Contributions to the Design of Novel Hand-based Interaction Techniques for Virtual Environments

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Advisors
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Using our hands in virtual environments

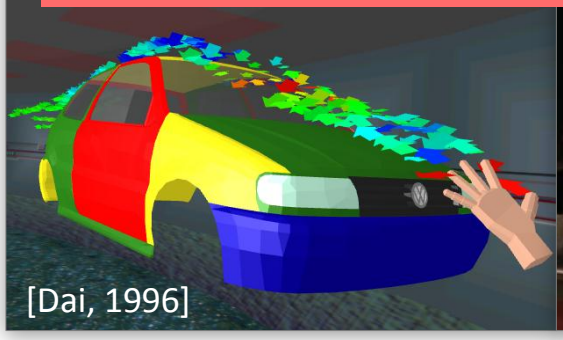
- ***The hand in the real world***
  - Action
    - Strength or precision
    - High flexibility
  - Perception
    - Different scales
    - High sensitivity to *touch*
- ***The hand in virtual environments***

[Catmull, 1972]

[Fisher, 1986]

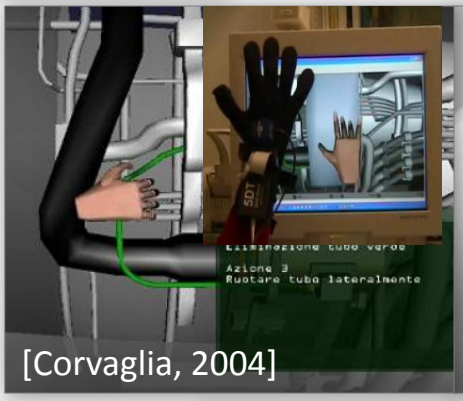
Applications of hand-based interaction

Virtual prototyping


[Dai, 1996]


[Seth, 2006]

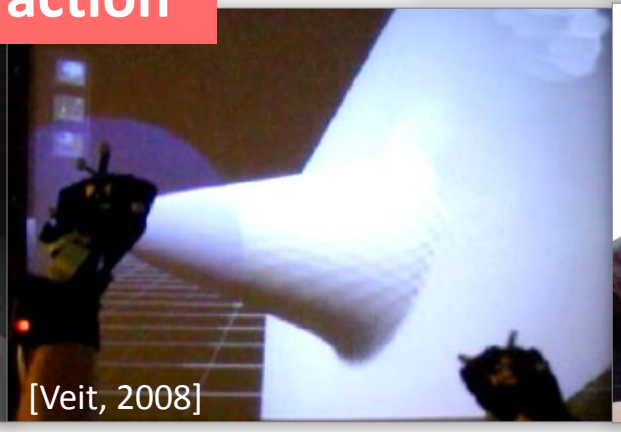
Virtual training


[Corvaglia, 2004]

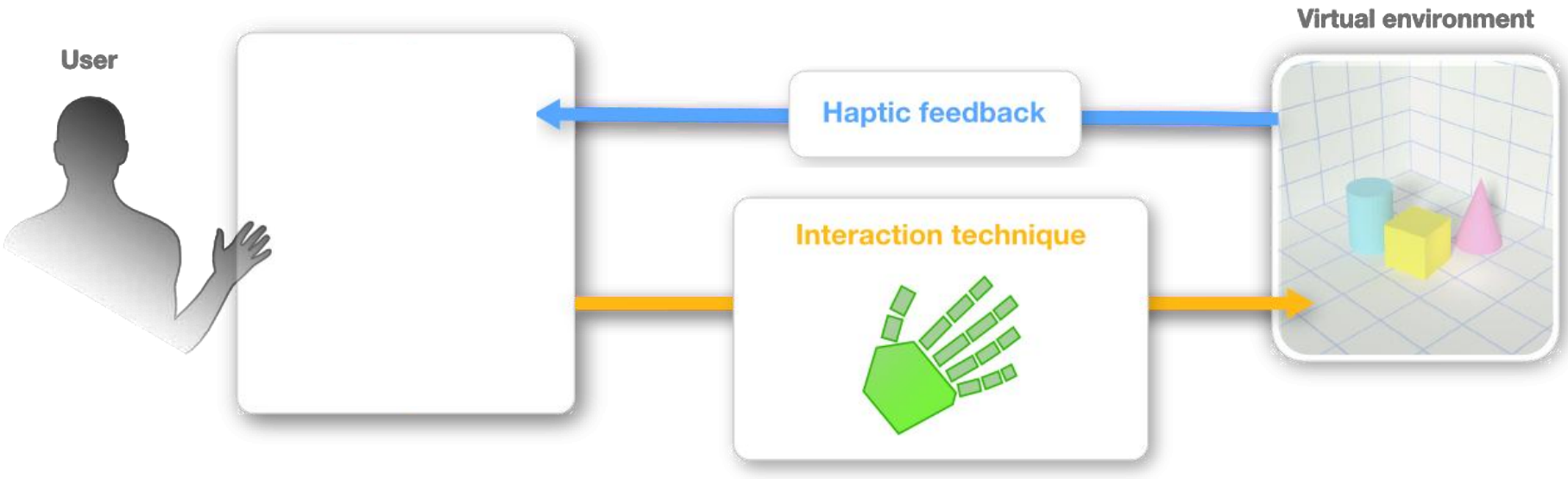

[Dinsmore, 1997]

Dextrous interaction


[Cutler, 1997]


[Veit, 2008]

Context of hand-based interaction in VR



Virtual reality (VR)

Immersive computer simulations that users can interact with and perceive

3D interaction techniques

Methods allowing users to accomplish a task via the user interface

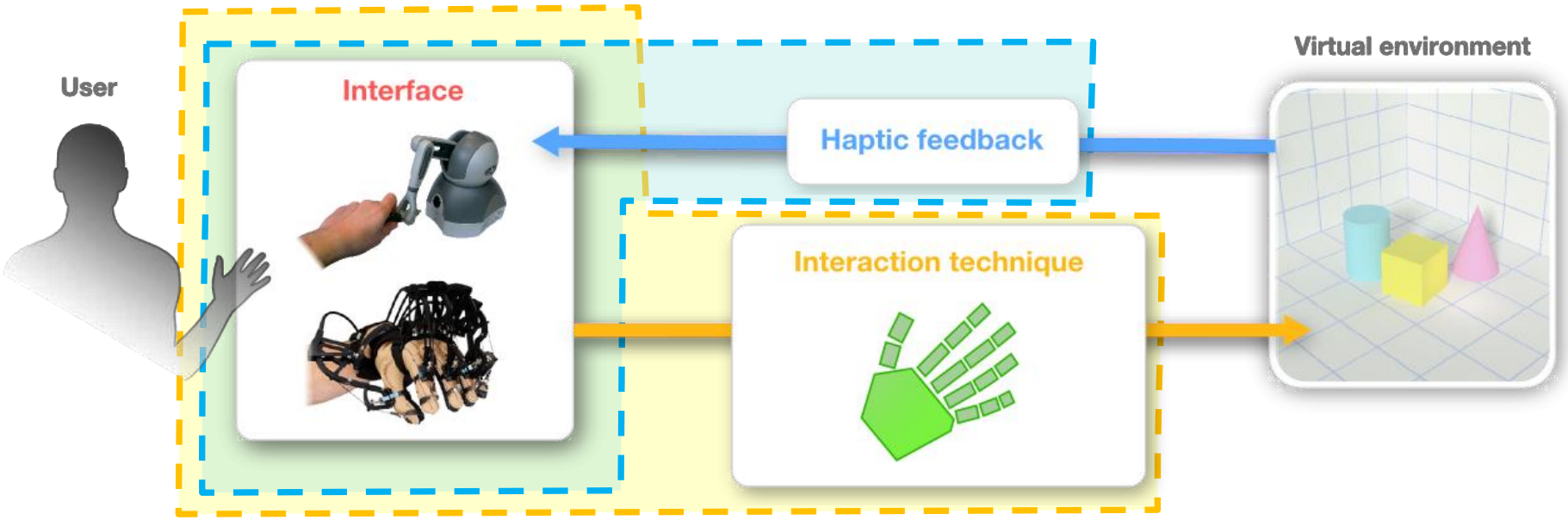
Haptic feedback

Sensory information relating to the sense of t*ouch*

Challenges of hand-based interaction

Challenge 2

Providing convincing haptic sensations



Challenge 1

Handling the many DoF of the hand

Degrees of freedom (DoF)

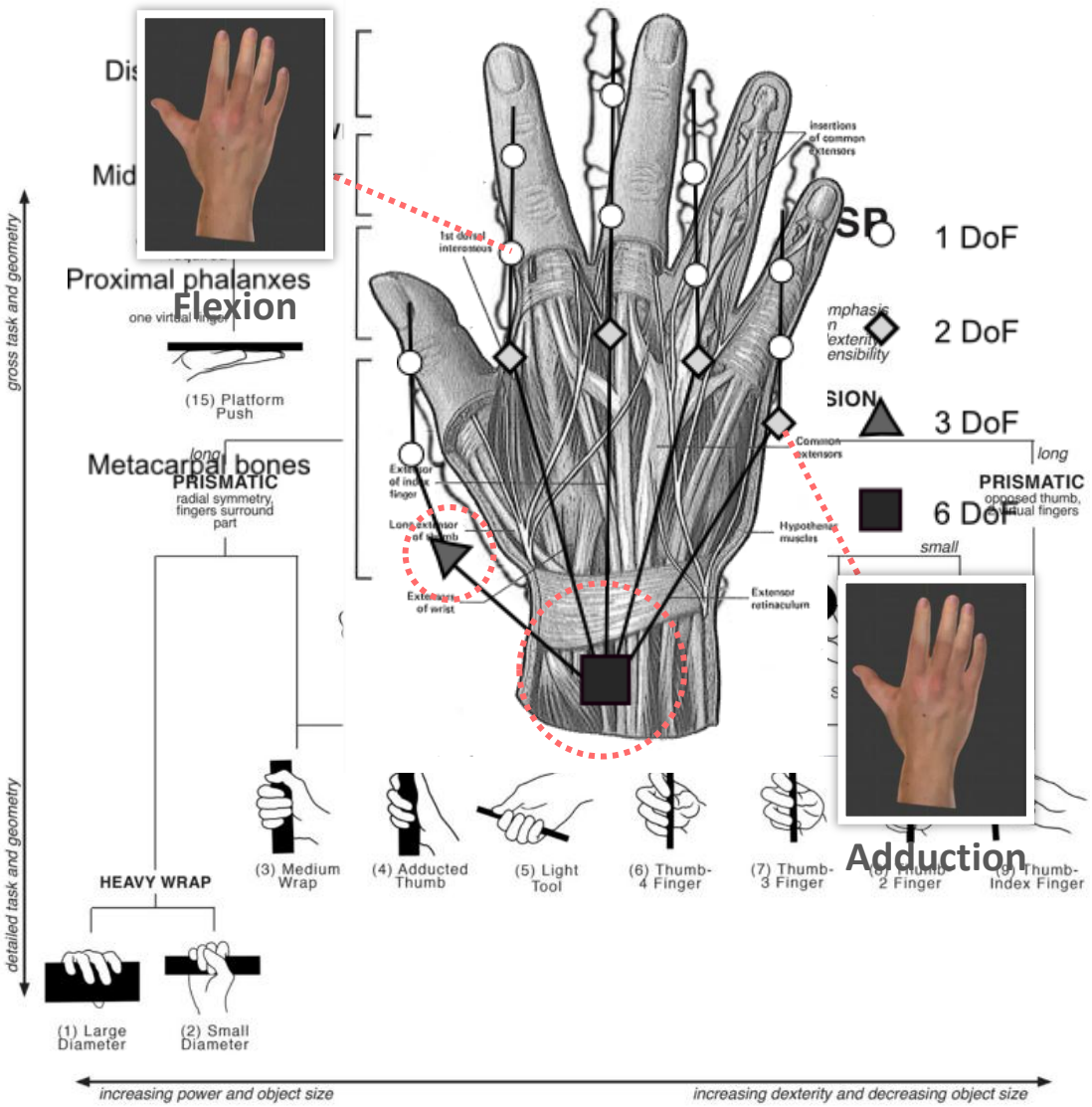
Independent parameters of a system defining its mechanical configuration

Related work – The human hand

- **Mechanics of the hand**
  - Highly articulated skeleton
  - Extrinsic muscles
  - 27 DoF in a small volume

    [ElKoura, 2003]

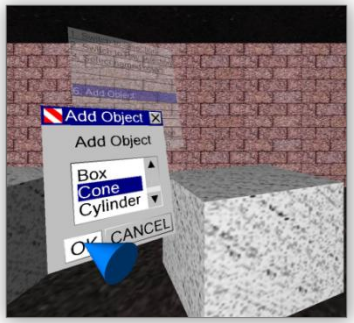
- **Function of the hand**
  - Depends on object shape
  - Depends on intended action



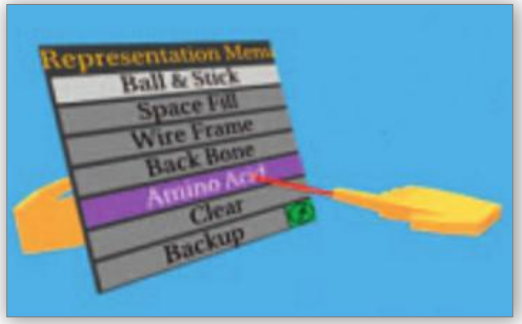
[Cutkosky, 1986]

Related work – Virtual hands

- **Rigid proxies**
  - ✓ Simple simulation
  - ✗ Limited to abstract interaction

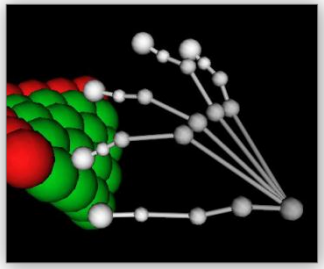


[Boeck, 2004]

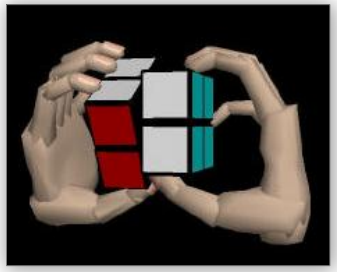


[Craig, 2009]

- **Articulated rigid hands**
  - ✓ Enable grasping
  - ✗ Only simulate hard contacts



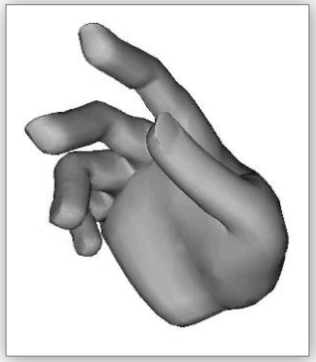
[Maciel, 2004]



[Borst, 2005]

- **Deformable models**
  - ✓ Realistic interaction
  - ✗ Higher computational cost

[Jacobs, 2011]



[Talvas, 2015]

Challenge 1

Handling the many DoF of the hand

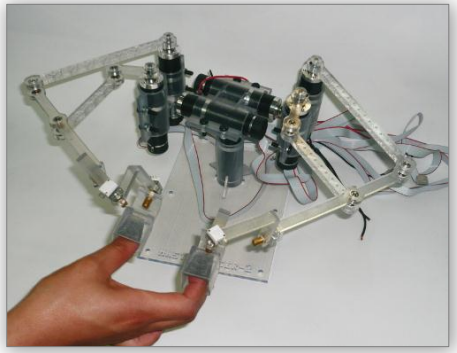
Related work – Haptic hardware

Whole-hand | **Multi-finger**

Desktop

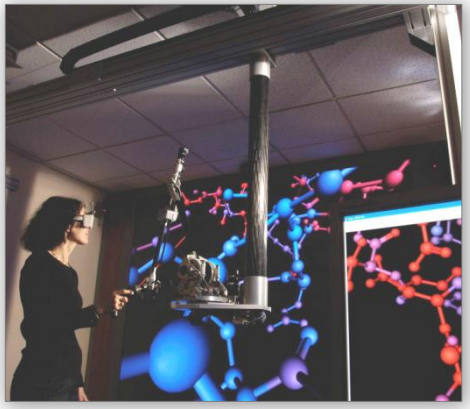
(Geomagic)

