A proposal for elderly frailty detection by using accelerometer-enabled smartphones

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Abstract—**Elderly people become weak until reaching a frailty state. At this time, health begins to get worse and is easier to suffer bone fractures. Therefore, delay or reduce the frailty state is important to improve the quality of life of elderly. One of the most important factors for the early frailty detection is the assessment of physical condition by studying gait and other physical activities. In this sense, geriatricians and physiotherapists are using several tests and scales based on indicators for diagnosis. However, the assessment of frailty remains dependent of a subjective viewpoint of the geriatrician.**

In this paper we propose a system for supporting to physicians by using an accelerometer-enabled mobile phone for determining an accurate elderly frailty level. Through the movement, study from physical activity by the accelerometer and a set of clinical indicators, our system provides a frailty assessment for supporting decision-making and the subsequent treatment.

Keywords — **frailty; elderly; health; mobile; accelerometer**

I. INTRODUCTION

Resistance and physiological reserves decrease in older people, leading to a cumulative wear resulting in an increased risk to suffer adverse health effects. This leads to frailty in the elderly.

Frailty is a difficult term to conceptualize, and in most cases is related to aging, disability and comorbidity. Most common clinical manifestations include the following:

- Involuntary reduction of body weight
- Decreased endurance and muscle strength
- Balance and gait disorders
- Decline in physical mobility

Also, it is important to consider a set of biological markers [1].

Furthermore, frailty concept is being developed in the last two decades. For its detection, it is classically appreciated the performance of activities of daily living (ADL) and instrumental activities of daily living (IADL). Some examples of these are shown in the table 1. An adult person may have the first symptoms of pre-frailty after 65 years old. However, all of them are not a homogeneous population and there are people who reach advanced ages of your life with good health. For that, the clinical syndrome of frailty is determined by different symptoms and signs, resulting in the phenotype of frailty proposed by Fried [2]. This author sets out five criteria to decide whether a person is frail or not. For this, if at least three of these criteria appear, the person is considered frail.

According to this phenotype, there are many tests and scales designed to assess several aspects of elderly frailty. For instance, *Barthel Index* [3] is used to measure dependence level on the performance of ADL and IADL. Most of these scales are related to the physical state. In fact, the study of physical activity in elderly people is very important because it offers plenty of information about that person. Specifically, gait analysis is a clear indicator to determine frailty. In this sense, authors such as Tinetti [4], propose a test to assess gait and balance. However, the result of this and other scales is quite subjective, and the score obtained, which determines the elderly physical condition, depends on geriatrician viewpoint. To avoid this, we propose a system based on gait and balance analysis, through the use of mobile phone accelerometer enabled, combined with clinical parameters, to support the decision and diagnosis of the geriatrician, in a more accurate and less subjective way.

This paper is organized into eight sections. Section 2 presents related work about accelerometer integration for elderly movement analysis. In Section 3, we detail our motivation for doing this work. Then, in Section 4 we present two standard tests to assess gait and balance. Section 5 describes the process of data acquisition, analysis and instantiation. In Section 6 we present the method used to compare instances. Section 7 presents the architecture for frailty detection and evaluation. Finally, Section 8 analyzes the conclusions and future work.

II. RELATED WORK

Nowadays, the advent of new embedded technologies and the need for its use in healthcare encourage the development of mobile systems to perform different tasks in these heterogeneous environments. In fact, there is a wide range of systems which use sensors and mobile phones to support the daily tasks of physicians. For example, diagnosis and monitoring of elderly patients in healthcare by using mobile devices is being developed in recent years. Within this context, Villarreal [5] proposes a mobile monitoring system based on mobile devices for patient diabetes monitoring.

Meanwhile, Fontecha [6] has developed a mobile system using NFC[1] technology to deploy nursing care services in healthcare environments. Apart from these, there are many researches in this area. However, in this section, we are focusing our efforts on current systems to analyze elderly people movement and physical activity by using accelerometer mechanisms. Finally, a general comparison with our system will be presented.

