PROPRIOCEPTION

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Outline

- Proprioception
- Force sensing and control
Proprioception 1/3

- Used to be defined as ”sense of locomotion” or ”muscle sense”
- Often used as a synonym to *kinesthesia* which tends to place a greater emphasis on motion
  - proprioception include the sense of balance that is not taken as a part of kinesthesia
- Proprioception is a feedback mechanism
  - information about the movements of the body is returned to the brain based on which related adjustments can be made
    - a closed loop system
Proprioception 2/3

• Provides feedback on the status of the body internally
  - indicates whether the body is moving with required effort
  - provides information about where the various parts of the body are located in relation to each other

• Mediated by receptors located in muscles, tendons, and joints
  - the sense of position and movement is complemented by the sense of force

• The gravity (or lack of it) has a great effect on sense of proprioception
Proprioception 3/3

- **Mechanoreceptors**
  - located at the joints (*and skin*)
  - detect pressure caused by movement (*as well as local skin stretch*)

- **Golgi organs**
  - located between muscles and tendons
  - detect localized tensions to regulate muscle coordination (*especially for fine motor control*)

- **Muscle spindles**
  - located between single muscle fibres
  - detect stretching between the neighbouring fibres
  - determine the rate of stretch in muscle length
Proprioception & haptics 1/2

• Babies learn their ranges of motion by twisting and stretching their limbs

• A key component in muscle memory and hand-eye coordination
  - allows us, e.g., walk with our eyes closed without falling down, control the pen when writing on a paper…
  - a highly trainable sense, often reasonably easy to rehabilitate

• There are different neural paths for conscious and unconscious proprioception (i.e., active and passive movement)
Proprioception & haptics 2/2

- Proprioception provides spatial and motor information about object properties
  - also interaction is strongly based on the forces experienced during touch
- We use combination of position and kinesthetic sensing to perform motor control
  - exploratory tasks are dominated by the sensory information (*e.g.*, *shape detection*)
  - active manipulation tasks are motor-dominant
An example: “The man who lost his body”

- Ian Waterman
  - in 1972 at the age of 19 a viral infection caused him to lose all sense of touch and proprioception from the neck down
  - at first he could initiate a movement but did not have any control over it neither he knew where it happened
  - over three years he taught himself how to move again by consciously controlling and visually monitoring every action
  - even today Ian must keep any limb that he wants to move, such as a leg for walking or an arm for grabbing, within his visual field in order to voluntarily control it
Force sensing and control
Force sensing

• The mechanism involved in using force is adaptable
  - the voluntary high level loop is utilized when maximum force is used
  - the low level (reflex) loop tends to minimize the applied forces to reduce physical fatigue

• Tactile sensing is also important, for example, for grasping
  - provides information about friction and object slippage
Pressure resolution

• Pressure JND decreases as a function of contact area
  - people are more sensitive to pressure changes when contact area is enlarged
  - independent of location

• *The contact area at the attachment points of exoskeletons should be minimized*
Position resolution

- Joint angle resolution is better at proximal (e.g., shoulder) joints than at distal (e.g., wrist) ones
  - JNDs for joint angle resolution: finger (2.5°), wrist (2.0°) and shoulder (0.8°)
  - Help humans to control end points (i.e., fingertips) accurately.
    - An error of 1° in shoulder joint angle sensing would result in an error of 1 cm at the index fingertip (in finger joint it would be 0.08 cm)

- The position sensing resolution that is desired in the device depends on the position resolution of the human operator
Force resolution

- A study on the maximum controllable force humans can produce with joints of the hand and the arm
  - maximum force resolution increases from the most distal joint (finger) to the most proximal joint (shoulder)
  - JND for human force sensing is around 7%

- The maximum force exerted by the device should meet or exceed the maximum force humans can produce
Torque resolution

- Torque discrimination and control is important for human motor capabilities
  - involves both force and position sensing
  - we are about as good in discriminating different torques as we are controlling them
  - JND for torque is about 12% for index finger + thumb
Softness resolution

- Judging softness information is critical in many daily tasks
  - JND for different softnesses is about 8% for index finger + thumb
  - for forearm it has been reported to be around 20%
Degrees of Freedom (DoF)

• DoF = “an independent axis of displacement or rotations that specify the position and orientation”

• Practically always limited by the mechanical design of the haptic display
  - contact point: grasping versus stylus
  - usually focus on hands/arms: resolution, detection, discrimination ability increase distally (i.e., from shoulder to finger)
  - movement speed decreases if movements are constrained
Human arm degrees of freedom

Caldwell et al. (1995)
Analysis of grasps

Cutkosky and Howe (1990)
Human sensing and control bandwidth

- **Sensing bandwidth**
  - frequency with which tactile and kinesthetic stimuli are sensed
- **Control bandwidth**
  - speed with which humans can respond to a change
- **Sensing bandwidth is larger than the control bandwidth**
  - the proprioceptive sensing bandwidth is about 20-30 Hz
  - the force control bandwidth is typically 5-10 Hz
Force bandwidth

- The force control and perceptual bandwidths of a human operator are quite different
  - vibrotactile stimuli can be perceived up to about 500 Hz
  - the upper bound of force control bandwidth is from 20 to 30 Hz
  - however, the practical bandwidth is considerably less, and has been reported to be about 7 Hz
Sensing and control bandwidth

- 5,000—10,000 Hz: The bandwidth over which the human finger needs to sense vibration during skillful manipulative tasks.

- 320 Hz: The bandwidth beyond which the human fingers cannot discriminate two consecutive force input signals.

- 20—30 Hz: The minimum bandwidth with which the human finger demands the force input signals to be present for meaningful perception.

- 12—16 Hz: The bandwidth beyond which the human fingers cannot correct their grasping forces if the grasped object slips.

- 8—12 Hz: The bandwidth beyond which the human finger cannot correct for its positional disturbances.

- 5—10 Hz: The maximum bandwidth with which the human finger can apply force and motion commands comfortably.

- 1—2 Hz: The maximum bandwidth with which the human finger can react to unexpected force/position signals.
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Haptic interface design

- The major perceptual issues are the following:
  - force sensing under static and dynamic conditions
  - pressure perception
  - position sensing resolution
  - the level of stiffness required for rigidity simulation
- The major manual performance issues are the following:
  - the maximum forces humans can produce
  - the precision with which humans can control a force
  - the control bandwidth of the force
- The issues of ergonomics and comfort are also important
Unintended vibration

• One of the most noticeable disturbances in a force reflecting device is the level of unintended vibration (i.e., noise)
  - a significant level of vibration can quickly destroy the feeling of free motion or disturb the perception and control of virtual objects in contact
  - the human body is very sensitive for low frequency vibration thus careful attention to hardware design and control software is needed