(CyberGlove Systems)



[Monroy, 2008]

Mobile



(Haption)

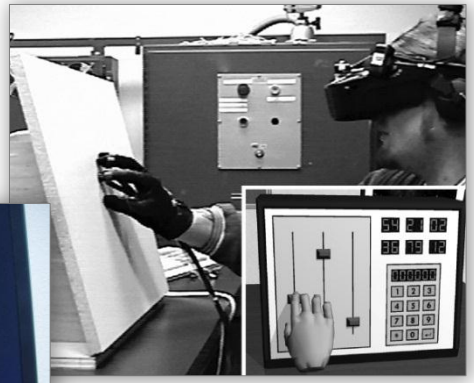
(CyberGlove Systems)

Challenge 2

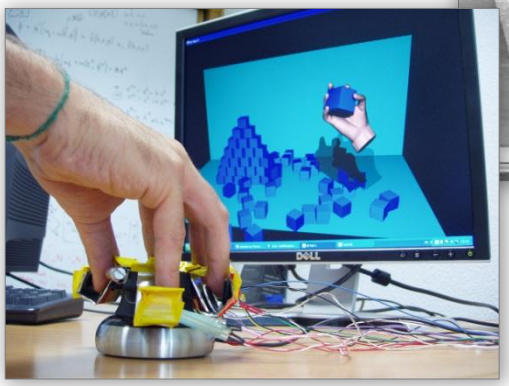
Providing convincing haptic sensations

Related work – Passive and pseudo-haptics

- **Passive haptic feedback**
  - Real objects to provide haptic cues
  - Elastic input devices
  - ✗ Less flexible than active haptics

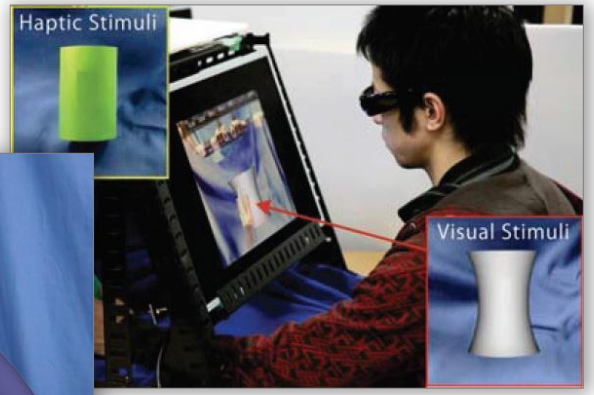


[Borst, 2005]



[Kry, 2008]

- **Pseudo-haptics** [Lécuyer, 2000]
  - Leverages the visual dominance on the perception of physical properties
  - For hand-based interaction: alter the motion of the user's hand

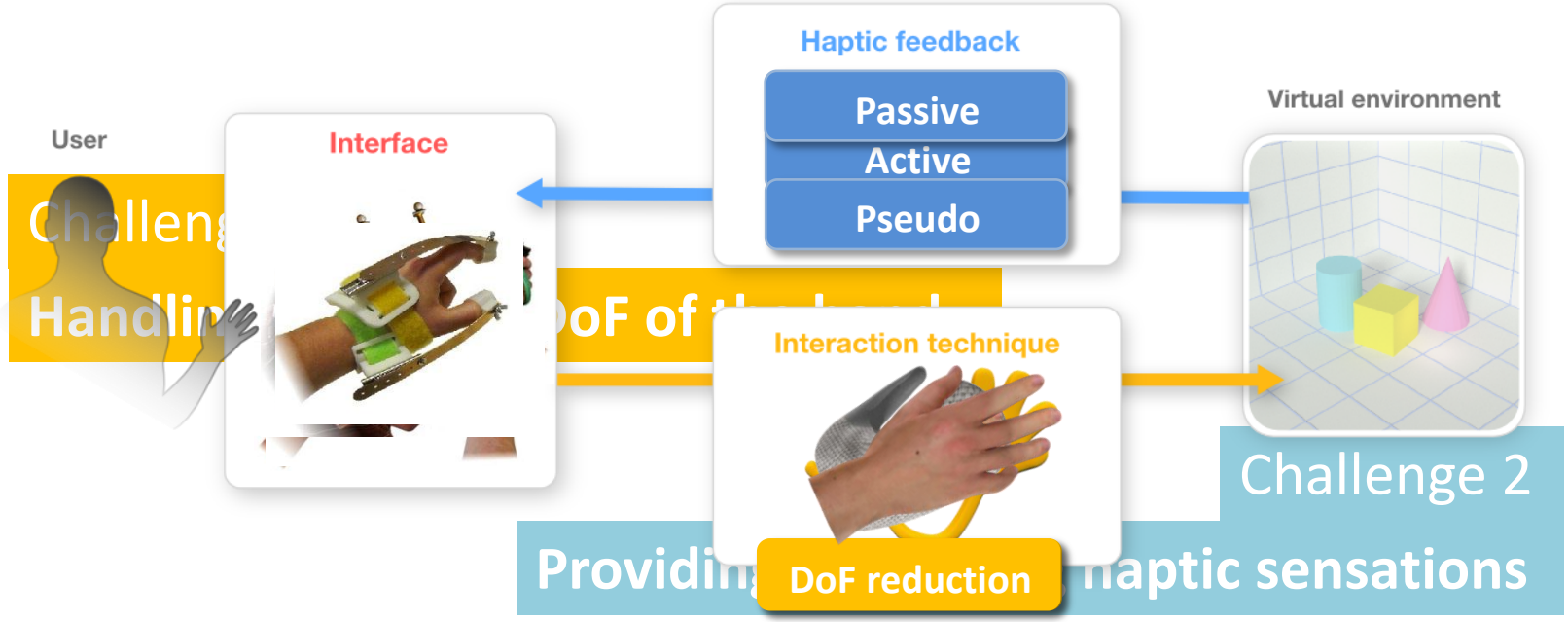


[Ban, 2012]

[Pusch, 2008]

Contributions

Objective: Improve hand-based interaction in virtual environments



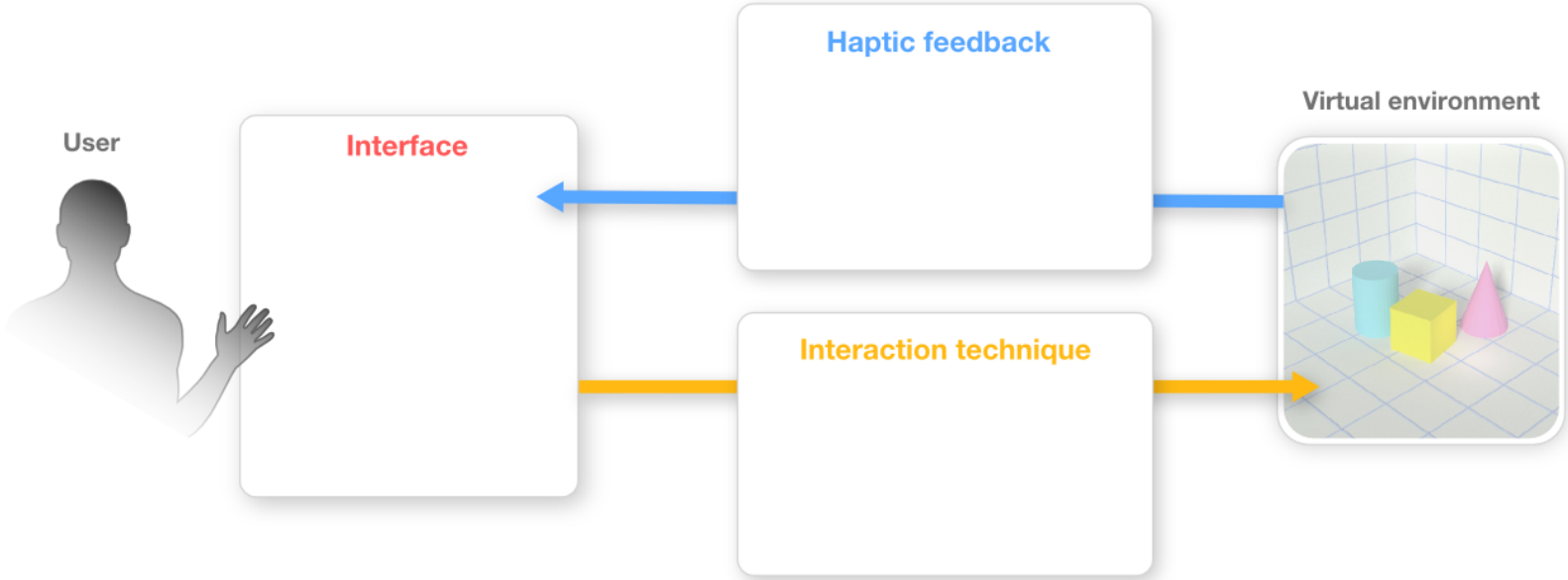
Axis I: **Improving the control of articulated hands**

Axis II: **Improving feedback with passive and pseudo-haptics**

Level of detail

DoF reduction **DoF separation** **Whole-hand** **Grasping** **Multi-finger**

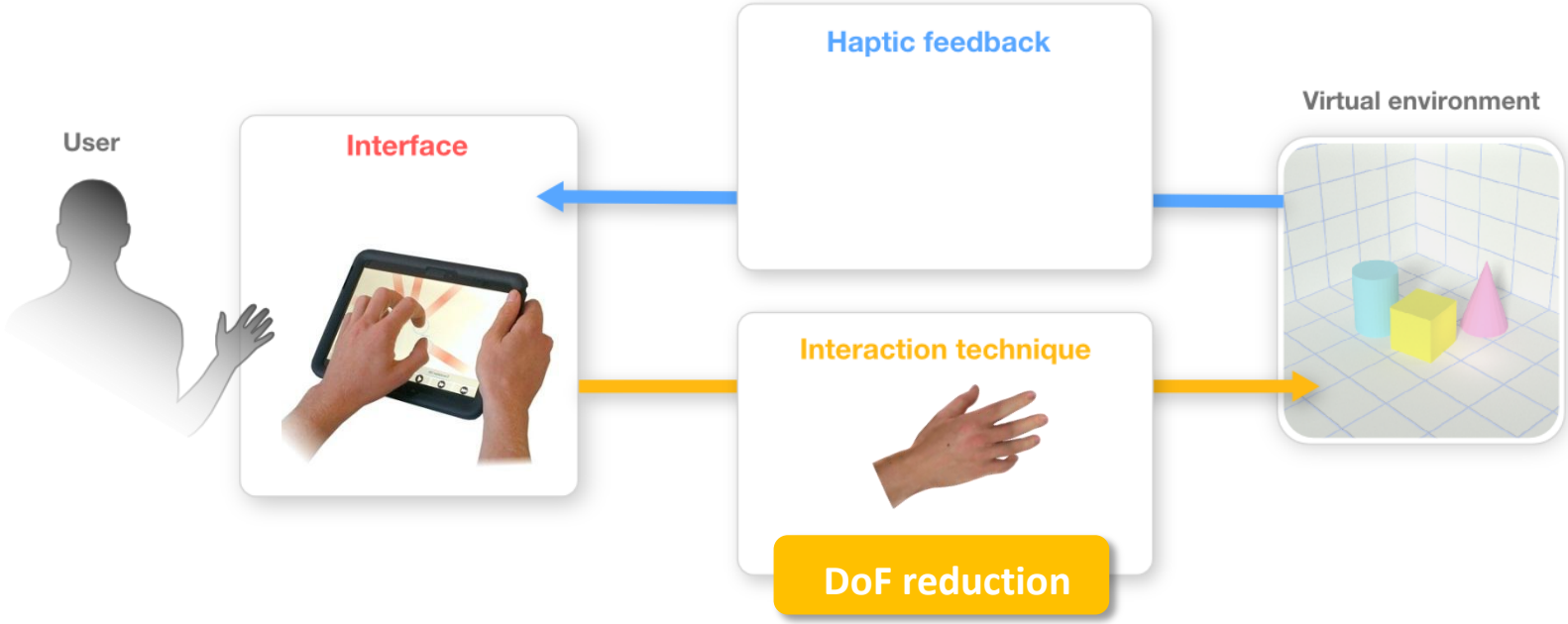
Axis I: Improving the control of articulated hands



Axis I: **Improving the control of articulated hands**

DoF reduction **DoF separation**

Contribution #1: THING



Axis I: **Improving the control of articulated hands**

DoF reduction

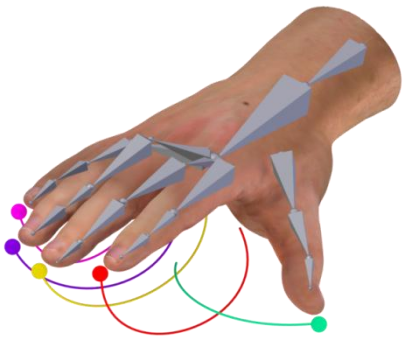
A multi-touch interaction technique for controlling 3D hand models

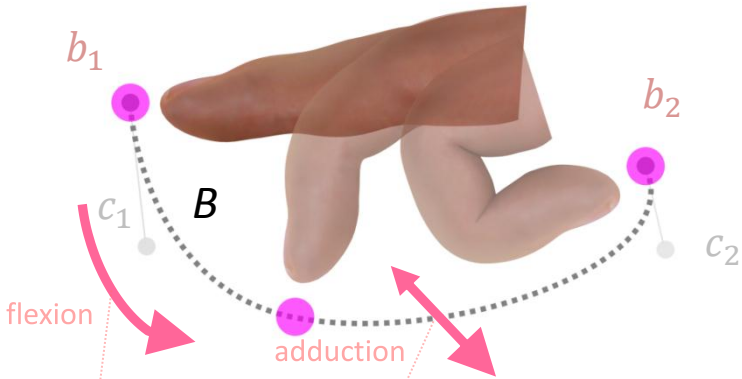
- **Approach**
  - **Reduce DoF** of hand models to couple them to **common input devices**

- ***THING*** *(in reference to the Addams Family character)*
  - Multi-touch control for animating hand models
  - Fingers animated via gestures on the tablet
  - Global position controlled via two variants, *mobile* and *desktop*

Animating the fingers

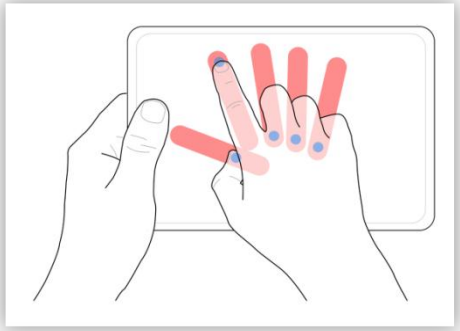
Hand model

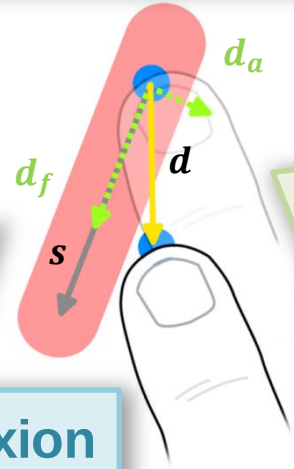




For each fingertip, $\boldsymbol{p_n} = B(f_n) + a_n * \left((\boldsymbol{c_1} - \boldsymbol{b_1}) \times (\boldsymbol{c_2} - \boldsymbol{b_2})\right)$

