Closed-loop solutions for motor rehabilitation

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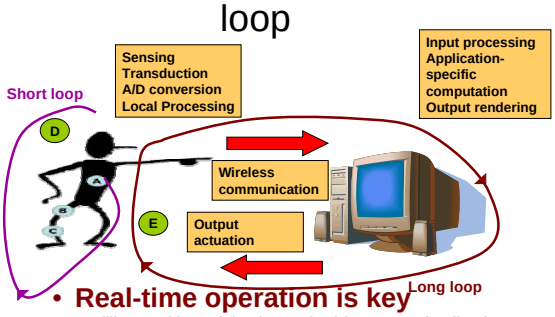
Body Area Networks: human in the loop

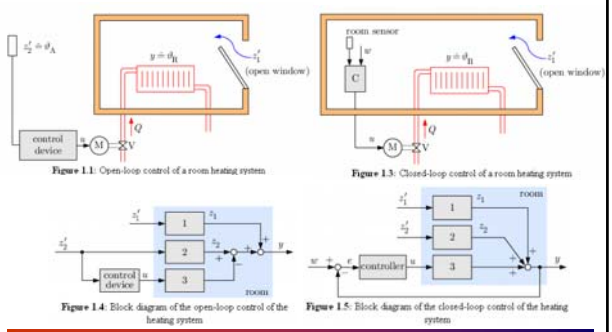


- **Real-time operation is key**

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

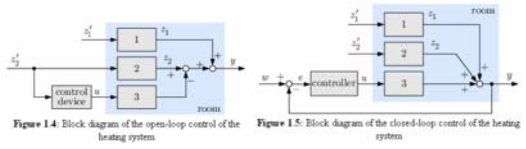
Closed-loop solutions…

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**.

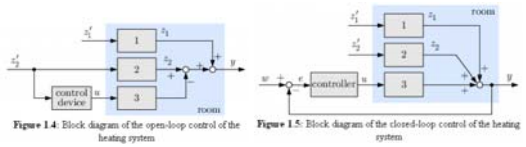
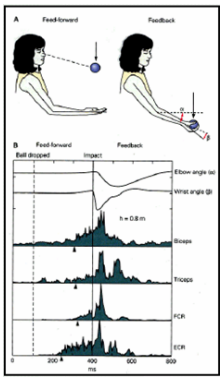
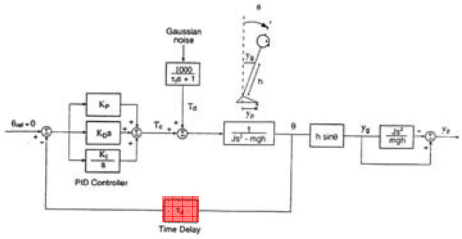


Figure 1.4: Block diagram of the open-loop control of the heating system

Figure 1.5: Block diagram of the closed-loop control of the heating system



Closed-loop model of postural control



Peterka, 2000

Open-loop model of postural control

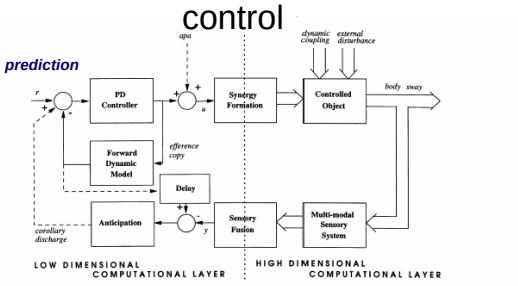
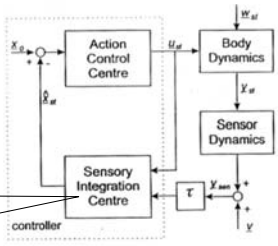


Fig. 5. Application of the Smith's predictor control scheme to the stabilization of standing posture. *u*: COP; *y*: COM; *r*: reference posture (desired value of the COM); *apa*: anticipatory postural adjustment.

