Literature review of haptic systems

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Table of contents

Tactile feedback

Tactile interfaces: a state-of-the-art survey 2004 (note: might be outdated)
Mohamed Benali-Khoudja, Moustapha Hafez, Jean- Marc Alexandre, and Abderrahmane Kheddar.

- Human haptic sense is divided into two submodalities:
    - The kinesthetic sense (force, motion)
    - The tactile sense (tact, touch)
- Tactile devices should be able to reproduce:
    - Texture
    - Roughness
    - Temperature
    - Shape
- Pin-matrix devices:
    - Sandia national laboratories
        - 2 x 3 electromagnetic actuators
        - Each actuator operates between 8-100 Hz
        - Max pressure of 1.2 N/cm^2
    - Ottawa university
        - 8 x 8 electromagnetic vibration needles
    - Armstrong laboratory (HAP-TAC device)
        - 5 x 6 actuators
        - Used shape memory alloy (SMA) wires to push and pull the tactile elements
        - Max force of 2 N with resolution of 0.12 N
    - Harvard university
        - Pins driven by SMA-based actuators
- Glove devices:
    - Teletact
        - Composed of a ceramic disc of PZT (lead zirconate titanate), a piezoelectric material that changes shape when an electric field is applied
    - DataGlove by VPL
        - 14 sensors to measure finger bending
        - Piezoelectric actuator under each finger
    - CyberTouch by Virtual Technologies
        - Tactile actuators are attached on each end of the finger and palm to provide impulses and vibrations
- EXOS
    - Reproduced sensations of slip and shearing
- ER fluid devices:
    - University of Hull at RU
        - 5 x 5 actuators using electrorheological fluid
    - Rutgers university (MEMICA device)
        - ER fluid-based gloves for haptic feedback

Nail-mounted tactile display for boundary/texture augmentation 2007

Hideyuki Ando, Eisuke Kusachi, and Junji Watanabe.

- Goal is to superimpose tactile information onto an object displayed on a screen
- Method:
    - Applied vibration to fingernail, instead of to the pad of the finger
        - Deformation of the fingerpad is indirectly produced
- Implementation:
    - Used a voice coil (the kind that drives a speaker) with a small mass
        - Multiactor Type 33, NEC Tokin Co.
        - Resonant frequency of 132 Hz
    - Drove the coil at the resonant frequency to produce vibrations
        - Took 20 ms for the transient response to go away
    - Finger position was measured by the touchscreen
    - 3 primary types of vibration pulses:
        - Boundary (high-low-high)
        - Plain texture (constant amplitude)
        - Bump (sinusoidal envelope)
- Note:
    - Vibration experienced during movement is perceived as texture
    - Otherwise, it’s interpreted as just vibration

Ultrahaptics: multi-point mid-air haptic feedback for touch surfaces 2013
Long, Bruce Drinkwater, and Sriram Subramanian.

- Goal:
    - Outline the principles, design, and implementation of an ultrasonic, mid-air haptic feedback system for touch surfaces
    - Investigate the desirable properties of an acoustically transparent display
    - Present a series of psychophysical studies that demonstrate feedback points with different tactile properties can be distinguished by users
- Background:
    - By stimulating neuroreceptors within the skin, it has been demonstrated that focused ultrasound is capable of inducing tactile, thermal, tickling, itching, and pain sensations [13]
    - Two methods to stimulate receptor structures with ultrasound:
        - Acoustic radiation force
            - Induces a shear wave in the skin tissue
            - Sensed by mechanoreceptors within the skin [11]
        - Bypass receptors and directly stimulate nerve fibres [12]
            - This requires powerful acoustic fields, making it unsuitable for applications designed for prolonged use
- Related work:
    - Haptic feedback methods:
        - Vary the friction coefficient of the surface, either through ultrasound [4] or electro-vibration [2]
            - This can only provide one haptic sensation at a time and apply it across the entire surface
        - FEELEX uses a pin array to deform the surface [19]
        - Embedded fluid layer can be manipulated with electromagnets [20] or pneumatics [15] to alter its shape
        - Haptic pen combines a pressure sensitive stylus with a physical actuator to provide vibrotactile feedback [23]
        - Separate static device such as SensAble PHANTOM [26] or maglev haptics [3]
        - SensableRays transfers haptic feedback to an actuator on the user's hand wirelessly through modulated light [30]
        - FingerFlux alters a magnetic field to stimulate the user's finger through an attached magnet [32]
    - Ultrasonic haptic feedback:
        - Two-dimensional arrays of ultrasound transducers allowed for dynamic systems, with ultrasound focused to a point that can be moved along two axes [17]
            - Creates strong focal point, but also creates four secondary maxima surrounding the central maxima

        - Attempts to create two or more focal points using spatial or temporal multiplexing [1]
- Implementation:
    - Designed a system consisting of an ultrasound transducer array positioned beneath an acoustically transparent display
        - (Discussion of transparent display not recorded here)
    - 320 muRata MA40S4S transducers arranged in a 16x20 grid
        - Each transducer 10 mm in diameter
        - Each transducer can generate 20 Pa at a distance of 30 cm
    - Custom-made driver boards containing two XMOS L1-128 processors
        - Output a 15V square wave to the transducers
    - Positions of user's hands are tracked by a Leap Motion
    - When haptic feedback is require, a phase delay and amplitude is calculated for each transducer to create an acoustic field forming the desired focal points
        - (Discussion of algorithm not recorded here)
- Perceptual issues:
    - Vibration is detected by mechanoreceptors within the skin, which are responsive to vibrations in the range 0.4 Hz to 500 Hz
    - Used a 40 kHz ultrasonic carrier wave, modulated by a frequency of 0.4 Hz to 500 Hz to achieve a variety of tactile sensations
        - Modulating different focal points at different frequencies gives each point of feedback its own feel
- Results:
    - Simulations show that the system creates discrete focal points with low amplitude secondary maxima
    - See figure 6 for experimental confirmation

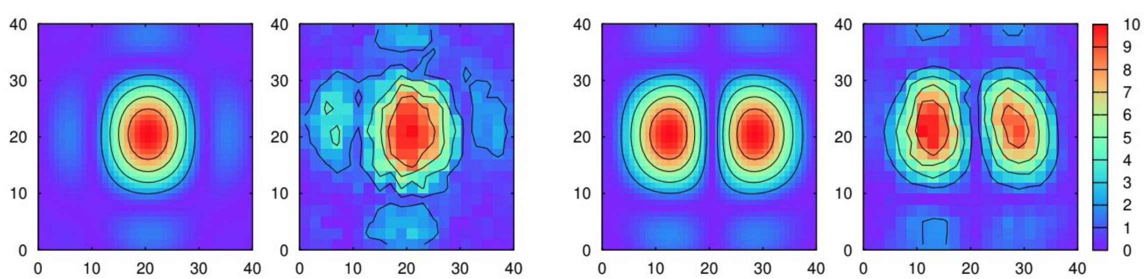


Figure 6: A comparison of the simulated and measured intensities of one and two focal points, each at 200mm from the emitting transducers. Far left: single focal point simulation. Centre left: single focal point measured with a microphone (RMSE 1.30, peak pressure 257 Pascals). Centre right: two focal point simulation. Far right: two focal points measured with a microphone (RMSE 0.77, peak pressure 234 Pascals). All axes are in *mm*.

