Biomechanical analysis of different aspects in virtual reality. Application

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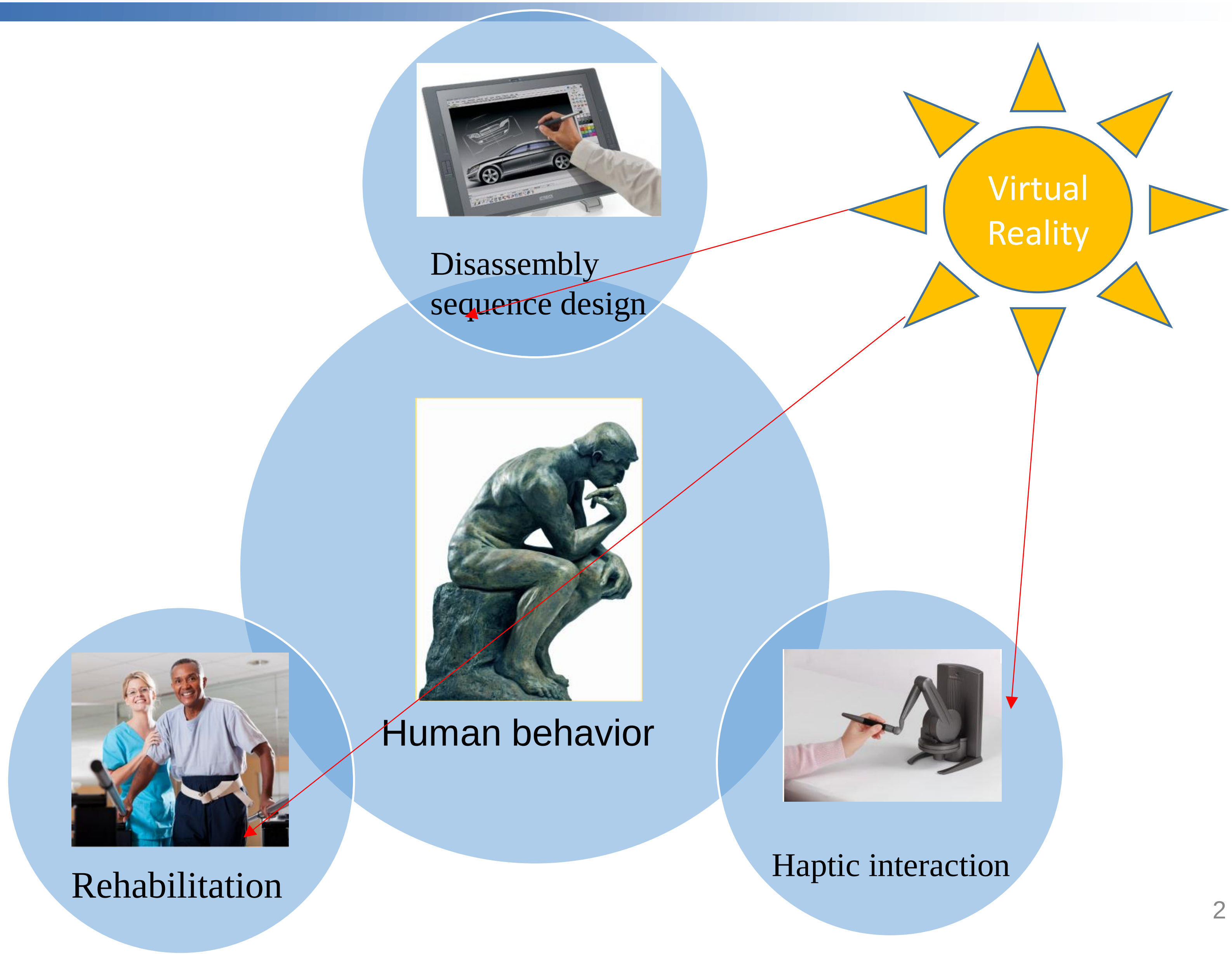
General introduction



General introduction

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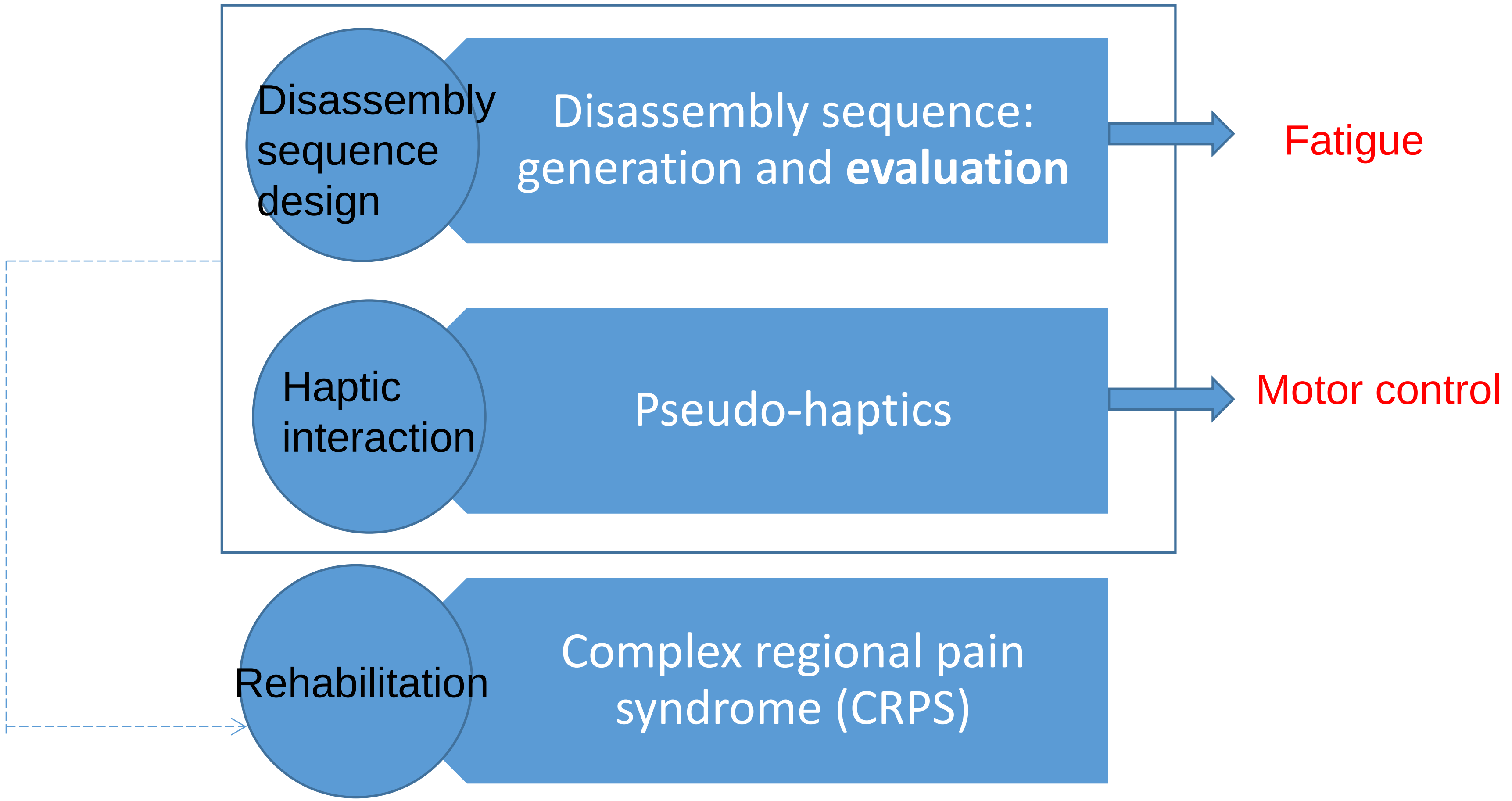
How virtual reality influence human behavior?



Outline

Part I. Biomechanical analysis of haptic-based concept

1. Evaluation of fatigue levels during disassembly
2. Motor behavior analysis of pseudo-haptic in stiffness discrimination

Part II. Application in CRPS (Complex regional pain syndrome)

1. Computer-based application and CRPS rehabilitation

Part I. Biomechanical analysis of haptic-based concept

1. **Evaluation of fatigue levels during disassembly**
2. Motor behavior analysis of pseudo-haptic in stiffness discrimination

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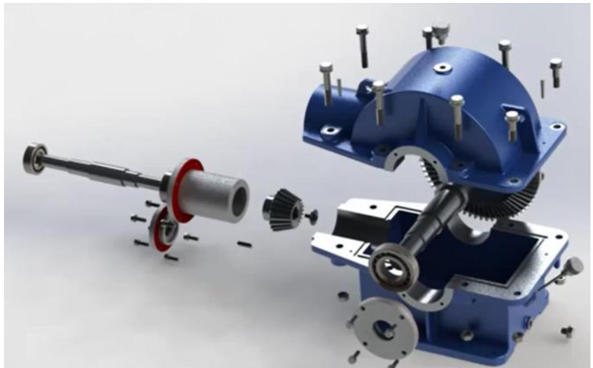
Disassembly sequence simulation



Design process

Disassembly sequence

Verification with real prototype

Verification with haptic device in virtual reality

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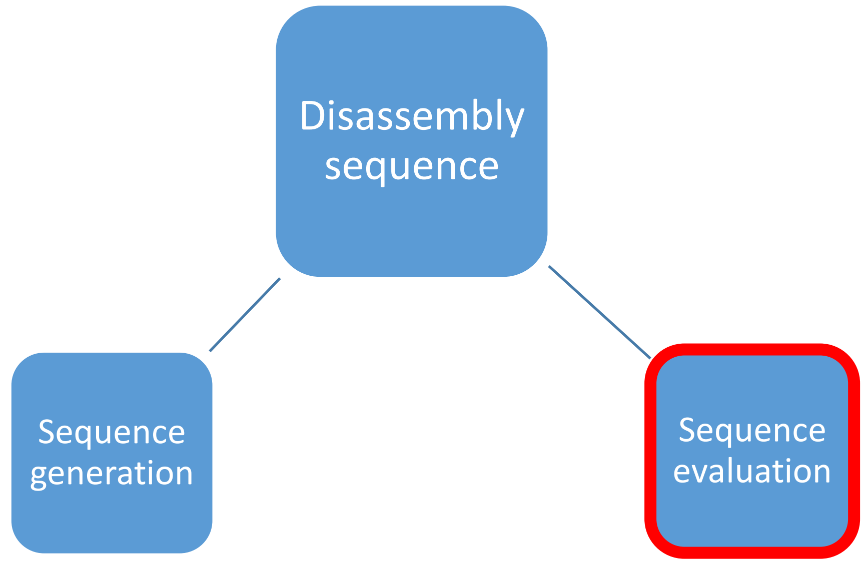
Disassembly sequence simulation

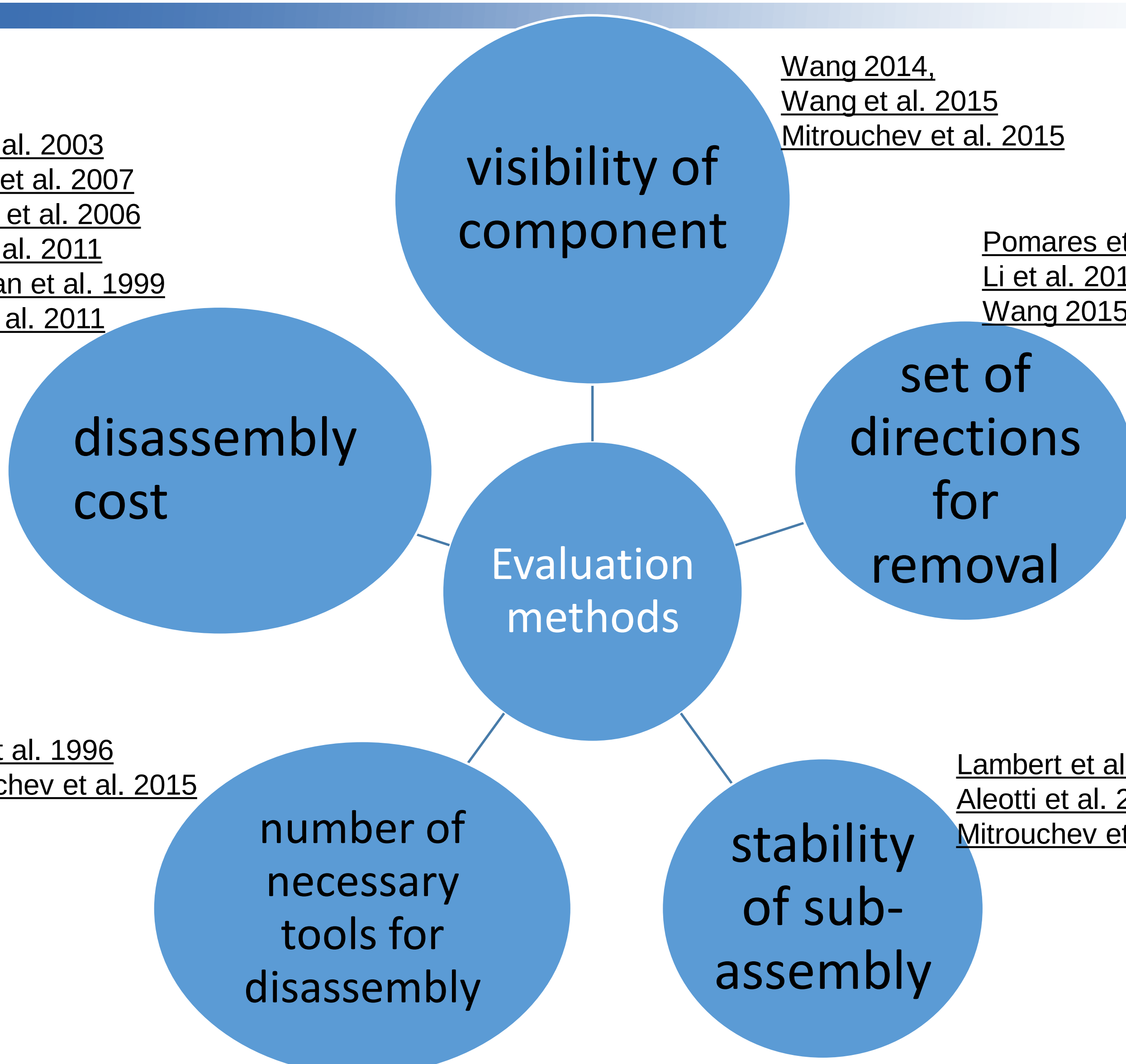


Disassembly types:

