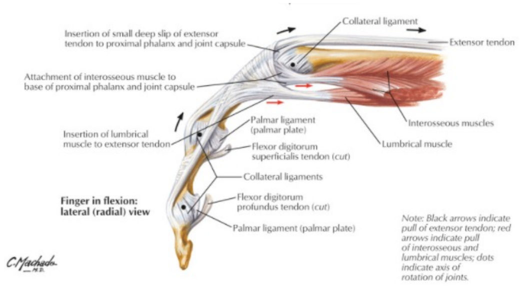
# Mechatronics details – Transmission of the torque 2/2

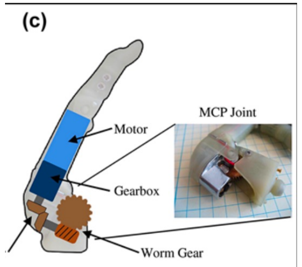
## ❖ Gear




Gear ratio $i = \frac{Z_A}{Z_B}$

- ✓ Change in torque/speed ratio
- ✓ Direction change
- ✗ Low transmission efficiency
- ✗ Noise
- ✗ Heavy





iLimb Finger Drive Mechanism

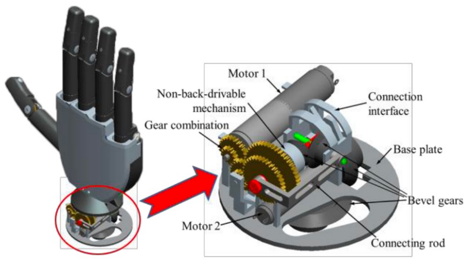
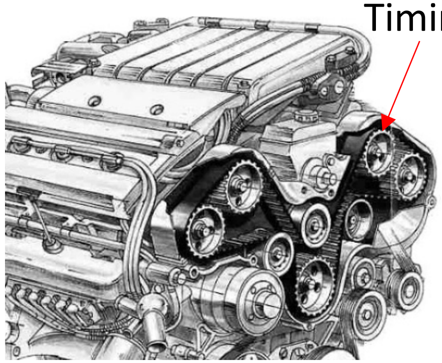
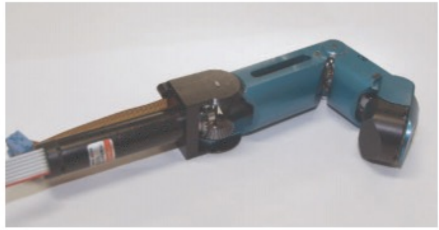


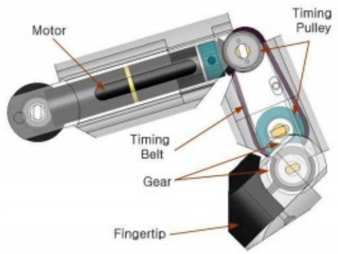
Fig.5.Structure of the wrist

## ❖ Timing belt




- ✓ Low back lash
- ✓ Light weight
- ✓ Less noise
- ✗ Slip in high torque
- ✗ Relatively large sized


(a) Finger module



(b) Structure of Distal Phalange

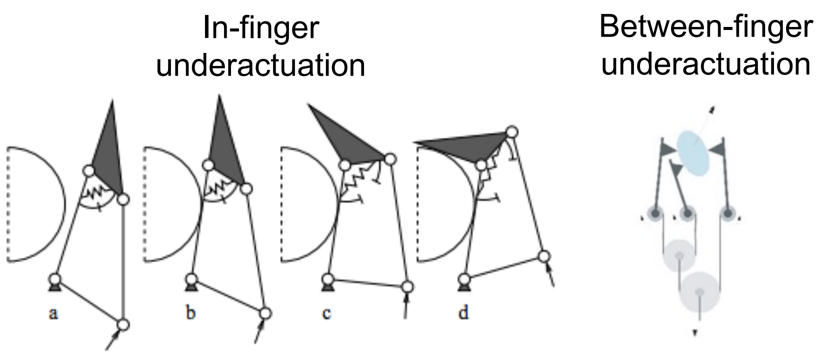
Fan et al. 2016
Choi et al. 2006

# Mechatronics details – Under actuation mechanism

❖ What is underactuated system?

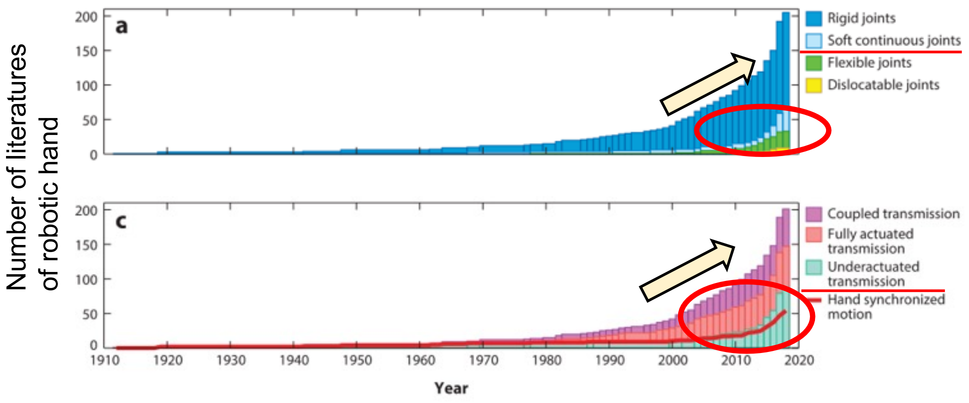
➢ <u>Actuate more DOF in less actuator</u>

Using the basics of differential mechanism




Can reduce the number of actuators

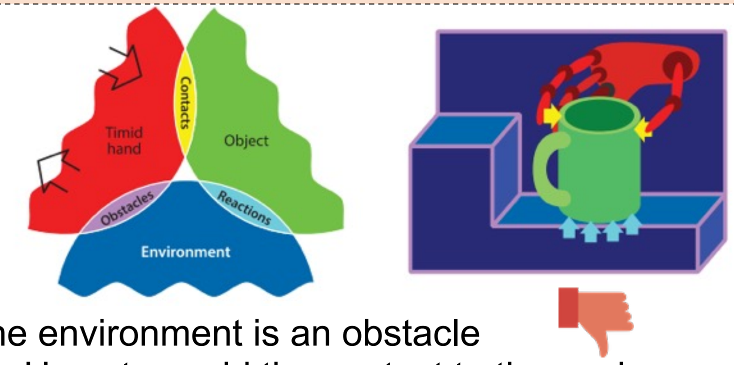
❖ Trend




There is an increasing trend

❖ Benefit

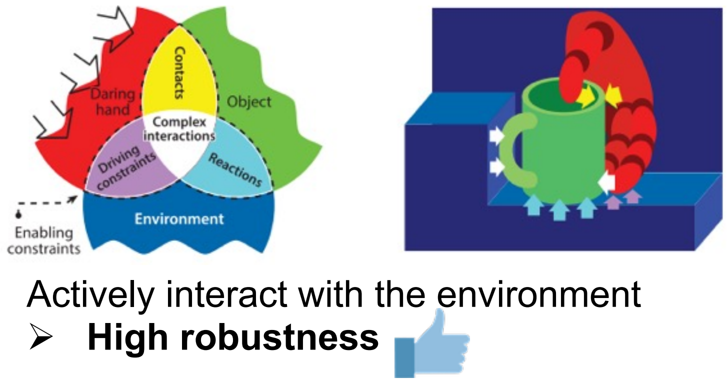
Conventional rigid manipulation paradigm




