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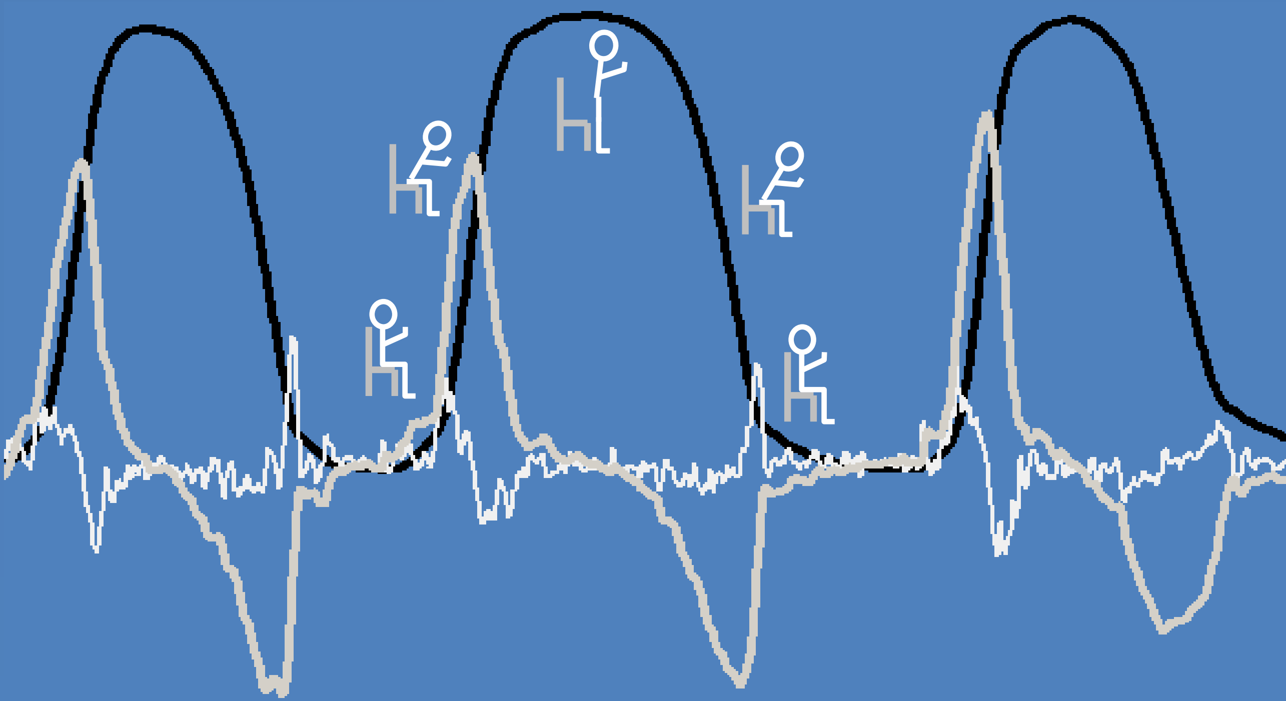
FRAILTY ASSESSMENT BASED ON THE INSTRUMENTED VERSION OF THE 30-S CHAIR STAND TEST



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2014

Tesis Doctoral

Frailty assessment based on the instrumented version of the 30-s Chair Stand Test

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To everyone who have supported me over these years.

"Research is what I'm doing when I don't know what I'm doing."
(WERNHER VON BRAUN)

"You can't outrun aging, but the better shape you're in, the longer it takes for your age to catch up to you" (ANONIMOUS)

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RESUMEN

Hoy en día, el envejecimiento de la población es una de las mayores preocupaciones de nuestra sociedad. Las personas de edad avanzada son más propensas a sufrir caídas y el síndrome de fragilidad, incrementando así el impacto en la atención y los recursos clínicos destinados a ellos. El estado de salud en este tipo de población debe medirse en términos de función y no de enfermedad ya que así se determina la esperanza de vida y los recursos o apoyos necesarios. Uno de los mejores indicadores para esto, incluso por encima de la morbilidad, es la capacidad funcional previa al desarrollo de discapacidad o dependencia. Además, el concepto de fragilidad se relaciona con los citados indicadores: las personas que padecen el síndrome de fragilidad, especialmente aquellas de edad avanzada, tienen un riesgo más elevado de que empeoren tanto su salud como su estado funcional. Sin embargo, el diagnóstico de la fragilidad no es fácil. Uno de los métodos más utilizados para su evaluación es el criterio de Fried basado en la presencia de tres o más de los siguientes componentes: lentitud en la marcha, debilidad, pérdida de peso, cansancio y baja actividad física. El problema de este tipo de valoraciones es que suelen ser más cualitativa que cuantitativa, de modo que la experiencia y habilidad de la persona que realiza el test juegan un papel decisivo en ellas.

De entre las actividades que se realizan en la vida diaria, levantarse de una silla es una de las más exigentes a nivel muscular y mecánico. La población de edad más avanzada es la que experimenta mayores dificultades para poder realizarla, aumentando así el tiempo que permanece sentada y reduciendo notablemente su capacidad para vivir de manera independiente. De este modo, test como el de sentarse y levantarse cinco veces (5-STS), el levantarse y andar (TUG) y el test de treinta segundos de la silla (30-s CST) son una de las piedras angulares para la detección temprana de la dependencia funcional. De

hecho, el 30-s CST es uno de los test más utilizados en la literatura no solo para evaluar niveles de capacidad funcional sino también para determinar los efectos de programas de ejercicio o rehabilitación. Sin embargo, hasta ahora, este test consistía en contar el número de veces que un sujeto se levantaba de la silla durante la duración del test. Recientes avances en el diseño y desarrollo de los sensores inerciales los han convertido en una herramienta capaz de proporcionar información cinemática de manera no-invasiva, portable y económica. Esto permite evaluar el movimiento humano de una forma más objetiva, obteniendo no sólo datos sobre la cantidad de movimiento sino también de cómo se ha realizado el mismo.

El objetivo de esta tesis es mejorar la evaluación de la capacidad funcional usando nuevos parámetros cinemáticos. Así, el personal clínico dispondrá de una serie de medidas objetivas y cuantificables para realizar sus diagnósticos. El movimiento que se ha analizado en este trabajo es el relativo al test de treinta segundos de la silla, y el instrumento de medida utilizado ha sido una única unidad inercial. La mayor parte de esta Tesis Doctoral está dedicada al análisis de las señales de aceleración y velocidad angular, que nos proporciona la unidad inercial, durante la ejecución del 30-s CST. En base a este análisis se obtienen parámetros significativos, capaces de distinguir diferentes niveles de fragilidad. Todo este trabajo ha sido publicado en revistas de impacto del JCR y aparece recogido en los capítulos dos, tres, cuatro y cinco. En el primero de ellos se realizó una revisión sistemática de la literatura correspondiente al análisis de la señal de los test relacionados con el movimiento de sentarse y levantarse de una silla, indicando también nuestras aportaciones. A continuación se desarrolló un algoritmo para la corrección del error de deriva que se produce al tratar de obtener la señal de posición vertical a partir de la aceleración en este eje que nos proporciona el sensor inercial. En el siguiente artículo se evaluó un modo de análisis, basado en parámetros cinemáticos, en un grupo de personas pre-frágiles. Y, finalmente, se escribió un último trabajo con el análisis final para obtener aquellos parámetros cinemáticos que son capaces de distinguir entre sujetos con distinto grado de fragilidad.

CHAPTER 1:

Introduction and Outline

1.1 POPULATION AGEING AND FRAILTY

1.1.1 The ageing trend

Since the mid-century, portions of older people has experience a significant rising in the total world population. The global share of population aged 60 years or over has increased from 9.2% in 1990 to 11.7% in 2013 and is expected to reach the 21.1% of the world population by 2050 [1]. Moreover, this older population is itself ageing. Globally, the share of persons aged 80 years or over, the so-called "oldest old", within the older population was 14% in 2013 and is projected to reach 19% in 2050. If predictions come true, by 2050 one out of five elderly people will have 80 years or over. Germany, France, UK, Italy and Spain are the countries of the European Union with a higher number of older people [2]. Specifically, in Spain, the UN's World Population Prospects Report forecast that 13 out of 100 people will have more than 80 years old by 2050. According to these predictions, this is in fact the range of population which is expected to suffer a higher increase (from 2.4 million in 2012 to 6.2 millions in 2050), (Figure 1.1).

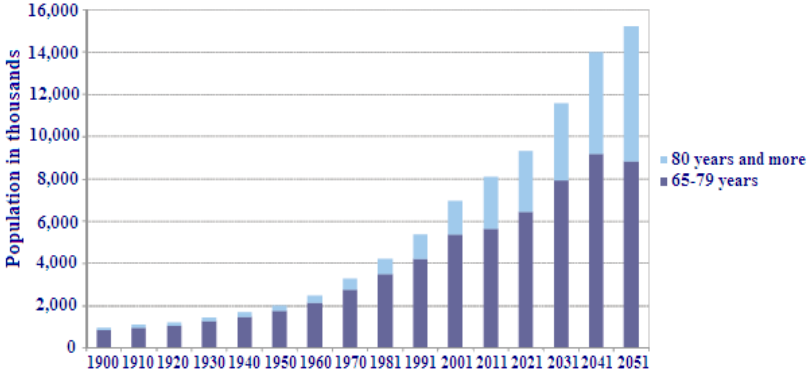

Figure 1.1: *Evolution of the elderly population in Spain from 1900 to 2051. Data from 1900 to 2012 is real while from 2021 to 2051 is projections to future events. Source INE: INEBASE accessed on April 2013.*

This ageing trend has become a major concern in our society. This explosion of large numbers of very old people living in our communities has brought to light critically important healthy problems (i.e. co-morbidities, frailty, fall-risk) [3]. The Survey of Health, Ageing and Retirement in Europe (SHARE) has estimated that approximately 17% of men and 23% of the women aged 65 and over experienced physical limitations [4].

Regarding the Spanish population, more than the half of the people aged 80 or more have limitations in their daily activities. Therefore, the chances of dependency on medical, welfare and other services will increase, soaring health-care cost. In special, long-term care refers to a range of services assistance for persons who over an extended period of time are dependent on help with basic activities of daily living. It is estimated that one in two women and one in three men will common to need intensive long-term care as their age. This expenditure has grown on average at an annual rate of over 9% since 2000 across 25 OECD countries, compared to 4% for public expenditure on health.

1.1.2 The frailty syndrome

Health status in elderly should be measured in terms of function rather than disease since it is what determines life expectancy, quality of life as well as the resources and supports required for these population. Therefore, functional status prior to the development of functional disability and dependency is one of the best indicators of health status. The concept of frailty is one of the approaches to this kind of evaluations. In the field of geriatrics, the term "frailty" has been largely used for those elderly who were particularly sensitive and vulnerable to repeated minor stressors or injuries. This expression was first used in 1974 to assess an individual's proximity to his own boundary for age-related vulnerability and predict prognoses [5]. However, frailty is not an age but a condition. This interesting emerging concept has evolved as a medically distinct syndrome based on the clinical experience of geriatricians [6-10]. Despite the difficulties in providing an exact definition [11], frailty is generally viewed as a physiologic loss of reserves and decreased adaptation (resilience) to any sort of external or possibly even internal stressors [9;12]. The best know of this concept are the overall consequences, including a higher risk of accelerated physical and cognitive decline, disability, institutionalization and finally death [9;12-14].

The identification of frailty is as difficult as its definition. Many geriatricians say that they know frailty when they see it but there is a lack of quantifiable variables for a distinct diagnosis [11;15;16]. In the absence of a gold standard, frailty has been operationally defined by Fried et al. as meeting three out of five phenotypic criteria indicating compromised energy: low grip strength, low energy, slowed walking speed, low physical activity, and/or unintentional weight loss [7]. Moreover, a pre-frail stage has also been established when subject meets one or two of the criteria, as a high risk of progressing to frailty. Although this hypothesis omits certain features (i.e. cognitive and psychosocial) which are well known to be predictive of adverse health outcomes, the frailty phenotype of Fried has demonstrated predictive power for adverse health outcomes in several [7;17].

Frailty has also been highlighted as a transitional state in the dynamic progression from robustness to functional decline [18], (Figure 1.2). As being a progressive syndrome that begins with a pre-clinical stage, the pre-frail status, there are opportunities for early detection and prevention [19]. Therefore, the identification of high risk individuals more prone to suffer from frailty or the pre-frail states could lead to validate rehabilitative programs able to postpone or reduce the severe consequences as functional decline and death [18].

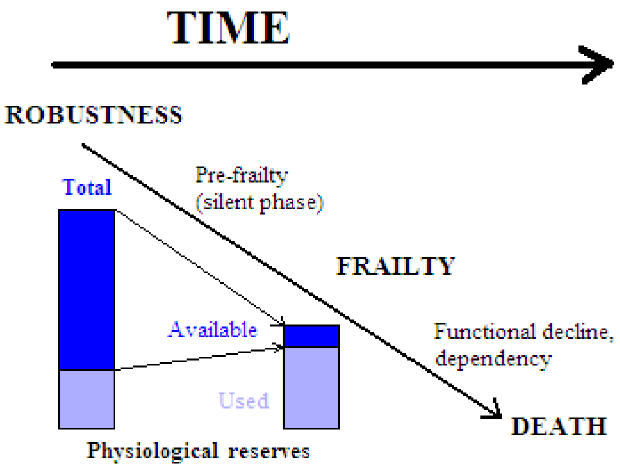

Figure 1.2: *Frailty process evaluation.*

According to various studies, the prevalence of frailty syndrome in people aged 65 an over ranges between 3% and 37%, depending on age and sex [20]. In particular, a recent survey of 7,510 community-dwelling older adults in 10 European countries, SHARE project, found a prevalence of frailty ranged from 5.8% in Switzerland to 27% in Spain, and an overall prevalence of 17% [21]. These rates provide an idea about the amount of people that will not be doom to the consequences of the frailty syndrome if no action is performed. An early identification as well as an adequate exercise or rehabilitation program would probably make those people boost energy, maintain their independency, manage symptoms of aging, and, as a result, achieve a better health-status their last years of life [22].

1.2 FRAILTY ASSESSMENT: FROM QUESTIONAIRES TO INSTRUMENTED TESTS

1.2.1 Identify frailty into clinical practice

The integration of frailty measures in the clinical practice is crucial for the development of interventions against disabling conditions in elderly population [23;24]. However, although the theoretical foundations of this syndrome are well established in the literature, its complicated and heterogeneous nature makes it especially difficult to translate the clinical profile of frail elderly people into a quantifiable assessment tool [25]. For instance, the Fried definition of frailty is impractical in the clinical setting. Ascertainment of 3 of its components (i.e. grip strength, walking speed, and physical activity) requires knowledge of the underlying distribution of the measure in a given population, as well as the instrumental and the space requirements to carry on and administrate the tests [23;26]. Therefore, there have been several attempts during the last few years to measure frailty oriented to the clinical practice [26-31]. For instance, there are the 5-item SHARE-Fit, based on the Survey of Health, Ageing and Retirement in Europe (SHARE); and the multidimensional 40-item index SHARE-Fix, obtained from comprehensive geriatric assessment (i.e. people older than 80 years, hospitalization, falls, polypharmacy, etc.) [32]. However, they are time-consuming, complex, and impractical for use in a primary care setting [30]. Other methods such as the Lawton Instrumental Activities of Daily Living Scale (IADL) is an appropriate instrument to assess independent living skills, more complex than the basic activities of daily living [33]. However, these kinds of assessments tend to be based on questionnaires or interviews [31] so they could be balanced by the subjectivity of the patient and medical experience.

As previously mentioned, the term of frailty has a multi-component origin including physical, functional, mental and social aspects [7;10;34]. However, many researches highlight that the manifestation of this syndrome merges into an altered physical function of the patient [35]. Frailty is associated with older age, female sex, and higher burden of disease, disability and cognitive impairment, among other factors. Genetic, hormonal, inflammatory, oxidative stress, neuromuscular, energy and nutritional factors have been identified as the main causes of the frailty syndrome [36]. On the other hand, it is also worth to highlight that one of the most popular prescriptions to deal with frailty is exercise [22;37-39]. Both ideas make measuring function in elderly adults interesting actions to take into account to identify frailty.

According to specialist, balance, gait and the ability to rise from a chair are most used measures in clinical settings to evaluate physical ability in elderly patients [40;41]. Balance is critical in the performance of normal physical activities, and balance impairment is a key risk factor for falls in older people. Static balance test such as the Berg Balance Test (BBT) and the Romberg Test have been developed as clinical measures to objectively determine a patient's ability, on inability, to assess postural steadiness in elderly population [41-43]. Another factor generally used by clinicians to evaluate an older patient's physical status is gait [44-46]. It has been defined as the manner in which a person walks, characterized by rhythm, cadence, step and stride length and speed [47]. Particularly, gait speed has been highlighted by many studies to be a critical clinical outcome [48;49]. Finally, standing from a seated position has been regarded as the most muscle demanding task undertaking during daily activities [50-55]. Therefore chair related test such as the 30-s Chair Stand Test, the 5-Stands Test (5STS) and the Timed Up and Go Test (TUG) are used in clinical settings to evaluate elderly functional levels. In particular, the 30-s CST is highly correlated to the lower body strength [56;57] and comprises enough number of repetitions to assess fatigue. Furthermore, this test has been widely used through the literature not only to evaluate functional fitness levels [58-60] but also to monitor training [61-64]and rehabilitation [65;66]. However, measures of all these tests are quite rough (i.e. durations, number of repetitions) and, in some cases, there is also an important level of subjectivity due to the significant weight of the tester ability and practice into the final clinical diagnostic.

1.2.2 The role of inertial units in clinical assessment

An inertial measurement unit (IMU) is an electronic device that measures and reports velocity, orientation and gravitational forces. To this aim, they use an adequate combination of accelerometers and gyroscopes, and, sometimes, magnetometers. Measurement from these instruments has been used in many applications through the last decades (i.e. navigation systems, airbag activation, car alarms, etc.).

The development of microelectromechanical systems (MEMS) has lead to a new field of application of these devices, performance assessment in clinical and home settings [67]. Until recent years, human body movement analysis has been based on kinetic (i.e. net forces and body segments) as well as kinematic (i.e. positions and trajectories) parameters obtained through different tracking systems such as force platforms or vision systems. However, these solutions were quite expensive, invasive and difficult to wear or use in the clinical settings so that they were restricted to laboratory environment. The use of IMUs has become a low-cost, innovative and non-invasive solution not only to functional capacity assessment in clinical diagnostics [68;69], but also to assess sports-related performance [70]. They represent quite an interesting advance in the clinical field since the introduction of devices able to provide quantitative and objective parameters related to the health status of the patients will surely improve actual diagnostics. Therefore, not only clinicians but also physiotherapists would be take advantage of this information to prescribe accurate actions as physical fitness program to correct or at least improve specific deficits.