Complete, Selective
Destructive, **No-destructive**
Sequential, Parallel
…

Technological factors
Ergonomic factors
- visibility
- risk of injury
- **Muscle fatigue**
- working posture

Disassembly sequences evaluation



visibility of component: Wang 2014, Wang et al. 2015, Mitrouchev et al. 2015

set of directions for removal: Pomares et al. 2004, Li et al. 2013, Wang 2015

stability of sub-assembly: Lambert et al. 2004, Aleotti et al. 2010, Mitrouchev et al. 2016

number of necessary tools for disassembly: Kroll et al. 1996, Mitrouchev et al. 2015

disassembly cost: Desai et al. 2003, Cappelli et al. 2007, Jayaram et al. 2006, Smith et al. 2011, Srinivasan et al. 1999, Tseng et al. 2011

Improvement of disassembly sequences evaluation

Evaluating the muscle fatigue associated with different disassembly sequences (tasks)

Human fatigue

- $FA = f(FAc, FAp)$

FAc: Fatigue in *central* nervous system

Brazil-Neto et al. 1993
David and Bailey, 1997
David et al. 2003

FAp: Fatigue in *peripheral* system (muscle)
Merton 1954
Sahlin 1985
Lamber et al. 2005
Dempsy et al. 2008

Our approach

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Using **mechanical energy expenditure** to evaluate the **muscle fatigue**:

$$FA_p = f(E(F,t,v))$$

E: mechanical energy
F: force
t: time
v: velocity

$$\frac{dFA_p}{dF} = \frac{\partial FA_p}{\partial E} \cdot \frac{\partial E}{\partial F}$$

$$\frac{dFA_p}{dF} > 0 \text{ (Rose et al. 2014)}$$

$$\frac{\partial E}{\partial F} > 0$$

- FAp: monotonically increasing function of *mechanical energy expenditure*

Mechanical energy expenditure (ΔE_{S1})

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$$\Delta E_{S1} = \sum_{i=1}^{n}[m_i g(h_{iu} + h_{id}) + 2m_a g h_{aiu}] \quad (i = 1,2,3 \ldots \text{n})$$

- m_i: mass of component
- h_{iu} and h_{id}: vertical displacements of end of hand in upward and downward direction
- m_a: mass of *arm*
- h_{aiu}: vertical displacement of the arm's mass center

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Validation

Task 1 and Task 2

Theoretical

Propose method

↓

Calculate ΔE_{T1} and ΔE_{T2}

↓

Which task induces more fatigue

Experimental

Perform T1 and T2

↓

Record and analyze EMG signals

↓

Which task induces more fatigue

Part I:

Fatigue

Issue

Previous work

Objective

Proposed method

Verification and validation

Limits of model

Part I: Pseudo-haptics

Part II: Application

Experimental setup, GINOVA Grenoble INP

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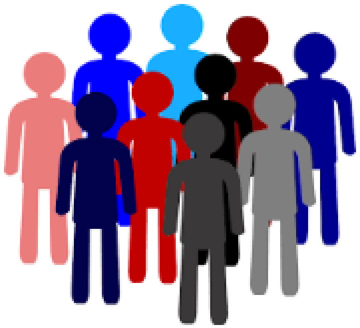
VIRTUOSE 6D35-45 haptic device

Task 1 : The first *2.5* minutes.

Task 2: The total *5* minutes

Subjects

9 subjects



Age : 24 to 58

Duration: 30 minutes

Part I:

Fatigue

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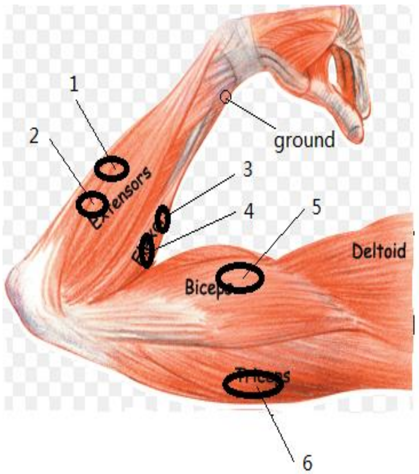
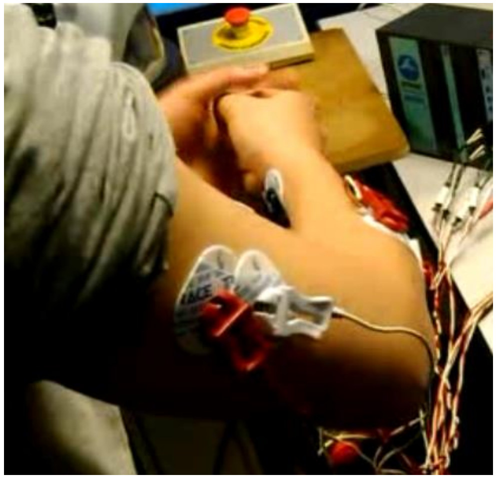
EMG muscle testing

Position of electrodes (SENIAM recommandations)





Fatigue evaluation

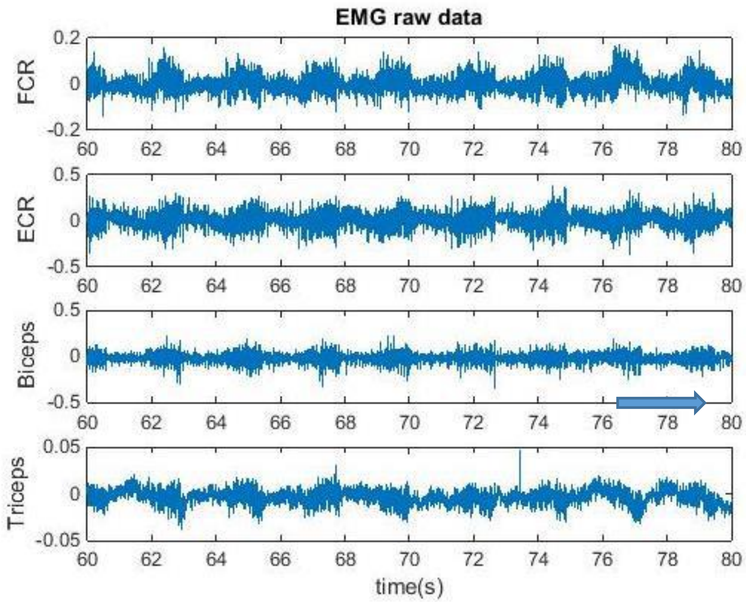
Median frequency:

- The more the slope of median frequency decreases, the more muscle fatigue there is (Don et al. 1999)

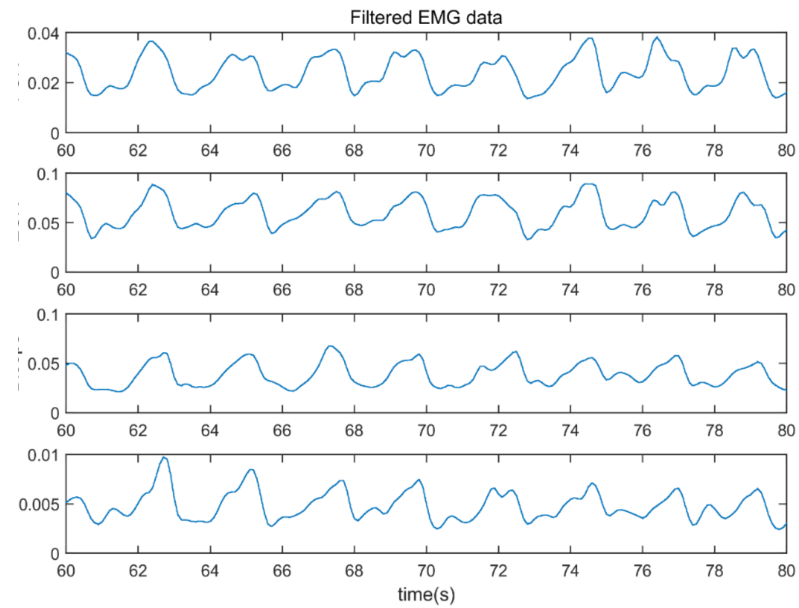
Peak value of EMG

- **Higher peak indicates more fatigue** (Boyas et Guevel 2014)

Recorded EMG



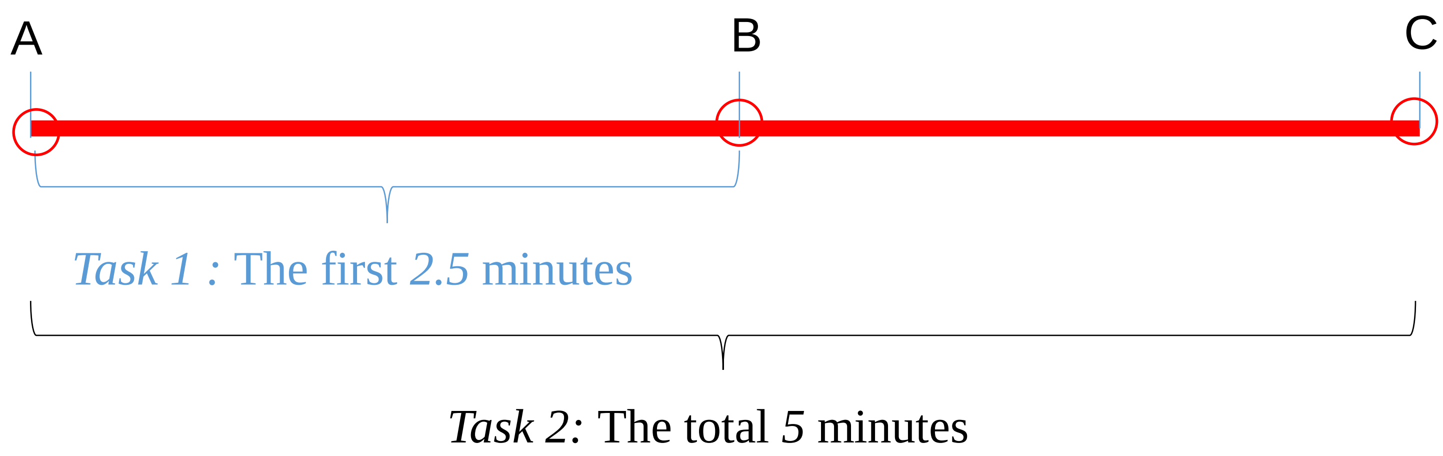
20s period EMG raw signals



20s period filtered EMG signals

200 order of bandpass FIR filter between *20Hz* and *500Hz*

EMG at three monents



A – start time of tasks
B – end time of task 1
C – end time of task 2

Part I:

Fatigue

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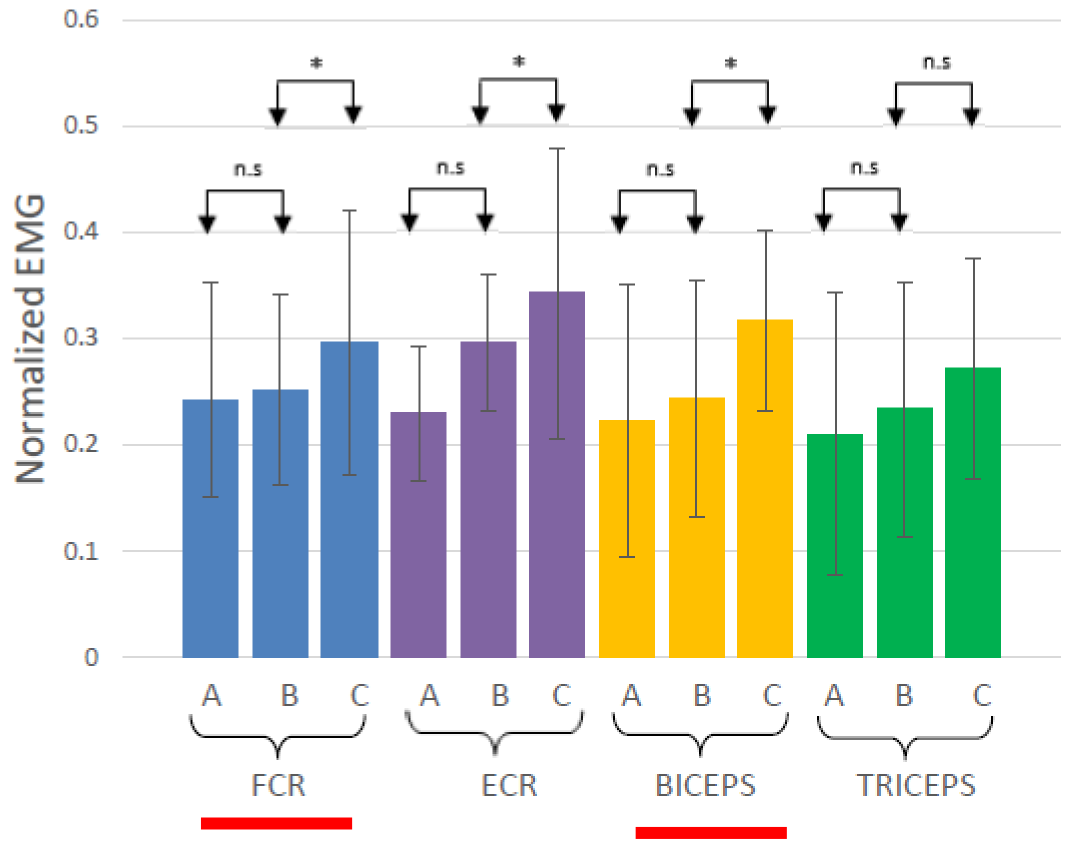
Limits of model