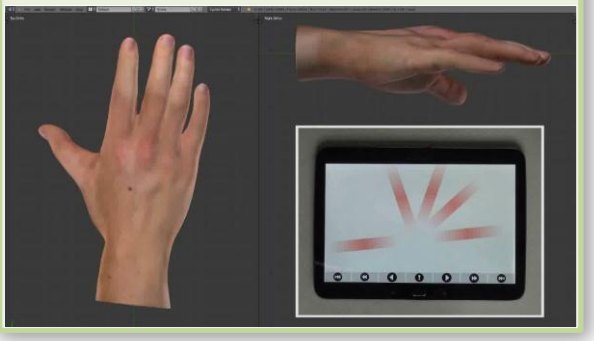
Multi-touch input





Adduction

$$a = \underbrace{sign(\boldsymbol{d} \cdot \boldsymbol{s}^{\perp})\,|\boldsymbol{d_a}|}_{\text{adduction/abduction}}$$

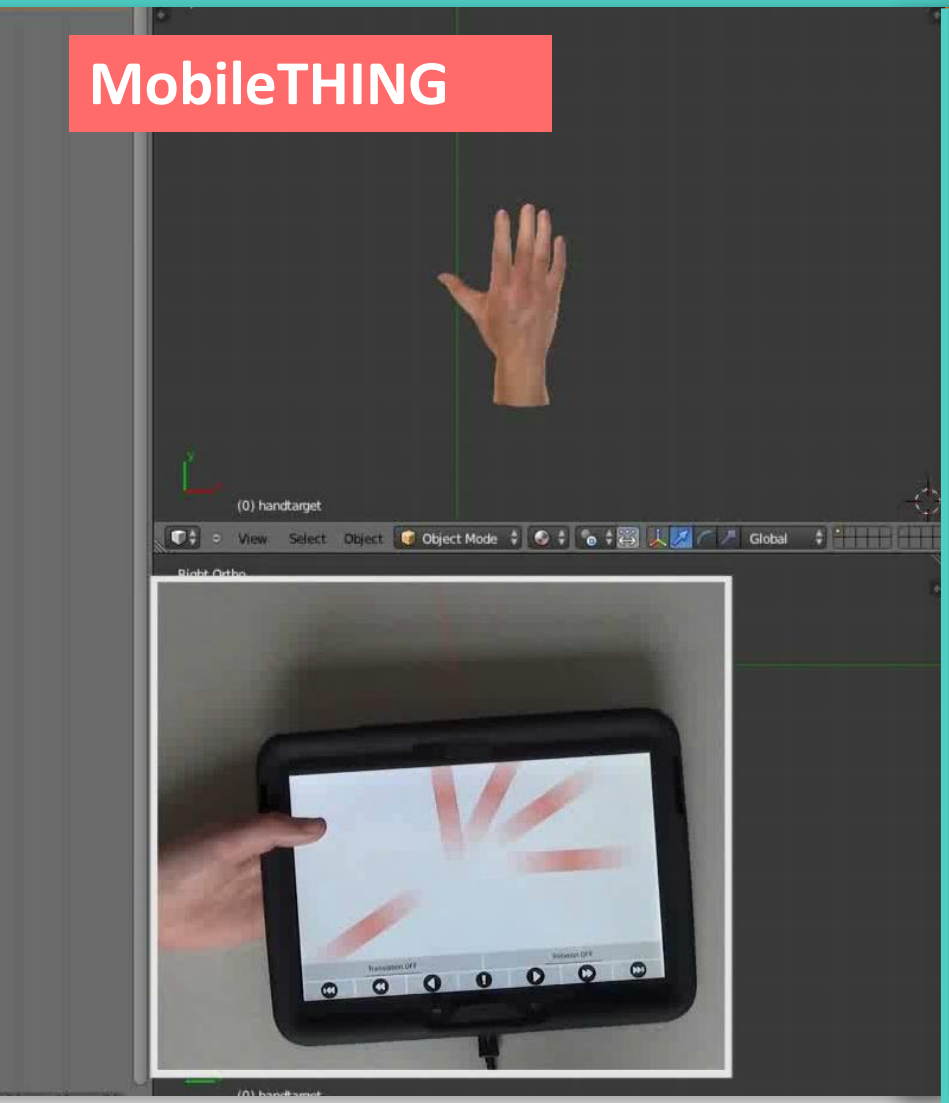


Flexion

$$\Delta f = \underbrace{|\boldsymbol{d_f}|\, sign(\boldsymbol{d} \cdot \boldsymbol{s})}_{\text{flexion/extension}}\, \underbrace{G(\boldsymbol{v_f})}_{\text{gain function}}$$

Moving the hand: two variants

MobileTHING

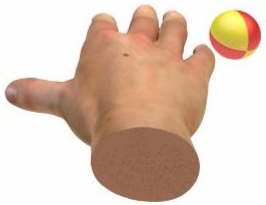


- All DoF integrated on the tablet
- Move and tilt controls

DesktopTHING

- Position DoF delegated to traditional mouse controls

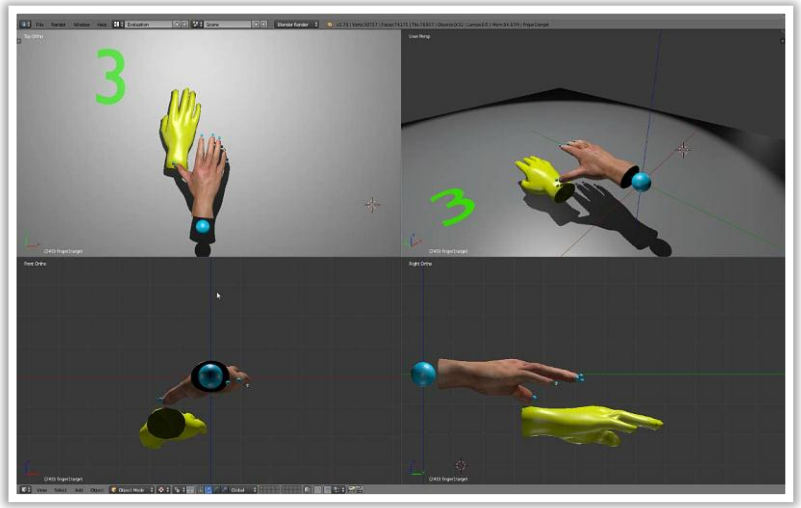
Example



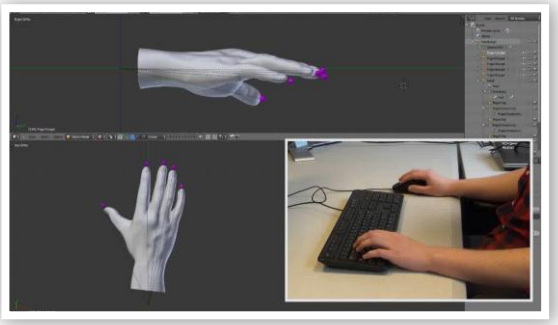
- Integrated in the Blender 3D editor
- Animation produced in ~7 minutes

User study #1

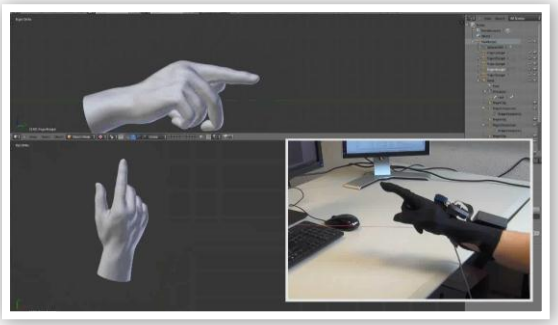
- **Objective**
  - Compare MobileTHING to traditional techniques of computer animation
- **Task**
  - Reproduce predefined postures



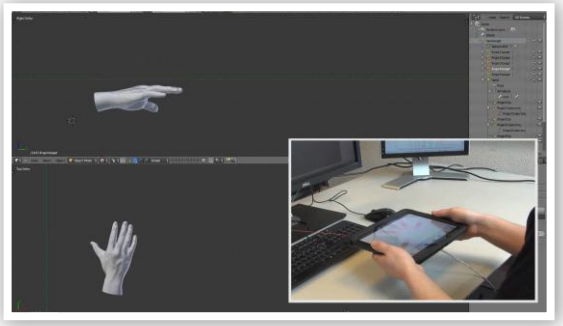
3 techniques × 4 poses × 5 repetitions × 12 participants



Computer mouse



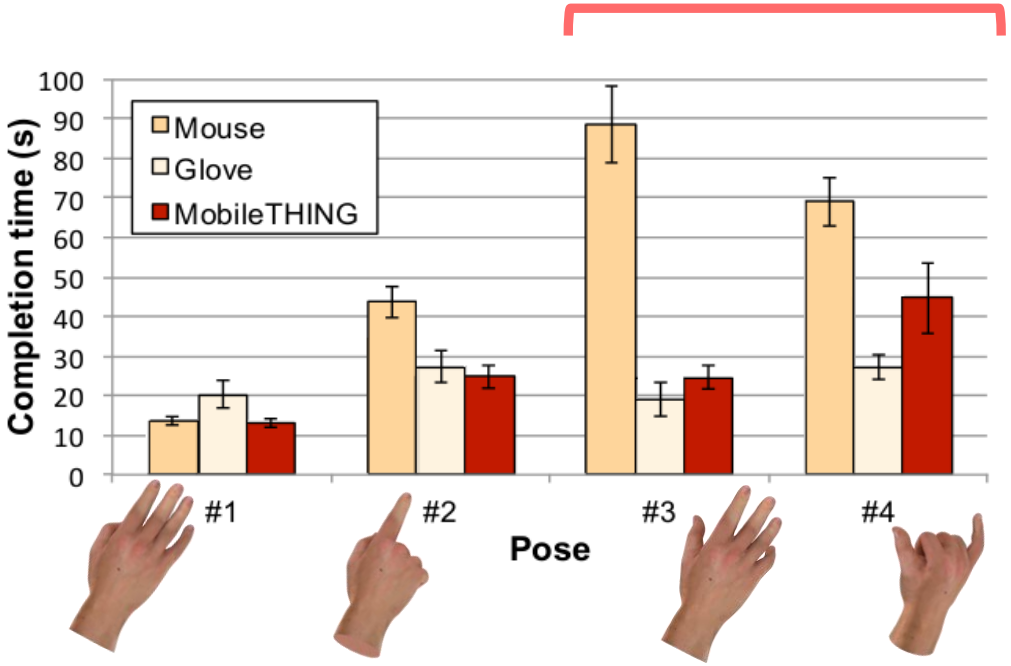
Data glove (mocap)



MobileTHING

User study #1

- **Performance**
  - `Glove` and `MobileTHING` outperform `Mouse`



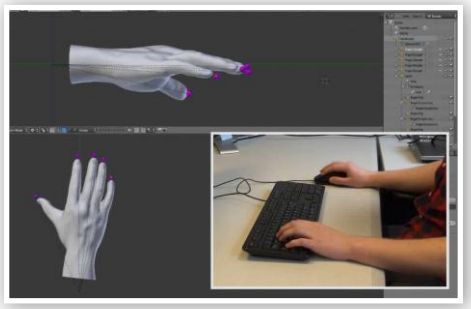
- **Subjective questionnaire**
  - No significant differences for `MobileTHING` in terms of *ease*, *speed*, *comfort*, *fatigue*
  - `Glove` did not fit 4 participants out of 16

User study #2

Protocol

- **Objective**
  - Compare `MobileTHING` vs. `DesktopTHING`

3 techniques × 3 poses × 5 repetitions × 12 participants



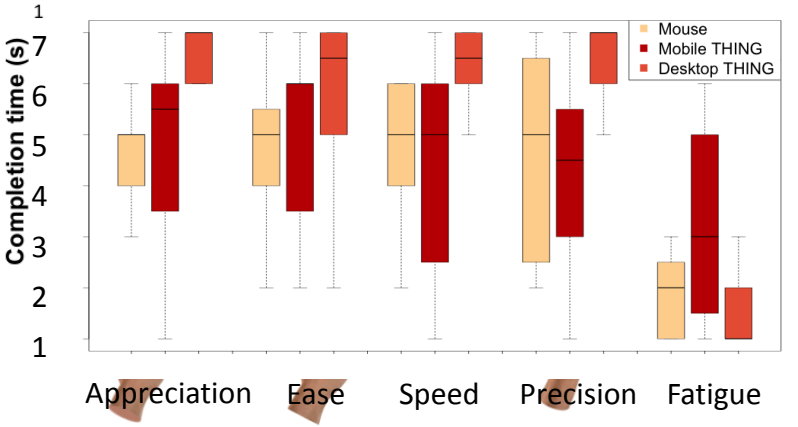
`Computer mouse`

`MobileTHING`

`DesktopTHING`

Results

- **Performance**
  - Both `THING` variants outperform `Mouse`
  - No differences between `DesktopTHING` and `MobileTHING`
- **Appreciation**
  - `DesktopTHING` for precision, fatigue
  - Overall preference for `DesktopTHING`



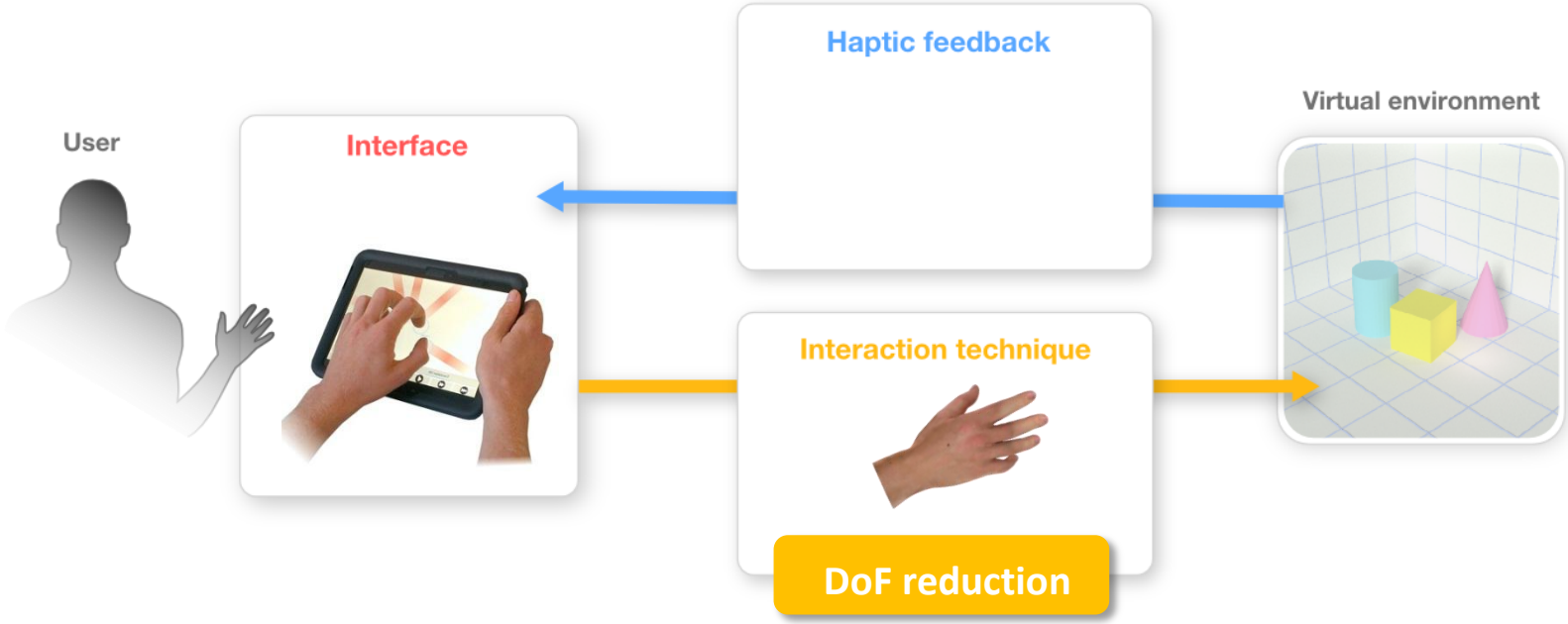
Conclusion

THING: Multi-touch technique for manipulating 3D hand models

- **Common** low-cost input device
- The **user's gestures** on the tablet are **reflected** on the hand models