Table 1. Examples of ADL and IADL

ADL	Hygiene (bathing, grooming, shaving and oral care)
	Continence
	Dressing
	Eating (the ability to feed oneself)
	Toileting (the ability to use a restroom)
	Transferring (actions such as going from a seated to standing position and getting in and out of bed)
IADL	Finding and using resources (looking up phone numbers, using a phone, …)
	Preparing meals (opening containers, using kitchen equipment)
	Shopping (getting to stores and buying like food or clothing)
	Doing housework
	Managing medication oneself

The integration of accelerometer sensors for movement recognition opens a new research field. In this sense, Hong [7] presents a method for activity recognition of daily life through accelerometers, Radio Frequency Identification (RFID) tagging objects and RFID sensors. While, in [8] Raso proposes a self-guided system for physical rehabilitation of patients using an iPhone device and a software application for activity monitoring by the physician. In terms of studies focused on elderly people, Lester [9], has developed a system for recognition of 8 different physical activities, evaluated in 12 elderly satisfactorily. This system is based on independent accelerometers, but the development of integrated system in a mobile phone is considered. In [10] is proposed the use of smart-phones to monitor physical activity levels and gait of the elders in their homes or at retirement homes.

On the other hand, fall detection in elderly through accelerometer sensors, is a widely used mechanism to prevent future bony fractures and other injuries. In this case, Zhang [11] proposes a mobile system for detection of falls by using tri-axial accelerometer embedded into a mobile phone. Accelerometer data is sent to a server through the internet. Then, several algorithms process the data and classify the movement. Similarly, *VitaliSHOE* project [12] uses multiple accelerometers to detect the risk of falls in older people with signs of frailty. In this case, sensors are inside the shoes and they obtain accelerometer data which are sent to a base station by wireless communication. At the same time, there is a software analyzing that movement.

[1] *Near Field Communication*

Gait analysis can provide relevant information about people diseases. At this point, it is important to mention the following systems: *Vitaport Activity Monitor* (VAM) and *GAITRite*, both analyzed by Lord [13]. These systems use accelerometers to study gait in people with Parkinson's disease.

Activity recognition for rehabilitation or injury prevention is the main goal of mobile systems based on accelerometers. However, the previous systems don't take into account clinical parameters such as patient record even though of being used in medical environments. We believe the study of patient record is essential in most cases, and for that reason in our system it is included. On the other hand, in these studies, accelerometer mechanisms are used only to gather movement data, with a simple signal preprocessing, and transmitting these ones to external systems for its analysis. Although some devices have a high processing capacity, it is not used. We consider the next-gen mobile phone as a crux of our work. In this case, unlike other systems, the smart-phone must be responsible for getting and processing movement data, analyzing the patient record and showing results in his screen, being on the side of the mobility in healthcare environments.

III. MOTIVATION

We propose a system for assisting to physician in frailty detection, reducing and removing the subjectivity level of current clinical tests and scales. Only objective evaluation methods may ensure homogeneous rating criteria [14]. Also, with our proposal, we can prevent falls, injuries and predict future pathologies, among others.

Furthermore, we believe that the integration of accelerometer-enabled mobile devices in healthcare environments to support geriatricians in frailty detection tasks is an essential instrument with several advantages. Some of these are:

- **Embedded sensors**. Next-Gen mobile phones integrate many sensors inside. In our case, as we know, tri-axial accelerometer is necessary for obtaining movement data of elderly people. Nowadays, accelerometer sensors of universal devices such as smart-phones have the same accuracy features as specific purpose accelerometers.
- **Processing capacity**. Algorithms for data analysis need a high processing capacity that exists in smartphones. Thus, no external hardware is required for that.
- **Communication mechanisms**. Mobile phones can transfer data to other computing devices through Wireless networks and Bluetooth technology.
- **Touch interaction**. Smartphone screen allows interact with the phone by natural way, although interaction with devices in health environments should be minimal.