Part I: Pseudo-haptics

Part II: Application

EMG Peaks



fatigue induced by *T1* is less than *T2*

FCR: flexor carpi radialis
ECR: extensor carpi radialis

B – end time of task 1
C – end time of task 2

*: significant difference
n.s: no significant difference

Verification and validation

EMG analysis results

Fatigue induced by *T1* is less than *T2*

=

Caculation results

ΔE_{T1}=308 J and ΔE_{T2}=616 J

Fatigue induced by *T1* is less than *T2*

Limits

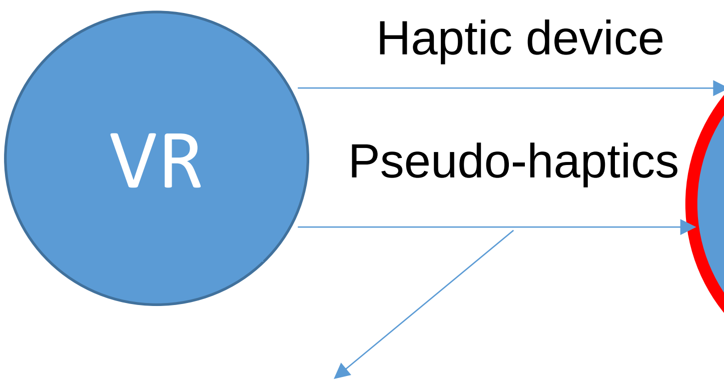
- Energy consumption of rotation movement is not considered
- Considering one hand disassembly operation simulation

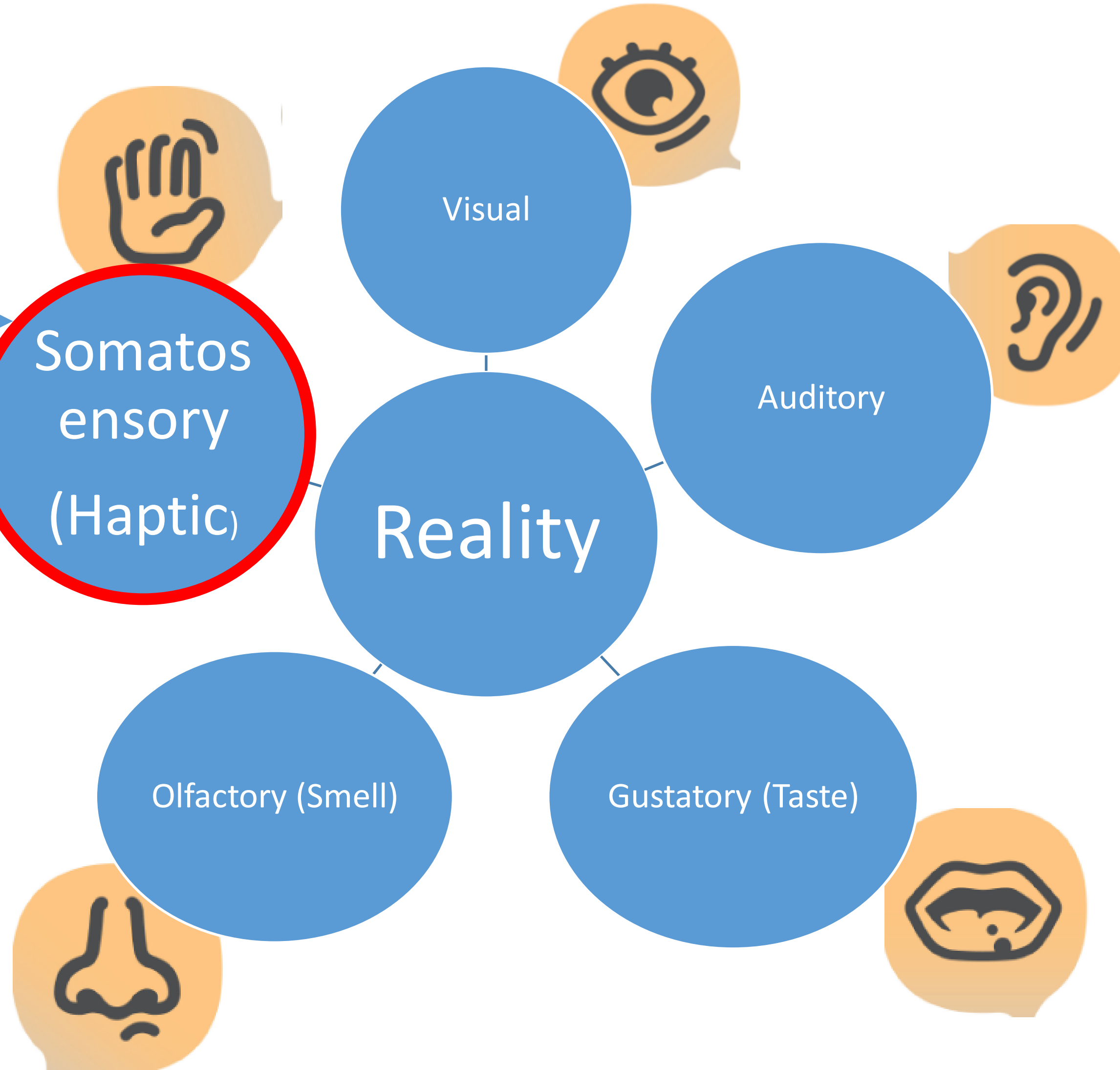
Limit the generalization of the proposed method into real disassembly task

Part I. Biomechanical analysis of haptic-based concept

1. Evaluation of fatigue levels during disassembly
2. **Motor behavior analysis of pseudo-haptics in stiffness discrimination**

Issue: Pseudo-haptics





A definition: *"Generation, augmentation or deformation of haptic sensations by information coming from other sensory modalities"* (Lécuyer et al.2001)

Part I:

Fatigue

Part I:
Pseudo-haptics

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Part II:
Application

Simulating different physical properties

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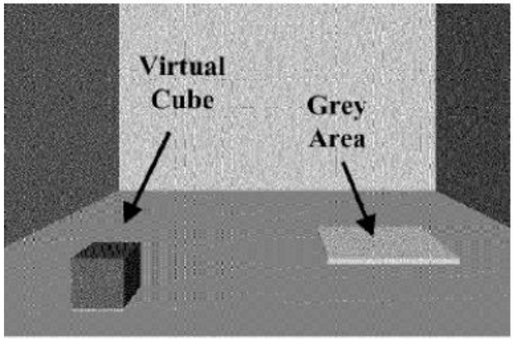
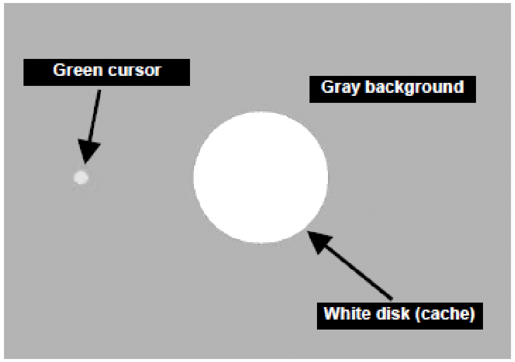
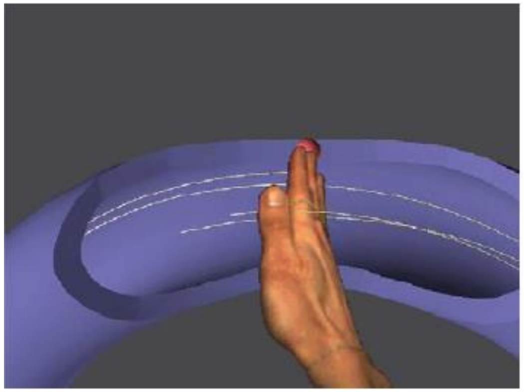
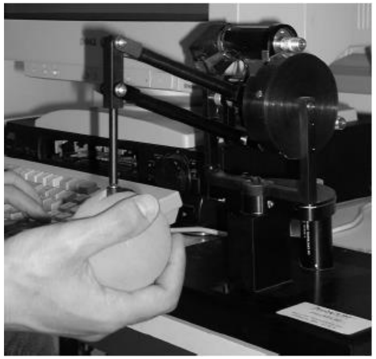
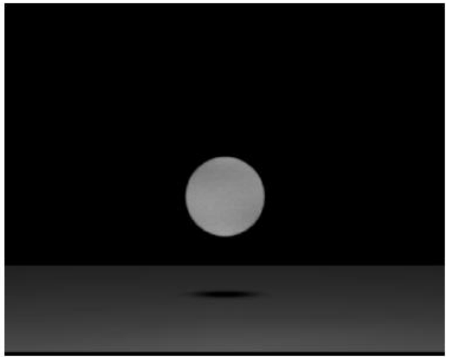
Friction (Lécuyer et al.2001)	Texture and shape (Lécuyer et al.2004)
	
Force field (Pusch et al.2009)	**Weight (Dominjon et al.2005)**
	 

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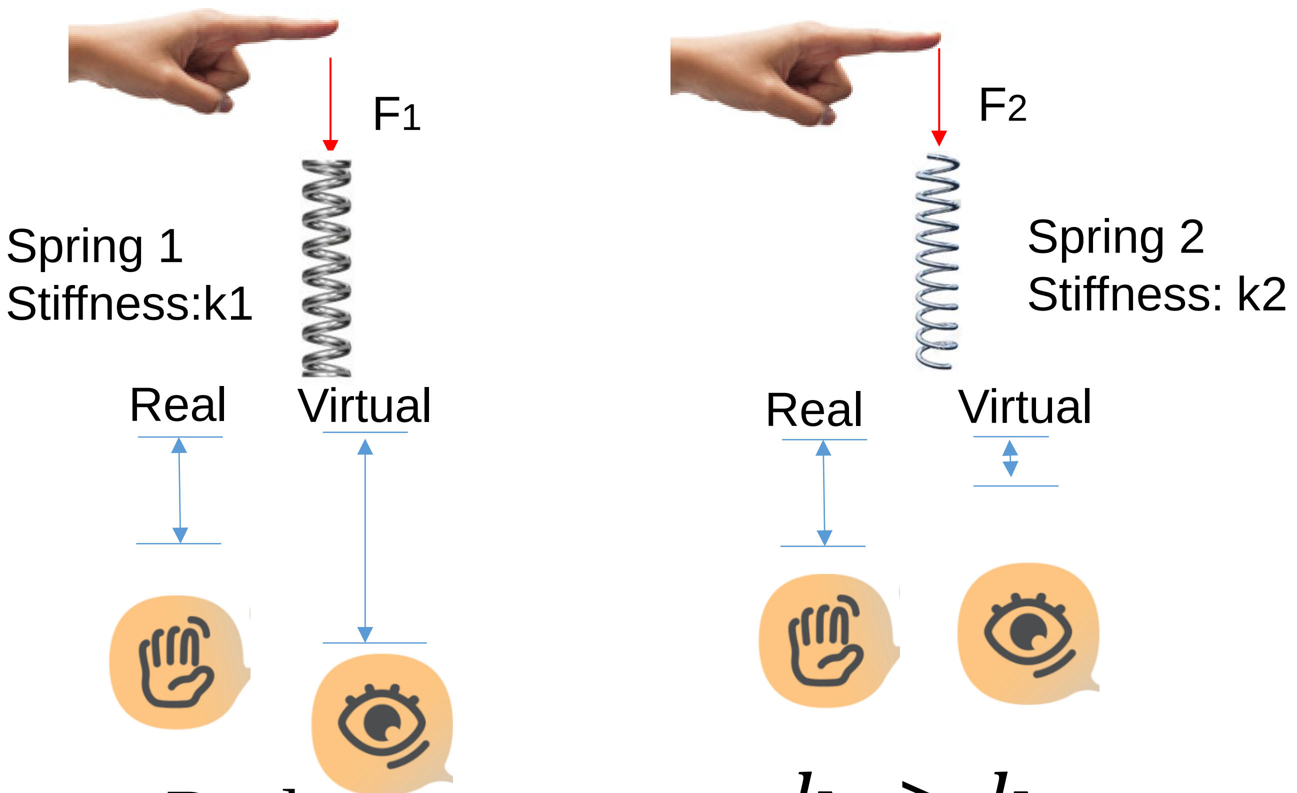
Stiffness perception

Influence of vision (Srinivasan et al. 1996)

