‘Neurogame therapy’ for improvement of movement coordination after brain injury

Developing a wireless biosignal game therapy system

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Abstract— **Emerging technology holds tremendous promise for improving recovery following brain injury. Here we describe a home-based rehabilitation system for improving volitional control of hand movement. People with cerebral palsy and those recovering from stroke or traumatic brain injury often have difficulty producing coordinated movements of the hand and arm on one side of the body. Surface electromyography (sEMG) recorded over affected muscles is used to provide enhanced visual feedback via a computer game interface. Several weeks of practice using this system has resulted in improved muscle coordination. Preliminary results are shown from the next generation of this system, which will employ ultra-low power wireless sensors to transmit muscle activity to a home computer.**

Keywords*- rehabilitation, hand therapy, low power wireless, MICS/ISM, bioelectrical interfaces, low nosie amplifiers.*

I. INTRODUCTION

Persons with cerebral palsy and those recovering from traumatic brain injury or stroke often experience reduced motor control. In the case of hand and arm motion, movement impairment can substantially disrupt daily activities and dramatically reduce quality of life. Two impairments that are common to all three groups are hemiparesis and spasticity. Hemiparesis is decreased motor control with secondary weakness that occurs on one side of the body, typically the side opposite the brain injury. Spasticity is characterized by over-active muscles, and is common after stroke and incomplete spinal injury, as well as for those with cerebral palsy [1]. Over half of persons after stroke exhibit some form of pathologic muscle tone well into the chronic phase [2]. Hemiparesis and spasticity make it difficult for persons to use their impaired upper extremity in daily tasks [3, 4].

Although disabilities can be severe, these individuals can substantially improve motor function with large amounts of physical therapy and repetitive practice at specific tasks [5-7]. Neural plasticity studies suggest that with adequate practice of key activities, where the individual is motivated and the demands on the nervous system are gradually increased, permanent improvements in motor control can occur [8-11]. Current clinical therapy regimens that are covered by insurance, however, cannot provide enough practice time to affect maximum recovery, and adherence to home exercise programs is generally poor.

II. NEUROGAME THERAPY CONCEPT

Here we demonstrate a method to overcome the limitations of in-clinic practice time and home exercise motivation by providing an effective, enjoyable and flexible home therapy solution. The final system will use wireless surface electromyography (sEMG) recorded from the skin over impaired muscle groups to control the movements of existing computer games (Figure 1).

Using this approach, any muscle or muscle group in need of improved volitional control can be used to control game movements in patterns chosen for therapy. Muscle-driven movements of the game provide enhanced visual feedback of neural activity, including weak muscle activity that does not cause overt movements. A similar approach of using surface EMG to control computer mouse movements has been used in the clinic for the lower extremity with great success in retraining gait for individuals with hemiplegia following brain injury [12, 13].

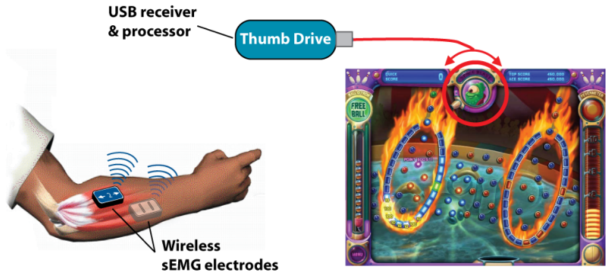

Figure 1: Schematic of the *Neurogame therapy* system where surface muscle electrical activity (sEMG) is converted to movements of popular computer games via wireless electrodes interfacing with a USB thumb drive receiver.

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Using a flexible transform from muscle activity to game control permits reinforcement of either increased or decreased activity (e.g., reduced spasticity) for each muscle, as well as coordination of multiple muscles into functional synergies.

The proven psychological reward schedule of popular computer games provides ample motivation to practice the desired muscle patterns, and even older adults enjoy computer games [14, 15]. Neurogame therapy users improve muscular coordination gradually by working through the incrementing difficulty levels of the game, as well as through tuning of the transform converting muscle activity to game control.

