Adaptive integration of psychophysiological variables for robotic training
(Adaptivna integracija psihofizioloških spremenljivk za robotsko urjenje)

Domen Novak, univ. dipl. inž. el.
Rehabilitation robotics

- patient–cooperative robots: recognize and adapt to patient movement intentions and motor abilities
Biocooperative robotics

- robots that recognize psychological factors: stress, boredom...

- psychological factors (esp. motivation) very important for rehabilitation, but hard to measure

- possible solution: psychophysiological measurements
Psychophysiological measurements

- Measure how *psychological* stimuli affect *physiological* responses

- respiration
- heart rate
- skin temperature
- skin conductance
Example: skin conductance
Physiological feature extraction

Heart rate
- mean HR
- SDNN
- RMSSD
- pNN50
- LF/HF ratio
- HF power (RSA)
- LF power

Skin conductance
- number of SCRs
- mean SCR amplitude
- final SCL (mS)

Well-established in literature!
State of the art prior to dissertation

- psychophysiological measurements suggested for use in motor rehabilitation, but never implemented or analyzed

- sensor integration and interpretation a big challenge in general psychophysiology
Goal of doctoral dissertation

- integration of psychophysiological measurements with biomechanical and other measurements in a biocooperative feedback loop

- biocooperative feedback loop: adapt task difficulty so that patient always faces a moderate challenge that motivates and does not cause stress
Dissertation structure

- Analysis of rehabilitation-specific factors
  - Effects of physical activity
  - Effects of stroke

- Sensor integration and biocooperative control
  - Controlled laboratory setting
  - Clinical rehabilitation task
Dissertation structure

- Analysis of rehabilitation-specific factors
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Effects of physical activity

typical psychophysiological task

rehabilitation
(video courtesy ETH Zurich)
Effects of physical activity

**Hypothesis**: In haptic human–robot interaction, physiological responses are affected by both cognitive and physical workload.

- The physiological effects of physical and cognitive workload are additive.
- Both types of workload contribute significantly to physiological responses.
Effects of physical activity

- task with physical and cognitive elements
- 2 physical levels
- 3 cognitive levels
- 2 rest periods
- 30 subjects
Results

- **heart rate**: physical activity

- **skin conductance**: both cognitive and physical activity

- **respiration**: cognitive activity

- **skin temperature**: cognitive activity
Analysis of effects of stroke

ECG (voltage in microvolts) vs. time (s)
Hypothesis: Stroke patients have weakened or even absent psychophysiological responses compared to control subjects.

- When performing a purely cognitive task, stroke patients nonetheless exhibit significant responses.
- When performing a rehabilitation task, stroke patients nonetheless exhibit significant responses.
Analysis of effects of stroke

- Task suitable for rehabilitation
- Physical control task (left–right movement)
- Cognitive control task (Stroop task)

- 23 stroke patients
- 23 controls
Rehabilitation task

2 difficulty levels!
Results

**Skin conductance:**
- few differences between controls and patients
- large differences between tasks
- well-correlated with self-reported arousal

**Skin temperature, heart rate:**
- responses much more evident in controls

**Respiration:**
- no useful information
Conclusions – statistical analysis

- respiration and skin temperature less affected by physical activity, but more by stroke
- skin conductance less affected by stroke, but more by physical activity
- decision made to nonetheless proceed with sensor integration
Dissertation structure

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Sensor integration

physiology

sensor integration

mood

bored

happy

angry

sad

22/40
Biocooperative feedback loop

- Biocooperative controller
- Virtual environment
  - Haptic (robot)
  - Audiovisual
- Human
  - Motor functions
  - Psychological state
- Integration
- Measurements
  - Task performance
  - Biomechanics
  - Psychophysiology
Our biocooperative feedback loop

- **state of the art** in applied psychophysiology:
  - classify 2 or 3 levels of workload
  - predefined action for each possible level (e.g. increase difficulty)

- **our implementation**:
  - classify task as too easy or too hard
  - too easy → increase difficulty
  - too hard → decrease difficulty
### Dimension reduction

#### Dimensional Reduction Techniques
- Principal Component Analysis (PCA)
- Sequential Feature Selection

#### Dimension Reduction Techniques

| Dimension Reduction |  \\
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<td>RMSSD</td>
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<td>LF/HF ratio</td>
<td>HF power</td>
<td>LF power</td>
<td>Skin conductance response frequency</td>
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<td>Skin conductance response amplitude</td>
<td>Skin conductance level</td>
<td>Final skin temperature</td>
<td>Mean respiratory rate</td>
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<td>Respiratory rate variability</td>
<td>Task score</td>
<td>Task difficulty level</td>
<td>Mean absolute velocity</td>
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<td>Mean absolute acceleration</td>
<td>Mean frequency of position signal</td>
<td>Mean frequency of velocity signal</td>
<td>Mean absolute force</td>
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<td>Total work</td>
<td>Mean frequency of force signal</td>
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#### Principal Component Analysis