However, there are some drawbacks of using a mobile phone against a special purpose device. In the table 2, a comparison of relevant features for us between universal and special purpose devices is shown. A small true tick indicates which one offers the best option for each feature.

Table 2. Comparison of relevant features for accelerometer-enabled devices

Features	**Devices**	
	Universal Device: Mobile phone	**Special Purpose Device**
Accelerometer	✓	✓
Processing	✓	
Storage	✓	
Communication	✓	✓
Communication range	✓	
Display	✓	
Battery		✓
Device cost		✓
System cost	✓	
Size		✓
Development platform	✓	
Ease of placement		✓
Versatility	✓	

Finally, the use of a single accelerometer-enabled smartphone is the most practical and useful option to collect movement data from the selected activities (see Section IV). Thus, a greater number of accelerometer sensors is not necessary for our purpose.

IV. ASSESSMENT OF GAIT AND BALANCE

According to the studies in this area, the analysis of gait and balance is one of the most important factors to determine elderly state. From a preliminary observation, physician makes a first diagnosis. Actually, geriatricians and doctors use the tests described in this section to assess physical condition of elderly people.

We propose that the elderly person carry an accelerometer-enabled mobile phone attached to the waist while performing these tests.

A. Tinetti Scale

The Tinetti test [4] is a widespread test to assess of the posture control and the motor abilities of elderly people. Although it was proposed for its application in geriatrics, it can be used also in other situations where a similar evaluation is required. This test is divided into two parts as follows:

- In the first part, person walks for a few meters, and thus the geriatrician can apply the Tinetti scale evaluating gait parameters such as symmetry, flow, path or speed.
- In the second part, a chair without armrest is used to perform several maneuvers by the patient. Also, stability is measured with different exercises. From this, an assessment of balance is determined.

B. "Get-Up and Go" Test

Initially, this test [15] is done to assess the risk of falls. From a sitting position, elderly must stand up and walk several paces, turn, and return to the chair. Meanwhile, geriatrician observes the exercise and provides a rating based on parameters such as turning and supports used to sit down and stand up, among others. This test only evaluates the balance. Moreover, its application is simpler than the second part of the Tinetti test, so it is most often used by physicians.

V. DATA ACQUISITION AND ANALYSIS

In this section we are going to detail the data acquisition procedure. Firstly, we have developed an android software application to collect data from accelerometer embedded. This mobile application allows us to select the physical activity to be performed by the elderly. Also, we can check if that person needs help to do the exercise. In Fig. 1 a screen capture of this application is shown.

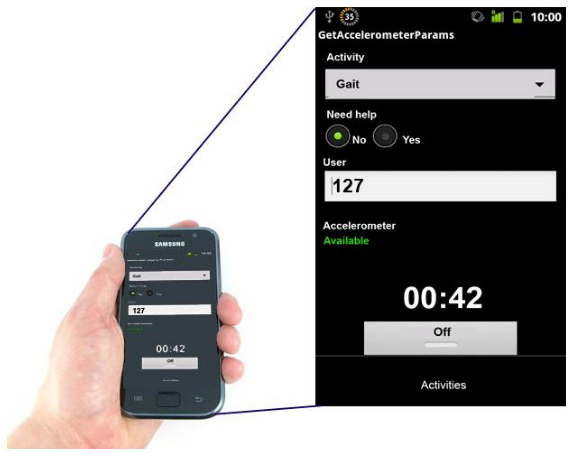

Figure 1. Android mobile application

A. Field Research

A field research to obtain movement data from the older people with the previous application was necessary. This study took place in a Retirement Home from Ciudad Real, Spain. Geriatrician conducted an assessment of gait and balance applying *Tinetti* and *Get-Up and Go* tests while elderly had attached the mobile phone to the waist as shown in Fig. 2. This process was repeated three times to ensure the integrity of collected data by the mobile phone.