A. Advantages over existing game rehabilitation methods

Using muscle activity directly to control computer games has several advantages over exiting methods of game-based rehabilitation [16, 17], including the use of virtual reality [18] or acceleration-sensing controllers like the Nintendo Wii [19]. The direct use of muscle electrical activity provides a more flexible control signal compared to overt movements of the limbs needed to register a force or acceleration of existing game controllers. For example, weakly activated muscles often produce detectable EMG signals without causing movements of the limb. Our approach amplifies these weak signals into enhanced visual feedback, while gradually increasing the magnitude of this activity through incrementing difficulty levels. In addition, many daily tasks do not require limb movements, but rather co-contraction of functional muscle synergies to stabilize a joint in a desired posture. Our method permits these functional muscle synergies to be selectively reinforced through the game environment, with the goal of improving activity and participation in life skills.

Direct feedback of muscle activity also permits training of accessory muscles that may be inhibiting movement. For example, muscles throughout the upper extremity are frequently spastic in children with cerebral palsy, leading to a flexed posture of the arm [3, 5]. This flexible approach could gradually reinforce children for relaxing these overactive muscles in order to control the game, leading to more natural movements of the entire extremity. A significant advantage of the *Neurogame therapy* approach is the ability to target the most impaired muscles throughout the body, and provide customized visual feedback for each user in order to improve his/her muscle coordination.

III. WIRELESS NEUROGAME SYSTEM

Recording sEMG signals requires a bipolar electrode placed directly on the surface of the skin. It is desirable to make the recording electronics and electrodes as small and unobtrusive as possible. To that end, wireless connectivity between the sensor and the computer is critical. The following system-level requirements were considered:

- sEMG signals are on the order of mV with a bandwidth of interest from roughly 10 Hz-1 kHz.
- The wireless electrode must perform amplification and digitization.
- An 8-bit ADC is demonstrated as being sufficient for *Neurogame therapy*.
- A low power custom IC would have a supply voltage of roughly 1V. Thus, the on-chip amplifier should have a programmable gain with a maximum of at least 60dB and a noise floor less than $100\mu V_{rms}$.
- Data must be continuously streamed at a rate of roughly 8bit * 3 ksps = 24 kbps.
- Small form-factor and weight (less than a few grams). Thus, a small hearing aid battery or rechargeable LiPo battery should be used.
- The power consumption must be minimized since a small battery is desirable. A 30mAh hearing aid battery, for example, would require an overall system current less than 5mA for a reasonable battery life.

Low noise amplifier ICs, ADCs, and microcontrollers that comfortably meet these specifications can be readily purchased. However, commercially-available RF transceiver technology is notoriously power hungry. Low power 2.4 GHz Zigbee radios, for example, dissipate over 20mW while transmitting and receiving. Thus, we conclude that the most challenging part of the system design will be the RF transceiver. This observation is reinforced by a review of commercially-available wireless EMG systems (see Table I).

Table I. Comparison of Wireless EMG sensors

	Battery Life	Weight (grams)	Freq (GHz)	Sample Rate	Range (m)
BTS FreeEMG	5h	9	2.4	4 kHz	50
ZeroWire	8h	12	2.4	2 kHz	20
TeleMyo	8h	14	2.4	3 kHz	10
Proposed	>70h	1	0.4	3 kHz	10

We have designed a customized IC that integrates all functions necessary for wireless EMG recording (programmable amplification, ADC, digital logic, 400 MHz transmitter). As shown in Table I, we achieve a significant reduction in weight as well as a large increase in battery life. Much of this improvement comes from the huge reduction in power consumption achieved by our RF transmitter design. This section will describe this system in detail.

A. Integrated Circuit Design

Our objective with this chip design was a single-chip wireless sensor for sEMG and other bio-signals. The chip architecture is shown in Figure 2 below [20].

