# A Low Cost Platform based on FES and Muscle Synergies for Postural Control Research and Rehabilitation

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Abstract: This paper presents a low cost system for the assessment, diagnosis and training of balance based on static posturography and functional electrical stimulation (FES). This system includes low cost technology as the Wii Fit Balance Board and the Kinect. The posturography is a complementary tool to clinical diagnosis, and allows to find sensory systems and inputs degraded by different pathologies. The presented system also allows to explore new rehabilitation techniques based on functional electrical stimulation. Precisely, this paper describes the implementation of a novel balance and posture control rehabilitation approach based on muscle synergies.

## 1 INTRODUCTION

There are several diseases that can affect human balance and posture control. Such diversity requires the participation of different specialists in the diagnosis and treatment process like neurologists, otolaryngologists and ophthalmologists among others. Posturography is defined as an objective assessment technique of postural control based. In this way, the monitoring of the center of pressure of the person has proven to be an effective tool complementary to clinical diagnosis in order to quantify this neuromotor disorder. This technique also can be be used as a complementary tool to help clinicians with the diagnosis of vertigo.

Posturography evaluates each of the sensory systems (visual, somatosensory and vestibular) involved in the complex balance system. Its purpose is to isolate the contribution of each of these systems to evaluate the status of each one separately. It also assesses movement strategies for maintaining balance, examines the stability limits of the person and the ability to control voluntary movement.

Balance control is an important functional component of human gait. After spinal cord injury (SCI) or stroke, balance control if one of the first rehabilitation objectives towards the restoration of functional gait. In this scenario, posturography also plays a key role to evaluate the progress of the affected subject. Classic therapies of posture control rehabilitation include exercises to improve stability limit or guided movements to reinforce control efforts of patient.

Over the last years muscle synergies have been described for several composed movements like those exerted during normal postural control. Muscle synergies can be understood as functional muscle coactivation patterns (D'Avella and Bizzi, 2005). This theory proposes the existence of simplified mechanisms and signals that can control several muscles at the same time. The most interesting aspect of this theory is the consistency of these synergies among subjects, and its stability intra subject. The use of this knowledge for rehabilitation is still a research goal, as well as the assessment of muscle synergies in functional tasks after stroke or SCI, (Torricelli et al., 2012).

The use of Functional Electrical Stimulation (FES) to interact with muscle synergies during the rehabilitation of balance is a novel approach proposed by Piazza et al., (Piazza et al., 2012). This paper presents a low cost system that enables the implementation of this novel rehabilitation paradigm. It is a posturography tool to help with the assessment of postural control and its rehabilitation. The main contribution of the work lies in its simplicity and its potential use in rehabilitation. It is an exploratory device to study new rehabilitation approaches of balance control while monitoring the status of human balance and postural control system. The presented tool enable the evaluation the effectiveness of current treat-

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ments and the design of new ones. The paper presents technical details of the system and preliminary results.

Further stages of this work include the validation of the designed posturography system comparing to similar ones like the NedSVE/IBV ®(Baydal et al., 2010) of the Institute of Biomechanics of Valencia, or the SMART Balance Master of Neurocom®. After this validation, the design of new herapies based on FES and muscle synergies will be possible and its evaluation in clinical environment.

# 2 ASSESSMENT METHODOLOGY AND POSTURAL CONTROL REHABILITATION

In this section, balance assessment methods used in posturography are reviewed, as well as the tests designed for this purpose and existing proposals for rehabilitation based on synergies.

## 2.1 The Computerized Dynamic Posturography (CDP)

Computerized Dynamic Posturography (CDP) was designed and developed by Nashner. It was clinically studied in collaboration with Black and marketed in 1986 as Equitest by Neurocom Inc., (Faraldo, 2009).

The CDP is a technique that analyzes subject's postural control in static standing and and his/her response to destabilizing conditions. It is is based on the idea that the center of gravity (COG) oscillations reflect postural instability. Generally CDPs are based on dynamometric platforms. These systems analyze the postural oscillations by recording the vertical projection of gravity force, known as Center of Pressure (COP). More frequent tests made with similar platforms are:

- **Sensory System or Romberg's Test.** It is aimed at determining the ability of the patient to integrate the three systems responsible for assessing standing balance and body sway while different sensory conditions are applied. The results of this test are compared with results of normal subjects. It is performed with eyes open and eyes closed, with and without foam on which the subject stands. It can also be performed with the patient's head retroflexed, causing distortion in neck proprioceptors. These tests can also be used to evaluate proprioceptive information by making patients to rely in vestibular information to maintain the balance, (Khasnis and Gokula, 2003).
- **Stability Limit Test.** It assess the capacity of the subject to bring his COP to the border of his/her stability limit. Basically, this test is used to assess the maximum distance the patient can move his/her COP without changing the base of support, i.e. without moving his/her feet. During the test, the subject can see his/her COP representation on a computer screen in front of him, and he/she should move it toward the stability limits without moving its base of support. The test includes up to eight sequential different targets located around theoretical stability limits (according to previous measurements with healthy subjects).
- **Rhythmic and Directional Tests.** These tests try to assess subject's ability to perform rhythmic movements around of its center of gravity (COG). The subject isa asked to follow with his/her COP moving targets whose speed and range are configurable. The target is moved to a percentage of the stability limit previously calculated for the subject. This test is usually performed in the anteroposterior and mediolateral directions.

