Methods: Mind the Gap
Webinar Series

Using Control Systems Engineering to Optimize Adaptive Mobile Health Interventions

Presented by

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Using Control Systems Engineering to Optimize Adaptive Mobile Health Interventions

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@ehekler
Just Walk “modeling and more” team
Everything changes and nothing stands still.
(‘Change is the only constant.’)
-Heraclitus
Take-home points

• If reducing lapses/relapses or promoting maintenance/abstinence is your goal, then a control optimization trial (COT) might help you.

• It’s not easy, but it’s easier than you think.

Collins & Krueger (2018) *Optimization of behavioral, biobehavioral, and biomedical interventions*
What can be optimized?

• Intervention package
  – Factorial/fractional factorial trial (FT)
• Infrequent, key decision rules (e.g., clinical practice)
  – Sequential Multiple Assignment Randomized Trial (SMART)
• Bout-specific decision rules (i.e., just-in-time adaptive interventions; JITAIbs)
  – Micro-randomization Trials (MRTs)
• Gradual, non-linear, idiosyncratic change
  – Control Optimization Trial (COT)
Gradual, non-linear, idiosyncratic change

- **Initiation**: The initial phase characterized by fluctuating trends.
- **Maintenance**: The phase where the steps per day stabilize and maintain a consistent level.

**Graph Details**
- **Y-axis**: Steps per day.
- **X-axis**: Days.
- **Lines**:
  - **Actual steps**: Black line showing the actual steps taken over time.
  - **Intervention objective**: Magenta line indicating the intervention objective.

The graph illustrates the gradual and non-linear nature of the change, with distinct phases identified as Initiation and Maintenance.
How to optimize?

• Review of evidence from optimization trials from prior participants
  – FT, SMART, MRT, & COT

• “Real-time” optimization algorithm for current individual
  – MRT+ Reinforcement Learning (RL)
  – COT
    • Individualized & perpetually adapting
Need for **individualized** and **perpetually adapting** interventions

People are different.
Need for individualized and perpetually adapting interventions

Reasons people offered via EMA on why they did not meet a daily step goal

People are different.  Context matters.

Slide adapted from @phataksayali
Everything changes and nothing stands still.
(Paraphrased into ‘change is the only constant.’)
-Heraclitus

People are different.  
Context matters.  
Things change.
Why use a real-time optimization algorithm?

- Inherent complexity of a problem
- Examples of complex problems
  - From non-active to maintaining physical activity guidelines
  - From obese to maintaining a normal weight
  - From smoking to maintaining abstinence
  - From depressed to maintaining good mental health

Diagram:
- Dynamic (things change)
- Manifest idiosyncratically (people are different)
- Multivariate (context matters)
Control Systems Engineering

NSF IIS-1449751: EAGER: Defining a Dynamical Behavioral Model to Support a Just in Time Adaptive Intervention, PIs, Hekler & Rivera
Hekler et al, JMIR 2018

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How a controller works

American Control Conference (ACC)
Normal intervention development steps

• Lit review - organize your understanding of prior work
• Define a hypothesis
• Test your hypothesis in naturalistic setting
  – e.g., observational trial/EMA trial
• Design your intervention
• Test your intervention
Step 1. Derive a dynamical model (organize prior work)

- Select/specify a general theoretical model
- Translate that into a dynamical model
- Vet dynamical model via simulation studies, secondary data analyses, or both.
Step 1: Derive a dynamical model

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It’s easier than you think...

• Many models have now been specified
  – SCT, TPB, etc
• Drawing on a whiteboard gets you pretty far
• You can find a control systems engineer partner
  – It’s a huge field! They are at your university.
  – Use our papers as a bridge
Step 1 (optional): test via simulation

Low Self-Efficacy

High Self-Efficacy

Step 1 (optional): test via secondary analyses


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Normal intervention development steps

• Lit review - organize your understanding of prior work
• **Define a hypothesis**
• Test your hypothesis in naturalistic setting
  – e.g., observational trial/EMA trial
• Design your intervention
• Test your intervention
The intervention seeks to promote physical activity (e.g., steps/day) among inactive adults by adjusting daily step goals and expected reward points, with the ultimate goal of reaching 10,000 steps per day (on average) per week.
Step 2: Define intervention options and outcomes:
Daily “ambitious but doable” step goals

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Hekler (PI), Rivera (Co-PI), NSF IIS-1449751
Normal intervention development steps

- Lit review - organize your understanding of prior work
- Define a hypothesis
- **Test your hypothesis in naturalistic setting**
  - e.g., observational trial/EMA trial
- Design your intervention
- Test your intervention
“...to find out what happens when you change something it is necessary to change it.”

-Box, Hunter, and Hunter (Statistics for Experimenters)
Step 3: Conduct a system ID experiment (test in natural setting)

• Design open loop system ID study and analytic plan
• Conduct data analyses
System identification (ID)

- System ID focuses on modeling of dynamical systems (such as humans) from data, ideally from experimentation, not merely observation.