Morasso et al, 1999



Extended Kalman Filter + Nonlinear Predictor

Van der Kooij et al, 1999-2001

The basic structure of closed-loop systems

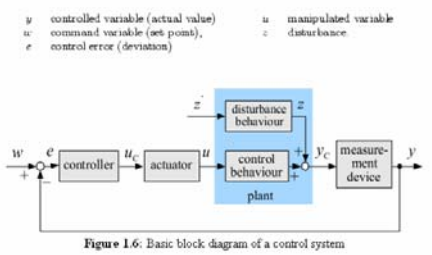
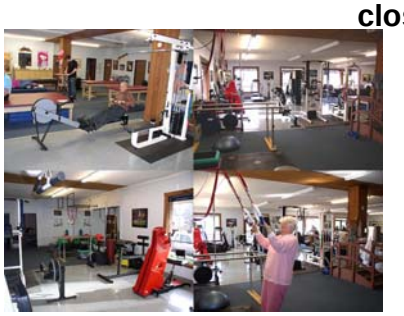


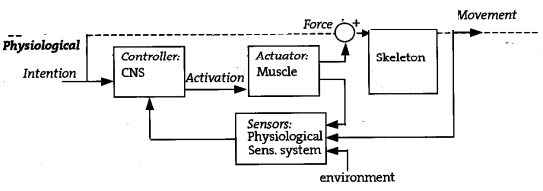
Figure 1.6: Basic block diagram of a control system

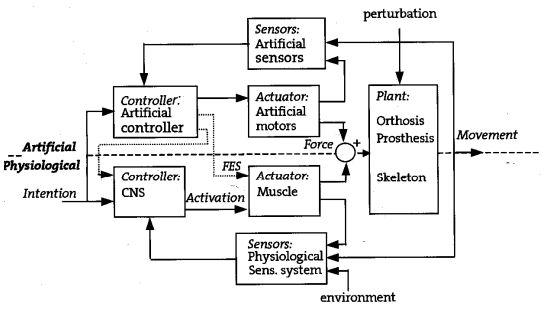
… for motor rehabilitation

Open-loop or closed-loop?

Open-loop or closed-loop?

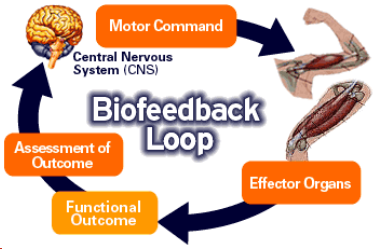






- One approach to improving balance, which has been widely used in physical therapy and rehabilitation, involves feeding back to the CNS **supplementary environmental information** about body motion.
- This supplemental information may be coming from artificial sensors, a therapist, or laboratory equipments (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



MayoClinic.com
Tools for healthier lives

COMPLEMENTARY & ALTERNATIVE MEDICINE

Original Article: http://www.mayoclinic.com/health/biofeedback/SA00083

Biofeedback: Using your mind to improve your health

Have you ever wished you could simply will your symptoms to disappear? With biofeedback you may be able to rely less on medication and more on the power of your mind.

What is biofeedback?

Biofeedback uses your mind to control your body. Biofeedback is a type of complementary and alternative medicine called mind-body therapy. Using feedback from a variety of monitoring procedures and equipment, a biofeedback specialist will try to teach you to control certain involuntary body responses, such as:

- Brain activity
- Blood pressure
- Muscle tension
- Heart rate

Once you learn to recognize and control these responses, you can use biofeedback to help treat a wide range of mental and physical health problems. Even if you don't have a specific disease or condition, biofeedback may help your overall health and sense of well-being.

What conditions benefit from biofeedback?

Biofeedback has been shown to be helpful in treating about 150 medical conditions, including:

- Asthma
- Raynaud's disease
- Irritable bowel syndrome
- Hot flashes
- Nausea and vomiting associated with chemotherapy
- Incontinence
- Headaches
- Irregular heartbeats (cardiac arrhythmias)
- High blood pressure
- Epilepsy

Clinical trials are evaluating biofeedback in other conditions as well.

What happens during a biofeedback session?

You can receive biofeedback training in physical therapy clinics, medical centers and hospitals. A typical biofeedback session lasts 30 to 60 minutes.

During a biofeedback session, a therapist will apply electrical sensors to different parts of your body. These sensors will monitor your body's physiological response to stress — for instance, your muscle contraction during a tension headache — and then feed the information back to you via auditory and visual cues. These cues may take the form of a beeping sound or a flashing light. With this feedback, you'll start to associate your body's response — in this case, pain — with certain physical functions, such as your muscles tensing.