The environment is an obstacle

➢ Have to avoid the contact to the environment

Underactuated manipulation paradigm




Actively interact with the environment

➢ **High robustness**

Thierry Laliberte et al. 2003, M.G. Catalano et al. 2014, C. Piazza et al. 2019

# Approaches on prosthetic limb development

**Economically-optimized approach**

❖Low cost, open-sourced, not functional enough
- ➢ Low DOF
- ➢ Not sensorised
- ➢ No wrist activation
- ➢ Low cost

**Task oriented approach**

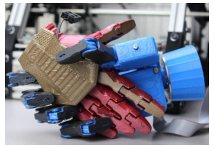
❖ Essential functions to achieve ADL
- ➢ Sufficient DOF/gripping force to achieve daily tasks
- ➢ Sensorised
- ➢ Partial wrist activation
- ➢ Middle cost

**Biologically-optimized approach**

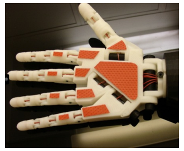
❖Mimic biological hand as much as possible
- ➢ High DOF
- ➢ Sensorised
- ➢ Full wrist activation
- ➢ High cost

Low-end　　Middle　　High-end

Open Hand project

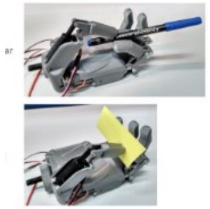


InMoov

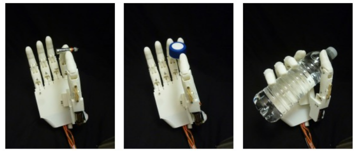


HACKBerry

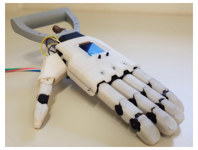
Grasp hand (2020)



Tact hand (2015)



Galileo Hand (2020)

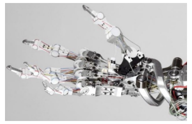



TAKUMI ARM

Shadow hand

MPL

DLR arm



Robonaut

# Task oriented approach – TAKUMI Hand

Economically-optimized approach | Task oriented approach | Biologically-optimized approach

Low-end — Middle — High-end


## ❖ Motivation

- ➢ Deliver a full prosthetic upper limb system to fulfill end-user needs

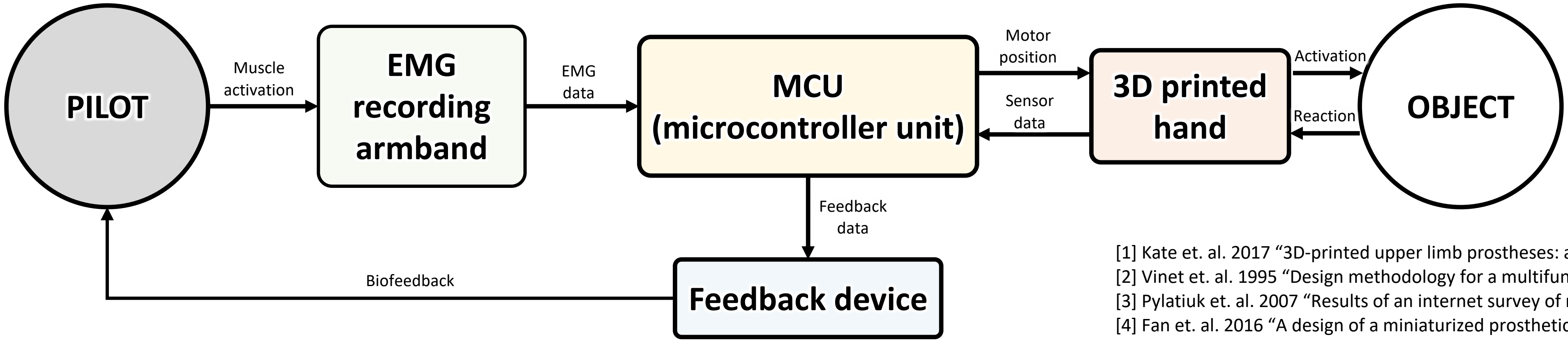

…Dexterous/Skilled/Craftsmanship/Creating a beauty



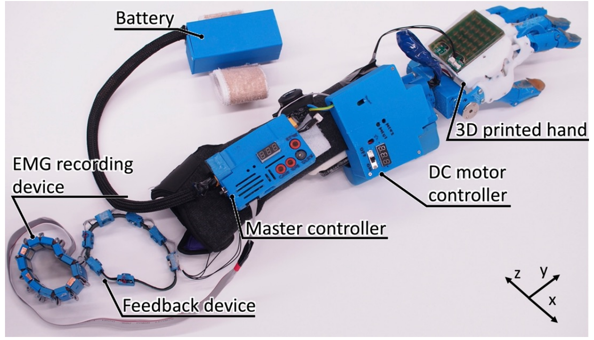
## ❖ Features of the system

- ➢ Sufficient grasping/pinching force for daily life activities
  (pinch 11.9N/power grasp 45N) [1, 2]
- ➢ Control multiple degrees-of-freedom simultaneously in closed loop
- ➢ Sensory feedback
- ➢ Active wrist
  (Flex/ext > pro/sup > rad/ulr deviation) [3, 4]
- ➢ Light weighted
- ➢ Mid ranged price
  (between £10,000 to £30,000 in the sales price)

## ❏ Block diagram




Developed limb




[1] Kate et. al. 2017 “3D-printed upper limb prostheses: a review”
[2] Vinet et. al. 1995 “Design methodology for a multifunctional hand prosthesis”
[3] Pylatiuk et. al. 2007 “Results of an internet survey of myoelectric prosthetic hand users”
[4] Fan et. al. 2016 “A design of a miniaturized prosthetic wrist based on repetition rate of human wrist daily tasks”

# Motor & mechanism selection

## ❖ Mechanism

❑ Index & thumb

Linkage mechanism
To ensure the rigid pinching

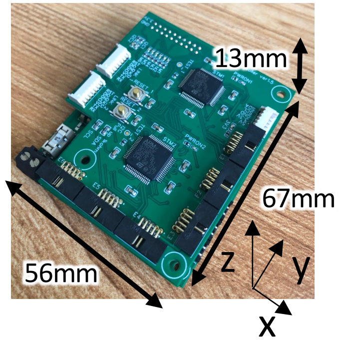
❑ Other fingers

Tendon + underactuation
To realize simple design and dexterous grasping


## ❖ Actuation

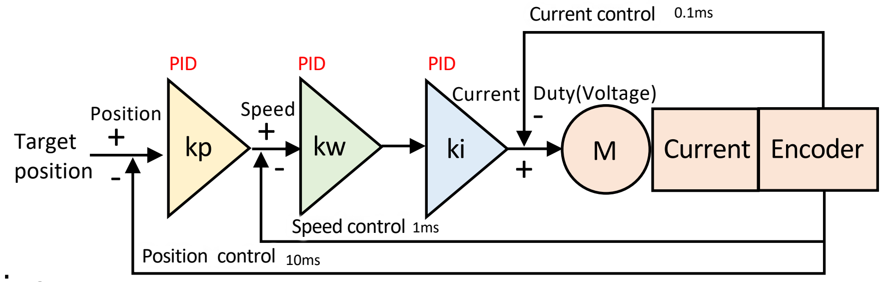
❑ DC motor actuation

Developed DC motor controller

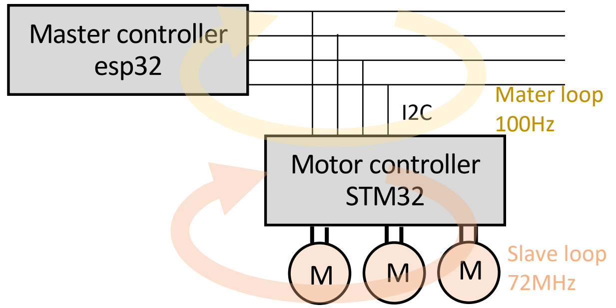



- ➢ 6 axis simultaneous control
- ➢ I2C communication
- ➢ Position + Speed + Current digital control
- ➢ Supports up to 2A in 12V
- ➢ £100/6axis

