Closed-loop solutions for motor rehabilitation

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Body Area Networks: human in the loop

Sensing
Transduction
A/D conversion
Local Processing

Input processing
Application-specific computation
Output rendering

Real-time operation is key
Millisecond loop delay is required for correct feedback operation, with human time constants

Open-loop vs Closed-loop

The order of events to organise a closed-loop control is characterised by the following steps:

- Measurement of the controlled variable $y$
- Calculation of the control error $e = w - y$ (comparison of the controlled variable $y$ with the set-point value $w$),
- Processing of the control error such that by changing the manipulated variable $u$ the control error is reduced or removed.
Comparing open-loop control with closed-loop control the following differences are seen:

Closed-loop control
- shows a closed-loop action (closed control loop);
- can counteract against disturbances (negative feedback);
- can become unstable, i.e. the controlled variable does not fade away, but grows (theoretically) to an infinite value.

Open-loop control
- shows an open-loop action (controlled chain);
- can only counteract against disturbances, for which it has been designed; other disturbances cannot be removed;
- cannot become unstable - as long as the controlled object is stable.

Summarising these properties we can define:
Systems in which the output quantity has no effect upon the process input quantity are called open-loop control systems.
Systems in which the output has an effect upon the process input quantity in such a manner as to maintain the desired output value are called closed-loop control systems.
The basic structure of closed-loop systems

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Open-loop or closed-loop?

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... for motor rehabilitation
One approach to improving balance, which has been widely used in physical therapy and rehabilitation, involves feeding back to the CNS supplementary environmental information about body motion.

This supplemental information may be coming from artificial sensors, a therapist, or laboratory equipments (Shumway-Cook et al., 1988).

In the past few years, increases in the speed of microprocessors, advances in miniature devices, and a growing interest in noninvasive patient monitoring and management have stimulated the development of real-time portable biomedical systems that are compact and have low cost.

One promising application of such systems is biofeedback, which can be used to enhance human perception of automatic biological processes, such as movement and balance.

What is biofeedback?
Biofeedback is a type of biofeedback and alternative medicine. It involves using environmental information about body motion to compensate for somatic sensations within the body. This information may be coming from artificial sensors, a therapist, or laboratory equipments (Shumway-Cook et al., 1988).

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Types of biofeedback
Biofeedback is a process that allows you to monitor your own physiological responses. This can help you improve your health and well-being. There are different types of biofeedback, such as:

- Motor response feedback
- Visual feedback
- Auditory feedback
- Tactile feedback
- Visual feedback
- Biofeedback

Finding a biofeedback therapist: Ask questions
When looking for a biofeedback therapist, it is important to find someone who is trained in the specific type of biofeedback that you are looking for. It is also important to find someone who is experienced in working with people who have similar concerns.

One of the most important questions to ask is whether the therapist has experience in treating patients with similar concerns. It is also important to ask about the therapist’s training and experience in biofeedback therapy.

Press and costs of biofeedback
Biofeedback may appear to be a cost-effective form of therapy. However, it is important to consider the potential costs associated with biofeedback. These costs may include the cost of the therapist’s services, the cost of the equipment used, and the potential for adverse effects.

Biofeedback does not guarantee a cure. The results of biofeedback therapy are not always predictable. It is important to talk to your therapist about the potential risks and benefits of biofeedback therapy. This will help you decide if biofeedback is the right choice for you.
**Spine-Check**
Spine Check Inc.
A small sensor is worn on a belt under clothing, which measures the movement of the spine and gently vibrates to warn the user when doing unsafe movements.

**Golf-3D**
Skill Technologies Inc.
System that provides real-time visual and auditory feedback to rapidly improve a golf swing mechanics, measuring 3D body motion by means of a customized software and models.

**The Ultimate Balance Trainer**
Ultimate Balance Trainer Inc.
A small sensor is worn on a hat, a voice warns the user whenever a tilting far from his/her vertical in the four directions: forward, backward, left, and right.

**NEUROGAMES by NEUROCOM**
NeuroPong - NeuroPong was modeled after the original Pong™ video game. The patient’s center of gravity movements control the position of various sports figures to return a ball as it bounces across the screen.

Gaming options include soccer, tennis, hockey and basketball.

Solitaire - The standard solitaire game found on all Windows® systems, offers a new twist to an old game where patients must shift their center of gravity to select and move the cards.
**Balance Depends on Sensory Information**

- Visual, Vestibular and Somatosensory information are the major sensory cues used by the brain to perform balance.

**Sensory Information**
- Vision
- Vestibular
- Somatosensory

**Brain**

**Muscles**

**Multisensory Integration**

**Internal Map**

**Movement**

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**Biofeedback (BF)** may add or substitute sensory information; e.g., audio BF may be used to involve more largely in the "game" the AUDITORY channel.

**The architecture of a BF system**

- Sensor (Accelerometer)

- Coding (Linear/Sigmoid)

- Modality (Audio/Videob)

- Subject (Healthy, Young)

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**Example #1**

Balance Prosthesis Based on Micromechanical Sensors Using Vibrotactile Feedback of Tilt

Wall et al. IEEE TBME, 2001

**Example #2**

Closing an open-loop control system: vestibular substitution through the tongue

Kadkade et al. IEEE TNSRE, 2003

Tyler et al. J Integr Neurosci, 2003
Example #3
An accelerometer-based audio-biofeedback (ABF) system

Chiari et al., IEEE Trans Biomed Eng, 2005

The sensory unit

2D ADXL203, Analog Device
3D LIS3L02DQ, ST-microelectronics

The sensory modality

The “biomechanics2sensory” trans-codification

Visual Biofeedback
Audio Biofeedback

The coding algorithms:
Linear and Sigmoid Coding

M. Dozza et al., IEEE Trans. Neural Syst. Rehab., under review

The motor task

Static
Dynamic

Wireless may be advantageous for dynamic tasks!
BF System for Rehabilitation Based on Wireless Body Area Network

HP iPAQ 5550 with Bluetooth and WiFi capabilities. It is equipped with an Intel XScale 400 MHz, 32-32 KB data and instruction caches, and 128 MB SDRAM.