Once you begin to recognize that your headache, in this case, is a result of tense muscles, the next step is to learn how to invoke positive physical changes in your body, such as relaxing those specific muscles, when your body is physically or mentally stressed. Your eventual goal will be to produce these responses on your own, outside the therapist's office and without the help of technology.

Types of biofeedback

Your therapist may use several different techniques to gather information about your body's responses. Determining the one that's right for you will depend on your particular health problems and objectives. Machines and techniques include:

- **Electromyogram (EMG).** An EMG uses electrodes or other types of sensors to measure muscle tension. By the EMG alerting you to muscle tension, you can learn to recognize the feeling early on and try to control the tension right away. EMG is mainly used to promote the relaxation of those muscles involved in backaches, headaches, neck pain and grinding your teeth (bruxism). An EMG may be used to treat some illnesses in which the symptoms tend to worsen under stress, such as asthma and ulcers.
- **Temperature biofeedback.** Sensors attached to your fingers or feet measure your skin temperature. Because your temperature often drops when you're under stress, a low reading can prompt you to begin relaxation techniques. Temperature biofeedback can help treat certain circulatory disorders, such as Raynaud's disease, or reduce the frequency of migraines.
- **Galvanic skin response training.** Sensors measure the activity of your sweat glands and the amount of perspiration on your skin, alerting you to anxiety. This information can be useful in treating emotional disorders such as phobias, anxiety and stuttering.
- **Electroencephalogram (EEG).** An EEG monitors the activity of brain waves linked to different mental states, such as wakefulness, relaxation, calmness, light sleep and deep sleep.

Finding a biofeedback therapist: Ask questions

Once you decide to try biofeedback, you'll need to find a qualified biofeedback therapist. Contact the Biofeedback Certification Institute of America (BCIA) and ask for the names of people certified in your area. BCIA therapists must be licensed in another area of health care — for instance, as a physical therapist — or be working under the guidance of a health care professional. They should be accustomed to working with patients, and you can expect them to have a good bedside manner.

If you can't find a BCIA-certified therapist in your area, ask your doctor or another medical expert with knowledge of complementary and alternative medicine to recommend someone who has experience in treating the specific symptoms that are bothering you. As with any health care practitioner, you may have to meet with several individuals to find the one with whom you feel most comfortable.

Be sure to ask each therapist to provide references. Find out the therapist's other areas of professional expertise, and whether he or she has experience treating the specific problem for which you're seeking help. Check to see whether your health insurer will cover the cost of treatment.

Pros and cons of biofeedback

Biofeedback may appeal to you for several reasons:

- It can reduce, or even eliminate, your need for medication.
- It has the potential to help conditions that have not responded to medication.
- It helps puts you in charge of your own healing by providing measurable feedback, allowing you to monitor your progress and learning.
- It can decrease your medical costs.

On the other hand, you may be hesitant to try biofeedback because experts aren't entirely sure how the therapy works. Many people who have tried biofeedback can't explain how they're able to control their bodies to relieve their symptoms.

To truly assess whether biofeedback is effective in treating your particular symptoms, keep a daily diary to monitor your use of the treatment as well as how you feel before, during and after the therapy.

Although biofeedback is considered safe, talk to a doctor knowledgeable about this form of complementary and alternative medicine if you have depression, severe psychosis, diabetes or other endocrine disorders. Biofeedback can interfere with the use of some medications, such as insulin.

By Mayo Clinic Staff
Jan 26, 2006

Complementary and alternative medicine: What is it?

When you were a child and sprained an ankle or came down with the flu, you probably visited a pediatrician to soothe your symptoms. As an adult, you most likely visit your primary care physician for everything that ails you. But now your friends are suggesting complementary and alternative medicine treatments that you've never heard of — things like homeopathy, ayurveda, acupuncture and herbs.

What are these complementary and alternative medicine therapies? Are they safe? Will they work? Educate yourself before starting any new complementary and alternative medicine therapy, and always tell your doctor which ones you're trying.

What is complementary and alternative medicine?

Complementary and alternative medicine generally refers to practices that aren't integral parts of conventional medicine. What is or isn't considered complementary and alternative medicine changes constantly as an increasing number of treatments undergo rigorous study and are proved to be effective or not.