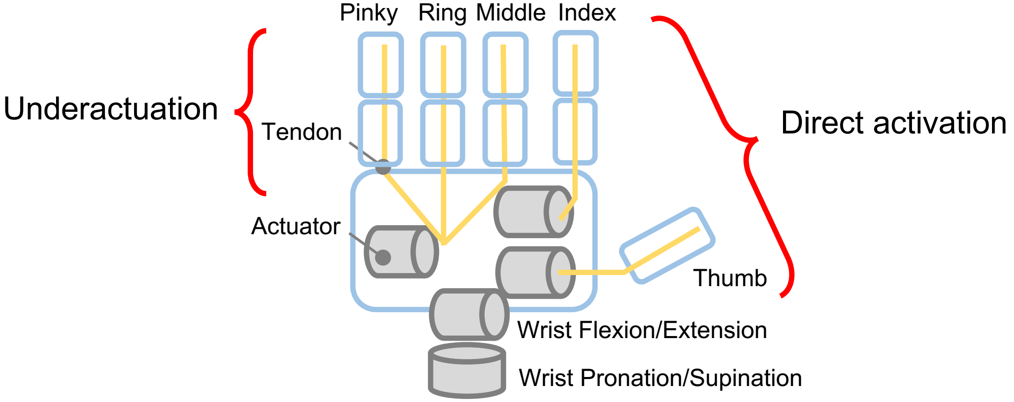
Control architecture



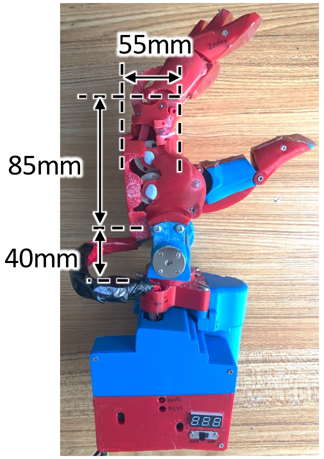

Communication architecture




❑ DoF topology



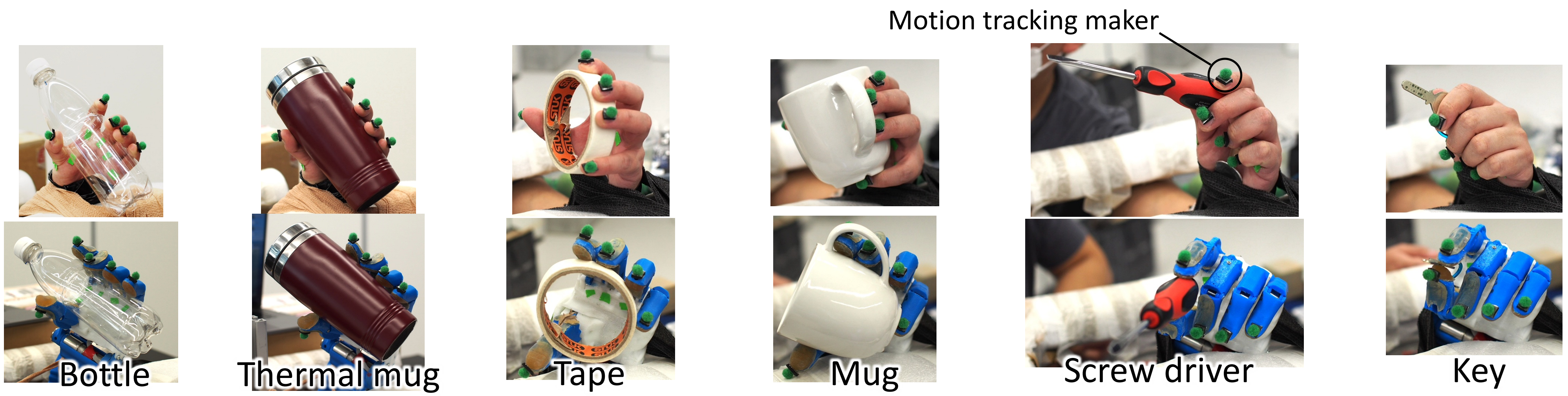

Fabricated size



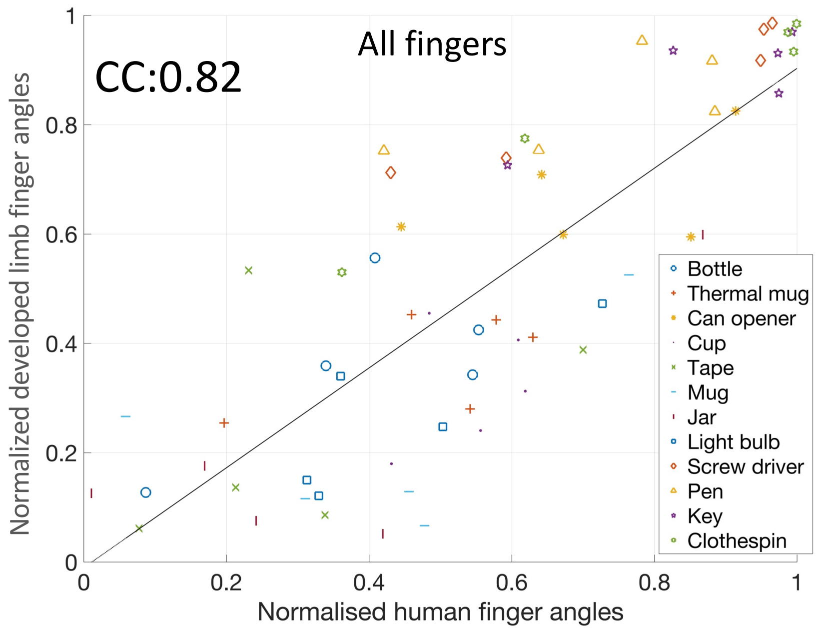

Total 5 DoF

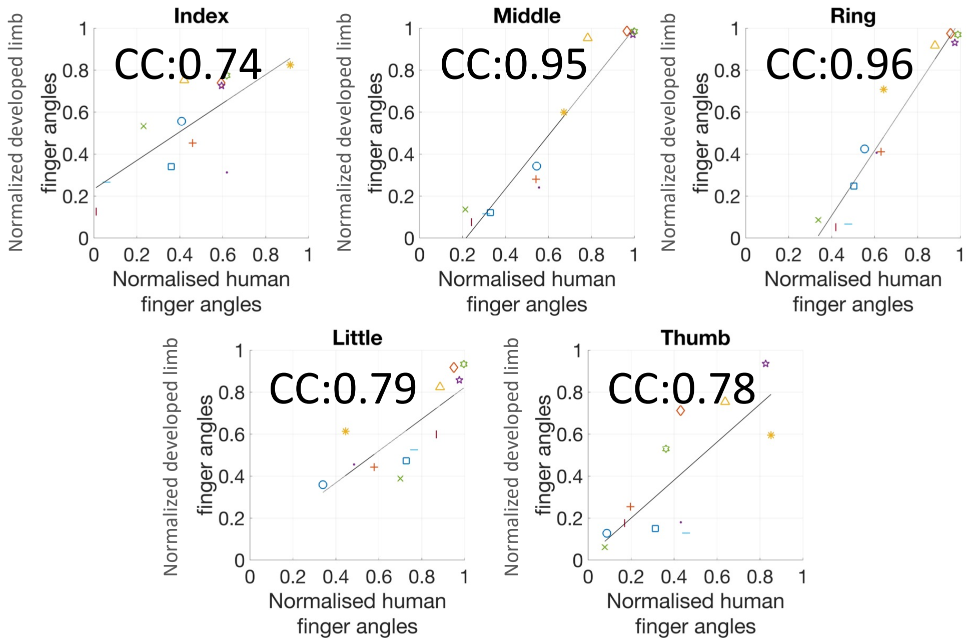
Kashiwakura et.al. 2023 “Task-Oriented Design of a Multi-Degree of Freedom Upper Limb Prosthesis With Integrated Myocontrol and Sensory Feedback”

# Demonstration – grasping adaptation




*Angles are tracked by Open CV



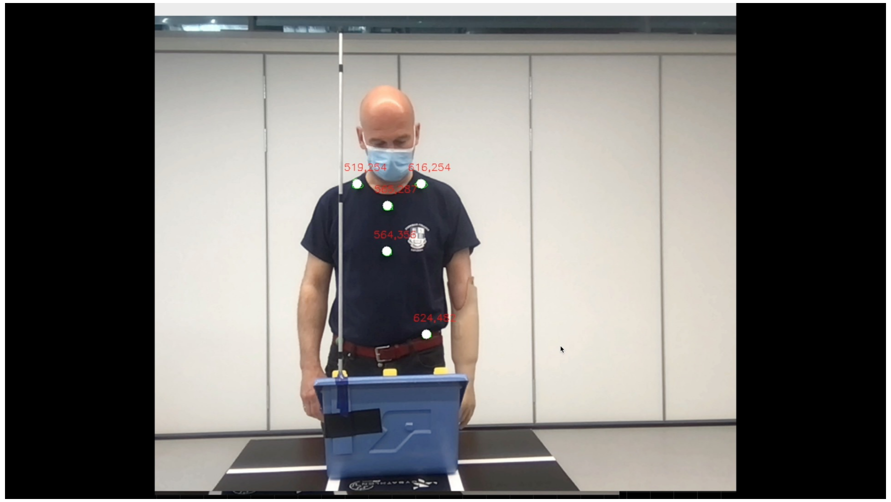

High correlation between the developed limb and a natural limb

Kashiwakura et.al. 2023 “Task-Oriented Design of a Multi-Degree of Freedom Upper Limb Prosthesis With Integrated Myocontrol and Sensory Feedback”

# Demonstration – wrist activation benefit

## ❖ Videos

No wrist activation