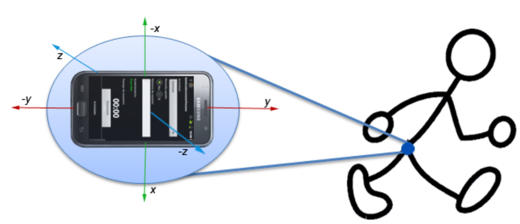

Figure 2. Device position in the elderly

1) Patient selection

In collaboration with geriatricians, it was important to select the most suitable group of elderly people for our study. For that, we had in mind the following principles:

- Elderly people who don't have permanent or serious signs of frailty, with an average age between 75 and 90 years old.
- It has been considered the same number of women than men.
- They preserve social abilities.
- They are independent in their everyday activities (ADL and IADL).
- And they don't present cognitive impairment.

The aim of this selection is to make up a set of analysis instances with which the system will work (see point D).

B. Pattern analysis

When elderly perform a physical activity, the mobile phone stores in a text file the movement data obtained by the tri-axial accelerometer, this includes the value of *X*, *Y* and *Z* coordinates and time, with a sampling frequency of 20Hz. Therefore, each text file contains a movement pattern of an elder for a specific exercise (e.g. Gait or *Get-Up and Go*).

Once the activity ends, a detailed study of data stored in each file is needed.

1) Segmentation and filtering

First of all, we must perform signal segmentation. In this stage, values related to the beginning and end of movement are deleted. Thus, it is necessary to establish a segmentation criterion. It depends on the type of activity, as well as external factors. In our case, has been considered the movement study in time domain on defined and bounded activities.

In this sense, we have developed an algorithm based on the *effective sample time* (T_{EM}) to delete invalid values related to the beginning and the end of each physical activity performed. Effective sample time is a valid time range where the accelerometer has obtained sufficient valid data of a particular movement, generating a valid sample. We have established an estimated effective sample time of 12 seconds based on results of field study and several tests, including the minimum recommended distance of Tinetti test. For obtaining data contained in this time, we have considered the following assumptions:

- Elimination of accelerometer values during the first and the last seconds (T_{seg}). In gait activity T_{seg} = 8 secs estimated. This time corresponds to placement and removal of the device from elderly waist.
- Elimination of accelerometer values related to the turn that elderly perform when they reach the end of the distance (T_{int}). In gait exercise T_{int}= 2 secs estimated.
- Elderly need a certain time to do the exercise (T_{Min}). To reach, at least, the effective sample time and taking into account the above, in the case of gait, this time must always be greater than 30 secs.

In Fig. 3 is presented the pseudo-code of our segmentation algorithm for extracting a valid gait sample from the accelerometer data stored in the file.

```
Define T_EM ←12, T_int ←2, T_segInferior ←8
Define T_segSuperior ←(T_Min - 8)
IF T_segSuperior – T_segInferior – T_int ≥ T_EM then
   Get all values of (X, Y, Z, Time) that satisfy Time > T_segInferior
   and Time < (T_segInferior + T_EM)
   FOR all (x, y, z) indices do
      X vector resizing
      Y vector resizing
      Z vector resizing
      Time vector resizing
   ENDFOR
   T_Min = max(Time) – T_segInferior  // T_Min = T_EM
ELSE
   "Invalid sample –> T_EM have not been reached"
ENDIF
```

Figure 3. Pseudo-code of gait segmentation algorithm

For *Get-Up and Go* activity, segmentation method is similar, but in this case, T_{int} doesn't exist and, T_{Min} and T_{EM} are lower than in gait.

Next step is signal filtering. It is necessary to remove the noise on accelerometer data and signal smoothing. For that, we have applied a low-pass filter because it is effective and simple. This filter is characterized by the base case defined in equation 1 and the general case of equation 2. In these equations, *f* is defined as the result function, *x* is the initial function and α is a filter factor with a value of 0,1.

$$f(0) = x(0) \tag{1}$$

$$f(i) = \alpha * x(i) + (1 - \alpha) * f(i-1), \quad 1 \le i \le n \tag{2}$$

2) Dispersion measures

After segmentation and signal filtering, we have calculated a set of dispersion measures from the values given by the accelerometer for every activity. In view of the fact that we work in the time domain is not required a high processing capacity unlike the study of characteristics in frequency domain, facilitating the run of the system in a mobile device.

