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FrailSafe: An ICT platform for unobtrusive sensing of multi-domain frailty for personalized interventions

Evangelia I. Zacharaki, Konstantinos Deltouzos, Spyridon Kalogiannis, Ilias Kalamaras, Luca Bianconi, Cristiana Degano, Roberto Orselli, Javier Montesa, Konstantinos Moustakas, Konstantinos Votis, Dimitrios Tzovaras, Vasileios Megalooikonomou

***Abstract*—The implications of frailty in older adults' health status and autonomy necessitates the understanding and effective management of this widespread condition as a priority for modern societies. Despite its importance, we still stand far from early detection, effective management and prevention of frailty. One of the most important reasons for this is the lack of sensitive instruments able to early identify frailty and pre-frailty conditions. The FrailSafe system provides a novel approach to this complex, medical, social and public health problem. It aspires to identify the most important components of frailty, construct cumulative metrics serving as biomarkers, and apply this knowledge and expertise for self-management and prevention. This paper presents a high-level overview of the FrailSafe system architecture providing details on the monitoring sensors and devices, the software front-ends for the interaction of the users with the system, as well as the back-end part including the data analysis and decision support modules. Data storage, remote processing and security issues are also discussed. The evaluation of the system by older individuals from 3 different countries highlighted the potential of frailty prediction strategies based on information and communication technology (ICT).**

***Index Terms*—health monitoring system, ageing population, frailty, virtual patient model, sensing devices, decision support system.**

I. Introduction

Ageing population is increasing worldwide to reach an estimated two billion people aged over 65 years by 2050, which will obviously affect the planning and delivery of health and social care. A consequence of age related decline is the clinical condition of frailty, that is a medical syndrome with multiple causes and contributors that is characterized by diminished strength, endurance, and reduced physiologic function that increases an individual's vulnerability for developing increased dependency and/or death [1]. Frailty is characterized by multiple pathologies: weight loss, and/or fatigue, weakness, low activity, slow motor performance, and balance and gait abnormalities. There is also a potential cognitive component [2]. It makes elderly more vulnerable to stressors and has major health care implications, such as increased risk of incident falls, delirium, worsening of mobility, disability, hospitalization, institutionalization, and mortality [3], [4], which eventually increase the burden of care and cost to the society. A recent study [5] on a very large cohort from the UK Biobank showed more than two times increase in 7-year mortality that is associated with frailty.

The European Union has placed specific importance on defining frailty, as frail persons are users of high community resources, health services, and nursing homes. It is assumed that early intervention on frail persons will improve quality of life and reduce health services costs. Frailty is a clinical entity, distinct from disability and co-morbidity. Disability is measured by impairment in activities of daily living and co-morbidity is defined by the presence of two or more diseases. However, all three conditions, often referred to as geriatric syndromes, are predictive in varying degrees of adverse health outcomes and therefore have a certain level of overlap, which increases with greater frailty.

The FrailSafe system [6] aims to identify quantitative and qualitative measures of frailty through advanced data mining approaches on multi-parametric data and use them to predict short and long-term outcome and risk of frailty. A key component of the system is the creation of a digital patient model of frailty sensitive to several dynamic parameters, including physiological, behavioural and contextual cues. This multi-domain (physical, cognitive, psychological, social) sensing and intervention platform offers safe, unobtrusive and acceptable monitoring of community living older adults in their domestic (home) environment, aiming to reduce the cost of health care.

II. Frailty Diagnosis

A. Clinical assessment of frailty

A single operational definition of frailty has not been agreed so far, as experts in a recent consensus conference have failed to agree [1]. The lack of standardized definition of

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E.I. Zacharaki, K. Deltouzos, S. Kalogiannis and V. Megalooikonomou are with the Dep. of Computer Engineering and Informatics, University of Patras, Rio, 26504 Greece (e-mail: ezachar@upatras.gr; deltouzos@upatras.gr; kalogianni@ceid.upatras.gr; vasilis@ceid.upatras.gr)

I. Kalamaras, K. Votis, D. Tzovaras are with the Information Technologies Institute, Centre for Research and Technology Hellas, Thessaloniki, 57001 Greece (e-mail: kalamar@iti.gr; kvotis@iti.gr; dimitrios.tzovaras@iti.gr).

K. Moustakas is with the Dep. of Electrical and Computer Engineering, University of Patras, 26504 Greece and with the Information Technologies Institute, Centre for Research and Technology Hellas, Thessaloniki, 57001 Greece (e-mail: moustakas@ece.upatras.gr)

L. Bianconi, C. Degano are with Gruppo SIGLA S.R.L., Genova, 16129 Italy (e-mail: luca.bianconi@grupposigla.it; cristiana.degano@grupposigla.it)

R. Orselli is with SMARTEX S.R.L., Prato, 59100 Italy (e-mail: orselli@smartex.it)

J. Montesa is with Brainstorm Multimedia S.L., Valencia, 46005 Spain (e-mail: jmontesa@brainstorm3d.com)

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frailty causes heterogeneity in studies. Frailty as a syndrome is characterized by a variety of symptoms and signs which are related to physical, cognitive, functional, and social domain. Among these domains, the physical frailty phenotype is more studied and described by weight loss and sarcopenia, weakness with low grip strength, exhaustion or poor endurance, slow motor performance (e.g., slow walking speed, decreased balance) and low physical activity, as a marker of low energy expenditure [7]. The cumulative deficit model provides an alternative operational definition of frailty. It is based on a comprehensive geriatric assessment and takes into account ninety-two baseline parameters of symptoms, signs, abnormal laboratory values, disease states and disabilities, referred as deficits, to define frailty [8]. The derived Frailty Index is a simple calculation of the presence or absence of each variable as a proportion of the deficits taken into consideration, thus frailty is defined as the cumulative effect of individual deficits. However, the Frailty Index does not distinguish frailty from disability or comorbidity; instead, it includes them. Other more recent frailty metrics include the Tilburg Frailty Indicator (TFI) [9], which is based on a multi-dimensional approach by including the physical, social and psychological domain, and excluding disability and diseases, and the Comprehensive Frailty Assessment Instrument (CFAI) [10], which captures - additional to the physical, psychological and social components - also the environmental domain.