## 2.2 Hybrid Approaches in Assisted Neuromotor Rehabilitation

Hybrid exoskeletons have emerged as a way to improve motor assistance using the benefits of FES and robotic exoskeletons. They overcome individual limitations of the methods used separately. The FES uses natural muscles as actuators to generate a movement, which provides benefits not only functional but physiological. Robotic exoskeletons artificial actuators are used to move the members that can not be fully or partially controlled voluntarily.

Generally, people affected by stroke and SCI have healthy muscles. The hybrid approach proposes the use of their own muscles to complement the action of the robotic exoskeleton. Muscles are activated coordinately with the exoskeleton controller by means of an electrical stimulation system, (Del-Ama et al., 2012). This approach results in a eduction of energy demand and allows the exoskeleton to use lighter and less powerful actuators. Moreover, this solution is considered more natural and help to preserve existing biological structures. Main problem when using FES is that it can produce muscle fatigue after long periods of stimulation. This problem limits the time of use. This is not a problem when using exoskeletons, which can be used for a longer time.

Balance control is an important not only when rehabilitating after stroke or SCI but also when using exoskeletons. Hyper is a spanish research project aimed at developing new neurorobotics and neuroprosthetics therapies for people affected by stroke or SCI. First clinical interventions include the rehabilitation of balance and postural control. The use use of hybrid approaches is well considered by clinicians but they way they are used in this rehabilitation process and it effectiveness is not clear yet for the scientific community.

The control of the assistive device is also not clear in terms of compensation actions and movement routines. The most most common approach over the last years, was the so called "assist-as-needed" (AAN) paradigm, (Cai et al., 2006). Following this paradigm, the interaction between the assistive device and the natural involved mechanisms in the considered task is given in terms of the final results, and not considering the underlying status of biological control mechanisms. In this way, Hyper encourages the study and development of new therapies to support classic ones. These novel treatments are mainly driven by bioinspired mechanisms for better and deeper interaction between the assistive device and remaining neuromotor control structures, in order to reinforce and rehabilitate them in a more natural way.

### 2.3 Muscle Synergies

The study of human control system is a open research field where there are still many questions to answer. One of them is how is coded the information to control the large number of degrees of freedom of human movements. More specifically, this problem states that to generate a specific motor task, there are multiple combinations of muscle activations that can generate similar results. Muscle synergies theory is a proposed answer to this question. The central nervous system can solve the complex task by choosing a specific set of muscle activations through a combination of a small set of neural patterns, called *synergy*, (D'Avella and Bizzi, 2005).

Each muscle receives as input a modulating signal from higher neural centers, and outputs a weighted activation signal to activate a set of muscles. The activation of each muscle can be seen is a weighted sum of all synergies commands connected to it, (Torricelli et al., 2011). Then, muscle synergies can translate small sets of variables coming from the central nervous system into higher dimensional signals. They are strictly correlated to the functional performance and their modulation are related with user workspace. The most interesting characteristic of muscle synergies is that they are consistent inter healthy subjects, (D'Avella and Bizzi, 2005)(Piazza et al., 2012).

Mathematically, as indicated in (Torricelli et al., 2011), can be expressed by the following equation that describes the activation of a single muscle $m$:

$$m(t) = \sum_{i}^{K} c_i(t) w_i \qquad (1)$$

in which

- $m$ is the activation of the muscle function of time.
- $c$ is the neutral command i-th synergy function of time.
- $w$ is the constant weight of the i-th synergy to the muscle in question.
- $K$ is the number of synergies.

The use muscle synergies knowledge to rehabilitate postural control is not clear. However, their role in functional movements and their importance have being already reported (D'Avella et al., 2006) (Piazza, 2013). This encourage Hyper scientific team to take them into account to favour the development of more efficient rehabilitation therapies by closely interacting with involved muscle synergies in balance control. In this way, FES can be used to develop and interact with synergies and muscle activation patterns.

## 3 PROPOSED SYSTEM

In this section we describe the low-cost platform developed to perform static posturography tests and support treatments based of FES and muscle synergies. Balance control assessment platforms are usually not open and they are commercially available only as a posturography tool. Thus, a novel low cost and open posturography platform was developed. The main objective of this platform is to support the development of novel balance control rehabilitation therapies in the framework of Hyper project.

Figure 1 shows the outline of the developed platform which is further described. The platform is based on a distributed architecture, which include several components: the posturography controller, the real-time neuroprosthetic controller, a Wii Fit Balance Board, a Kinect camera and the TEREFES electrostimulation system, (Brunetti et al., 2011).

### 3.1 Wii Fit Balance Board

Wii Fit balance board is an input device included in the Wii Fit from Nintendo ®. It is a wireless device that uses Bluetooth technology to communicate with the Wii console. It is equipped with four resistive pressure sensors located in each corner of the table.

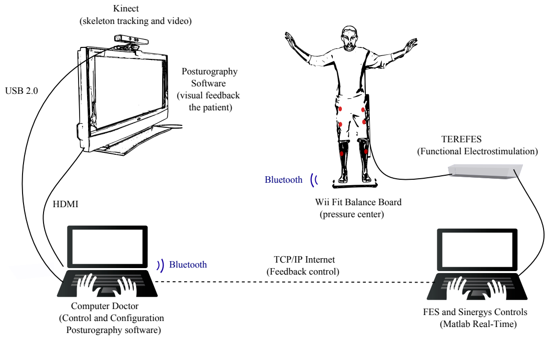

Figure 1: Proposed platform.

In effect, it measures the displacement of the center of pressure and the weight of the user. It also gives an indication of the battery status.

Over the last years, the Wii Fit Balance Board have been used by the scientific community, specially as computer interface for disabled, (Martin, 2008). This device has two attractive features: it is wireless and low-cost. In our project, the Board will be used to measure the COP.