- It is focused on estimating/validating a model to describe the system (e.g., a human).

- It is **NOT** focused on effect size estimates of intervention components.
One key COT sub-experiment

- Open loop system ID

Tests understanding of the “system”

a) theory-testing
b) individualized tailoring variable selection

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Figure 9  Time-series plot of a fitted 4-input model that was selected one of the participants. @ehekler
Step 3 (cont). Study: “Just Walk”

@ehekler

Hekler et al. *JMIIR, 2018*
Step 3 (cont) Participants

- BMI 33.7 ± 6.7
- 22 inactive, overweight Android users
- Age = 47 ± 6.2 years
- 87% women
- Living anywhere in the US
- Average Baseline Median Steps: 4972 steps/day (SE = 482)

Step 3 (cont): Feasibility results

+2,650 (t=8.25, p<0.01) Average step increase from baseline to intervention

69% (SD = 24) Average goals met

>90% Adherence to EMA

100% enjoyed variable goals

85% found app easy to use

88% interested in continuing to use

Korinek et al. JoBM, 2018
Step 3 (cont). Data analysis

- **Data prep**: The data is preprocessed for missing data entries.

- **Define your model**: The filtered data is fitted to a multi-input AutoRegressive with eXternal input (ARX-[na nb nk]) parametric model:

\[
y(t) + \ldots + a_{n_a} y(t - n_a) = b_{11} u_1(t - n_k) + \ldots + b_{n_b} u_1(t - n_k - n_b + 1) \\
\quad \vdots \\
+ b_{1i} u_i(t - n_k) + \ldots + b_{n_i} u_i(t - n_k - n_b + 1) \\
\quad \vdots \\
+ b_{1n_u} u_{n_u}(t - n_k) + \ldots + b_{n_n} u_{n_u}(t - n_k - n_b + 1) + e(t)
\]

- **Validate your model**: Various measures used, among these the Normalized Root Mean Square Error (NRMSE) fit index:

\[
\text{model fit (\%)} = 100 \times \left(1 - \frac{||y(k) - \hat{y}(k)||_2}{||y(k) - \bar{y}||_2}\right)
\]

where $y(k)$ is the measured output, $\hat{y}(k)$ is the simulated output, $\bar{y}$ is the mean of all measured $y(k)$ values, and $||\cdot||_2$ indicates a vector 2-norm ($||x||_2 \overset{\text{def}}{=} \sqrt{x^T x}$).
Figure 9 Time-series plot of a fitted 4-input model that was selected one of the participants.

@ehekler Phatak et al. JBI, 2018
What does this get us?

• A model to simulate future responses for each individual.

• This simulation enables dynamic, idiosyncratic, self-correcting decisions for each person.
**Individualized tailoring variables!**

**Table 6 Final Selected Models and Input Combinations**

<table>
<thead>
<tr>
<th>Model/Input Combination</th>
<th>Number of cases for each variable (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekend(^b)</td>
<td>1</td>
</tr>
<tr>
<td>Typical &amp; Weekend(^b)</td>
<td>1</td>
</tr>
<tr>
<td>Busy(^b)</td>
<td>2</td>
</tr>
<tr>
<td>Base Model(^a)</td>
<td>1</td>
</tr>
<tr>
<td>Stress(^b)</td>
<td>1</td>
</tr>
<tr>
<td>Typical(^b)</td>
<td>1</td>
</tr>
<tr>
<td>Busy &amp; Weekend(^b)</td>
<td>1</td>
</tr>
<tr>
<td>Stress &amp; Typical(^b)</td>
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<tr>
<td>Busy &amp; Stress</td>
<td>1</td>
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<tr>
<td>Stress &amp; Typical</td>
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<td>Typical &amp; Weekend(^b)</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^a\) base model that includes goals, expected points and granted points
\(^b\) base model + specified inputs.

Assuming individualized tailoring variables are better, prior evidence tailoring variables would have been inappropriate for 75% of our sample.
It’s easier than you think...

- There’s likely a control theory person at your school

- Standard toolkits in MatLab
  - Translatable to R
Normal intervention development steps

• Lit review - organize your understanding of prior work
• Define a hypothesis
• Test your hypothesis in naturalistic setting
  – e.g., observational trial/EMA trial
• Design your intervention
• Test your intervention
Step 4: Define optimization criteria & controller (design your intervention)

- **Physical activity**
  - Initiation “Set-point”
    - 10,000 steps/day, on average per week
    - +3,000 steps/day, on average per week relative to baseline
  - Transitions (both positive & lapses/relapses):
    - achieving 10,000 steps/day set point for 3 consecutive weeks OR
    - AFTER at least 6 months, +3,000 steps/day set point for 3 weeks.
  - Maintenance
    - Continue to meet PA targets
    - Reduce total interactions, ideally, to 0, except self-tracking
Closing the intervention loop