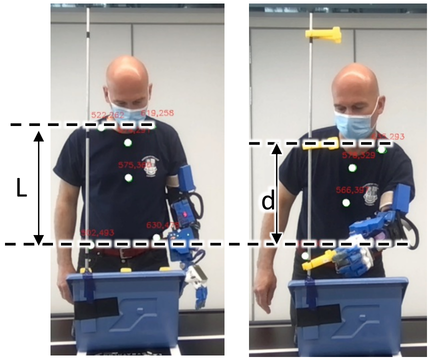

Developed limb

*First trials

$$D_r = \frac{L'}{L}$$

## ❖ Evaluation

### ❑ Shoulder height

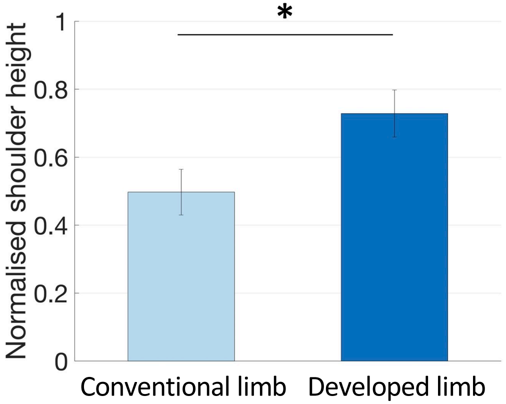



$$R = \frac{d}{L}$$

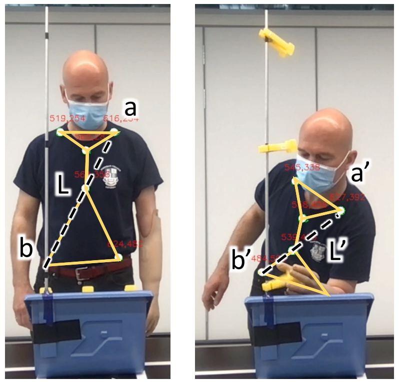
$R$: *Shoulder height ratio*

$L$: *Neutral position shoulder height*

$d$: *Bended shoulder height*




### ❑ Torso diagonal length

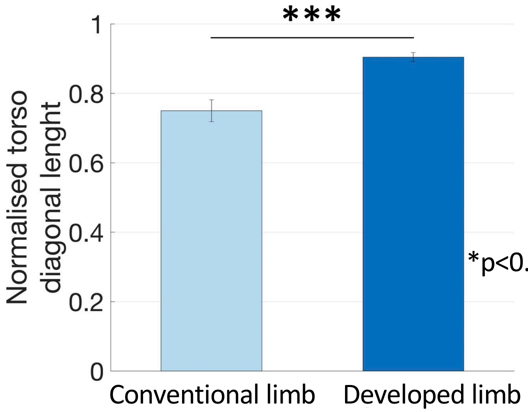



$$D_r = \frac{L'}{L}$$

$D_r$: *Torso diagonal lenght ratio*

$L$: *Neutral torso diagonal lenght*

$L'$: *Moved torso diagonal lenght*



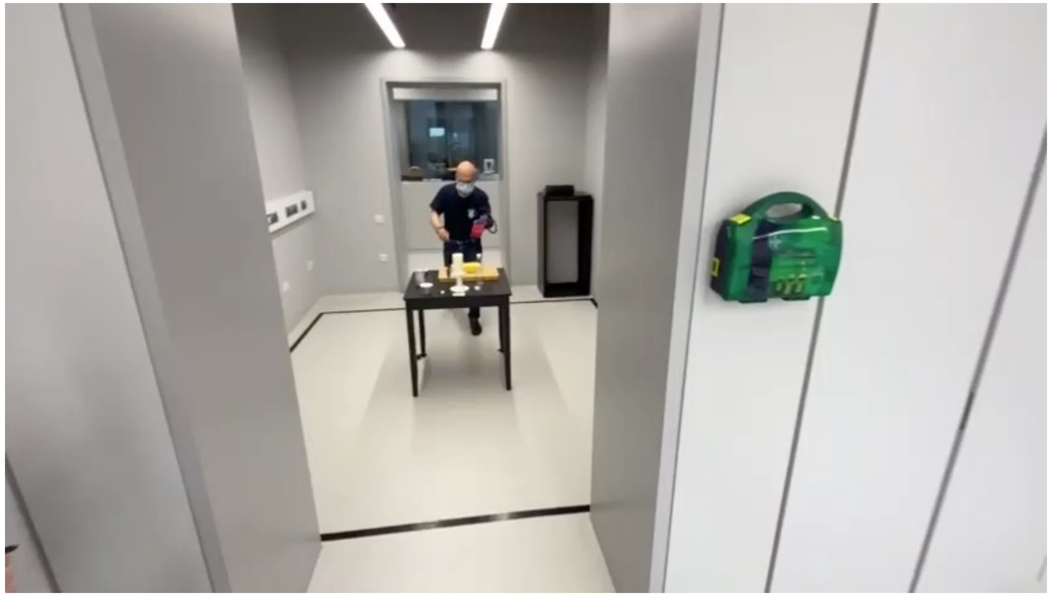

*p<0.05, **p<0.01, ***p<0.001

**Less compensatory movements with an active wrist**

Kashiwakura et.al. 2023 "Task-Oriented Design of a Multi-Degree of Freedom Upper Limb Prosthesis With Integrated Myocontrol and Sensory Feedback"