Frailty together with functional decline and disability are common conditions in older people, and are increasing with ageing. However, frailty is a dynamic and not an irreversible process; it seems preventable, may be delayed, or reversed. Transition between frailty states, i.e., non-frail, pre-frail, frail, has been documented [11]. It is more likely to progress from the non-frail status to frail than the opposite. The rate of progression varies among elderly and some cases show sudden onset and rapid transition, whilst others slow and progressive changes. Interventions that alter the natural course of frailty may prevent or reduce adverse health outcomes, and thus, may be proved beneficial not only to individuals, but to families, carers, and society. Moreover, frailty is believed to be preceded by behavioural adaptation made in response to declining physiologic reserve [7]. Behavioural changes may precede the transition to pre-frail or frail state and often pass undetected. More importantly, such changes may not be captured by conventional clinical assessments.

A comprehensive overview of existing frailty measurements has identified 27 metrics, but none of them has been recognized as a gold standard [12] and half of them have not ever been used by other investigators. Another more recent study [13] summarizes the main procedures and frailty assessment metrics based on their ability to predict risk of negative outcomes and classifies them to those for screening and those for assessment according to their level of complexity and predictive power. As the measured variables are largely based on questionnaires, the article highlights the importance of introducing ICT tools as means to facilitate the data collection process.

B. Technological tools for frailty diagnosis

With the advancement of technology and the growing cost and complexity of healthcare, screening tools and health monitoring systems collecting and analyzing biomedical data come to substitute or support the standard clinical assessment [14]. The concept of technology-based innovations for the management of frailty is not new. A first overview of the usage of emerging information technologies measuring the different frailty aspects was presented in 2012 [15], while a more recent study [16] presents existent technological solutions and categorizes them as means of frailty diagnosis, prevention, treatment and care. In respect to diagnosis, the first studies incorporating technological tools or devices appear after 2011 [16].

In order to characterize differing health and frailty states, some studies examined measurements obtained with an inertial sensor and portable data recorder fitted to the waist [17] or analyzed signals from a triaxial inertial magnetic sensor during balancing trials [18], while others introduced multimedia interactive games with several measuring devices (grip strength meter, pressure pad, functional reach measuring instrument) [19], or used a hand-grip electronic dynamometer to test the association between handgrip strength and mortality [20]. Video games enabling muscle strength measurement were introduced in [21] to study age-related loss of muscle strength. Different studies later on estimated the grip force using an adopted dynamometer [22], or combined grip force and exhaustion measured by a modified ball during remote assessment with gait velocity and physical activity level evaluated based on a smartphone with accelerometer [23]. Others collected data of daily life from furniture-based measuring devices equipped with wireless sensors [24], mobile tools [25], smart phones with inertial sensors [26] [27] [28], or smartphones with different integrated devices (accelerometer, gyroscope, digital compass, camera, proximity sensors, Global Positioning System (GPS), etc.) [29]. Additionally, several packages have been exploited to assess frailty and functional decline, such as the GAITRite which is a portable pressure sensitive walkway providing easy identification of gait anomalies [30], or the ARPEGE package which consists of a set of measurement devices wirelessly connected to a tablet PC allowing easy manipulation by social caregivers [31].

FrailSafe extends previous approaches by combining sensing and data analysis capabilities in an effort to provide and integral view on human functioning addressing the understudy of multi-domain frailty. It therefore targets cognitive, functional, environmental and social domains in addition to the physical domain of frailty. Overall the aim of FrailSafe is to address challenges, such as the lack of an agreed single operational definition of frailty, lack of a reliable frailty model, the fact that behavioural changes may precede the transition to pre-frail or frail, and the need to develop real life tools for the assessment of physiologic reserve. Such tools can be used to evaluate interventions that might alter the natural course of frailty, since frailty is a dynamic and potentially reversible process.

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III. FrailSafe System Overview

The FrailSafe system monitors unobtrusively the usual activities of older people in their habitual environment, through the usage of smart devices and software tools, aiming at detecting the progression of frailty. The developed system consists of several components, such as various sensors able to record a large amount of data, games, sensor-equipped wearables and other devices, as well as software applications for data collection and processing and smartphone applications. The interconnection of all these entities plays a strategic role in the entire project. The end-users of the platform can belong to different categories: Older people monitored by the FrailSafe platform who benefit from the guidance and the interventions proposed by the system; families and relatives taking care of the older people; researchers who are interested in studying and analysing the collected data; and finally, doctors, who are responsible for the clinical care of the elderly.

Before proceeding with the architectural details of the system (Section IV), a general introduction to its key components is provided for better perception. A high-level overview of the FrailSafe system is provided in Figure 1. The system is organized into three layers, that include the sensing and monitoring devices, the software front-ends and the cloud services. Each layer is described next.

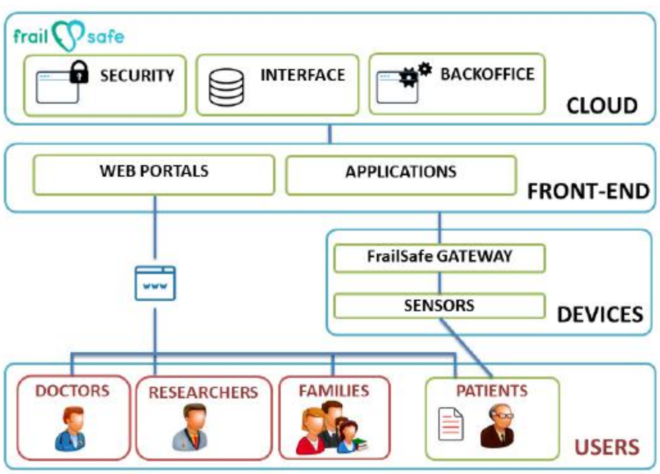

Fig. 1. FrailSafe system overview. The system is organized into three layers including (i) the sensing and monitoring devices, (ii) the software front-ends for data retrieval and providing the user interface to the platform services, and (iii) the cloud services mainly for secure remote storage.

A. *Sensing and monitoring devices*

Two sets of devices can be distinguished with respect to their nature and functional role. One set constitutes the FrailSafe Gateway that allows the interface of users with the FrailSafe platform. The other set includes the variety of sensors used for monitoring the older people, for collecting data and interacting with the FrailSafe Gateway to send data to the upper layers. More specifically, the set of sensors includes:

- A wearable health monitoring system developed by SMARTEX [32] that is based on a wireless body area network (WBAN) for physiological and kinetic assessment. It is composed of a sensorized garment, an electronic device and a software tool, altogether referred to as WWBS (wearable WBAN system). It allows monitoring of adults at home during standard day-time activities, collecting data from their heart (a full electrocardiogram (ECG) lead), respiration, posture and physical activity including inertia measurement units (IMUs) with nine degrees of freedom;
- A digital blood pressure monitor (FORA Active plus P30) designed to be used by the older person autonomously or with the help of the clinical personnel, a digital weight scale (FORA W310), and a pulsewave monitor (Agedio B900) that collects an enriched set of parameters regarding arterial stiffness;
- A dynamometer which is used by the medical personnel during clinical evaluation sessions for measuring the older persons' strength as well as during the autonomous game playing by the elderly;
- A sensor with GPS used for monitoring the outdoor habits and mobility patterns of the subjects, and a network of bluetooth low energy transmitters (Beacons) installed at the subjects' houses for monitoring indoor behavioural patterns.