HapThimble: a wearable haptic device towards usable virtual touch screen 2016
Hwan Kim, Minhwan Kim, and Woohun Lee.

- Goal:
    - Develop a wearable haptic device that provides tactile, pseudo-force, and vibrotactile feedback
    - Conduct three experiments regarding user experience with the device
- Background:
    - Physical surfaces have two functions:
        - Provide haptic information
        - Provide physical constraint
    - Haptic constraint has been treated as one important factor constituting haptic feedback
        - Restores the laws of physics between the user's hands and a virtual object by restricting the hands [12, 24, 38]
        - Actively guides and supports hand movements to enable stable and careful manipulation [1, 21, 30, 39]
- Related work:
    - Ring and thimble type wearable devices render constant and monotonous vibrotactile feedback with vibration motors while the user's fingertip is in the interaction space [10, 13, 40]
    - Pseudo-force feedback by tightening the user's fingertips with strings or straps to simulate the reaction forces corresponding to the pushing of virtual objects [3, 15, 28, 33] or the weight of virtual objects [26]
- Implementation:
    - See figure 1
    - Designed to fit onto the user's index finger (25 mm diameter cylindrical body, 150 mm length, 100 g weight)
    - Movable cap, powered by a servo motor (Hitec HS-7115TH, 3N of force max), in contact with the fingertip, consists of:
        - Touch sensor (copper tape, Arduino capacitive sensing library)
        - Pressure sensor (Interlink FSR 402)
        - Linear resonant actuator (Samsung electromechanics, linear motor 0832, resonant frequency 235 Hz, 1.8 V, 8 x 3.2 mm)
- Haptic feedback design:
    - HapThimble provides three types of feedback to the user's fingertips
        - See figure 2
        - Contact haptic feedback (contact vibration)
        - Past-screen feedback (variable force feedback, grain vibration)
        - Bottom-out feedback (max force feedback, bottom-out vibration)
    - User's perception of a hard surface is enhanced when a damped vibration is provided to coincide with the fingertip coming into contact with the virtual screen [22, 30]

- To replicate feedback from a physical button, Kim and Lee [19] divided a force-displacement curve into slope and jump sections
    - Grain vibration was provided in the slope section
    - Jump vibration was given in the jump section to mimic the bump/collapse sensation immediately after the tactile position
    - Each section had a different vibration frequency
- Experiments and results:
  - Experiment 1:
    - Measure time of a clicking and dragging task with four conditions: no feedback (bare), tactile feedback, force feedback, and a real physical screen
    - See figure 9
    - Note: under the physical condition, the subjects became aware that hitting the acrylic panel at high speed would result in pain, so they moved slower to prevent this from happening
  - Experiment 2:
    - Determine if subjects could differentiate between different types of virtual button feedback
      - See figure 11 for different response curves
    - Two conditions: force feedback (F) and force and vibrotactile (F+V)
    - See table 2 for results
- Design recommendations for wearable haptic devices:
  - Haptic feedback is not require for applications that primarily rely on clicking tasks
  - Haptic feedback for depth perception is necessary if the application primarily relied on dragging tasks
  - If virtual button feedback is not required, the provision of only tactile feedback can cover most operations
  - Providing virtual button feedback can be achieved using only pseudo-force feedback, which can provide a variety of types of feedback. Vibrotactile feedback can be used to supplement this.

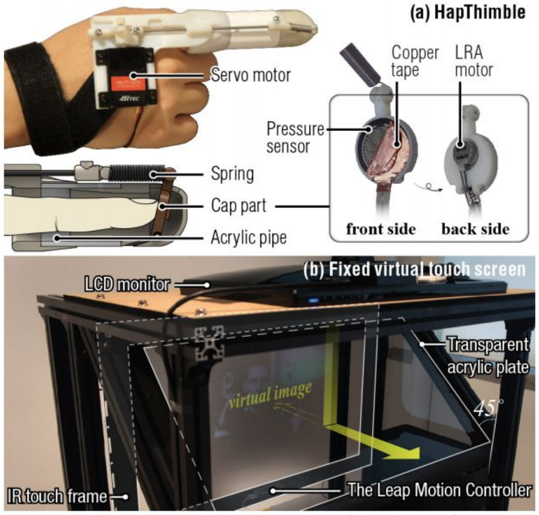


Figure 1. HapThimble system. Structures of
(a) HapThimble and (b) fixed virtual touch screen.

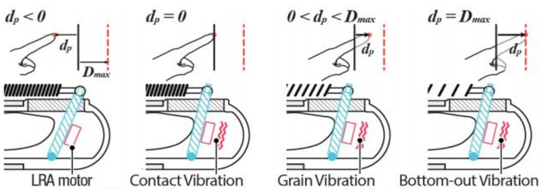


Figure 2. Three types of haptic feedback
along the penetration depth of user's fingertip.

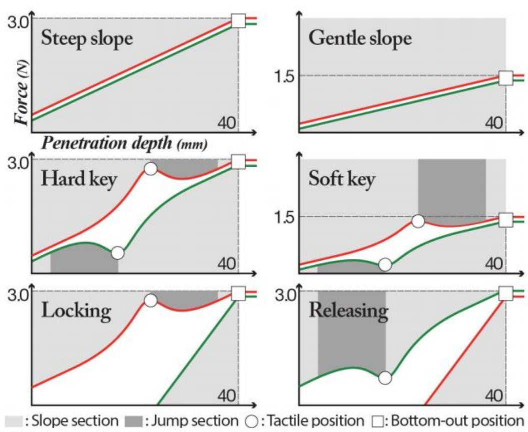


Figure 11. Force-penetration depth curves of six virtual buttons.

