Evaluation of Haptic Virtual Fixtures in Psychomotor Skill Development for Robotic Surgical Training

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Teleoperated Minimally Invasive Surgery

- Natural dexterity
- Tremor filtering
- 3D magnified vision

Substantial differences in kinematic, kinetic and sensory perceptions due to use of master devices with respect to laparoscopy

[Patel et al., 2009]

https://www.masseyattorneys.com

http://www.scottishhernia.com
Surgeon Training Curricula

- Apprenticeship model
  - Time consuming approach to develop and maintain advanced laparoscopic skills

- Defined by experts
  - Lack of objective evaluation

Feasible solution $\iff$ Virtual Reality Simulators

- Quantitative
- Adaptive
- Safe

https://www.intuitivesurgical.com
Visual, haptic and acoustic feedback can be given to users
Haptic Feedback

- Kinesthetic (muscles)
- Intelligent assistance (*Force fields*)

Touch 3D Stylus, 3D Systems

Sigma.7, Force Dimension
• Convergent guidance

• Divergent (disturbance)

Successful applications in rehabilitation

[Stuart A. et al., 2013]
Based on the concept of “learning by mistake”

- Makes errors more noticeable
  → Increase focus on the task

- **Faster learning and higher carry over** for both **visual** and **haptic** augmentation

[Wei Y et al., 2005]

**Limit-Push condition**

[Sharp I et al., 2006]

https://www.sralab.org
Can we use force fields to affect psychomotor skill training for robotic surgery?
Error Augmentation for Training

Pure divergent force fields implementations gave rise to controversial results.

“Our results showed that there was no statistically significant difference between the three training methods [convergent force fields divergent force field, and no forces applied].”

[Coad, M et al., 2017]

“Our experiment demonstrated that the noise-like haptic disturbance was marginally better than the other three training methods [visual information only, progressive haptic guidance and repulsive haptic disturbance].”

[Lee, J et al., 2010]
Experimental Setup

Trajectory-following task
Experimental Setup

Virtual Environment

Haptic Device

Combination of:

➢ Haptics
➢ Graphics
➢ Computational Geometry

LACE

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LACE Library

C++ based Software Development Kit

QuickHaptics

Visualization Library

Wykobi Library

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Force Fields

Cross-Section

Limit-Push

- Ideal Trajectory
- Graphic Representation of Trajectory
- Distance Threshold
- Force Field
Force Fields

Cross-Section

- Ideal Trajectory
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Limit-Push

Limit-Trench
Linear force fields, as function of the distance from the trajectory:

$$\mathbf{F}_n = G \Delta d_n \mathbf{v}_n$$

$$\Delta d_n = \| \mathbf{X}_n - \mathbf{C}_n \| - d_{LP,LT}$$

**Limit-Push**

**Limit-Trench**
Video Demonstration

Limit Push

Distance

Force

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Experimental Hypothesis

**Limit-Push**

Combination of positive effects of error augmentation with the traditional training protocols will rise in higher training performances

**Limit-Trench**

Studying the effects of training in high challenging condition: is it even better to push users to their limits?
Training Protocol

A sequence of 4 trajectories (T) followed 48 times by 18 subjects equally divided into 3 groups:

<table>
<thead>
<tr>
<th>Task</th>
<th>Pre</th>
<th>Training</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td># trials</td>
<td>1x4</td>
<td>10x4</td>
<td>1x4</td>
</tr>
<tr>
<td>Force applied</td>
<td>No Haptics</td>
<td>LP group</td>
<td>LT group</td>
</tr>
<tr>
<td></td>
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Performance Metrics

<table>
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<tr>
<th>$t_{\text{trial}}$</th>
<th>RMSE</th>
<th>TPE</th>
<th>SA</th>
<th>IQR</th>
</tr>
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</table>

The time users employed to move the end-effector from the starting to the end point for each repetition.
Performance Metrics

Overall index of user perform

\[
RMSE_u = \frac{\sum_{n=1}^{N} \|X_n - C_n\|}{N}
\]

Integral accuracy metric

\[
TPE_u = \sum_{n=1}^{N} \|X_n - C_n\| \|C_n - C_{n-1}\|
\]

\(u^{th}\) user, \(n^{th}\) time frame

\(N\) is total number of samples.

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### Performance Metrics

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**Speed-accuracy trade-off measurement**

$$SA_u = TPE_u \cdot t_{\text{trial},u}$$

**For variability estimation of end-effector position**

$$IQR_u = Q_3 - Q_1$$

$u^{th}$ user, $n^{th}$ time frame

$N$ is total number of samples.
$\Delta_{BE} = I_{i,Baseline} - I_{i,Evaluation}$

Non-parametric analysis of Longitudinal Data in factorial experiments ($\alpha = 0.05$)

- **RMSE**
  - LP
  - LT
  - C

- **TPE**
  - LP
  - LT
  - C

- **IQR**
  - LP
  - LT
  - C

$p \leq 0.05$; $** p \leq 0.01$; $*** p \leq 0.001$
Non-parametric analysis of Longitudinal Data in factorial experiments ($\alpha = 0.05$)

\[ \Delta_{BE} = I_{i,\text{Baseline}} - I_{i,\text{Evaluation}} \]
Results Analysis

• **Consistent trend** in all metrics
  Control group improvements overcome both force fields

Limit-Push

• Users performance increase, but rapid and unexpected force changes could slow the learning process

Limit-Trench

• Unstable haptic environment might be detrimental for training
Further Observations

Large fluctuation of subjects' improvement within C group

Force fields seem to reduce the variability in users' capabilities to learning the task
Further Observations

- Large fluctuation of subjects’ improvement within C group

- Force fields seem to reduce the variability in users’ capabilities to learning the task
Psychomotor skill development is affected by the implemented haptic force fields

- Changes of training effects depending on task characteristics and forces generation
- Differences of force fields effects on healthy subjects with respect to stroke patients (freezing effects)
- Haptics training could lead to more robust training protocols
Limitations & Future Work

- Extended sessions for the experiment are needed
  - Multi-session training protocol

- Limit-Push and Limit-Trench as novel approaches for psychomotor skill development
  - Effect of different parameters
    - \textit{(distance threshold and gain)}
  - Non-linear force algorithm
Thank you for your attention!

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