The data from the various sensors and application are collected and uploaded to a remote cloud system through the FrailSafe Gateway, which includes smartphones for executing data collection applications and particularly those interacting with both internal and external sensors (i.e. GPS, beacons), tablets providing interaction interfaces to the end-users for playing games, and docking stations for automatic downloading and uploading data from the sensorized garment. Moreover, augmented reality (AR) glasses are used for particular games which provide AR experience to the older people and monitor data of cognitive interest.

Figure 2 illustrates the FrailSafe Gateway with the WWBS, the indoor/outdoor monitoring systems, the dynamometer, the auxiliary devices (impedance scale, blood pressure monitor) and the games, used to collect data and subsequently send them via secure internet connection to the FrailSafe Cloud.

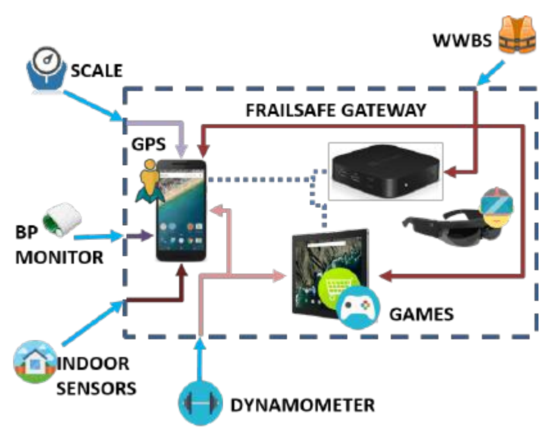

Fig. 2. FrailSafe Gateway data inputs include the WWBS, the indoor/outdoor monitoring systems, the dynamometer, the auxiliary devices (impedance scale, blood pressure monitor), and the games.

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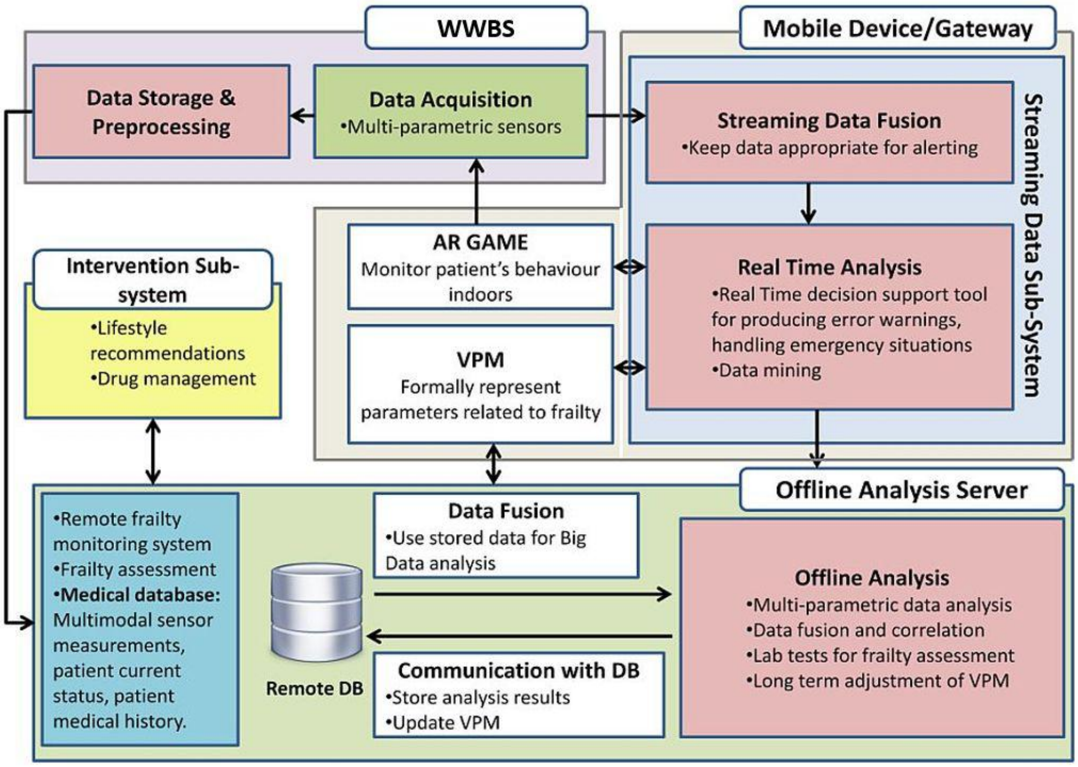

Fig. 3. The FrailSafe architecture. The data acquired from the clinical examinations and the different technological means (WWBS, a mobile device, and augmented reality (AR) games) are analyzed in real time, and also introduced to the offline analysis server. After data fusion, parameters related to frailty are calculated and used to populate the virtual patient model (VPM). The VPM, which is stored in the database (DB) is used to personalize the recommendations in the intervention sub-system.

B. The software front-ends for interaction of the users with the FrailSafe system

The front-end software allows the retrieval of the data collected through the devices, is responsible for the data exchange, and provides the user interfaces to the platform services (mobile and web applications). Overall it includes the web portals and the software applications. The web portals guarantee and facilitate the interactions between all groups of users and the system. They are web applications accessed via any medium that provides a web browser, e.g. smartphone, tablet, PC, etc. The applications are mainly dedicated to the interactions required by the user for data acquisition and transmission to the cloud. Details on the software front-ends are provided in section IV-A.

In respect to the usability of the FrailSafe system, seventy-five older adults (Cypriots, French and Greek), were requested to evaluate it. The timeline and tools used included (i) qualitative evaluation of their experience with the system during and after each of the FrailSafe visits (three in total) to their home, (ii) a thinking aloud protocol during their second interaction with the system, (iii) administration of a user satisfaction questionnaire after completing their participation to the study. The results showed that participants did not experience significant difficulties in charging the devices, playing with the tablet serious games or using the mobile phone. Users evaluation of the smartphone apps showed that the apps acted as a motivation for them to remain active. The autonomous use of the WWBS device neither presented significant problems, which was a very positive finding considering older adults general difficulties and reluctance towards technology use [33] [34].