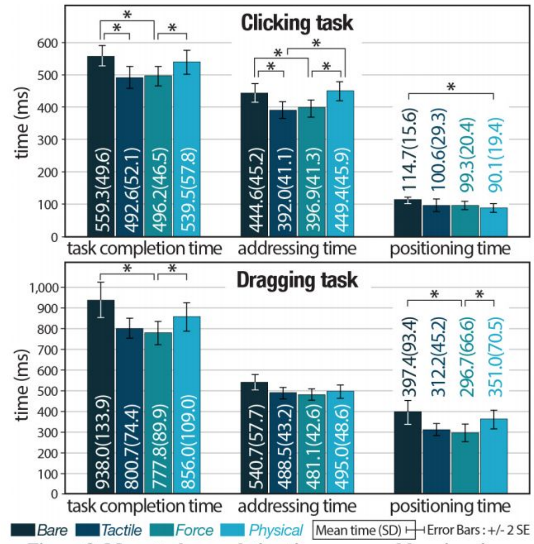


Figure 9. Mean task completion time, mean addressing time,
and mean positioning time.

Results

	F+V condition	*F condition*
Steep slope-Gentle slope	100% (0)	100% (0)
Hard key-Soft key	99% (0)	100% (0)
Locking-Releasing	97% (0)	91% (3)
Steep slope-Hard key	96% (0)	94% (1)
Hard key-Locking	94% (1)	90% (2)
Steep slope-Locking	96% (1)	92% (2)
Total	97% (2)	94.5% (8)

Table 2. ABX test result.

Skin-stretch devices

Gravity grabber: wearable haptic display to present virtual mass sensation 2008
K. Minamizawa, S. Fukamachi.

- Goal:
    - Present a wearable haptic device to create the sensation of a virtual object, based on the insight that the deformation of finger pads makes a reliable weight sensation even in the absence of proprioception
- Background:
    - Weight sensation is perceived as the integration of the proprioceptive sense on the arm and the tactile sense on the finger pad
    - Forces perceived on the finger pad can be decomposed into normal and shear
        - Normal stress is equal to the grip force of the fingers
        - Shear stress is equal to the gravitational force acting on the object
        - See **figure 5** and **figure 4**
- Related work:
    - Maeno et al [2004]
        - Showed a method for controlling the grip force by detecting the stick-slip distribution on the fingerpad
    - Johansson and Wrestling [1984]
        - Partial slippage plays an important role in human ability to grasp objects
    - Inabe and Fujita [2006]
        - Simple constrictive pressures on the fingers replicate the grip sensation
- Implementation:
    - See **figure 2**, **figure 3**, and **figure 7**
    - Two motors mounted above the finger, each attached to one end of a belt
        - To create the grip sensation, the motors are driven in opposite directions so that they roll up the belt
        - To create the gravity sensation, the motors are driven in the same direction so the belt moves against the finger tip
    - Hardware specifications:
        - Belt of width 20 mm
        - 2 x Maxon Motor RE 10, 1.5 W, gear ratio 1:16
        - Body made of ABS resin
- Experiment and results:
    - The subjects fixed their arm in an armrest, attached the device to their index finger and thumb, and grasped a light-weight styrofoam cube (**figure 8**)
    - The shearing stress on the fingers was increased and the subjects were asked to report how much they perceived the weight of the object in comparison to real world objects
    - Result:
        - The perceived virtual weight scaled linearly with the applied shearing stress, indicating skin-stretch as a good mechanism to simulate weight

Comparison of skin stretch and vibrotactile stimulation for feedback of proprioceptive information 2008

Karlin Bark, Jason W. Wheeler, Sunthar Premakumar, and Mark R. Cutkosky.

- Goal:
    - Perform an experiment to compare the ability of subjects to perform blind cursor movements without haptic feedback and with two types of feedback: skin stretch and vibration
- General background:
    - Vibration is the most widely used haptic feedback modality in small devices
        - Compact
        - Relatively low-power
        - Easy to implement
    - Skin stretch is an important component of the human proprioceptive apparatus, particularly for the distal joints [7, 5]
- Technical background:
    - Vibration stimuli activate the fast-acting mechanoreceptors (pacinian and meissner corpuscles)
        - Sensitive to vibrations in the range of 200-300 Hz
        - Afferent fibers fire at a rate proportional to the frequency of the stimulus
            - Other mechanoreceptors typically use the firing rate to encode the amplitude of the stimulus
        - However, the pacinian corpuscles, which dominate vibrotactile perception, have large receptive fields (low spatial resolution)
    - Skin stretch activates slow-acting (SA) and fast-acting (FA) mechanoreceptors
        - Humans are more sensitive to tangential forces than normal ones [3]
        - People reporte greater sensitivity when the skin stretch was applied in shear instead of compression of tension
    - Vibration [14] and skin stretch [5] can create the illusion of muscle movement
- Related work:
    - Vibrotactile:
        - Two main ways to implement vibration feedback:
            - Rotational motor with an unbalanced inertia
            - Linear actuator, such as a voice-coil or piezoelectric element
        - Motion across the skin can be conveyed by vibration arrays [28]
        - Experiments have evaluated subjects' ability to discriminate the frequency and amplitude of vibrotactile stimulations on their skin [22]
        - Subjects performed a telemanipulation task better with proportional vibration feedback applied to their fingertips than without [25]
    - Skin stretch:
        - Suction-based display that produces illusions of skin pressure [23]
- Experiment:

- Subjects were instructed to use a force-sensitive controller to move a cursor, displayed on a screen, a given number of steps
- Subjects could not see the cursor during trials, but were given a trial period before the experiment to learn the relationship between tactile feedback method and cursor position
- Four cases (in order), corresponding to different types of tactile feedback:
    - No feedback
    - Vibration (either 2nd or 3rd)
    - Skin stretch (either 2nd or 3rd)
    - No feedback again (to evaluate training effects)
- Technical implementation:
    - Vibrotactile feedback provided by a C2 Tator (EAI Inc.)
        - Consists of a linear electromagnetic actuator that produces relative motion between two moving parts
        - A mechanical resonance was found near 250 Hz, near the peak sensitivity of the pacinian corpuscles
    - Skin stretch provided by custom device:
        - Circular disc (d = 3.8 cm) with two smaller circular contact points (d = 0.127 cm) spaced 1.275 cm apart, in contact with the skin
        - Disc was rotated between +/- 45º, mapped to cursor position
        - Maintaining flat contact with the skin was important
- Results:
    - Measured three values:
        - Absolute error (**figure 9**)
        - Relative error (**figure 10**)
            - Absolute error divided by desired movement length
        - Final cursor velocity to measure of overshoot (**figure 11**)
    - In all values, skin stretch provided was better than vibration
- Discussion:
    - Skin stretch's superiority can be attributed to two factors:
        - The effective analog resolution of skin stretch is higher [1]
        - Skin stretch is an important part of the proprioceptive sense
    - Even though vibration was less effective, it is arguably more attractive than skin stretch for wearable devices due to its size and power characteristics
    - Issues to address when implementing skin stretch in a wearable device:
        - If skin contact area is small, care must be taken so that the device does not slip against the skin
        - The varying stiffness of skin on different parts of the body, as well as subject-to-subject variation of skin properties, present significant design and control challenges