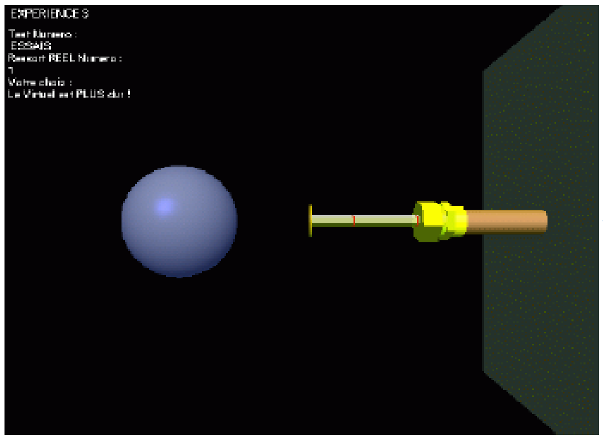


Real: $k_1 > k_2$

Subject perception: $k_1 < k_2$

Pseudo-haptic feedback

Stiffness discrimination between real and pseudo-haptic spring

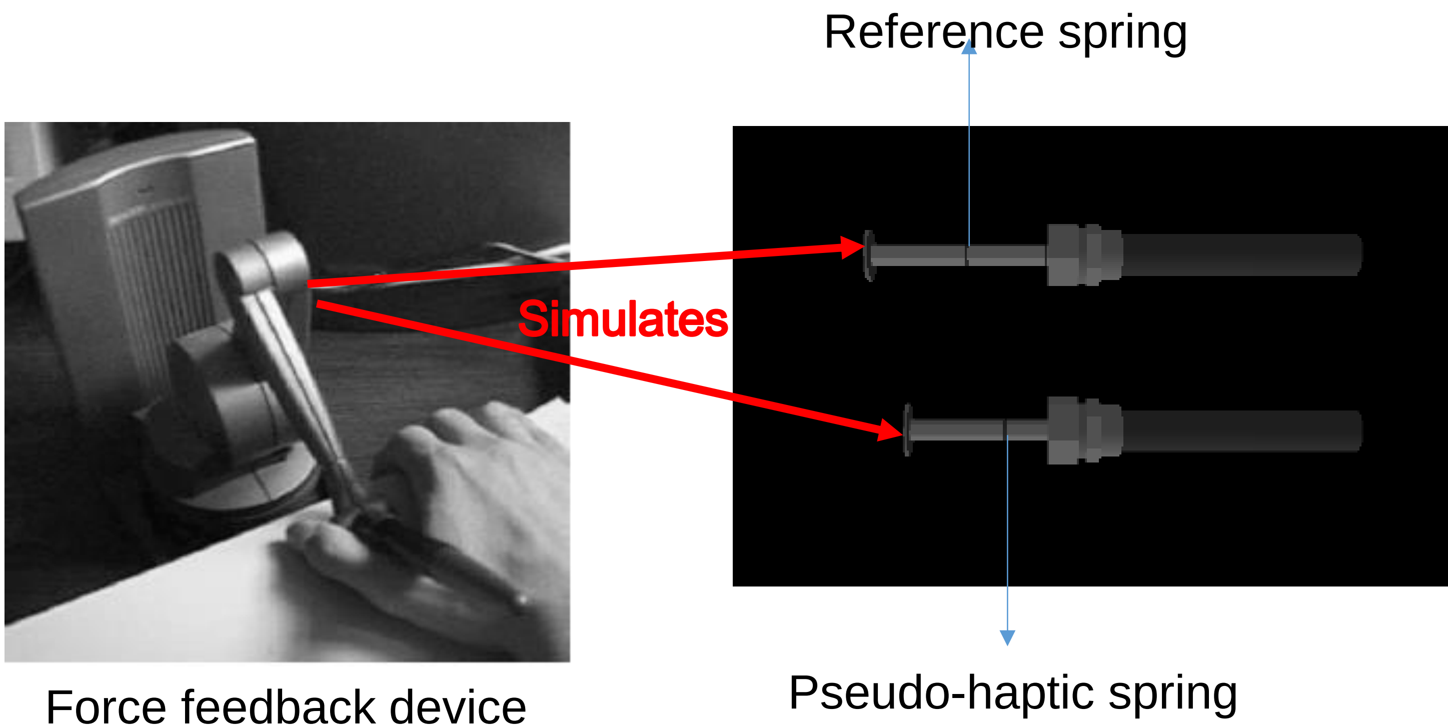


Stiffness discrimination

Changing the stiffness of virtual spring can change subjects' stiffness perception results in different levels (Lécuyer et al. 2000)

Pseudo-haptic feedback

Stiffness discrimination between real and pseudo-haptic spring ?



Subject answers change following the changes of stiffness of pseudo-haptic spring

Discrimination result is different when the subject relies on his/her haptic sense rather than on his/her visual sense *(Lécuyer et al. 2001)*

Part I:

Fatigue

Part I: Pseudo-haptics

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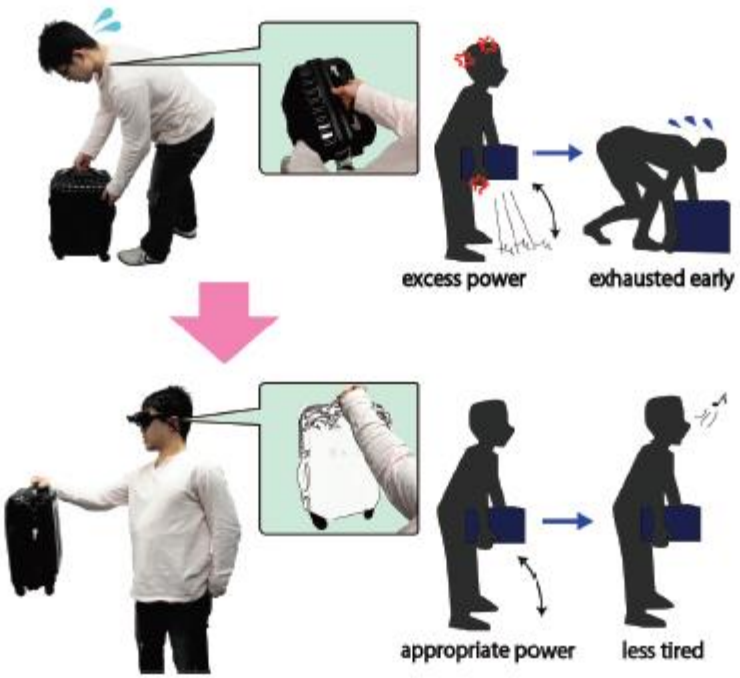
Pseudo-haptic feedback



Pseudo-haptic feedback can influence muscle fatigue during lifting objects (Yuki et al. 2014) → Muscle involvement

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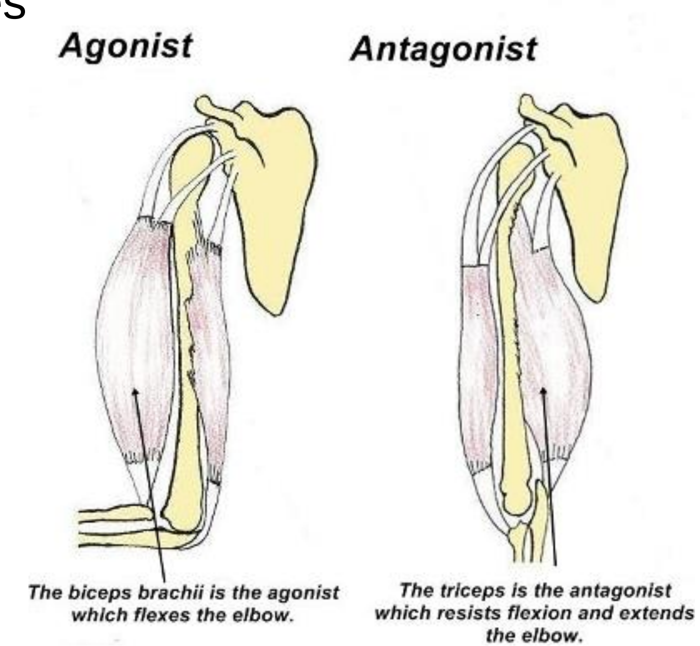
Muscle co-activation

Muscle co-activation: simultaneous contraction of both agonist and antagonist muscles



$$CI = \frac{2 \times EMG_{Ant}}{EMG_{Ago} + EMG_{Ant}} \times 100\%$$ (Ervilha et al. 2012)

EMG_{Ant} and EMG_{Ago} : peak values of the most involved antagonist muscle (extensors) and agonist muscle (flexors)

Muscle co-activation

Dynamic task (Suzuki et al. 2001, Gribble et al. 1998)	Static task (Yang et Winter 1983, Hébert et al. 1991)
V↑ Co↑	F↑ Co↑
Control of limb movement	Control of joint stability

V - joint velocity
Co - muscle co-activation
F - applied force

Research question

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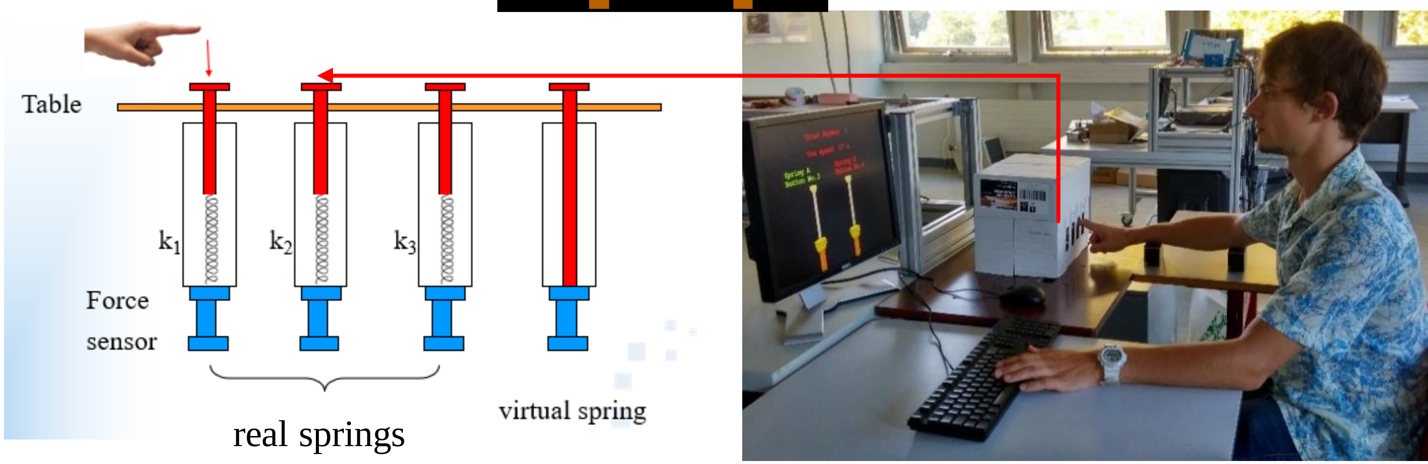
Assessment of previous work	**Pseudo-haptics influence on perception**
Problematic	• **Does pseudo-haptic influence on biomechanical aspects of human movement and muscle involvement in stiffness discrimination ?** ↓ **Better understand the pseudo-haptics**

Experimental setup

Stiffness discrimination task: **virtual spring vs. real spring**



$$k_v = k_i(1+p) \quad (i = 1,2,3)$$

k_i : stiffness of real spring ($k_1 = 202N/m, k_2 = 304N/m, k_3 = 608N/m$)
k_v : stiffness of virtual spring
p= -40%, -30%,…,0%,…, +60%

Part I:

Fatigue

Part I: Pseudo-haptics

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Experimental protocol

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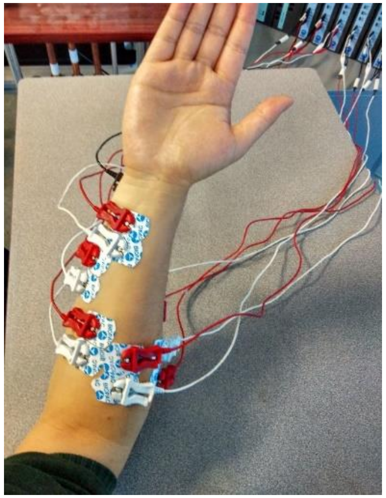
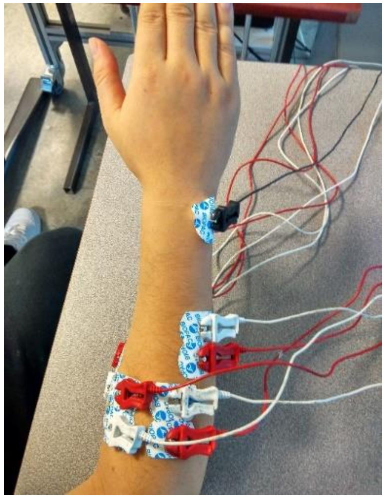
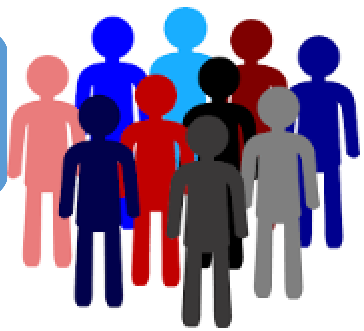
Flexors	Extensors
	
Four sets of electrodes	Two sets of electrodes

Subjects

14 subjects

Duration:
1 hour 30minutes



Age : 20 to 33

198 trials per subject

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Experimental data

For real and virtual spring

1. Pressing force
2. EMG (electromyogram) on six muscles at forearm
3. Subject's answers

→

1. **Stiffness perception**
2. **Force**
3. Pressing duration
4. Number of presses
5. **Pressing velocity**
6. EMG on flexor
7. EMG on extensor
8. **Muscle co-activation**

