Goal-directed Generation of Exercise Sets for Upper-Limb Rehabilitation

José C. Pulido, José C. González,
Arturo González-Ferrer, Javier García, Fernando Fernández,
Antonio Bandera, Pablo Bustos and Cristina Suárez

WS 5: Knowledge Engineering for Planning and Scheduling
Overview

1. Introduction
2. Therapy Model
3. Comparison
   - Classical Planning
   - HTN Planning
4. Experiments
5. Discussion
6. Future work
• Obstetric Brachial Plexus Palsy
  – Damage in nerves around the shoulder
  – Loss of movement in the upper limbs
  – Requires physical rehabilitation

• Rehabilitation helps to:
  ✓ Recover upper limb mobility
  ✓ Reduce muscles rigidity
  ✓ Increase patient’s autonomy
    • Dressing
    • Eating
Rehabilitation Procedure

- A session is composed of exercises
- Cumbersome task for therapists
Objectives

Start therapy → Diagnosis → Determine objectives → Define therapy → Execute sessions

Medical record → Primary evaluation → Therapeutic objectives → Constraints

Patient’s expectations → Planned sessions

Physician Patient

Therapist

Automation Planning Techniques to generate sessions:
Classical and HTN Planning

1. Introduction
2. Therapy Model

Goal-directed Generation of Exercise Sets for Upper-Limb Rehabilitation
**Model**

- **TOCL (Therapeutic Objectives Cumulative Level)**

<table>
<thead>
<tr>
<th>Therapeutic Objectives</th>
<th>TOCLs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bimanual</td>
<td>15</td>
</tr>
<tr>
<td>2. Fine unimanual</td>
<td>30</td>
</tr>
<tr>
<td>3. Coarse unimanual</td>
<td>5</td>
</tr>
<tr>
<td>4. Arm positioning</td>
<td>0</td>
</tr>
<tr>
<td>5. Hand positioning</td>
<td>0</td>
</tr>
</tbody>
</table>

- Each exercise has an **adequacy level** associated to each TOCL

- **Objective: reaching the TOCLs**
  - The sum of the adequacy levels of the planned exercises must **reach the respective TOCL** for each session
Model

• Exercises
  – Adequacy level for each therapeutic objective
  – Duration, intensity and difficulty
  – Group of exercise

• For instance: “drawing figures”

<table>
<thead>
<tr>
<th>Adequacy levels</th>
<th>Other Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimanual</td>
<td>Duration</td>
</tr>
<tr>
<td>Fine unimanual</td>
<td>3 min.</td>
</tr>
<tr>
<td>Coarse unimanual</td>
<td>Intensity</td>
</tr>
<tr>
<td>Arm positioning</td>
<td>Medium</td>
</tr>
<tr>
<td>Hand positioning</td>
<td>Difficulty</td>
</tr>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Group of exercise</td>
</tr>
<tr>
<td></td>
<td>“handwriting”</td>
</tr>
</tbody>
</table>
Constraints

- A session has a max. and min. duration
  1. Warming up
  2. Training
  3. Cooling down

- Variability constraints
  - Exercises cannot reappear in one session
  - Distribution of exercises should be assorted throughout sessions

- Constraints of the patient
  - Avoid a certain group of exercises according to patient conditions
Learning (designing) new exercises

If there are no available exercises in the database, the planner can suggest to **learn a new exercise** to find a suitable plan.

- The attributes of the new exercise must allow to reach the TOCLs
- Previous knowledge is not needed
- Exercises from the database are preferred
- Therapists can “teach” new exercises
Planning Process

Exercise Database

\[ \sum_{i=1}^{\text{numEx}} \text{adequacy}_{\text{TOCL}_i} \geq \text{TOCL} \]

Reaching the TOCLs

TOCLs Constraints

Planned sessions

Learning action

1. Introduction
2. Therapy Model
3. Comparison

Goal-directed Generation of Exercise Sets for Upper-Limb Rehabilitation
• Domain and problem in PDDL

• Our model is based on:
  – Fluents and numeric preconditions
  – Action costs to control the exercise insertion

• We use CBP planner (Cost-Based Planner)
  (Fuentetaja et al. 2010)
• Example plan with CBP-IPC2011 (first solution):