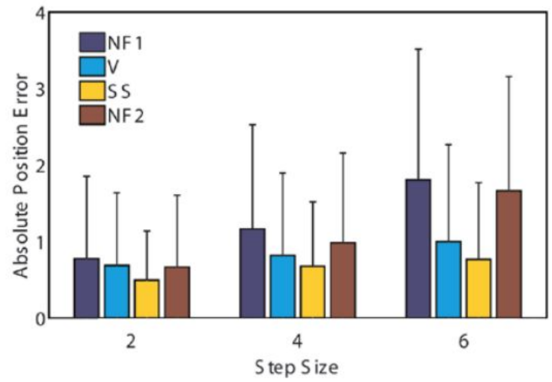


Figure 9: Average absolute position errors relative to step size. As expected, absolute errors tend to increase with increasing step sizes across all feedback modes. Both skin stretch and vibration feedback result in smaller errors at each step size, with skin stretch performing best, though not significantly.

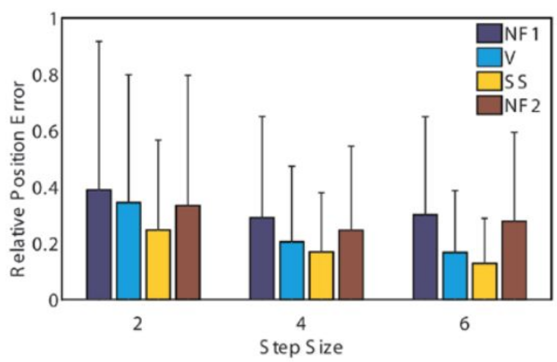


Figure 10: Average relative position errors by step size. The general trend is that relative errors decrease with increasing step sizes with feedback. At large step sizes (6), subjects perform significantly better ($p < 0.002$) with feedback than without, though there is no significant difference between skin stretch and vibration. In addition, relative error decreases significantly ($p < 1 \cdot 10^{-6}$) as step size increases from 2 to 6 when feedback is provided

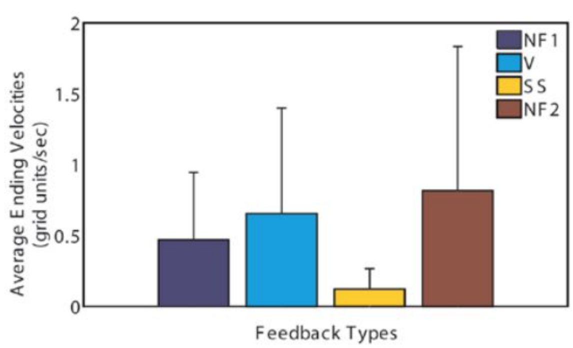


Figure 11: Overall average ending velocities. Skin stretch is far superior to all other feedback modes in maintaining low end velocities ($p < 1 \cdot 10^{-9}$).

EMS-based devices

Adding force feedback to mixed reality experiences 2018
Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch.

- Goal is to create a force feedback device that still gives users the use of their hands, cause in mixed reality stuff users encounter not only virtual objects, but real ones too
- Used EMS to render constraints on motion
    - Stopped a person from rotating a VR dial too far
    - Stopped person from moving through a wall
    - Simulated friction when pushing a simulated object
- Limitations:
    - Subject to the limitations of all EMS systems:
        - Requires electrode placement and per-user calibration prior to use
        - Can cause muscle fatigue
        - Actuation of hands is typically limited to a single dimension of translation
    - Doesn't integrate with tactile feedback systems
- Related work:
    - Haptics is divided into tactile feedback and force feedback
- Implementation:
    - Medical-grade muscle stimulator
    - Microsoft HoloLens
    - Laptop served as the interface between the two
- Electrode placement allowed the following motions:
    - Wrist extension
    - Wrist flexion
    - Wrist pronation
    - Wrist supination
    - Elbow flexion
    - Elbow extension
    - Shoulder stuff
- Results:
    - Perceived realism was higher with EMS than without
    - Participant comments:
        - "I immediately feel when I touch something"
        - "The muscle feedback makes pushing the couch much easier...I could not see if it was hitting the wall, but I could feel it"
        - "It helps me know how far I will shoot (the catapult) because I feel that the amount of EMS feedback is related to how much I pull"
    - Suggested points of improvement
        - Adding tactile stimulation to the user's hands
        - Finer EMS resolution
- Recommendations for future work:
    - Align haptic physics with expected physics as much as possible rather than resorting to exaggerations

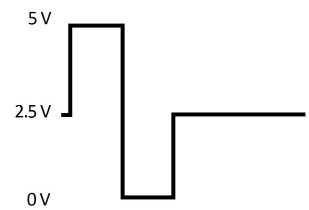
- Future work:
    - Simplify or automate electrode placement
    - Include calibration routines that users can invoke in runtime
    - Increase the system’s robustness to variations in body posture and muscular fatigue
    - Design control loops that distinguish between induced and voluntary muscle contractions

An electrical muscle stimulation haptic feedback for mixed reality tennis game 2007
Farzam Farbiz, Zhou Hao Yu, Corey Manders, and Waqas Ahmad.

- Goal:
    - Construct an EMS system that is wirelessly controlled from a computer
    - Simulate the force feedback effect caused by a collision
- Implementation:
    - Player sees the virtual ball through a head mounted display
    - Racket trajectory is calculated in each frame to estimate the collision time and the impact velocity
    - Microcontroller receives this information and generates EMS pulses at the time of the collision that are proportional to the collision impact
- Competitive advantage:
    - Wireless
    - Mobile
    - Low-cost
    - Does not need a ground reference like mechanical force-feedback systems
- Related works:
    - Mad Catz Bioforce:
        - Not a successful product because users expressed slight discomfort
        - There was no relation between haptic sensations and what was happening in the game, so the EMS feedback was unwarranted
        - In contrast, with the system developed by the authors the EMS feedback was a natural reaction to what was happening in the game

Muscle-propelled force feedback: bringing force feedback to mobile devices 2013
Pedro Lopes and Patrick Baudisch.

