Coaching and Monitoring Rehabilitation in the Home & Virtual Coach for Congestive Heart Failure

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Fellow of the IEEE for Contributions to Wearable Computers & Context Aware Computing
Joint Work with Dan Siewiorek, CMU

DHTI-Highmark Seminar on Wearable Health and Diagnostic Devices
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Overview

- Background - 23 Years of CMU Wearable Computers and Their 35 Different Generations
- Coaching and Monitoring Rehabilitation in the Home
- Example Virtual Coaches: Stroke Therapy and Congestive Heart Failure (CHF)
- Close collaboration with Clinicians
- Future Work
Family Tree of CMU Wearable Computers
(by Operational Delivery Dates and Application Areas)

☆ = IDA Award Winner
<table>
<thead>
<tr>
<th>Year</th>
<th>Exploratory Systems Design</th>
<th>Customer Driven Systems Design</th>
<th>Visionary Design and Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>Vu-Man 1 1 Manufacturing</td>
<td>Vu-Man 3 Vehicle Maintenance</td>
<td>Tactile Display</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sprout Wireless Communicator</td>
</tr>
<tr>
<td>1992</td>
<td>Vu-Man 2 Navigation Assistant</td>
<td></td>
<td>Streetwear Fashionable Computers</td>
</tr>
<tr>
<td>1993</td>
<td>Navigator 1 Navigation Assistant</td>
<td></td>
<td>Design for Wearability Wearable Shape Research</td>
</tr>
<tr>
<td>1994</td>
<td></td>
<td></td>
<td>Folio Foldable Display</td>
</tr>
<tr>
<td>1995</td>
<td>Frogman Underwater Maintenance</td>
<td></td>
<td>Promera Handheld camera/projector</td>
</tr>
<tr>
<td>1996</td>
<td>ISSAC Speech Interface Assistant</td>
<td>OSCAR Plant Operation Assistant</td>
<td>Digital ink Digital Pen Computer</td>
</tr>
<tr>
<td>1997</td>
<td>Metronaut Navigation + Information</td>
<td>TIA-P Language Translator</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Itsy/Cue Wireless Communication and</td>
<td>TIA-O Maintenance</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>Low Power Innovation</td>
<td>Moca Mobile Work Assistant</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>IBM Wearable Aircraft Maintenance</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td>Language Translation</td>
<td></td>
</tr>
</tbody>
</table>
Aircraft Inspection

A. Smailagic
CMU Wearable Computers

- Itsy/Cue
- TIA-P
- Speech Translator
- A. Smailagic
- MoCCA
- WPC
One participant designs button shapes for the face of the remote. Participants collaborate on an experimental ball-shaped remote control. The final design (curved, rectangular), with a jog dial for FF and REW.

Final design stage, each participant had their own pen color.

Buttons to change screen
Four Month Design Cycle

- Initial visit
- Conceptualization
- Detailed Design
- Implementation

Month:
0 1 2 3 4

Final System
Smart Watches

18-540 eWatch, 2004
(Sensors: Accelerometer, Light, Temperature, Microphone)

Samsung Gear Live, 2014
(Sensors: Accelerometer, Compass, Gyroscope, Heart Rate Monitor)
Wearable Computers

18-540 VuMan 3, 1993

Google Glass, 2013
Autosense wearable sensor system
Virtual Coaches

• Our virtual coaches continuously monitor users' activities and surroundings, detect situations where intervention would be desirable, offer prompt assistance, and give feedback and encouragement.

• Feedback and guidance are matched to user’s cognitive states.

• Sensors, combined with machine learning, can determine a user’s context, their location, physical activity, emotional state, and social context.