- User studies
  - Performance similar to data glove, better than traditional computer mouse
  - Desktop version preferred over mobile variant, similar performance

Contribution #2: DesktopGlove



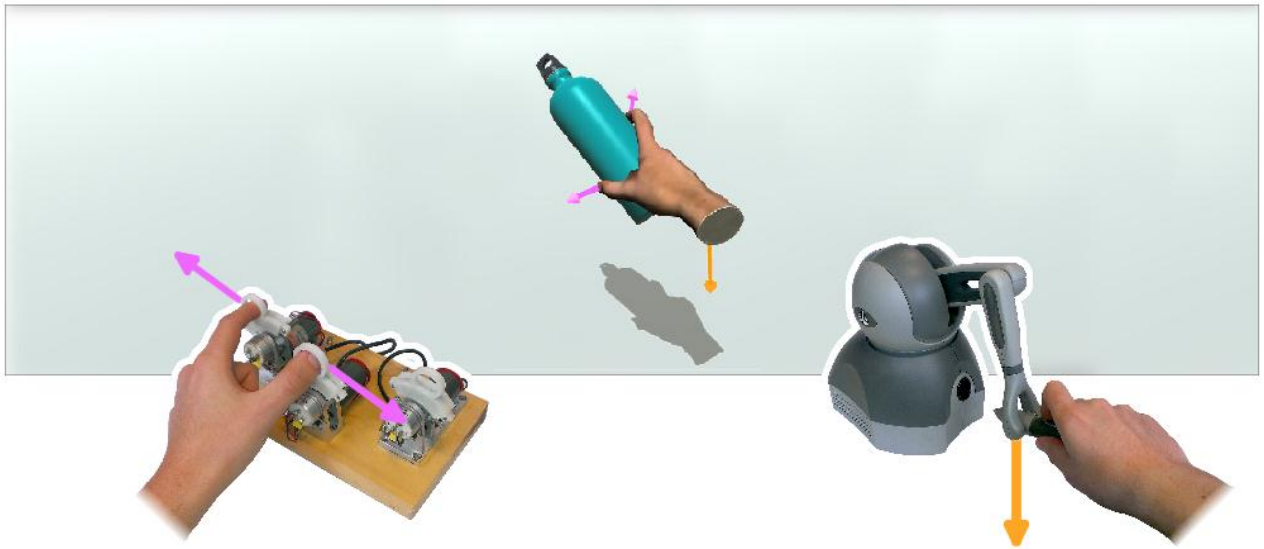
Axis I: **Improving the control of articulated hands**

DoF separation

Separating the DoF of virtual hands for haptic manipulation

- **Approach**
  - **Separate DoF** between two distinct interfaces

- ***DesktopGlove***
  - Distribute the DoF of **one virtual hand** between **both user's hands**
  - **Global wrist** control on one side, **Local finger** control on the other



System

Global motion

Interface
Common haptic arm

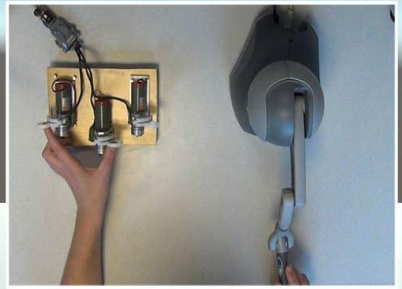
Input
Position and orientation

Output
Global forces (collisions, weight)

Interface
Modified DigiHaptic [Casiez, 2003]

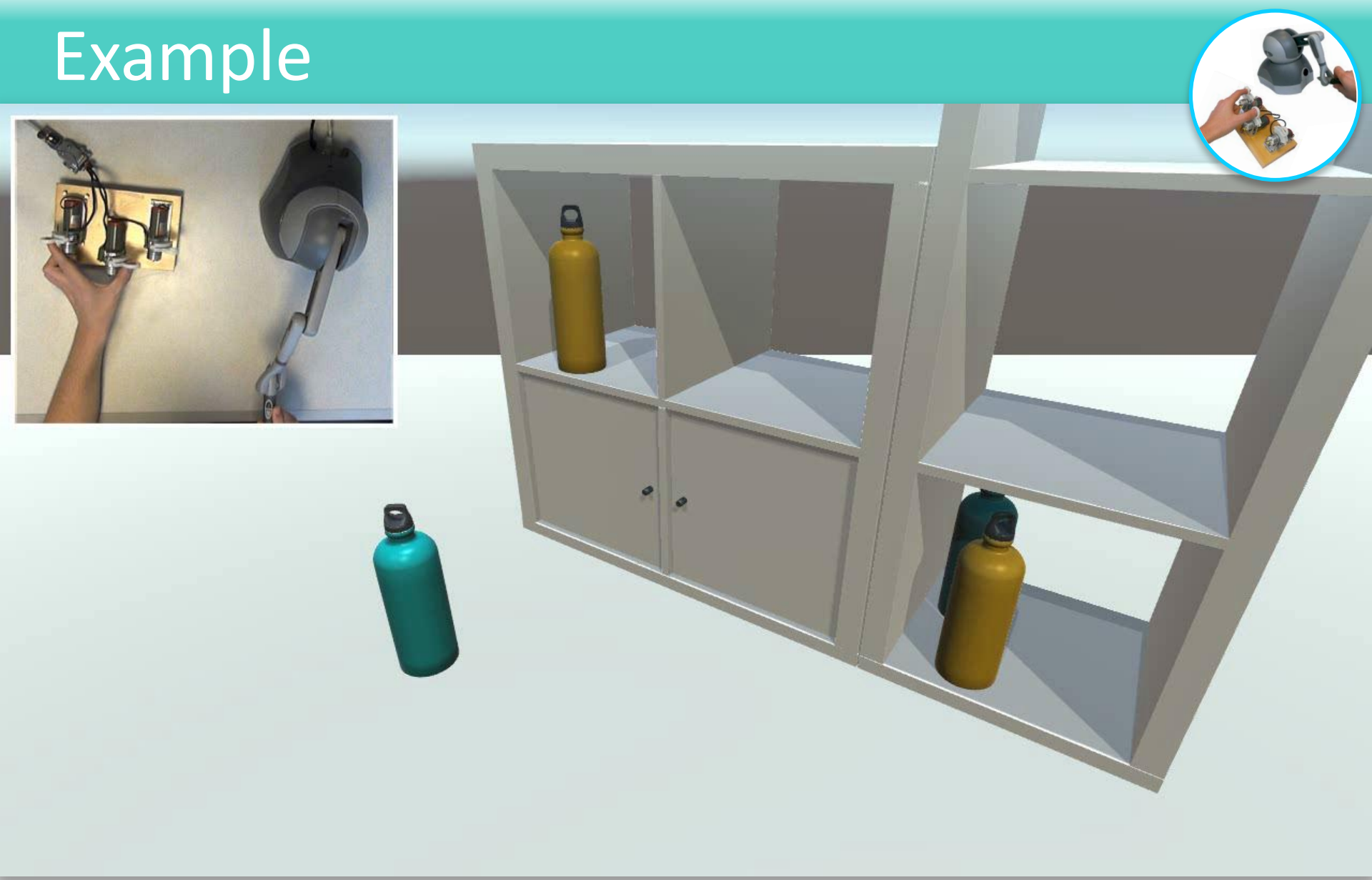
Input
Finger flexion

Output
Local grasping force



Local motion

Example



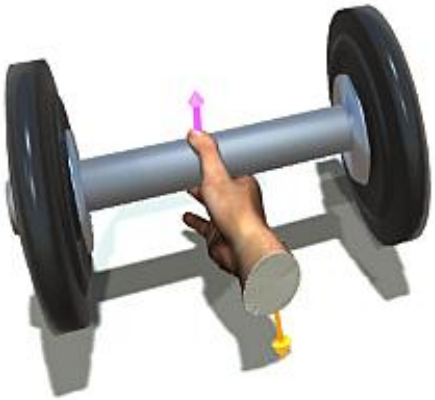
- Pink arrows: forces sent to the fingers (left hand)
- Orange arrow: force sent to the wrist (right hand)

Conclusion

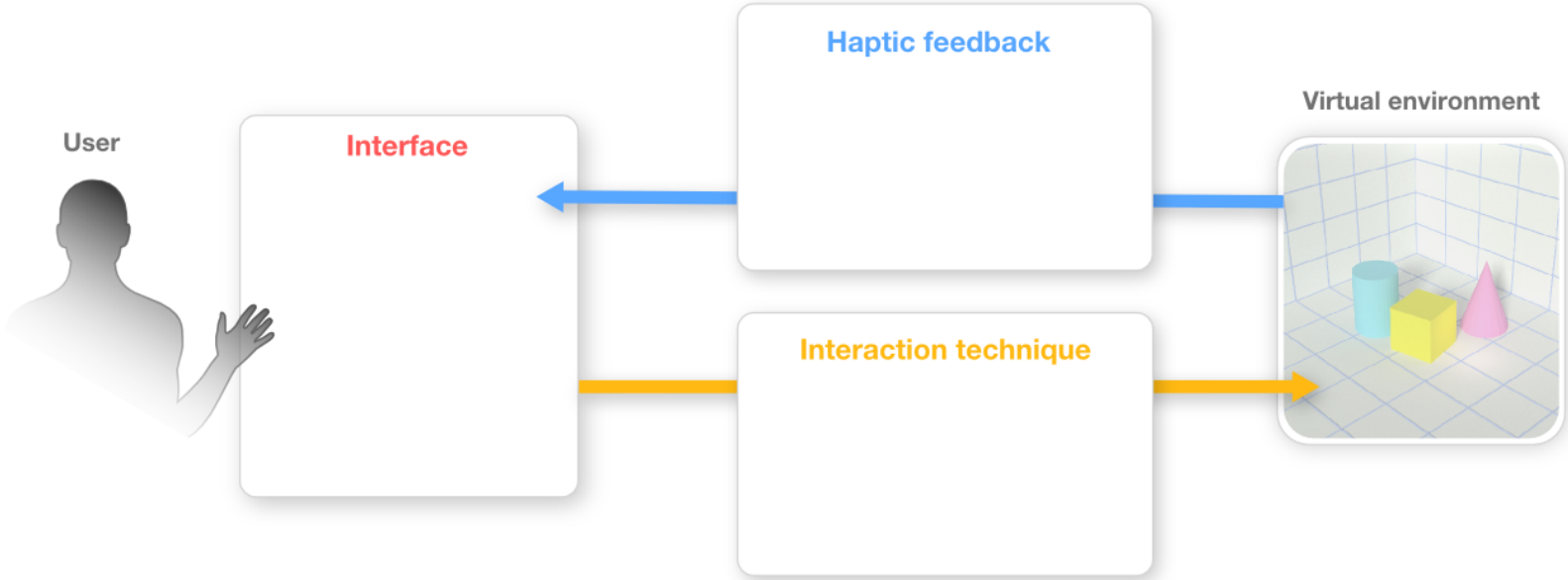
DesktopGlove: Separate the degrees of freedom of one virtual hand between both user's hands

- **Exhaustive haptic feedback** (local + global forces) with **accessible** interfaces

- User studies
  - Separated control: no significant negative effect on performance, preferred by users
  - Separated feedback: no significant negative effect
  - User preference:
    - global controls with dominant hand,
    - full force feedback on both hands



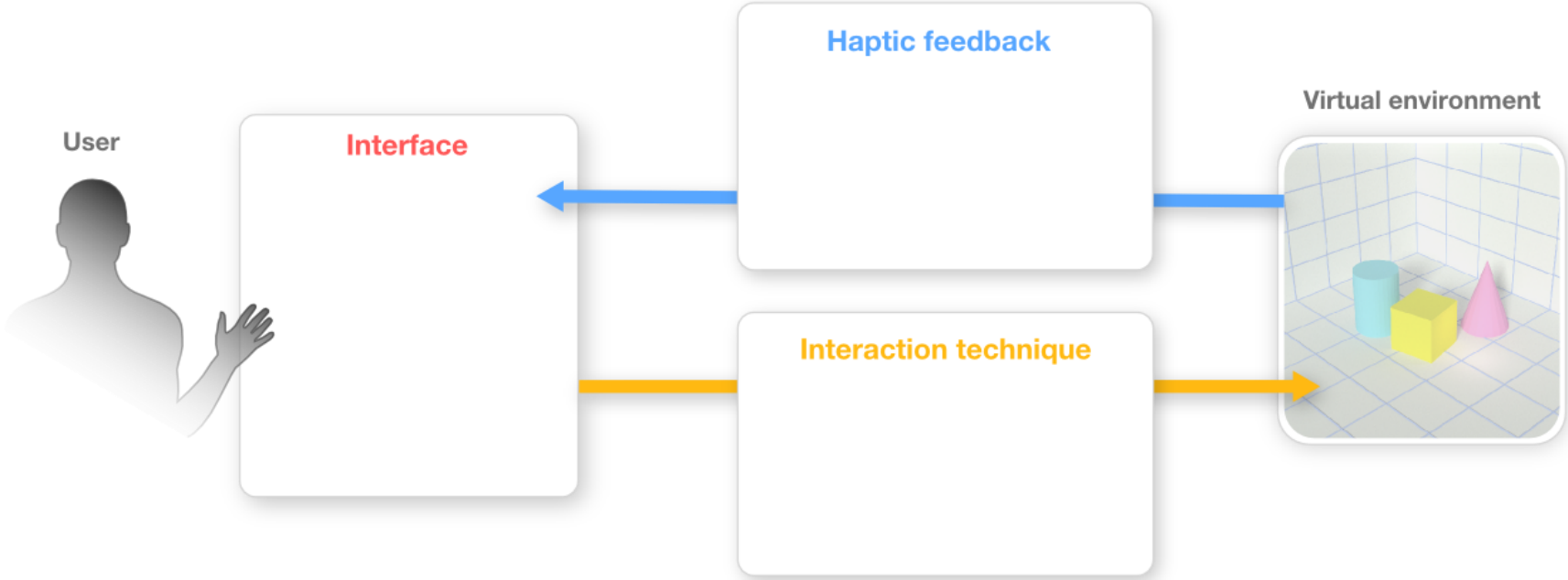
Axis I: Improving the control of articulated hands



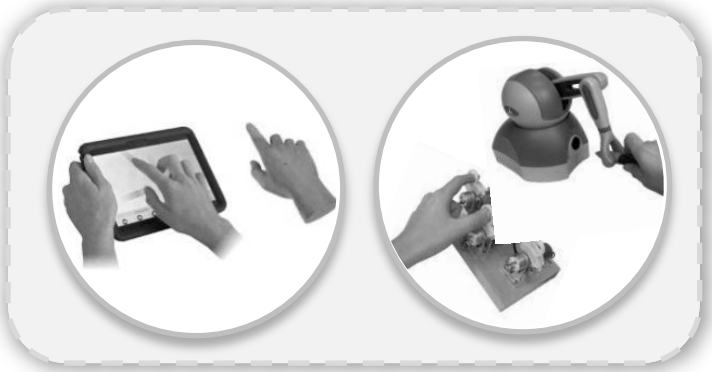
Axis I: **Improving the control of articulated hands**