As previously mentioned, accelerometers and gyroscopes from the IMUs directly provide accurate estimation of the acceleration and angular velocity of a particular movement of the subject. Moreover, magnetic sensors are also used to reckon the heading of the sensor with respect to the global coordinate system. Finally, an accurate estimation of the orientation can be assessed by fusion of inertial and magnetic sensing in a Kalman filter structure [71;72]. However, it is needed an extra analysis of these amount of data to obtain the corresponding kinetic and kinematic parameters normally used in clinical evaluations. At present, there is a wide amount of authors that have included IMU into their researches to outperform functional test with this kind of parameters able to catalogue certain diseases (i.e. Parkinson, frailty, etc.)[73-78]. Signal analysis goes from identification of peaks and ranges of acceleration and angular velocity data in time domain [79-82], to complex Wavelet analysis into the frequency domain [70;75;80]. Identification of the specific task under study, especially when the test involves different movements or the consecution of a set of cycles is a prerequisite to evaluating kinematic parameters, adding toughness to the whole signal analysis process [83-85]. Moreover, there is a lack of a gold standard and a lot of different approaches to use which makes it more difficult to compare results. However, the advantages of furnishing clinicians with a set of objective and quantitative parameters that can classify a patient depending on their imbalance make the integration of IMUs a trending topic into the biomechanical field.

1.3 AIM AND OUTLINE OF THE THESIS

The primary aim of this thesis was to evaluate the use of inertial and magnetic measurement systems to outperform the 30-s CST, motivated by the urge of objective parameters to identify as soon as possible the complex frailty syndrome.

Chapter 2 begins the development of this thesis with a systematic review for the assessment of the SiSt and StSi transitions performance by using IMUs. The aim of this chapter is to assess the role of IUs in physical performance evaluation so that clinicians can have at their disposal new devices and objective measures to improve their diagnostics. Moreover, the most significant inertial sensor-based parameters and the most interesting results for each pathological condition were listed in different tables.

Chapter 3 shows the novel “PB-algorithm” to obtain drift-free position estimation for periodic movements. Z-axis acceleration data from a single IMU located on the lower back was used to estimate the up and down position of the subject when performing the different cycles of the 30-s CST. Drift disturbances were removed based on polynomial data fitting, splines interpolation and the wavelet transform, one after the other. The Vicon optical measurement system was used as gold standard and also another drift-correction algorithm was tested to compare results. High accuracy respect of the Vicon’s reference was showed and a reduction of the mean-square-error (RMSE) was obtained from the previously proposed algorithm. This study means the first step to analyze the kinematic parameters within the 30-s CST duration since Z-position is actively used in the cycle’s recognition.

Chapter 4 explains, for the first time, the inertial measures of the 30-s CST using a single IMU attached on the lower back in a pre-frail population. Z-position drift-free signal was used to automatically count the number of performed cycles and the three corresponding cycle's phases (i.e. "impulse", "stand-up" and "sit-down") were detected thanks to the IMU data. A collection of meaningful data based on kinematic parameters is selected for further analysis.

Chapter 5 extends the study done for the time-domain information from the 30-s CST in pre-frail subject. The aim is to identify subjects with different frailty levels (i.e. frail, pre-frail and healthy). Here, other parameters such as the X-orientation ranges and the standing-up and sitting-down "modified-impulses" are also evaluated. Moreover, a subset of pre-frail and healthy subjects with the similar number of performed cycles was assessed in terms of kinematic parameters. So, the developed procedure seems to be a clear improvement of the current clinical evaluations based on the 30-s CST.

Finally, chapter 6 sums up the most important results of the thesis. Here, the conclusions and the recommendations for future research in this field were included.

CHAPTER 2:

Kinematic Parameters to Evaluate Functional Performance of Sit-to-Stand and Stand-to-Sit Transitions Using Motion Sensor Devices: a Systematic Review

Millor N., Lecumberri P., Gómez M., Martínez-Ramírez A. and Izquierdo M.

(IEEE Transactions on Neuronal Systems and Rehabilitation Engineering, 2014; DOI:10.1109/TNSRE.2014.2331895)

2.1 ABSTRACT

Clinicians commonly use questionnaires and tests based on daily life activities to evaluate physical function. However, the outcomes are usually more qualitative than quantitative and subtle differences are not detectable. In this review, we aim to assess the role of body motion sensors in physical performance evaluation, especially for the sit-to-stand and stand-to-sit transitions. In total, 53 full papers and conference abstracts on related topics were included and 16 different parameters related to transition performance were identified as potentially meaningful to explain certain disabilities and impairments. Transition duration is the most used to evaluate chair-related tests in real clinical settings. High-fall-risk fallers and frail subjects presented longer and more variable transition duration. Other kinematic parameters have also been highlighted in the literature as potential means to detect age-related impairments. In particular, vertical linear velocity and trunk tilt range were able to differentiate between different frailty levels. Frequency domain measures such as spectral edge frequency were also higher for elderly fallers. Lastly, approximate entropy values were larger for subjects with Parkinson's disease and were significantly reduced after treatment. This information could help clinicians in their evaluations as well as in prescribing a physical fitness program to correct a specific deficit.

Index Terms: Body motion sensors, functional performance, kinematic parameters, signal analysis, sit-to-stand, and stand-to-sit.

2.2 INTRODUCTION

Standing from a seated position and sitting from a standing location are the most commonly performed daily activities [86]. These activities are not simple movements; in fact, they have been regarded as the most mechanically and muscle demanding tasks undertaken during daily activities [51-55;87;88]. Optimal coordination, balance, adequate mobility and enough strength and muscle power outputs are required for successful sit-to-stand-to-sit (SiStSi) cycle performance [89;90]. In particular, the elderly population experiences notable difficulties when performing these transitions [51] due to their generally reduced mobility, which is caused by acute illness, trauma or progressive de-conditioning (i.e., sarcopenia), [22;87;91]. As a result, the time that the elderly spend sitting is likely to be increased, and potentially ambulant subjects remain, in fact, prisoners in their chairs [92-94]. Moreover, an inability to rise independently often contributes to impaired functioning and mobility in activities of daily living (ADL), an increased risk of falling [95;96], needs of extra-help [97], and even death [98-100].

Clinicians usually evaluate elderly physical function through a battery of feasible tests, which are based on daily life activities, using stopwatch measures. Sophisticated technologies such as force platforms [101-103], and/or optical motion systems [55;104] make it possible to capture another dimension of physical function, supplementary to the currently available information. However, laboratory setting requirements as well as high cost and processing time make them unfeasible in clinical evaluations [67;105] and even more for elderly population [106;107]. The development of micro-electromechanical systems (MEMS) has led to a new alternative for movement performance assessment in medical and home settings: motion sensor devices (MSDs) [108]. Recent studies highlight interest in using this tool to assess functional capacity [68;109;110] and sports performance [70;111]. However, MSDs provide an extensive amount of kinematic and kinetic data, so extra signal analysis is needed to obtain meaningful parameters that can explain specific disabilities or pains (e.g., an assessment of acceleration, angular velocity or segment orientation) (Figure 2.1), [80;90;112].

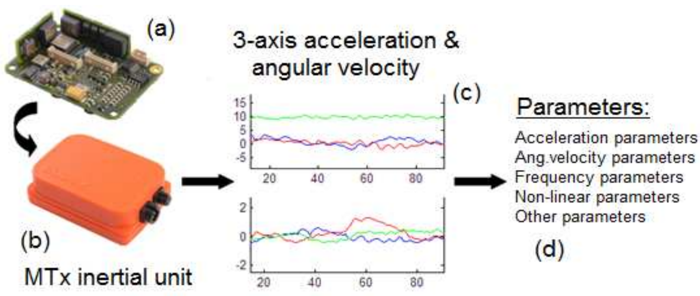

Figure 2.1: *Process to obtain meaningful kinematic parameters using IUs: from MEMs (a) to MTx inertial unit (b), derived signals (c) and final parameters (d).*

Recently, MSD technology has been incorporated into protocols to assess functional performance through different tests [113]. In particular, age-related diseases, such as the frailty syndrome (FS), have been widely studied in the literature based on kinematic information [73;75;76;108]. Different accelerometer-based, physical activity-monitoring review papers have also provided results for walking activity [78] or analysis of specific impairments, such as the fall risk assessment [74;77]. However, there is a need for a critical and comprehensive evaluation of the complex performance of the sit-to-stand (SiSt) and stand-to-sit (StSi) transitions that addresses study methodologies; specific assessment activities; the nature of the inertial sensor used and its location; and, in particular, meaningful parameters that are able to differentiate certain disorders and therefore retain potential clinical significance. In this review, we present a critical examination of the literature related to SiSt and StSi assessment using inertial sensors and submit a list of parameters as evidence of the usefulness of this promising technology.

2.3 METHODS

2.3.1 Search strategy

The PubMed, Scopus and ISI Web of Knowledge databases were searched up to December 31, 2013, for relevant studies based on original scientific investigations during the period from 1990 to 2013. The search terms included various combinations of the following groups of keywords: (1) one term related to the employed technology ('accelerometry', 'accelerometer', 'sensor' or 'inertial unit') and (2) one term describing the evaluated transition ('sit to stand' or 'stand to sit'). For the PubMed search, all databases were reviewed, but only PubMed and PubMed Central (PMC) were taken into account. The Scopus search was performed within all fields, whereas the ISI search was conducted only for the topic field. The names of authors who were cited in several of the studies were also used in the searches. This systematic review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [114].

2.3.2 Research criteria

A systematic literature review was conducted with a pre-planned protocol specifying inclusion and exclusion criteria for the identified studies and data analysis. The search criteria were as follows: (1) the studies must have been published in English-language, peer-reviewed scholarly journals; (2)

dissertations, reviews and theses were excluded; (3) only conference proceedings with novel results and detailed information about the signal analysis were considered; (4) the studies must have used accelerometer and/or gyroscope technology with the aim of assessing the SiSt and/or StSi transitions, but not only with a classifier purpose and (5) the activity test must have been a clinical test or a battery of movements (i.e. stand-up, sit-down, walk, etc.), evaluated for a limited period of time (i.e. several minutes).

2.3.3 Process of study inclusion

From the preliminary search, 468 manuscripts were collected. To check whether the articles fulfilled the inclusion criteria, a review of the titles and abstracts was performed. Only 142 studies were selected for a second analysis, which consisted of a full reading and summary in a pre-established table containing information on the following items: author and year; study aim; instrument used; test performed; signal analysis; principal variables obtained; and group comparison, if done. A third analysis was performed to evaluate whether there were repeated studies in different forms (i.e. a conference proceeding and a journal article). Lastly, 53 original articles based on assessment of the SiSt and/or StSi transitions using parameters from accelerometers and/or gyroscopes were evaluated in depth (Figure 2.2). The information extracted from the selected papers was methodological features of the overall process, information about the performed tests and further details about the used MSD. Moreover, these kinematic parameters that have been highlighted to their ability to assess physical function were listed based on their contributions to detect or explain certain impairments.

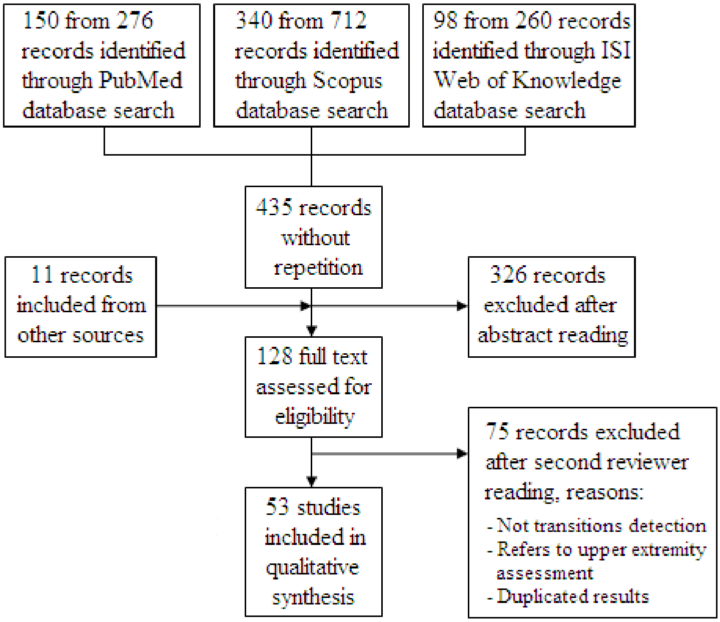

Figure 2.2: *Systematic review process (PRISMA statement).*

2.4 TRANSITION EVALUATION

2.4.1 Overall considerations

The authors who first incorporated an accelerometer into their measurement system for chair-related tests were Kerr et al. in 1994 [115]. They highlighted the importance of analysing the sit-stand-sit cycle to provide researchers with a means of standardizing and quantifying information, similar to the approach from which gait analysis has benefited greatly [115-118]. In this case, an accelerometer was used to measure only accelerations, whereas other tools (i.e., a goniometer and a vector stereograph) were employed to obtain joint angles and displacements. However, subsequent studies assessed the accuracy of measuring the kinematics of rising from a chair with accelerometers and gyros [68;119-123]. These studies determined that the acceleration and angular velocity signals directly provided by MSDs could be used to obtain further information (i.e., orientation and position). Therefore, a system only based on the use of accelerometers and/or gyroscopes was able to evaluate both the SiSt and the StSi transitions [124-126].

2.4.2 Tests

Four main tests were used to evaluate transition performance: tests based on daily life activities, including the SiSt and StSi transitions (12.5%), a single SiSt transition (20%) and sets of SiStSi cycles (41%), and traditional tests (43%). In the last group, the tests employed in the literature were the timed up-and-go (TUG) test (62.5%), the five times SiSt (STS5) test (25%) and the 30-s chair-stand test (CST) (12.5%). Percentages indicate the amount of studies that are related to a specific feature from the total of them.

2.4.3 Motion Sensor Devices

Three different sensors were used in the reviewed papers: gyroscopes (angular velocity), accelerometers (acceleration) and magnetometers (magnetic fields). Accelerometers were the only inertial sensor in 28% of the studies, whereas gyroscopes or magnetometers were the only inertial tool in 2% of the articles. However, the vast majority of authors employed a combined measurement unit (68%) based on accelerometers and gyroscopes (59%) or the three units (9%). Regarding the number of units used in movement assessment, the majority of authors employed a single unit (61%) located at different parts of the body. These locations varied in the literature, from the front sternum or chest (27%) to the back trunk (57%) or another location, such as the thigh, shank or ankle (44.5%). The L5-L3 region was typically used for the back trunk location due to its proximity to the centre of mass [108;124].

2.4.4 Kinematic information

MSDs directly provide acceleration and angular velocity data, and further information (i.e., orientation and position) can be obtained through signal analysis. Only 16% of the reviewed articles aimed to assess how to obtain trajectory-related information (i.e., orientation and position) or analyzed how to reduce the drift effect to correct impairments. The remaining 84% assessed how kinetic parameters could provide clinicians with quantitative information to improve their evaluations. Only 5% of those studies were based on the parameters directly provided by an MSD (i.e., acceleration and angular velocity), whereas 95% of them employed further information, such as time duration, ranges of motion or frequency-derived measures. Regarding the impairments evaluated, the vast majority (95%) of studies assessed age-related conditions, whereas few studies (5%) assessed other types of impairments (i.e., total knee or hip arthroplasty).

2.5 DATA PROCESSING: FROM SIGNAL TO INFORMATION

MSDs yield raw datasets (i.e., acceleration and angular velocity), but analytical techniques are needed to obtain clinically relevant information such as meaningful kinematic parameters [83-85]. Identification of the SiSt and StSi transitions is a prerequisite to evaluating kinematic information, such as peak values, ranges and impulses (Figure 2.3). In total, 254 different parameters were assessed in the literature, and these parameters can be categorized as temporal (22%), acceleration-derived (46%), orientation-derived (14%), frequency-derived (11%) and other (7%). Moreover, 127 of the parameters have been outlined as clinically relevant to evaluating patients ($p<0.05$): 22% of these were temporal; 43%, acceleration-derived; 17%, orientation-derived; 3%, frequency-derived; and 11%, other.

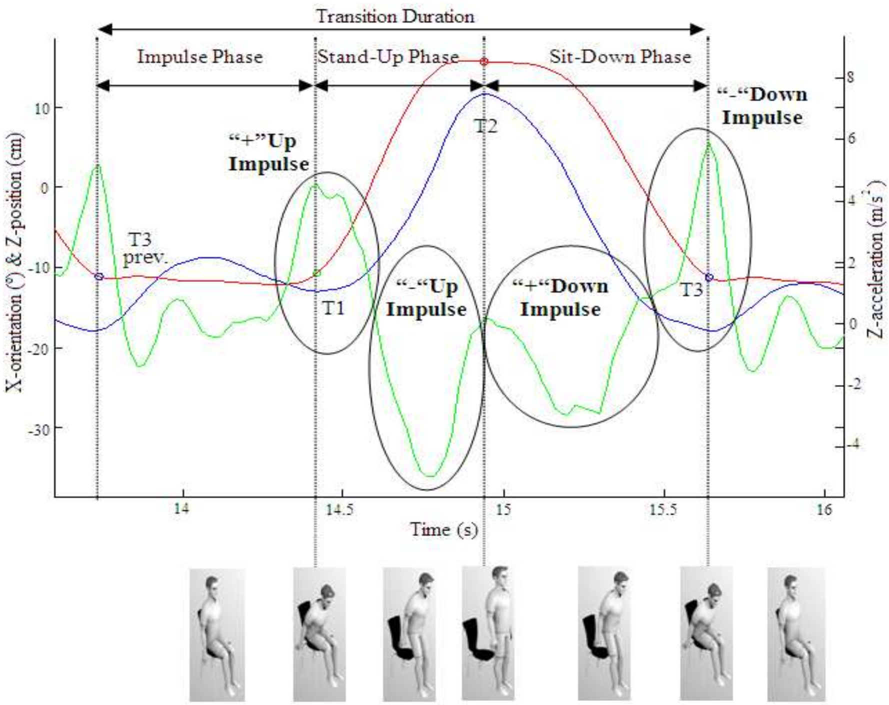

Figure 2.3: *Summary of meaningful parameters obtained from the 30-s CST. Lines blue, green and red are the corresponding X-orientation, Z-acceleration and Z-position signals. Sit-to-stand-to-sit transition duration was divided into the phases: impulse, stand-up and sit-down. The signalled parameters are the positive and negative "impulse" during the stand-up and sit-down phases.*

2.5.1 Transition duration

The time expended in performing the SiSt and/or StSi transitions [i.e., transition duration (TD)] has been described as a clinically relevant factor that can potentially be extracted from accelerometer signals using different analyses [106]. Conventionally, this value has been obtained under laboratory conditions using force platforms [127]. However, data from MSDs make it possible to automatically calculate this parameter in an easy-to-use manner. In general, authors tend to estimate TD based on peak detection or thresholds using the acceleration or orientation data from an MSD. There are also other methods based on the use of more than one reference signal or complex algorithms. The majority of these techniques use this parameter to identify certain disabilities (Table 2.1).