0: (SESSION-START)
1: (WARMUP-PHASE)
2: (WARMUP-DATABASE-EXERCISE E0)
3: (TRAINING-PHASE)
4: (TRAINING-DATABASE-EXERCISE E11)
5: (TRAINING-DATABASE-EXERCISE E12)
6: (TRAINING-DATABASE-EXERCISE E10)
7: (TRAINING-DATABASE-EXERCISE E9)
8: (LEARN-TRAINING-EXERCISE T_SPATIAL_HAND A_MEDIUM D_LONG I_INTENSE)
9: (COOLDOWN-PHASE)
10: (COOLDOWN-DATABASE-EXERCISE E15)
11: (SESSION-END)
Classical Planning

• Action for including exercises from database

(:action training-database-exercise
 :parameters (?e - exercise_training)
 :precondition (and
 (current_phase p_training)
 (< (p_duration p_training) (p_max_duration p_training))
 (> (- (session_index) (e_last_session ?e) ) 2)
 (not (= (exercise_index) (e_last_position ?e))))
 :effect (and
 (assign (e_last_session ?e) (session_index))
 (assign (e_last_position ?e) (exercise_index))
 (increase (p_duration p_training) (e_duration ?e))
 (increase (intensity_cumulative) (e_intensity ?e))
 (increase (difficulty_cumulative) (e_difficulty ?e))
 (increase (exercise_index) 1)
 (increase (TOCL t_bimanual) (e_adequacy ?e t_bimanual))
 (increase (TOCL t_unimanual_coarse) (e_adequacy ?e t_unimanual_coarse))
 (increase (TOCL t_unimanual_fine) (e_adequacy ?e t_unimanual_fine))
 (increase (TOCL t_spatial_arm) (e_adequacy ?e t_spatial_arm))
 (increase (TOCL t_spatial_hand) (e_adequacy ?e t_spatial_hand))))
• **Action for learning new exercises**
  
  – High cost to penalize overuse and favor exercise variability
  
  – The planner searches a suitable combination of the attributes of the exercise to reach the TOCLs
Classical Planning

• Due to the interaction between sessions, planning multiple sessions in one execution is much harder than planning a single session

• **Divide and Conquer strategy (D&C)**

![Diagram showing the process of Classical Planning]

- Initial Problem
- CBP Planner
- Planned session
- Planner Control
- Next Session Problem
- Therapy Plan

Revised for N sessions

N sessions planned

2. Therapy Model
3. Comparison
4. Experiments
HTN Planning

- Hierarchical representation of the problem
- Extensible and configurable model to include human expert knowledge
- We use JSHOP2 (Simple Hierarchical Ordered Planner) (Nau et al. 2003)
HTN Planning

• HTN Model Schema

HTN Planning

generate-therapy

new therapy
generate-session

new session
generate-exercises

fill-warmup-exercises

add exercise
learn exercise

fill-training-exercises

add exercise
learn exercise

fill-cooldown-exercises

add exercise
learn exercise

finish therapy

finish session

2. Therapy Model
3. Comparison
4. Experiments

Goal-directed Generation of Exercise Sets for Upper-Limb Rehabilitation
HTN Planning

• Planning Strategy:

Heuristic function of each exercise

\[ h_{t_{ex}} = \sum_{i=1}^{n_{objects}} \left( \frac{1}{d_i^2 + 1} - \frac{\text{extimes}_{-used}}{\text{num}_{sessions}} \right) \]

1. Contribution of the exercise to the TOCLs
   • \( d_i \) is the difference between the desired TOCL and the cumulative level after including the exercise