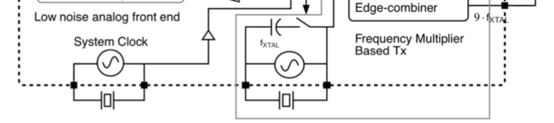

Figure 2: Architecture of the wireless EMG chip

The chip has a fully-differential low noise input (noise floor of $3\mu V_{rms}$, programmable gain up to 80dB, and bandwidth of 7kHz). This front-end exceeds the specifications for sEMG recording by a large margin and dissipates less than 20μW. An on-chip 8-bit successive-approximation ADC is integrated and allows a variable sample rate. A 400 MHz frequency-multiplying transmitter was used. This architecture allows extremely low levels of power dissipation (less than 0.5mW) and can be configured to operate in multiple frequency bands (e.g. 405 MHz MICS or 433 MHz ISM bands). We have since published subsequent versions of this transmitter and an accompanying receiver [21-23].

This chip was fabricated in a 0.13μm CMOS process. The die photo is shown below in Figure 3. The entire chip dissipates 500μW when transmitting continuous EMG data. This represents a significant reduction in power dissipation and size compared to solutions using commercially-available ICs.

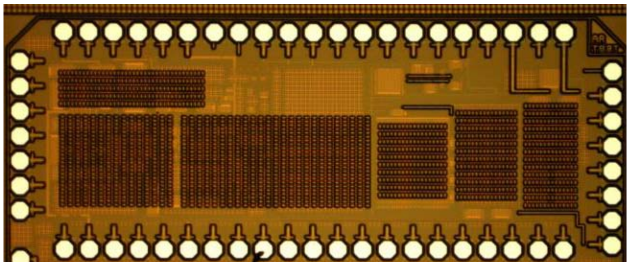

Figure 3: Wireless sEMG die photo (1mm x 2.5 mm).

B. Board and electrode design

All circuitry is integrated onto a single chip, so the final product can be extremely small since minimal support circuitry is required. The system uses a thin 4-layer PCB measuring only 7.6 x 8.7 mm^2 which incorporates the single chip, two quartz reference crystals, a voltage regulator and matching circuitry to interface the chip to an attached antenna. The fully-populated PCB weighs 0.18g without battery, 0.3g with a 337 battery, and 0.34g with a size 5 zinc-air battery. The deployed board used epoxy encapsulation to protect the bondwires.

A simple enclosure (seen in Figure 6a) was developed to house this PCB, leaving only two electrodes outside the case for direct skin contact for sensing EMG signals. The case itself was created using Computer Aided Drafting (CAD) software and a rapid prototyping machine, which takes the digital design from the CAD software and directly creates a plastic part. The electrodes are comprised of silver wires, which provide good electrical contact to the skin and are easily solderable, facilitating connection to the electronics.

C. Receiver design

An inexpensive receiver system was designed to collect the data transmitted from the EMG tag. The block diagram for the receiver is shown in Figure 4. This receiver demodulates the incoming RF signal from the tag, decodes the received packet and outputs the raw EMG data, both digitally via USB as well as outputting a pure analog waveform for use with analog sensing equipment such as an oscilloscope.

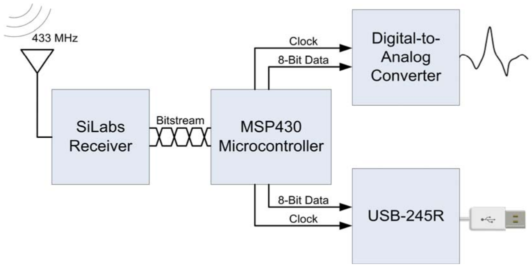

Figure 4: Companion receiver block diagram

Demodulation occurs within the SiLabs 4320 receiver. The resulting baseband bitstream is processed by a Texas Instruments MSP430 microcontroller, which runs a custom clock and data recovery (CDR) algorithm to determine the 1's and 0's of the bitstream.