Najafi and co-workers presented the first method, using only MSDs to obtain TD. This method was based on the change in the trunk tilt in the sagittal plane, computed from the time integral of the gyroscope signal [126]. In this case, TD was defined by two positive peaks, before and after the maximum negative peak of the trunk tilt. Vertical (V) displacement, obtained through second integration of V acceleration information, was able to differentiate between the SiSt and the StSi transitions [128]. The authors observed that high-fall-risk elderly fallers experienced a lower and more variable TD [126]. This procedure demonstrated high agreement with the gold standard based on force plates [129]. In the literature, other authors have also used this methodology to assess the influence of TD on certain impairments. For instance, in [80] was found that frail subjects experienced a significantly greater TD than did healthy counterparts. This parameter significantly decreased after the completion of a rehabilitation program but further analysis was needed to detect minor improvements, [130]. Similarly, in [112] was proved that older adults needed a longer and more variable TD compared with young adults when performing the STS5 test.

Janssen and co-workers delimited the SiSt transition through a threshold of 5°/s of the trunk angular velocity signal, which was also based on the idea that body trunk movements define TD [123]. Boonstra et al. used this TD identification method as well [68;131;132]. In this case, they found that after total knee arthroplasty (TKA), patients needed longer to perform the SiSt transition [68]. Similarly, Higashi et al. selected a threshold of 10°/s in the pitch and yaw directions to assess TD from the TUG test [133]. However, they did not find any difference when evaluating hemiplegic patients and healthy subjects in terms of TD values [133].

Another technique employed to estimate TD was the use of the acceleration signal, as it is related to the forces needed to perform the transition. The first authors to use this method were Bidargaddi and colleagues, who employed a wavelet approximation of the signal vector magnitude (SVM) from a tri-axial accelerometer mounted on the chest. In this case, the global maximum and minimum were identified, and the SiSt duration was assumed to be two times the difference between them. Healthy and geriatric subjects were evaluated in terms of TD, and SiSt duration values were significantly lower for the first group. In contrast, StSi duration values did not present such differences [106]. Janssen et al. also used the acceleration information to obtain TD. In this case, the derivative of the acceleration signal was taken as a reference, and a threshold of ±0.05 m/s^3 was employed to identify the beginning and the end of the TD [125;126;134]. This parameter showed discriminative validity in comparing stroke subjects with healthy [125]. Additionally, Zijlstra et al. estimated the TD of the SiSt using the acceleration due to gravity as a threshold based on the V acceleration [135]. Regterschot et al. also employed this methodology and showed how older adults have a significantly reduced SiSt duration after training [136]. The acceleration of other axes was assessed when evaluating transitions in tests such as the TUG and the STS5. For instance, Weiss et al. used the anterior-posterior (AP) acceleration signal to obtain the SiSt and StSi TDs from the TUG test [137;138]. A clear 'M-shaped' pattern was identified, and TD was defined as the time interval between the maximum peaks. However, this parameter was not able to differentiate between healthy subjects and subjects with Parkinson's disease (PD) [137] or between idiopathic fallers and non-fallers [82;138]. Using the same methodology, Mellone et al. demonstrated that the embedded MSD of current smart phones could be used to this end [139]. Millosevic et al. noted that PD patients have a longer TD than their control counterparts [140], and Doheny et al. showed that there was no difference in this parameter as an effect of training in middle-aged adults [141]. Regarding the STS5 test, Doheny et al. estimated SiSt and StSi durations from the medio-lateral (ML) acceleration. In this case, they first identified a minimum acceleration point for each SiSt, A_{MS}, and used it as a percentage (20% or 80%) of the threshold to recognize the start and end of each SiSt and StSi component [142]. This TD was described as a potential parameter to identify those elderly subjects who were more prone to fall [142], and in particular, the SiSt duration was suggested as indicative of fall risk [141].

Other studies employed more than one signal to obtain TD. Giansanti and co-workers defined thresholds on both the modulus of the acceleration and angular velocity information to estimate the SiSt transition duration [123-125;134;143]. This methodology was used to assess fall risk. Similarly, Aissaoi et al. detected the SiSt duration through the dot product of the acceleration and the angular velocity signal [50]. Recently, Millor et al. used four different signals (i.e., V acceleration, velocity and position and AP orientation) to obtain

SiSt and StSi durations from the 30-s CST [76;108]. They also distinguished a new phase, the so-called 'impulse phase', whose value was significantly lower for higher frailty levels [76].

Lastly, some authors used other techniques to obtain TD. For instance, Salarian et al. used kinematic features of trunk movements during the transitions and a statistical classifier to detect the SiSt and StSi [81]. They highlighted that this parameter was significantly higher for PD patients than for controls, which did not happen when assessing TD from the TUG test with the same methodology [144]. Similarly, Redmond et al. automatically segmented the TUG and STS5 tests based on a criterion function from predefined 3D acceleration features (i.e., standard deviation and mean magnitude) and a peak-search procedure [145]. Additionally, Adame et al. developed a method built on dynamic time warping (DTW) for the detection and duration assessment of associated state transitions based on gyroscope signals along the pitch axes [146]. However, in this case, TDs showed no significant differences for the healthy control and early PD groups.

2.5.2 Time domain parameters: linear and angular kinematics.

To evaluate how a transition was performed, insight into the signals recorded by an MSD is necessary, after which kinematic parameters can be obtained (i.e., maximum and minimum peaks, ranges of motion and dispersion measures). To describe SiSt and StSi motion, both linear and angular kinematics has been evaluated to determine the rotation and translation movements that compound a general motion.

TABLE 2.1: SIGNIFICANT INERTIAL SENSOR-BASED PARAMETERS ($p<0.05$)

Category	Parameter: Value	Parameter: Movement|$_{test}$	Imbalances
Temporal	TD	SiSt/StSi	FR [126], AE [106], PD [81], SR [125;126;134], TP [136]
	TD	SiSt/StSi|$_{cycles}$	FS + RP [80;147]
	TD	SiSt/StSi|$_{TUG}$	PD [146]
	TD	SiSt/StSi|$_{STS5}$	AE [112]
	TD	SiSt/StSi (sub-phases)|$_{STS5}$	AE [112]
	TD	Imp./ SiSt /StSi|$_{30s\text{-}CST}$	FS [76]
	SD	SiSt/StSi	FR [126]
	CV	SiSt/StSi|$_{STS5}$	AE [112]
	CV	SiSt/StSi (sub-phases)|$_{STS5}$	AE [112]
	Max. min. Z-acc.	SiSt	PD [81]
Linear Acceleration	Max., min., V[1]	SiSt	PD [79], AE [136]
	Max., min. range (V+AP)[1]	SiSt	FS [73], PD [81]
	Range, mean (AP)[1]	SiSt/StSi|$_{TUG}$	PD [137], FR [138], TP [141]
	Range (AP)[1]	SiSt/StSi (sub-phases)|$_{TUG}$	PD [137], FR [138]
	RMS, range (ML, AP)[1]	StSi|$_{TUG}$	TP [141]
	RMS (AP, ML, V)[1]	STS5	FR [148]
	Max., min. (V, AP)[1]	SiSt|$_{STS5}$	FS [149]
	Max., min. (V, ML)[1]	StSi|$_{STS5}$	FS [149]
	Min. (V+ML)[1]	StSi|$_{STS5}$	FS [149]
	Max. SI jerk	StSi	TP [82]
	Max., mean, Δ |3D-acc.| jerk	SiSt/StSi|$_{TUG}$	PD [137]

Linear Acceleration	Max., mean, Δ |3D-acc.| jerk	SiSt/StSi (sub-phases)|$_{TUG}$	PD [82], FR [82]
	Max., min. V-lin. veloc.	SiSt/StSi|$_{30s\text{-}CST}$	FS [76]
	Max., min (SI+AP) lin. veloc.	SiSt/StSi|$_{30s\text{-}CST}$	FS [76]
	TEm	SiSt/StSi	FS+RP [80;147]
	AUC$^{+,-,T}$ (V-acc.)	SiSt/StSi|$_{30s\text{-}CST}$	FS [76]
	Peak power (V)	SiSt	TP [136]
Angular Velocity	Max knee_veloc.[2]	SiSt	TKA [131;150]
	Knee_veloc.[2] asymmetry	SiSt	TKA [150]
	Max. roll rate	StSi(sub-phases)|$_{STS5}$	AE [112]
	Roll cTrunk3	SiSt/StSi|$_{cycles}$	PD [73]
	Roll range	Impulse/SiSt|$_{30\text{-}s\ CST}$	FS [76]
Frequency	RMS (HF ML acc.)	SiSt	SR [134]
	AUC (HF ML acc.)	SiSt	SR [134]
	Total SEF	STS5 test	FR [132]
	Mean SEF	SiSt/StSi|STS5	FR [132]
	Mean SEF	SiStSi cycle|STS5	FR [132]
	RMS (HF ML acc.)	SiSt	FR [132]
Other	d_F	SiStSi cycle	FS+RP [147]
	d_F	SiSt/StSi	FS+RP [80]
	ApEn ang. vel.	SiSt	PD [151]
	ApEn pitch ang.	SiSt	PD [151]
	ApEn pitch acc.	SiSt	PD [151]

[1] This kind of parameters refers to the category.
[2] Angular extension velocities measured from a MSD unit located on the knee.
[3] Core of trunk or the negative peak range value.

A. ***Linear kinematics***

Linear kinematics involves the study and description of the shape, form, pattern and sequencing of linear movements over time. The SiSt and StSi transitions are executed in the sagittal plane, so linear information (i.e., acceleration, velocity and linear displacements) along the V and AP axes are usually considered in the literature [68;80;81;128] (Table 2.1).

The acceleration signal is the rate of change in velocity and is directly related to the forces needed to perform a specific movement. The first authors to evaluate acceleration from the SiSt and StSi using an accelerometer were Kerr et al. [118]. In this case, only the times of both positive and negative acceleration peaks were used to assess the transition pattern, without further evaluations. However, subsequent studies employed more parameters from the acceleration data to explain certain impairments. In particular, for the SiSt and/or StSi transitions, V and AP acceleration were typically used to assess movement performance [76;125;130]. Only in a few cases was ML acceleration considered as being related to balance [134;142]. In particular, the maximum and minimum peaks of V acceleration during the SiSt showed preliminary feasibility for discriminating between parkinsonian and non-pathological subjects [152]. Additionally, maximum acceleration considering the norm of V and AP acceleration was significantly higher after a rehabilitation program for frail elderly people who performed the SiSt transition [80]. These maximum, minimum and range of acceleration values were also significantly higher for control subjects compared with PD patients and for PD patients with stimulation compared with subjects without it [81]. Taking into account the norm of the 3D acceleration, the maximum value showed significant improvement after an exercise program in older adults [136]. Differences were also found in these values when performing clinical tests. For the STS5 test, the maximum and minimum values of the acceleration along different axes showed significant differences between populations with different frailty levels [149]. In particular, V acceleration for both the SiSt and the StSi was significantly lower for a frail population than for physically active elderly. Parameters from this test were also selected as interesting features to take into account when developing a model to improve the fall-risk classification [148]. For the 30-s CST, differences in the frail group were also detected based on maximum and minimum acceleration peaks [76]. In this case, minimum Z-acceleration values during the SiSt and StSi were significantly greater for healthy subjects than for pre-frail and frail subjects. For the TUG test, the range of the AP acceleration from the SiSt and StSi parts of the test was significantly lower for PD patients than for controls [137]. The researchers also found that PD patients showed significantly greater values for the range of and median acceleration during descending than during rising, most likely due to a lack of control of movement performance [137]. Similar results were found when comparing elderly fallers with healthy counterparts [138]. Fallers shared a heightened risk of falling with PD patients [138]. AP and ML ranges, as well as RMS values of the acceleration of the SiSt and StSi from the TUG test, also showed a significant improvement after an exercise program for functional mobility in middle-aged adults [141]. In particular, after the intervention, AP values increased, whereas ML values decreased.

The derivative of the acceleration data with respect to time, or 'jerk', indicates how fast change occurs over time. These forceful and sudden variations have also been used in the literature to assess SiSt and StSi transition performance. One example is the TUG test, where the AP jerk for the SiSt and StSi transitions presented promising results as those for acceleration [137;138]. This result was explained here by the difficulties presented for both PD patients and idiopathic fallers present difficulties when actively rising. Similar results were obtained using the STS5 test. Here, the ML jerk was significantly higher for fallers than for healthy subjects, probably due to their minor ability to control movement performance [142]. Finally, it was also observed that maximal positive jerk during the acceleration phase of a single stand-up was significantly higher for older adults who have followed an exercise-based intervention [136].

Linear velocity is the time rate of change of linear displacement. In the SiSt and StSi transitions, this parameter indicates how fast the subject reaches the upright position and/or a seat. Although it has been stated that there is a tendency for forward lean velocity to decrease with age [118], few authors have reported linear velocity values in the literature. Millor et al. showed that the peak and range of the linear velocity along the V axis during both the SiSt and the StSi in the 30-s test were able to detect frailty levels [76]. In particular, higher values for the maximum velocity peak during the SiSt and the minimum peak during the StSi showed significantly decreased values with frailty. Similarly, the peak velocity based on the three axes of acceleration was significantly higher after an exercise intervention in older adults [136].

Lastly, other acceleration-derived parameters, such as the SVM, the summed magnitude area (SMA), and the 'modified impulse', have been evaluated in the literature for the SiSt and StSi. However, neither the SVM nor the SMA present any favourable results for assessing fall risk in the TUG test [153]. However, the positive, negative and total "modified impulse" ($AUC^{+,-,T}$) of the V acceleration showed a decreased value with increasing frailty [76].

B. *Angular kinematics*

Angular kinematics provides a description of the rotation of one movement. In the case of the SiSt and StSi transitions, the trunk usually leans forward and backward, described as a rotation through the X-axis or pitch angle. However, measures along the other axis can also provide meaningful information about the balance control of a subject (Table 2.1).

Regarding the angular velocity, certain parameters stand out in the literature as meaningful to detect certain impairments (i.e. maximum and minimum peaks). One of these parameters is the maximal knee angular extension velocity, an indicator of patients' quadriceps weakness [154]. There was a significant decrease of this value after total knee arthoplasty (TKA) [150], as well as after total hip arthoplasty (THA) [132]. Moreover, results some months after the operation were also promising. There was an increase the first 6 months, but one year post-operation, patients still showed lower values during stand-up compared to the control group [132]. In the case of THA, it was observed that patients did not perform the SiSt movement kinematically differently, than primary THA. Similarly, the peak angular velocity during the flexion and extension phases of the SiSt and StSi transitions was also lower for older adults than for young subjects [112]. This parameter was also useful to detect frailty subjects. In particular, the maximum and minimum peaks and the mean value of angular velocity for the different axes were lower for frail subjects than for physically active elderly subjects [149].

An orientation signal can be obtained from an MSD's raw information. Positive and negative peaks and the range of motion have been typically evaluated as being related to the trunk movement needed to perform the transition. It has been noted that the SiSt and StSi transitions in the TUG test do not yield meaningful information. For instance, no significant differences were found for the range of the AP tilt of the trunk during the SiSt and/or StSi in the TUG test [81;144]. However, a test involving several SiStSi cycles provided interesting parameters. Trunk tilt was significantly lower in healthy subjects compared with frail subjects for the StSi transition alone [80]. Furthermore, a significant decrease in this value was observed after a rehabilitation program in frail subjects [80]. Similarly, frail adults have significantly lower roll rotation during the SiSt and StSi than do the physically active elderly when performing the STS5 test [149]. No differences were found in the trunk tilt of the SiSt and StSi transitions in the 30-s CST in subjects with different frailty levels [76]. However, this value was significantly higher for frail subjects during the linking phase from the StSi to the SiSt or the so-called 'impulse phase' [76].

C. Frequency derived parameters

During the last decade, parameters from the frequency domain have also been used to evaluate the SiSt and StSi transitions (i.e., energy measures obtained by the FFT algorithm) (Table 2.1). In particular, a different energy distribution of the V acceleration was noticed when comparing PD patients and healthy subjects [79]. Similarly, trunk dynamics measured based on local energy also differed between healthy and frail subjects and this parameter was also meaningful for measuring improvement after a rehabilitation procedure [147]. The energy of the signal can be quantified using the local wavelet energy [154]. In particular, local energy at third and fourth levels were significantly lower for frail subjects but increased significantly after a rehabilitation program [80].

Measures derived from the high-frequency component of the transversal acceleration signal have been used to measure balance during the SiSt transition [125]. In this case, the root mean square (RMS) and the area under the curve (AUC) were taken into account. The RMS was only influenced by the amplitudes, whereas the AUC also depended on the duration of the signal. Both parameters showed significantly higher values for stroke patients than for healthy subjects, and the AUC was clearly more sensitive [125]. Similarly, the steadiness of the ML movement during the SiSt and StSi transitions was assessed during the STS5 test [142]. In this case, the authors used the spectral edge frequency (SEF) of the ML acceleration, defined as the frequency below which 95% of the power of the signal is contained. This study showed significantly higher values of SEF for fallers in the total assessment and in the SiSt and StSi transitions [142]. This result suggests that fallers exhibit less smooth ML sway, perhaps due to their compensation strategies because of their fear of falling. Furthermore, SEF values along the other axis were assessed, and the mean value of the SEF from the AP acceleration signal was used, along with other parameters, to develop a model to classify subjects according to their fall status [148].

D. Dynamics and non-linear parameters

Signals from MSDs have also been used to evaluate the dynamic characteristics of the SiSt and StSi (Table 2.1). It was shown that the conjugated momentum estimated by a non-linear dynamic model during the SiSt was correlated with an accelerometry index that was obtained from AP and V acceleration signals by Aissaoui et al. (Equation 2.1):

$$S_{acc} = |a_v| \cdot |a_{ap}|/2 \qquad \text{(Equation 2.1)}$$

The authors hypothesized that this parameter will increase in the elderly and pathological elderly groups, but further studies should be performed to investigate this hypothesis further.