DoF reduction **DoF separation**

Axis II: Improving feedback with passive and pseudo-haptics



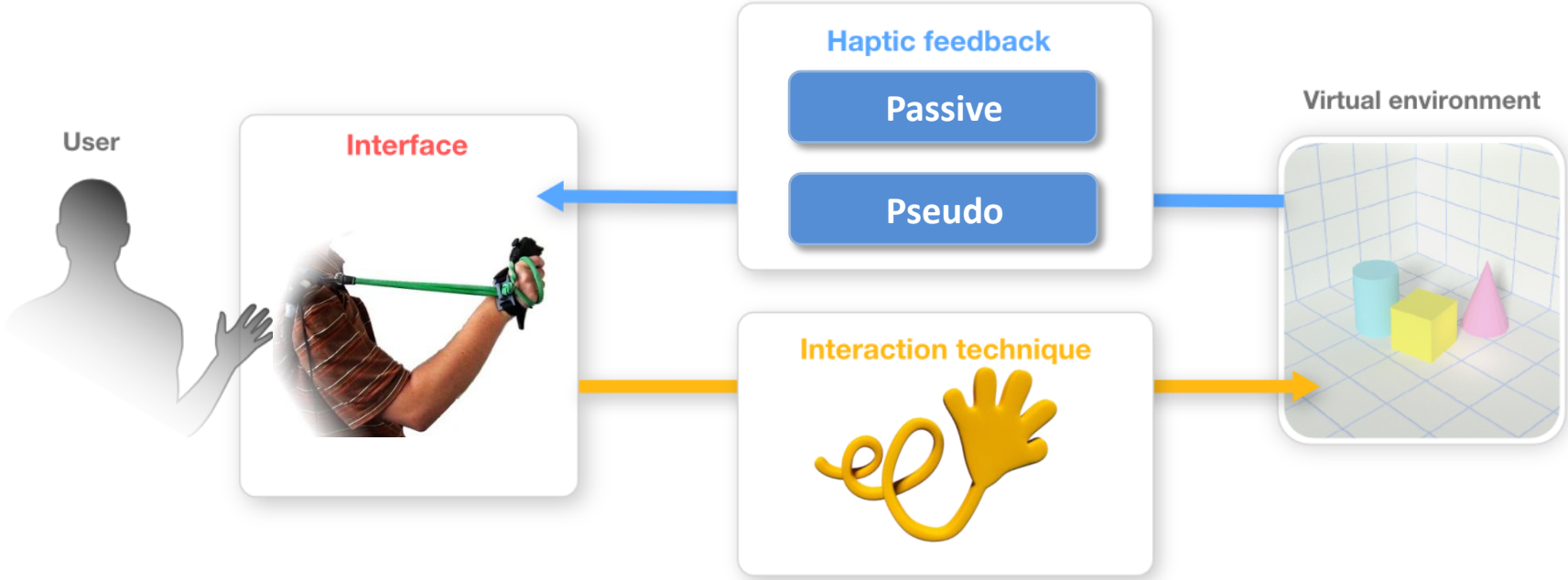
Axis II: Improving feedback with passive and pseudo-haptics



Level of detail

Whole-hand **Grasping** **Multi-finger**

Contribution #3: Elastic-Arm

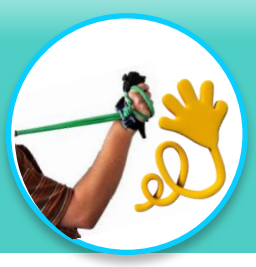


Axis II: Improving feedback with passive and pseudo-haptics

Level of detail

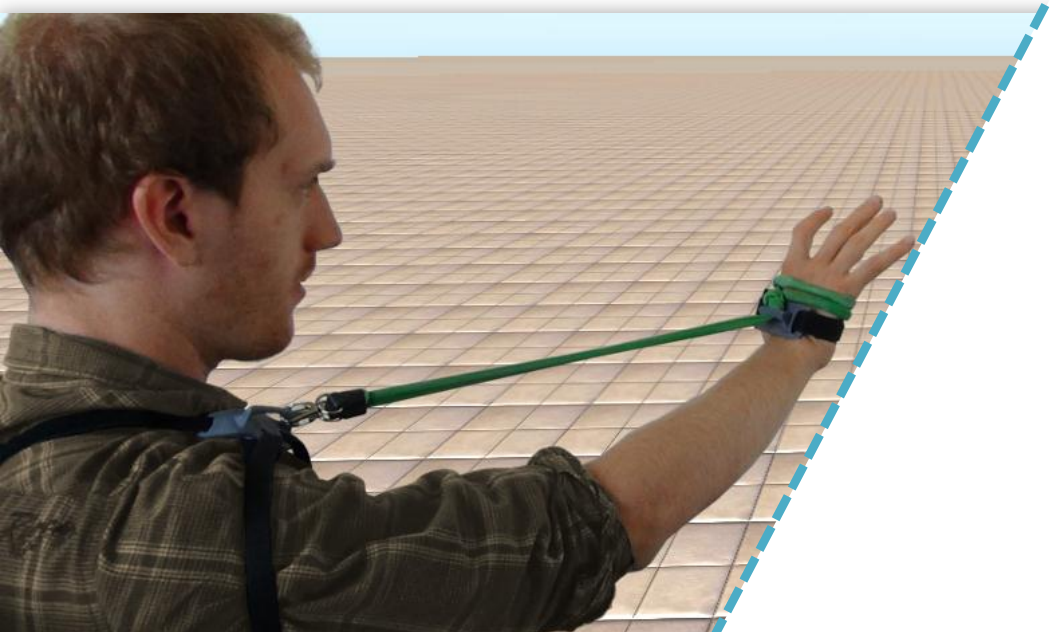
Whole-hand

Human-scale haptic feedback for augmenting 3D interaction

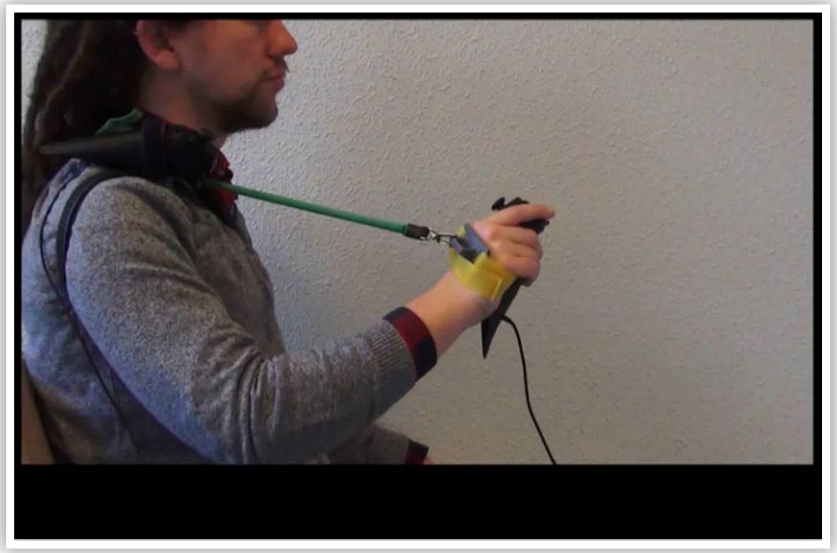


- **Approach**
  - Leverage **passive components** to design **lightweight and mobile** haptic interfaces

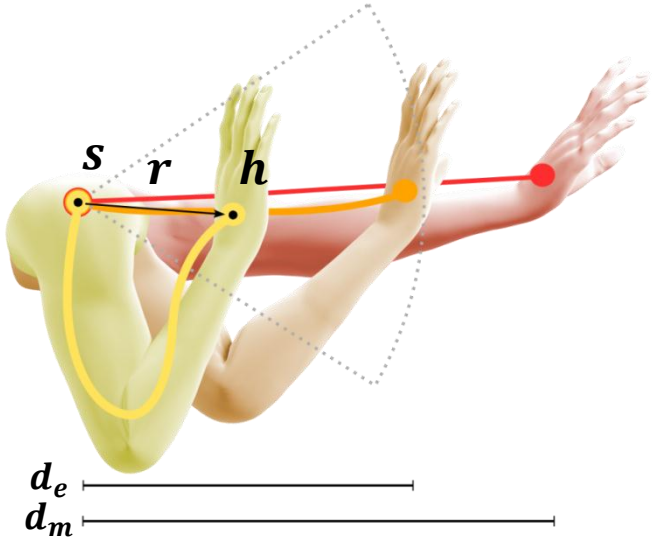
- ***Elastic-arm***
  - Elastic armature providing egocentric force feedback to the hand
  - Several interaction techniques based on a stretchable arm



System



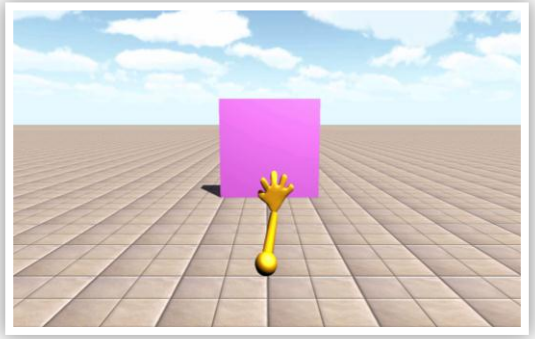
- **Two states**
  - Relaxed (feedback on)
  - Extended (feedback off)

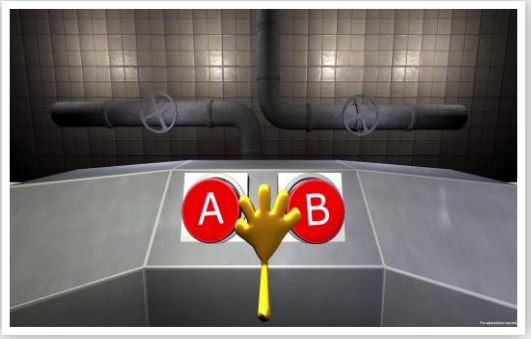


- **Main parameters**
  - Reach $\boldsymbol{r} = \boldsymbol{h} - \boldsymbol{s}$
  - Rest length d_e
  - Max. extension d_m

Interacting through the Elastic-Arm

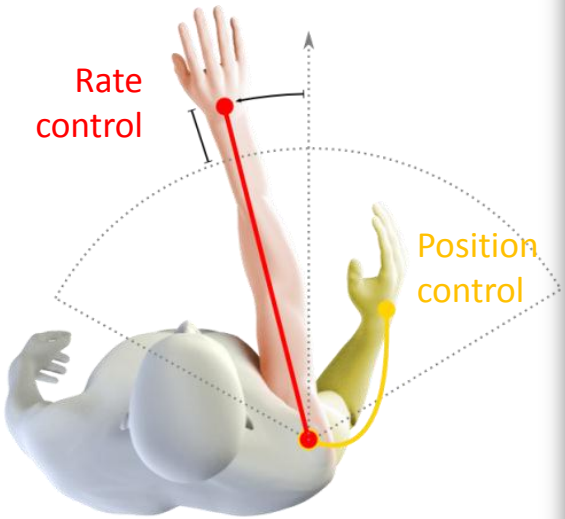
Navigation → Exploration → Manipulation

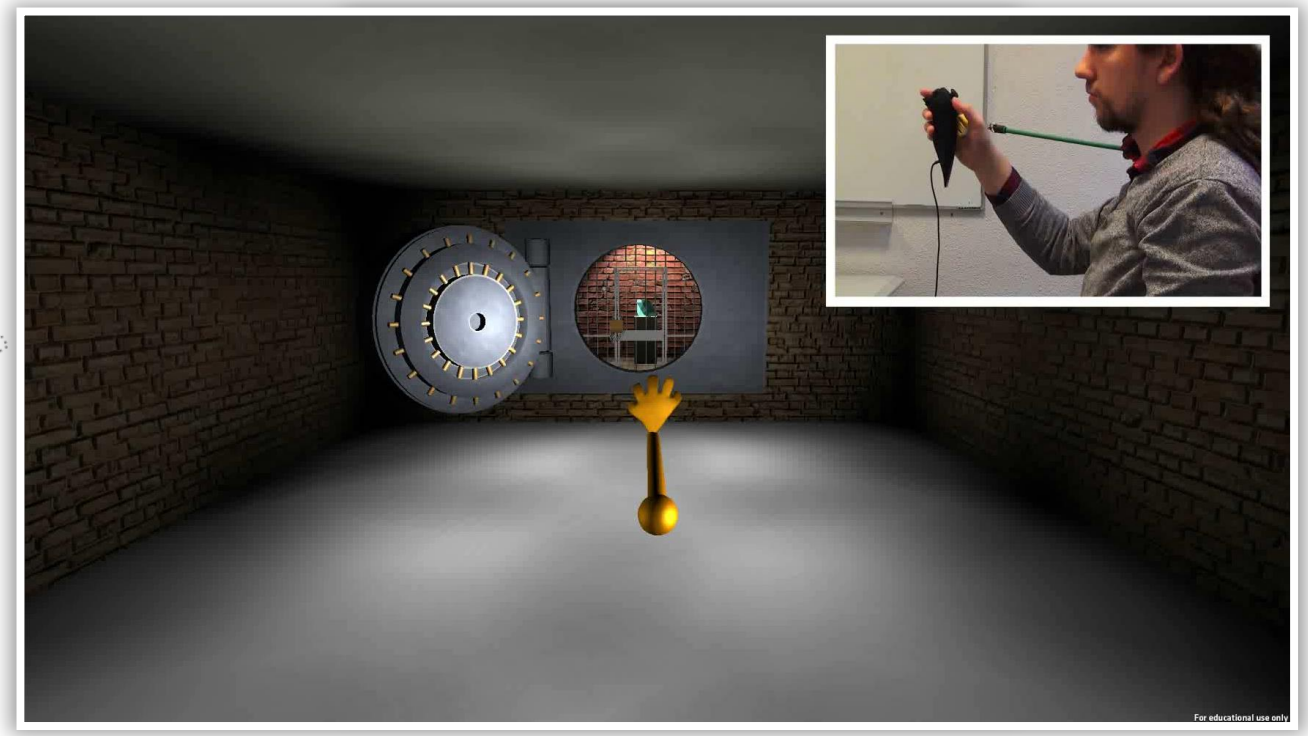




Navigation

- **Stretchable arm to navigate towards out-of-reach objects**
  - *Go-Go*: extension of the user's arm [Poupyrev, 1996]
  - *Bubble*: hybrid *position/rate control* [Dominjon, 2005]





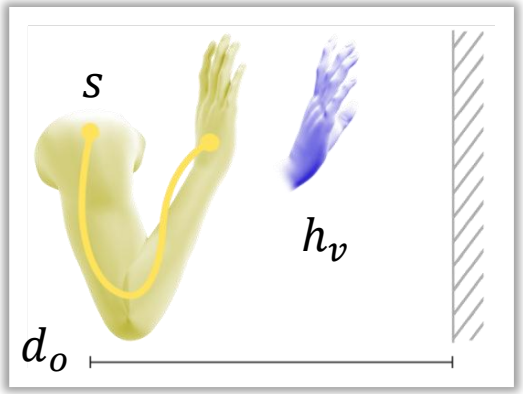
Exploration

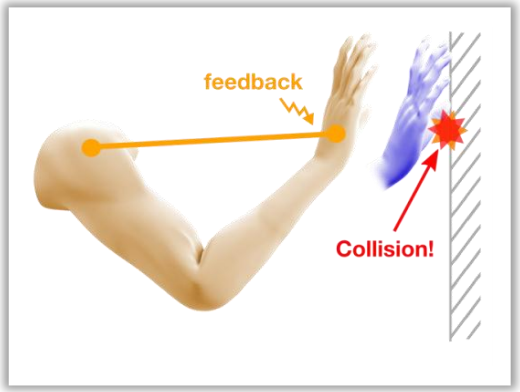
- **Simulate collisions with the Elastic-Arm**
  - *Redirected touching*: warp virtual hand to simulate shapes [Kohli, 2010]
  - Match the rubber band extension with virtual collisions

Virtual hand position — Distance to facing obstacle

$$\boldsymbol{h}_v = s + \mathrm{d_o} \min\left(1, \frac{|\boldsymbol{r}|}{d_e}\right)$$