• Clinician input incorporated into the design.
Virtual Coach Examples

Wheelchair Seating

Health Kiosk

Head Coach

Osteoarthritis

IMPACT

Myomo Robotic Arm

Hang Guider Game

<table>
<thead>
<tr>
<th>Activity</th>
<th>Parameter</th>
<th>Duration</th>
<th>Gap</th>
<th>Alert after</th>
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<td>Tilt</td>
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<td>Ideal</td>
<td>Max</td>
<td>10</td>
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<tr>
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<td>25°</td>
<td>30°</td>
<td>35°</td>
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<td>25 sec</td>
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<td>20 min</td>
<td>30 min</td>
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<td></td>
<td>10</td>
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<tr>
<td>Recline</td>
<td>Min</td>
<td>Ideal</td>
<td>Max</td>
<td>15</td>
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<tr>
<td></td>
<td>10°</td>
<td>15°</td>
<td>20°</td>
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<td>4 mins</td>
<td>5 mins</td>
<td>6 mins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 hrs</td>
<td>5 hrs</td>
<td>6 hrs</td>
<td></td>
</tr>
<tr>
<td>Feet Elevation</td>
<td>Min</td>
<td>Ideal</td>
<td>Max</td>
<td>20</td>
</tr>
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<td></td>
<td>25°</td>
<td>30°</td>
<td>35°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 sec</td>
<td>1 min</td>
<td>1 min 10 sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 hr 30 mins</td>
<td>2 hrs 30 mins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Min</td>
<td>Ideal</td>
<td>Max</td>
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<td></td>
<td>0</td>
<td>60 mm</td>
<td>200 mm</td>
<td></td>
</tr>
<tr>
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<td>0 sec</td>
<td>0 sec</td>
<td>0 sec</td>
<td></td>
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<tr>
<td></td>
<td>0 sec</td>
<td>0 sec</td>
<td>0 sec</td>
<td></td>
</tr>
</tbody>
</table>

General Tilt angle : Min 10, Ideal 20, Max 30
General Recline angle : Min 10, Ideal 30, Max 40
Virtual Coach for Stroke Rehabilitation Exercises

• The virtual coach can evaluate and offer corrections for rehabilitation of stroke survivors
• It is based on a Kinect for monitoring motion and a machine learning model to evaluate the quality of the exercise
• A normalized Hidden Markov Model (HMM) was trained to recognize correct and erroneous postures and exercise movements
• Encouragement and corrections are provided by audio and textual feedback, as well as summaries of user’s performance and progress
Virtual Coach -cntd

• Automatically detects a person’s emotions and hence allow the system to adapt to it thereby providing an improved user experience.

• Stroke survivors from four rehabilitation centers in Pittsburgh have tried or being testing the emotion recognition on the Virtual Coach.
Audio Based Emotion Recognition

- Vocal communication is a mode of interaction that people rely upon.
- The datasets used: Linguistic Data Consortium Dataset (LDC) and CMU/Pitt Audio Dataset
- Our emotion recognition system is based on prosodic features (i.e. intensity, pitch, formant frequencies of sounds) combined with short term perceptual features.
- We reported the highest emotion recognition accuracy (see the table on the next slide)
Emotion Recognition Integrated with Virtual Coach for Stroke Rehabilitation

For ‘angry’ emotion, the system advises user to take rest

Projection of emotion data onto LDA subspace

Accuracy results
Coach Dashboard

Select Exercise:

Exercise 2
Exercise 3
Exercise 4

Dashboard

Exercise Duration

ScoreBoard

Patient History

(a) Trends of Each Duration [Minutes/Session]

(b) Exercise Number

(c) Completion Status
Results per Exercise

Arm curl

Two handed stand up
Clinician Interface

Clinician can define exercise thresholds by selecting the corresponding body part.
Microsoft Kinect used for body tracking
Each game relates to a prescribed exercise
- “Bow and Arrow” <=> Reach a light switch
- “Fishing” <=> Drinking (Bring a cup up to the mouth)
Variety of games brings motivation and alternation in movements
Examples: IMPACT, Seating Coach, Head Coach
Gaze Stabilization Exercise

Figure 2A: Look straight ahead.
Figure 2B: Turn your head 45 degrees towards the right.
Figure 2C: Turn your head 45 degrees towards the left.

Note: Business card should be positioned at eye level.

(c) T.C.Hain, 2002

Improves Vestibulo-Ocular Reflex (VOR)
Facial Expressions Based Emotion Recognition

- A multi-class Support Vector Machine (SVM) model was trained using the leave-one-subject-out cross-validation method.
- The Extended CK+ dataset was used and results averaged for all subjects in the database.
- Emotions with large distortion (e.g. disgust, happy and surprise) get very high classification performance – over 97%, and the other emotions slightly lower.
- Major part of CK+ database contained posed facial expressions that may differ from natural expressions, like real-time evaluation performed for the Health Kiosk users.
Emotion Recognition Screeshot

Visualization of the particular emotions level

Real-time emotion recognition screenshot
CHF - Primary Stakeholders

Patient
- Least amount of upfront detail
- “Am I achieving my goals?”