Data from Wii Fit Balance Board is accessed through a Microsoft Visual Studio C# application, using a library called WiimoteLib available at wiimotelib.codeplex.com. Visual C# was chosen because it is also compatible with the *Kinect* and its *Windows Software Development Kit* (SDK). Thus, the Wii Fit is connected as a HID interface device. Provided services by the Board are detected using the Service Discovery Protocol (SDP) of Bluetooth.

An important aspect to consider is the sampling frequency at which the Wii Fit sends the data to the PC, or more specifically, how often the data arrives, considering the nature of wireless transmission and the operating system behavior. To answer this question, we measured the time interval between samples using methods and public properties of the Microsoft Visual Studio C# class `System.Diagnostics.Stopwatch`. The program is executed in a almost dedicated HP Pavilion g6-1b70us Notebook (Intel Core i3 CPU M 370 @ 2.4GHz, 4GB of RAM) running Windows 8 64-bit. Wii Fit Balance Board measured data sampling periods are depicted in figure 2. As it can be seen, the average sampling frequency is 100 samples/second.

The probability density function obtained with from the data shown in Figure 2 is depicted in Figure 3. This function was calculated with the `Distribution Fitting Tool` from `Matlab`. The parameters defined in the tool were: core (normal), bandwidth (auto), domain (unlimited).

The aim of this analysis it to know how deterministic is the access to the data of the the Board in terms of time. In other words, we want to know the probability that the sampling period of the Wii Fit is less than or equal to any given time. Cumulative distribution function for the Wii Fit data is depicted in figure 4. For example, the probability that the sampling period remain less than or equal to 0.02 s is 94.02%.

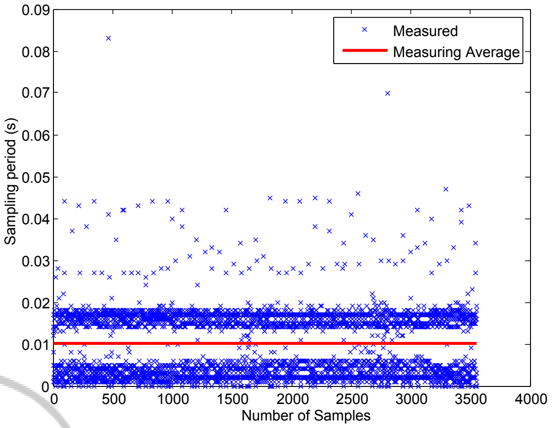

Figure 2: Time oscillations between consecutive samples received from the Wii Fit Balance Board. Sampling period is expected to be 10 ms.

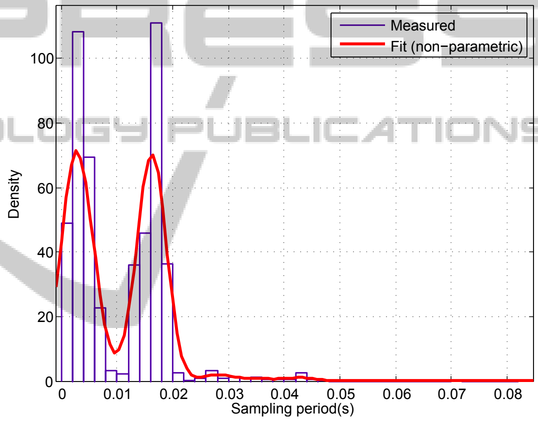

Figure 3: Probability density function of the sampling period of the Wii Fit.

## 3.2 Microsoft Kinect

Since 2009, when it was announced, the Kinect for Microsoft Xbox 360 has been widely used in many applications. The Kinect device is a natural user interface, which allows users to interact with games without physical contact with any command. It was developed by PrimeSense Company. The user becomes the controller itself, having to rely on movements, natural gestures and voice commands to control game elements.

Kinect is equipped with an RGB-D camera that acquires images of 640x480 at 30 fps. It has a vi-

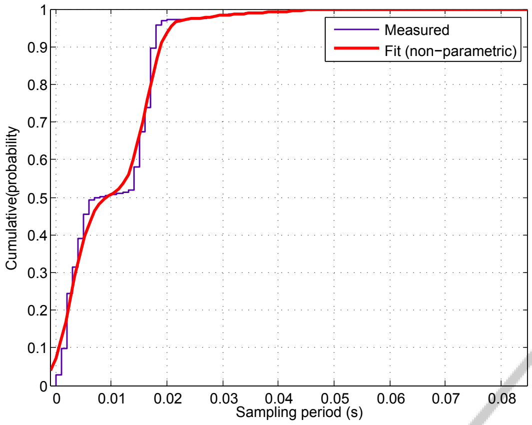

Figure 4: Cumulative distribution function as a function of the sampling period (s).

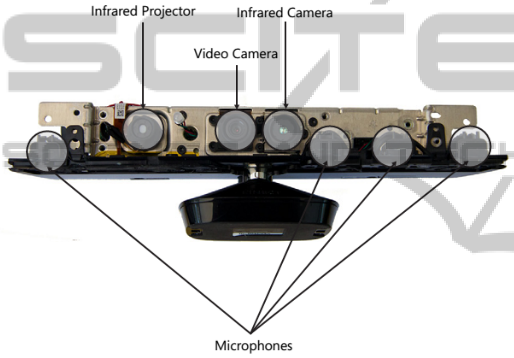

Figure 5: A Kinect camera unwrapped (Miles, 2012).