Though the two terms are often grouped together, complementary medicine and alternative medicine aren't necessarily the same thing. Complementary treatments are often thought of as treatments used along with the conventional therapies your doctor may prescribe, such as using tai chi or massage in addition to prescription medicine for anxiety.

Alternative approaches are generally thought of as being used instead of conventional methods. For example, this might mean seeing a homeopath or naturopath instead of your regular doctor.

Many complementary and alternative medicine practitioners base their work around a few common principles. Some of these are similar to what your conventional doctor might do, while others are quite different. Basic philosophies of complementary and alternative medicine include:

- **Your body heals itself.** Complementary and alternative medicine practitioners see themselves as facilitators. To them your body does all the healing work, and you only need treatment to encourage your natural healing processes.
- **Prevention is key.** Your complementary and alternative medicine practitioner may wish to see you before you get sick to make sure you're doing all you can to keep yourself healthy.

What are some examples of complementary and alternative medicine?

To make sense of the many therapies available, it might help to look at them in the five broad categories that the National Institutes of Health uses for classification.

Healing systems
Healing systems are complete sets of theories and practices. A system isn't just a single practice or remedy — such as massage — but many different practices that all revolve around a philosophy or lifestyle, such as the power of nature or the presence of energy in your body. Many healing systems developed before the conventional Western medicine commonly used in the United States.

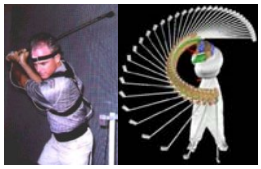
Examples of complementary and alternative medicine healing systems include ayurveda, which emphasizes a unique cure per individual circumstances, homeopathy, which uses minute doses of medicine to evoke cures, and naturopathy, which focuses on noninvasive treatments to help your body do its own healing. Traditional Chinese, Asian, Pacific Islander, American Indian and Tibetan practices also fall into the healing systems category.

Mind-body connections
Mind-body techniques strengthen the communication between your mind and your body. Complementary and alternative medicine practitioners believe these two systems must be in harmony for you to stay healthy. Examples of mind-body connection techniques include meditation, yoga, [redacted] prayer, hypnosis, relaxation and art therapies, such as poetry, music and dance.

Dietary supplements and herbs
These treatments use ingredients found in nature. Examples of herbs include ginseng, ginkgo and echinacea, while examples of other dietary supplements include selenium, glucosamine sulfate and SAMe. Herbs and supplements can be taken as teas, oils, syrups, powders, tablets or capsules. Many people trust herbal medicine because it's been used for thousands of years. Others like it because it's "natural." Remember, though, that natural doesn't mean that herbs and supplements can't hurt you.

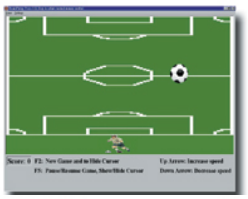
Some examples of commercial systems for BF

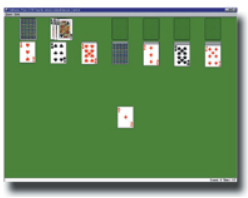
Spine-Check
Spine Check Inc.
A small sensor is worn on a belt under clothing, which measures the movement of the spine and **gently vibrates** to warn the user when doing unsafe movements.



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 is tilting far from his/her vertical in the four directions: forward, backward, left, and right.





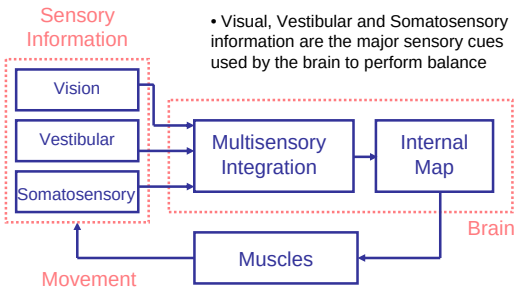
NEUROGAMES by NEUROCOM

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.