C. The Cloud services

The FrailSafe Cloud is where collected and produced data are securely stored, processed and analyzed. The FrailSafe Cloud is composed of several modules and sub-systems that are documented in Section IV in respect to their functionality and role in the overall architecture.

D. System's modularity

The organization of the system into three layers (devices, software front-ends and cloud infrastructures and services) allows modularity of the system, i.e. new modules can be added at each level any time without affecting the general organization of the system or its function. Another important aspect to preserve modularity of the platform is the adoption of a service oriented architecture (SOA) design. In SOA each software module of the system is regarded as a discrete unit of features that can be deployed, consumed and updated in full independence. It is like a black-box for the rest of the system and its facilities can be accessed only through a clear interface, the Application Programming Interface (API), that each module exposes. By implementing the FrailSafe platform according to SOA design, it is guaranteed that (i) the delivery

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and deployment of each module can be performed individually, (ii) the testing phase is naturally organised in individual units, (iii) the maintainability of the whole platform should benefit from an integration based on a limited number of touching interfaces making easier to understand and isolate problem sources or identify bottlenecks.

IV. FrailSafe System Architecture

In this section, the FrailSafe system architecture is presented in more detail to provide a rigorous description of the platform and of the technologies adopted for each distinct component. A conceptual diagram is illustrated in Figure 3.

A. *Software front-ends*

As described in section III the end-users mainly interact with the FrailSafe system through several software components (front-ends) which can be web portals or applications (Figure 4).

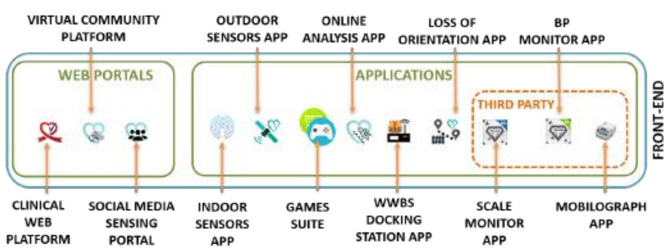

Fig. 4. FrailSafe software front-ends including web portals and applications (apps). The web portals consist of the clinical web platform, the virtual community platform, and the social media sensing portal. The developed apps provide an interface for indoor and outdoor monitoring, for the games suite, for online data analysis, the WWBS docking station, as well as for the third party devices (blood pressure monitor, weight scale and mobilograph).

1) Applications: Several modules have been developed which include applications (apps) for indoor and outdoor monitoring, the games suite, for tracking and online data analysis, as well as for the WWBS docking station, as described next.

Indoor monitoring app: It is responsible for monitoring of the indoor position of the older person [35] [36], within his/her home environment, and for the interaction with the FrailSafe Gateway. It receives signals from indoor sensors, i.e. Bluetooth Low Energy beacons, processes them for extracting location information, and transmits the collected data to the mobile gateway. The indoor monitoring module is implemented as a mobile application with configurable parameters through a mobile graphical user interface.

Outdoor monitoring app: The outdoor monitoring module is responsible for (a) gathering of the tracked position (latitude, longitude and other location-specific measurements) through the mobile phone which acts as a GPS receiver (b) extracting step activity of the older person based on the multiaxis accelerometer and gyroscope sensors (c) the transmission of the collected information to the FrailSafe Gateway. As in the indoor monitoring app, a graphical user interface, implemented as a mobile application, allows the configuration of the module's parameters by the user.

Games suite: The games suite of FrailSafe consists of a variety of games aiming both at sensing the physiological and cognitive status of the older people, and providing them with rehabilitation exercises. Most of the games are integrated in just one Tablet application, allowing the user to interchange between games based on his/her own interests and doctors' recommendation, while two games, namely "Floating Archery" and "Memory" were developed for AR glasses. During the game play, the user performance is monitored by the application and the collected data are transmitted and stored to the system database. The games included in FrailSafe's games suite have been developed by Brainstorm Multimedia [37] and CERTH and are presented in Table I. Besides the games suite there exist additional tools, like the force analyzer, measuring a series of parameters related to the user force and fatigue. Some illustrations of the RedWings, Railroad, Simon and Virtual Supermarket [38] games are shown in Figure 5.

Online data analysis apps: One of the FrailSafe project's objectives is the real-time monitoring of the older people towards detecting frailty risks and triggering alarms in case of emergency situations. The online data analysis app collects the data streams which are transmitted by the WWBS through Bluetooth and performs a real-time analysis in two directions: (a) to monitor the stability of the older person [39], and (b) to identify falls, by classifying activity as a detected fall or as an activity of daily living [40] [41]. Moreover, it uses the outdoor localization API based on the GPS data in order to detect loss of orientation or wandering events [39]. More details on the online data analysis and loss of orientation functionalities are provided in section V.

WWBS Docking Station app: Many applications of the FrailSafe system rely on the data collected by the WWBS. To improve the usability of this device and facilitate data transfer, a Docking Station is used. The WWBS Docking Station app performs authentication of the person that uses the WWBS, enables the device battery recharging, and is also responsible for downloading data from the WWBS to the Docking Station and then uploading them to the FrailSafe Cloud. The synchronization of the data residing locally into the Docking Station with the FrailSafe cloud repository is performed every time a Wi-Fi connection becomes available, thus enabling seamless data transfer from the WWBS to the FrailSafe cloud.

Third party devices front-ends: The third party devices apps are responsible for the management of data from the third party auxiliary devices that can be used autonomously by the older persons while being at home, i.e. the blood pressure monitor, weight scale and mobilograph. These three apps are responsible for collecting and displaying the measurements from the corresponding devices and transferring them to the cloud once connection to internet is provided.

2) Web portals: The modules of the Web portals are all accessible via a web browser and are (i) the clinical web platform, (ii) the virtual community platform, and (iii) the social media sensing portal.