The most significant features and whose calculation requires few computing resources are presented in the table 3 with the corresponding equation. All measures are calculated for the three coordinate axes.

Also, these measures can be used for data classification and data mining, in order to improve the accuracy of our frailty detection system in the future.

C. Clinical factors

For diagnosis and frailty detection is not enough the study of physical condition from the tests performed. Also, it is necessary to study different clinical factors which involve risk factors for frailty [16].

Table 3. Dispersion measures

Measure	Equation	Description
Arithmetic mean	$\text{mean}(x) = \frac{\sum_{i=1}^{n} x_i}{n}$	Arithmetic mean of acceleration values
Standard deviation	$desv = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \text{mean}(x))^2}{n}}$	Standard deviation of acceleration values
Maximum amplitude	$\text{max\_amplitude}(x) = \lvert max(x) - min(x) \rvert$	Maximum amplitude of acceleration values
Absolute mean difference	$\text{abs\_mean\_diff}(x) = \frac{\sum_{i=1}^{n} \lvert x_i - \text{mean}(x) \rvert}{n}$	Mean of absolute value of each value difference.
Acceleration mean	$\text{accel\_mean} = \frac{\sum_{i=1}^{n} \sqrt{x_i^2 + y_i^2 + z_i^2}}{n}$	Square root mean of sum of squares of axes values
Variance	$\text{variance} = \frac{\sum_{i=1}^{n} (x_i - \text{mean}(x))^2}{n}$	Variance of acceleration values

In this sense, geriatricians establish a set of clinical parameters from the lab report belonging to the patient record. Seven groups have been identified (see Fig. 4).

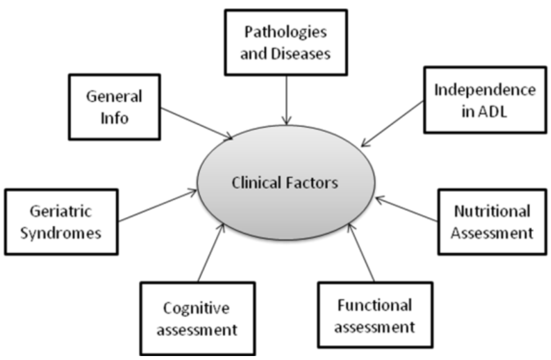

Figure 4. Clinical Factors groups

Most of these groups consist of a set of relevant indicators to determine the state of frailty. These ones must be quantified and discretized before being used by our system. So far, these variables have been taken into account by geriatricians to make a decision or diagnosis. All these indicators are detailed in table 4.

We propose the analysis of physical activity in combination with these indicators to support geriatrician decision. All variables from the physical and clinical study are known as **influential variables**.

D. *Instantiation*

An instance is a set of influential variables associated with a patient and a specific exercise (in our case: Gait and *Get-Up and Go*), at a given moment. Mobile phone stores all instances in a stack of instances. When a new elder is studied, a new instance is created, and this is compared with other instances of stack to determine frailty state. We call instantiation to the creation of instances.

Arrival of new instances increases the stack and this improves the accuracy of the detection system. Generally, Fig. 5 shows how a new instance becomes part of the stack. Otherwise, in Fig. 6, the structure of an instance is shown in detail. Each instance is characterized by user id, instance id, physical activity (gait or *Get-Up and Go*), date-time value and influential variables. These variables are divided into accelerometer data and clinical factors as mentioned above.

In this manner, the mobile system provides a frailty assessment to support geriatrician decision, based on comparison and classification methods of these instances in relation to the new instance. The system can establish similarities and differences between instances, which can be useful for prediction of future pathologies, among others.