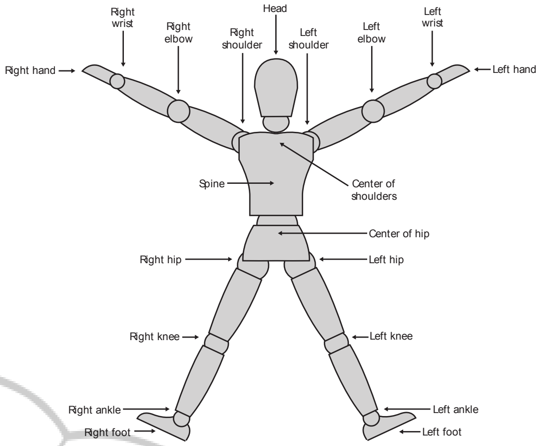

Figure 6: Schematic of the 20 points of the human skeleton that can track the Kinect (Catuhe, 2012).

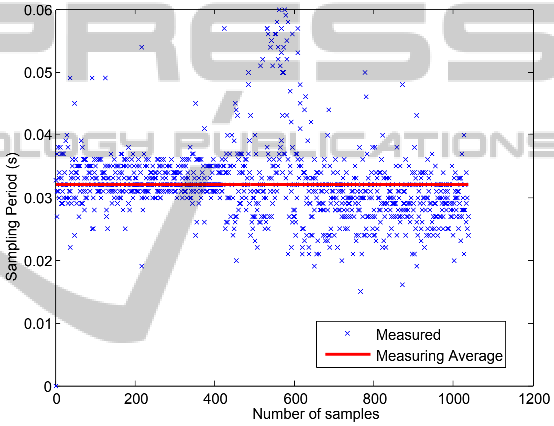

Figure 7: Sampling time the Kinect sends data to the PC.

sual field range from 1.2 to 3.5 meters, but can be reduced by optical coupling, as Niko Zoom Lenses ®. Furthermore, its viewing angle is 57° horizontally, and 43° vertically. The vertical visual field can be expanded 27° with its servomotor. It is also equipped with an array of four microphones, each with a recording resolution of 16 bits sampled at 16 kHz. It also contains a stack of signal processing hardware that is able to handle all the data that cameras, infrared light, and microphones generate. By combining the output of these sensors, a program can track and recognize objects in front of it, determine the direction of the sound signals, and isolate them from the background noise. The disassembled hardware is shown in Figure 5.

This unique device has not gone unnoticed by the scientific community. Proof of this is the immediate development of free SDK such as OpenNI[1] and OpenKinect[2], used in many research projects as a novel human-computer interface, (Brunner, 2012).

The role of the Kinect in the platform is to enrich the visual feedback provided to the patient. Common posturography platforms are limited to provide users information about the center of pressure but the user does not know precisely his/her position and how good it is for the intended task. In this way, the Kinect provides kinematic information of full body segments (Figure 6), thus providing more complete information to users as well to the neuroprosthetic controller enabling better actuation commands.

Both the Wii Fit as the Kinect, help to give visual feedback to the evaluated subject, and the information generated can be used by the neuroprosthetic controller to generate more precise and adequate stimulation patterns. A similar analysis done with the Wii Fit Board, was carried out with Kinect to evaluate the jitter effect when acquiring the frames. Samples taken during a period of approximately 20 seconds are shown in Figure 7.

The probability density function of the data in Figure 7 corresponds to a normal distribution pattern, now depicted in Figure 8. The distribution has a mean

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[1] www.openni.org

[2] openkinect.org/wiki/Main_Page

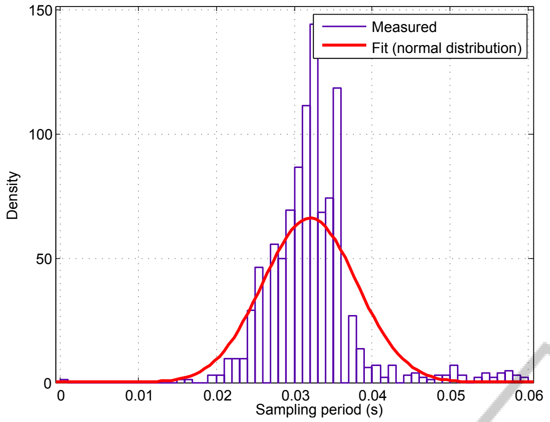


Figure 8: Probability density function of the sampling period kinect.

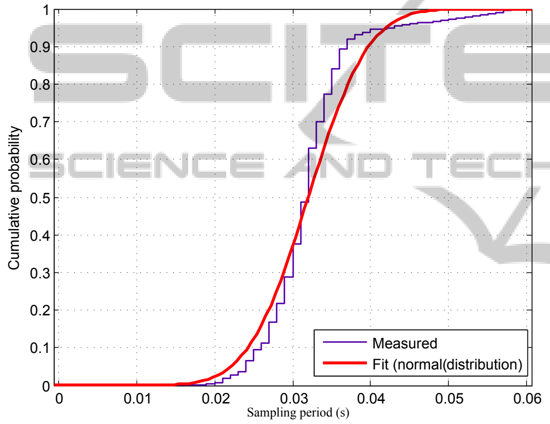


Figure 9: Cumulative distribution function of the sampling period Kinect.

of 0.032 s (∼ 30 fps) and a variance of 3.62e-5.

The cumulative distribution function in Figure 9. For example, the probability that the sampling frequency is maintained below 35 fps is 75%, approximately.