Clinical web platform: The clinical web platform provides access to three different subsets of functionalities that share a unique web interface: the electronic case report form (eCRF),

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TABLE I
GAMES SUITE CONSISTING OF 9 GAMES CONCEIVED TO TRAIN SPECIFIC MOTOR AND COGNITIVE CAPABILITIES OF THE USERS OF FRAILSAFE PLATFORM

Game	Type	Content	Measurement
RedWings	horizontal scrolling	The user flies a plane by means of the force applied in the dynamometer sensor	force and reflexes
Railroad	endless runner game	The player controls an avatar in a mine cart by means of body movement. It uses the accelerometers included in the WWBS	flexibility, agility, reflexes
Simon	tablet touch game	The user needs to find and remember music and color patterns	memorization
Memory	tablet touch	The user needs to find and remember image matches	short term memory
Reflex	tablet touch	The user needs to find and touch elements as soon as they appear on screen	reflexes
Virtual Supermarket	3D game	Simulates activities performed in a real supermarket, such as memorizing the shopping list, finding the items, doing calculations when paying	calculations, spatial memory, navigation
Gravity Ball	tablet with AR graphics	It displays simple mazes where the user needs to control a ball by manipulating a tangible element in front of the camera	coordination, reflexes
Floating Archery	AR game	The user needs to point and shoot AR elements floating on the real scene	visual capabilities, reflexes, endurance
Memory	AR game	The user's first objective is to find all the objects by looking directly at them and try to remember the order in which he saw them	visual capabilities, memorization, balance, coordination

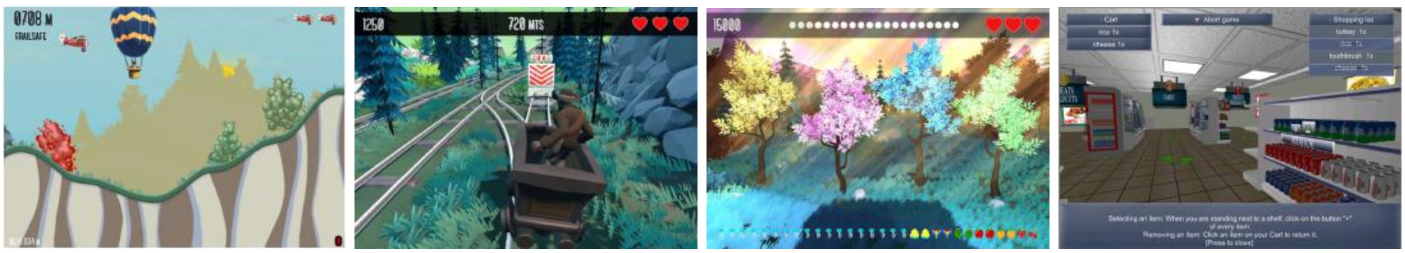

Fig. 5. Screenshots of some VR games included in FrailSafe's games suite. From left to right: RedWings, Railroad, Simon, Virtual Supermarket. Please refer to Table I for further explanations.

the authorization user interface (AUTH UI), and the decision support system user interface (DSS UI).

1. eCRF: It is a web application, as an electronic case report form (CRF), where the clinical personnel can capture, review, manage, store and report data obtained during the older person's participation in the geriatric assessment. The main utility of eCRF is to record information about the older people by filling questionnaire forms related to various domains and contents (clinical history, cognitive evaluation, nutritional assessment, etc.) and to upload the information created by devices or reported by the participants (written text, sketch, etc.). In FrailSafe the development of an electronic CRF has been preferred over a usual paper CRF in order to facilitate the collection of accurate and complete information eliminating unnecessary duplication of data and reducing the possibility for transcription errors. Moreover the eCRF enables remote monitoring of data and promotes real-time access for data review and data analysis.

2. AUTH UI: It is a web application used to manage the accounts of the users who need to have access to the system in a secure way. Each user must be registered to the system and be associated with a role defining his/her privileges. Only registered users can have access to the data and perform different operations, according to their assigned privileges.

3. DSS UI: The decision support system user interface provides access to the collected data through information visualization techniques. Through the DSS UI, the user (an older person or a clinician) can exploit the information collected by the FrailSafe sensors and applications, guided by intuitive and interactive visualization techniques. The interactive visual analytics methods allow the viewer to interact with the visualization, in order to better explore the available data, make comparisons and spot interesting patterns and unusual cases. In the information visualization dashboard, a number of interaction types are supported, such as panning, zooming, and brushing/linking.

The DSS UI also provides mechanisms for notifications about the user's status, alerts when an undesired incident (e.g. a fall) happens and recommendations according to predefined or customizable rules in events such as high blood pressure (e.g. see doctor). Four types of user roles are supported by the DSS UI, with different access privileges to information and visualization functionalities: The older person and family members which have access to information about a single person, the doctor, who has access to information about several older people under his/her supervision and finally, the researcher, who has access to information about a group of older people. Furthermore, the researcher has access to more sophisticated data visualization types, such as graph-based and multi-objective visualization techniques, which allow to gain intuition about group populations, discover similarities and differences among them, distinguish sub-groups of common characteristics, etc. Figure 6 describes which functionalities and interfaces are available to the different user roles, while Figure 7 contains a representative screenshot of the DSS UI for the doctor's role.

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	Feature	Older person / family interface	Clinician interface	Researcher interface
Functionality	Single person monitoring	✓	✓	
	Collective monitoring		✓	✓
	Alerts	✓	✓	
	Interventions	✓	✓	
	Comparative analysis			✓
Interface	Web interface	✓	✓	✓
	Mobile interface	✓		

Fig. 6. Functionalities of the different interfaces according to the user role. For instance, the older person interface allows users to have access only to personal data, while clinicians have access both to the personal data of a single older person and to the collective data of several older persons.

Virtual Community Platform: It is a web platform for caregivers, older people, and their families that provides a news feed space for news and socialization, for older people to ask and answer questions about diagnoses, etiology, and treatment and to exchange disease and health related information. It supports personalized interactions and suggestions as needed and required by the health condition, capabilities and skills of the subjects. Moreover, it maintains the older people profiles and personal calendars with info considering their health status, social life and their feeling of well-being.

Social media sensing portal: The main scope of this module is to measure social interaction and behavioural parameters of the older people through their activity in social media (written text), in an effort to assess their mental and psychologic status. Mental frailty is associated with depression in the psychologic domain and memory vulnerability in the cognitive domain [42]. The social activity is monitored through various steps of processing after the users register using their username and password. The data are collected with use of crawlers (dedicated software components which perform a search across the social media) for fetching users' social media texts, such as Facebook posts, Twitter messages, and emails. The implemented techniques connect symptoms of frailty with the five-factor theory that has emerged to describe the essential traits serving as the building blocks of personality [43]. For this purpose, text features and multiple values of the Big Five personality traits (openness, conscientiousness, extraversion, agreeableness, and neuroticism) were extracted from the older persons' response to questionnaires. It is important to note that all collected data pass through an anonymization process which removes any personal information before data storage. Further details are provided in section V-A (Online analysis module).