The tag transmits a 011 binary pattern before each packet of data; our CDR takes advantage of this guaranteed 0-to-1 transition before a packet by re-syncing the receiver's timing to the transmitter by using this time as a known point (effectively zeroing out the Rx clock). This makes the receiver quite tolerant to variances between the Tx and Rx clocks. An extreme example of Tx/Rx clock mismatch is shown below in Figure 5. Here we see that the microcontroller waits a given amount of time, determined by its internal clock, to sample the bitstream and determine the value of each bit. If this internal microcontroller clock does not match perfectly with the clock used by the transmitter, the sampling train of the microcontroller will appear to drift away from the center of each bit, eventually resulting in either skipping a bit entirely (clock too slow) or reading a single bit twice (clock too fast). To avoid this potential problem the microcontroller re-syncs its sampling train during the 0-1 transition contained in the header pattern by scheduling the next sample to take place one half of a bit period after this transition, instead of a full bit period after the previous sample as is done every other time. Theoretically, this method can tolerate as much as a 4.5%

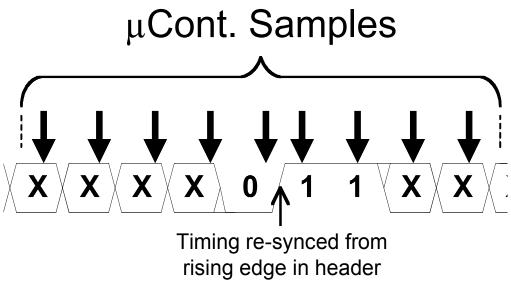

Figure 5: Rx timing synchronization with frequency mismatch.

mismatch in clocks (maximum drift of ±50% of a bit period over eleven total bits per packet).

The final extracted data is then sent digitally via USB (using FTDI's FT245R chip) to a PC. In addition, there is a digital-to-analog converter onboard the receiver that outputs a reconstructed analog signal. This CDR algorithm is run on the fly, allowing real-time reconstruction of the analog waveform for viewing on a scope or for audio playback. The entire receiver system is powered by USB from the 5 V bus connection.

Based on the custom IC described in the previous section, we have developed miniaturized wireless EMG electrodes. This circuit measures less than 1 cm^2 and fits easily in the electrode casing shown in Figure 6a. We used this device to record activity from a forearm muscle and transmit the signal five meters to the USB-compatible receiver (Figure 6b).


(a) (b)

Figure 6: (a) Prototype electrode casing, showing the electrodes (left) and wireless transmitter circuit inside (right), (b) Functioning receiver board with USB output to a computer

Figure 7 shows the functional block diagram of an early prototype of the wEMG system. The entire system is powered from a single 0.13g coin-cell battery, which is subsequently regulated to 1V. Other than this regulator IC, all functionality is performed by the custom-designed IC.

Our initial deployment of the board is as a low power, unobtrusive EMG sensor. Differential EMG probes were used to record muscle activity for *Neurogame therapy*. The probes were attached to the skin over forearm muscles. The signal was transmitted over 10 meters to our USB-compatible receiver. Figure 8 (right) shows the reconstructed waveform resulting from three muscle contractions.

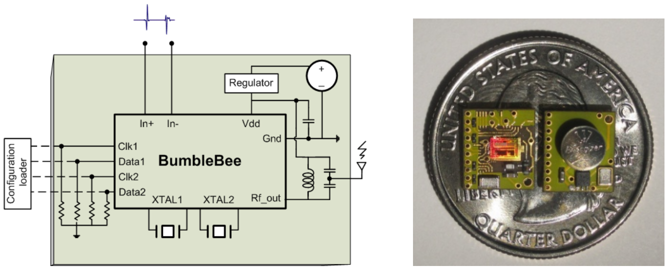

Figure 7: Left: Wireless sEMG "datasheet" block diagram. Right: Front and back of the PCB. A thin 30 gauge wire-wrap monopole wire antenna a few cm long allows >10m range.