2. Repetition penalty
   • The higher the repetition, the higher the penalty
HTN Planning

<table>
<thead>
<tr>
<th>Method 1</th>
<th>Task definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>;; Receives the session number</td>
<td>(:method (fill-cooldown-exercises ?csn))</td>
</tr>
<tr>
<td></td>
<td>(:sort-by ?ht &gt;)</td>
</tr>
<tr>
<td></td>
<td>((e-target1 ?e ?et1)</td>
</tr>
<tr>
<td></td>
<td>(current-acc t1 ?csn ?ctl1)</td>
</tr>
<tr>
<td></td>
<td>(baseline t1 ?tbl1)</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(assign ?d1 (call - ?tbl1 (call + ?et1 ?ctl1)))</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(assign ?h1 (call / 1 (call + (call * ?d1 ?d1) 1)))</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(e-used ?e ?n-used) (t-session-number ?tsn)</td>
</tr>
<tr>
<td></td>
<td>(assign ?ht (call - (call + ?h1 ... ?h5) (call / ?n-used ?tsn)))</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(cooldown-time ?cst ?minST ?maxST)</td>
</tr>
<tr>
<td></td>
<td>(cooldown-exercise ?e ?minST ?maxST)</td>
</tr>
<tr>
<td></td>
<td>(not (used ?e ?csn)))</td>
</tr>
<tr>
<td></td>
<td>(!add-ex ?e cool-down)</td>
</tr>
<tr>
<td></td>
<td>(fill-cooldown-exercises ?csn))</td>
</tr>
<tr>
<td>Method 2</td>
<td>Precondition 2</td>
</tr>
<tr>
<td></td>
<td>(forall (?e) ((exercise ?e)) (used ?e ?csn))</td>
</tr>
<tr>
<td></td>
<td>(!learn))</td>
</tr>
<tr>
<td>Method 3</td>
<td>Precondition 3</td>
</tr>
<tr>
<td></td>
<td>((current-session-time ?csn ?cst)</td>
</tr>
<tr>
<td></td>
<td>(session-max-time ?csn ?maxST)</td>
</tr>
<tr>
<td></td>
<td>(call &lt;= ?cst ?maxST)</td>
</tr>
<tr>
<td></td>
<td>(current-acc t1 ?csn ?ctl1) (TOCL t1 ?tbl1) (call &gt;= ?ctl1 ?tbl1)</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(!finish-session ?csn))</td>
</tr>
</tbody>
</table>

2. Therapy Model
3. Comparison
4. Experiments

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Experiments

- Full therapy plan for 15 sessions using CBP

<table>
<thead>
<tr>
<th>Sessions</th>
<th>Planned exercises</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>e0</td>
</tr>
<tr>
<td>2</td>
<td>e4</td>
</tr>
<tr>
<td>3</td>
<td>e1</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
</tr>
<tr>
<td>5</td>
<td>e0</td>
</tr>
<tr>
<td>6</td>
<td>e4</td>
</tr>
<tr>
<td>7</td>
<td>e1</td>
</tr>
<tr>
<td>8</td>
<td>L25</td>
</tr>
<tr>
<td>9</td>
<td>e0</td>
</tr>
<tr>
<td>10</td>
<td>e4</td>
</tr>
<tr>
<td>11</td>
<td>e1</td>
</tr>
<tr>
<td>12</td>
<td>L</td>
</tr>
<tr>
<td>13</td>
<td>e0</td>
</tr>
<tr>
<td>14</td>
<td>e4</td>
</tr>
<tr>
<td>15</td>
<td>e1</td>
</tr>
</tbody>
</table>

Few initial exercises
- Warm-up: 5
- Training: 8
- Cool-down: 5

<table>
<thead>
<tr>
<th>e#</th>
<th>Initial stored exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Learning action</td>
</tr>
<tr>
<td>L#</td>
<td>Learnt exercise reused</td>
</tr>
</tbody>
</table>
Experiments

- Experiment using JSHOP2 to test the plan generation
  - Average value of **intensity** and **difficulty** for 30 generated sessions
Discussion

- **Classical Planning**
  - The search is driven using action costs
  - Hard constraints to control the variability
  - Learning actions make backtracking among sessions unnecessary

- **HTN Planning**
  - Heuristic function handles the variability constraints and improves the planning time
  - It can plan multiple sessions without losing the possibility of backtracking
  - Axioms improve the expressiveness of the possible configurations of the model
Future Work

• Working on a better quantitative comparison

• Planners with better heuristics for fluents could improve planning time without the need of D&C strategy

• Temporal representation of the problem

• Implement *replanning* methods in case of updates after patient evaluation.

Clinical Decision Support System (CDDSS)

*Img. source: dryicons www.therapist.uma.es*
Thank you for your attention
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See you in the poster session! 😊
Clinical Decision Support Systems (CDSS) implement models based on expert knowledge to ease many tasks of physicians.

E.g.: Developing clinical practice guidelines.

- **Mixed Integer Linear Programming (MILP)** to determine appointments for patients of rehab hospitals.
  

- **Automated Planning** for generating scenarios helping handicapped people.
  

- **Planning algorithm** able to generate oncology treatment plans, including temporal constraints difficult to manage by physicians.
  