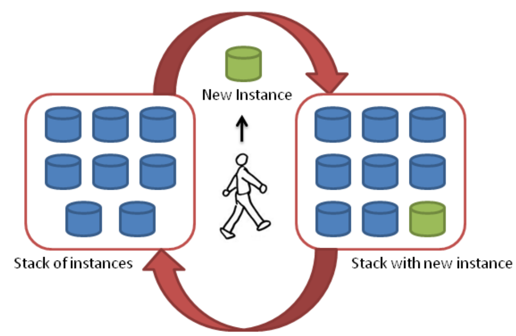

Figure 5. Integration of a patient instance at the instances stack

Table 4. Relevant Clinical Factors

Risk indicators related to frailty in old age					
General Info	**Functional Assessment**	**Nutritional Assessment**	**Cognitive Assessment**	**Geriatric Syndromes**	**Independence in ADL**
Gender	Tinetti gait score	Total protein	Mini Mental Status	Dementia	Independent
Age	Tinetti balance score	Serum albumin	CRP	Depression	Mild dependence
Size	Barthel index	Cholesterol level		Incontinence	Moderate dependence
Weight	Lawton score	Triglycerides		Immobility	Great dependence
Body mass index	Get-Up and Go	Blood iron		Recurrent falls	Serious dependence
Drug number	Need help	Ferritin		Polypharmacy	
		Vitamin B12		Comorbidity	
		Serum folic acid		Sensory deprivation	
		Serum transferrin		Pressure ulcer	
		Leukocytes		Malnutrition	
		Lymphocytes		Terminally illness	
		Hemoglobin			

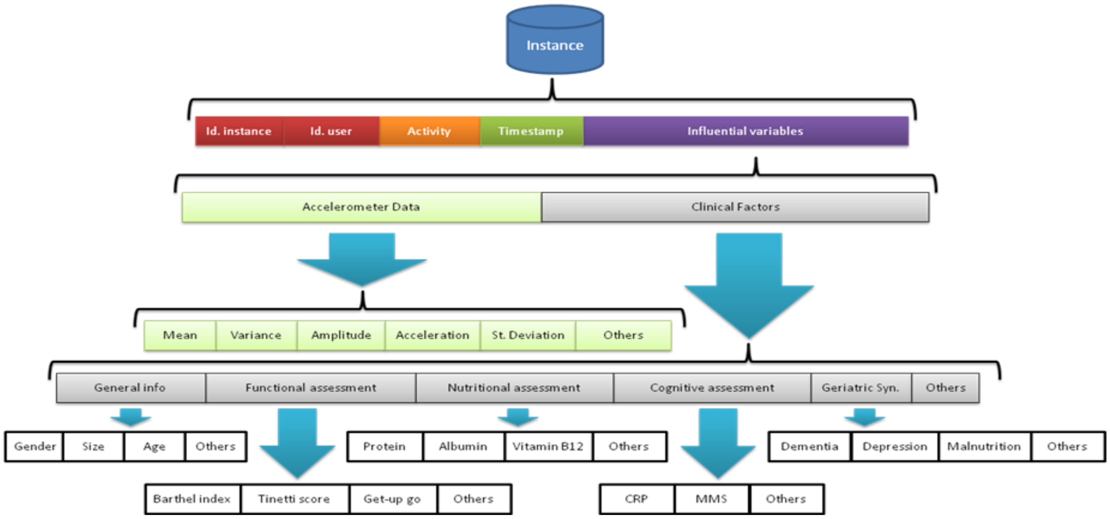

Figure 6. Influential variables of an instance

VI. Instances Comparison Method

At first, we have chosen a specific method to compare instances of the instances stack with new ones. This procedure is based on **affinity degrees**. Apart from the influential variables, each instance may have an affinity degree in connection with one or more instances, in such a way that our mobile system, knowing the state of these instances, also knows the state of the instance to compare.