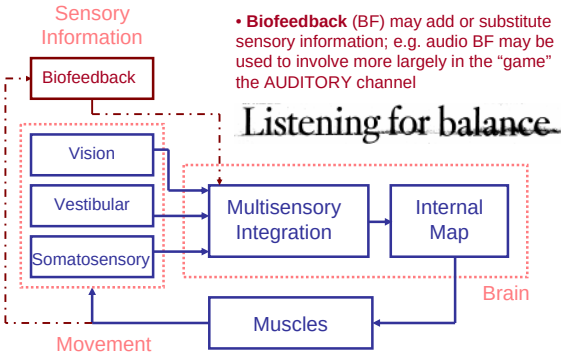
Solitaire - The standard solitaire game found on all Windows® systems, offers a new twist to an old game where patients must shift their center of gravity to select and move the cards.

Balance Biofeedback

Balance Depends on Sensory Information



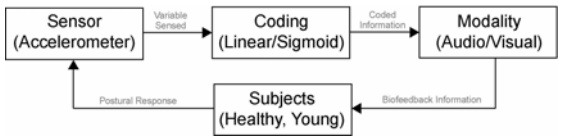
• Visual, Vestibular and Somatosensory information are the major sensory cues used by the brain to perform balance



• **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

Listening for balance

The architecture of a BF system



Example #1
Balance Prosthesis Based on Micromechanical Sensors Using Vibrotactile Feedback of Tilt

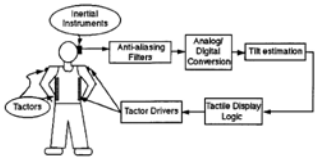
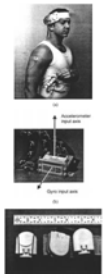


Fig. 1. Diagram of prototype balance prosthesis with head-mounted sensors.



Wall et al. IEEE TBME, 2001

Fig. 3. (a) Subject with one sensor module, and tactors. (b) Close up of single axis tilt sensor module. (c) Close-up of tactors.

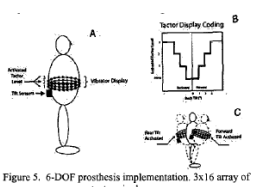


Figure 5. 6-DOF prosthesis implementation. 3x16 array of tactors is shown.

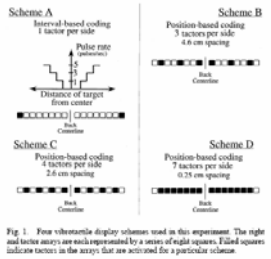
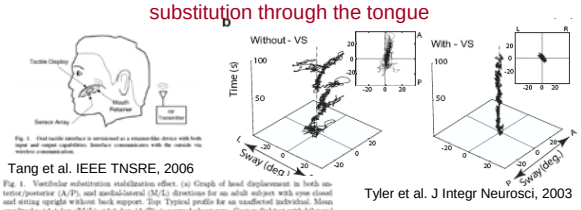


Fig. 1. Four vibrotactile display schemes used in this experiment. The right and tactor arrays are each represented by a series of eight squares. Filled squares indicate tactors in the arrays that are activated for a particular scheme.

Kadkade et al. IEEE TNSRE, 2003

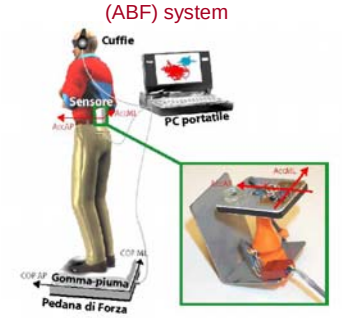
Example #2
Closing an open-loop control system: vestibular substitution through the tongue