B. Back-end and Security

The core module of the FrailSafe system are the back-end components on the server side. Several processes work remotely in background to provide end-users with various core functionalities, such as

- Secure remote storage of the data produced by the different client front-ends
- Application of all the necessary data processing and transformations to produce additional information and results
- Provision of services to the end-users through proper front-ends
- Secure and private users' account management to guarantee proper handling of data access
- Secure and proper exchange of data among different users and system components.

All the back-office elements of the system, hosted in remote servers, form the "FrailSafe cloud". The FrailSafe cloud is responsible of collecting, elaborating and storing the data produced by the mean of the monitoring of the patients and also providing the features for interacting with the platform through interfaces. For its implementation and for hosting the services, Amazon Web Services have been chosen as service provider. A main component of the cloud concerns the security system modules, which define the identity and security framework of the platform. Since the FrailSafe cloud is based on a service oriented architecture, each component of the system is seen as an independent module that exposes services, by means of application programming interfaces that can be exploited by other modules or by the end users via the proper front-end software. Aiming to facilitate this complex process, an API gateway has been introduced in order to control and manage the services exposed by the separate modules. With this API gateway, we can create a single entry-point for all the APIs that can be consumed. Moreover, the API gateway can guarantee the security of each API call by directly interacting with the authentication module, and hence it verifies that every single API call is legitimate. Furthermore, the API gateway traces all the activity of the users by logging the API calls that are performed. The access to system resources is controlled by an authorization module restraining unauthorized individuals to have access to the system or to request a forbidden resource.

The back-office or back-end part of FrailSafe system includes the social media components, the offline data analysis, the data grabber and the decision support system (DSS). All the data, generated by the various medical devices, or collected by the medical personnel, are gathered by the Data Grabber (an Amazon EC2 machine) and stored consistently into the FrailSafe database. For each data stream (coming from the eCRF, the WWBS, the blood pressure monitor or the games module), a different process has been designed and implemented. The data are subsequently analyzed and aggregated in order to make feasible the development of the FrailSafe Virtual Patient Model (VPM) [44] which provides the necessary information to the FrailSafe DSS and facilitates the design of interventions by clinicians. More details on the data analysis modules are provided in the subsequent section.

V. Data Analysis

The data analysis platform includes methods for offline and online management, fusion and pattern analysis of multimodal

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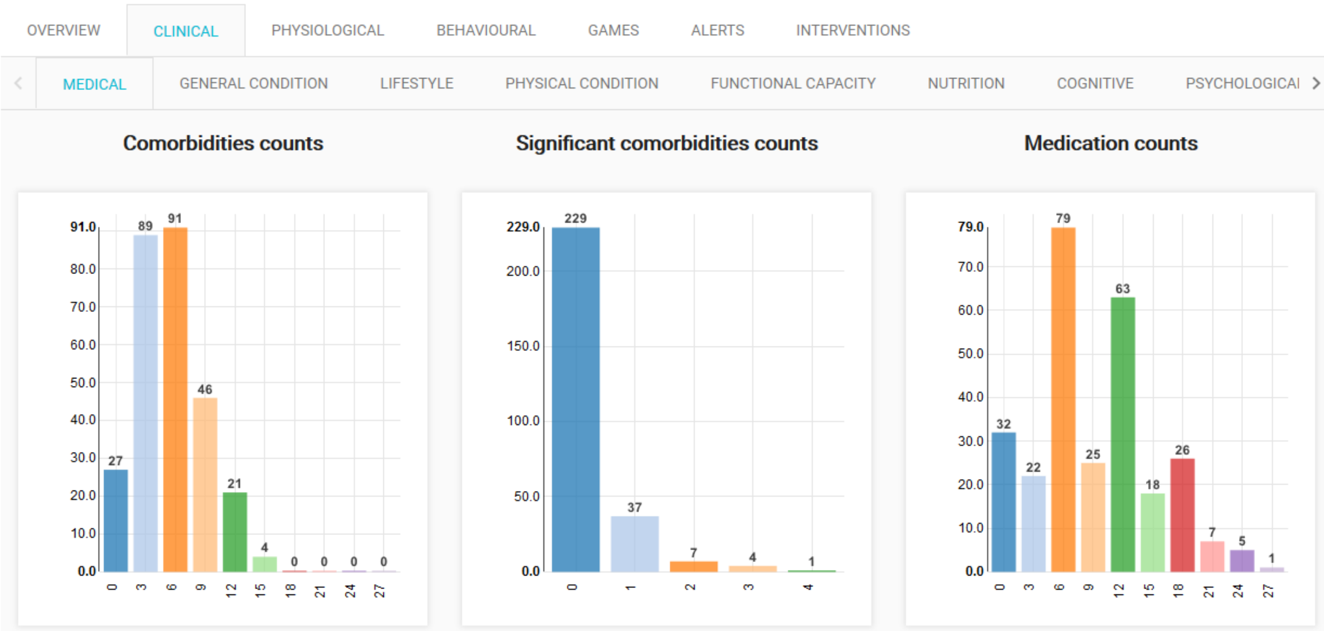

Fig. 7. Example of the DSS UI for a doctor. Selected medical parameters, like the comorbidities count, are visualized in the form of histograms.

and advanced technology data from social, behavioural, cognitive and physical activities of the older people. The online analysis module concentrates on the FrailSafe monitoring system aiming to cover specific situations during day time normal activity both indoors and outdoors, while the offline analysis module processes the large amounts of data taking also into account the clinical and behavioural information available, leading to integrative interpretation and better understanding of frailty. The overall aim is to propose new frailty metrics that will advance the decision making capabilities assisting diagnosis by medical professionals.

The analysis platform first builds a multi-dimensional profile of each participant by processing the multiple physiological signals to extract meaningful secondary variables computed from the raw measurements, such as heart rate from raw ECG. The noise in the data is reduced and the measurements are normalized to standard scales. Outlier detection is performed as well as data imputation to fill in missing values. Statistical features are then extracted from the raw measurements or secondary variables representing the physiological and cognitive state and indoor and outdoor mobility behavior [45]. The multi-parametric features are subsequently fused into a long feature vector and introduced into linear or non-linear dimensionality reduction techniques for extracting a small number of distinct patterns.

A. *Online analysis module*

The online analysis module is based on the prior exploration of data that helps to define the minimal number of modalities and sensors. Data reduction and summarization techniques are applied for reducing raw streaming data to secondary or tertiary parameters, required for minimal but effective processing of real-time streaming data. Individual components of the online analysis module include the triggering of alarms in case of emergency situations, such as fall [40] [41], loss of orientation or manifestations of depression in text written online (in social forums).