The affinity degree is calculated depending on the importance given to the influential variables by the physician. Thus, user selects the most important influential variables to consider for an elderly patient at the moment, and these are compared with the same variables of the others instances searching for equality or similarity coincidences.

A. Equality and Similarity Coincidences

Some influential variables are compared by equality, meanwhile others are compared by similarity.

- In the first case, the system decides if the influential variables to be compared have the same measurable value or not. For example, the Tinetti gait score.
- In the second case, influential variables are compared based on a range of similarity. Maximum and minimum values of this range are defined either by the physician or by the system (if it has enough information). Thus, it is observed if the value of compared influential variable is in range or not. For example, to study variances of acceleration values.

Then, the system implements an affinity tree based on the previous comparison results.

B. Result Affinity Tree

We propose the creation of a tree formed from the most relevant instances according to the affinity degrees (see Fig. 7).

The root node of the tree represents the current instance or the instance to compare. The rest of the instances are obtained through the comparison method.

On the other hand, two affinity degrees are adequate and these have been established to make run the mobile application faster and easier to interpret. The first one (1) determines a high affinity level, and the second one (2) a medium level.

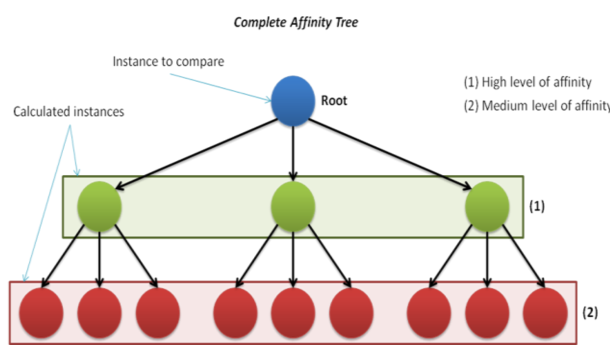

Figure 7. Result Affinity Tree with the maximum number of children

For the root node and all nodes of the first affinity degree, a maximum of three children instances are taken into account. While, the second affinity degree has a maximum of 9 instances (3 from each parent node).

Finally, mobile system uses all of these instances to create an aim set of indications and recommendations related to the patient, which are used by the physician to make a more effective diagnosis of frailty.

VII. FLOW OF FRAILTY DETECTION ARCHITECTURE

In this section, we detail the frailty detection architecture of our system and a first evaluation carried out on the group of selected patients (see Section IV-A).

A. *Flow of Frailty Detection Architecture*

Firstly, we present the flow of our frailty detection architecture as a summary of the work presented in this paper. The flow is divided into the following, and it is shown in Fig. 8:

- First, geriatrician places the mobile device attached to the elderly waist before the physical activity is performed. The patient wears the device throughout the test (1).
- When exercise ends, data of movement are stored in the mobile phone and all necessary statistical information is calculated (2).
- After that, several clinical features are obtained from elderly patient record, which can be found in the mobile phone or in a centralized system that is accessed through the network (3).
- Thus, the combination or matching of these clinical factors with statistical characteristics of movement makes up instances (4).
- The next step is the comparison between instances based on equality and similarity coincidences. With this, a result affinity tree is created (5).
- Data from that affinity tree provides essential information for frailty assessment, which is shown to physician through information tips and charts (6).

B. *Evaluation*

We have preformed a first approach to evaluate our mobile system. For this, 20 elderly people have been selected at the retirement home. They satisfy the selection criteria listed in section V-A. Once we have collected movement and clinical data, these were processed by the system. After processing, several results were obtained.

Mobile phone detected motion asymmetry in elderly patients with bone fractures. Also, the need for technical assistance in the exercise affects the rhythm, flow and gait trend. Through an average valuation of the results, we conclude the following:

- Men have a less advanced level of frailty than women.
- The women studied have a higher rate of cardiovascular diseases.
- The score of Tinetti test and Barthel index is more satisfactory in men than in women (see Fig 9).