Shoulder position — = 1 when the cable is extended

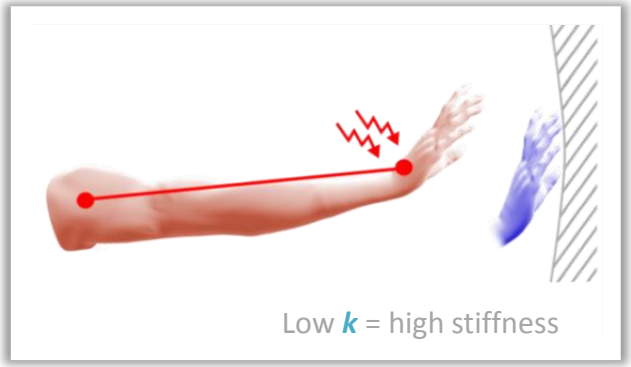


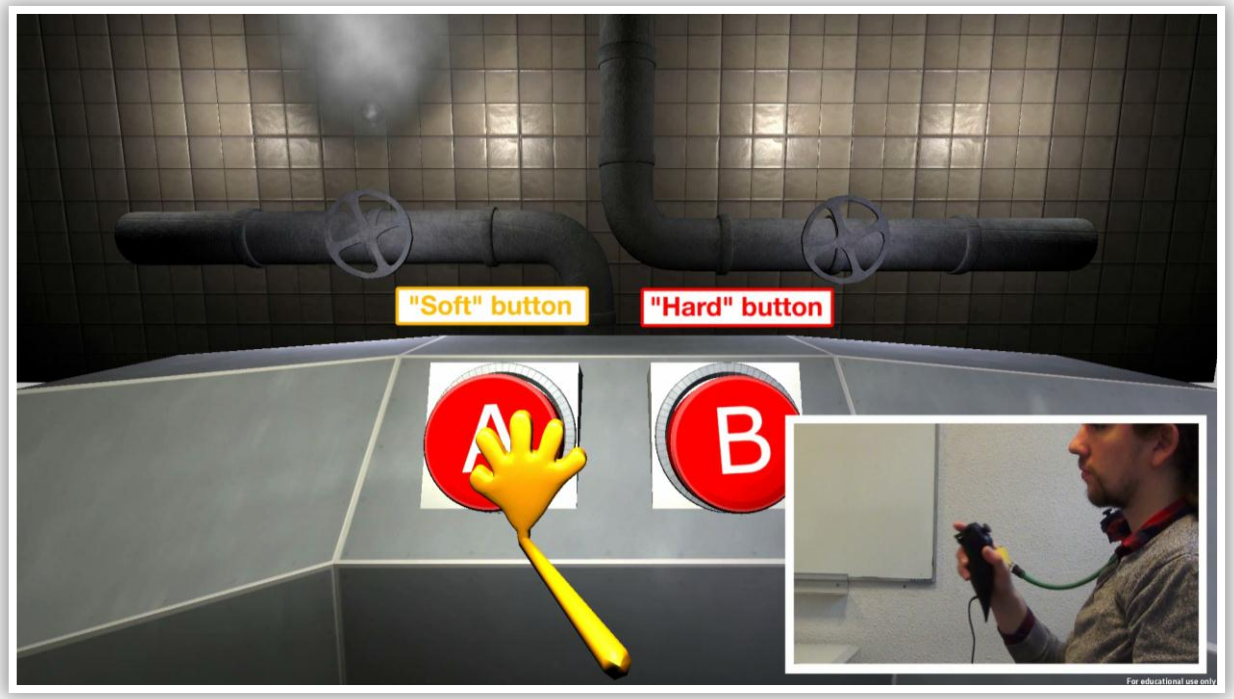


Manipulation

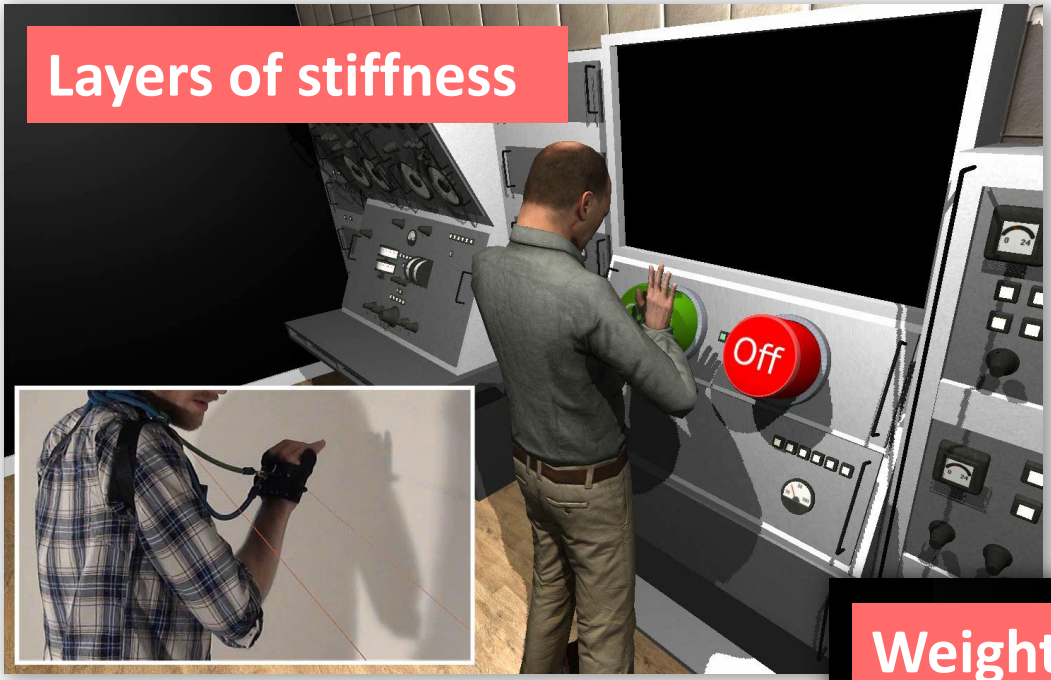
- **Simulating different levels of effort with the Elastic-Arm**
  - Inspired by pseudo-haptic stiffness [Lécuyer, 2000]
  - First, match the rubber band extension
  - Then, scale the Control/Display ratio

$$\boldsymbol{h}_v = \overbrace{\boldsymbol{s} + \mathrm{d_o}\ \min\left(1, \frac{|\boldsymbol{r}|}{d_e}\right)}^{\text{Same as with redirected touching}} + \overbrace{\frac{|\boldsymbol{r}| - d_e}{d_m - d_e}}^{\text{Extension beyond rest length}} \underbrace{\boldsymbol{k}}_{\text{Object-dependent Control/Display ratio}}$$





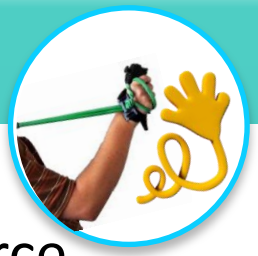
Alternative designs



- Rubber bands with different lengths
- Each band matches a different event

- Rubber bands attached to the waist
- Pseudo-haptic simulation of weight

Conclusion

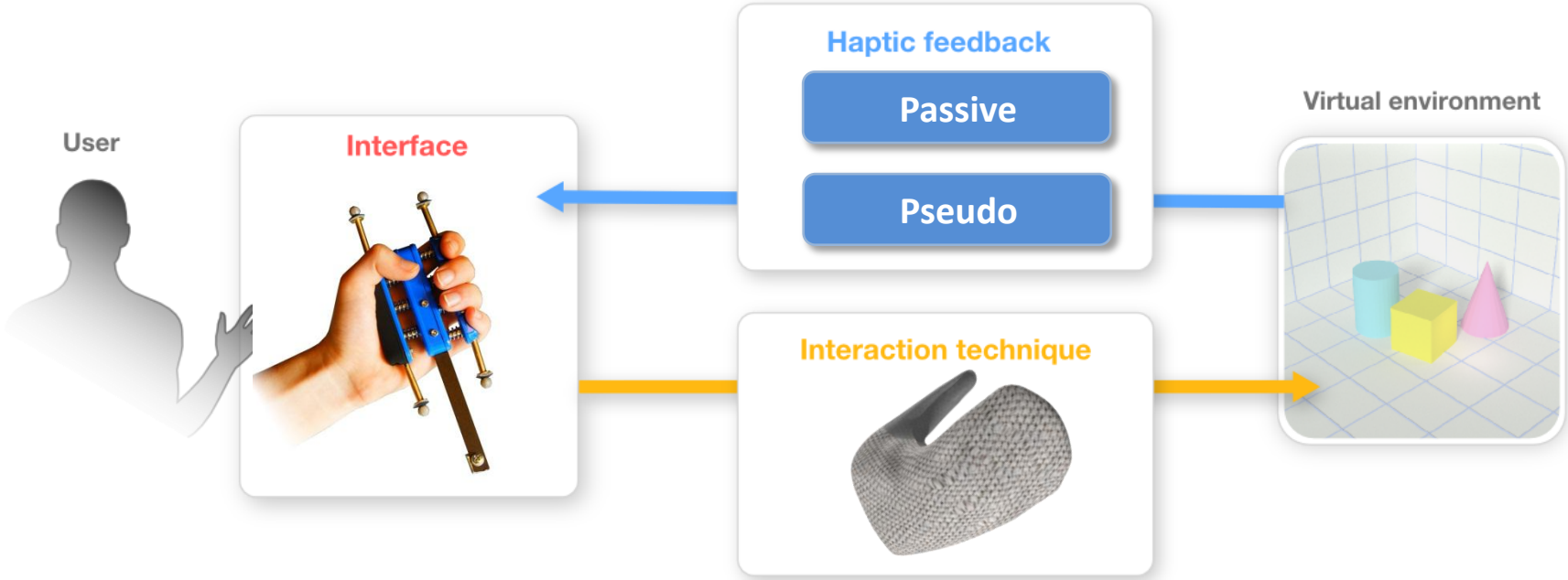


Elastic-Arm: Body-mounted armature providing egocentric force feedback to the user's hand

Proposed 3D interaction techniques:

- Navigation/selection by **stretching the arm**
- Perceptual effects: **collisions** and **different levels of effort**
- Alternative designs: **layers of stiffness** and **weight**

Contribution #4 – The Virtual Mitten

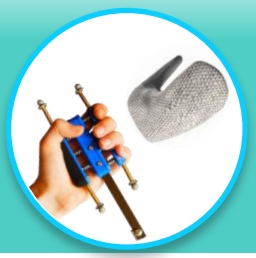


Axis II: Improving feedback with passive and pseudo-haptics

Level of detail

Grasping

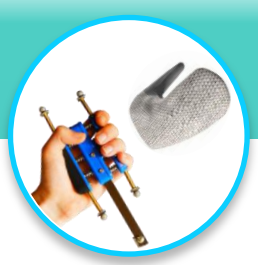
Haptic manipulation of virtual objects using grip force

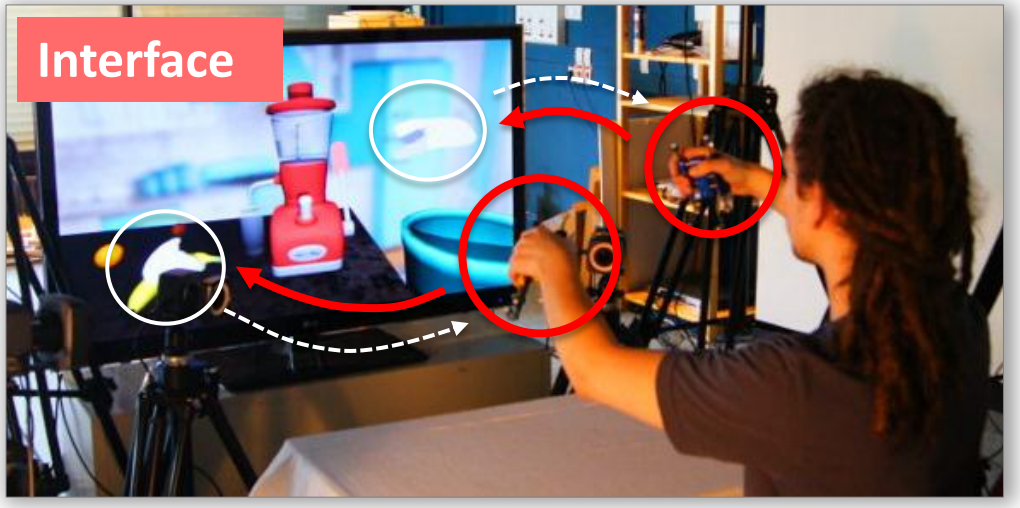


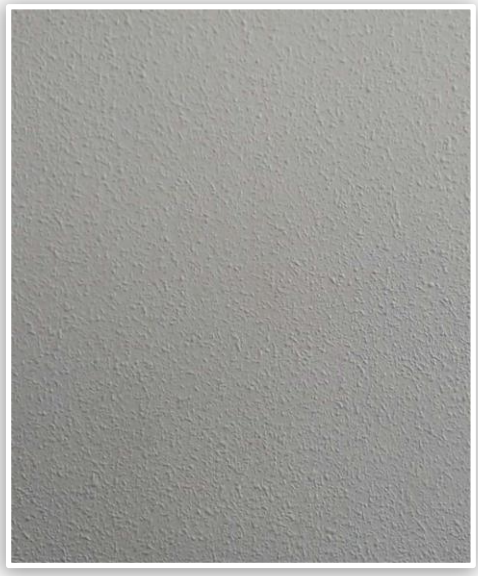
- **Approach**
  - Simulate grasping sensations with passive devices providing grip forces

- ***Virtual mitten***
  - Real hands represented by simplified mittens
  - Elastic devices to control the mitten and deliver grip force
  - Visual feedback and pseudo-haptic effect to vary perceptions