Fall/Instability detection: An Android app is available that implements in real-time the fall detection algorithm described in [40] using recordings from WWBS. The API handles all Bluetooth communication with the WWBS and enables the easy processing of the WWBS sensor and IMU data by the fall detector app. While fall detection is critical for triggering of alarms in critical situations, an innovative strategy was implemented to assess the loss of stability of an older person that is linked to risk of falling [39]. Specifically, a Stability Index was extracted using an algorithm based on Principal Component Analysis (PCA) decomposition of the raw acceleration signals, communicated to the gateway smartphone device for processing. Since the principal component concerns the kinematics regarding the gait orientation, it was eliminated and the secondary gait component was used instead to study secondary dynamics to the participants gait, such as lateral movements, minor instabilities, staggering.

Loss of orientation: The loss of orientation application requests daily localization logs from the FrailSafe Cloud and specifically the outdoor localization API, which provides a polygon of coordinates that act as geo-fencing boundaries for a selected user. The application processes the localization logs and after filtering them, extracts wandering patterns and triggers geo-fencing breaching alarms if the user has crossed his set geo-fencing boundaries. It also extracts pacing and lapping indexes, indicating irregular walking patterns, which are often an early warning for wandering events.

Social Media Processing: The offline social media processing module (Lingtester) is the FrailSafe language analysis tool that aims to process the user's written (typed) text and detect signs of mental frailty and personality trait shifts, based on

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- Social interaction, measured by the number of incoming/outgoing phone calls/SMS, emails, use of social networks
- Questionnaires in which the participants are asked to describe a major life event and also an attached picture
- Big five personality traits (from social media) [43].

The linguistic analysis was performed in several layers ranging from word spelling to speech analysis. In order to create the training model, all participants' text was fetched from the offline database and features were extracted utilising different resources from custom developed or third-party tools. A binary prediction model was then created for testing and evaluation. More details on the online mode of Lingtester can be found in [46].

Personalized decision support via a VPM: At the core of the online analysis module is a detailed definition of a personalized virtual patient model composed of static and dynamic information of the older people, reflecting their medical condition [44]. The model includes data categories related to the (i) user identification, (ii) summary of the parameters from the integrated sensor recordings, questionnaires and game analysis, (iii) archived medical data essential to the clinicians, such as comorbidities and test results, and finally (iv) a list of parameters that are linked to the recognition of short-term scenarios, such as loss of balance and orientation, and parameters that change in long-term reflecting for example frailty progression. The VPM, which is at the core of the system, supports the physician in his/her decision process ranging from general health preservation monitoring to critical situation management, allows an adaptation of the user interfacing of collected data and notification system, and provides the means for a personalized feedback to the older person via lifestyle change suggestions, behaviour guidelines and medical intervention strategies [47]. As semantic interoperability of health information across monitoring systems is a crucial point, the VPM methodology is based on an open standard specification, the openEHR [48], to facilitate storage, management, retrieval and exchange of health data between different healthcare providers or other interest groups [44].

B. Offline analysis module

The main focus of the offline analysis module is to find patterns and associations between external indicators and patient states, and detect vital signs of a persons' frailty level changing in a significant manner [45] [49] [50] [51]. The goal is to develop a clinical state prediction engine that predict critical clinical parameters, such as the change of frailty level or the risk of an adverse event, taking into account up-to-date measurements of the multi-domain variables. The conceptual structure of the offline analysis back-end module is presented in Figure 8. It is directly connected with the FrailSafe Database Management System (DBMS), which stores all data coming from different sources. Several advanced offline analysis algorithms use the data to generate models which lead to integrative interpretation and better understanding of frailty. The offline analysis process follows in general the next steps:

- Data integration in which multiple data sources are combined;
- Data selection for retrieval of data relevant to the analysis from the database;
- Data transformation, where data is transformed or consolidated into forms appropriate for mining by performing summary or aggregation operations;
- Extraction of secondary measurements from the primary raw recordings, like recognition of physical activity, for a more complete user profiling;
- Data mining and pattern evaluation involving the application of artificial intelligence methods for the assessment of higher levels patterns. Techniques like clustering and correlation analysis are among the many different techniques used for mining the multi-parametric data;
- Knowledge discovery and representation in appropriate form to be exploited for decision making.

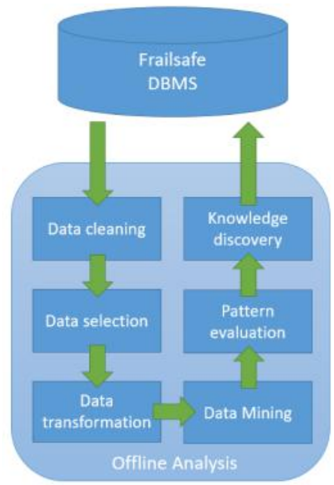

Fig. 8. Diagram illustrating main data processing and analysis steps performed in the offline analysis module. Data are retrieved from the Database Management System (DBMS) and the results are stored back at the DBMS.

The output of the offline data analysis module is saved in the database, while part of the analysis results are introduced to the VPM module for visual representation. For better understanding, we describe next with more details one of the tools included in the offline analysis module, and specifically the methodology for the prediction of FrailSafe's frailty index associated with the risk of serious undesired events, such as falls, unintended hospitalizations or death, in the near future.

1) Activity recognition: The recognition of physical activity [52] is based on the accelerometer recordings from the WWBS. The type of recognizable activities include sitting, standing, walking, walking upstairs or downstairs, and laying down actions or transition events. Recognition is performed based on supervised learning via support vector machines, while more recent work [53] has shown that the incorporation of deep learning techniques can further improve recognition accuracy. The method also addresses data inconsistencies that are caused by device-relative issues or possible sensor misplacement during monitoring of physiological activity [54].

2) Prediction of FrailSafe's frailty index: The ultimate goal of the DSS is to provide a frailty index that is predictive of the risk of adverse outcomes (undesired events), such as falls, unexpected hospitalization and death. The idea is to examine

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whether we can extract early indicators of deterioration in the participants' health condition that might lead to dangerous events. In order to build such a metric, we employ machine learning techniques that exploit features from subjects with known outcomes and find the appropriate decision boundaries (in the original or transformed feature space) that can distinguish between profiles that are more or less prone to future adverse events. The training of the prediction model was performed by examining the temporal multi-dimensional profile captured by the multiple sensing modalities (WWBS, the dynamometer, the game suite and the GPS) during a predefined time period (a year) before the adverse event. First temporal alignment of the sensor's recordings and clinical variables was performed to project all measurements acquired in different time points into a common reference frame. Then statistical features were extracted within a daily time span from the raw or secondary measurements representing physiological and cognitive state, as well as indoor and outdoor mobility behavior. Since the devices were used on multiple days (usually a few days per month for 2-6 months) prior to the adverse event, the temporal evolution of each feature could be tracked. Each time series was then modeled by a linear function whose parameters (the slope) formed the final descriptors. The multi-parametric descriptors derived from all sensors were subsequently fused into a long feature vector and introduced to Principal Component Analysis for dimensionality reduction, such that 98% of the data variance was retained. Classification was subsequently performed on the orthogonally transformed and reduced variables using the SPEC_MIL algorithm, which is a specializing multi-instance learner that follows a generalization of the miSVM classifier [55]. The classifier returns a decision score that is indicative of the risk having an adverse event in the near future and is used as FrailSafe's frailty index.