The dynamic complexity of the transitions was evaluated based on the fractal dimension (d_F) [155] using the acceleration and angular velocity information from an MSD. The norm of the acceleration signal, the V and transversal acceleration, and the trunk angular velocity in the sagittal plane were plotted. Finally, d_F was obtained using the box-counting method [156] (Equation 2.2). This parameter was able to quantify the smoothness or complexity of the SiSt and StSi transitions [80;147].

$$d_F = -\lim_{l_b \to 0} \frac{log_{10} N_b(l_b)}{log_{10} l_b} \qquad \text{(Equation 2.2)}$$

where $N_b(l_b)$ is the number of boxes needed to completely cover the pattern l_b is the box length, and d_F corresponds to the slope of the plot $log_{10} N_b(l_b)$ vs. $log_{10} l_b$. The larger the d_F value, the 'rougher' the (|a|, ω) pattern is. This parameter has been described as a relevant metric to distinguish between the healthy elderly and the elderly with a medium level of fall risk, and also able to detect subtle changes in physical performance (i.e., during a rehabilitation program) [80;147].

Lastly, entropy measures can also been obtained for the SiSt and StSi using an MSD to measure the pattern of the transition [151]. In particular, the ApEn has been evaluated, showing larger values in PD patients than in healthy controls. Furthermore, PD patients who switch from deep brain stimulation (DBS)-off to an on state experience a decrease in ApEn values. This finding means that PD increases the irregularity of both the SiSt and the StSi patterns, whereas DBS decreases this irregularity and makes the transitions more predictable [151].

2.6 CONCLUSSIONS

Motion sensor devices are a viable technology for studying the complex movements of the sit-to-stand and stand-to-sit. These portable, unobtrusive and low-cost systems make it possible to obtain kinetic and kinematic data from the transitions. Therefore, meaningful parameters can be obtained through signal analysis to provide a basis for a more precise and quantitative assessment of transition performance in clinical practice.

The main difficulty in this review has been the lack of a gold standard to measure the kinematics of the SiSt and/or StSi transitions. First, there is no agreement about the test that should be used to measure both transitions. The possibilities involve using a battery of daily life movements, including the SiSt and/or StSi [81;143], and clinically accepted tests, such as the STS5 test [142], the 30-s CST [108] and the TUG test [138;157]. Second, different measurement instruments have been used and placed in diverse body regions. Several studies have been based on the use of only accelerometers [106;123;142] or gyroscopes [106;158]. However, it has been reported that measures derived from both instruments (i.e., orientation angles and durations) provided not only more accurate results [68;130] but also linear and angular information. Device placement is also uncertain, but the L3-L5 position is assumed to be appropriate for measuring the motion of the entire body, being the centre of mass [123-125;134;143]. Third, the analysis methodology also differs in the literature. In general, lineal kinematics related to V acceleration and angular kinematics from pitch angle has been selected to explain movement performance [80;158]. In contrast, balance is usually measured using the transversal acceleration signal, which is assumed to be related to misbalance [125;159]. Wavelet analysis is presented as a suitable and powerful technique for enhancing the transition pattern so that it can be properly recognized while eliminating noise during dynamic activities [126;160]. Lastly, techniques based on peak detection seem to perform better than do methods based on thresholds because it is difficult to generalize these values and they also tend to be influenced by noise and movement artifacts [144].

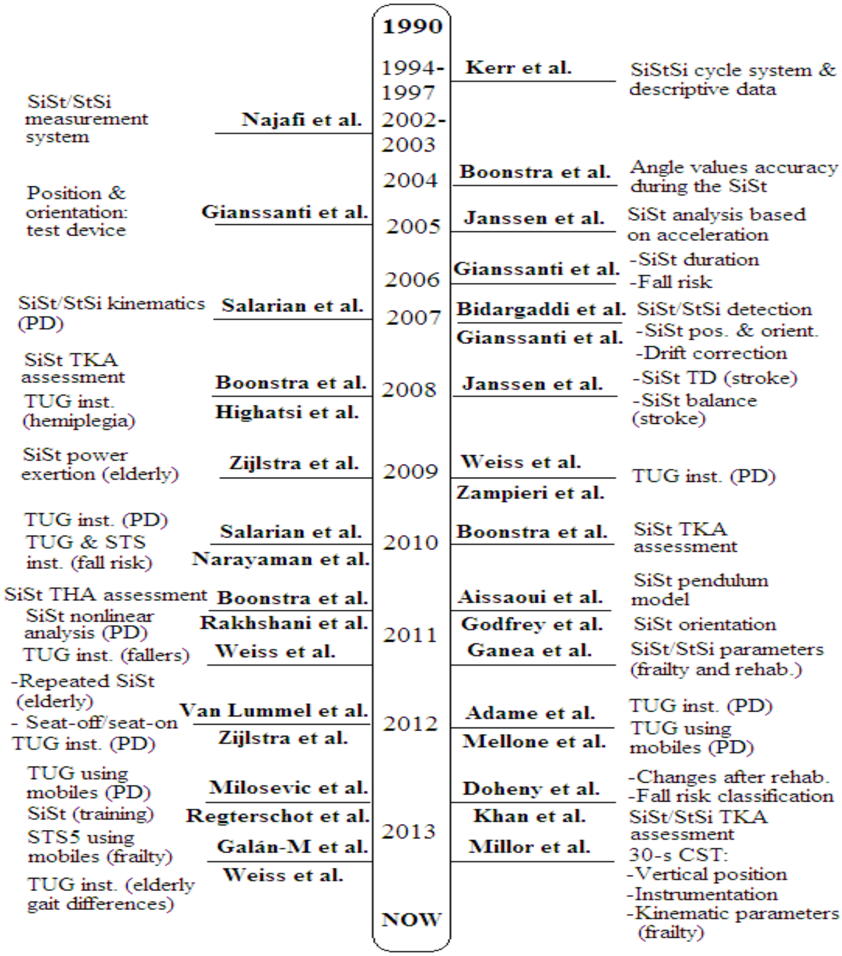

Figure 2.4: *Evolution of the motion sensor technology for the assessment of test involving a chair. Significant years, authors and main characteristics of the studies are specified in this diagram. Here, "inst." means instrumentation while "rehab." refers to rehabilitation.*

Regarding the literature, there was initially concern about validating MSD technology for the SiSt and StSi transitions (Figure 2.4). Therefore, certain studies aimed to show that MSD outputs were accurate enough to measure both transitions [123-125;134;143], and other studies assessed information derived from raw MSD data (i.e., orientation and position) [68;119-121;129]. Next, the aim was to obtain kinematic parameters from MSD data through different signal analyses to furnish clinicians with quantitative information to improve their evaluations. TD, obtained through accelerometer monitoring, was likely the parameter used by the vast majority of studies to measure patients' condition over time. In certain cases, TD was the only measure in the study [106;123;126]. However, in most studies, TD was jointly considered with other kinematic parameters [80;81;112;121;123;137;142;147]. The approach based on time-domain kinematic features was able to discriminate patients with movement disorders [80]. However, these parameters are not able to detect subtle differences [132] or minor improvements resulting from rehabilitation [80]. Therefore, additional information on the global pattern (i.e., dynamic and smoothness) of transitions should be assessed. Furthermore, other types of analyses, such as those related to the frequency domain, are able to provide other types of information, such as balance control [123;123;142]. The ultimate goal is to furnish clinicians with a set of objective and quantitative measurements that can classify a patient depending on the patient's imbalance. For instance, frail subjects need extra time and lean forward to perform a transition, and their acceleration, energy and smoothness are lower than those of their counterparts (Table 2.2).

TABLE 2.2: PARAMETERS RESULTS ACCORDING TO PATHOLOGICAL CONDITION

Pathological condition	Parameter: Value	Parameter: Transition	Results	Clinical Explanation
TKA	knee_veloc. [132;150]	SiSt	Lower A year after: lower increment than control	Decreased ability to generate lower extension velocity
	knee_veloc. Asymmetry [132;150]	SiSt	Unloaded A year after: loaded	Weight shifted from the affected leg
Age Effect	TD [106;112]	SiSt/StSi[1]	Higher	Less movement control
	CV [112]	SiSt/StSi[1]	Lower	Loss of automation
	Max. roll rate [112]	SiSt/StSi[1]	Lower	Moments-related
Frail syndrome	TD [76;80]	Imp./ SiSt /StSi	Higher	Slower movements
	Max., min. V-acc. [76;149]	SiSt/StSi	Lower	Less strength to carry on the impulse
	$AUC^{+,-,T}$ of V acc. [76]	SiSt/StSi	Lower	Reduced lower extremities power
	Roll range [76]	SiSt/StSi	Lower	Compensatory movement strategy
	$TE_{3,4}$ [80]	SiSt	Lower	Less energy
	D_F [80]	SiSt	Lower	Rougher movements
Fall Risk	TD [126;142]	SiSt/StSi	Lower	Lower and more variable movements
	SD [126]	SiSt/StSi	Higher	
	Range, mean AP acc. [138]	SiSt/StSi	Lower	Restricted and cautious movements, reduced ability to regulate balance and compensatory mechanisms
	Range AP acc. [138]	SiSt/StSi	Lower	
	Max., mean AP jerk [138]	SiSt/StSi	Lower	
	Total SEF [142]	STS5 test	Higher	Less steadiness of the medio-lateral movement
	Mean SEF [142]	SiSt/StSi	Higher	
	Mean SEF [142]	SiStSi cycle	Higher	

Parkinson disease	TD [81]	SiSt/StSi	Higher	Slower movements
	Max., min., range (V+AP) acc. [81]	SiSt	Lower	Decreased motor functions
	Range |3D-acc.| [137]	SiSt/StSi	Lower but pronounced over B-SiSt and A-StSi	General bradykinesia and slower movements
	Max., min, |3D-acc.| jerk [137]	SiSt/StSi		
	Range Jerk |3D-acc.| [137]	SiSt	Lower	Rigidity, less PT[3] adaptation
	Median |3D-acc.| [137]	StSi	Higher	Larger trunk flexion
	ApEn values ang.veloc. ; 3-axis accel. [151]	SiSt	Higher	Increased irregularity of PT[3] pattern and decreased predictability
Rehab. training	TD [73;80;136]	SiSt/StSi	Reduction	Improved quickness
	RMS, range (ML,AP) acc. [141]	StSi	Reduction	Improved eccentric control
	Max.value of: V-acc., V-jerk, V-vel. [136]	SiSt	Increase	Higher muscle strength and improved coordination
	Peak power V [136]	SiSt	Increase	
	TT[4] [80]	StSi	Reduction	Movement improvement
	D_F [80]	SiSt/StSi	Higher	More stable PT[3]
	D_F [80]	2-SiStSi	Higher	Decreased unsteadiness
Training program	TD [125;134]	SiSt/StSi	Higher	Slower movements
	RMS (HF[5] ML acc.) [125]	SiSt	Lower	Decreased balance
	AUC (HF[5] ML acc.) [125]	SiSt	Lower	Decreased balance during time

[1] Both transitions are divided into flexion and extension sub-phases or [2] into A,B sub-phases

[3] Postural transition

[4] Roll angle of the trunk tilt

[5] High frequency component.

Recently, MSDs have begun to be used in the systematic assessment of chair-related tests, such as the TUG test [137], the STS5 test and the 30-s CST (Figure 2.4) [137;142]. The qualitative and quantitative data provided by this new test lead to a more detailed analysis of the test. Thus, for engineers, clinicians and physicians, it is possible to work together for the early detection of impairments. Lastly, recent studies reveal that the development of a measurement system based on mobile phone technologies could be an interesting instrument for clinicians to evaluate patients, providing kinematic measures [139] and integrating both kinematic parameters and subjective clinical tests [161].

CHAPTER 3:

Drift-Free Position Estimation for Periodic Movements Using Inertial Units

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3.1 ABSTRACT

Latest advances in microelectromechanical systems have made inertial units (IUs) a powerful tool for human motion analysis. However, difficulties in handling their output signals must be overcome. The purpose of this study was to develop the novel "PB-algorithm" based on polynomial data fitting, splines interpolation and the wavelet-transform, one after the other, to cancel drift disturbances in position estimation for periodic movements. High-accuracy position measurements from an optical system (Vicon Nexus 1.0) were used to validate the proposed method and comparison with another drift-correction algorithm was provided. Results indicate the accuracy with respect to the Vicon's reference signal (Euclidean Error (EE) lower than 54.62 x 10-3m and correlation coefficient higher than 0.968). A reduction of the Root-Mean-Square-Error (RMSE) of 68.74% was obtained when the proposed two-step method was compared with a Modified-Band Limited Fourier Linear Combiner (BMFLC). All methods were applied to data from the 30-s Chair Stand Test (CST), which is one of the most used clinical tests dealing with lower body strength assessment, falls prediction and gait disorders in older adults. The relevance of this study is that after cancelling drift disturbances, and obtaining an accurate Z-position estimation, it is possible to evaluate the sit-to-stand and stand-to-sit transitions from the whole test.

Index terms: accelerometer, drift-problem, human movement analysis, wavelets, splines, 30-s chair stand test.

3.2 INTRODUCTION

Inertial units (IUs) comprising accelerometers, gyroscopes and, in some cases, magnetometers have become an innovative, non-invasive solution not only to assess sports-related performance [70], but also as a clinical source of functional capacity assessment [68;69;162;163]. This is of special interest when dealing with frailty or with Parkinson disease since patient's displacement to a clinic or an institution to make the measurements is often inadvisable [111;164;165]. Indeed, expensive and sophisticated measurement tools such as force platforms or vision systems are being confined to making experiments in laboratories.

One of the main limitations of IUs is that their outputs are relative data sets (i.e. angles between segments and their acceleration or velocity), while standard technologies directly provide absolute and relative body segment position/and orientation in a fixed reference frame. In fact, finding 3-D segment position, absolute angles and complete kinematics is the major difficulty when using body-fixed inertial sensors [83-85]. In this regard, one of the most common problems is the drift effect, an encumbering noise that arises when integrating the acceleration signal to obtain velocity or position, which can even hide the real outcome.

Through the literature different methods can be found to partially solve this problem: aided sensors or sensing systems data fusion [85;166-168] wavelet analysis [126;169], Fourier-based filters [170-174], band-pass filtering [175] and polynomial data fitting [176]. Generally they tend to use the aid of an externally referenced sensor or prior knowledge of the motion as well as complex linear and adaptive filtering or other data processing to estimate displacement from the acceleration signal. The present study develops a new method to cancel the drift effect based on the use of a single IU and jointly considering different processing methods. In particular, polynomial data fitting [176], spline interpolation and wavelet transform were employed one after the other. The idea is to obtain an accurate estimation of the Z-position signal without any restriction (i.e. previous knowledge of acceleration, velocity and/or position at reference points [176]) other than the movement's periodicity. This way, inertial technology arises as a powerful tool to measure activity during mobility related activities in a non invasive manner.

The 30-s chair stand test (CST) is one of the most used clinical tests dealing with lower body strength assessment in older adults [56;67;177]. Moreover, this test has been reported to be a good falls predictor [178] and to have a high correlation to gait and other activities performance [179;180], especially in elderly frail population [181-183]. The relevance of this study for 30-s CST user lies in its enabling automatic cycle's counting and subsequent definition of the movement's phases. Secondly, the current 30-s CST's output information would be improved by automatic analysis of kinematic and kinetic variables describing the movement's performance from IU's data recordings. In addition, to the best of the author's knowledge, drift-cancelling methods have not been deeply tested with long duration and wide movement's amplitudes as the ones of the 30-s CST.

The aim of this study was to develop a novel two-step processing method (i.e. polynomial data fitting followed by baseline estimation) to cancel drift disturbances in position estimation for periodic movements. High-accuracy position measurements from an optical system (Vicon Nexus 1.0) were used to validate the proposed method and to compare its performance with another drift-correction algorithm [170].

3.3 MATERIALS AND METHODS

3.3.1 Subjects

Seven healthy subjects (5 males and 2 females, age: 22 ± 5 years, body mass: 68.5 ± 8.6 kg, height: 1.7 ± 0.1 m) volunteered to participate in this study. All of them were thoroughly informed about the experimental procedure, the purpose, nature and possible risks associated with the study, as well as the right to finish their participation at their will. Subsequently, subjects gave their written informed consent to participate.

These experimental procedures were approved by the Institutional Review Committee of the Public University of Navarra, and Department of Health Sciences of the Government of Navarra, according to the Declaration of Helsinki.

3.3.2 Testing procedures

The 30-s CST consists in standing up and sitting down from a chair with arms crossed across the chest as many times as possible within 30 seconds. All trials were performed in a laboratory with the same chair and ambiance conditions. The chair was backless to permit full visibility of the marker tracker by the optical system during the task performance. Each subject was asked to perform two sets of the 30-s CST under two different conditions. The first one, called self- adjusted-test (SA-test), was carried out after the command "slow but comfortable velocity performance", while the second one, called high-speed test (HS-test), obeyed the command "as fast as possible". There were two minutes of resting time between both trials in order to let the subject recover from the first performance. The reasoning behind this methodology is that during the self-adjusted trial the movement performance is expected to be different from the high-speed one. In fact, trunk angular displacements were assessed to be lower during the high-speed trial [123], raising the impact of geometrical errors [184]. Similarly, smoother displacements were detected when carrying out the 30-s CST for the self-adjusted conditions compared to the fast ones. Therefore, the HS-task is regarded as an extreme scenario in terms of position estimation's difficulty.

3.3.3 Instrumentation

An IU integrating 3 accelerometers, 3 gyroscopes and 3 magnetometers (MTx, Xsens Technologies B.V. Enschede, Netherlands) attached over the L3 region of the subject's lumbar spine provided the kinematic data recorded in each trial at a sampling rate of 100 Hz. MTx combines itself nine individual MEMS sensors to furnish accurate 3D orientation as well as other kinematic data such as: 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field. A detailed description of the MTx's calculation methods can be found elsewhere [75]. Optical motion analysis system (Vicon Nexus 1.0) was used as truth-reference and it was time synchronized with the MTx to compare both signal results.

The IU provided linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (xyz). Before the beginning of the test, with the subject sitting on the chair and his back in upright position, the sensor-fixed reference frame was aligned with the Earth-fixed global reference frame (XYZ), whose Z axis lies on the vertical pointing upwards, its X axis lies on the lateral direction and its Y axis on the anterior-posterior direction (Figure 3.1).

