Proprioception & force sensing

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Outline

- Proprioception
- Force sensing and control
Proprioception 1/3

• Used to be defined as ”sense of locomotion” (1557) or ”muscle sense” (1826)

• Often used as a synonym to *kinesthesia* (1880) which tends to place a greater emphasis on motion
  - Proprioception includes 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 1/3

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

• Proprioception is a key component in muscle memory and hand-eye coordination
  - Allows us, e.g., walk with our eyes closed without falling down and 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)

Unconscious proprioception is responsible, e.g., for the human reflex to level the eyes against the horizon when the body tilts in any direction
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
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 or know 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 within his visual field in order to voluntarily control it
Example: Field sobriety test

- American police officers use the field sobriety test to check for alcohol intoxication
  - Touch the nose with eyes closed

- This should be a rather easy task (error no more than 2 centimeters) unless suffering from impaired proprioception caused by alcohol intoxication
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
Forces in haptic interaction

- Haptic force-feedback devices have two basic functions (Tan et al., 2004)
  1. To measure the positions and contact forces of the user’s hand
  2. To display contact forces and positions to the user

- Understanding of human force-sensing system is important for the development of haptic force-feedback interfaces
Pressure resolution

- Human pressure perception increases as a function of contact area
  - People are more sensitive to pressure changes when contact area is enlarged
  - Independent of body location (i.e., elbow and wrist)

- The perimeter of contact area in exoskeletons (e.g., haptic gloves) should be maximized to improve the illusion of grounding
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 haptic force-feedback 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 force-feedback device
  - 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 human 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
  - The perceptual bandwidth for vibrotactile stimuli can be 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

- Frequency is an important sensory parameter

- We can sense tactile frequencies much higher than kinesthetic
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.
- **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.
Haptic interface design

• The major technical 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
  - 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
  - Therefore, careful attention to hardware design and control software is needed