# Whole system in action – ADL demo

Breakfast preparation



Clean sweep

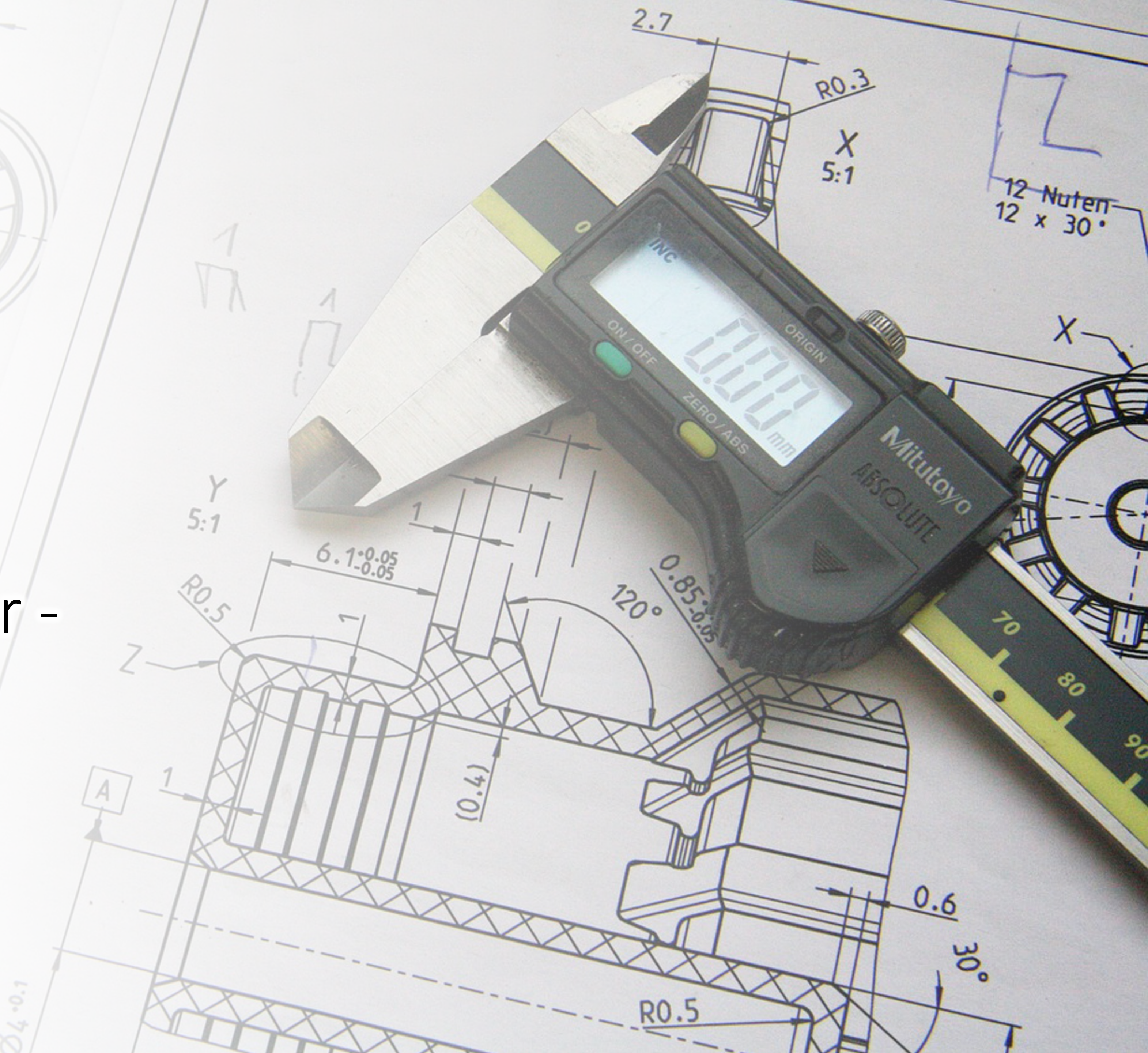
Home maintenance

Cup stacking

Let’s be creative

Part 1

- Designing a bionic finger -



# Files and software to get started

**1st Day**
**Build your bionic limb**

**[Hands-on]**

- CAD (get an idea on how to design a bionic limb) – 45 min
    Software
    - Fusion 360

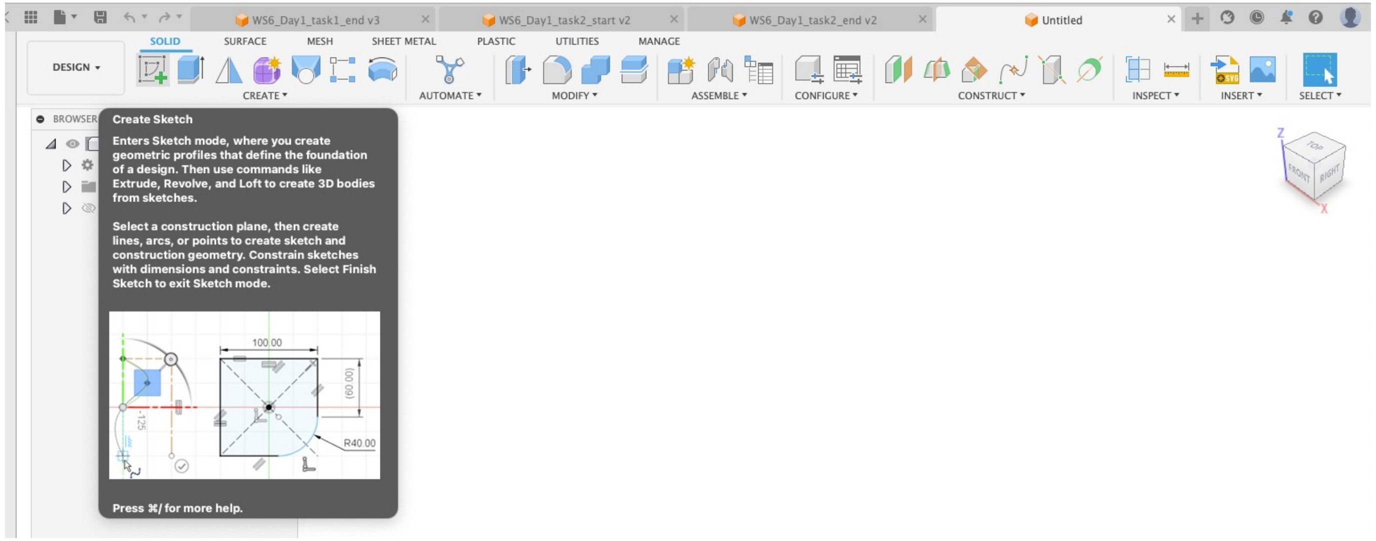
    File
    - WS6_Day1_task1_start.f3d
    - WS6_Day1_task1_end.f3d
    - WS6_Day1_task2_start.f3d
    - WS6_Day1_task2_end.f3d
    - WS6_result v1.f3d
- Assemble simplified limb (in 3 groups) – 45 min
    Software
    - Arduino IDE
    - CH340 driver