Step 4. Design the controller

Prior steps Report (Measured Outcome)

Prior Environmental Context Report (Measured Disturbance)

Forecasted Environmental Context Report $d_7(k+i)$ (if available)

Future Step Goals $u_8(k+i)$

Manipulated Variable

Controlled Variable

Disturb. Variable

Desired steps (Setpoint $y_{4r}(k+i)$)

Predicted steps $y_4(k+i)$

Past Future

Prior Step Goals $u_8^{max}$ $u_8^{min}$

Move Horizon

Time (days)

$k$ $k+1$ $k+m$ $k+p$
Step 4 (optional): Examine robustness via simulation

![Graph showing daily steps (y4) over time with different parameter mismatches.]

![Graph showing prediction error (PE) over time with different parameter mismatches.]

Martin, Rivera, & Hekler (2016)
Normal intervention development steps

- Lit review - organize your understanding of prior work
- Define a hypothesis
- Test your hypothesis in naturalistic setting
  - e.g., observational trial/EMA trial
- Design your intervention
- Test your intervention
Step 5: Conduct a Control Optimization Trial (COT) (test your intervention)

- Clearly specified adaptive intervention (already discussed)
- Design of sub-experiments and data analysis plan
- Conduct the trial and the analyses
COT sub-experiment options

- **Open loop system ID**
  - Tests understanding of the “system”
    - a) theory-testing
    - b) individualized tailoring variable selection

  ![Diagram of open loop system ID](https://www.mathworks.com/videos/understanding-control-systems-part-1-open-loop-control-systems-123419.html)

- **Closed loop controller optimization**
  - Tests understanding of the feedback/decision rule
    - a) real-time algorithm optimization

  ![Diagram of closed loop controller optimization](https://www.mathworks.com/videos/understanding-control-systems-part-2-feedback-control-systems-123501.html)
Proposed COT example

Open-loop System ID

Closed loop optimization (initiation)

Closed loop optimization (maintenance)
What does this get us?

• Immediate benefits to individual
  – Individualized models
    • Enables simulations of future responses for each person
  – Individualized tailoring variables
    • Enables matching the intervention to each person
  – Real-time optimization algorithm
    • Enables perpetual adaptation to changing people and contexts

• Secondary optimization benefits
  – Rigorous data about each adaptive intervention element
    • Enables data-driven optimization of elements (e.g., tailoring variables, algorithms)
  – Effect size estimates of intervention components via stats
    • Enables estimation of generalized effect of intervention components
  – Rich experimental data
    • Enables dynamic theory testing in alignment with Riley, Rivera, et al’s call (Riley et al 2011)
MOST & Control Systems Engineering

• MOST
  • Preparation
    – Create a conceptual framework
    – Select intervention components/options
    – Conduct a feasibility study
    – Define optimization criteria
  • Optimization
    – Run an optimization trial (e.g., FT, SMART, or MRT)
  • Evaluation
    – RCT of “optimized” intervention package compared to meaningful comparator

• Control Engineering
  • Step 1: Derive a dynamical model
  • Step 2: Define intervention options and outcomes
  • Step 3: Conduct a System Identification Experiment
  • Step 4: Design the Controller, Including Optimization Criteria
  • Step 5: Conduct a Control Optimization Trial (COT)
  • Evaluation
    – RCT comparing COT intervention to meaningful comparator

Rivera, Hekler et al. 2018; Hekler, Rivera, et al. JMIR 2018
Limitations

• COT approach has not been evaluated in an RCT
  – Prior work justifies advancing this approach
  – “Back to the future” as Carver, Sheier and others wanted to use these methods but technology was not ready
  – It now is
Testing a COT intervention in an RCT

Randomization Design

Outcome Measures

Acti-Graph
1) Steps/day
2) MVPA, min/week

In-person
1) BMI
2) Blood pressure
3) Heart rate
4) Heart rate variability

Just Walk Charge 3 Apps
1) Engage with apps

Fitbit
1) Steps/day
3) Resting heart rate

Measurement only (not to scale)

COT-based Intervention

Non-COT-based Intervention

Timeline
Baseline 6 12 18
Limitations

• COT approach has not been evaluated in an RCT
  – Prior work justifies advancing this approach
  – “Back to the future” as Carver and Sheier and others wanted to use these methods but technology not ready
  – It now is

• Just like stats, you need a control systems engineer

• Approach opens up ethical issues
Repertoire of optimization trials

• Intervention package
  – Factorial/fractional factorial trial (FT)

• Infrequent, key decision rules (e.g., clinical practice)
  – Sequential Multiple Assignment Randomized Trial (SMART)

• Bout-specific decision rules (i.e., just-in-time adaptive interventions; JITAIls)
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• It’s not easy, but it’s easier than you think.
Helpful references


UC San Diego

Control Systems Engineering Laboratory