### 3.3 Posturography Controller

The Posturography Controller is implemented in a personal computer running Windows 8 operating system. The developed software includes traditional posturography tools and tests like Romberg's test, test of the stability limits and rhythmic directional test.

The software was developed for easy use by medical personnel. It includes a database in which data of each patient is stored, allowing the physician to evaluate subject progress after several sessions. It also helps to diagnose and program rehabilitation exercise routines for each one subject. The application is also able to generate Matlab scripts containing the center of pressure points recorded during each rehabilitation session. In this way, the therapists can analyze data recorded in previous sessions.

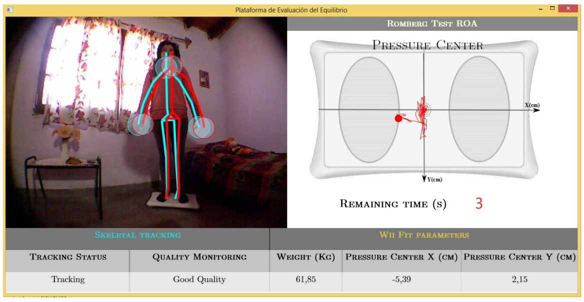
The Posturography Controller receives all the data from the Kinect camera and the Wii Fit Balance Board. It fuses and displays the acquired data showing information like the center of pressure, the rigid body kinematic chain of the studied/analyzed subject, and information about current routines and tests. This controller is connected to the Neuroprosthetic Controller thought a TCP/IP connection.

In next sections details of the various parameters used to quantify the results of each test will be described, (García, 2012).

- **Romberg's Test.** The subject is positioned on the Wii Fit Balance Board in an upright position with arms straight and close to the body trying not to move the head in neutral position facing forward, bare feet at an angle Opening of 30°. In this position is assessed for $T$ seconds (configurable by the doctor) their ability to maintain balance in the following conditions:
  - Eyes Open (REO) and Eyes Closed (REC).
  - Foam on Wii Fit with Eyes Open (RGA) and Eyes Closed (RGC).

  The parameters evaluated in each test are:
  - *Shift angle (degrees).* The angle of the vector extending from the initial point to the subject portion to the end point of the trajectory.
  - *Swept Area ($mm^2$).* It estimates the area swept by the COP by mean of an ellipse whose axes correspond to the maximum mediolateral and anteroposterior displacement.
  - *Average speed (cm/s).* It estimates the average speed, which is the ratio between the displacement and time $T$ that lasts the test.
  - *Maximum mediolateral and anteroposterior displacements (mm).* These parameters represent the longest displacement in the mediolateral and anteroposterior axis during the exercise.

  Figure 10 shows a screenshot during the execution of the application designed in this project. Specifically, this screenshot corresponds to a REO Test. The figure shows two visual feedbacks. The first one is the position of the center of pressure on the Wii Fit Balance Board, and the second, provided by Kinect, is the RGB image and a trace of its skeleton. The screen provides information about subject's skeleton (skeleton blue) and a given reference (red skeleton). The reference indicates correct estimated position during the tests.



Remaining time (s) 3

| Skeletal tracking | | Wii Fit parameters | | |
|---|---|---|---|---|
| Tracking Status | Quality Monitoring | Weight (Kg) | Pressure Center X (cm) | Pressure Center Y (cm) |
| Tracking | Good Quality | 61,85 | -5,39 | 2,15 |

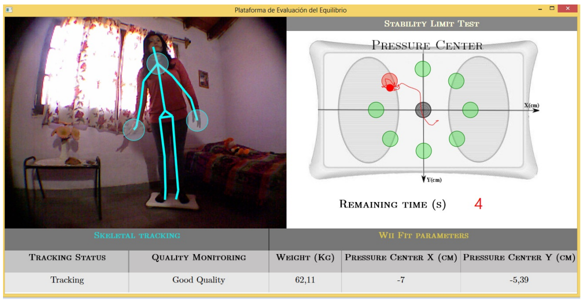
Figure 10: Screenshot during the execution of REO Test. On the right,it is shown the center of pressure on the Wii Fit while on the left the subject with his/her skeleton (blue lines) and the given reference (red lines).

Some parameters are provided in real time by the application. For example, regarding the Kinect, it monitors the status of the tracking task, which can be *Tracking* (OK) or *not skeleton* (Subject not detected). Another parameter is the quality of the skeleton, this parameter indicates if the Kinect is showing the complete skeleton of the subject (*Good Quality*). If the quality is poor, the clinician or therapist can ask the patient to move up, down, left or right, depending on the case, to get a better result. This will help the doctor to point the camera in the correct position. Regarding the Wii Fit Balance Board, the parameters observed are subject's weight and the coordinates of the COP.

- **Stability Limit Test.** This test evaluates the following parameters:
  - *LE max (mm).* It is the maximum value reached by the COP in the corresponding direction (8 targets separated of 45° and whose radial distance from the origin is configurable).
  - *Stability zone (cm)*: It is approximately the mean distance at which the patient is 90 % of the time. It is calculated for each direction.

  Figure 11 shows a screenshot during the execution of limit test. The variation of the COP on the Wii Fit for the Limit Test is depicted on the right side. The red circle represents the current target to which you should direct your COP, while the green ones represent those already targeted. Traces of COPs in these directions have been deleted to not disturb the patient with current target.