ABF coding of movement

Safety Region (SR)
- represents the limit of stability
- is the region in which the COM projection is inside the subject’s support base
- is estimated according to anthropometric parameters (feet length and width)

Reference Region (RR)
- represents the region for natural sway (±1 degree)
- is estimated using the subject’s height

Example of ABF-driven sound

- ABF can provide similar information as one otolith:
  - If the trunk/head moves slowly, primarily gravitational information is provided
  - If the trunk/head moves quickly, primarily acceleration information is provided
- Continuous ABF sound also provides trunk VELOCITY information (critical)

- Subjects learn to use ABF in 1 minute
- Subjective balance score (Schieppati et al., 1999) is lower also when ABF seems NOT actually helpful
  - It is small, light-weight and comfortable to wear (but so far wired…)

They are both estimated in the first few seconds of the first trial
Results: quiet standing

- Improve balance (Sway Area decreases)
- Increase control (Mean Velocity increases)

ABF can restore standing stability in bilateral vestibular loss patients

ABF has a Tuning-Fork effect

- Platform rotation: 6 deg, 1 deg/s
- BVL subject

What's behind the effectiveness of ABF?

Increase in postural stability is not at the expense of leg muscular activity, which remains almost unchanged

Examination of the structural properties of the COP and the EMG activity support the hypothesis that ABF does not induce an increased stiffness (and hence more co-activation) in leg muscles, but rather helps the brain to actively change to a more feedback-based control activity over standing posture

Mechanisms behind ABF are direction-specific

- A. Individual Time Series
- B. Group Mean Change Due to ABF
Using direction-specific, ABF information, subjects reduced their sway in the specific direction of the audio-biofeedback by increasing the frequency of their postural corrections in the specific direction of the biofeedback.

This suggests that sway reduction is not the consequence of a simple passive mechanism, such as body stiffness, or the consequence of a task involving a higher attentional demand, but rather the consequence of active control from the central nervous system.

Experimental Set Up and Protocol
- 8, healthy, young subjects (23yrs±3.04)
- Standing on foam
- In 6 different conditions:
  1) Eyes closed with audio BF (linear coding)
  2) Eyes closed with audio BF (sigmoid coding)
  3) Eyes open with visual BF (linear coding)
  4) Eyes open with visual BF (sigmoid coding)
  5) Eyes closed (control for condition 1-2)
  6) Eyes open with random visual BF (control for condition 3-4)
- Each condition was repeated 5 times (random order)
- Each trial was 60 seconds long
- Acceleration and center of pressure were recorded

Influence of sensory modality and coding on BF
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Audio vs Visual BF : effects on Acceleration
- BF reduced the standard deviation (std) of the accelerations which were fed back.
- Sigmoid coding of audio BF information was more effective than linear coding in reducing sway.
- Linear coding of visual BF information was more effective than sigmoid coding in reducing sway.
- This result suggests that both the different sensory channel (audio and visual) and different coding function (linear and sigmoid) chosen to represent the BF information, may influence the effectiveness of BF.

Visual and Audio BF Evoke Different Postural Strategies for the Control of Upright Stance
- Only sigmoid audio BF reduced the std of the center-of-pressure (COP) displacement.
- An inverted pendulum model (ankle strategy) can explain the reduction of both acceleration and COP std found using sigmoid audio BF.
- However, in order to explain the opposite behavior of acceleration and COP standard deviations found with visual BF, it is necessary to use a multi-segmental model (hip strategy).
- Thus, subjects may have preferred an ankle strategy in response to sigmoid audio BF and a hip strategy in response to visual BF.

Both the effectiveness of the BF information in reducing sway and the strategy chosen by the subjects to control the BF signal may be dependent on the BF coding function and presentation.

Insole Sensor System
1. Addressing area of 24 sensor cell
2. 5-bit digital address through 50 channels, +5V supply, 0V ground
3. Acquisition of analog voltage signal with max 2.7V
4. Amplification of analog signal in 0-5V range
5. ADC conversion with 8-bit resolution
6. A/D conversion every 24-bit full scale level
7. Sound in headphones maps COP correction movements
8. Sound in headphones maps COP correction movements

Accelerometers; Gyroscopes; others
Linear/Nonlinear; Delays; Gain
Sensor (Accelerometer)
Coding (Linear/Sigmoid)
Modality (Audio/Visual)
Subjects (Healthy, Young)
2 DoF platform for diagnosis and rehabilitation of subjects with postural disabilities

Device design

Device prototype

The near future

Short loop

Long loop

Example of application of models in the stabilization of standing posture using functional neuromuscular stimulation (Soetanto et al., J. Biomech., 2001)

T includes an 'artificial' torque, elicited by a stimulator on healthy muscle, in lack of natural efficient control algorithm

Closing the closed-loop

Block diagram representation of the FNS control system components. The control system may include feedforward, feedback, and/or adaptive components. Note that the feedback controller uses measurements of system outputs to determine its contribution to the stimulation delivered to the muscles; the adaptive controller uses the measurements to modify parameters of the feedforward or feedback controller equations. If feedforward control is used by itself, it is usually referred to as an "open-loop" control.

Thank you for your attention

www.starter-project.com