Tang et al. IEEE TNSRE, 2006

Tyler et al. J Integr Neurosci, 2003

Example #3
An accelerometer-based audio-biofeedback (ABF) system



Chiari et al., IEEE Trans Biomed Eng, 2005

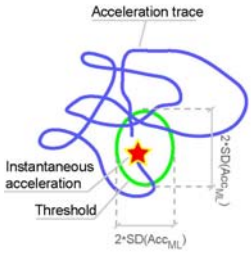
The sensory unit

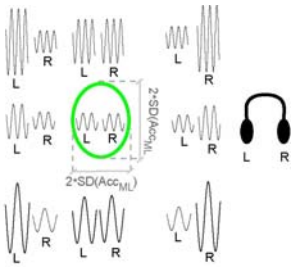
2D ADXL203, Analog Device

3D LIS3L02DQ, ST-microelectronics

The sensory modality

The "biomechanics2sensory" trans-codification

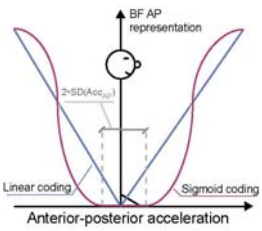


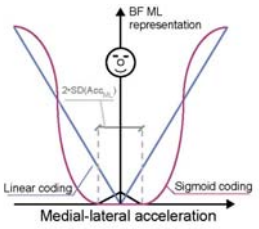


Visual Biofeedback

Audio Biofeedback

The coding algorithms: Linear and Sigmoid Coding

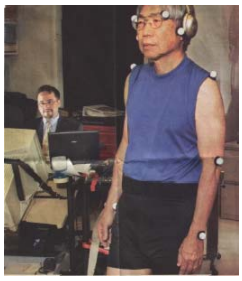




M. Dozza et al., IEEE Trans. Neural Syst. Rehab., under review

The motor task

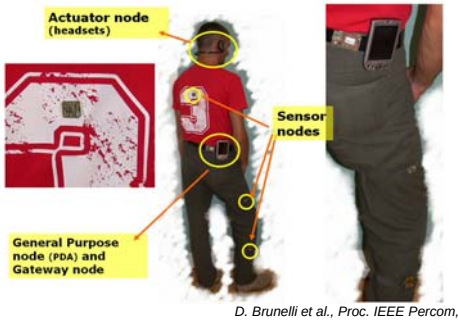
Static



Dynamic

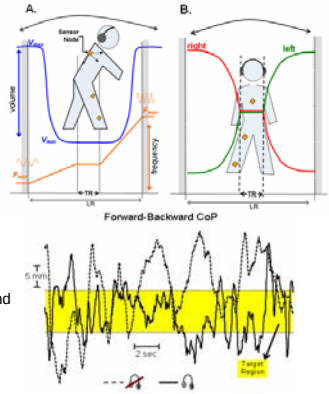
→ **Wireless may be advantageous for dynamic tasks!**

BF System for Rehabilitation Based on Wireless Body Area Network

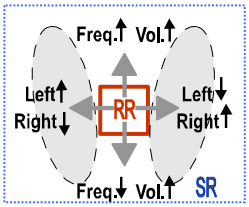


D. Brunelli et al., Proc. IEEE Percom, 2006

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



They are both estimated in the first few seconds of the first trial

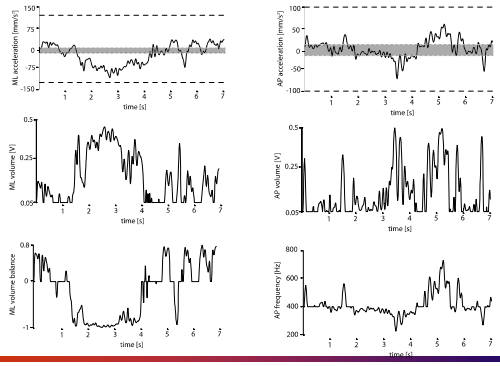
Safety Region (SR)

- 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)

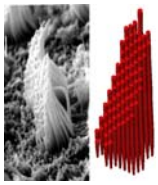
Reference Region (RR)

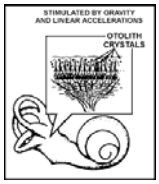
- represents the region for natural sway (±1 degree)
- is estimated using the subject's height

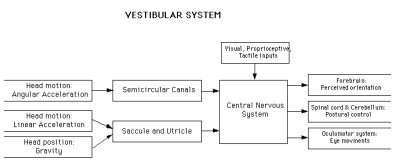
Example of ABF-driven sound



- 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)



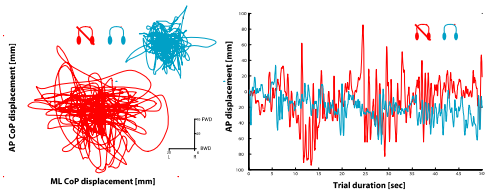




- Subjects learn to use ABF in 1 minute
- Subjective balance score (Schieppati et al., 1999) is lower also when ABF seems NOT actually helpful
- It is small, light-weight and comfortable to wear (but so far wired…)