Stiffness perception

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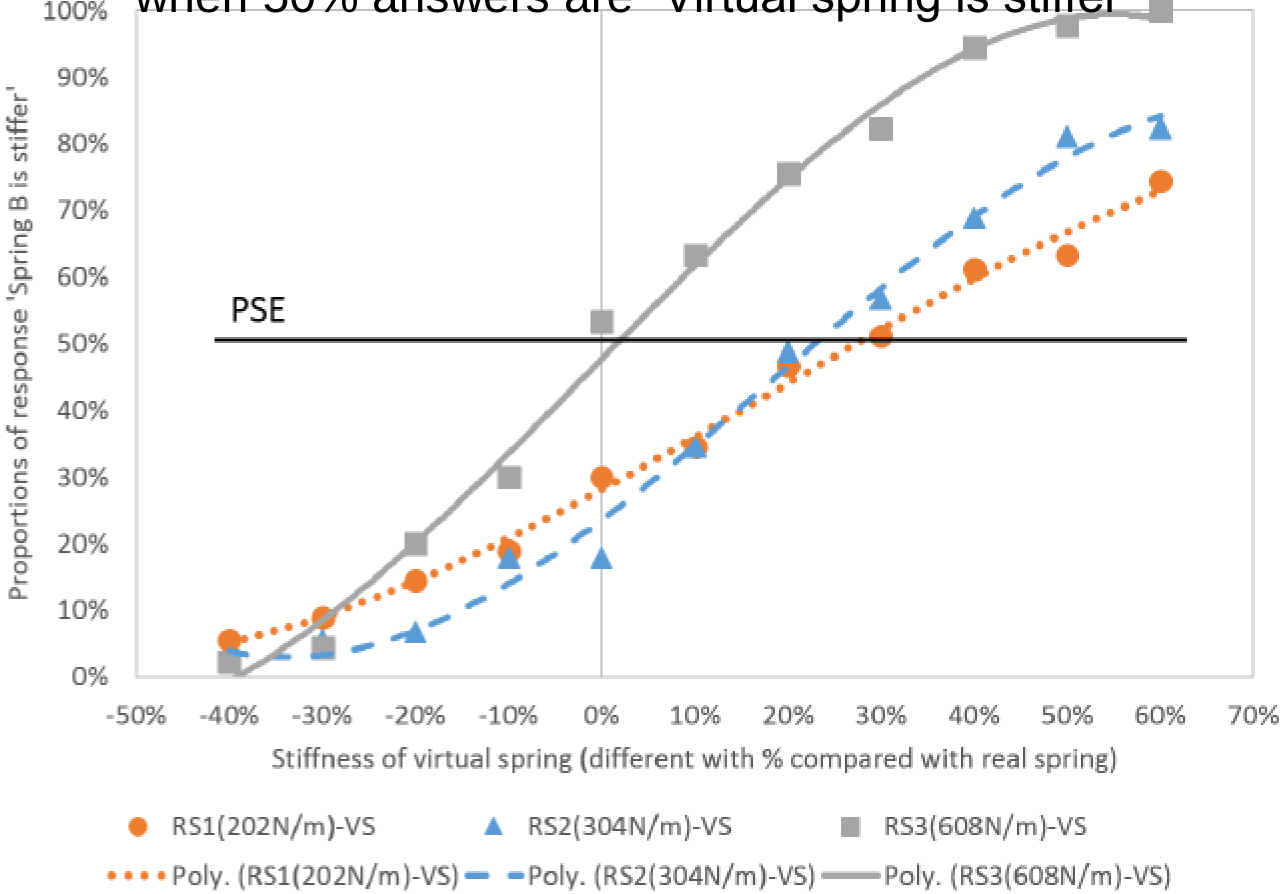
PSE=point of subjective equal

when 50% answers are “Virtual spring is stiffer”



Results confirm that the experiment induces pseudo-haptic effect

Statistical analysis

Two-way ANOVA tests with repeated measures

Independent variables:

- stiffness scale (202N/m, 304N/m, 608N/m)
- change percentage(-40%,-30%,…,0%,…+60%)

Part I: Fatigue

Part I: Pseudo-haptics

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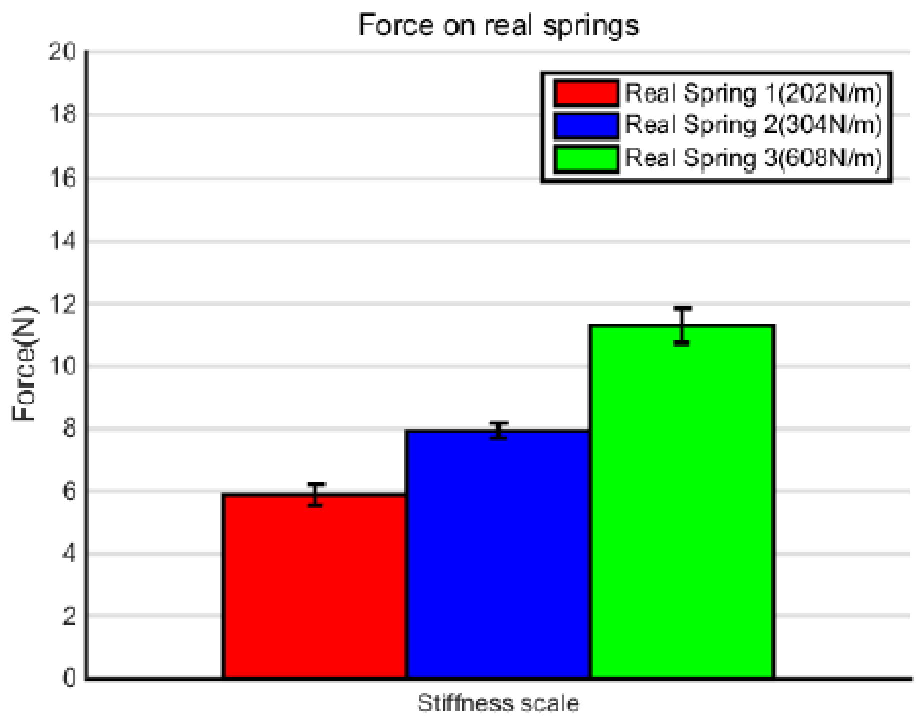
Part II: Application

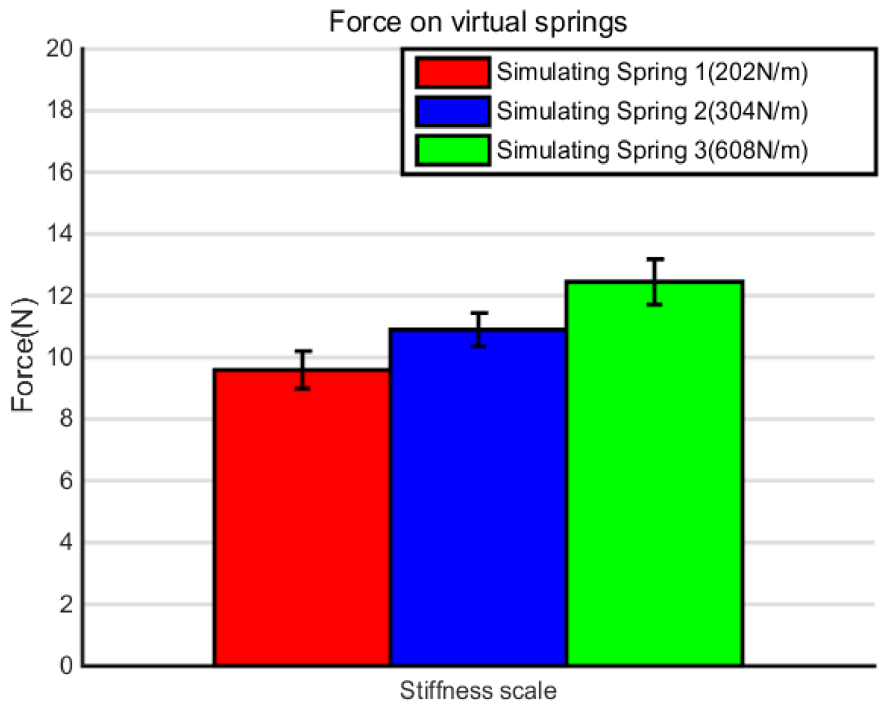
Force on real springs



F=9.9012, p-value<0.001

Force applied on real spring increases significantly with the increase of stiffness of real spring

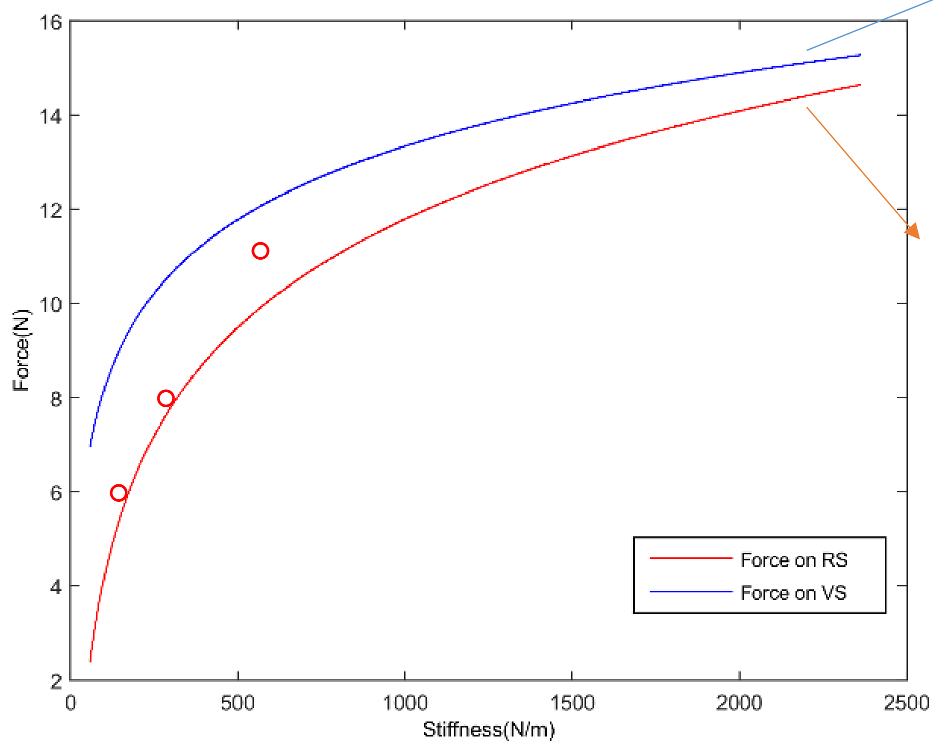
Force on virtual spring



F=31.495, p-value<0.001

Force applied on virtual spring increases when the stiffness of virtual spring increases

Forces on real and virtual springs



Virtual spring
(Our results)

Real spring
(Endo 2016)

○Real spring
(Our results)

- Force increases with the increasing of stiffness
- Approaching a limit

Force experimental results: 1st order linear regression

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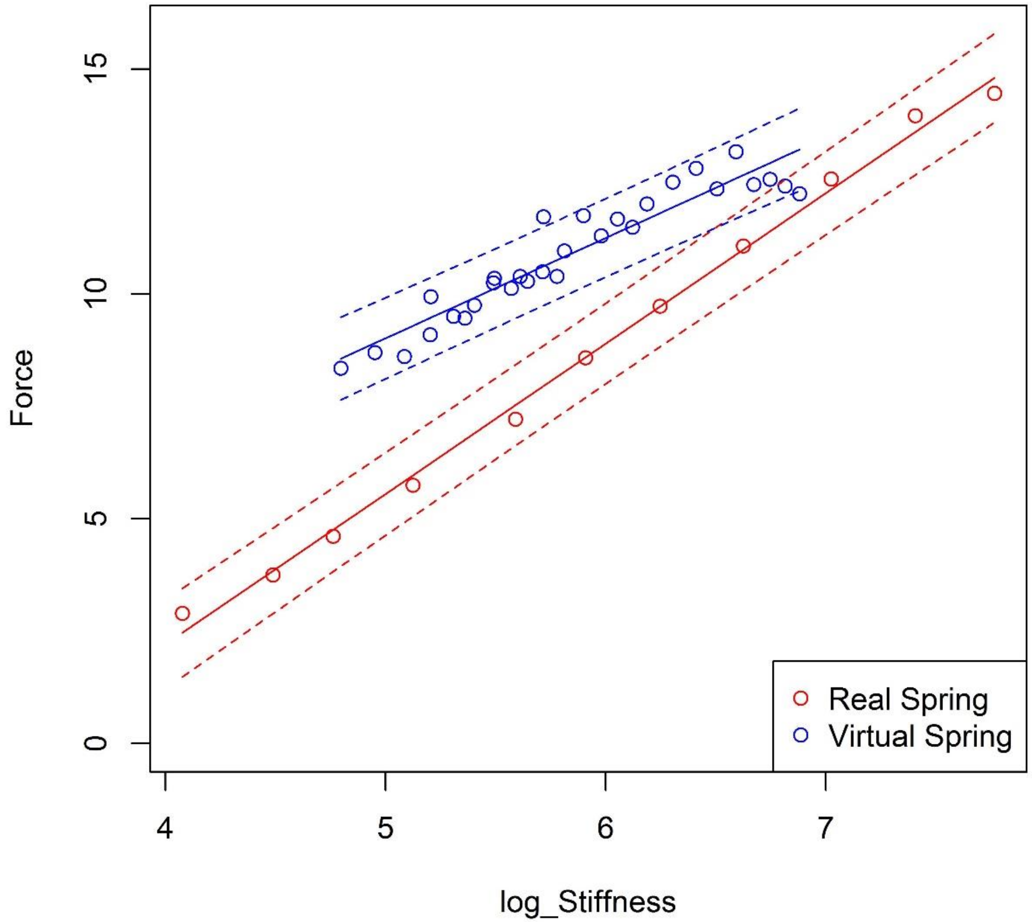

$$F_R = -11.175 + 3.345.\,ln(k_R)$$

$$F_V = -2.148 + 2.232.\,ln(k_V)$$

Part I:

Fatigue

Part I:
Pseudo-haptics

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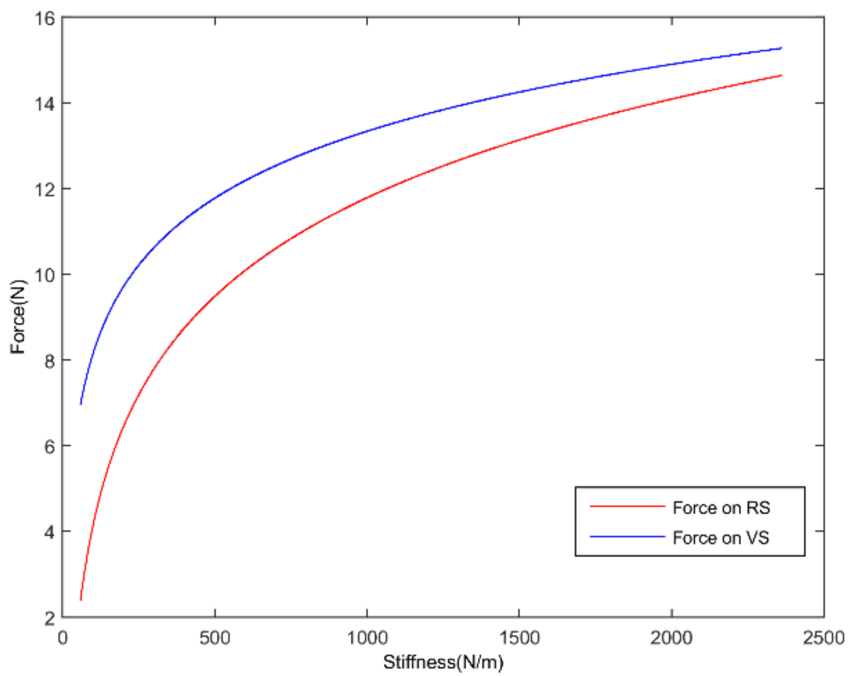
Experimental results: forces