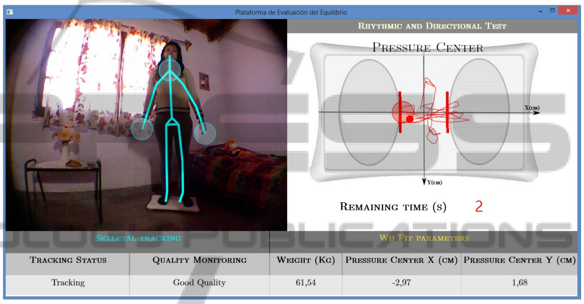
- **Rhythmic and Directional Test.** In this test, the patient is asked to follow the movements of a moving target (configurable frequency ) in mediolateral and anteroposterior directions. The maximum excursion limit is calculated based on the parameters of normal stability limits (previously recorded with healthy subjects).



Remaining time (s) 4

| Skeletal tracking | | Wii Fit parameters | | |
|---|---|---|---|---|
| Tracking Status | Quality Monitoring | Weight (Kg) | Pressure Center X (cm) | Pressure Center Y (cm) |
| Tracking | Good Quality | 62,11 | -7 | -5,39 |

Figure 11: Screenshot during the execution of the limit test. On the right side of the screen, the COP on the Wii Fit is shown in real time. On the left side is shown the patient with his/her stickman representation (blue lines).



Remaining time (s) 2

| Skeletal tracking | | Wii Fit parameters | | |
|---|---|---|---|---|
| Tracking Status | Quality Monitoring | Weight (Kg) | Pressure Center X (cm) | Pressure Center Y (cm) |
| Tracking | Good Quality | 61,54 | -2,97 | 1,68 |

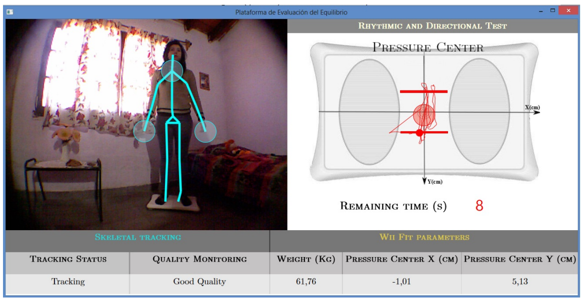
Figure 12: Screenshot for Rhythmic Test ML execution. On the right, we see the COP on the Wii Fit. To the left is shown the patient with his skeleton (blue lines).

The following parameters are evaluated for each direction.

- *Reaction Time (s).* It is defined as the time that the subject takes to bring his/her center of gravity closer than two centimeters from the reference target.
- *Tracking Capability (%).* It quantifies subject's ability to follow the movement of the target in ML or AT directions. This parameter is calculated as the mean of error ($DesiredCOP - MeasuredCOP$), after the reaction time. If the error is lower than 2cm (configurable), in other words the COP is inside the target circle, it is considered as zero for this sample.
- *Directional Control (%)*: quantifies the subject's ability to remain in the expected direction of the test. For example, if the target moves in the axis ML, is evaluated AT axis error using the same process for calculating the tracking capability.

Figure 12 shows a screenshot during the execution of the application for Mediolateral (ML) Rhythmic Test. On the right, the screen shows the moving target.

Figure 13 shows a screenshot during the execution



Remaining time (s) 8

| Tracking Status | Quality Monitoring | Weight (Kg) | Pressure Center X (cm) | Pressure Center Y (cm) |
|---|---|---|---|---|
| Tracking | Good Quality | 61,76 | -1,01 | 5,13 |

Figure 13: Screenshot for AT Rhythmic Test execution. On the right, the COP on the Wii Fit is depicted. On the left, it is shown the subject with his stickman representation (blue lines).

of the application, more specifically, a anteroposterior (AP) Rhythmic Test.

### 3.4 Neuroprosthetic Controller

The Nueroprosthetic controller is responsible for the generation of muscle activation patters and for control of the actuation system: the TEREFES electrostimulator. It receives from the Posturography controller all the kinematic data of the subject (acquired with the kinect) and the coordinates of the center of pressure (COP). A driver will decode or convert the information to muscle activation patterns and specific TEREFES commands accoding to previously programmed synergies sets, theory and rehabilitation parameters. Full detail of the proposed synergistic controller can be found in (Denis et al., 2012)

The functional stimulator TEREFES must act synchronously according with the exerted movements. This imposes the real-time nature that must fulfill the Neuroprosthetic Controller. To achieve this and ease the development of novel controllers a real time Matlab kernel is used. Thus, the delay caused by the Posturography Controller can be determines before generating actuation command. Further analysis of the performance of system timing should be realized in next stages.

### 3.5 TEREFES

The TEREFES was proposed within the framework of the TERERE and Hyper projects (Brunetti et al., 2011). The TEREFES electrostimulator provides up to 32 stimulation channels driven by controllable and stable and close loop current sources. In addition, the system is portable and flexible. This functional stimulator is powered by 4 AA batteries and includes a USB communication interface that allows its configuration via external software. Monophasic and biphasic stimulation signal can be obtained in its 32 available channels. This channels are divided in two independent groups of 16 channels each, that can be stimulates simoultaneously.

## 4 PRELIMINARY RESULTS

In this section preliminary results of posturography software are presented. Described results were obtained with 6 healthy people, 4 men and 2 women. The purpose of this functional validation is to technically verify the platform and to compare result between different subjects. Unfortunately, at this stage of the work, the system could not be tested with previously diagnosed pathological subjects, and the results could not be compared with those obtained with other commercial platforms like Neurocom.

The procedures for the tests were explained in previous sections. REO and REC tests were conducted, as well as Stability Limit and Rhythmic tests. All of them were realized a couple of times in order to make sure that the subjects understand the test but without producing fatigue or previous learning/training (García, 2012). The sampling frequency was 30 frames/second, enough to detect any COP variation (Enbom et al., 1988).