- Goal is to produce a mobile device, based on EMS, that is capable of producing force feedback
- Custom EMS hardware:
    - Biphasic signal generator
        - 25 Hz
        - 290 us pulse width
        - Example biphasic waveform -->



    - Arduino nano
    - Op amp
        - Max 50V/100mA over 500 ohm load
    - 9V battery
- Device achieved miniaturization by:
    - Eliminating mechanical actuators
    - Reducing battery size
        - Two orders of magnitude more energy efficient to actuate a muscle than to drive a motor
- Results:
    - At 1 second of high intensity stimulation participants produced an average of 18.7N of force

Providing haptics to walls & heavy objects 2017
Pedro Lopes, Sijing Young, Lung-pan Cheng, Sebastian Marwecki, and Patrick Baudisch.

- Goal is to prevent the users hands from penetrating virtual objects by means of EMS
- To simulate heavy objects, the systems actuates the respective *opposition* muscles
    - To put a load on the user's biceps, it acuates the triceps
    - To put a load on the user's pecs, it actuates the shoulder muscles
- Two things have substantial impact on the experience:
    - The intensity pattern used to actuate the user's muscles
    - The visuals and sound presented during the haptic event
- Criteria for measuring how good a haptic system is:
    - Believable: do users actually think it's real
    - Impermeable: does it stop the user from passing through objects
    - Consistent: do the visual and haptic sensations match
    - Familiar: does the sensation resemble objects from the real world
- Hard object design
    - Applied enough force to stop the user's arm completely from moving through a wall
    - Drawbacks:
        - The EMS signal became arbitrarily strong
        - The EMS signal activated muscles in the wrong direction
            - Instead of feeling a burning in their biceps when lifting a heavy cube, they felt a tingling in their triceps
- Soft object design
    - EMS intensity was cut off after a certain threshold
    - Users were allowed to penetrate objects by about 10 cm
    - Gave the impression of soft objects
- Repulsion object design
    - Short but intense EMS pulses (200-300 ms)
    - Repelled users hands rapidly
    - Coupled with a vibration motor on the user's hand to give tactile feedback and make the sensation more real
- Results:
    - The majority of participants picked the *repulsion* design as their favorite
        - Rated the most impermeable
- Limitations:
    - Users need to wear EMS equipment
    - The device works best for soft and repulsive objects, rather than truly rigid ones
    - Could add more channels to create more complex haptic fields, but that would also require attaching more electrodes and EMS hardware
- Participant response to "grabbing" a cube:
    - "Hard to believe, because there are many ways to hold it and (the EMS) does not always work that well."

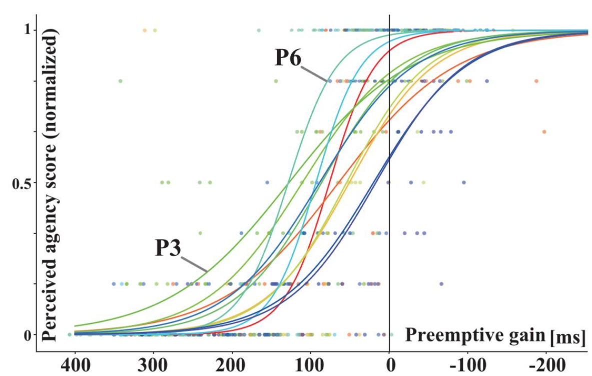
        - “I would also like to feel something in my hand, not just the muscles of the arm, it feels misplaced.”
- Hardware implementation:
    - 8-channel muscle stimulator (Hasomed Rehastim)
        - 100 mA per channel max
        - Commands generated from inside Unity3D
    - Modulated the pulse width, constant amplitude
        - Allowed greater control (sub-mA) than by varying the current
    - System required calibration:
        - Continuously increased current until they observed a small movement of the targeted muscle
    - VR was implemented in Unity3D
    - Tracked the user’s headset and hands using optical markers and cameras
        - 8x OptiTrack Prime 17W

Proprioceptive Interaction 2015
Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch.

- Proprioception is the users' sense of the relative position of neighboring limbs of the body. It can be used for input *and* output.
- Pose-IO (an input/output device using proprioception)
    - Produces output by writing to the user's arm muscles using EMS
    - Receives input from accelerometer
    - Motivations:
        - Allows for eyes-free and ears-free use
        - Symmetric setup (same limb for input and output) allows implementing the same interaction "language" for input and output, resulting in an intuitive interaction
    - Hardware setup:
        - EMS unit (TruTens V3)
            - 120 Hz, 100 mA max output with a pulse-width of 150 us
        - 4 pre-gelled electrodes (50x50mm)
        - Arduino connected to bluetooth module
        - Amplifier for EMS output
        - WAX9 3-axis wireless accelerometer
        - 3 x 3.7V LiPo batteries
        - Voltage regulator (L7809CV)
    - 4 hours of battery life
    - Used PID control loop to drive the user's arm to a given setpoint
- Related work:
    - Proprioception is independent from the visual and auditory channels
    - Sense of position comes from muscle spindles and golgi tendon organs
    - Wearable devices that use the body as input:
        - Skinput [13]
        - Imaginary interfaces [11]
        - Imaginary phone [12]
    - While mechanical actuators are great for their accuracy and output power, they require attaching exoskeletons, motors, and large batteries to the user
    - The discomfort caused by EMS is being addressed by multipath stimulation [23] and microelectrode arrays [4]
- They drove a user's hand to a position, then asked them to recreate that position
    - Participants recreated poses with an average error of 5.8º across all trials
    - The conditions were ideal though, so this is really a lower bound of the error
- Wondered how users perceive the aspect of "limb ownership" in proprioceptive interaction and what emotional response it might produce

Preemptive action: accelerating human reaction using electrical muscle stimulation without compromising agency 2017
Shunichi Kasahara, Jun Nishida, Pedro Lopes.

- Goal:
    - Find a relationship between agency and the gain in preemption (i.e. how much a system speeds up a user)
- Background:
    - Haptic actuated systems offer the potential to speed up a user's physical reaction time by means of preemptive actions
    - Interactive systems that act automatically and preemptively will reduce the user's sense of being in control [5, 42]
- Related ideas:
    - Three principles that condition the sense of agency [59]
        - *Priority*: conscious intention to perform an act must immediately precede the action, which should precede the outcome
        - *Consistency*: the sensory outcome must fit the predicted outcome
        - *Exclusivity*: one's thoughts must be the only apparent cause of the outcome
    - The perception of time is what binds together the degree of association we create between a voluntary action and its outcome [31, 21]
    - Discrepancies between our sense of time and our sense of action reduce our sense of agency [12]
- Design considerations:
    - While designing interactive systems, the sense of agency is key to achieve a user experience that grants a sense of control to the user
- Related work:
    - Stimulated Percussions
        - An EMS-based system that actuates a drummer's hands to automatically make the user play at the correct tempo [14]
    - Affordance++
        - Forces users to shake a can of spray paint [38]
    - Wired Muscle
        - Speeds up a user's reaction time with EMS so that they can pass the pen-drop test [46]
- Results:
    - Graph describing agency as a function of preemption (gain of zero corresponds to moving the user's hand when they would've anyways)



PossessedHand: techniques for controlling human hands using electrical muscle stimuli 2011
Tamaki, E., Miyaki, T., and Jun Rekimoto.