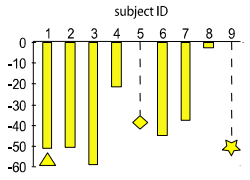
Results: quiet standing

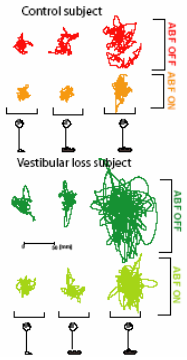
- Improve balance (Sway Area decreases)
- Increase control (Mean Velocity increases)



Dozza et al., Arch. Phys. Med. Rehab., 2005

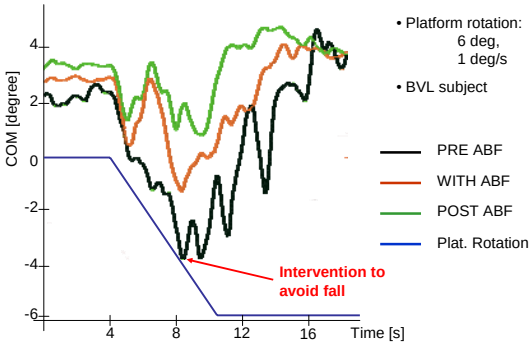
ABF can restore standing stability in bilateral vestibular loss patients





Dozza et al., Exp. Brain Res.,under review

ABF has a Tuning-Fork effect

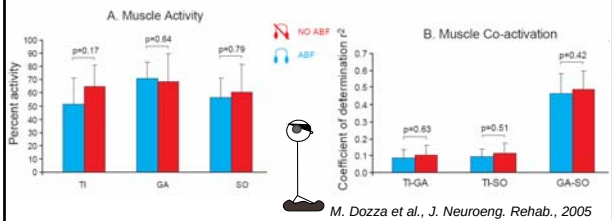


- Platform rotation: 6 deg, 1 deg/s
- BVL subject

PRE ABF
WITH ABF
POST ABF
Plat. Rotation

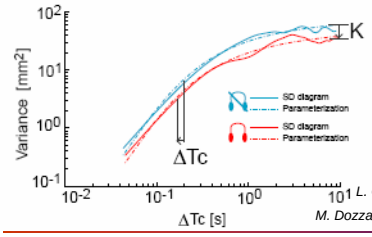
What's behind the effectiveness of ABF?

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



M. Dozza et al., J. Neuroeng. Rehab., 2005

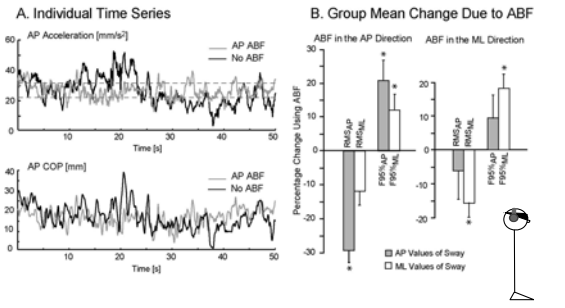
Examination of the structural properties of the COP and the EMG activity support the hypothesis that ABF does not induce an increased stiffness (and hence more co-activation) in leg muscles, but rather helps the brain to actively change to a **more feedback-based** control activity over standing posture



L. Chiari et al., Hum. Mov. Sci., 2000

M. Dozza et al., J. Neuroeng. Rehab., 2005

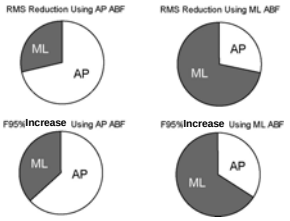
Mechanisms behind ABF are direction-specific



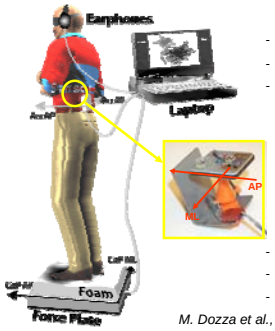
M. Dozza et al., Neurosci. Lett., under review

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.