3) Proof of concept: The evaluation study was performed in 3 clinical centers: University of Patras, Greece; INSERM-Nancy, France; and MATERIA- Nicosia, Cyprus. Each center has recruited during the duration of the project approximately 170 adults aged 70 years and older. By taking into account the drop-offs and deaths, the number of community living older adults participating in the study ended up being 479 (207 non-frail, 198 pre-frail, 74 frail) in total. The data collection was subject to the provision of informed consent and all relevant approvals by the competent ethical committees. In order to be able to comply better with the requirements of the study, subjects with highly debilitating conditions, such as inability to walk, presence of clinically significant cognitive impairment, or active psychiatric disorder were excluded from the study. Similarly, subjects with serious medical conditions that convey a guarded prognosis (estimated life expectancy of less than 12 months) were excluded as well. The participants were allocated in four groups: the start up group being monitored at the beginning and end of the project, the main group that received the FrailSafe devices in frequent intervals after the standardization of the platform, the evaluation group (for standard and long-term evaluation), and the control group which will not use the FrailSafe system.

The construction of the frailty index was based on the main group that included specifically 40 subjects per center that received 7 FrailSafe sessions [1] and 3 clinical evaluations in a 16 months period. Any measurements up until 6 months after an adverse event were considered post-event and excluded from the analysis. Out of all participants of the main group, 79 of them had one or multiple measurements from all devices (WWBS, games, GPS, text) and had not missed the comprehensive geriatric assessment by the time of the analysis, therefore, were used to construct the technical frailty index. Twenty-one participants had an adverse event in a short time period after the measurements and comprised the positive class, while the rest of the 79 comprised the negative class. Evaluation was based on cross-validation, i.e. the subjects were split in disjoint training and test sets used for model estimation and prediction, respectively. This procedure resulted in subject-independent models that can be used for prediction of risk for any new subject given his/her personal multi-domain profile. After development of the prediction model using the main group, it was applied to the rest of the participants (from the start up group and the evaluation group) to extract their frailty index. Participants with incomplete measurements or drop-outs were excluded from the analysis. The remaining number of participants used in the evaluation was 188 (of which 66 had an adverse event), and their the total number of sessions was 2757. From the 188 participants, 105 remained non-frail and 27 pre-frail during the whole duration of the study, while the rest had at least one transition between frailty states (49 non-frail/pre-frail) and 7 pre-frail/frail) according to Fried scale.

4) FrailSafe's frailty index evaluation: Two types of features were examined for the calculation of FrailSafe's frailty index: the features accumulated over the multiple sessions for every participant, and the estimated temporal change of extracted features (slope). Some of the variables were extracted automatically from the technological devices (WWBS, games suite, GPS), whereas others corresponded to the clinical measurements from the comprehensive geriatric assessment. The discriminating power of every sensing modality was assessed independently, as well as in combination with each other, using the raw or slope features respectively. We used for assessment two criteria, the classification accuracy, i.e. the percentage of correctly classified samples, and the balanced accuracy, that expresses the average of sensitivity and specificity and that prevents the minority class to be out-weighted by the majority class. We also calculated the area under the receiver operating characteristic curve which provides an estimate of prognostic performance independently of the cut-off point or criterion value selected to discriminate between the two populations (having or not having not experienced an adverse outcome).

The cross-validation accuracy was slightly higher for the slope features, which were therefore selected as the final prediction model of the FrailSafe platform. As sensing modalities for this *technical Frailty index* we selected the WWBS and the games, in an effort to keep the smallest number of modalities achieving the highest possible accuracy and less variation in

[1] A session refers to the use of the FrailSafe devices over a few (2-5) consecutive days

the results.

Moreover, the performance of the device-related features was compared against the performance of all the clinical variables collected in the standard CGA, as well as the frailty phenotype by Fried [7] that constitutes a common reference frame. Frailty is identified by the Fried phenotype if three or more of the following criteria are present: slow walking speed, low physical activity, unintentional weight loss, self-reported exhaustion and weakness (measured by grip strength). Our results showed that both the multiple raw measurements of clinical variables and Fried status are much more informative than the temporal change of their values (slope features), respectively. Those raw clinical variables showed similar performance with the raw features from the FrailSafe devices, whereas the slope clinical variables and Fried status showed worse performance than the slope features obtained from the FrailSafe devices. This indicates that the continuous monitoring based on unobtrusive sensing technology has the potential to outperform the standard clinical measurements and Fried status, especially for the assessment of frailty progression.

VI. Conclusions

In this paper the main components of the FrailSafe system architecture were presented. The system consists of an integrated platform that aims to early detect frailty in the older people through the use of ICT technologies equipped with artificial intelligence tools, and to delay the progress of frailty by designing personalized interventions. The architecture requirements were guided by common practices performed in eHealth and mHealth applications [56], justifying the decisions made during the development of the system's modules. The visualization functionalities of the platform facilitate the handling of the wide variety of data collected in the FrailSafe project, including clinical measurements gathered through the eCRF, physiological parameters gathered through the WWBS and medical devices, behavioural measurements from indoor and outdoor sensors and game performance measurements, while the decision support system allows the exploitation of the physiological and behavioral characteristics that can be used to define biomarkers of frailty being of significant predictive value [57]. Classification algorithms were incorporated in order to build prediction models for the different clinical metrics [49], as well as to predict adverse events. The results encourage further investigation of the prognostic capacity in terms of predicting frailty transition and subsequent risk factors. It is estimated that the use of the FrailSafe system in a larger population will allow to shed light into the understanding of frailty as a deregulated situation and reduction in physiological reserve leading to proneness to a range of adverse events. Such an improved understanding could provide the basis for the design of appropriate interventional strategies targeting personalized prevention and rehabilitation. This may be an important factor to reduce cost and burden of frailty in family and caregivers, as well as the consumption of resources by the national health systems.

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