- Goal:
    - Introduce PossessedHand, a device with a forearm belt that can control several hand gestures and inform their timing
- Background and related work:
    - The muscles involved in finger motions are clustered in the forearm [3, 23]
    - The wrist can be controlled with two degrees of freedom by stimulating four muscles [15, 30]
        - Used invasive electrodes embedded in the skin
    - Types of electrode pads:
        - Dry type:
            - Made of metallic sheets, can cause pain
            - Used to get galvanic skin response (GSR) values
        - Liquid gel type:
            - Have a sponge base
            - User must apply a liquid gel before placing the pad
            - Causes pain when the skin becomes dry
        - Solid gel type:
            - Include conductive gel on thin metallic sheets
            - Does not cause much pain because the pads attach consistently to the user's skin and the contact area does not decrease
- Implementation:
    - Stimulates seven muscles:
        - Superficial flexor, deep flexor, long flexor, common digital extensor, flexor carpi radialis, long palmar, and flexor carpi ulnaris
        - Five EMS channels to stimulate the muscles used to bend finger joints
        - Two EMS channels to cause wrist flexions
    - Selects the depth of the muscle by different stimulation levels
        - E.g. the flexor digitorum superficialis and the flexor digitorum profundus are located on top of one another
        - It is difficult to select them without the use of invasive needles
        - The two muscles trigger at different intensities of stimulation , though they are still coupled to some degree (see **figure 5**)
    - Device specifications:
        - Consists of a battery, condenser, switching board, and microcontroller
        - 40 Hz stimulation, pulse width of 0.2 ms, voltage in the range of 17-29 V
        - Used 24 solid gel type electrode pads (10 x 30 mm self stick tyco gel carbon electrodes) on two belts (see **figure 6**)
            - 14 electrodes places circumferentially on upper belt
            - 10 on lower belt, so 140 possible paths for current to flow

- Calibration instructions:
    - Wear possessed hand
    - Auto-calibration gives 168 stimulation patterns that include 14 paths and 12 stimulation levels
    - Push the joint button on the gui when the joints are moved
    - System records the correspondence between path, muscle, and stimulation level
- Results:
    - System was able to move finger joints (see **table 1**), but most joint movements were coupled to other joint movements because the system could not activate singular muscles
    - All forces were too weak to grasp real objects (see **figure 9** and **figure 10**)

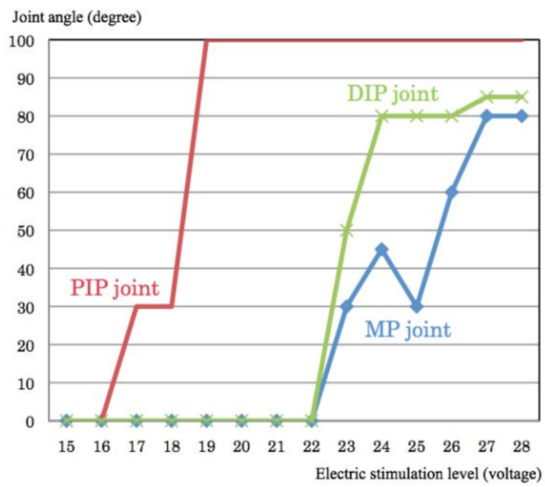


Figure 5. An example of the selected muscle depth and movement by the electric stimulation levels (voltage). Blue line with Diamond makers: MP joint movement. Red line: PIP joint movement. Green line with times makers: DIP joint movement.

Table 1. Probability of each joint movement (%)

joint name	with other joints	independently
MP(Index finger)	100	0
MP(Middle finger)	100	0
MP(Medicinal finger)	100	0
MP(Littile finger)	100	0
PIP(IP) (Thumb)	100	0
PIP(Index finger)	100	100
PIP(Middle finger)	100	100
PIP(Medicinal finger)	100	100
PIP(Littile finger)	100	12.5
DIP(Thumb)	100	12.5
DIP(Index finger)	100	0
DIP(Middle finger)	87.5	0
DIP(Medicinal finger)	75	0
DIP(Little finger)	87.5	0
Palmar flexion	100	0
Dorsal flexion	100	0
Radial flexion	37.5	0
Ulnar flexion	0	0

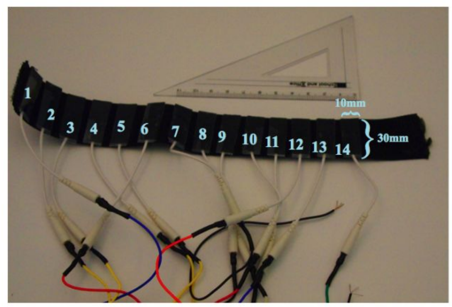


Figure 6. A belt and pads.

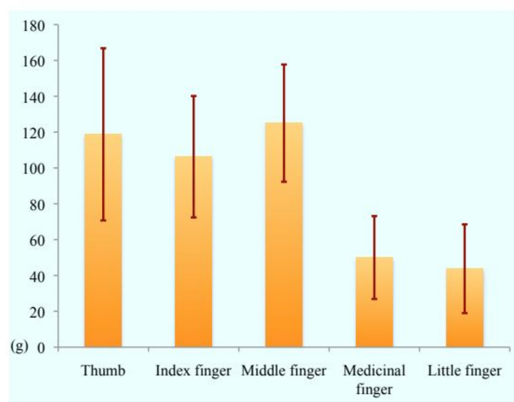


Figure 9. Measured forces for each finger.

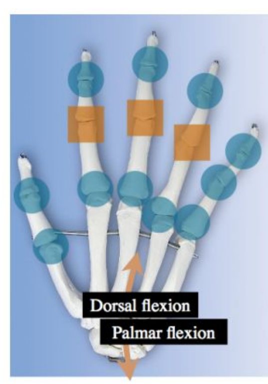


Figure 10. Operable joints. Squares indicate independently operable joints. Arrows and circles indicate ganed operable joints.

Impacto: simulating physical impact by combining tactile stimulation with electrical muscle stimulation 2015
Pedro Lopes, Alexandra Ion, and Patrick Baudisch.