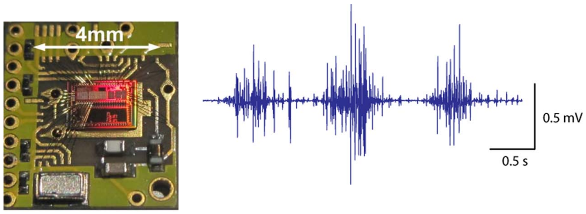

Figure 8: A miniature wireless EMG circuit (left) capable of amplifying, filtering, digitizing and transmitting bi-polar EMG signals (right).

IV. EVIDENCE FOR IMPROVED MUSCLE COORDINATION

Two children with cerebral palsy and two adults, one with traumatic brain injury (TBI) and one with stroke, have successfully used an early prototype of the *Neurogame therapy* system both in the clinic and at home. Muscle activity recorded from their affected wrist flexor and extensor muscles controlled the game system for 30 minutes/session occurring 3-5 times/week over 4-5 weeks. The total number of game sessions ranged from 15-30. All subjects improved muscle coordination as a result of game training.

A. Improved range of motion

The first subject with cerebral palsy improved active range of motion substantially after playing the game. This was evident in his ability to extend his wrist (Figure 9). Before game training, this child could not extend his wrist beyond approximately 92° (Figure 9 left). After 15 days of game practice, he could extend his wrist to 170° (Figure 9 right). This improvement was maintained for over three months with no further therapy.

B. Volitional control of paretic extensor muscles

Both of our adult subjects dramatically improved their ability to activate weak and paretic extensor muscles as a result of game training. Figure 10 shows the 3.5-fold improvement in muscle activity demonstrated by adult subject #3 with

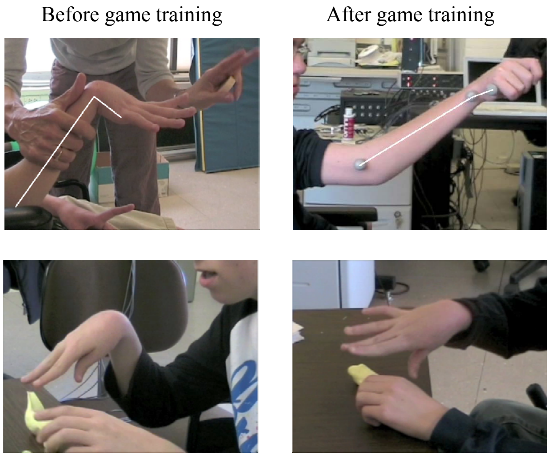

Figure 9: Wrist movements for subject with cerebral palsy before (left) and after (Right) game play for only 15 sessions. White lines indicate angle of maximum wrist extension within the sagittal plane (top row). Bottom row shows the subject spontaneously adopting a more extended wrist posture during functional testing.

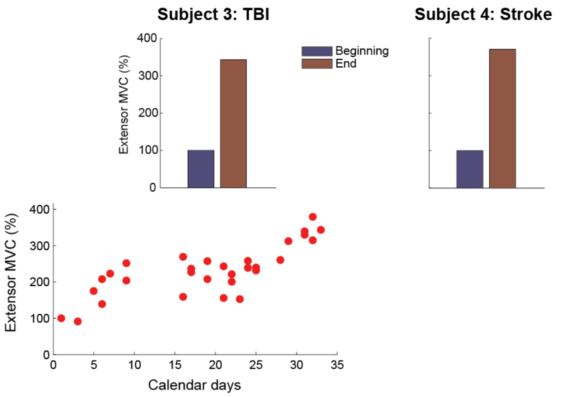

Figure 10: Maximal extensor muscle EMG for an adult with TBI increased by nearly 4-fold with 1 month of game training

traumatic brain injury over the one-month game training period. This improvement is especially notable given that this subject was in the chronic phase of recovery, 4 years after injury. The fourth subject recovering from stroke also improved extensor muscle activation by nearly 4-fold during her period of game training.

C. Independent muscle activity

All subjects dramatically improved their ability to independently activate antagonist muscle groups. Before game training, no subject could activate wrist flexors and extensors independently more than 20-40% of the time (Figure 11). After game practice, all subjects could consistently achieve 60-90% independent muscle control.

