Musical Heart:
A Hearty Way of Listening to Music

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What is Musical Heart?
Let’s hear some music ...
Let’s hear some music ...

- **Artist:**
  - R. Agarwal
- **Genre:**
  - Indian classic
- **Tempo:**
  - 32 BPM
- **Effect:**
  - Calming
Let’s try a different one …

- Artist: Psy
- Genre: Korean pop
- Tempo: 132 BPM
- Effect: Excitement
What is Musical Heart?

- Musical Heart is a **biofeedback**-based, **context**-aware, and automatic **music recommendation** system for smartphones.
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• Musical Heart is a biofeedback-based, context-aware, and automatic music recommendation system for smartphones.
What is Musical Heart?

- Musical Heart is a **biofeedback**-based, **context**-aware, and automatic **music recommendation** system for smartphones.

Contexts: jogging, relaxing, traveling, etc.
Musical Heart: Hardware and Software

Sensor Equipped Earphones + Smartphone App
Musical Heart: Earphone Hardware

- **Sensors:**
  - IMU
  - Microphone

- **Computation:**
  - Tiny OS

- **Communication:**
  - Audio Jack

- **Power:**
  - Thin film battery

SEPTIMU Platform

Beijing, China
Musical Heart: The Smartphone App

- User Profile
- Heart Rate
- Activity Level
- Music Player
Musical Heart: Smartphone Software

- Music Recommender
  - Music Player
  - Proxy

- Combiner
  - Heart Rate Detector
  - Activity Level Detector
  - Context Detector

- Sensor Data Dispatcher
  - Septimu Sensors
  - In-phone Sensors

- Septimu Sensors
- Septimu Mic.
- Septimu Acc.
- In-phone GPS
- In-phone WiFi
Musical Heart: Smartphone Software

Sensor Data Dispatcher

Septimu Sensors

In-phone Sensors

Sensor Combiner

Heart Rate Detector
Activity Level Detector
Context Detector

Septimu Mic.
Septimu Acc.
In-phone GPS
In-phone WiFi

Music Recommender

Music Player
Proxy

Sensing
Musical Heart: Smartphone Software

Detect: Heart Rate, Activity level, & Context

Sensing
Musical Heart: Smartphone Software

Sensing

- Septimu Sensors
- In-phone Sensors

Detect: Heart Rate, Activity level, & Context

Music Recommender

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Combiner

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- Activity Level Detector
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Why Musical Heart?
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Musical Heart:
- Convenient
- Non-invasive
- Personalized
- Low cost ($20)

Rule of thumb:
- Not personalized
- But free

Bluetooth PulseOx:
- Inconvenient
- Invasive
- Costly $80

Wrist Watch:
- Inconvenient
- Invasive
- Costly $100

Chest Strap:
- Highly Inconvenient
- Highly Invasive
- Costly $400
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Outline of the rest of the talk

• **What** we did.

• **Results** we achieved.
What we did?
What we did?

• Building **SEPTIMU** platform.
• A study on **effect of music** on smartphone users at different **activity levels**.
• 3 Algorithms for:
  ▪ Detecting **heart rate**,  
  ▪ Detecting **activity level**, and  
  ▪ Music **Recommendation**
• Implement a complete system: **Musical Heart**
SEPTIMU Platform

- SEPTIMU v1

- Sensors:
  - IMU
  - Microphone

- Computation:
  - Tiny OS

- Communication:
  - Audio Jack

- Power:
  - AAA battery
SEPTIMU Platform

- **SEPTIMU v2**

- **Sensors:**
  - IMU
  - Microphone
  - IR Reflective Sensor
  - Thermometer

- **Computation:**
  - Tiny OS

- **Communication:**
  - Audio Jack
  - Bluetooth

- **Power:**
  - Li-Polymer battery
SEPTIMU Platform

• **SEPTIMU v2**

  ![SEPTIMU Platform Image](image)

• **Sensors:**
  - IMU
  - Microphone
  - IR Reflective Sensor
  - Thermometer

• **Computation:**
  - Tiny OS

• **Communication:**
  - Audio Jack
  - Bluetooth

• **Power:**
  - Li-Polymer battery
Empirical Study
Empirical Study

• 37 volunteers:
  ▪ 3 Activity levels: Low, moderate, high.
  ▪ At least 10 persons in all 3 levels.