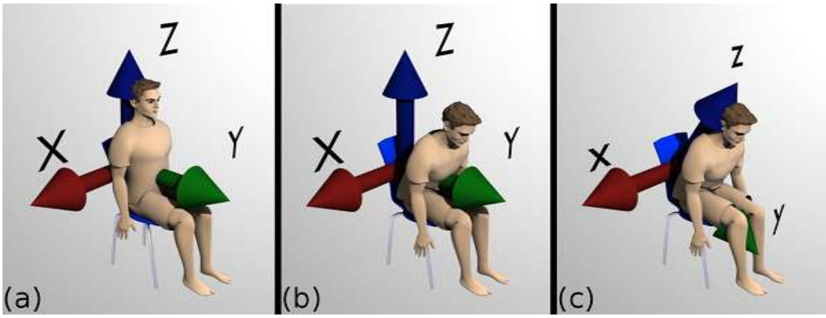

Figure 3.1*: Changes in global and IU's local Cartesian reference axes when the subject is trying to stand up at the beginning of the 30-s CST. In the initial position global and local reference axes coincide (a). When the subject changes position, the global axis remains unchanged (b) whereas the IU's local reference axis rotates with the physical device (c).*

Orientation data consisting in the Euler angles (in XYZ or roll-pitch-yaw order) defined the rotation that aligned the global axis to the sensor- fixed reference frame at each time instant. Then, linear acceleration in the global reference frame was obtained from the acceleration and orientation data provided by the IU (Figure 3.2 (a)). Furthermore, optical data were also collected using a 100Hz six-camera Vicon system (Vicon Motion System, Oxford, UK), in order to check the new method's accuracy [121]. Specifically, in our study, a Vicon Nexus 1.0 was employed, using only three from the six available cameras. They were previously calibrated similarly to [185] and the data from the two systems were time-synchronized through sync pulses in order to compare both of them in an off-line analysis with Matlab (Math Works, Massachusetts, USA). One 4 mm. Vicon reflective marker was placed on the MTx to acquire its three dimensional position for subsequent comparisons.

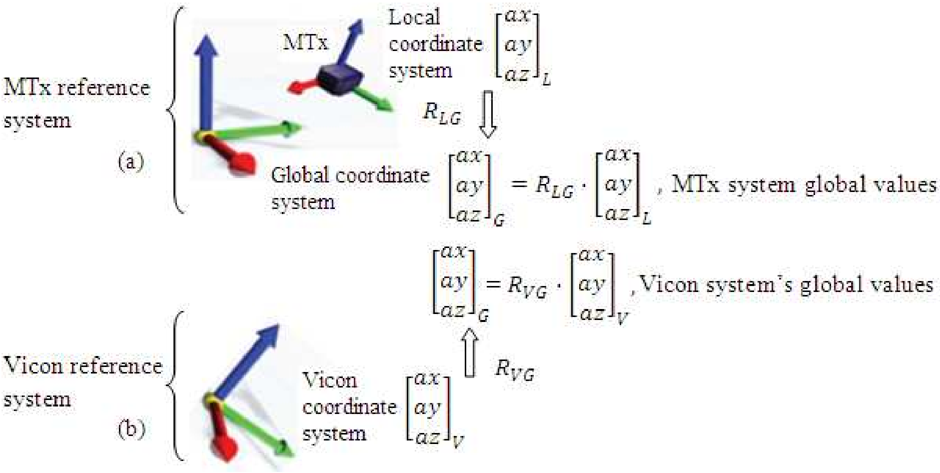

Figure 3.2: *Reference systems changes to obtain the global values from MTx and Vicon. Sub-indexes "L", "G" and "V" refer to the MTx local, global and Vicon local coordinate systems respectively and R_{LG} and R_{VG} to the rotation matrices to change coordinates from the first indicated reference system to the second one.*

3.3.4 Signal processing

A. Drift correction

Z-position signal, obtained through double integration of the Z-acceleration, was used to detect the subject's up and down positions and hence automatically obtain the number of complete sit-stand-sit repetitions during the 30-s CST. However, the raw Z-acceleration signal provided by the IU has to be treated as previously mentioned. Firstly, the coordinate reference system needed to be changed from local to global. Secondly, the gravity acceleration component, roughly estimated as 9.8 m/s2, had to be removed (Figure 3.3).

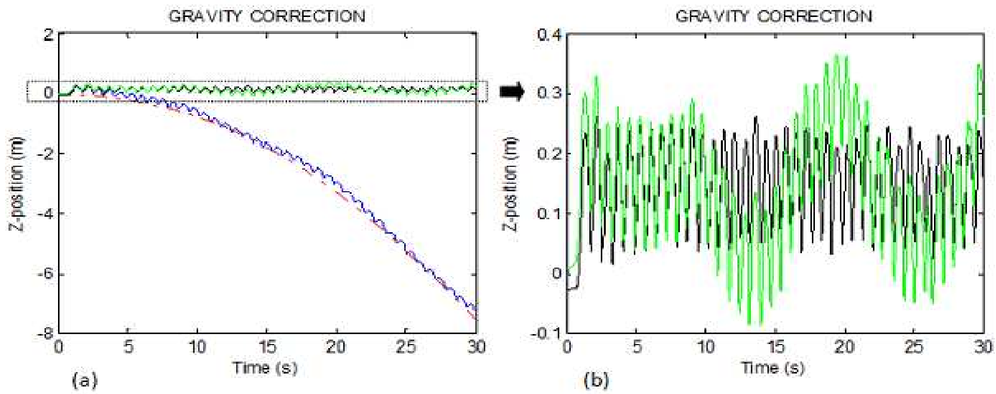

Figure 3.3: *Figure (a) shows the Z-position signal (blue line) gravity error correction (green line), and the Vicon reference signal (black line). Red line is the tendency line based on fourth level polynomial estimation that tracks the gravity error. Part (b) shows the corrected and reference signal enlargement.*

Finally, relative position was obtained through double integration of the acceleration data (Figure 3.4 (a)), assuming resting initial conditions. However, this straightforward process was hindered by noise in the acceleration signal as well as by approximation errors due to numerical integration. This drift effect that occurs for various reasons (e.g. vibration or environmental temperature fluctuations) can, in practice, make the position or velocity signals became unusable within several seconds. Here, a new method based on polynomial curve adjustment and splines approximation is proposed. In doing so, we will be able to achieve a correct Z-position overcoming the drift error problem.

Our correction method first tries to estimate the drift caused by a small DC bias in the Z-acceleration signal principally due to assuming a gravity component of 9.8 m/s^2. This gross approximation leaves a small continuous component which gives rise to a quadratic component in the double-integrated signal. Here, a fourth order polynomial was used to obtain the estimation parameters from the position signal, without incurring in over-fitting. Then, the derivative of the estimated polynomial was employed to adjust the velocity signal and get the position signal through integration (Figure 3.4 (b)).

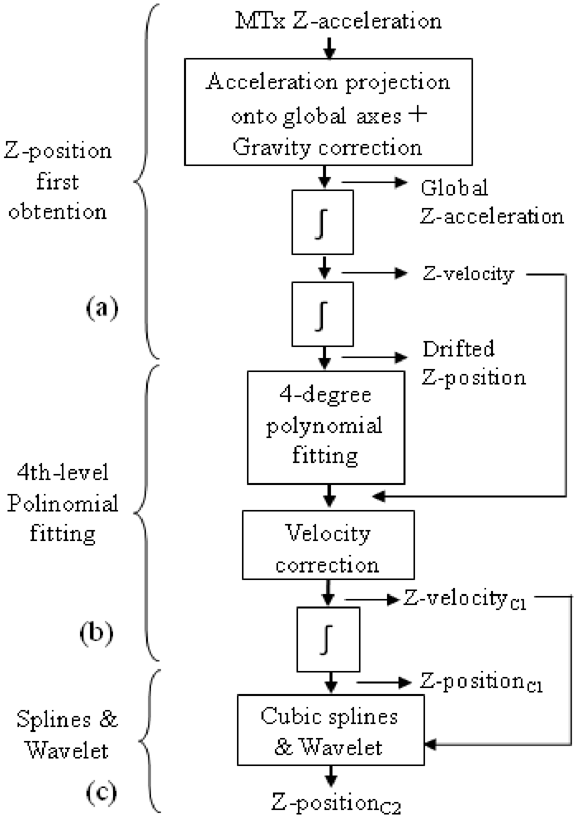

Figure 3.4: *Z-position free-drift obtaining algorithm: double integration process, part (a), first correction (C1), part (b), and second correction (C2), part (c).*

However, some baseline fluctuations can still be observed after removing the polynomial estimation of the drift component so a second step is needed to correct them. In this case, local maxima and minima position signal information and one of the following assumptions, were used:

1. Hypothesis 1: "Subjects reach the same position when they make contact with the chair each cycle". Therefore, differences in the minimum values of the Z-position signal are due to baseline drift. This baseline is estimated as a cubic spline passing through the minima (with a tolerance of 5 mm) and minimizing the differences between movement ranges in different standings (Figure 3.5 (a)).

2. Hypothesis 2: "Subjects reach the same vertical position when they get to the upright position". In this case the baseline drift causes the variation of the maximum peaks from the Z-position. The baseline is then estimated as the signal in the 0-0.25 Hz frequency range with minimum distance to the Z-position maximum points (Figure 3.5 (b)). Here, low frequency interpolation of the maxima series was employed. The condition of zero initial velocity is imposed to reduce inaccuracies in the first samples' estimation.

3. Hypothesis 3: "Subjects don't always get to the same upright or sitting positions; instead, they reach different maximum and minimum peaks each cycle." In this case baseline drift is assumed to be common to both maxima and minima series of peaks and of low frequency. Firstly, two cubic splines are used to interpolate the maxima and minima series respectively. Secondly, the wavelet analysis was used to extract the common low frequency component. In this case a wavelet analysis of 15 levels using a fourth order Coiflet was applied to both interpolation signals and, the mean of the coefficients up to level 7 is used to synthesize the low-frequency baseline estimation (Figure 3.5 (c)).

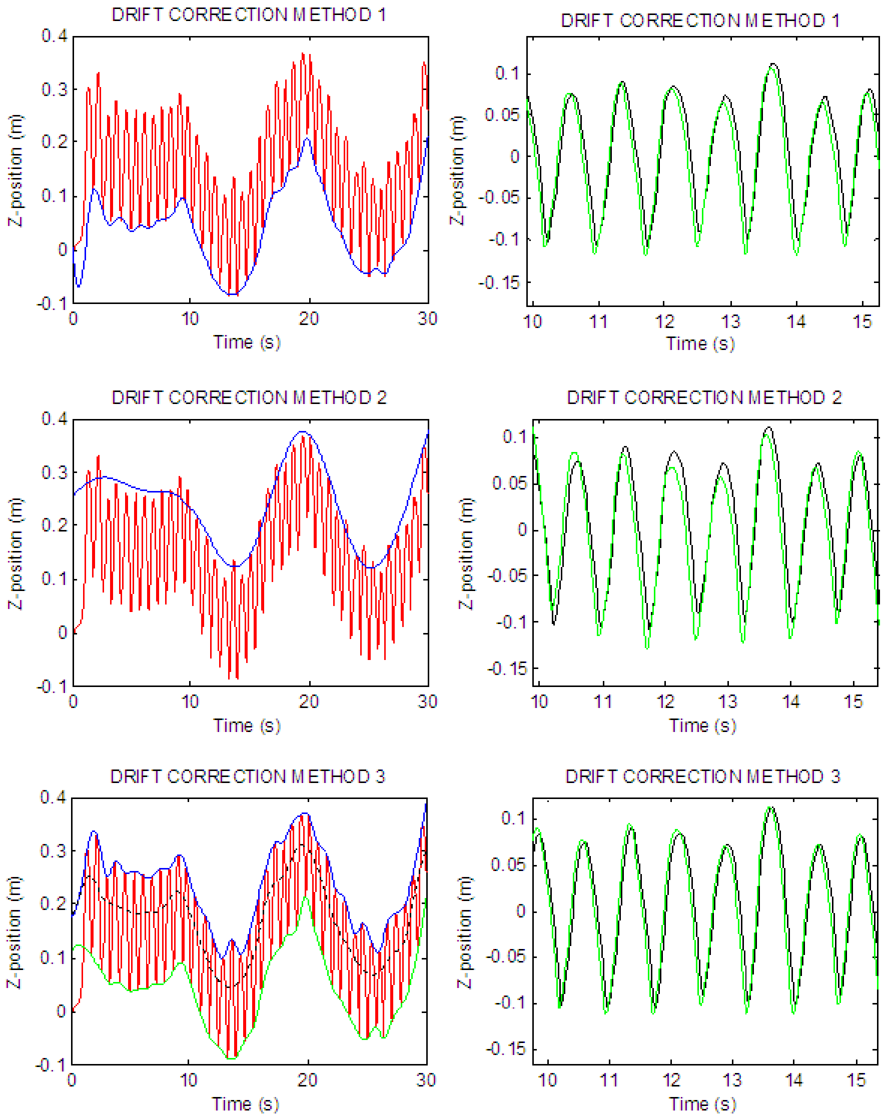

Figure 3.5: *Final drift effect correction under different conditions from one subject performing the high speed test. The left side shows the drifted Z-position signal (red line) along with the estimated baseline (blue line in (a) and (b), black dotted line in (c)). The blue and green lines in (c) are the spline-based interpolation of maxima and minima respectively. The right side shows the corrected Z-position (green line) with the reference Vicon Z-position.*

B. Reference systems unification

Vicon reference system had to be changed to the global axes used by the MTx. To this purpose, some calibration measures from the Vicon system collected after each measurement were used to obtain the rotation matrix needed to make the coordinates change (Figure 3.2 (b)). This arrangement makes it possible to compare the trajectory reconstructed from IU's data and the one provided by the Vicon system.

C. Statistical parameters for comparisons

Comparisons were done based on parameters such as the Euclidean Error (EE), (Equation 3.1), similarly to [121], and accuracy, defined as the percentage of the whole signal without error. Furthermore, statistical parameters such as the root mean squared error (RMSE), (Eq. 3.2), and the correlation coefficient (r) were also obtained to check our method's accuracy:

$$EE = \left\| \overline{Z_{posV}} - \overline{Z_{posMTX}} \right\| \qquad \text{(Equation 3.1)}$$

$$MS = \sqrt{\frac{\left(Z_{posV} - Z_{posMTX}\right)^2}{n-2}} \qquad \text{(Equation 3.2)}$$

D. Modified-BMFLC vs. PB-algorithm

The method reported in the present study was compared to a recent Modified-BMFLC drift-correction algorithm [168]. The 30-s CST meets the quasi-periodic motion requirement for this drift-correction algorithm to be applied. In the literature there are other methods to correct the drift effect, but this was probably the first one which tried to cancel it when obtaining the position from the acceleration signal. Firstly, as in [170], the cut-off frequency and the order of the high-pass filter were selected according to the 30-s CST conditions. A fourth level filter was chosen and the cut-off frequency was set at the movement's fundamentals frequency. Finally, in order to achieve a good BMFLC algorithm performance, 200 intermediate sub-frequencies were selected between the movement's fundamental and tenth harmonic frequencies.

3.4 RESULTS

3.4.1 Number of full stands

The mean and standard deviation of the number of full stands was 12±3 and 29±6 repetitions for the SA-test and the HS-test, respectively.

3.4.2 Vicon reference signal vs. hypothesis 1, 2, 3

Z-position obtained from the present two-step IU's data processing method provided the same number of full stands as that reported by the Vicon system. A maximum error of the order of 0.002 m was observed when calculating the difference of both trajectories, (Figure 3.6).

Table 3.1 shows the values of the EE, RMSE and the correlation coefficient (r) of each 30-s CST task in the sagittal plane (i.e. the one where the up and down trajectory is principally located). Mean EE and RMSE values were always lower than 21.58×10^{-3} m and 27.80×10^{-3} m, respectively. The correlation coefficient was always greater than 0.96. Moreover, since the HS-test represents an extreme scenario for vertical trajectory assessment, better accuracy was obtained at SA-test performance (mean EE of $13.85 \times 10^{-3\ m}$ and a coefficient of correlation of 0.99).

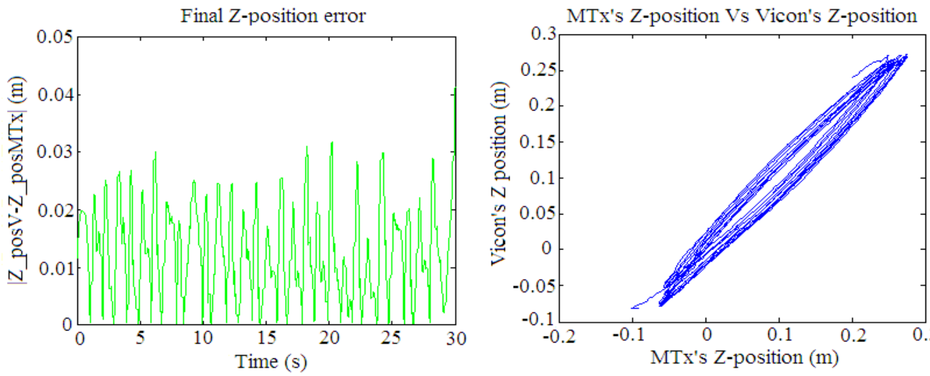

Figure 3.6: *Part (a) shows the Z-position signal error after the selected correction methodology. Part (b) shows the representation of the MTx signal vs. the Vicon reference one.*

The corrected signals showed, after the gravity correction, a mean EE of 31.4 ± 24.7 x 10^{-3} m, (Table 3.1). Then, it was improved up to 19.5 ± 12.3 x 10^{-3} m after the second step. Accuracy differences, however, were noticed depending on the method used. Second and third procedures gave better Z-position approximations. Specifically, for the HS-test, the maximum EE decreased using the third assumption instead of the first one from 100.4 x 10^{-3} to 54.62 x 10^{-3} m. Overall, the third assumption was regarded as the more accurate due to the high variability of the maximum and minimum positions reached by the subjects during the test performance.

3.4.3 Modified-BMFLC vs. PB-algorithm

Compared to the Vicon's reference signal, the modified- BMFLC algorithm showed an EE of 32.81 ± 37.12 x 10^{-3} m. and a correlation coefficient below 0.890. By using this paper's drift-correction proposal, an improvement of 40.75% and 62.90%, with respect to the BMFLC's mean EE was achieved under the HS and SA test conditions respectively.

TABLE 3.1: HYPOTHESIS AND "BMFLC-ALGORITHM" COMPARISONS

Correction	30-s CST type	Euclidean Error ($x10^{-3}$m)			Accuracy (%)	RMSE ($x10^{-3}$m)	r
		Max.	Mean	SD			
Gravity	SA-test	122.82	21.18	21.39	97.76	30.14	0.96
	HS-test	134.01	31.40	24.69	96.72	40.20	0.89
Hypothesis 1	SA-test	61.67	13.84	11.33	98.53	17.94	0.99
	HS-test	100.40	21.58	17.18	97.77	27.80	0.94
Hypothesis 2	SA-test	45.89	12.28	9.31	98.69	15.44	0.99
	HS-test	66.83	20.61	14.21	97.86	25.11	0.96
Hypothesis 3	SA-test	48.35	12.89	9.71	98.63	16.16	0.99
	HS-test	54.62	19.45	12.33	97.99	23.06	0.97

3.4.3 Modified-BMFLC vs. PB-algorithm

Compared to the Vicon's reference signal, the modified- BMFLC algorithm showed an EE of 32.81 ± 37.12 x 10^{-3} m. and a correlation coefficient below 0.890. By using this paper's drift-correction proposal, an improvement of 40.75% and 62.90%, with respect to the BMFLC's mean EE was achieved under the HS and SA test conditions respectively.