Bar graphs in Figure 11 show independence at the beginning and end of each stage of game training. Prolonged game training for Subject 2 permitted the game to be adjusted in several stages of difficulty, each requiring progressively more independent muscle control. All subjects improved their independence to nearly the level of a healthy subject – indicated by the horizontal line at 70%.

All subjects performed the game therapy at home as much or more than requested (3-5 days/week). They also rated the game therapy very highly for both enjoyment and for its positive effect on their hand function in general activities.

V. CONCLUSION

This flexible and enjoyable method of retraining muscle activity for functional movements has the potential to substantially impact the treatment of brain injury and other movement disabilities. Prolonged practice with visual feedback of specific patterns of muscle activity under strongly motivating conditions likely leads to long-term changes in the strength of neural connections within the motor system. Further prototype development will potentially lead to a low-cost version of Neurogame therapy that could be made affordable enough for individuals to purchase (even without insurance coverage). Thus, this intervention could prove an affordable and effective method for retraining the brain to produce coordinated movements after injury.

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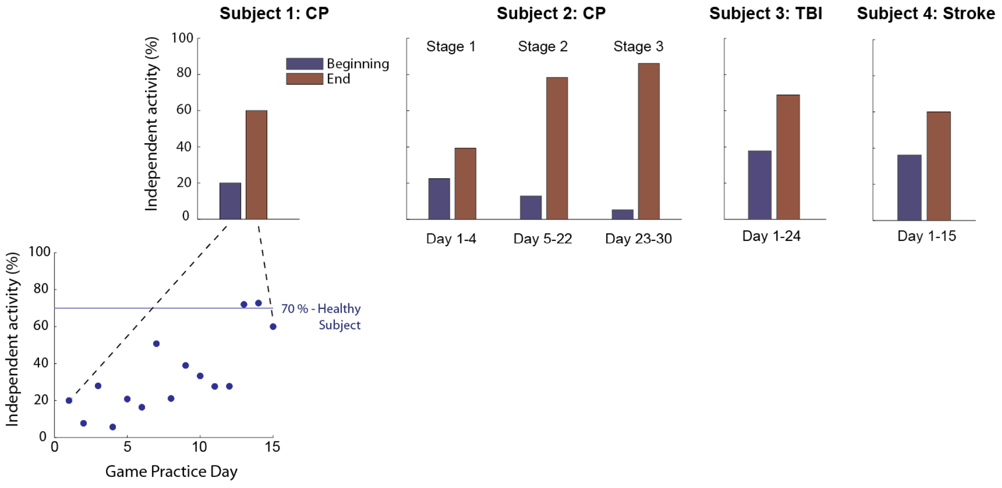

Figure 11: Independent muscle activity for two children with cerebral palsy (CP), one adult with traumatic brain injury (TBI), and one adult recovering from stroke. Bar graphs show independence at the beginning and end of each stage of game training. All subjects improved independence to near the level of a healthy subject (horizontal line at 70%).

REFERENCES

[1] Bradley, N. and S.L. Westcott, *Motor Control: Developmental Aspects of Motor Control in Skill Acquisition*, in *Pediatric Physical Therapy, 3rd Ed.*, S.K. Campbell, Editor. 2006. p. 77-130.

[2] Kong, K.H., K.S. Chua, and J. Lee, *Symptomatic upper limb spasticity in patients with chronic stroke attending a rehabilitation clinic: frequency, clinical correlates and predictors.* J Rehabil Med, 2010. **42**(5): p. 453-7.

[3] Eliasson, A.C., et al., *Development of hand function and precision grip control in individuals with cerebral palsy: a 13-year follow-up study.* Pediatrics, 2006. **118**(4): p. e1226-36.

[4] Franceschini, M., et al., *Is health-related-quality of life of stroke patients influenced by neurological impairments at one year after stroke?* Eur J Phys Rehabil Med, 2010. **46**(3): p. 389-99.