### 4.1 Romberg's Test

Each Romberg's test lasted 30 seconds. The results of the 6 subjects are shown in Table 1.

Table 1: REO and REC Test results.

| **Subject** | Sex | Years | Disp. angle (°) | | S. Area ($cm^2$) | | A.Speed (cm/s) | | Disp. ML (cm) | | Displ. AT(cm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | REO | REC | REO | REC | REO | REC | REO | REC | REO | REC |
| 1 | M | 23 | 108,22 | 114,45 | 18,28 | 17,21 | 1,94 | 2,28 | 2,42 | 3,16 | 1,82 | 3,00 |
| 2 | M | 26 | 90,77 | 91,45 | 2,71 | 6,06 | 1,25 | 1,65 | 0,817 | 1,552 | 1,01 | 1,22 |
| 3 | M | 34 | 95,89 | 113,77 | 12,91 | 12,52 | 1,69 | 2,15 | 2,46 | 2,71 | 2,01 | 2,31 |
| 4 | M | 47 | 76,55 | 75,71 | 9,05 | 4,88 | 1,23 | 1,34 | 1,81 | 1,55 | 1,85 | 1,21 |
| | **Average** | | 92,86 | 98,84 | 10,74 | 10,17 | 1,53 | 1,86 | 1,88 | 2,23 | 1,67 | 1,94 |
| 5 | F | 19 | 122,49 | 112,1 | 4,94 | 5,85 | 1,53 | 1,95 | 2,06 | 2,05 | 1,06 | 2,45 |
| 6 | F | 18 | 106,79 | 103,85 | 8,99 | 7,45 | 1,34 | 1,65 | 2,15 | 2,03 | 1,13 | 2,32 |
| | **Average** | | 114,64 | 107,96 | 6,97 | 6,65 | 1,44 | 1,80 | 2,11 | 2,04 | 1,095 | 2,385 |

All proposed parameters were calculated and they are presented in Table 1. Results suggest a decrease of fine postural control in most subjects when they close their eyes. For both men and women, the displacement angle is usually in the second quadrant, and no significant differences are found among REO and REC tests. In fact, according to (García, 2012) this parameter does not change significantly under these test conditions.

Figure 14 shows the results of subject 4. Using similar data, proposed parameters were calculated for each subject.

Regarding the swept area, calculated by many professionals in the field according to the literature (Black et al., 1989), it does not reflect noticeable

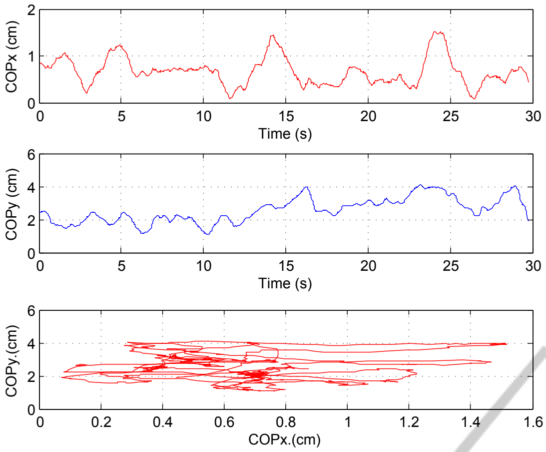


Figure 14: Subject 4 (S4) REC Romberg's test plotted using Matlab. Parameters for S4 are calculated with these data.

changes with the changing sensory conditions. Balaguer, in his work, (García, 2012), has suggested that the calculation by fitting a geometric figure may not be adequate to quantify this parameter.

Finally, the average speed of displacement, is found to increase without visual feedback. This same behavior is observed in the mediolateral and anteroposterior displacement. Therefore, these parameters are used to differentiate visual system impact and potential dysfunction in balance control. Both men and women present larger variations in the mediolateral direction, being even larger in men in these particular tests.

## 4.2 Stability Limit Test

The stability limit test lasted 10 seconds for each direction, and each target was located at a distance of 10 cm from the origin. The subject was asked to make his/her best effort to reach the targets.

Table 2: Stability Limit rest results. The average values are shown. Similar data can be used to obtain normality patterns.

| Sex / Direction | Average Max. LE (cm) | | Average Stability Zone (cm) | |
|---|---|---|---|---|
| | Male | Female | Male | Female |
| Front | 7,51 | 9,04 | 5,77 | 8,32 |
| Front-right | 9,68 | 9,695 | 8,05 | 8,73 |
| Right | 10,59 | 9,165 | 9,28 | 7,70 |
| Rear-right | 9,44 | 8,58 | 8,92 | 7,33 |
| Rear | 10,06 | 8,00 | 8,68 | 6,915 |
| Rear-left | 9,88 | 9,33 | 8,32 | 8,64 |
| Left | 11,01 | 10,05 | 9,00 | 8,35 |
| Front-Left | 9,335 | 9,97 | 8,2675 | 8,55 |

Figure 15 shows the results of subject 1. Using similar data, proposed parameters were calculated for each subject.

According to these tests, areas of stability in both men and women vary with direction. In general terms, there are no significant differences. These results agree with (Cortés, 2007). However, a larger population is needed to obtain robust conclusions. Balaguer found that the subject own subjective perception (Previous Q&A about disability condition of the subject) of his/her skill or disabilities does not influence the stability limits, (García, 2012).