3.5 DISCUSSION

The present study is the first step to obtain a procedure to analyze the 30-s CST data. By instrumenting the test, both current parameters such as the number of performed cycles and new kinematic information could be automatically obtained.

The main result of this paper was that the new two-step processing method, or PB-algorithm, is able to cancel drift disturbances in position estimation for periodic movements facilitating the analysis of the 30-s CST using a single IU. Polynomial curve adjustment followed by splines interpolation and wavelet transform was used as an innovative method to correct the drift signal from the integrated acceleration. These results are useful for establishing movement's phases and computing kinematic parameters from the 30-s CST's data. This methodology could also be used in other tests involving periodic movements with little or no modification.

One of the preliminary steps of the 30-s CST evaluation is to determine the beginning and end of each up-and-down cycle from the recorded sensor's signals. In this regard, the Z- position stands as the best reference for cutting the whole 30-s signal into cycles since it is the main component of the stand-up and sit-down movement. This approach allows for the automatic recording of the number of full stands without the encumbrance of human counting error. So, once the sit-to- stand test is divided into cycles, it is possible to examine each of their phases separately in order to obtain kinematic variables related to the movement's performance.

It is know, however, that the accuracy of the displacement obtained from IU's data may be rather poor due to the inherent drift effect, mainly caused by the noise and dc bias of the acceleration signal, which grows quadratically with time. These are the reasons why IUs are seldom used alone in the measurement of displacement and different techniques are available through the literature in order to solve this problem. They range from using either aided sensors or sensing systems [85;166;167;172] to using signal analysis such as filters [175], frequency treatment [170;174] or baseline estimation [176] to remove the sensor noise. Regarding signal analysis tow techniques are typically used: adaptive filtering methods based on Fourier series and the wavelet transform. In the first case, the WLFC (Weighted Frequency Fourier Linear Counter) [173;174;186] and especially, the BMFLC (Band Limited Multi Fourier Linear Combiner) are used to estimate the displacement due to a periodic motion from an accelerometer's data. In doing so, periodic signals can be modelled by series of sine and cosine components and zero phase band-pass filtering removes the unwanted noise. However, for the 30-s CST signals, better Z-position estimation was obtained when using the PB-algorithm instead of the BMFLC algorithm. The reason for this difference may be that both algorithms area tailored to different kinds of movements. While the displacements typically analyzed with the BMFLC techniques were tremors of about 0.2 mm. [170;174;176], the 30-s CST entailed up and down movements of about 30 cm. In this manner, a reduction of approximately 70% of the RMS error was obtained with the proposed two-step processing method (Table 3.2). In addition, another disadvantage of the BMFLC algorithm was the fact that is specifically focused to periodic signals, something that is not always true for the quasi-periodic 30-s CST's movement. Furthermore, a large number of intermediate frequencies were needed when using the BMFLC algorithm to obtain a good Z-position approximation which makes it dependent on the input signal.

TABLE 3.2: PAPER METHOD VS MODIFIED-BMFLC

30-s CST type	Correction	Euclidean Error ($x10^{-3}$m)			Accuracy (%)	RMSE ($x10^{-3}$m)
		Max.	Mean	SD		
SA-test	Vs Drift2	73,51	64,65	75.62	64.34	70.15
	Vs Drift3	72,10	62,90	74.59	62.69	68.74
HS-test	Vs Drift2	65.56	37.17	61.72	37,54	70.14
	Vs Drift3	71.86	40.75	66.79	41,27	68.75

In this study, polynomial curve adjustment, and baseline interpolation (i.e., cubic splines and wavelet analysis) were used in an innovative method, called PB-algorithm, to correct the drift from the double-integrated acceleration signal. Firstly, the use of a fourth-level polynomial was able to correct the effect of the gravity vestige that biased the acceleration signal and which completely hid the true Z-position. Secondly, baseline interpolation from local maxima and minima yielded an even better Z-position estimation eliminating the remaining drift artefact. Three alternative hypotheses were proposed to drive the interpolation process: 1) Equal minimum values when sitting down; 2) equal maximum values when standing up and 3) maximum and minimum values affected by the same low-frequency baseline deviation. Min. and max. Z-position variability has been assessed from Vicon system. The average values were 1.94% and 82.21% for max. and min. Z-positions, while there was a maximum variation of 6.28% and 207.9 % for max. and min. Z-position. Therefore, the third hypothesis provides a more accurate Z-position estimation since subjects do not always get the same position either when they are upright stand up or when they reach the seat. Moreover, results show it provides better results in almost every test condition. We obtained an original method to firstly obtain the drift corrected Z-position signal from the Z-acceleration and secondly to have a reference to automatically analyze the 30-s CST.

A comparison with the position provided by a Vicon system was used in the present study to check the validity of the PB-algorithm for the 30-s CST. The present results showed higher accuracy of the Z-position estimation for the 30-s CST than that obtained with the Modified-BMFLC algorithm, even for the HS-test. As reported in Giasanti et al. [184], lower accuracy in the position estimation is achieved when the movement involves greater accelerations (i.e. in high speed movements). The PB-algorithm proposed in the present study outperformed the BMLFC algorithm under both test's conditions (SA-test and HS-test).

Despite the extra processing, the use of IUs shows several advantages over optical systems. Firstly, IUs do not constrain the measurement volume and do not suffer from shadowing problems. In addition, they can be easily attached to the human body without hindering the execution of motor tasks. Finally, the results show that the PB-algorithm performs satisfactorily under different velocity conditions. This suggests that the proposed procedure could be applied to evaluate the test performance of aged or Parkinson's affected subjects with low-velocity movements without the constraint of a laboratory setting.

3.6 CONCLUSSION

In summary, this study introduces a new perspective for analyzing periodic movements based on the position signal. Once the drift is removed, the position information obtained from IUs' data is similar in quality to the one provided by expensive laboratory-fixed instruments like optical systems. This paper presents an accurate two-step processing method, or PB-algorithm, based on considering polynomial data fitting followed by cubic splines and wavelet analysis, for drift cancellation in periodic movements with a single IU. In the case of the 30-s CST, it leads to obtaining automatically the test outcome (the number of completed cycles) as well as meaningful kinematic data for the evaluation of the movement execution as in [76]. It could also be applied to other tests dealing with stand-up or sit-down movements such as the Sit- to-Walk test, widely used in medical applications [187]. This could lead to an improvement of clinical settings as well as rehabilitation therapies and fall risk identification, which is nowadays based on parameters obtained from visual observations.

CHAPTER 4:

Automatic Evaluation of the 30-s Chair Stand Test Using Inertial/Magnetic – Based Technology in an Older Pre-Frail Population

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4.1 ABSTRACT

The aim of this study was to evaluate the inertial measures of the 30-s chair stand test using modern body-fixed motion sensors. Polynomial data fitting was used to correct the drift effect in the position estimation. Thereafter, the three most important test cycles phases (“impulse,” “stand up,” and “sit down”) were characterized and automatically analyzed. Automated test control is provided, making it possible for researchers without engineering knowledge to run the test. A collection of meaningful data based on kinematic variables is selected for further research. The proposed methodology for data analysis is a feasible tool for use in clinical settings. This method may not only improve rehabilitation therapies but also identify people at risk for falls more accurately than simply evaluating the number of cycles.

Index Terms—Accelerometer, frailty, gyroscope, signal analysis, 30-s chair stand test.

4.2 INTRODUCTION

Aging is related to considerable loss in muscle strength, which affects the ability of older people to function independently and makes them more vulnerable to falls and frailty syndrome [75;188;189]. Rising from a chair is regarded as one of the most demanding tasks in our daily life [118], and it has been accepted as a prerequisite for successful gait performance [190]. Indeed, the 30-s chair stand test has been tested as a useful assessment tool for predicting falls [178] and to measure lower body strength in older adults [56]. This procedure also has high test-retest reliability, an ICC of 0.84 for mean and an ICC of 0.92 for women [180;191]. For example, a sensitivity of 88% has been found in [178] for the 30-s CST related to the history of falls. Similar correlations have been found in the ability to toilet independently in facility-dwelling elderly patients and in gait in people who have suffered a cerebrovascular accident [180]. While the 30-s chair stand test is in wide usage, only the total number of visually counted full stands is used as a clinical predictor index.

The sit-to-stand or stand-to-sit movements have already been studied separately and without the repetition effect, and different kinematic and kinetic parameters have been described. Duration is one of the most straightforward parameters to characterize both postural transitions [80;126]. Nevertheless, other studies have suggested other parameters that could be of special interest in studying these transitions; specifically, these parameters could distinguish performance between different kinds of subjects. Therefore, maximum trunk, ankle, or head flexion has been assessed while subjects rise to standing from sitting [192]. By contrast, ground reaction forces [190] have also been measured to characterize both movements. Moreover, velocity peaks while standing up or sitting down [193], hip flexion, lower extremity joint angles, and the displacement of the centre of mass [194] have been calculated as predictor variables related to Alzheimer's disease. The trunk is important in generating the momentum that carries the body during the dynamic transition of standing up [90], and changes in the management of the trunk movements have been investigated as an early indicator of aging [53]. Overall, these studies confirm that both stand-to-sit and sit-to-stand transitions are complex enough to be evaluated in more detail. Furthermore, their kinematic variables may explain the motor control and performance involved.

Modern body-fixed motion sensors based on accelerometers and gyroscopes are powerful tools for sports studies and as clinical instruments to assess functional capacity [69;70;195;196]. These types of measurements have been performed commonly in laboratories, using expensive and complex tools such as cam- era motion analysis systems and/or force plates. Lately, authors have started to take advantage of inertial units (IU) as a useful tool to measure kinematics from sit-to-stand and stand-to-sit transitions [68]. Durations were widely assessed [123-125] and stated as a useful indicator of actual physical ability in a community setting [197]. Moreover, other features such as balance [134] and power [135] were also obtained from the IU's outputs. However, the previously mentioned studies were focused on one single transition whereas our interest lies in the dynamic capability required for a more demanding task of performing a set of them consecutively. Moreover, this repetition approach allows the assessment of other features such as fatigue. Therefore, the first aim of this study was to evaluate the 30-s test from this inertial measures' point of view with a cheaper and portable tool. The second goal was to characterize and automatically analyze the three most important phases of the 30-s chair stand test cycles ("impulse," "stand up," and "sit down").

We hypothesized that this new clinical method to examine the 30-s test performance could yield meaningful variables to evaluate motor control, stability, and muscle power.

4.3 MATERIALS AND METHODS

4.3.1 Subjects

Twenty-six older subjects (14 males and 12 females M (SD) 83.16 (4.32) years, 74.26 (10.78) kg, 1.51 (0.73) m) volunteered to participate in this study. These subjects were chosen from the baseline data of the Toledo study for healthy aging (TSHA), a Spanish longitudinal population-based cohort aimed at studying the determinants of frailty in older adults. The study methods have been reported elsewhere [198]. The selected ones were all prefrail subjects according to the criterion described by Fried and co-workers [7]. Frailty was determined by the presence of three or more of the following components: slowness, weakness, weight loss, exhaustion, and low physical activity. Otherwise, subjects were classified as nonfrail if no component were present, and as prefrail if they had one or two of them. The components' definition has been described elsewhere [198]. Briefly, weight loss was defined as an unintentional loss of at least 4.5 kg during the last year; slowness was defined using the 3-m walking speed test, adjusted for sex and height according to the standards of the short physical performance battery [199]. To assess weakness, strength was measured with a Jaymar hydraulic dynamometer, according to the standards of the Hispanic EPESE [200]. Exhaustion was assessed using two questions ("I felt that anything I did was a big effort" and "I felt that I could not keep on doing things" at least 3 to 4 days a week") of the Centre for Epidemiological Studies Depression Scale [201]. Finally, low physical activity was defined as the lowest quintile in the PASE scores [202].

All subjects completed a survey and a follow-up interview with a research team member. Then they were thoroughly informed about the experimental procedure, the purpose, nature, and possible risks associated with the study, as well as their right to finish their participation at their will. Their health history was also regarded to exclude those subjects who would not be able to perform the test properly due to poor health. All study participants gave a signed informed consent. If a participant was not able to consent, his/her caregiver (member of his/her family or legal tutor) consented on his/her behalf. The study protocol was approved by the Clinical Research Ethics

Committee of the Hospital Complex of Toledo, the Institutional Review Committee of the Public University of Navarra, and the Department of Health Sciences of the Government of Navarra, according to the Declaration of Helsinki.

4.3.2 Testing Procedures

The 30-s chair stand test was initially developed to assess lower body strength and evaluate functional performance and disabilities in the elderly population [56]. This test consists in standing up and sitting down from a chair with arms crossed across the chest as many times as possible within 30 s. Every subject performs the test as required and the mean number of completed cycles for this group was 12. All trials were performed in a hospital environment with the same chair and ambiance conditions.

4.3.3 Instrumentation

An inertial orientation tracker MTx (3 degree-of-freedom (DOF) human orientation tracker, Xsens Technologies B.V. Enschede, the Netherlands) attached over the L3 region of the subject's lumbar spine provided the kinematic data recorded in each trial at a sampling rate of 100Hz. MTx combines itself nine individual MEMS sensors to provide drift-free 3-D orientation as well as other kinematic data: 3-D acceleration, 3-D rate of turn (rate gyro), and 3-D earth's magnetic field. Moreover, its fusion data algorithm based on the Xsens Kalman filter for 3 DOF computes statistically optimal high-accuracy 3-D orientation estimates with no drift from the 3-D acceleration, rate of turn, and earth magnetic field sensors.

The IU provides linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (xyz). Before the beginning of the test, with the subject seated on the chair and his back in upright position, the sensor-fixed reference frame was aligned with an earth-fixed global reference frame (XYZ). Thereafter, the Z-axis was on the vertical pointing upward; the X-axis lied on the lateral direction and its Y-axis on the front-back direction. Orientation data consisted in Euler angles (in XYZ or roll–pitch– yaw order) defining the rotation that aligns the global axis to the sensor-fixed reference frame at each time instant. Linear acceleration in the global reference frame without the gravity component was obtained from the acceleration provided by the IU by applying a rotation defined by orientation data.

4.3.4 Signal Processing

A. Sit-Stand-Sit automatic calculation

The Z-position signal was used as reference to accurately cut the signals into full sit–stand–sit cycles and to evaluate each of them separately. However, although we only needed to integrate the Z- acceleration twice to obtain this reference signal, the resultant signal became unusable within several seconds due to the drift effect. Thereafter, a novel method was used here based on polynomial curve adjustment and also on splines approximation. Firstly, a fourth-level polynomial was employed to estimate the tendency line that tracks the error due to the gravity component vestige. Second, cubic splines made it possible to reconstruct the signal between outstanding points from the Z-position curves eliminating the inconstant MTx's bias. Finally, with both of them as a whole we were able to overcome the drift error constraint. Then, it was possible to obtain automatically the number of times that a subject performs the whole cycle without mistakes due to human observation.

B. Sit-Stand-Sit phase determination

Once the 30-s signals were cut into sit-stand-sit cycles, each individual cycle was divided into different movement phases. The first sit-to-stand transition was discharged from analysis since starting from a quiet sitting position influences the movement pattern. Therefore, it was not taken into consideration for the definition of the movement phases and the computation of the corresponding kinematic parameters. Three relevant phases according to different performance goals ("impulse," "stand up," and "sit down") were identified for each stand-sit-stand cycle. During the impulse phase, the subject accommodates its weight to the chair and obtains the necessary push to leave the chair again and reach the upright position. The stand-up phase starts when the subject leaves the seat and finishes when he completely stands up. And, finally, the sit-down phase comprises the movement needed to reach the chair from the previous upright position. Throughout the text, the boundaries between the impulse/stand-up, stand- up/sit-down, and sit-down/impulse phases will be referred to as T1, T2, and T3, respectively (Figure 4.1). The events that define the phases' boundaries were detected from distinct marks in the Z-acceleration and X-orientation signals and so they were analyzed to assess the test performance.

All local maxima and minima of the *X*-orientation signal as well as the *Z*-acceleration outstanding positive peaks were obtained. A threshold for the peak-to-peak level was established to eliminate local extreme caused by signal noise instead of relevant angular displacements.

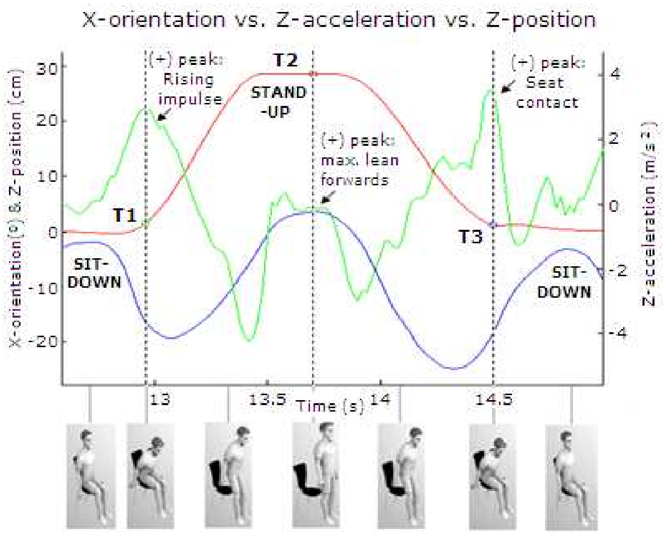

Figure 4.1: *X-orientation signal (blue line), Z-acceleration signal (green line), and Z-position signal (red line) from a signal sit-stand-sit cycle. The principal event markers are also included. The green, red, and blue bubbles show, respectively, T1, T2 and T3.*

Consecutive orientation extreme differing in less than two degrees was discarded. Similarly, outstanding *Z*-acceleration peaks were obtained to establish the up-and-down transitions' limits. For every cycle, the *Z*-velocity signal was used to distinguish the acceleration peak for the stand-up transition (subject moving upward—positive *Z*-velocity) from the sit-down related acceleration peak (subject moving downward—negative *Z*-velocity). All that information was combined to define the boundaries between the three relevant phases: impulse, stand up, and sit down (Figure 4.2).