Doctor
- Status at a glance, details with a tap
- “Does anyone need specific attention?”

Caregiver
- Schedule and reminders
- “What does the patient need today?”
Overview of CHF Project

• Our goal is lower cost chronic disease management in the patient’s home and other ambulatory settings.

• We are focusing on the CHF patients who have recently been discharged from acute care.

• We use wearable devices to continuously monitor physical activity and certain symptoms.

• Using a set of monitoring instruments that includes wearable devices and possibly traditional tele-health stations, we aim to gather metrics about the patient’s patterns of activity and to detect symptoms and warning signs of decline.

• Data will be summarized and made available to medical professionals on your staff through tele-monitoring interfaces that allow trend analysis, comparisons to baselines, setting of alarm trigger points, drilling down into details of the measurements, etc.
Congestive Heart Failure

- There were 1 million hospitalizations for congestive heart failure (CHF) in 2000 and in 2010.

- From 2000 to 2010, the rate of CHF hospitalization for males under age 65 increased significantly while the rate for females aged 65 and over decreased significantly.

- In both 2000 and in 2010, a greater share of inpatients under age 65, compared with those aged 65 and over, were discharged to their homes.
Risks and Symptoms to be monitored

**Risks : Causes of CHF**
- Too Much Sodium
- Too Much Food
- Less Activity
- Less Food Intake
- Too Much Water
- Too Much Activity
- Hypertension
- Overweight
- Malnutrition
- Increase of Blood Amount
- Physical Stress
- Psychological Stress
- Lack of Medication
- Diabetes
- Sleep Apnea
- Structural Heart Disease
- Thyroid Disease
- Chronic Anemia
- Addiction: Cocaine, Alcohol
- Drug Toxicity

**Symptoms : Result of CHF**
- Shortness of Breath
  - Physical Activity
  - Orthopnea
  - PND
  - Bendopnea
- Pulmonary Congestion
- Cough
- Low Blood Saturation
- Lack of Appetite
- Edema
- Rapid Weight Gain
- Chest Pressure
- Rapid Heart Beat
- Low Blood Pressure
- Fatigue
- Frequent Night Urination
- Nausea
- Decrease of Pumped Blood
- Body Vein Congestion
- Heart Failure

**Ordinary Peripherals**
- Sleep
- Breath & Posture
- Daily Activity
- Food Intake

**Medical History**
- Ordinary Peripherals
- Sleep
- Breath & Posture
- Daily Activity
- Food Intake

**Quality of Life Technology Center**

\[\text{National Science Foundation Engineering Research Center}\]
Dashboard Design and Function

Patient Name

Alerts:

The operator can see and make judgement if the patient needs to be contacted today or if they need immediate hospital visit.

Graphs of data reported from monitoring devices:

If the operator can’t make judgement form the alerts, he/she can get more detailed graphical information.
Congestive Heart Failure

Zephyr HxM Smart Heart Rate Monitor

Thinklabs Digital Stethoscope

Fitbit Flex for Activity Monitoring

iHealth Pulse Oximeter

iHealth Weight Scale

iHealth Blood Pressure Monitor
Congestive Heart Failure

John JingleHimerschmit
Age: 68
Primary Care Physician: John Bahener
Spouse: Janis JingleHimerschmit
Admitted: January 2014
Other Diseases: None
Health Kiosk Improvements

Revised Resident Main Page

Resident View of Assessment Results

Resident View of Assessment History
Multiple Sensors Improve Activity Recognition

Sensor Placement

![Sensor Placement Image]

**Performance Comparison - Additional Sensors**

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Classification Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>67%</td>
</tr>
<tr>
<td>HD, HL</td>
<td>73%</td>
</tr>
<tr>
<td>HD, HL, AR</td>
<td>76%</td>
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<tr>
<td>HD, HL, AR, AN</td>
<td>75%</td>
</tr>
<tr>
<td>HD, HL, AR, AN, WR</td>
<td>77%</td>
</tr>
</tbody>
</table>