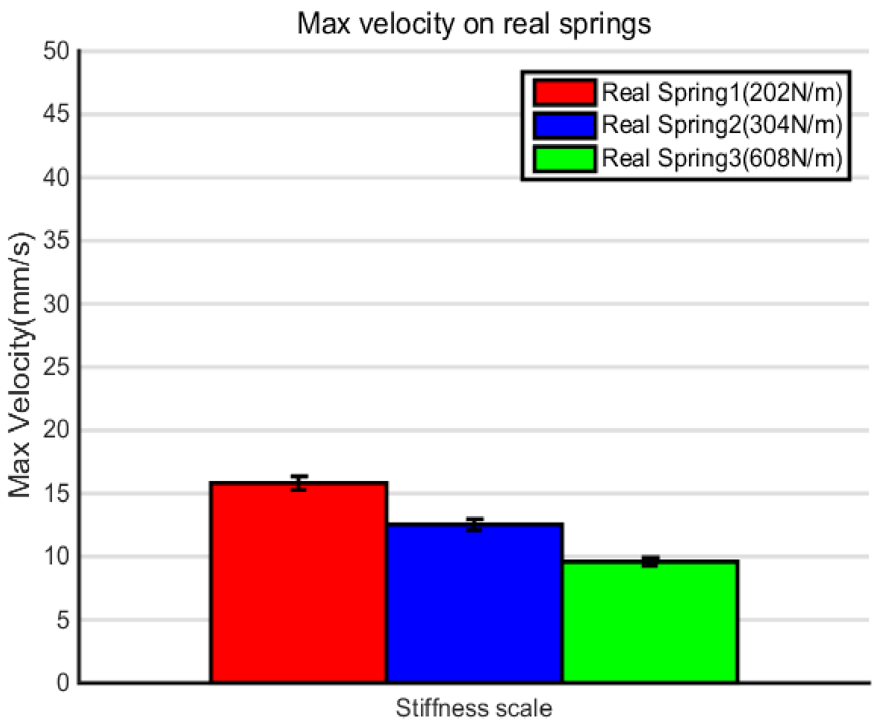


$$F_R = -11.175 + 3.345.ln(k_R)$$

$$F_V = -2.148 + 2.232.ln(k_V)$$

$$\begin{cases} \frac{dF_R}{dk_R} = \frac{3.345}{k_R} \\ \frac{dF_V}{dk_V} = \frac{2.232}{k_V} \end{cases}$$

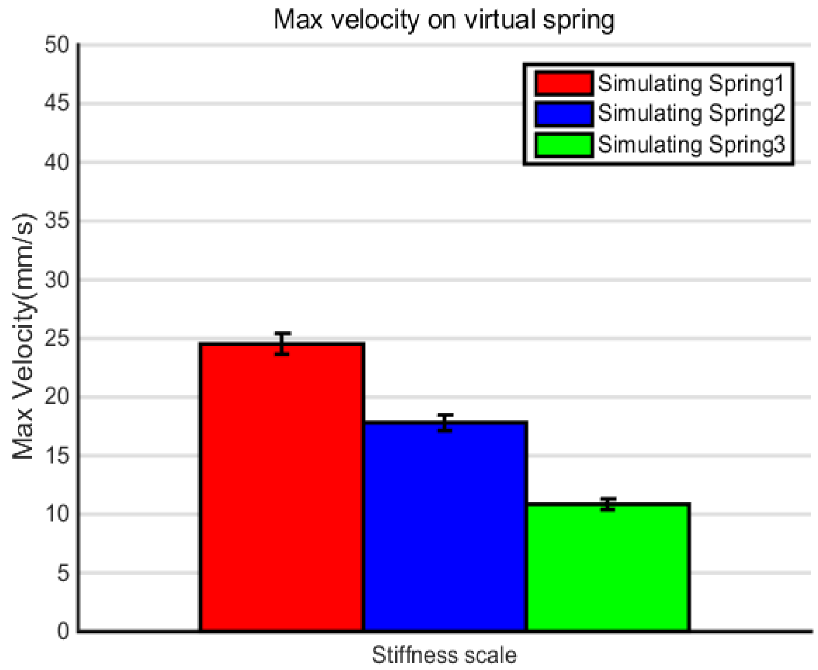
Maximal pressing velocity (real spring)



F=440.62, p-value<0.001

The velocity decreases when the stiffness of real spring increases

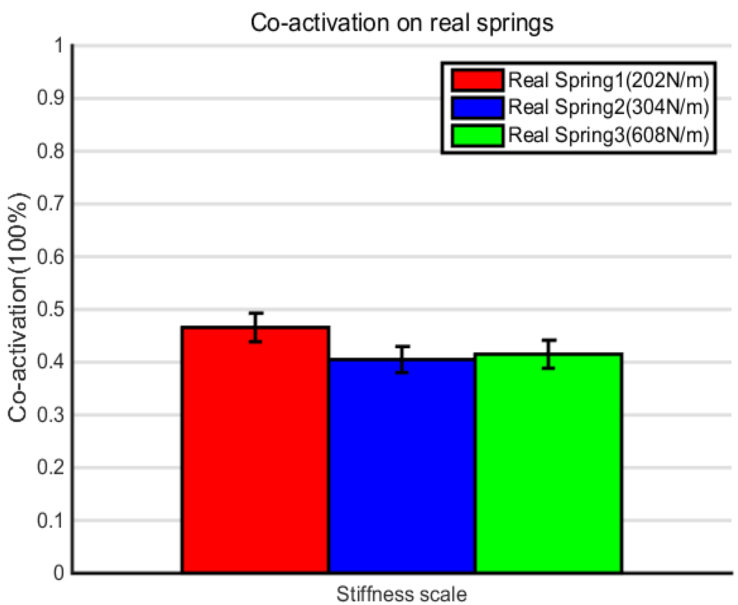
Maximal pressing velocity (virtual spring)

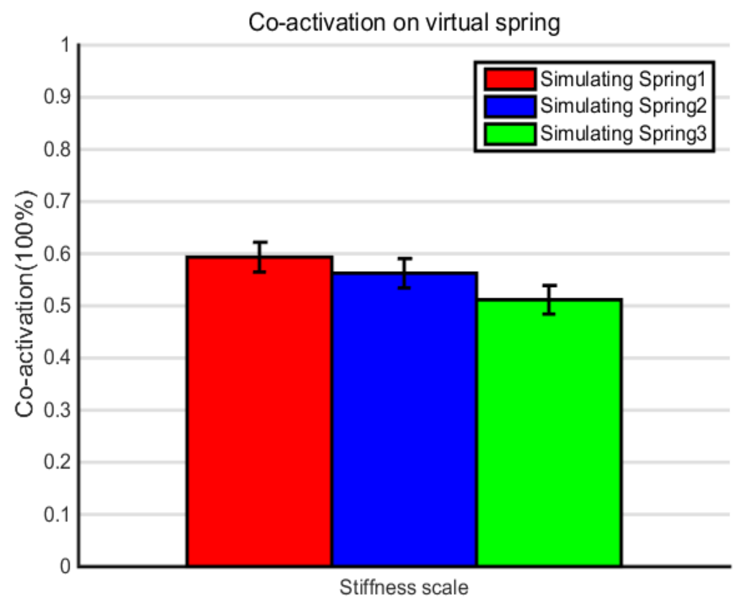


F= 950.81, *p*-value<0.001

The pressing velocity decreases following with increase of the stiffness of virtual spring

Muscle co-activation





F=440,62, p-value<0.001

F=29.93, p-value<0.0001

Muscle co-activation of wrist decrease for stiffer spring

Experimental results and comparison with previous work results

Dynamic task (Suzuki et al. 2001, Gribble et al. 1998)	Static task (Yang et Winter 1983, Hébert et al. 1991)
V↑ Co↑	F↑ Co↑
Real spring: Joint velocity ≠0: Dynamic task	Virtual spring: Joint velocity=0. Static task
k ↑ { Co ↓, F ↑, V ↓ }	F ↑ Co↓ V↓

≠

Co=muscle co-activation; F=force; V=maximal pressing velocity

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Main conclusions

- Pseudo-haptics can induce the similar force behavior as in real spring
- Pseudo-haptics can induce different levels of muscle co-activation
- Co-activation does not depend solely on mechanical constraints, but also component associated with the cognitive and/or central nervous system for muscle involvement planning

Part II Application in CRPS (Complex regional pain syndrome)

SDRC (Syndrome douloureux régional complexe)

Computer-based application and CRPS rehabilitation

Part I:

Fatigue

Part I:
Pseudo-haptics

Part II:
Application

CRPS

Proposed method

Pilot study

Results

Summary

CRPS (Complex regional pain syndrome)

Key CRPS symptoms :

- Prolonged pain
- Changed stiffness of joint
- Sensitive skin
- Painful swelling
- Abnormal posture
- Deficient muscle activation

CRPS (Complex regional pain syndrome)

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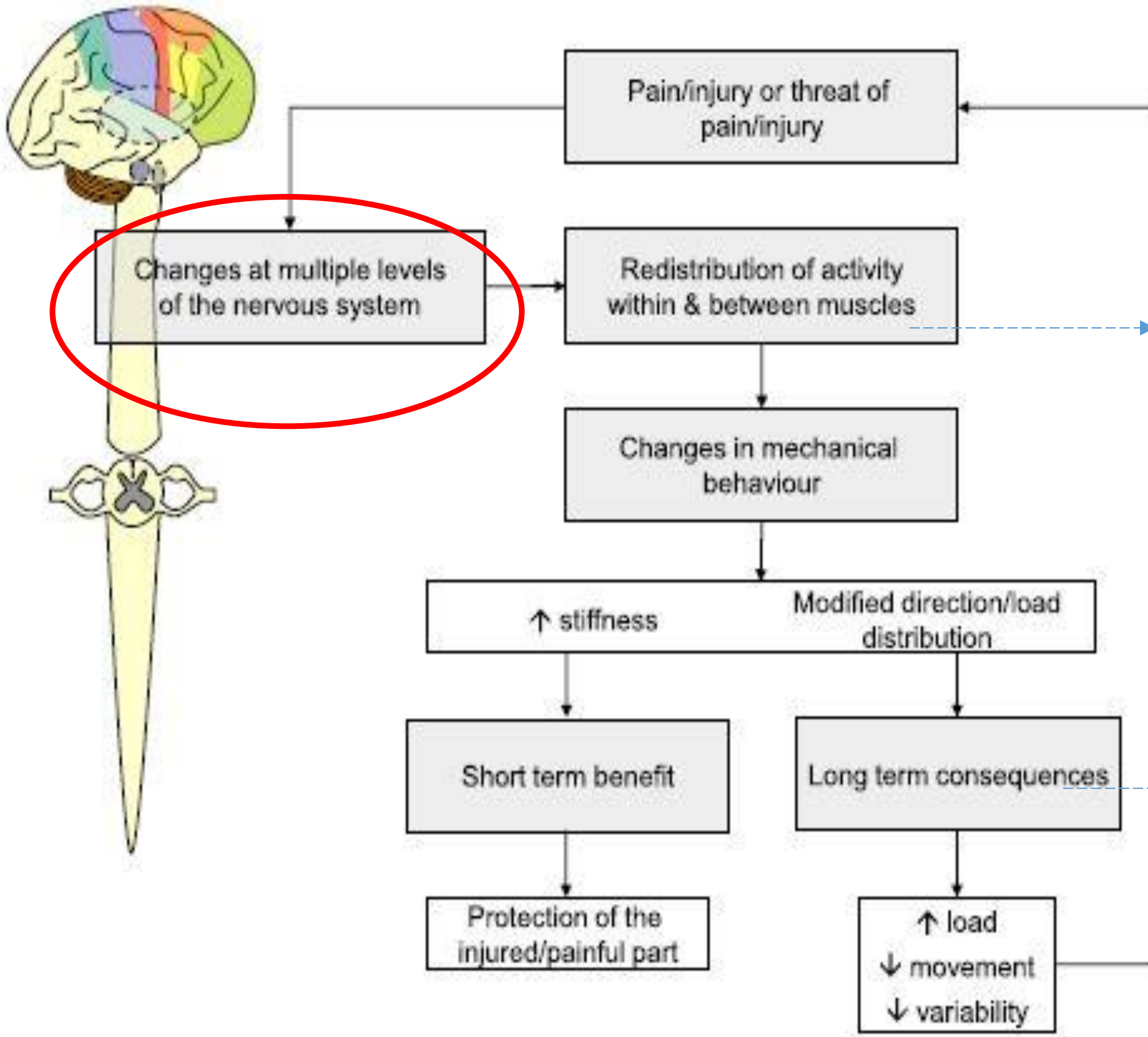
Motor adaptation to pain (Hodges et al. 2011)



loss of voluntary modulation of muscle activity. (Bank et al. 2013)

Negative consequence (Hug et al.2015)