The beginning of the cycle was set at the time when the subject reaches the seat after the previous sit to stand and a *Z*-acceleration peak is produced. During this phase, the subjects' weight is transferred from the legs to the seat and there is a trunk and balance adjustment. Next, the subject leans the trunk forward to take the necessary impulse to rise up, hence this phase's name "impulse phase." In some cases, a pointed backward lean (X-orientation positive peak) which allows us to distinguish two sub phases (the trunk and balance adjustment and the standing up impulse taking) was observed. However, in this study they were not taken into consideration as we focus on the basic movements of the sit–stand–sit cycle.

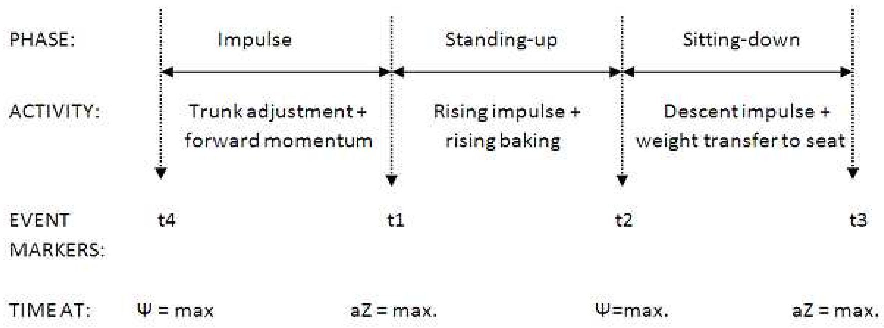

Figure 4.2: *Sit-stand-sit cycle diagram with phases, activities, and event marker definitions. Here, "aZ" refers to the Z-acceleration and "ψ" to the roll angle.*

Next, the standing-up movement was performed during the "stand-up phase." The start time (T1 event) was signalled by an abrupt positive change of vertical position and a Z-acceleration positive peak, which means that the subject has started leaving the chair, the "seat-off" event. During this phase, the vertical acceleration was converted to deceleration while the upward movement of the body mass was in progress. The vertical upward movement ended when the subject reaches the upright position. Just at that moment, there was a maximum backward trunk inclination that compensates the stand-up impulse (T2 event).

Finally, the cycle ended with the "sit-down phase" during which the subject changes its posture from erect standing to sit- ting down. As all movements occurred consecutively, the sitting down started just after the subject finishes the stand-up phase (T2 event). During this phase, negative *Z*-acceleration values reflect the impulse taken to initiate the downward movement, and then positive *Z*-acceleration was produced when the subject tried to slow down before reaching the chair. The descent finished when the seat contact was produced (T3 event), signalled by a characteristic positive peak in the *Z*-acceleration signal.

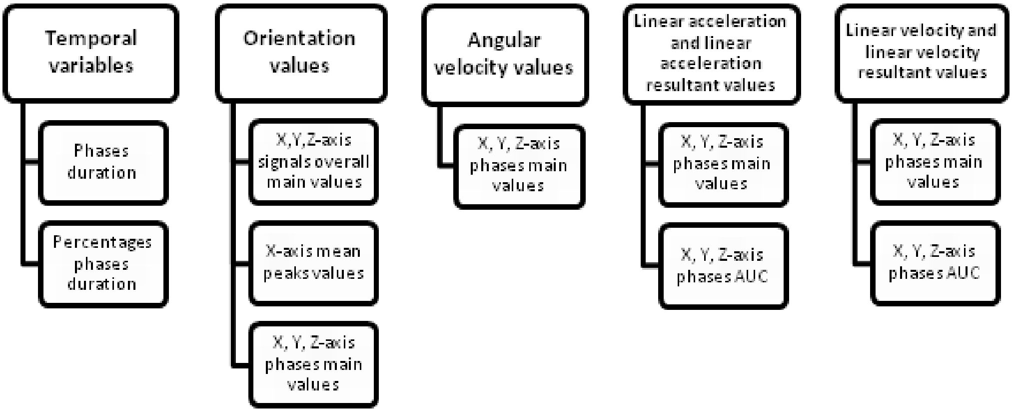

Figure 4.3: *Classification diagram for the obtained variables according to the signal they were obtained from.*

Once the different phases have been identified, linear acceleration, linear velocity, orientation, and angular velocity were evaluated to obtain relevant parameters at each phase. Kinematic parameters such as the phases' duration or the maximum acceleration in each phase were automatically computed (Figure 4.3). However, this paper only presents those parameters that are envisaged to be more related to movement performance such as seen in Table 4.1. The AUC_{acc} parameter was defined as the acceleration's area under the curve related to the movement duration. This parameter expresses the sum of the acceleration amplitudes in order to take into account not only amplitudes but also time length. This is a tantamount to the increase in velocity between the summation time limits. According to the displacement's direction, the AUC_{acc} is composed of a positive component (AUC^{+}_{acc}, with the movement's direction) and a negative one (AUC^{-}_{acc}, with the opposite direction). The first parameter evaluates the necessary impulse to carry out each transition (movement acceleration), while the second one is related to the transition control since the first impulse must be compensated to reach the stand-up or the sit-down position (movement deceleration). These are interesting parameters since they have been related to the extremities strength to perform a movement and so the functional ability [203-205].

E. Statistical analysis

The standard statistical methods were used to obtain the mean (M) and standard deviation (SD) of each phase parameter across cycles and subjects. The differences between the predefined movement phases (impulse, stand up, and sit down) were determined using one-way analysis of variance (ANOVA), with Newman–Keuls post hoc comparisons. When normality test failed ($P < 0.05$), the Mann–Whitney rank sum test was employed. The "$p<0.05$" criterion was used for establishing statistical significance. Box plots of each parameter for the different movement phases are used to graphically display the variable's location. The box itself contains the middle 50% of the data, the upper and lower edges of the box indicate the 75th and the 25th percentile, and the central line is the median value of the data. The ends of the vertical lines or "whiskers" are the minimum and maximum data values whereas points outside whiskers' ends represent outliers or suspected ones.

4.4 RESULTS

4.4.1 Temporal and Kinematic Parameters

A. Phase's Times

The duration M (SD) of an impulse phase was similar (0.71 (0.13) s) to those observed in the corresponding stand-up and sit-down phases (0.74 (0.06) s) and (0.80(0.10) s), respectively).

B. Orientations

The average roll angle range of the 30-s chair test (46.88 (11.16) º) was greater ($p < 0.01$) than that of pitch yaw angles (14.50 (8.15) º) and (18.83 (7.15) º), respectively. The roll angle ranges during the impulse, stand-up, and sit-down phases were of (14.25 (4.44) º), (26.97 (3.92) º), and (31.38 (3.90) º), respectively.

C. Angular Velocity

The maximum angular velocity in the X-axis was greater at the impulse phase (0.46 (0.07) º/s) than those recorded during the stand-up (0.32 (0.09) º/s) and sit-down phases (0.34 (0.08) º/s) ($p < 0.01$), (Table 4.1).

D. Linear Velocity

The maximum linear velocity in the Z-axis in the stand-up phase (0.81 (0.05) $m \cdot s^{-1}$) was greater ($p < 0.01$) than that obtained in the sit-down phase (0.70 (0.05) $m \cdot s^{-1}$) (Table 4.1).

TABLE 4.1: PRINCIPAL VARIABLE VALUES, MEAN (SD)

X-axis Orientation (°)	Impulse phase	Stand-up phase	Sit-down phase
Max. Pos. Var.	2.88 (4.10)	16.94 (3.65)	16.94 (3.65)
Max. Neg. Var.	11.99 (2.98)	9.92 (3.16)	14.37 (2.95)
Range	14.25 (4.44)	26.97 (3.92)	31.38 (3.90)
Mean	-3.80 (3.06)	2.04 (2.90)	-0.36 (3.20)
SD	4.76 (1.41)	9.86 (1.47)	11.71 (1.55)
X-axis V_{ang} (rad/s)	Impulse phase	Stand-up phase	Sit-down phase
Peak Max.	0.46 (0.07)	0.32 (0.09)	0.34 (0.08)
Mean (SD)	0.08 (0.28)	-0.03 (0.16)	-0.05 (0.17)
Z-axis Acc. (m/s^2)	Impulse phase	Stand-up phase	Sit-down phase
Mean (SD)	0.94 (1.96)	0.44 (2.35)	0.20 (2.06)
AUC^T_{acc}	0.97 (0.15)	1.76 (0.15)	1.49 (0.15)
AUC^+_{acc}	0.88 (0.11)	0.91 (0.10)	0.69 (0.06)
AUC^-_{acc}	0.09 (0.06)	0.85 (0.06)	0.81 (0.11)
Res.Acc. (m/s^2)	Impulse phase	Stand-up phase	Sit-down phase
Mean (SD)	2.81 (1.28)	2.85 (1.24)	2.49 (1.15)
Peak Max.	6.41 (1.44)	5.26 (0.63)	2.09 (0.24)
AUC^T_{ResAcc}	2.01 (0.32)	1.59 (0.20)	2.09 (0.24)
Z-axis V_{lin} (m/s)	Impulse phase	Stand-up phase	Sit-down phase
Mean (SD)	0.01 (0.12)	0.41 (0.31)	-0.39 (0.25)
|Peak Max.|	0.33 (0.11)	0.81 (0.05)	0.70 (0.05)
AUC^T_{Vlin}	0.15 (0.03)	0.22 (0.03)	0.31 (0.02)
AUC^+_{Vlin}	0.13 (0.03)	0.20 (0.03)	0.01 (0.01)
AUC^-_{Vlin}	0.02 (0.01)	0.02 (0.01)	0.03 (0.02)
Res. V_{lin} (m/s)	Impulse phase	Stand-up phase	Sit-down phase
Mean (SD)	0.45 (0.22)	0.52 (0.26)	0.50 (0.25)
Peak Max.	0.76 (0.09)	0.84 (0.06)	0.80 (0.07)
$AUC^T_{ResVlin}$	0.39 (0.08)	0.28 (0.04)	0.43 (0.04)

'Vang.' = angular velocity, 'Max.' = maximum, 'Min.' = minimum, 'Var.' = variation, 'Acc.' = acceleration, 'ResAcc.' = acceleration resultant, 'Tot.' = total, 'Pos.' = positive, 'Neg.' = negative, 'Vlin' = linear velocity, 'ResVlin' = linear velocity resultant.

E. Linear Acceleration

The maximum positive and negative accelerations in the z-axis were similar during the stand-up (3.73 (0.46) $m{\cdot}s^{-2}$) and 4.15 (0.61) $m{\cdot}s^{-2}$) and sit-down phases (3.36 (0.53) $m{\cdot}s^{-2}$) and (4.70 (1.15) $m{\cdot}s^{-2}$), ($p>0.01$). AUC_{acc} during the stand-up phase was significantly greater ($p<0.01$) (1.76 (0.15) $m{\cdot}s^{-1}$), than the one during the sit-down (1.49 (0.15) $m{\cdot}s^{-1}$). Although the AUC^{-}_{acc} part is similar for both (0.85 (0.06) m·s-1) stand-up, and (0.81 (0.11) $m{\cdot}s^{-1}$) sit-down, the AUC^{+}_{acc} one is greater for the stand-up transition (0.91 (0.10) $m{\cdot}s^{-1}$) than for the sit-down one (0.69 (0.06) $m{\cdot}s^{-1}$).

4.5 DISCUSSION

The 30-s chair stand test is regarded as a good indicator of lower limb strength [56;177], but the only quantitative result currently obtained is the number of full cycles counted by the tester. A unique outcome of this study was the description of an automated procedure for a detailed analysis of the 30-s chair stand test, based on the processing of the signals provided by an IU. The proposed automatic procedure eliminates the inaccuracy that results from human supervision. This study also enables the definition of meaningful kinematic variables that indicate movement performance and may be related to functional activity indicators, especially in elderly patients who are more liable to experience muscle strength loss and frailty syndrome.

The sit-to-stand movement has been thoroughly studied in the literature, [123;124;134;135;194;205-210]. The stand-to-sit transition, however, has received much less attention, [80;118;126;190;193], despite being of paramount importance in the elderly. Tests that involve continuous repetition, such as the 30-s chair stand test, had not yet been evaluated with body-fixed inertial sensors. To our knowledge, this is the first study describing a method to extract multi-parametric kinematic measures in order to analyze both transitions during a 30-s test. As a result, mean values were obtained to characterize an individual's performance of a given movement. Additionally, a new impulse phase was defined which links the last sit down to the next stand up. However, comparison of these results with those of single-transition studies must be performed cautiously because different initial conditions clearly influence the performance of a movement. In this study, the subject does not begin the movement from an initial resting state. To perform the sit-to-stand transition, the subject must first compensate for the sit-down impulse and gather enough momentum to stand up. After sitting down, subjects do not get any rest time before initiating the next transition.

In the literature, postural transitions are most often characterized by their duration [80;124;125;135] or by the trunk range of motion [53]. Although not assessed here, balance derived parameters [134] and power [135] had been also studied in the literature. Duration was commonly obtained by using the angular velocity [123], the integration of the orientation signal [197], or the derivative of the transversal acceleration. However, this study used the vertical acceleration to determine when the subject left or reached the chair [208]. Moreover, most papers compare the performance of elderly and young populations [211] or determine descriptive parameters for the standing and sitting movements [118]. In this study, we followed the latter approach, describing the transitions involved in the 30-s chair stand test for a group of pre-frail elderly people. Nevertheless, the same parameters could be analyzed to compare different populations.

Regarding specific time values, published studies of single sit-to-stand transitions have reported movement durations ranging from 1.2 to 5.9 s. In these reports, 2 s. was the most frequently observed duration [210]. However, in our study, the mean length of the sit-down phase is 0.80 s. This noticeable decrease may be explained by the fact that subjects are encouraged to complete as many cycles as possible and by the difference in initial conditions (described previously). Because the time spent performing a specific activity is a simple but important indicator of the subjects' functional capabilities [52], transition duration has also been regarded as an indicator of fall risk [197;206]. For instance, a significant increase in the mean and standard deviation of transition duration has been reported when comparing a high and low fall-risk group [126]. When comparing stroke patients to healthy subjects, it is generally the case that the stroke victims spend more time performing standing-up and sitting-down transitions (separately evaluated) [52;212;213]. Furthermore, stroke fallers tend to spend more time performing the sit-to-stand task than no-fallers do [206].

The duration comparison between the three defined phases (i.e., impulse, stand up, and sit down) showed no significant differences. Interestingly, when normalized to the total cycle duration, significant differences arise between the percentage of time corresponding to the sit-to-stand and stand-to-sit transitions (Figure 4.4). In this study, the pre-frail older group examined tends to allocate a larger part of the total cycle time to descending 34.6% rather than to rising 32.3%. This is in agreement with the results of single-transition studies [190;211]. This result reinforces the idea that elderly populations tend to perform the sitting-down transition more slowly and with more caution than the standing-up one. This difference may be due to the different centre of mass location adjustment or to the lack of visual information regarding the location of the endpoint (seat) [190]. Additionally, when considering the number of times that the subjects performed full cycles of standing up and sitting down, we observed a tendency to invest more time for each individual sitting phase when the number of repetitions is smaller. The slower movements may be a function of the decreased ability to generate power in this population [118].

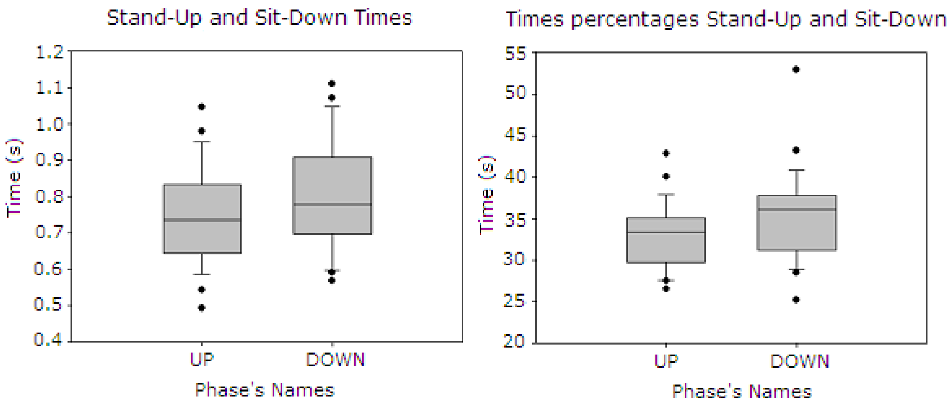

Figure 4.4: *Box-plots for the time invested during the stand-up and sit-down phases, left, and for the time percentage inverted during the stand-up and sit-down phases, right.*

As expected, the greatest range of motion was found in the sagittal plane (rotation around the X-axis, 46.88°) when compared to the range of motion around the Y- and Z-axes (14.50° and 18.83°, respectively). The X-axis orientation signal shows a characteristic pattern with four distinct local extreme that correspond to different movement tasks. At the beginning of the cycle, a maximum in the X-axis orientation is registered; this maximum corresponds to a backward lean immediately following contact with the seat (as the body is accommodated by the chair). The subsequent minimum reflects a forward inclination of the trunk that gives the subject enough impulse to rise up. Next, a maximum is observed when the subject reaches the standing position and leans the trunk backward. Finally, a last minimum in the X-axis orientation indicates the forward inclination of the trunk needed to reach the chair during the sit-down movement.

During the rising up and descent phases, no significant differences were observed in the angular displacements for the X-axis orientation. This result is in agreement with the findings of Mourey et al. [211] who reported no differences in angular displacement during the standing-up and sitting-down transitions (evaluated separately). The maximum x-axis angular value recorded during the impulse phase seems to be another meaningful parameter for the task of movement procedure assessment. This parameter indicates how the subjects manage his/her body movements when standing up. However, further studies are required to determine the utility of these and other parameters in distinguishing different populations. Acceleration values were related to the forces employed to perform the required sit-to-stand cycle. Attempts have been made to identify a variable that would allow the 30-s chair test to evaluate the lower extremities strength [205]. Peak values from the different phases may give an idea about the muscular power required to perform both the standing-up and the sitting-down transitions. In this study, absolute values were recorded, but positive and negative peaks were distinguished according to the movement's direction. Thereafter, positive values were those that were in the same direction as the performed movement, while the negative ones were those in the opposite direction. During the standing-up and sitting-down phases, no significant differences were found for the positive and negative peaks. This means that this population tends to invest similar forces for both starting and compensating the impulse needed to execute the stand-up and sit-down transitions.