- Goal:
    - Build a device that simulates physical impact by decomposing the impact stimulus into two sub stimuli, each of which can be rendered effectively
    - These two stimuli are:
        - Tactile (pressure sensed by skin)
        - Force feedback (movement of body in response to the impact)
- Background:
    - *Impact*: the sensation of hitting or being hit by an object
    - Tapping the skin leads to a better tactile sensation than vibrotactile actuation because the taping stimulates the SA1 receptors that sense pressure
        - Vibrotactile feedback is only sensed by the pacinian corpuscles [18]
- Benefits and contribution:
    - Makes the simulation of a strong impact feasible in a small form factor
    - Disadvantages:
        - Simulating multiple impact locations require multiple units
        - Using a solenoid adds inherent latency
- Mechanical implementation:
    - Solenoid to tap the skin when the virtual impact occurs
    - At the end of the solenoid are exchangeable 3D printed tips to refine the desired tactile experience
    - EMS to trigger force feedback
- Electrical implementation:
    - See figure 1
    - 22.2 V, 1050 mAh LiPo battery pack
    - Arduino pro micro
    - Bluetooth module (RN42XVP)
    - EMS unit (TruTens V3)
    - Relay (HFD4/3) to turn EMS unit on/off
    - Power consumption: EMS (0.1 A), solenoid (0.7 A), arduino/bluetooth (0.2 A)
- Results:
    - See figure 2
    - Higher solenoid intensity and higher EMS intensity both led to a higher “realism” rating than either feature alone
- Notes:
    - State-of-the-art EMS systems are starting to feature closed-loop sensing with galvanic reading of the user’s skin resistance [6]

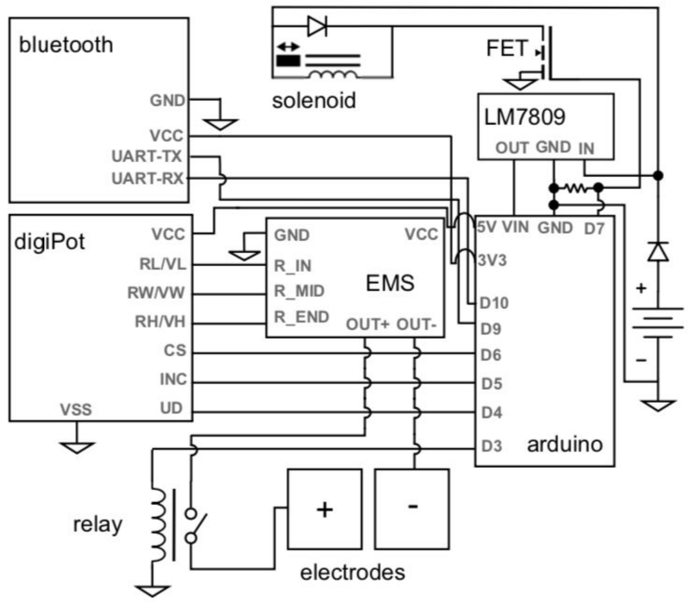


Figure 1

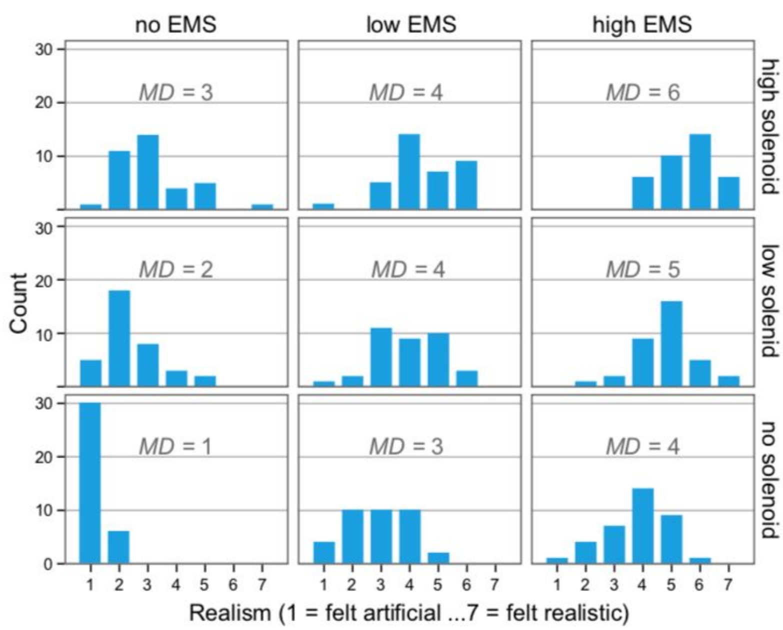


Figure 2

EMS general research

Implanted user interfaces 2012
Holz, C., Grossman, T., Fitzmaurice, G., and Agur, A.

- Goal:
  - Explore four core challenges of implanted devices:
    - How can users produce input?
    - How can the device provide output?
    - How can the device communicate and transfer information?
    - How can the device remain powered?
  - Perform a technical evaluation of various implanted devices
- Related work:
  - Input has been sensed by:
    - Muscle tension [37]
    - Tongue motions using prototypes worn inside the mouth [21, 36]
    - Micro-devices integrated into worn contact lenses [19]
  - Output with the body has been achieved by:
    - EMS systems
    - Electrodes that stimulate the user's ear to influence the sense of balance [9]
  - Wearable devices:
    - Ultra-small visual sensors [31]
    - Clothing has been made interactive by using conductive thread to sense pinches [24] and touch on clothing, such as on keypads made of fabric [33] or entire touchpads [35]
  - Human implants:
    - Powered implanted electrodes using induction through the scalp [30]
    - Implanting a small magnet in the user's finger [48]
    - RFID implants to automatically open doors and turn on lights [46]
      - Also discussed interaction with the user's nervous system
    - Body area networks [22]
    - Transmit recorded sounds wirelessly [43]
- Design considerations:
  - Contact-based input through the skin:
    - Button
    - Tap and pressure sensors
    - Brightness and capacitive sensor
  - Alternative methods of input:
    - Implanted microphone
    - Small exposed camera [20, 31]
  - Output methods:
    - Visual output such as LEDs (low-bandwidth)
    - Audio output (also low-bandwidth and audible to others in the vicinity)
    - Tactile output

- Communication methods:
    - Bluetooth for short-range p2p communication
    - WiFi (longer range, but requires more power)
- Power supply:
    - Replaceable battery (such as the ones used in pacemakers)
    - Rechargeable batteries with inductive charging [34]
    - Harvest energy from body functions:
        - Heartbeats [27]
        - Body heat [39]

- Experiment:
    - For input:
        - Button (PTS125)
        - Pressure sensor (0.2” Interlink circular force sensor)
        - Touch sensor (Murata 20mm piezoelectric disc)
        - Capacitive sensor (AD7746)
        - Brightness sensor (12mm cadmium sulfide photoresistor)
        - Microphone
    - For output:
        - Speaker (only relevant output device)
    - Communication:
        - Bluetooth module (Roving Networks RN-42)
        - Connected to ATmega328
    - Power:
        - Inductive charging system (PMR-PPC2 universal power-cube receiver, PMM-1PA powermat)
- Results:
    - Pressure sensor:

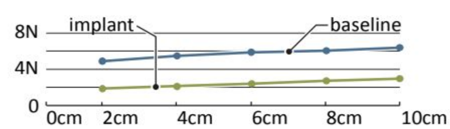


Figure 6: On average, skin accounts for 3N overhead for impact forces on pressure and touch sensors.