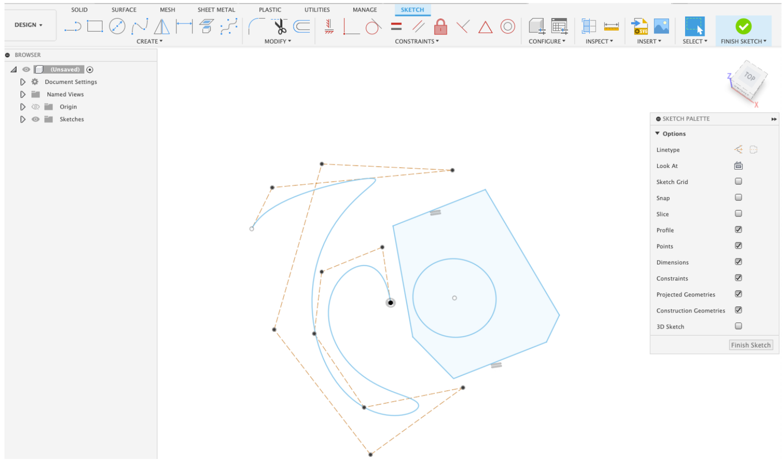
https://www.autodesk.co.uk/campaigns/education/fusion-360

# Get yourself familiarized to CAD

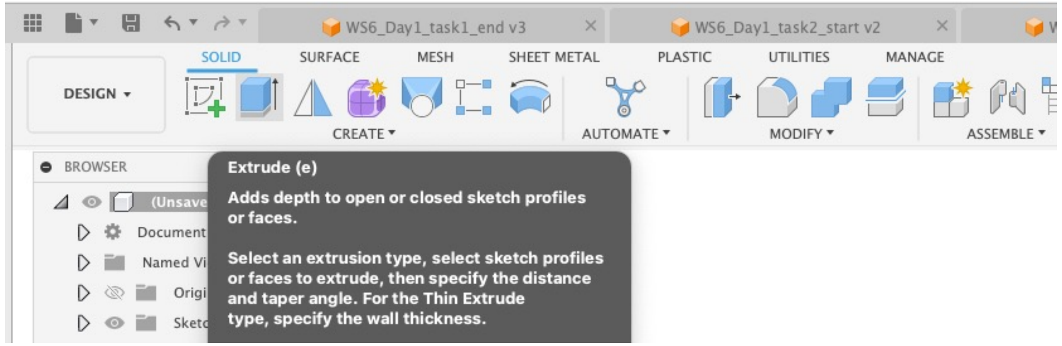
## Main functions

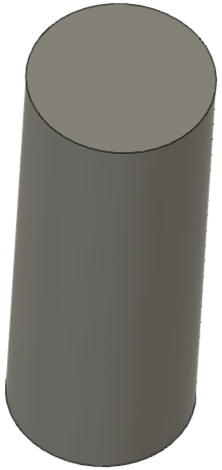
### ”Sketch”



### ”Extrude”



https://www.autodesk.co.uk/campaigns/education/fusion-360

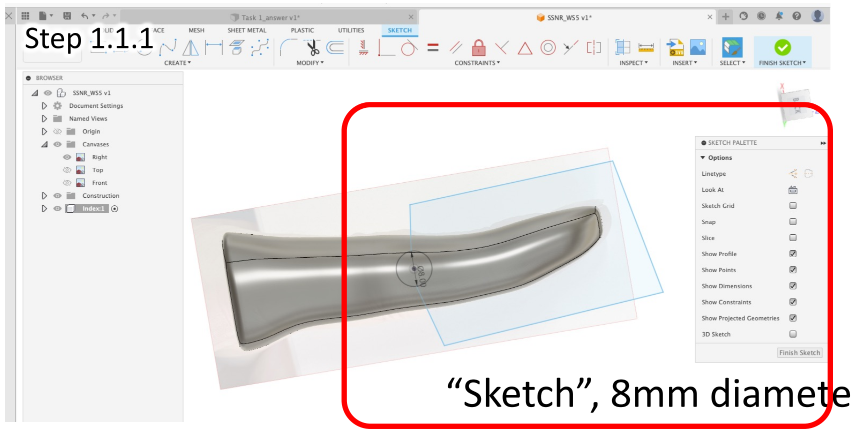
## Task 1
## Cut the bodies to be functional as a finger