• Music:
  ▪ 10 – 60 min sessions.
  ▪ 1 – 5 min gaps.
  ▪ Top 100 songs in 2011 from YouTube.

• Devices:
  ▪ Pulse-Ox and ECG (for ground truth)
  ▪ SEPTIMU
Result: Effect of Music on Heart Rate
Result: Effect of Music on Heart Rate

![Graph showing the correlation of music parameters on heart rate change across different activity levels.](image-url)
Result: Effect of Music on Heart Rate
Result: Effect of Music on Heart Rate
Result: Effect of Music on Heart Rate
Result: Effect of Music on Heart Rate

The diagram illustrates the correlation between music features and heart rate change across different activity levels (L1, L2, L3). The features include Tempo, Pitch, Energy, and Composite (u). The bars indicate the correlation values, with a trend line showing a decrease in correlation with increasing activity level.
Result: Effect of Music on Heart Rate

None of the music features (Tempo, Pitch, or Energy) show high correlation at all activity levels.
Result: Effect of Music on Heart Rate

\[ u = [\alpha_1 \alpha_2 \alpha_3] \times [\text{Tempo Pitch Energy}]^T \]

‘The composite feature, \( u \) is more correlated to heart rate change at all three activity levels.’
Algorithm: Heart Rate Detection
Algorithm: Heart Rate Detection

• **Problem:** Extraction of heart beats from a mixture of heart beats, music and noise.
Algorithm: Heart Rate Detection

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• **Solution steps:**
  - Filtering
  - Beat detection
Algorithm: Heart Rate Detection

- **Filtering**: A low pass filter to remove non-heart beat signals.

Signals from Ear (music + heart beats)
Algorithm: Heart Rate Detection

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- **Filtering**: A low pass filter to remove non-heart beat signals.
Algorithm: Heart Rate Detection

- Detection: simple thresholding does not work
Algorithm: Heart Rate Detection

- **Detection**: simple thresholding does not work

Large Threshold: *Too few candidates (8)*
Algorithm: Heart Rate Detection

- **Detection**: simple thresholding does not work

Large Threshold: *Too few candidates (8)*

Small Threshold: *Too many candidates (27)*
Algorithm: Heart Rate Detection

- **Detection**: as an optimization problem
Algorithm: Heart Rate Detection

• Detection: as an optimization problem

Step 1: *Use a small threshold to pick initial candidates – so that we do not lose any actual heart beats.*
Algorithm: Heart Rate Detection

• **Detection:** as an optimization problem

  **Step 1:** *Use a small threshold to pick initial candidates – so that we do not lose any actual heart beats.*

  ![Candidates Selected: 6](image)
Algorithm: Heart Rate Detection

• **Detection**: as an optimization problem

**Step 2**: Assign a score to each candidate based on their peak-peak distance and resemblance to a heart beat.
Algorithm: Heart Rate Detection

- Detection: as an optimization problem

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Algorithm: Heart Rate Detection

• **Detection**: as an optimization problem

**Step 3**: Maximize the sum of scores, while minimize the variance of time-gaps. (for an assumed number of beats)

0.9 0.8 0.4 0.8 0.7 0.6
Algorithm: Heart Rate Detection

- **Detection:** as an optimization problem

**Step 3:** Maximize the sum of scores, while minimize the variance of time-gaps. (for an assumed number of beats)
Algorithm: Heart Rate Detection

- **Detection**: as an optimization problem

**Step 3**: Maximize the sum of scores, while minimize the variance of time-gaps. (for an assumed number of beats)

For example, to select 5 out of the 6 candidates:

- Max Sum = 3.8
- Min Variance = 0, if we select the red ones.
Algorithm: Heart Rate Detection

- **Detection**: as an optimization problem

**Step 3**: Maximize the sum of scores, while minimize the variance of time-gaps. (for an assumed number of beats)

For example, to select 5 out of the 6 candidates:
- \( \text{Max Sum} = 3.8 \)
- \( \text{Min Variance} = 0 \), if we select the red ones.