### CBP IPC-2011

0: (SESSION-START)
1: (WARMUP-PHASE)
2: (WARMUP-DATABASE-EXERCISE E0)
3: (TRAINING-PHASE)
4: (TRAINING-DATABASE-EXERCISE E11)
5: (TRAINING-DATABASE-EXERCISE E12)
6: (TRAINING-DATABASE-EXERCISE E10)
7: (TRAINING-DATABASE-EXERCISE E9)
8: (LEARN-TRAINING-EXERCISE SPATIAL_HAND LONG RELAXED)
9: (COOLDOWN-PHASE)
10: (COOLDOWN-DATABASE-EXERCISE E15)
11: (SESSION-END)

### Metric-FF

0: SESSION-START
1: WARMUP-PHASE
2: LEARN-WARMUP-EXERCISE SPATIAL_HAND LONG MAXIMUM
3: TRAINING-PHASE
4: TRAINING-DATABASE-EXERCISE E7
5: LEARN-TRAINING-EXERCISE UNIMANUAL_COARSE MEDIUM MAXIMUM
6: LEARN-TRAINING-EXERCISE UNIMANUAL_COARSE MEDIUM MAXIMUM
7: TRAINING-DATABASE-EXERCISE E12
8: LEARN-TRAINING-EXERCISE UNIMANUAL_FINE MEDIUM MAXIMUM
9: COOLDOWN-PHASE
10: LEARN-COOLDOWN-EXERCISE SPATIAL_HAND LONG INTENSE
11: SESSION-END
• Action to plan the learning of a new exercise

(:action learn-warmup-exercise
 :parameters (?t - target ?a - l_adequacy ?d - l_duration
   ?i - l_intensity)
 :precondition (and
   (current_phase p_warmup)
   (< (p_duration p_warmup) (p_max_duration p_warmup))))
 :effect (and
   (increase (exercise_index) 1)
   (increase (intensity_cumulative) (l_intensity_value ?a))
   (increase (p_duration p_warmup) (l_duration_value ?d))
   (increase (adequacy_cumulative ?t) (l_adequacy_value ?a))
   (increase (total-cost)
     (- (+ (l_adequacy_value ?a) 10) (l_duration_value ?d))))
HTN Planning (Extra)

(:- (\textit{warmup-time} ?current ?min ?max)
  ((\text{call} \geq \text{?current} \ 0) (\text{wup-limit} \ ?lw)
   (\text{call} \leq \text{?current} (\text{call} \star (\text{call} / (\text{call} + \ ?min \ ?max) \ 2) \ ?lw)))))
)

(:- (\textit{warmup-exercise} ?e ?min ?max)
  ((\text{wup-ex-config} \ ?maxDuration \ ?maxIntensity \ ?maxDifficulty) (\text{e-duration} \ ?e \ ?d)
   (\text{call} \geq \text{?d} \ 1) (\text{call} \leq \text{?d} (\text{call} / (\text{call} \star (\text{call} / (\text{call} + \ ?min \ ?max) \ 2) \ ?maxDuration) \ 2))
   (\text{e-intensity} \ ?e \ ?i) (\text{call} \leq \text{?i} \ ?maxIntensity)
   (\text{e-difficulty} \ ?e \ ?dif) (\text{call} \leq \text{?dif} \ ?maxDifficulty))
)
)
• Variability constraints are handled with a sortby function

• One execution of 20 sessions using:
  • Heuristic function $\approx 5$ min.
  • Relaxed Round Robin policy $> 30$ min.
### Pros and Cons (Extra)

<table>
<thead>
<tr>
<th></th>
<th>STRIPS</th>
<th>HTN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Search strategy</strong></td>
<td>• CBP planner task, limiting learnings with action costs.</td>
<td>• Heuristic function to guide the search among the exercises.</td>
</tr>
<tr>
<td><strong>Multiple sessions</strong></td>
<td>• Divide-and-conquer strategy.</td>
<td>• Can plan as usual, in one run.</td>
</tr>
<tr>
<td></td>
<td>• Impedes backtracking among sessions, but it is not needed.</td>
<td></td>
</tr>
<tr>
<td><strong>Avoids repeated exercises</strong></td>
<td>• In the last 3 sessions.</td>
<td>• In the same session.</td>
</tr>
<tr>
<td></td>
<td>• In the same position than in the last occurrence.</td>
<td>• Penalizes repeated exercises, but allows them.</td>
</tr>
<tr>
<td><strong>Learning</strong></td>
<td>• Suggests attribute values.</td>
<td>• Adds new predefined exercises during planning time.</td>
</tr>
<tr>
<td></td>
<td>• Prefers exercises which improve variability.</td>
<td></td>
</tr>
<tr>
<td><strong>Phase parameterization</strong></td>
<td>• Controlled by predicates and functions.</td>
<td>• Axioms allows to model expert knowledge easily.</td>
</tr>
</tbody>
</table>