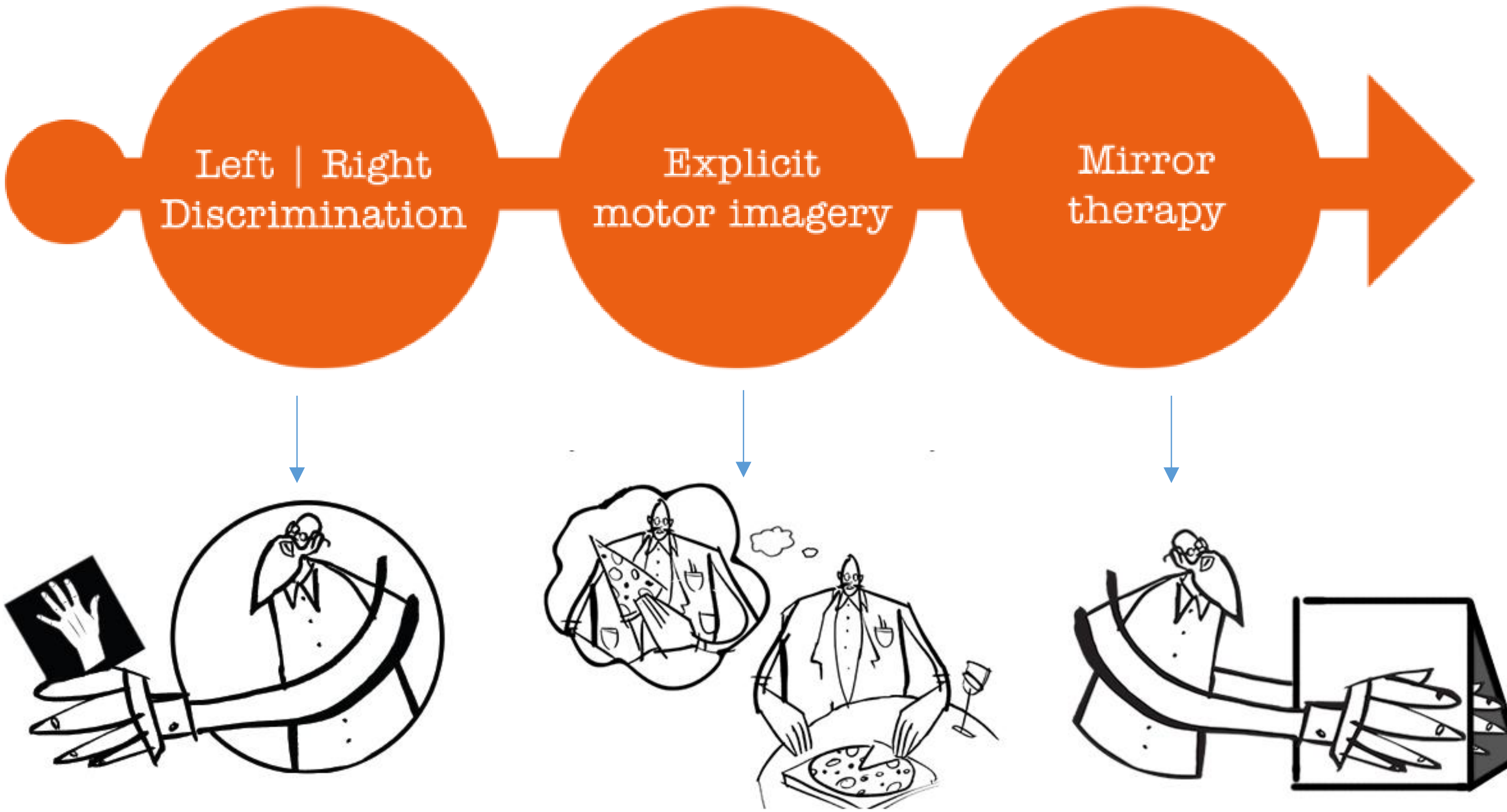
Treatments for CRPS

- Intervention on patient's nervous system (Schwartzman et Mclellan 1987, O'Connell et al. 2013)
  - paravertebral sympathetic block technique
  - removal of peripheral arterial sympathectomy

- Physical therapy (Moseley 2013)
  - Movement therapy
  - Graded motor imagery
  - Mirror Box Therapy

Physical therapy

Graded motor imagery (Moseley 2004)



Part I:

Fatigue

Part I: Pseudo-haptics

Part II: Application

CRPS

Proposed method

Pilot study

Results

Summary

Physical therapy (continue)

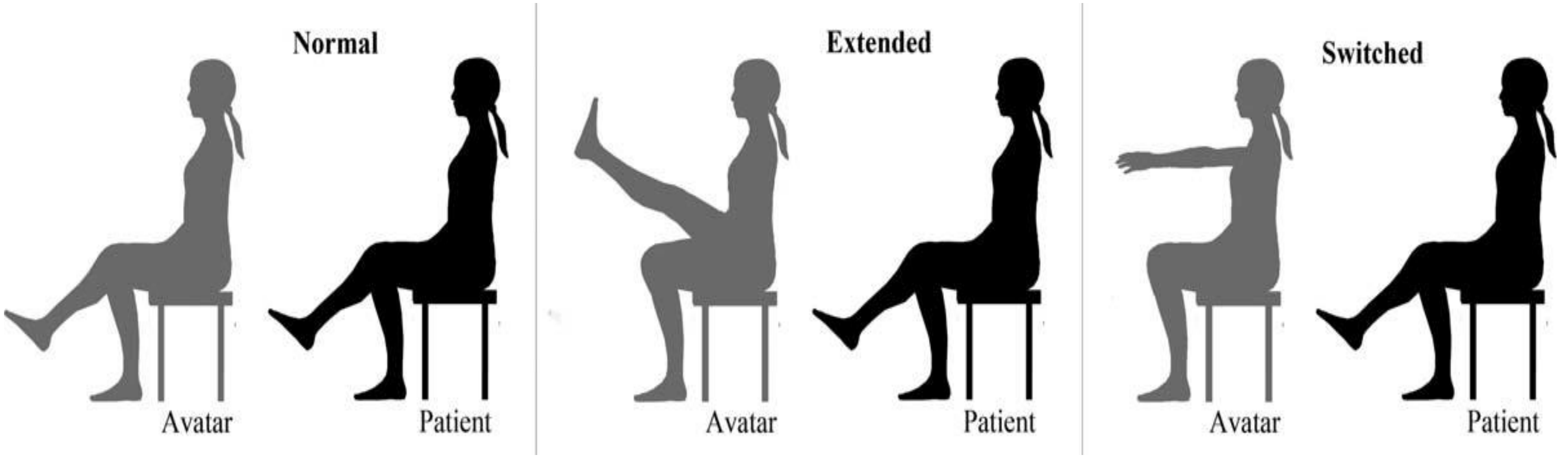
Mirror therapy (Cacchio et al. 2009)

CRPS (Complex regional pain syndrome)

Physical therapy

VR therapy (Won et al. 2016)

Avatar control conditions:



(a). Normal condition; (b). Extended condition; (c). Switched condition

Pain tolerance

- Pain cognition influences the physical performance (Moseley 2004)
- Altered somatic vigilance may lead to a change in pain threshold (Geisser et al. 1993)

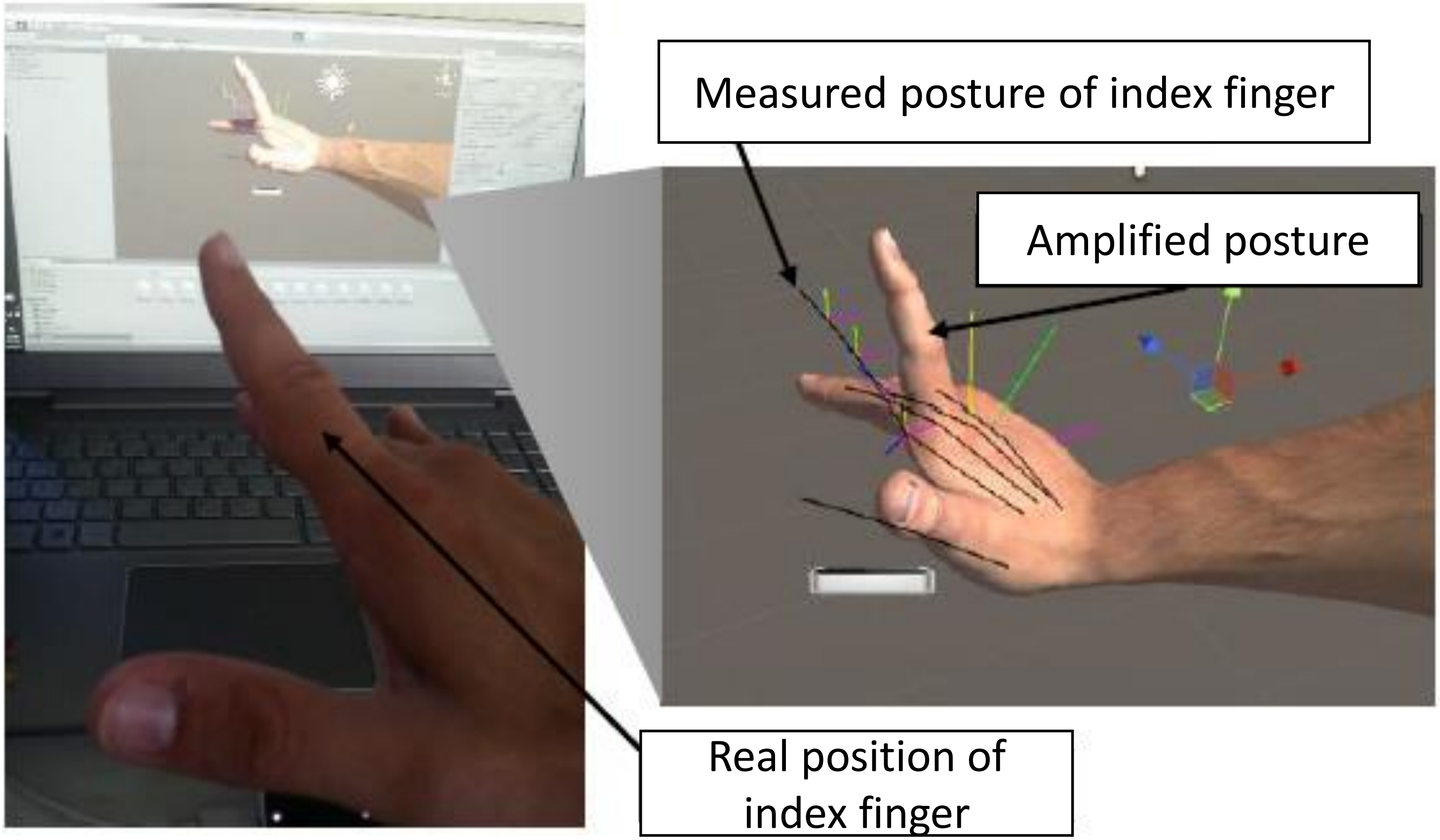
Propose method

Can VR (modified visual feedback) change the pain tolerance?

1. Develop an application
2. Test the feasibility

Developed application

Based on Leap Motion and Unity (Dufetel 2015)



Amplify or decrease the joint motion

Subjects can see some movement they cannot see in reality

Pilot study: experiment in CHU

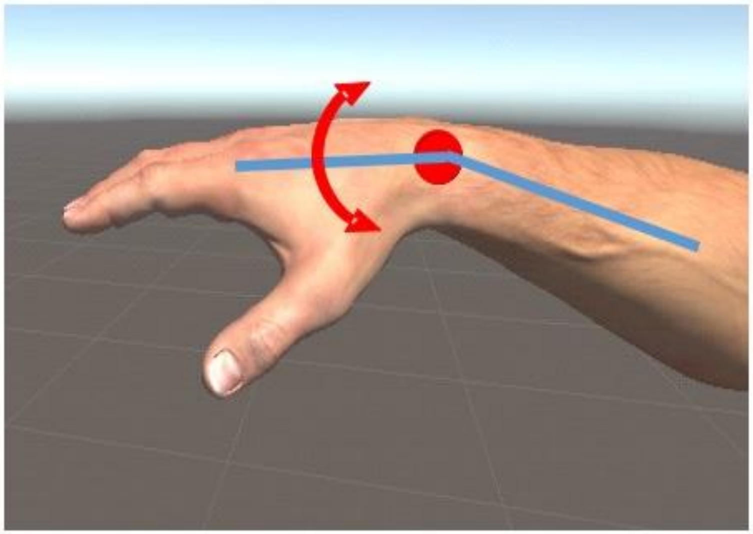
Types of hand models for right and left hands

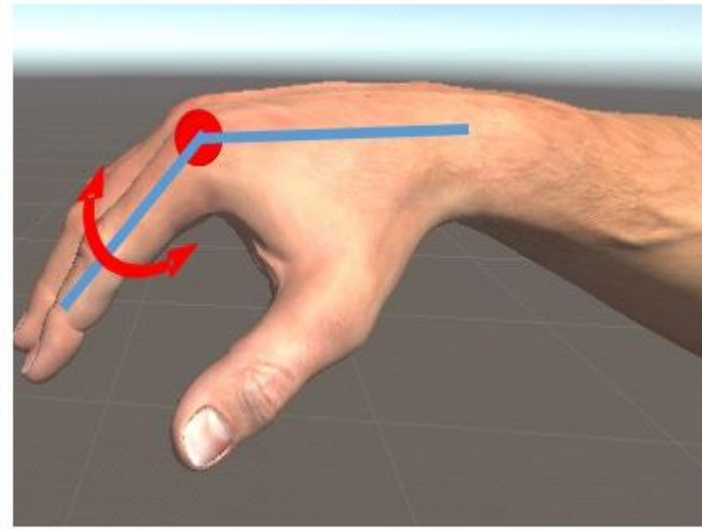
Natural skin

Silver skin

Pilot study: experiment in CHU (Hand surgery service)

Movement amplification





Task 1: Flexion and extension of wrist

Task 2: Flexion and extension of MCP (metacarpophalangeal) joint

Rotation angle of the joint (wrist or MCP) in avatar hand (θ_A)

$$\theta_A = C_A \cdot \theta_U$$

C_A: amplification coefficient (0.25, 0.5, 1, 2 ,4)
θ_U: rotation angle of user hand joints

Part I:

Fatigue

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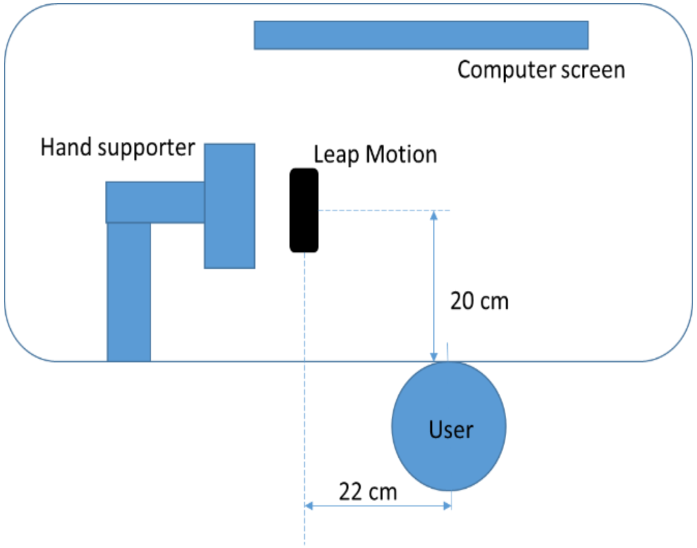
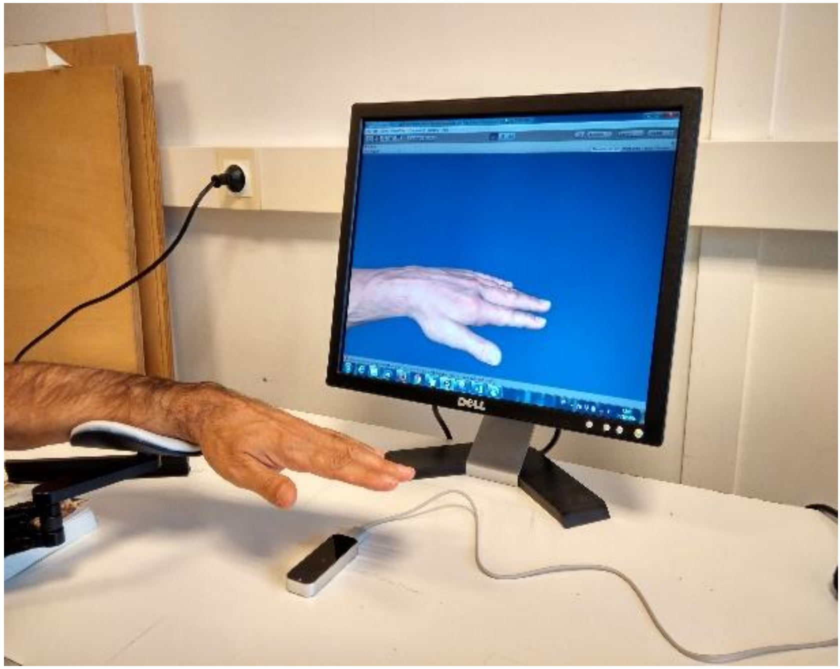
Pilot study: experiment in CHU

Experimental setup

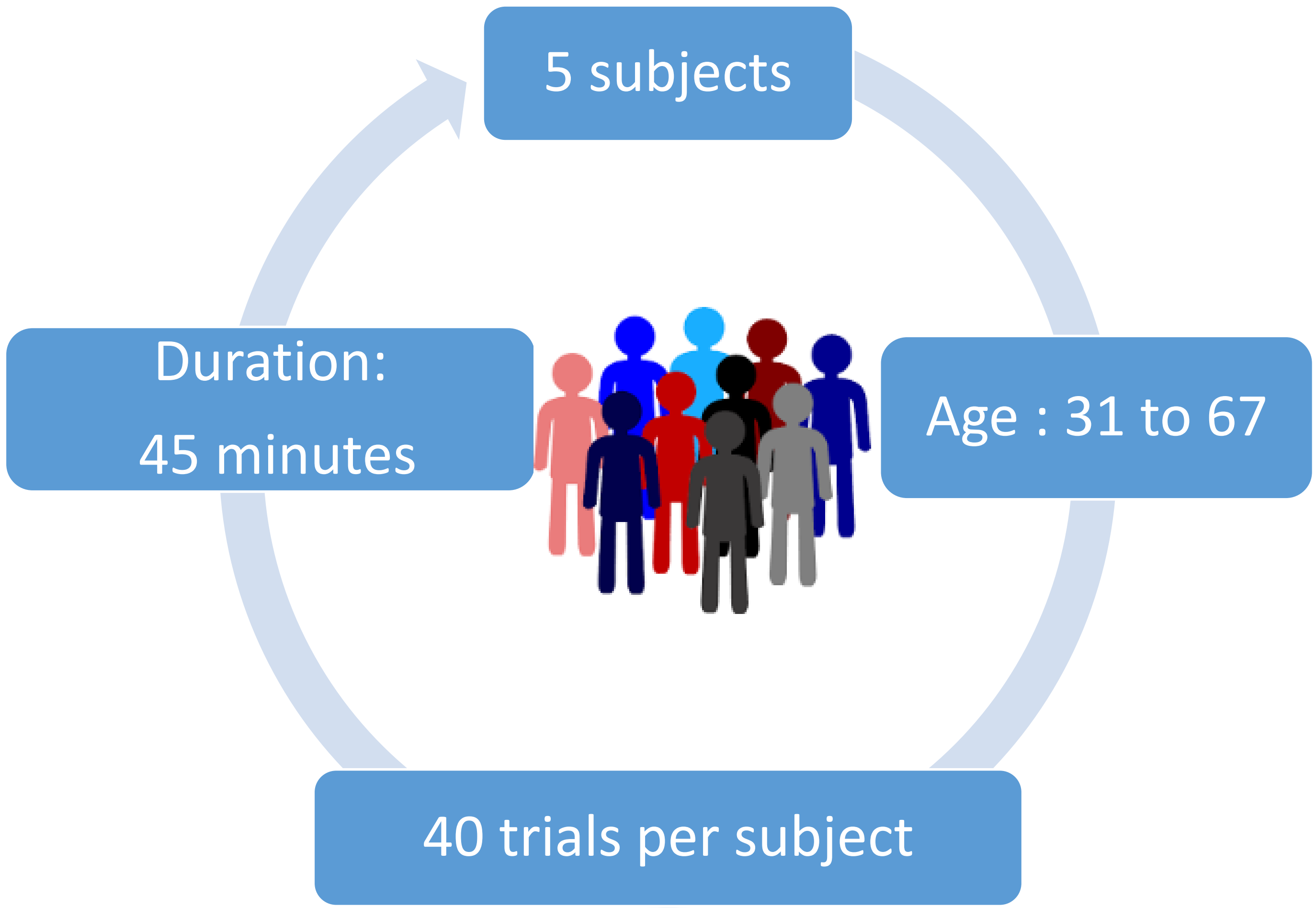


Top view



Experimental scenario

Subjects


5 subjects
Age : 31 to 67
40 trials per subject
Duration:
45 minutes

Pain evaluation

Method:

Wong-Baker FACES Pain Rating Scale

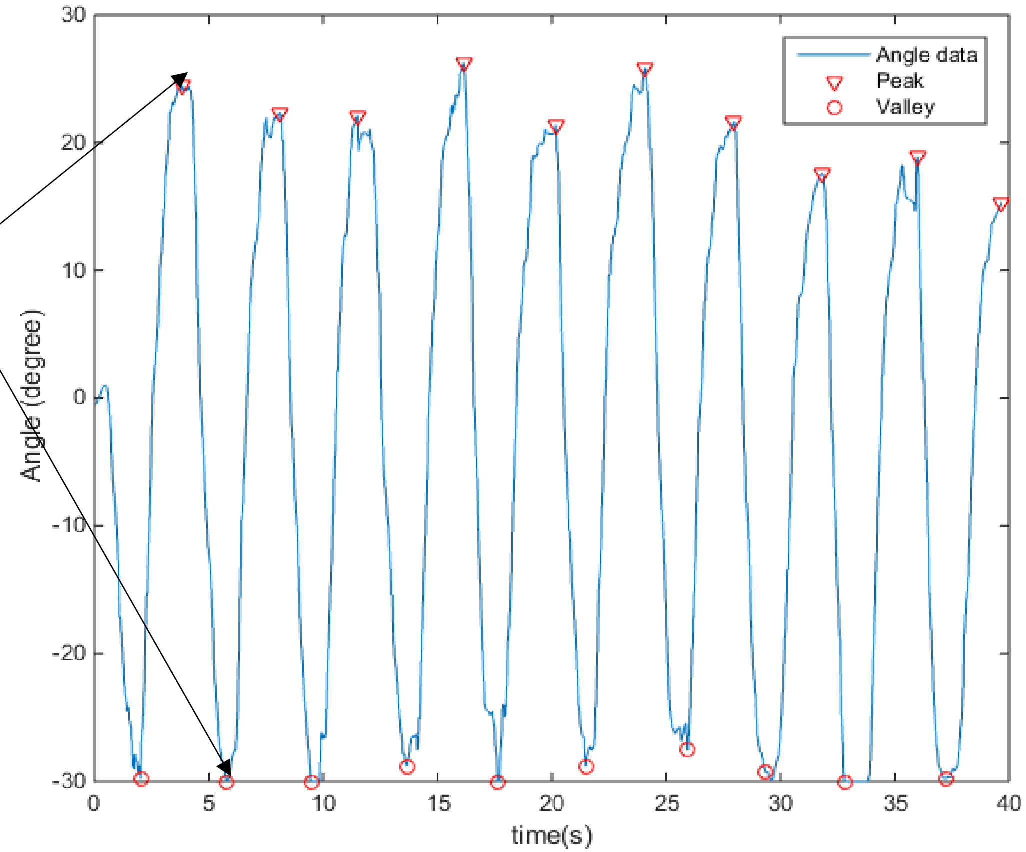
(Hockenberry et al. 2001)

Pain evaluation → Experiment with natural hand model → Pain evaluation → Experiment with silver hand model → Pain evaluation

Recorded angles on avatar hand

findpeaks function of MATLAB

$$D_{min} = L_D / n$$



D_{min}: minimal sample number between two peaks

L_D : length of the recorded data

n: total number for flexion and extension movements (here n=10).

Part I:

Fatigue

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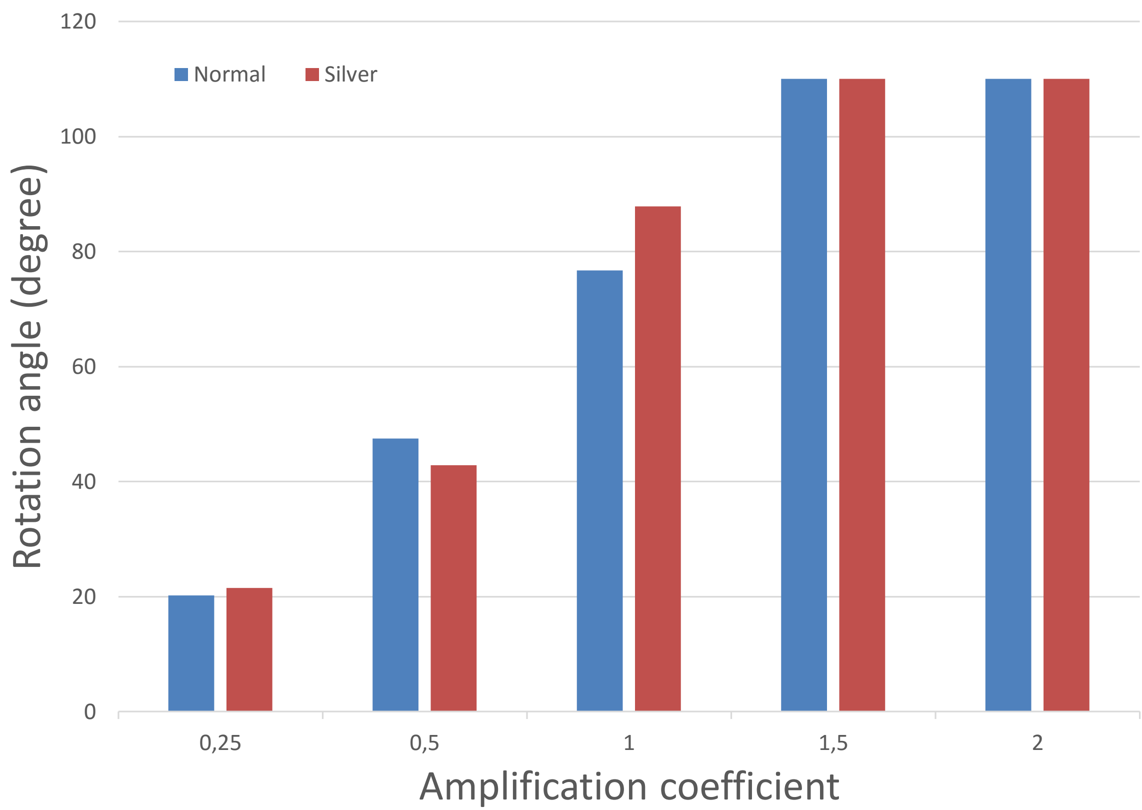
Range of movement

Wrist of avatar hand



$$\overline{ROM} = \frac{1}{n}\sum_{i=1}^{n} ROM_i$$

$\overline{ROM}$: range of movement in the joint

Part I:

Fatigue

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Main achievements

- Application allows to amplify or decrease the user’s hand movement

- The rotation angles of joint can be recorded

Subjects’ opinions

More than half of the subjects preferred the silver hand

General conclusion

- New method for quantifying fatigue associated with disassembly tasks performed in VR was proposed

- Pseudo-haptics
  - Force behavior of finger while pressing the pseudo-haptic spring is similar as pressing the real springs
  - Changing visual information of pseudo-haptic feedback can induce the muscle co-activation as in a dynamic task for finger even if the fingertip is static

- Application for CRPS
  - Proposing the first step toward an application for hand rehabilitation of CRPS patients
  - Subjects prefer the less realistic avatar hand

In future

- To confirm effect of pseudo-haptics on muscle co-activation in a more simple biomechanical task
- To combine the proposed application and the pseudo-haptics
  - using pseudo-haptic as a static task to avoid the pain in dynamic rehabilitation task
  - using pseudo-haptic feedback to strengthen patient's deficient muscle
- To improve hand motion tracking of application
  - accuracy
  - stability
  - …
- To test whether modified visual feedback can increase pain threshold

Acknowledgement

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- Subjects for participating to all the experiments
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Thank you for your attention!

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