Influence of sensory modality and coding on BF

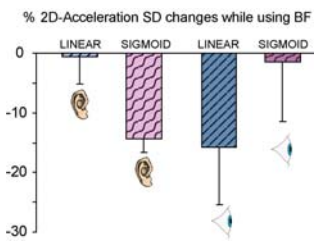


Experimental Set Up and Protocol

- 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

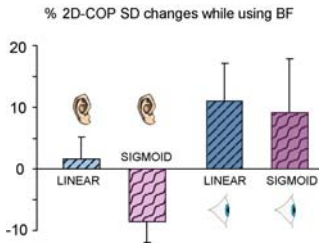
M. Dozza et al., IEEE Trans. Neural Syst. Rehab., under review

Audio vs Visual BF : effects on Acceleration

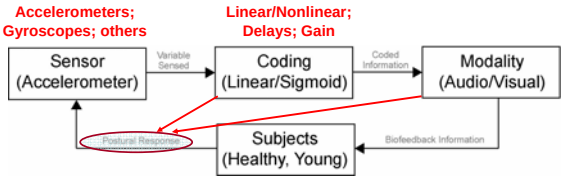


- BF reduced the standard deviation (std) of the accelerations which were fed back.
- Sigmoid coding of audio BF information was more effective than linear coding in reducing sway.
- Linear coding of visual BF information was more effective than sigmoid coding in reducing sway
- This result suggests 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

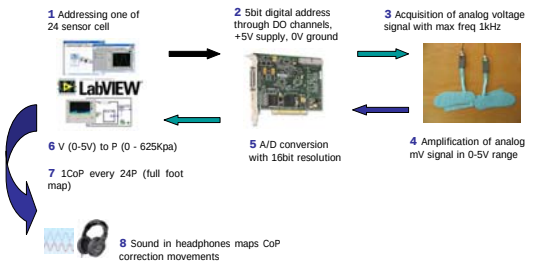


- Only sigmoid audio BF reduced the std of the center-of-pressure (COP) displacement.
- An inverted pendulum model (ankle strategy) can explain the reduction of both acceleration and COP std found using sigmoid audio BF.
- However, in order to explain the opposite behavior of acceleration and COP standard 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.**

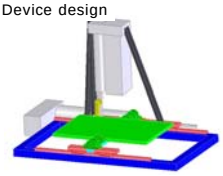
Insole Sensor System



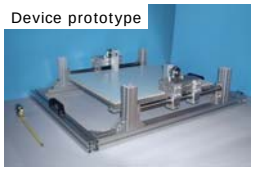
UNIVERSITY OF BOLOGNA *Department of Electronics, Computer science & Systems*

2 DoF platform for diagnosis and rehabilitation of subjects with postural disabilities

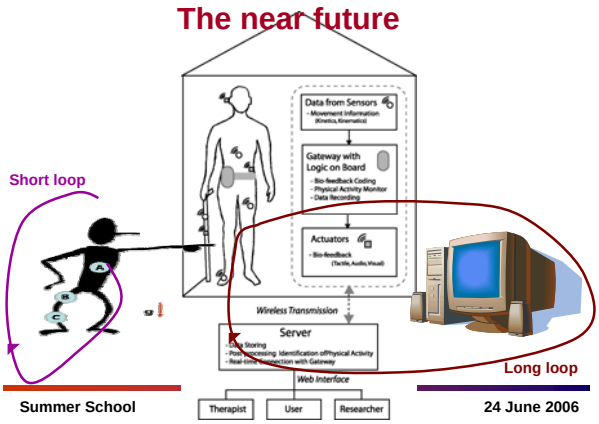
Device design



Device prototype

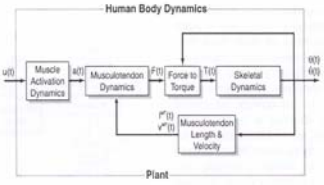


The near future

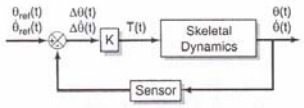


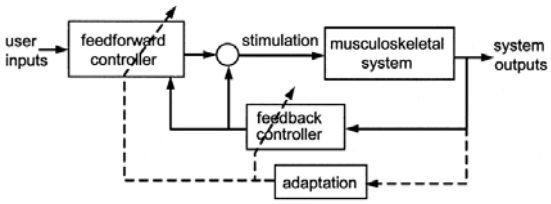
Closing the closed-loop

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





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.

Summer School 2006

Thank you for your attention

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