- Tap sensor:

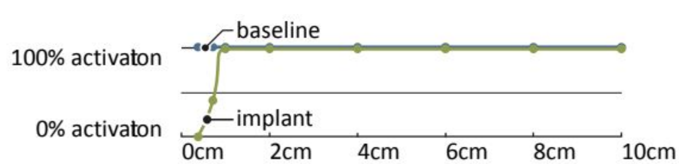


Figure 7: The piston activated the button from all tested heights in the baseline condition, but activated the button reliably only from a height of 1cm and up when implanted.

- Brightness and capacitive sensor:

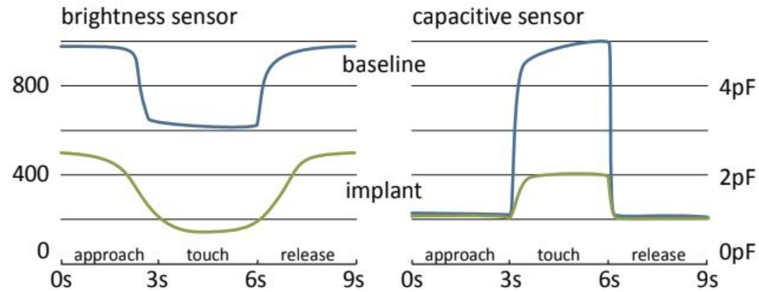


Figure 8: (left) Impact on sensed brightness and on sensed capacitance (right). Curves average the values of all five trials.

- Speaker (output):

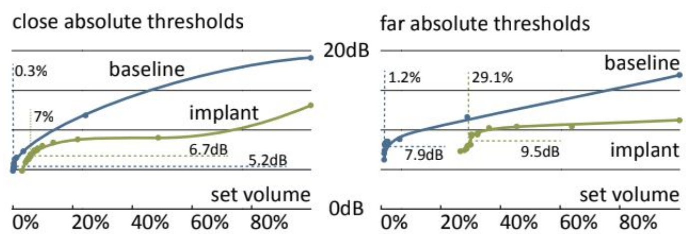


Figure 11: Sound perception through skin is possible, but skin substantially takes away from the output intensity (left). This effect grows with the distance between listener and speaker (right). Dotted lines indicate absolute perception thresholds.

- Microphone (input):

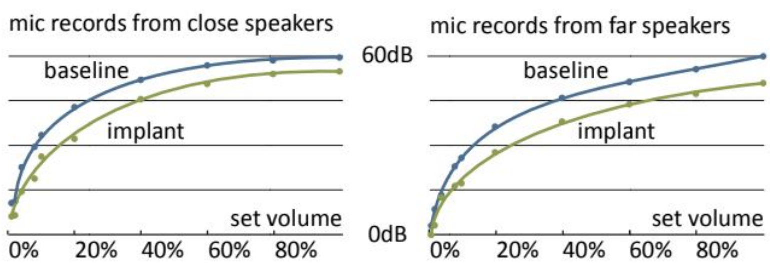


Figure 12: The differences in perceived sound intensities were nearly constant between the implant and the baseline session.

- Inductive charging:

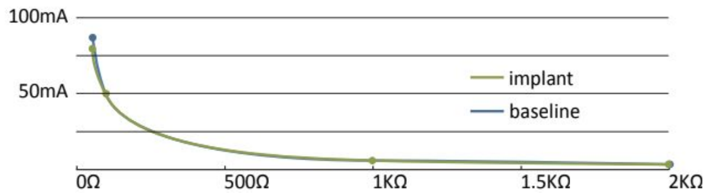


Figure 14: Skin affected the current provided through the wireless connection only at higher current values.

- Communication:

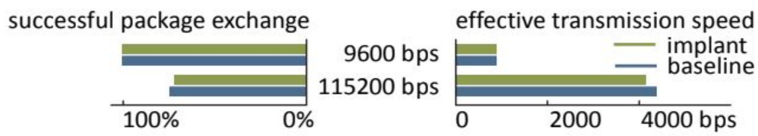


Figure 15: (left) Bluetooth exchanges data reliably when running slow, but comes with data loss when running fast. (right) Implanting affected fast transmission rates negatively.

Motor-based devices

SPIDAR-G&G: a two-handed haptic interface for bimanual VR interaction 2004
Murayama, J., Bougrila, L., Luo, Y., Akahane, K., Hasegawa, S., Hirsbrunner, B., Sato, M.

- Goal:
    - Present a new haptic interface that provides users with the ability to use both hands to interact with virtual objects in an intuitive manner
- Related work:
    - Non-haptic-feedback devices:
        - 3-Draw system [5]
        - ToolGlass and Magic Lenses [6]
        - Neuro-surgical planning system [7]
        - Responsive Workbench system [8]
    - Haptic feedback devices (all previous versions of the device presented here):
        - Original SPIDAR [12]
        - SPIDAR-8, a two-handed, multi-fingered, string-based haptic device [15]
        - SPIDAR-G [16]
            - 6 DOF, string-based force feedback
- Implementation:
    - SPIDAR-G&G is two SPIDAR-G's next to each other, one for each hand
        - Users are required to grasp a special grip provided by each SPIDAR-G
        - The sphere can be moved and rotated within a 20 cm cubic frame
    - System senses position and orientation by measuring the strings' lengths
    - System outputs force feedback by controlling the tension of each string
        - Tension is created by a DC motor
- Experiment:
    - Subjects were asked to bring a virtual pointer into contact with a set of targets positioned on the surface of a floating virtual sphere
        - Compared SPIDAR-G vs. SPIDAR-G&G
        - Compared haptic feedback vs. no haptic feedback
- Results:
    - The task time of uni-manual manipulation by SPIDAR-G alone was longer than bi-manual manipulation by SPIDAR-G&G
    - The task time with haptic feedback was shorter than the task time without

Input/sensing methods

(coming soon)

Related technology

(coming soon)