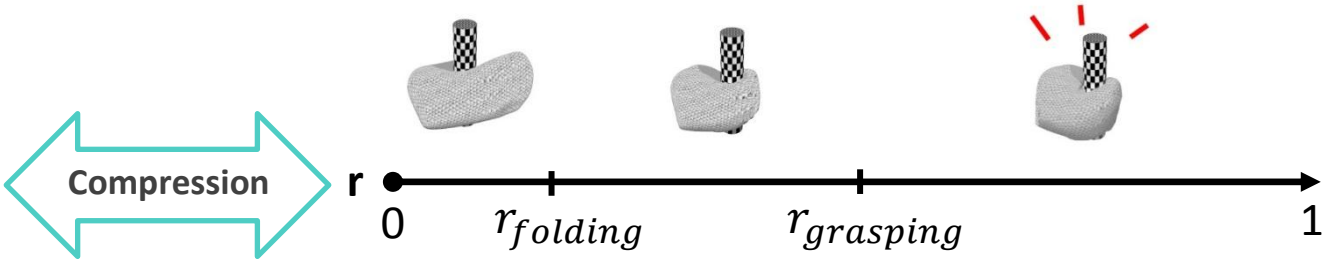
System





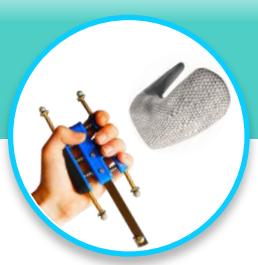


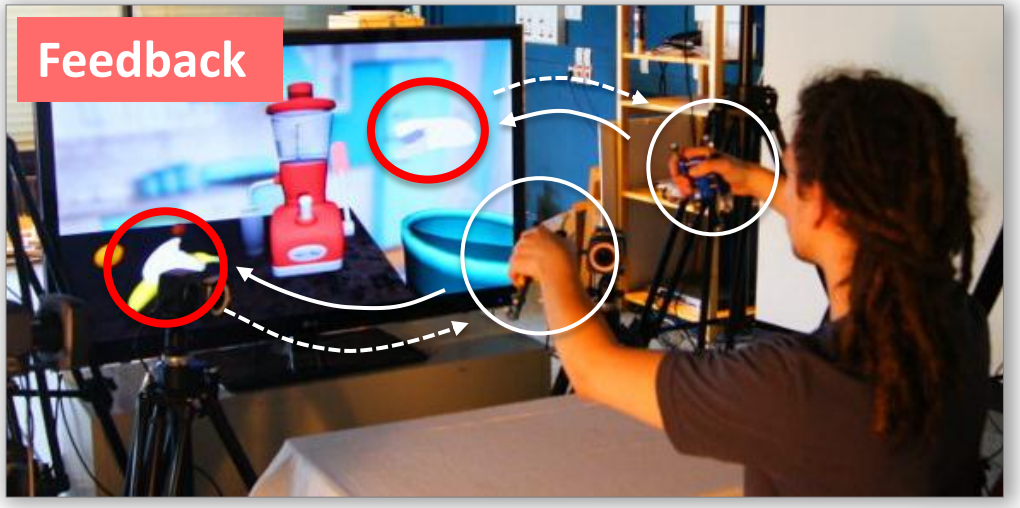
Elastic device



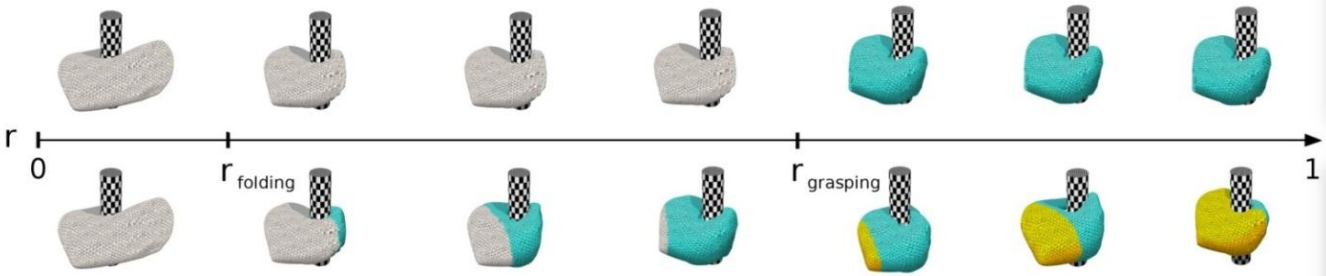
Control scheme

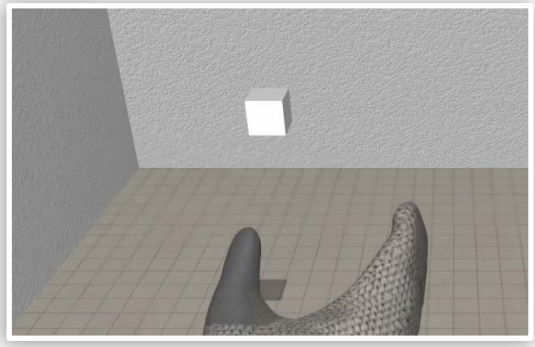
System



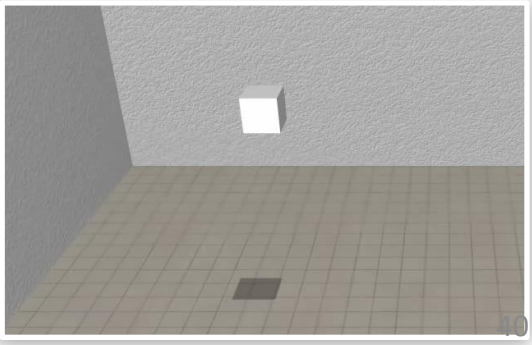


Boolean

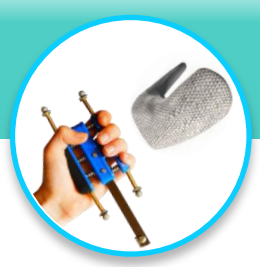


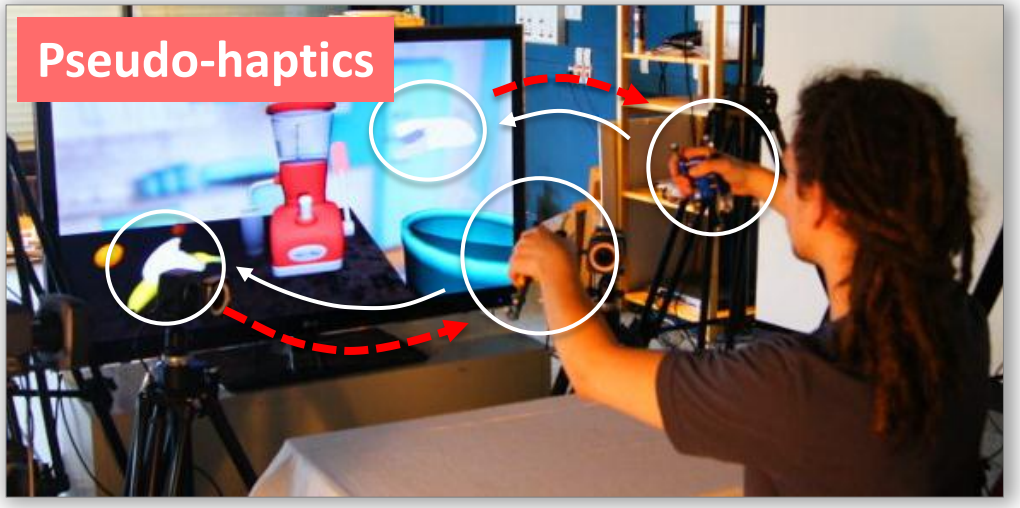


Progressive

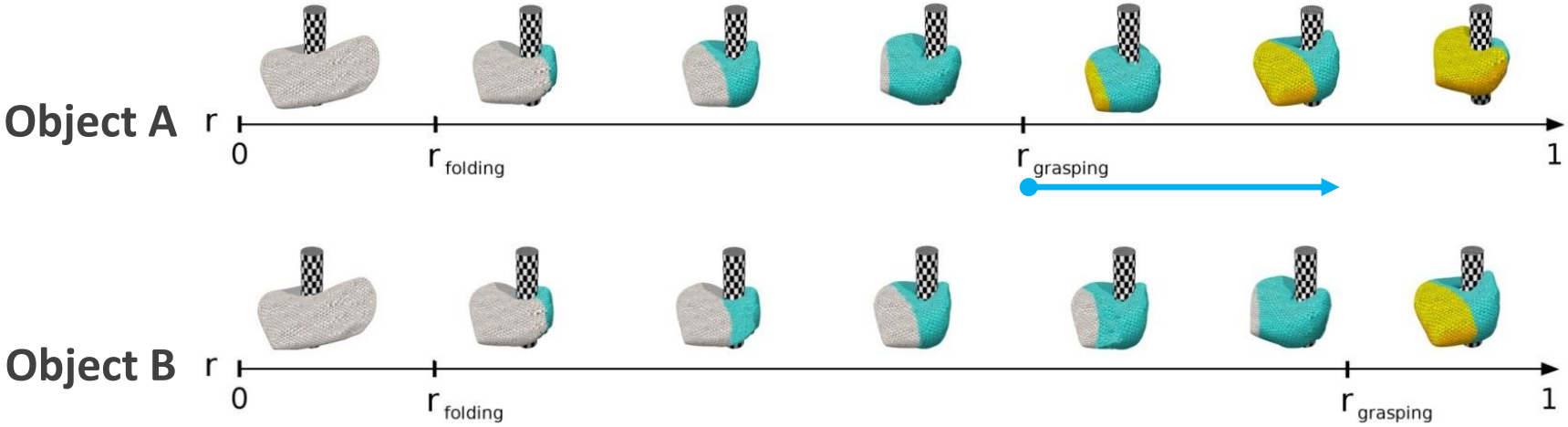


System

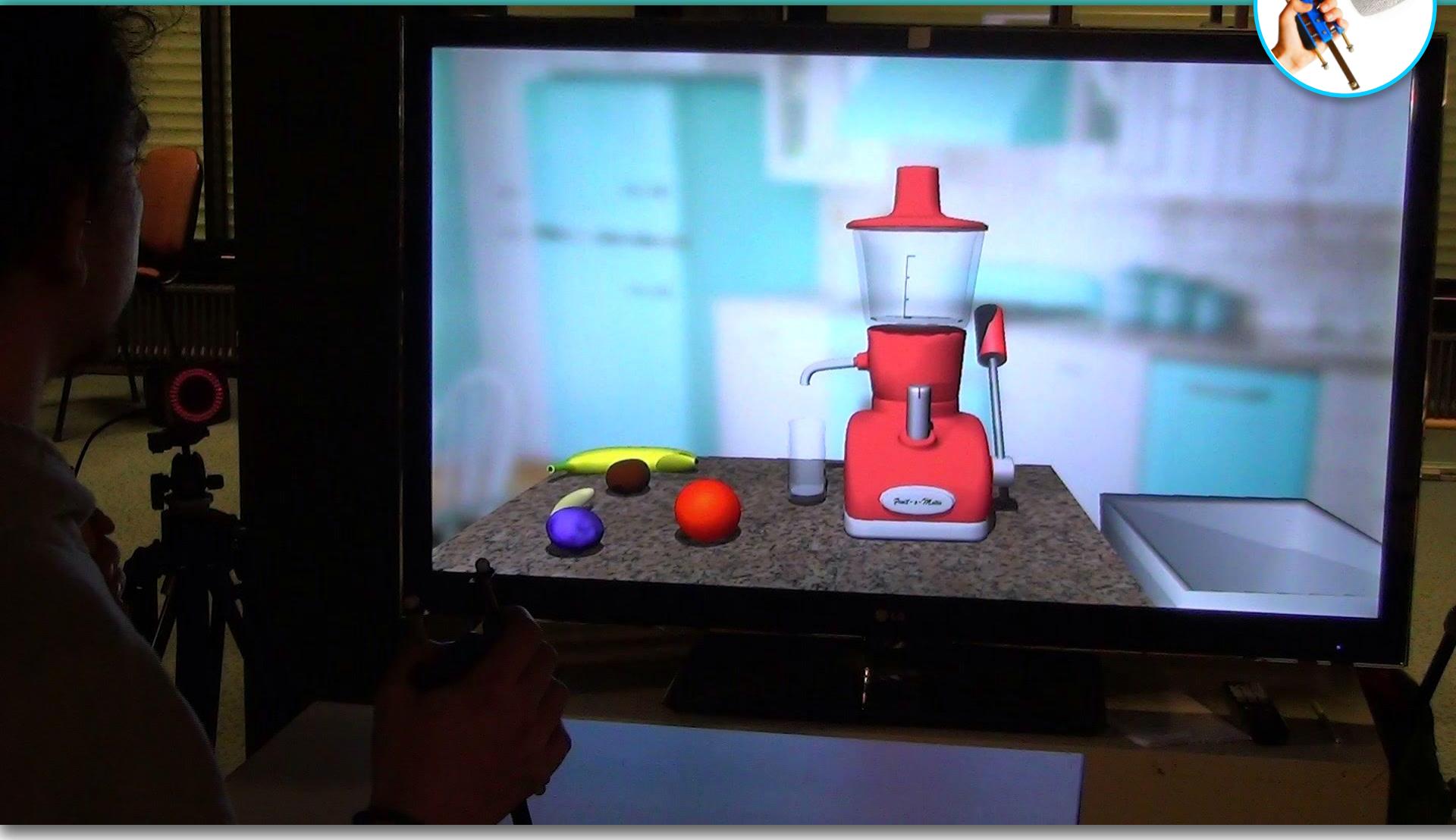




Objective: simulate different levels of effort for different virtual objects



Example



- Bimanual cooking scenario
- Stiffness of the fruits, weight of the glass, different interactive parts

User study #1

Protocol

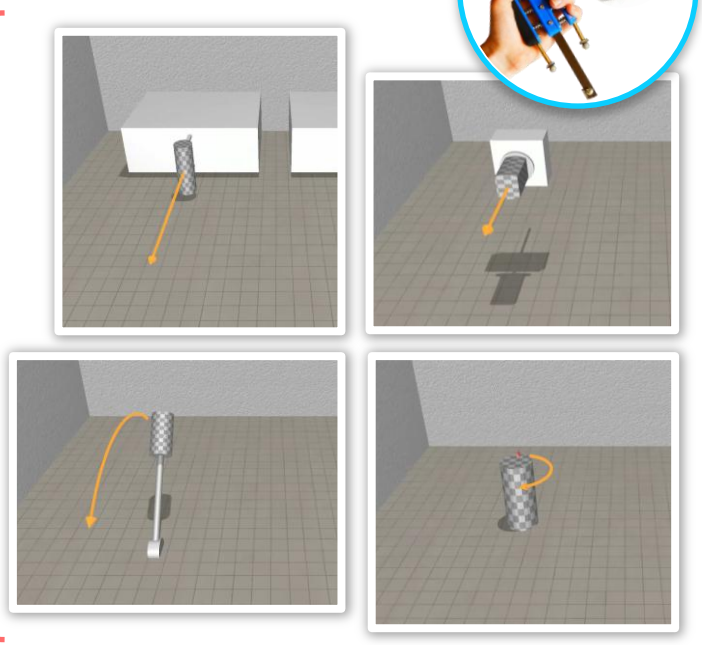
Objective

- Evaluate if users can perceive levels of effort
- Compare *Boolean* and *Progressive* feedback

Task

- Perform various manipulation tasks with pairs of object
- « Which object required more effort? »

2 types of feedback × 4 tasks × 3 repetitions × 12 participants

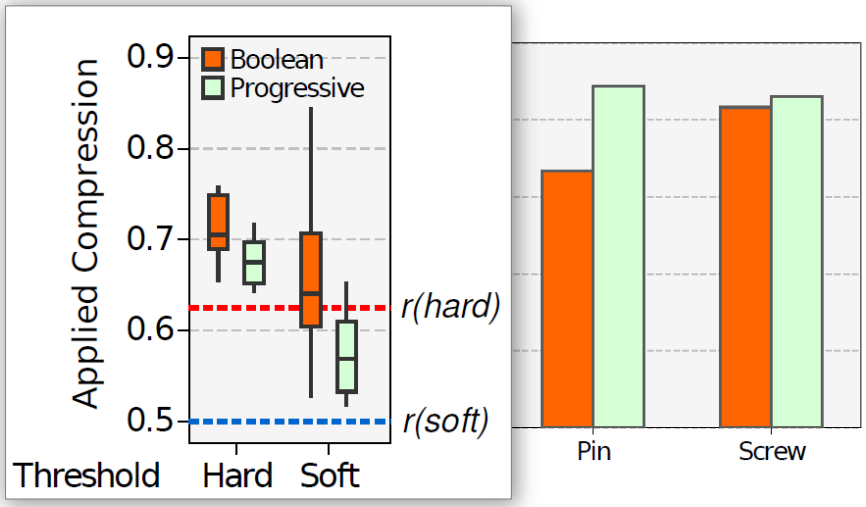


[Bloomfield, 2003]

Results

With Progressive feedback

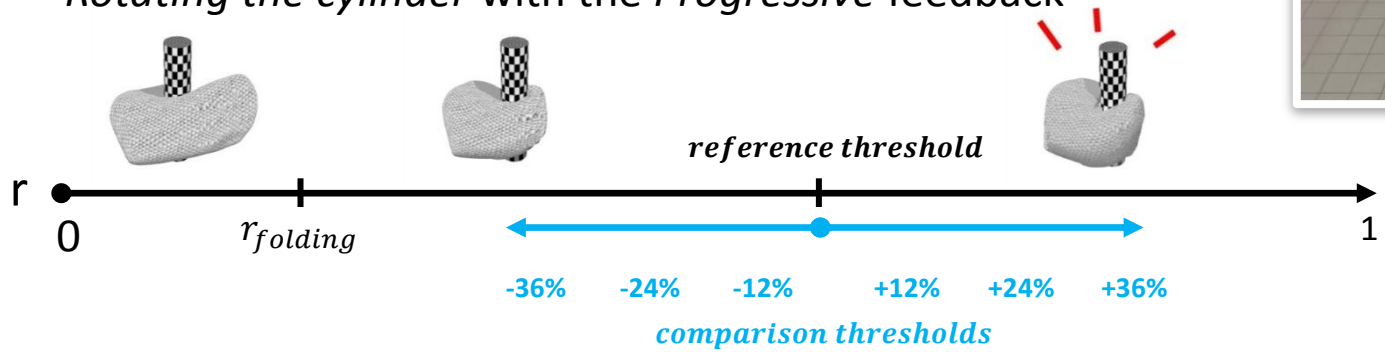
- Significantly more correct answers
- Compression applied closer to the grasping threshold