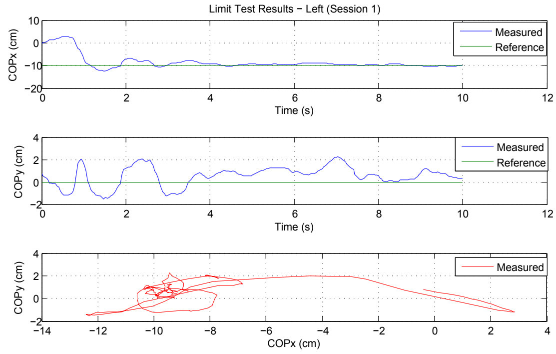


Figure 15: Subject 1 (S1) Limit Test Results plotted using Matlab. Parameters for S1 are calculated with these data.

## 4.3 Rhythmic and Directional Control Test

For the rhythmic tests, windows of 10 cm (configurable) long were defined directionally. First in the mediolateral direction and then in the anterior-posterior one. The subject was asked to follow a moving target traveling at a frequency of 0.25 Hz. Each test lasted 20 seconds. The results are shown in Table 3 for each patient.

Table 3: Test results rhythmic control.

| **Subject** | Sex | Years | Reaction time(s) | | Tracking capability(%) | | Directional control (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | ML | AT | ML | AT | ML | AT |
| 1 | M | 23 | 0,037 | 0,50 | 81,86 | 85,7 | 81,7 | 99,9 |
| 2 | M | 26 | 0,119 | 0,039 | 80,55 | 70,44 | 90,17 | 99,05 |
| 3 | M | 34 | 0,12 | 1,059 | 87,7 | 63,8 | 78,22 | 99,83 |
| 4 | M | 47 | 0,198 | 1,046 | 79,6 | 57,8 | 77,51 | 99,92 |
| | **Average** | | 0,1185 | 0,66025 | 82,43 | 69,43 | 81,9 | 99,675 |
| 5 | F | 19 | 0,40 | 0,035 | 66,5 | 70,23 | 79,7 | 98,5 |
| 6 | F | 18 | 0,42 | 0,21 | 71,5 | 55,26 | 88,53 | 96,94 |
| | **Average** | | 0,4125 | 0,1225 | 69 | 62,74 | 84,11 | 97,72 |

Figure 16 shows the results of the subject 5. Similar results were used to calculate all parameters for each subject.

According to these results, the reaction time increases with age. In addition, there is a shorter reaction time in women. In men, the reaction time is better in the ML direction with respect to the AT. Although this work has not made a study of subjects with specific pathologies, (García, 2012) found that vestibular disorders can affect rhythmic and directional control in disagreement with the findings of Cortés, (Cortés, 2007).

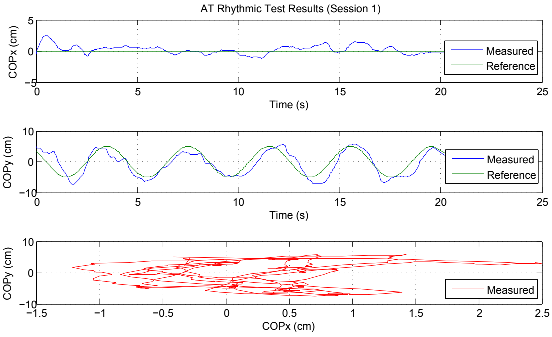


Figure 16: Subject 5 (S5) Rhythmic test Results in the AT direction plotted using Matlab. Parameters for S5 are calculated with these data.

## 5 DISCUSSIONS

Posturography helps to assess the influence of any vestibular dysfunction in postural and balance control. However, a pathology that affect the balance in one patient, in other word the vestibular-spinal reflex, not necessarily will do it in another one. In this case, tools like the one described in this work are not effective for the diagnosis of the impairment.

Regarding the tool presented in this paper, it i not very clear in the literature the way how different assessment parameters are calculated. This lack of information make more difficult to compare results. However, overall conclusions and trends obtained with this tool are similar to those reported in the literature and obtained with other platforms.

Nowadays, there is still a discrepancy between scientist regarding the results of each parameter and associated information. According to (García, 2012), this discrepancy exits because it is difficult to find clear relationships between functional assessment of balance and patient-perceived disability. Tests may be influenced by many factors like social, professional, technical, psychological, affective, and cognitive ones.

The current drawback of classical static posturography is limited only to study the subject during standing position, so it does not provide information on the dynamic aspects of postural control. To solve this shortcoming, we have followed the line proposed by (García, 2012) and set dynamic tests, such as the rhythmic test.

## 6 CONCLUSIONS AND FUTURE WORK

Postural rehabilitation boosts patient confidence and contribute to their self-improvement. In addition, knowledge of the particular deficit in postural control helps clinician and patient to develop prevention plans to avoid falls, and as mentioned before, it is the first step towards the rehabilitation of more complex processes like gait.

Current research projects in neuromotor rehabilitation like Hyper, are devoted to develop novel bioinspired rehabilitation treatments. The use of hybrid solutions including neurorobotics and neuroprosthetics devices has been shown as an efficient approach. However, the use and development of modern rehabilitation therapies based on novel knowledge need the support of non existing research tools.

We have seen how to make a low cost posturography system. It is based on a Wii Fit Balance Board, the Microsoft Kinect and the TEREFES electrostimulator. This tool can serve as a low cost balance control assessment tool and will allow the implementation of novel therapies that could improve current ones for the rehabilitation of balance control.

Future work includes the evaluation of the tool and developed system in clinical environments. After this validation, the final integration of the neuroprosthetic controller and the implementation of therapies based on muscle synergies will be done.

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