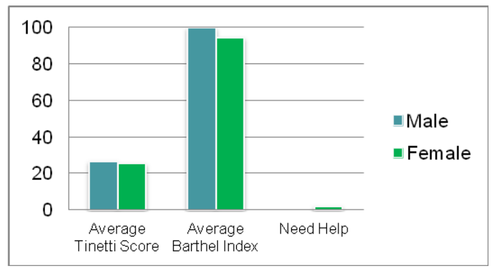

Figure 9. Tinetti and Barthel scores

- On the other hand, it has been detected several common geriatric syndromes such as polypharmacy and comorbidity in men, and polypharmacy, comorbidity and depression in women.

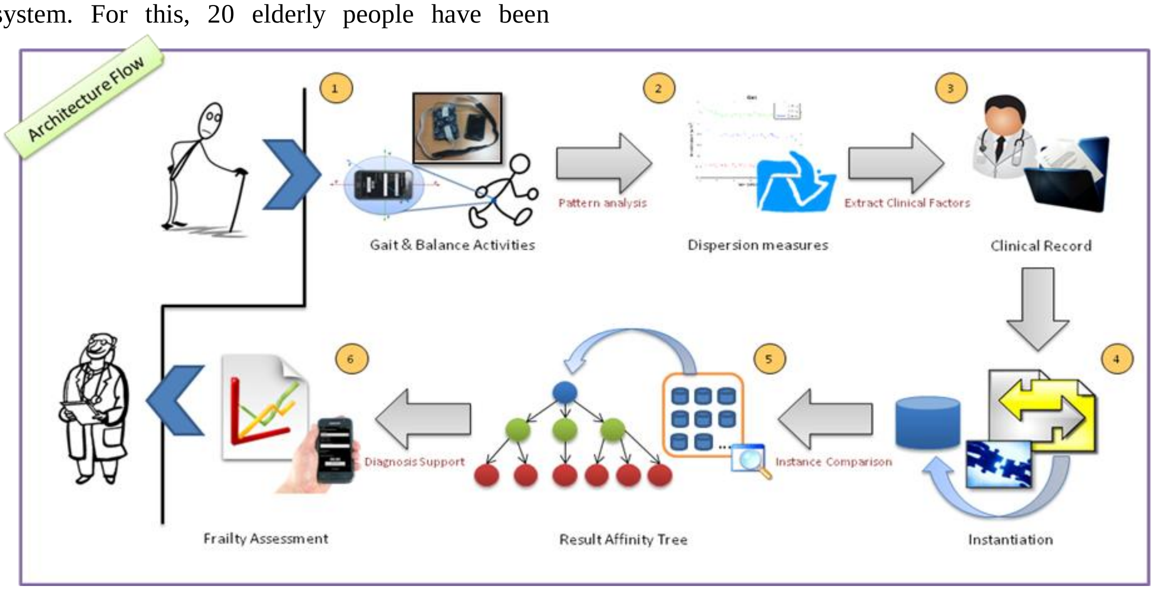

Figure 8. Flow of Frailty Detection Architecture

VIII. Conclusions and Future Work

This work presents the advances of a mobile system for healthcare environments to support physicians in frailty detection and diagnosis in a more accurate way. Through an accelerometer-enabled smartphone, we obtain elderly movement data related to two basic tests of gait and balance. Then, the calculated measures from its analysis can be combined with specific clinical factors to create instances. Each instance consists of a set of influential variables, and all instances are stored in a mobile instance stack. From the study of instances, the system establishes different affinity degrees to create an affinity tree with a subset of them. So, we can determine elderly frailty state. The ongoing work is to define a model for physical daily activity monitoring of elderly in daily living [17], by using a mobile phone in order to reduce the frailty. Also, we are considering a platform to recommend healthy habits for elderly people and physicians based on frailty detection and monitoring results.

In future work, we propose the development of a complete architecture for frailty treatment, supervised and unsupervised by geriatricians, based on modules for elderly frailty detection, monitoring and prediction of pathologies.

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