Repeat Step 3 for HR = [40, 220]
Result: Heart Rate Detection
Result: Heart Rate Detection

![Graph showing error and musical heart rate for different activity levels L1, L2, L3.]

- Error (BPM)
  - Activity Level:
    - L1: No Music: 5, Music: 2
    - L2: No Music: 10, Music: 8
    - L3: No Music: 20, Music: 16

![Graph showing musical heart rate versus baseline HR for Activity L1.]

- Activity L1: 85%
Result: Heart Rate Detection

Activity $L_1$

- Error (BPM)

- No Music
- Music

Activity $L_2$

- Musical Heart (BPM)

- Baseline HR (BPM)

85%

84%
Result: Heart Rate Detection

Activity $L_1$

- No Music: 85%
- Music: 75%

Activity $L_2$

- Musical Heart Rate: 84%

Activity $L_3$

- Musical Heart Rate: 75%
Algorithm: Activity Level Inference
Algorithm: Activity Level Inference

- **3** Activity Levels:
  - **L1**: Low activity level
    - e.g. sitting, standing, traveling.
  - **L2**: Moderate activity level
    - e.g. walking.
  - **L3**: High activity level
    - e.g. jogging, exercising.
Algorithm: Activity Level Inference

- Example: $L_1 \rightarrow L_2 \rightarrow L_3 \rightarrow L_1 \rightarrow L_3 \rightarrow L_2 \rightarrow L_1$
Algorithm: Activity Level Inference

• **Example:** $L_1 \rightarrow L_2 \rightarrow L_3 \rightarrow L_1 \rightarrow L_3 \rightarrow L_2 \rightarrow L_1$

• **Plot:** variance in acceleration per second
Algorithm: Activity Level Inference

- **Example:** $L_1 \rightarrow L_2 \rightarrow L_3 \rightarrow L_1 \rightarrow L_3 \rightarrow L_2 \rightarrow L_1$
- **Plot:** variance in acceleration per second
Algorithm: Activity Level Inference

- **Example:** \( L_1 \rightarrow L_2 \rightarrow L_3 \rightarrow L_1 \rightarrow L_3 \rightarrow L_2 \rightarrow L_1 \)
- **Plot:** variance in acceleration per second

We use k-means clustering to learn the thresholds.
# Result: Activity Level Inference

- **Single Activity**

<table>
<thead>
<tr>
<th>Actual level</th>
<th>Predicted level</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L₁</td>
<td>0.9998</td>
<td>0.0002</td>
</tr>
<tr>
<td>L₂</td>
<td>0</td>
<td>0.9997</td>
</tr>
<tr>
<td>L₃</td>
<td>0</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

- **Sequence of Activities**

<table>
<thead>
<tr>
<th>Actual level</th>
<th>Predicted level</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L₁</td>
<td>0.989</td>
<td>0.011</td>
</tr>
<tr>
<td>L₂</td>
<td>0</td>
<td>0.951</td>
</tr>
<tr>
<td>L₃</td>
<td>0</td>
<td>0.037</td>
</tr>
</tbody>
</table>

99.1%  

96.8%
Algorithm: Music Recommendation
Algorithm: Music Recommendation

• **Problem:** Suggest the music that helps maintain a target heart rate (given current heart rate and activity level).
Algorithm: Music Recommendation

- **Problem:** Suggest the music that helps maintain a target heart rate (given current heart rate and activity level).