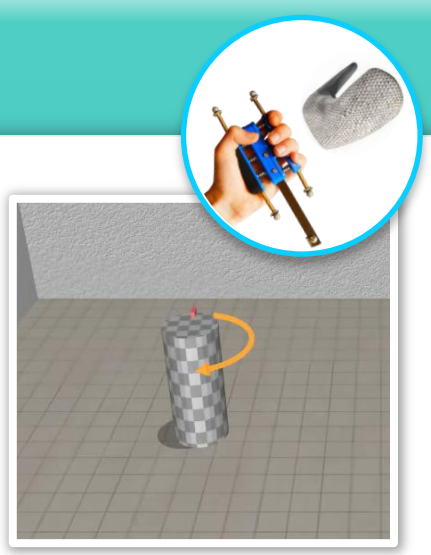


User study #2

Protocol

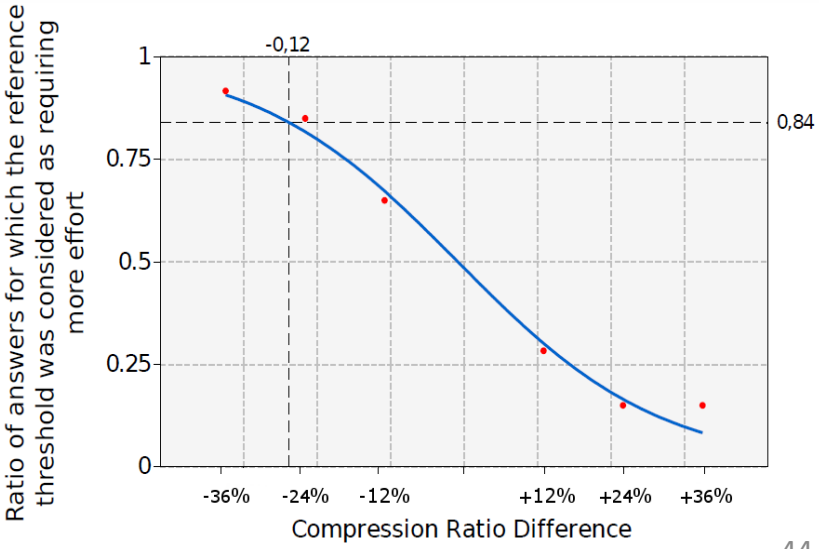
- **Objective**
  - Determine the resolution of the effect
- **Task**
  - *Rotating the cylinder* with the *Progressive* feedback





Results

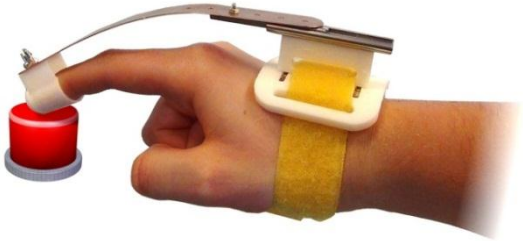
- **Just Noticeable Difference:**
  minimum difference between stimuli that can be discriminated
- **Four** different levels of effort

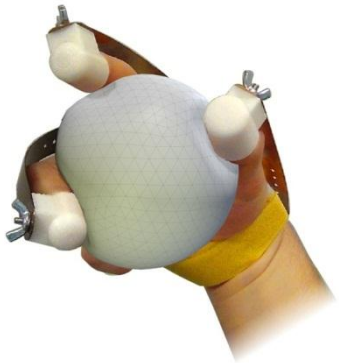


Multi-finger extension

System

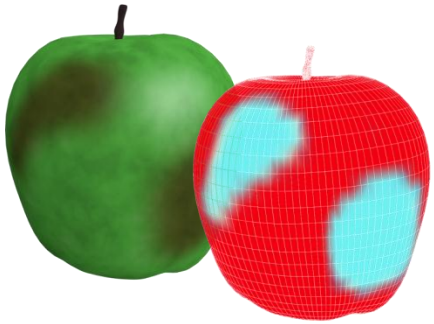
- ***ElasticGlove***
  - Modular passive exoskeleton
  - Constrains each finger individually

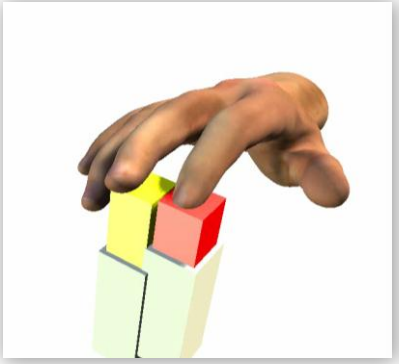




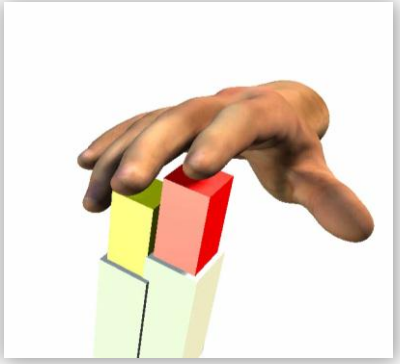
Pseudo-haptics

- **Pseudo-haptic simulation of heterogeneous materials**
  - Finger-specific Control/Display ratio
  - Haptic data embedded into mesh



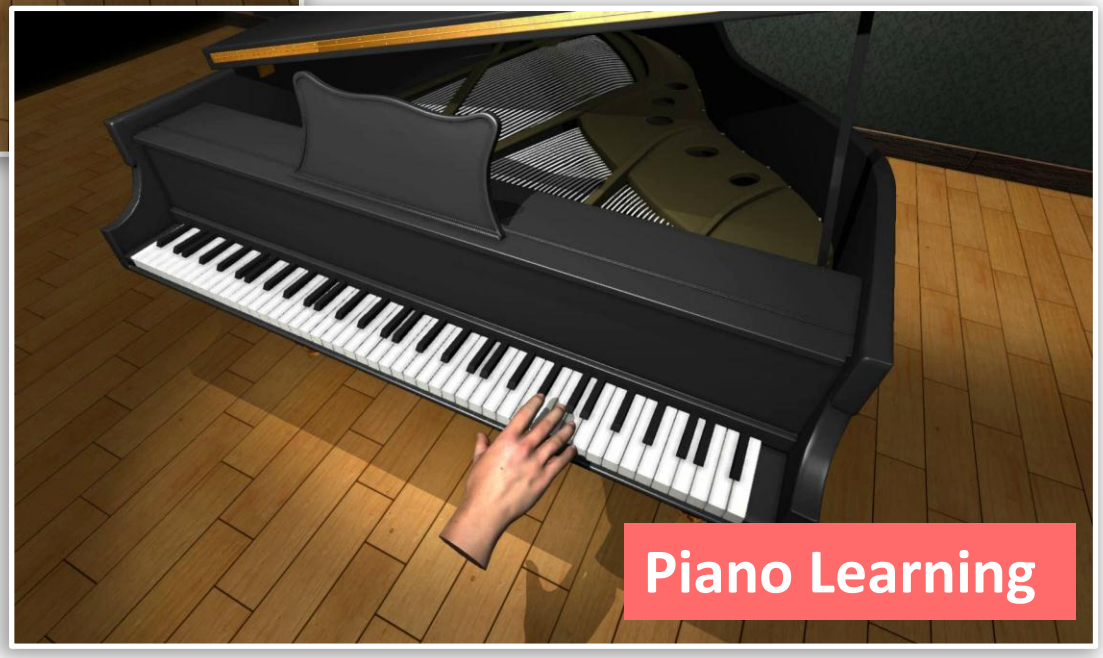


Same C/D ratio



Different C/D ratios

Examples



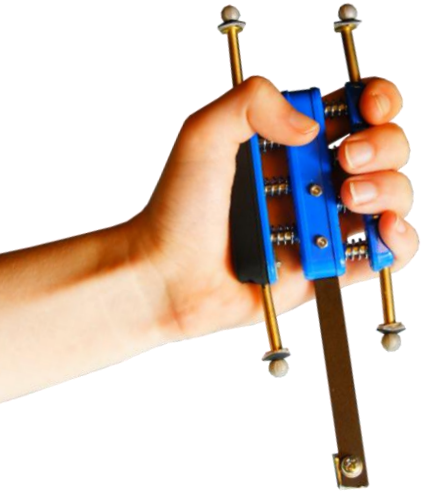
Conclusion

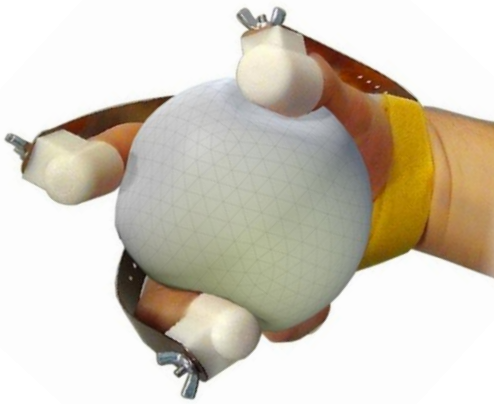
Virtual Mitten: Interaction metaphor based on an elastic device

- **Lightweight elastic** input device
- Pseudo-haptic effect to **simulate different levels of effort**

- User studies
  - *Progressive* visual feedback provided better results
  - Can simulate up to 4 levels of effort

ElasticGlove: Extension to multi-finger interaction with passive exoskeleton





General conclusion

- **Objective**
  - Improve hand-based interaction in virtual environments

- **Contributions**
  - **Axis I:** Improving the control of articulated hand models
    - **DoF reduction** and multi-touch input
    - **DoF separation** between two haptic devices

  - **Axis II:** Combining passive and pseudo-haptics
    - Body-mounted elastic interface for **whole-hand** interaction
    - Elastic grip force device for simulating **grasping**
    - Passive exoskeleton for **multi-finger** manipulation

Future work

Axis I

- **Additional input to handle more DoF**
  - Force sensing for THING,
  - Greater number of fingers for DesktopGlove
- **Bimanual interaction**
  - Parallel hand animation for THING
  - Bimanual interaction techniques for DesktopGlove

Axis II

- **Low-cost tracking**
  - Pressure sensing for Virtual Mitten, bend sensing for ElasticGlove
- **Evaluate passive interfaces *vs.* active counterparts**
  - Elastic-Arm *vs.* Desktop interfaces
  - ElasticGlove *vs.* active exoskeletons

Perspectives

- **Software control of the missing DoF**
  - Inspiration from robotics (grasp planning),
    computer animation (shape matching, behavioral data)

- **Pseudo-haptic feedback for the simulation of complex sensations**
  - Multiple stimuli (multi-finger, bimanual)
  - Complex environments

- **Combining different haptic modalities**
  - Design a passive exoskeleton from passive components
  - Active/Passive/Crossmodal feedback combinations

Publications

- **International conferences**
  - **M. Achibet**, A. Girard, A. Talvas, M. Marchal, and A. Lécuyer. “Elastic-Arm: Human-scale Passive Haptic Feedback for Augmenting Interaction and Perception in Virtual Environments”. In *Proc. of Virtual Reality*, pp. 63–68, 2015.
  - **M. Achibet**, G. Casiez, A. Lécuyer, and M. Marchal. “THING: Introducing a Tablet-based Interaction Technique for Controlling 3D Hand Models”. In *Proc. of Conference on Human Factors in Computing Systems*, pp. 317–326, 2015.
  - **M. Achibet**, M. Marchal, F.Argelaguet, and A. Lécuyer. “The Virtual Mitten: A Novel Interaction Paradigm for Visuo-haptic Manipulation of objects using Grip Force”. In *Proc. of Symposium on 3D User Interfaces*, pp. 59–66, 2014.

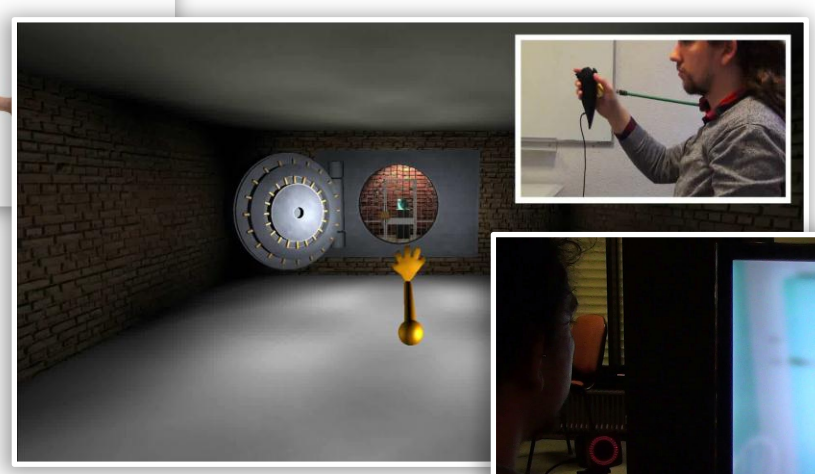
- **National conferences**
  - **M. Achibet**, A.Girard, M. Marchal, F. Argelaguet, and A. Lécuyer. “Elastic-Arm: A Novel Human-Scale Passive Haptic Approach for Augmenting Interaction and Perception in Virtual Environments”. In *Annual Conference of the AFRV*, 2015.
  - **M. Achibet**, M. Marchal, F. Argelaguet, and A. Lécuyer. “Visuo-haptic Manipulation of Objects with the Virtual Mitten”. In *Annual Conference of the AFRV*, 2014.

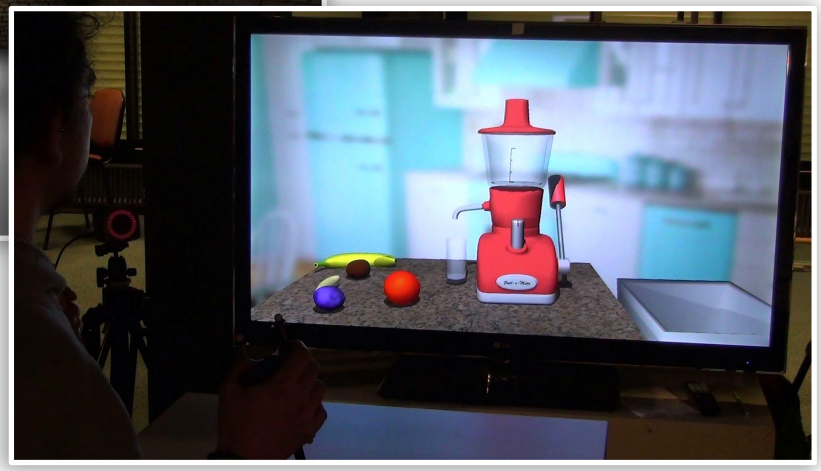
- **Submitted**
  - **M. Achibet**, A. Girard, M. Marchal, and A. Lécuyer. “Leveraging Passive Haptic Feedback in Virtual Environments with the Elastic-Arm Approach”. Submitted to *Presence*.
  - **M. Achibet**, G. Casiez, and M. Marchal. “DesktopGlove: a Multi-fingered Force Feedback Interface Separating Degrees of Freedom between Hands”. Submitted to IEEE *Symposium on 3D User Interfaces*.
  - **M. Achibet**, M. Marchal, A. Lécuyer, and H. Kajimoto. “Elastic Exoskeleton: Multi-Finger Interaction Combining Passive Haptics and Pseudo-Haptics”. Submitted to *IEEE Transactions on Haptics*.

- **Patents**
  - A. Lécuyer, **M. Achibet**, M. Marchal, and F. Argelaguet. “Système d’interaction avec des objets virtuels”. French patent, 3016451-A1.

Contributions to the Design of Novel Hand-based Interaction Techniques for Virtual Environments

Merwan Achibet





Thank you for your attention