- HD = Hand
- HL = Holster
- AR = Arm
- AN = Ankle
- WR = Wrist

**Training 10 Fold Cross Validation**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Handheld</th>
<th>Holster</th>
<th>Handheld + Holster</th>
<th>Complete Set</th>
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</thead>
<tbody>
<tr>
<td>Loading Boxes</td>
<td>0.67</td>
<td>0.67</td>
<td>0.73</td>
<td>0.76</td>
</tr>
<tr>
<td>Walking</td>
<td>0.73</td>
<td>0.73</td>
<td>0.80</td>
<td>0.83</td>
</tr>
<tr>
<td>Scanning Documents</td>
<td>0.76</td>
<td>0.76</td>
<td>0.83</td>
<td>0.85</td>
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<tr>
<td>Standing</td>
<td>0.76</td>
<td>0.76</td>
<td>0.83</td>
<td>0.85</td>
</tr>
<tr>
<td>Sitting</td>
<td>0.76</td>
<td>0.76</td>
<td>0.83</td>
<td>0.85</td>
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<tr>
<td>Moving a Cart</td>
<td>0.75</td>
<td>0.75</td>
<td>0.82</td>
<td>0.84</td>
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<tr>
<td>Holding a Box</td>
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<td>0.77</td>
<td>0.84</td>
<td>0.86</td>
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<td>Running</td>
<td>0.77</td>
<td>0.77</td>
<td>0.84</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Prototypes used as research platforms in large proposals and projects:

- **VuMan 3** in 1994 NSF Mobile Computing
- **eWatch** in 2003 DARPA RADAR 2006 NSF ERC on Quality of Life Technology and 2006 NIH Stress Detection
- **Handy Andy** in 2002 NSF Aura
- **Health Kiosk** in 2014 Agency for Healthcare Research & Quality (AHRQ)

Impact on creating new companies: Inmedius, Bodymedia, InspectTech

Prototypes exemplifying new paradigms in computing and related technologies

- **Wearable Computers, Context Aware Systems, Virtual Coaches**
Back-up Slides
Activity Recognition Accuracy at Body Locations
Accuracy Classification Recorded Over 100 Minutes
Improvements to the Scoring Function

The scoring function is determined by the variable called percentage_probability. It is percentage_probability divided by 10 and then rounded to its nearest integer.
Requirements per Exercise

1. **ARM CURL EXERCISE:**
   Patient must take the wrist all the way to the mouth to attain a high score.
   Elbow must not be arched outward

2. **TWO HAND STAND UP EXERCISE:**
   Slouching the back must be avoided.
   The hands must be placed close to body at all times.

3. **SWITCH ON THE LIGHT EXERCISE:**
   The hand movement should reach the top of the head.
   The pace at which the hand moves should match the pace in the demonstration video.

4. **TROUBLED CANE EXERCISE:**
   At the time of measurement and capture, the hand should be arched behind the body closer to the back
   Hand should be placed on the highest part of the cane.
   For the furthest extension, the arm should be stretched out to form a straight line from the shoulder, elbow and wrist.
Results per Exercise

Arm curl

Two handed stand up
Results per Exercise

Switch on the Light Exercise

Troubled Cane Exercise
Health Kiosk Improvements

Revised Resident Main Page

Resident View of Assessment History

Resident View of Assessment Results
Personalization

We ran experiments to see if there are improvements if the model is personalized to a specific user (e.g. voice).

For personalization, we had certain number of researchers using application, and recording additional files (e.g. audio), files i.e. (~ 20-50% of the original data set size), and ran the analysis again.
Examples: IMPACT, Seating Coach, Head Coach
Most discriminative features for LDC dataset

<table>
<thead>
<tr>
<th>Classification Problem</th>
<th>Features Count</th>
<th>Accuracy</th>
<th>Features used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anger vs Fear</td>
<td>41</td>
<td>91.42</td>
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<tr>
<td>Anger vs Rest</td>
<td>35</td>
<td>90.02</td>
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<tr>
<td>Happy vs Rest</td>
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<td>76.06</td>
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<tr>
<td>Sadness vs Rest</td>
<td>38</td>
<td>76.18</td>
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<tr>
<td>Disgust vs Rest</td>
<td>29</td>
<td>87.16</td>
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</tbody>
</table>

Classification methodologies with highest accuracy and corresponding set of most discriminative features for LDC dataset

First 16 Cepstral Coefficients

<table>
<thead>
<tr>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Pitch</th>
<th>Amplitude</th>
</tr>
</thead>
</table>

Quality of Life Technology Center

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