**X**: 
- $X_1$
- $X_2$
- $X_3$
Classification

- statistics and machine learning
- methods:
  - discriminant analysis
  - naive Bayes
  - nearest-neighbors
  - support vector machine
  - classification tree
Adaptive classification

- large **intersubject differences** in physiology

- **require an adaptive method** of sensor integration that adapts to the current user during the task

- **does not yet exist in psychophysiology!**
Adaptive discriminant analysis

**Offline**
- Training data (multiple data points) with known class labels
- Create discriminant function that separates training data points based on class labels

**Online**
- New data point
- Discriminant function
- Estimated class (e.g. task is too easy)

**Adaptation**
- Recursively update weights of discriminant function
- Probability that estimate is correct

**Linear discriminant analysis**
\[
D(x) = b + w^T \cdot x \\
b = -w^T \cdot \frac{1}{2} \cdot (\mu_1 + \mu_2) \\
w = (\Sigma_1 + \Sigma_2)^{-1} \cdot (\mu_2 - \mu_1)
\]

**Kalman adaptive linear discriminant analysis**
\[
H_k = \begin{bmatrix} 1, x_k^T \end{bmatrix} \\
e_k = y_k - H_k \cdot \hat{\omega}_{k-1} \\
v_k = 1 - UC \\
Q_k = H_k \cdot A_{k-1} \cdot H_k^T + v_k \\
k_k = \frac{A_{k-1}H_k}{Q_k} \\
\hat{\omega}_k = \hat{\omega}_{k-1} + k_k \cdot e_k \\
\tilde{A}_k = A_{k-1} - k_k \cdot H_k \cdot A_{k-1} \\
A_k = \frac{\text{trace}(\tilde{A}_k) \cdot UC}{p} + \tilde{A}_k
\]
Adaptive biocooperative feedback
Implementation: laboratory task

- 8 difficulty levels
- 20 subjects
- each subject increases or decreases difficulty 6 times
- measurements: task performance and psychophysiology
Results of classification

Classification accuracy (%)

- performance
- psychophysiology
- both

(leave-one-subject-out crossvalidation)
Implementation: rehabilitation task

- ball-catching task as used previously
- 7 difficulty levels
- each subject changes difficulty 6 times

- two phases:
  - open-loop
    - 24 controls
    - 11 patients
  - closed-loop
    - 10 controls
    - 6 patients
Open-loop results: controls

Classification accuracy (%)

- performance
- biomechanics
- psychophysiology
- all

nonadaptive | adaptive
---|---

34/40
Open-loop results: patients

Classifier accuracy (%)

- **Performance**
  - Nonadaptive: 85%
  - Adaptive: 80%

- **Biomechanics**
  - Nonadaptive: 75%
  - Adaptive: 70%

- **Psychophysiology**
  - Nonadaptive: 50%
  - Adaptive: 60%

- **All**
  - Nonadaptive: 85%
  - Adaptive: 90%
Closed-loop validation

- nonadaptive linear discriminant analysis with performance and psychophysiology
- tested online in a fully closed loop

- controls: accuracy of 88.3%
- patients: accuracy of 88.9%
Conclusions of sensor integration

- online closed loop successfully implemented
- psychophysiological measurements not ideal as a primary source of information
- adaptive method can improve accuracy
- can provide supplementary information
- useful when task performance measures not available (many rehabilitation tasks)
- potentially very useful for other HCI fields
Original scientific contributions

- Analysis of healthy subjects’ psychophysiological responses to a combination of psychological and physical activity in haptic human–robot interaction
- Analysis of psychophysiological differences between healthy subjects and hemiparetic patients in clinical rehabilitation scenarios
- Psychophysiological sensor fusion for task suitability assessment in rehabilitation robotics using different methods
- An adaptive method that can adapt to intersubject differences in psychophysiological responses
- A biocooperative controller that can adapt the parameters of a rehabilitation task based on adaptive fusion of psychophysiological, biomechanical and other sensors
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  and all the rest...
Thank you for your attention!

“Science is like sex; it may give some practical results, but that’s not why we do it.”