## Task 2
## Joint them together

**File: WS6_Day1_task1_start.f3d**

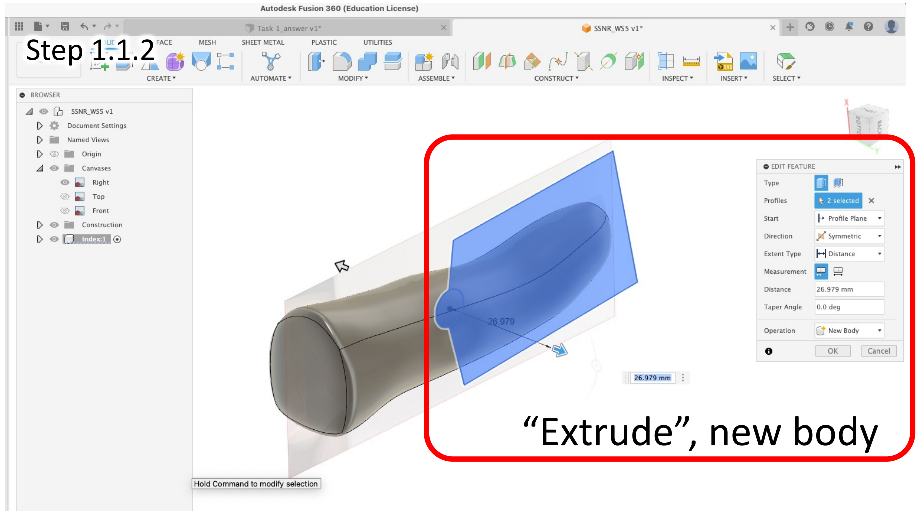
# Task 1 Step 1

Create the body for the PIP phalange



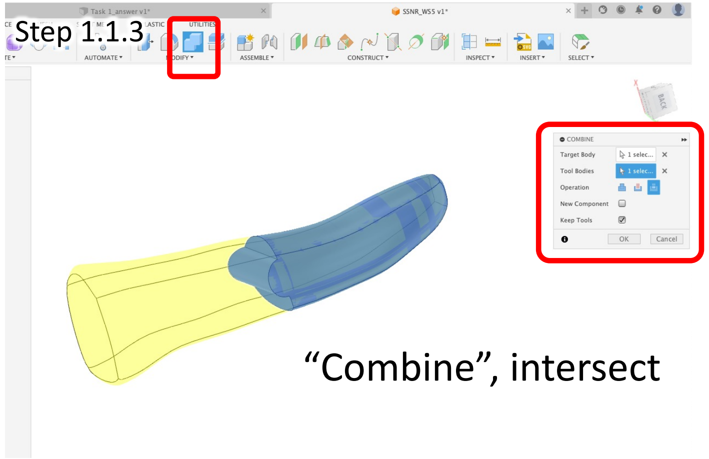
Step 1.1.1

“Sketch”, 8mm diameter



Step 1.1.2

“Extrude”, new body



Step 1.1.3

“Combine”, intersect

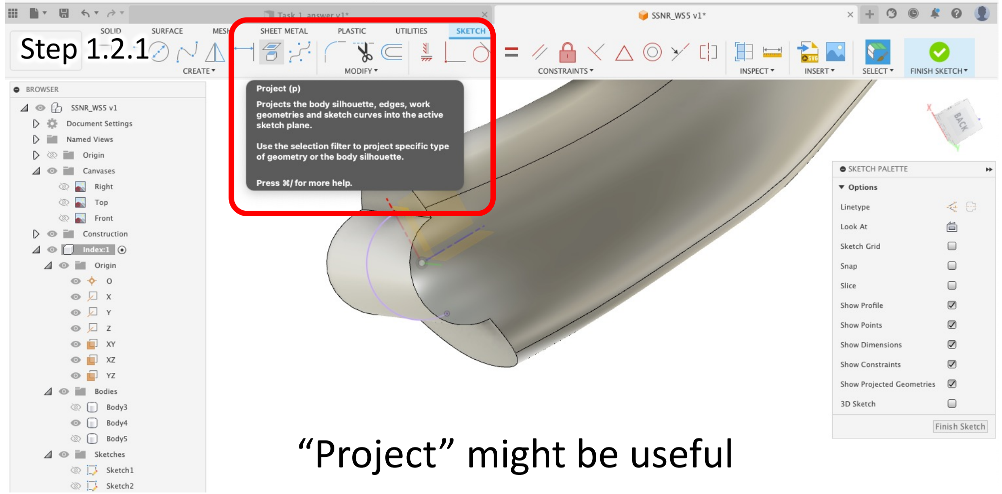
Task 1
Cut the bodies to be functional as a finger