[5] Gordon, A.M., et al., *Efficacy of a hand-arm bimanual intensive therapy (HABIT) in children with hemiplegic cerebral palsy: a randomized control trial.* Dev Med Child Neurol, 2007. **49**(11): p. 830-8.

[6] Oujamaa, L., et al., *Rehabilitation of arm function after stroke. Literature review.* Ann Phys Rehabil Med, 2009. **52**(3): p. 269-93.

[7] Urton, M.L., et al., *Systematic literature review of treatment interventions for upper extremity hemiparesis following stroke.* Occup Ther Int, 2007. **14**(1): p. 11-27.

[8] Beekhuizen, K.S. and E.C. Field-Fote, *Massed practice versus massed practice with a stimulation: Effects on upper extremity function and cortical plasticity in individuals with incomplete cervical spinal cord injury.* Neurorehabilitation and Neural Repair, 2005. **19**(1): p. 33-45.

[9] Garvey, M.A., et al., *Cerebral palsy: new approaches to therapy.* Curr Neurol Neurosci Rep, 2007. **7**(2): p. 147-55.

[10] Johnston, M.V., *Plasticity in the developing brain: implications for rehabilitation.* Dev Disabil Res Rev, 2009. **15**(2): p. 94-101.

[11] Kleim, J.A. and T.A. Jones, *Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage.* J Speech Lang Hear Res, 2008. **51**(1): p. S225-39.

[12] Coleman, K.A. and J. Harry, *Development and Testing of a Novel EMG Feedback Technology to Induce Movement.* Neurology Report, 2002. **26**(2): p. 94-100.

[13] Coleman, K.A. and J. Harry, *Functional gait changes in patients with chronic lower extremity hemiplegia treated with a technology to induce movement (TIM)-type system.* Top Stroke Rehabil, 2004. **11**(4): p. 43-54.

[14] Goldstein, J., et al., *Video games and the elderly.* Social Behavior and Personality, 1997. **25**(4): p. 345-352.

[15] Nacke, L.E., A. Nacke, and C.A. Lindley, *Brain training for silver gamers: effects of age and game form on effectiveness, efficiency, self-assessment, and gameplay experience.* Cyberpsychol Behav, 2009. **12**(5): p. 493-9.

[16] Betker, A.L., et al., *Video game-based exercises for balance rehabilitation: a single-subject design.* Arch Phys Med Rehabil, 2006. **87**(8): p. 1141-9.

[17] Goude, D., S. Bjork, and M. Rydmark, *Game design in virtual reality systems for stroke rehabilitation.* Stud Health Technol Inform, 2007. **125**: p. 146-8.

[18] Bryanton, C., et al., *Feasibility, motivation, and selective motor control: virtual reality compared to conventional home exercise in children with cerebral palsy.* Cyberpsychol Behav, 2006. **9**(2): p. 123-8.

[19] Graves, L.E., N.D. Ridgers, and G. Stratton, *The contribution of upper limb and total body movement to adolescents' energy expenditure whilst playing Nintendo Wii.* Eur J Appl Physiol, 2008. **104**(4): p. 617-23.

[20] Rai, S., et al., *A 500uW Neural Tag with 2uVrms AFE and Frequency-Multiplying MICS/ISM FSK Transmitter.* IEEE International Solid-State Circuits Conference (ISSCC), 2009.

[21] Pandey, J. and B. Otis, *A Sub-100 µW MICS/ISM Band Transmitter Based on Injection- locking and Frequency Multiplication.* IEEE Journal of Solid-State Circuits (JSSC), 2011: To appear.

[22] Pandey, J. and B. Otis, *A 90uW MICS/ISM Band Transmitter with 22% Global Efficiency.* IEEE Radio Frequency Integrated Circuits (RFIC), June 2010: p. 285-288.

[23] Pandey, J., J. Shi, and B. Otis, *A 120µW MICS/ISM-Band FSK Receiver with a 44µW Low-Power Mode Based on Injection-Locking and 9x Frequency Multiplication.* IEEE International Solid State Circuits Conference (ISSCC), February 2011.