- **Solution:**
  - **Modeling** heart’s response to music.
  - Formulating as **feedback-control** problem.
Algorithm: Music Recommendation

Typical PI-controller
Algorithm: Music Recommendation

Typical PI-controller
Algorithm: Music Recommendation

Typical PI-controller
Algorithm: Music Recommendation

Typical PI-controller
Algorithm: Music Recommendation

Let’s modify this ...
Algorithm: Music Recommendation

Process: Human Heart
Algorithm: Music Recommendation

**Set-point: Desired Heart Rate**

Desired Heart Rate

Current Heart Rate

Exertion Threshold Zone

Target Heart Rate Zone

Fat Burning Zone

Recovery Zone

Proportional $P$

Integral $I$

Chart

Exercise Target Zone Chart

% of Max. Heart Rate

Set-point: Desired Heart Rate
Algorithm: Music Recommendation

PI : suggests music feature (u)
Algorith: Music Recommendation

Find a matching song
Result: Model Fitness

The fitness of model gets better as users listens to more and more songs.
Deployment: Goal directed jogging
Deployment: Goal directed jogging

• Typical Cardio Exercise Plan:

<table>
<thead>
<tr>
<th>Time</th>
<th>Desired Intensity (%)</th>
</tr>
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<tbody>
<tr>
<td>5 min</td>
<td>60% - 70%</td>
</tr>
<tr>
<td>3 min</td>
<td>70% - 80%</td>
</tr>
<tr>
<td>2 min</td>
<td>80% - 90%</td>
</tr>
<tr>
<td>3 min</td>
<td>70% - 80%</td>
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<tr>
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Intensity = \[
\frac{\text{Target HR} - \text{Resting HR}}{\text{Max HR} - \text{Resting HR}}
\]
## Result: Activity Level Detection

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![Graph showing changes in activity level over time]
## Result: Activity Level Detection

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![Raw data](image)

![Detected level](image)
## Result: Activity Level Detection

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![Graph showing Raw data and Detected level over time](image-url)

- **Time (min):** 0, 5, 10, 15, 20
- **$\sigma_{acc}$:** 0, 2, 4, 6, 8
- **Raw data** and **Detected level** are indicated.
Result: Activity Level Detection

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![Graph showing raw data and detected level over time]
**Result: Achieving Desired Heart Rate**

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![Intensity Graph](chart.png)
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![Graph showing desired and achieved intensity over time with control input (music feature, u)]
Result: Achieving Desired Heart Rate

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Control Input (music feature, u)
Result: Achieving Desired Heart Rate

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![Graph showing desired and achieved intensities with time](image-url)

**Desired Intensity**

- 5 min: 65%
- 3 min: 75%
- 2 min: 85%
- 3 min: 75%
- 5 min: 65%

**Achieved Intensity**

- 5 min: 30.1%
- 3 min: -0.6%
- 2 min: 26.2%
- 3 min: -50.6%
- 15 min: -4.7%

**Control Input**

- (music feature, u)
Result: Achieving Desired Heart Rate

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![Graph showing desired and achieved intensity](chart.png)

- **Desired Intensity**
- **Achieved Intensity**
- **Control Input**
  (music feature, u)
### Result: Achieving Desired Heart Rate

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![Graph showing desired vs. achieved intensities over time with control input (music feature, u)]
Result: Achieving Desired Heart Rate

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Avg. Deviation: 11.4%
Concluding Remarks

• Musical Heart brings together **entertainment** and **wellness**.

  ▪ Detects **Heart Rate** and **Activity Level** (using SEPTIMU earphones)
  ▪ Learns the relationship among: **Heart Rate**, **Activity Level**, and **Music**.
  ▪ **Suggests** music, given a goal.
Thank You

Demo: SEPTIMU and Musical Heart
Date: Tomorrow
### Table 3. The context detection algorithm is shown in a tabular form. Dashed entries are don’t cares.
Figure 8. The roll and pitch angles obtained from Septimu are used to differentiate between sitting and lying.
Backup slide: SEPTIMU v1 and v2

![Graph showing error (BPM) for MusicalHeart and IR-based at different levels.
- Level 1: MusicalHeart - 1 BPM, IR-based - 2 BPM
- Level 2: MusicalHeart - 9 BPM, IR-based - 4 BPM
- Level 3: MusicalHeart - 10 BPM, IR-based - 3 BPM]