Task 2
Joint them together

# Task 1 Step 2

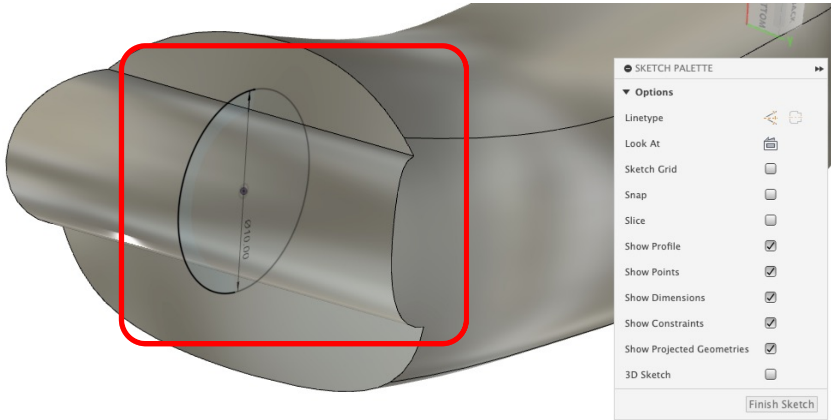
## Create a joint

Step 1.2.1



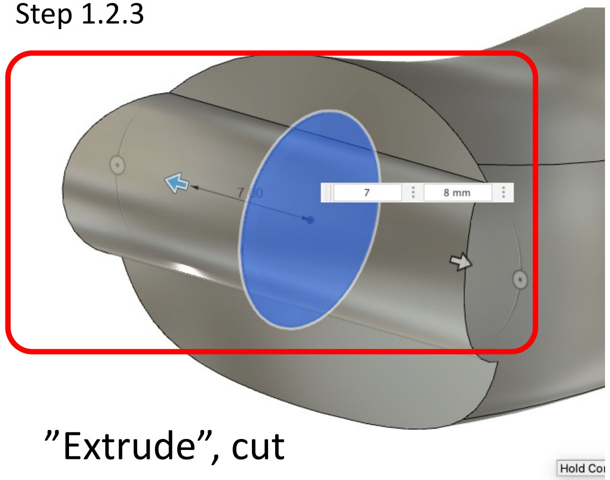

"Project" might be useful

Step 1.2.2

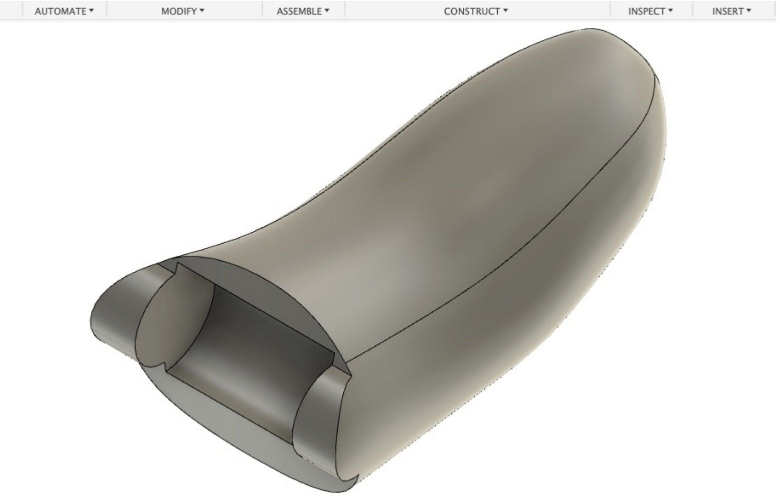



Sketch a 10mm diameter at the mid plane

Step 1.2.3




"Extrude", cut 8mm

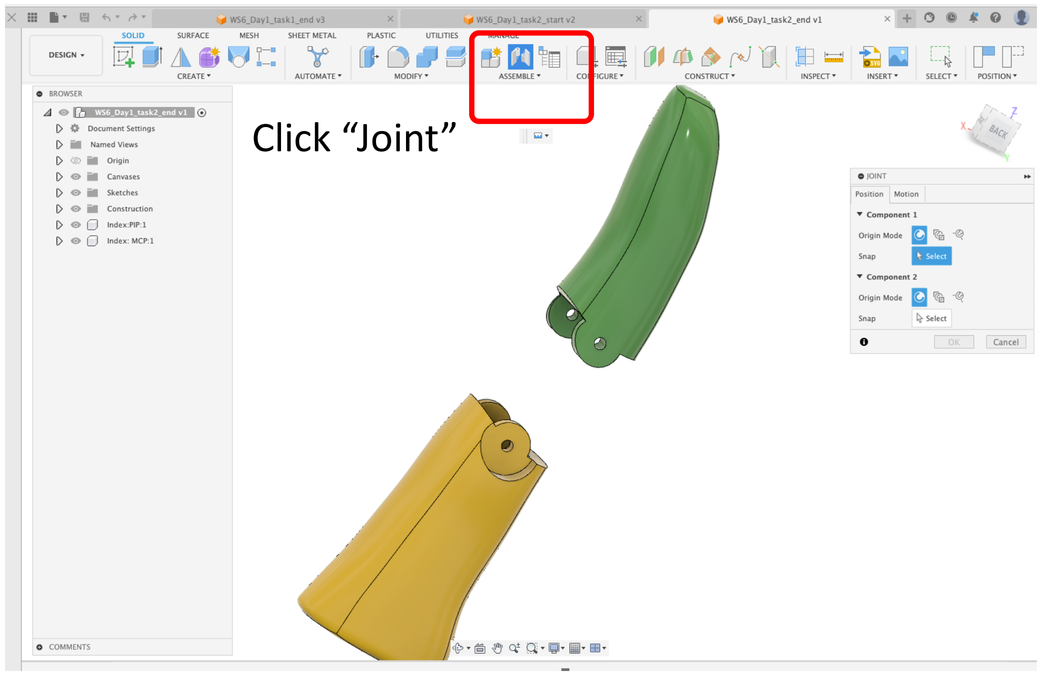



Result

Task 1
Cut the bodies to be functional as a finger

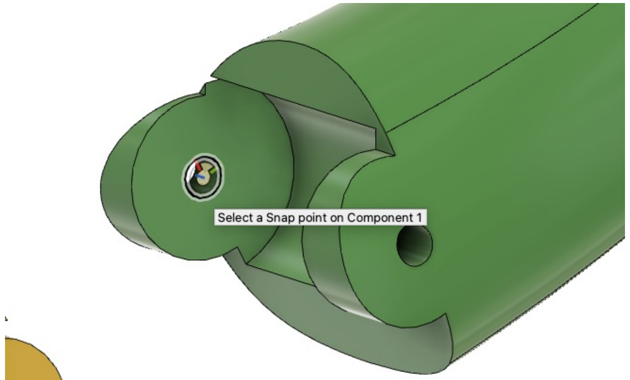
Task 2
Joint them together

## Task 2 Step 1

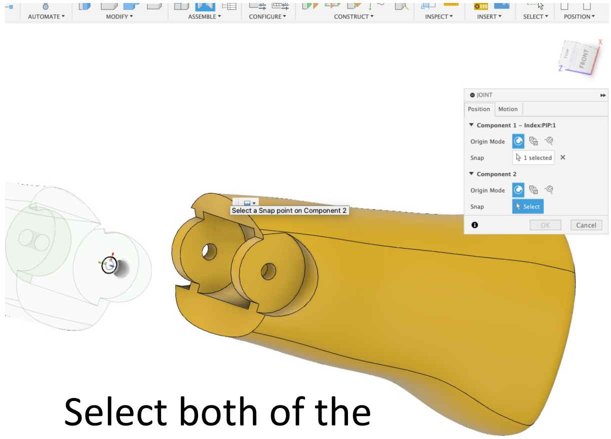



Click "Joint"

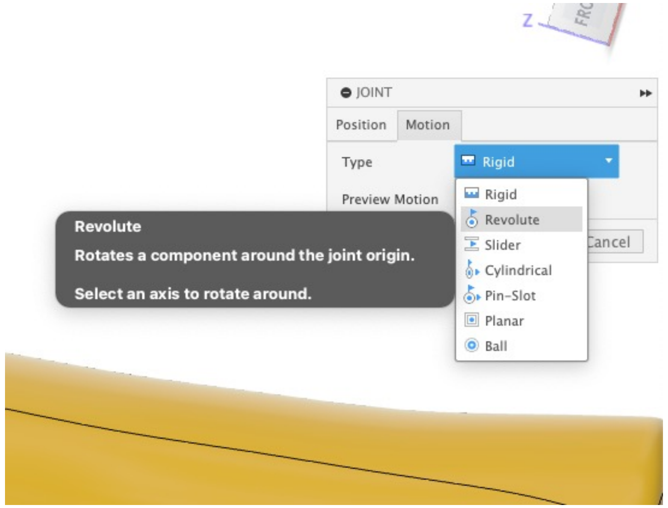
## Task 2 Step 2




Select both of the phalanges joints



Select both of the phalanges joints



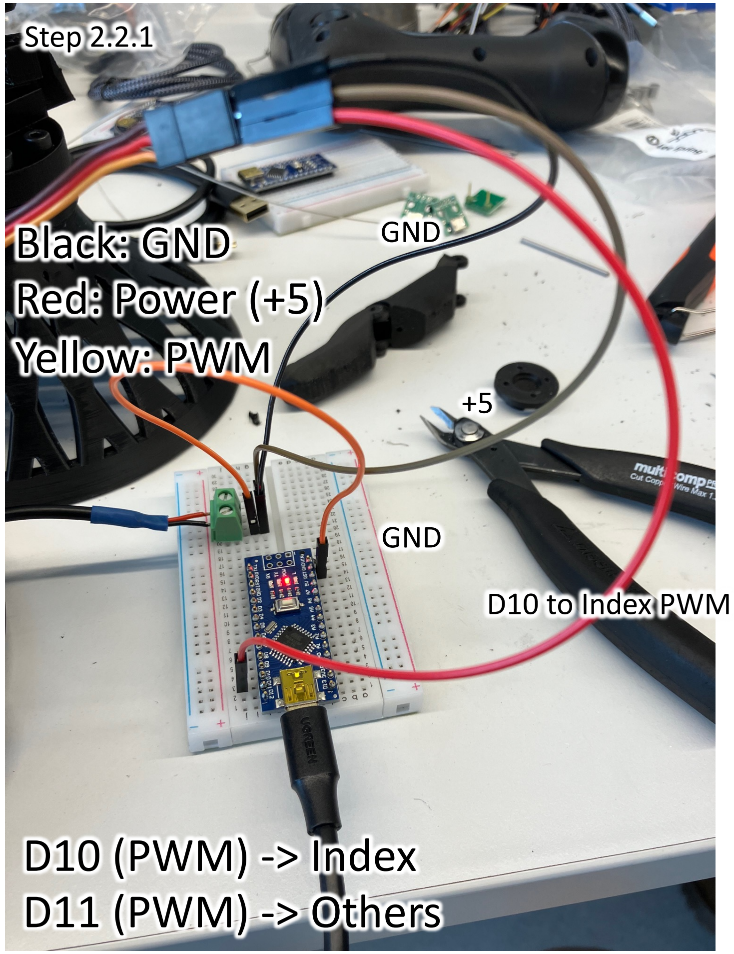

Select "Revolute"

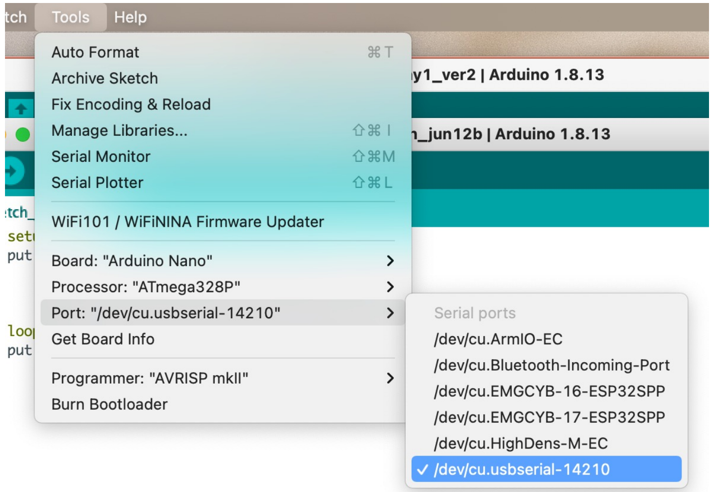
# Let’s be creative
# Part 2
# - Assembling the finger -

Arduino IDE 2.1.0

https://www.arduino.cc/en/software

## Wire the cables and upload the code




- Make sure the GNDs are common between the power and the microprocessor
- The default position should be at middle (command 0)
- Command example: <u>a-100,-100</u> (go index and other fingers to close)
- Mapping is -100:100 command -> 0:180 degrees