Movement's impulses are related to muscular power management and may be an indicator about the subject's state of health [203;204;213]. In this study, acceleration related to the sit-to-stand transition was assessed according to the AUC_{acc} parameter, which indicates the area under the curve of the acceleration signal of each transition or, what is the same, the impulse that a subject executes to completely perform both the stand-up transition and the sit-down transition. Moreover, not only the net parameter but also the AUC^{+}_{acc} (impulse needed to start the movement) and AUC^{-}_{acc} (impulse needed to compensate for the initial one) components were obtained. Here, significant differences were found for the positive (in the same direction as the movement), but not for the negative parameter (in the opposite direction of the movement). There are also differences in the net value of AUC_{acc} (i.e., the sum of the negative and positive components) when comparing the standing-up and sitting-down phases (Figure 4.5). As with the maximum and minimum peaks, different values were observed between the AUC_{acc} parts for the impulse with the same direction as the performed movement, AUC^{+}_{acc}, and another part with the opposite direction, AUC^{-}_{acc}. These subjects generated different AUC_{acc} values when standing up or sitting down, which indicates that these two tasks were performed in different ways. AUC^{+}_{acc} values represent the forces that the subject exerted to reach the upright position or to reach the chair while AUC^{-}_{acc} values are those required to counteract the previous ones. This population generally invests more positive force during the sitting-down process. This result is logical because pre-frail subjects tend to let themselves fall down into a seat rather than controlling their descent. Thereafter, high positive forces while sitting means that the subject takes advantage to the gravity force to descent instead of doing the effort to have power over it. However, the similarity to the AUC^{-}_{acc} values indicates that these individuals tend to control in a similar way both transitions. When comparing the net AUC_{acc} values, differences indicate that subjects from this population tend to need more force to stand up than to sit down. This result reinforces the notion that uncontrolled sit downs occurred, especially in older frail populations.

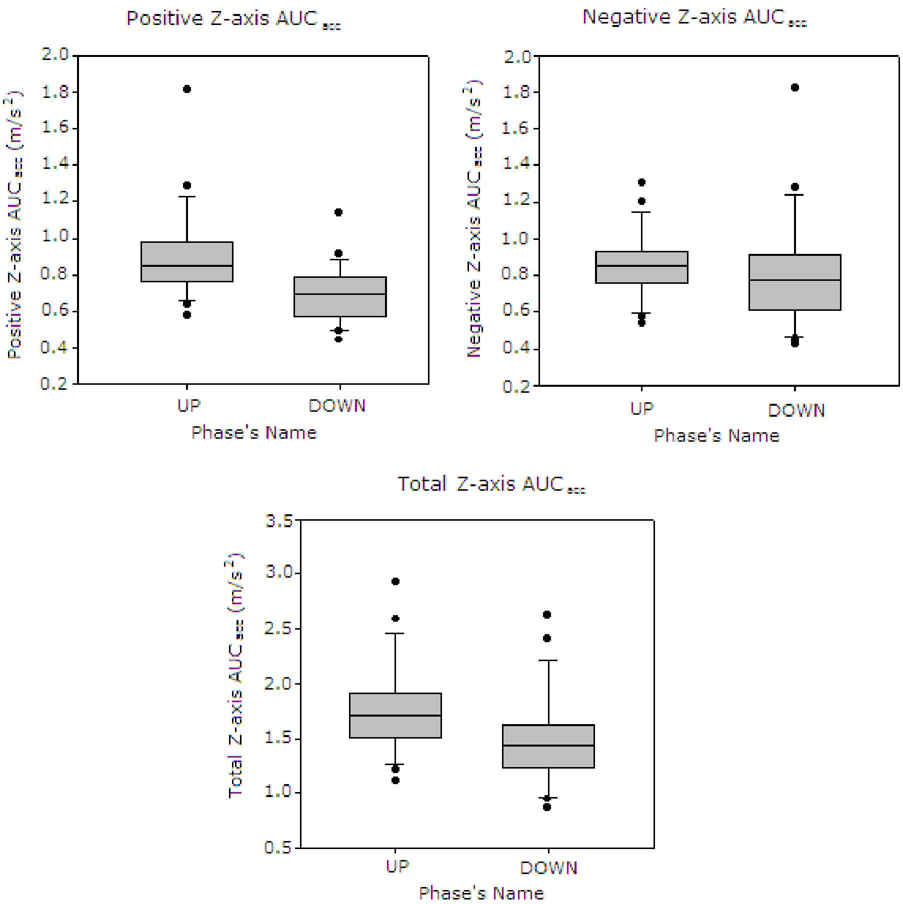

Figure 4.5: *(a) Positive, (b) negative, and (c) total Z-axis AUC_{acc} box plots for the stand-up and sit-down phases.*

A limitation of this study, from the scientific research point of view, was the use of a single sensor attached to the body's centre of mass (over the L3 region of the lumbar spine). As an alternative several matchbox-sized sensor nodes could be attached to different trunk locations to obtain better information about the trunk displacements [135]. An optoelectronic tracking system could also be used [214]. Similar sensors could be located on other parts such as the knee [192] to evaluate the test. Then, further information could be gathered to evaluate the role of other body parts during the sit-stand-sit test.

4.6 CONCLUSION

In summary, this study provides a unique approach to analyze the 30-s chair stand test and suggests that body-fixed sensors are a powerful tool for this analysis. Two important improvements have been introduced. First, this method allows for automated control of the test. This automation makes it possible for researches without any engineering knowledge to run this test. Furthermore, this method avoided the human errors that occur during testing. Second, this method also allowed the collection of meaningful data based on kinematic variables throughout the performance of transitions. This ability may be of special interest when discriminating among healthy, pre-frail and frail subjects.

These results demonstrate that accelerometry can complement the currently utilized test outcome of the 30-s test, namely, the number of cycles performed. The kinematic values obtained provided information about the motion's quality and an evaluation of how the movements were carried out. The proposed methodology for data analysis is a feasible tool for use in clinical settings. This method may not only improve rehabilitation therapies but also identify people at risk for falls more accurately than simply evaluating the number of cycles.

CHAPTER 5:

An Evaluation of the 30-s Chair Stand Test in Older Adults: Frailty Detection Based on Kinematic Parameters from a Single Inertial Unit

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5.1 ABSTRACT

Background: A growing interest in frailty syndrome exists because it is regarded as a major predictor of co-morbidities and mortality in older populations. Nevertheless, frailty assessment has been controversial, particularly when identifying this syndrome in a community setting. Performance tests such as the 30-second chair stand test (30-s CST) are a cornerstone for detecting early declines in functional independence. Additionally, recent advances in body-fixed sensors have enhanced the sensors' ability to automatically and accurately evaluate kinematic parameters related to a specific movement performance. The purpose of this study is to use this new technology to obtain kinematic parameters that can identify frailty in an aged population through the performance the 30-s CST.

Methods: Eighteen adults with a mean age of 54 years, as well as sixteen pre-frail and thirteen frail patients with mean ages of 78 and 85 years, respectively, performed the 30-s CST while their trunk movements were measured by a sensor-unit at vertebra L3. Sit-stand-sit cycles were determined using both acceleration and orientation information to detect failed attempts. Movement-related phases (i.e. impulse, stand-up, and sit-down) were differentiated based on seat off and seat on events. Finally, the kinematic parameters of the impulse, stand-up and sit-down phases were obtained to identify potential differences across the three frailty groups.

Results: For the stand-up and sit-down phases, velocity peaks and "modified impulse" parameters clearly differentiated subjects with different frailty levels ($p < 0.001$). The trunk orientation range during the impulse phase was also able to classify a subject according to his frail syndrome ($p < 0.001$). Furthermore, these parameters derived from the inertial units (IUs) are sensitive enough to detect frailty differences not registered by the number of completed cycles which is the standard test outcome.

Conclusions: This study shows that IUs can enhance the information gained from tests currently used in clinical practice, such as the 30-s CST. Parameters such as velocity peaks, impulse, and orientation range are able to differentiate between adults and older populations with different frailty levels. This study indicates that early frailty detection could be possible in clinical environments, and the subsequent interventions to correct these disabilities could be prescribed before further degradation occurs.

Keywords*:* Inertial units, Frailty syndrome, Kinetic parameters, 30-s chair stand test, Signal analysis.

5.2 BACKGROUND

Frailty occurs often in people older than 65 years (ranging from 7 to 16.3%), and its prevalence increases with age [6;7;198]. Frail individuals are at particular risk for poor outcomes such as disability, fall, death and hospitalization from minor stressors [9;215;216]. The diagnosis of frailty is based on several health domains, including physical impairments (e.g., low gait velocity, fatigue and low grip strength), weight loss, and low physical activity [7]. Despite some vagueness in its definition, clinicians have indicated that early detection is one of the most effective methods for reducing the severity of physical frailty and for improving a patient's well-being. Functional ability assessments aim to detect mobility impairments such as physical weakness so that early interventions are possible.

The 30-s CST is one of the most important functional evaluation clinical tests because it measures lower body strength and relates it to the most demanding daily life activities (e.g., climbing stairs, getting out of a chair or bath tub or rising from a horizontal position) [56;217;218]. Low levels of body strength are the primary cause of both balance problems and falls in the elderly population [59;219]. The 30-s CST, similar to tests such as the 5-stands test and the timed up and go test (TUG), is able to differentiate between subjects with different functional levels. However, the 30-s CST is also able to assess the fatigue effect caused by the number of sit-to-stand repetitions. Indeed, the 30-s CST has been widely used in many studies not only to evaluate functional fitness levels [58-60] but also to monitor training [61-64] and rehabilitation [66;220].

Classically, the 30-s CST consists of manually counting the number of sit-stand-sit cycles completed during the 30 seconds of the test. Since the early 1990s, IUs have been increasingly used to measure kinematic and kinetic parameters [69]. This technology is a non-invasive, portable and economical method to capture accelerations and angular velocities in three orthogonal planes [221]. However, signal analysis is needed to separate out the sit-to-stand (SitTS) and/or stand-to-sit (StandTS) transitions from the entire test duration. Recently, a wide range of studies have positively shown that IUs can furnish accurate kinematic transition-related measures, particularly when a test subject is standing up or sitting down, [69;73;142;222]. There is no gold standard yet, but this task has typically been achieved through the use of thresholds on either the angular velocity [54;68] or the acceleration information [106;125]. However, threshold values are hard to generalize, as they are influenced by noise and by movement artefacts. Thus, peak detection techniques, such as those considered here, seem to per- form better [144]. Other authors have preferred to obtain transition durations from the orientation signal of the trunk, which is the angle between the vertical axis and the anterior wall of the subject's thorax. In this paper, the sinus function is used to soften the signal and the time of postural transition is defined from the previous to the posterior maximum from a minimum point which is the transition indicator [160]. A major difficulty associated with transition detection is the fact that movement patterns depend on the subject's physical condition. Healthy subjects do not show the same transition indicator as frail subjects, and frail subjects may perform several attempts before completing a valid cycle [108]. Thus, this manuscript uses a novel technique to separate the sit-stand-sit cycles and their phases from the remainder of the signal. First, the vertical position signal is used to clearly differentiate the cycles, and then, transition events are detected using both acceleration and orientation signals to separate the phases, which include "impulse", "stand-up" and "sit-down".

Vertical position is the most intuitive indicator of up and down movements and is a good source of information to separate sit-stand-sit cycles within the 30-s CST. Several authors have recognized the value of vertical position data for analyzing SitTS and StandTS transitions [121;128] but details about the derivation of the position signal are lacking. To the best of our knowledge, this is the first study that uses the vertical position signal to separate cycles. While this lack is surprising, it is perhaps because obtaining a position value from acceleration data is made difficult by the inherent drift effect. In the proposed method, vertical position and velocity were obtained from acceleration data and drift-corrected. The IU's vertical position is a square-like signal that reflects the subject's vertical movement pattern, which is also very useful for the detection of failed attempts.

Furthermore, the joint use of both acceleration and orientation information enables our algorithm to obtain the duration of SitTS and StandTS transitions irrespective of the subject's physical condition, overcoming one common problem. The onsets of these movements are based on specific notable events such as acceleration or orientation maximum peaks instead of an empirically determined threshold [106;108;125;144;160].

Finally, all of this information (vertical position, velocity, orientation and acceleration) was used to detect failed at- tempts in which subjects did not reach the upright position. In the literature, only Van Lummel et al., [130] differentiate between correct SitTS movements and failed attempts. They employed the velocity information instead of the position, but they did not provide any further information about their methodology. Our study illustrates how the position and velocity signals were obtained and validates them against the gold standard provided by a Vicon optical system. This is the first study to analyze the 30-s CST and to obtain kinematic measurements related to the subject's frailty level.

The present study contains two parts. First, a set of parameters from an IU were evaluated to assess their ability to predict the subjects' frailty status (frail, pre-frail or healthy) according to the Fried et al. classification, [7]. Specifically, we hypothesized that these body motion-related parameters would enhance an analysis of the current test information (the number of completed cycles). Therefore, in the second part of this study, the aforementioned parameters were further assessed in a situation that highlighted the limited sensitivity of the standard test outcome. Specifically, a subset of pre-frail and healthy subjects performing the same number of cycles was chosen, and the proposed procedure was applied to their kinematic data. The sensitivity of the computed parameters to detect subtle differences was analyzed.

5.3 METHODS

5.3.1 Subjects and protocol

In this experimental study, 47 subjects with different frailty levels were asked to perform the 30-s CST. Specifically, 13 frail subjects (4 males and 9 females, aged 85 ± 5 years, body mass 67.5 ± 8.6 kg, and height 1.54 ± 0.05 m), 16 pre-frail (8 males and 8 females, aged 78 ± 3 years, body mass 71.6 ± 10.5 kg, and height 1.61 ± 0.08 m) and 18 healthy subjects (14 males and 4 females, aged 54 ± 6 years, body mass 75.2 ± 3.4 kg, and height 1.76 ± 0.04 m) volunteered to participate in this study. The frail and pre-frail subjects were selected from the population used for the baseline data of the Toledo Study for Healthy Aging (TSHA) [223]. According to the criteria defined by Fried et al., [7], frailty was determined as the presence of three or more of the following criteria: slowness, weakness, weight loss, exhaustion, and low physical activity. Subjects were classified as pre-frail if one or two criteria were present and as non-frail if no criteria were present. All of the subjects were thoroughly informed about the experimental procedure; the purpose, nature, and possible risks associated with the study; and their right to terminate participation at their discretion. Subsequently, the subjects provided their written informed consent to participate. These experimental procedures were approved by the Institutional Review Committee of the Public University of Navarra and the Department of Health Sciences of the Government of Navarra, according to the Declaration of Helsinki.

The 30-s CST consists of standing up and sitting down from a chair as many times as possible within 30 seconds. A standard chair (with a seat height of 40 cm) without a backrest but with armrests was used. Initially, subjects were seated on the chair with their back in an upright position. They were instructed to look straight forward and to rise after the "1, 2, 3, go" command at their own preferred speed with their arms folded across their chest. All trials were performed using the same chair and with similar ambient conditions. The medical staff who supervised the performance of the test did not participate in analyzing the kinematic data, and they did not have any knowledge about the analysis whatsoever.

As described in the background section, the present study contains two parts. In the first part, all of the subjects from the three frailty groups were evaluated. Everyone was able to finish the test properly. In the second part, a subset of the data from the initial test was considered. A group of seven pre-frail and eight healthy subjects, with a mean number of 17 sit-stand-sit cycles per group and a range of 15–20 were evaluated.

5.3.2 Instrumentation

An inertial MTx Orientation Tracker (WSENS, Xsens Technologies B.V., Enschede, Netherlands) was attached over the L3 region of the subject's lumbar spine to provide the kinematic data for each trial. It recorded at a sampling rate of 100 Hz. The L3 position was chosen because of its proximity to the body's centre of mass (CoM) in the standing position. The nine individual MEMS sensors from the MTx provided kinematic data such as the 3D acceleration and the 3D rate of turn (rate gyro). More- over, the drift-free 3D orientation was also provided by the MTx using Kalman filters and the previously mentioned kinematic data.

Before starting the test, when the subject was sitting on the chair in an upright position, the sensor-fixed reference frame was aligned with the global reference system (X, Y, and Z). This global reference system was defined as the Earth-fixed global reference frame (XYZ), whose Z-axis points vertically upwards, with the X-axis in the lateral direction and the Y-axis in the anterior-posterior direction. The orientation data, consisting of the Euler angles in either XYZ or roll-pitch-yaw order, defined the rotation aligning the global axis to the sensor-fixed reference frame at each time point. The IU provides both the linear acceleration and the rate of turn in its sensor-fixed Cartesian reference frame (xyz). The linear acceleration in the global reference frame can be translated into the global reference frame using the orientation data.

5.3.3 Data analysis

An automated data analysis procedure was implemented using Matlab 7.11 (Math Works Inc., Natick, MA, USA) to improve the objectivity and simplicity of the current 30-s CST evaluation. The automated analysis provides an accurate count of the number of repetitions, removing failed attempts as determined by the roll rotation angle (X-orientation) in combination with the Z-acceleration signal, and the derived Z-velocity and Z-position, and the kinematic parameters. The procedure was implemented as a three-stage algorithm:

First, the raw signals were processed to obtain the Z-velocity and Z-position. Specifically, single and double integration of the Z-acceleration was performed. Furthermore, a two-step processing method (a fourth-level polynomial curve adjustment followed by baseline interpolation from local maxima and minima) was chosen to correct the inherent drift effect. A fourth-level polynomial fitting was chosen to accommodate for slow changes in the acceleration bias without incurring in over-fitting. Then, remaining baseline fluctuations were estimated by spline interpolation of local maxima and minima.

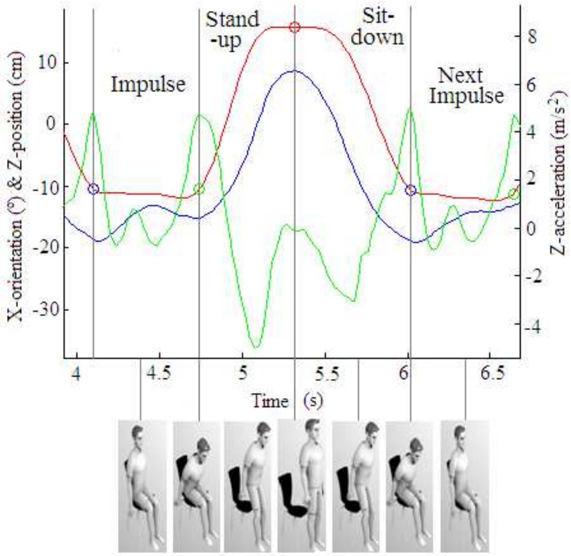

Figure 5.1: *Raw MTx signals during the 30-s CST of one pre-frail subject. The blue line is the X-Orientation signal; the green line is the Z-Acceleration signal from a sit-stand-sit cycle. Impulse, stand-up and sit-down phases are also marked.*

Second, the corresponding sit-to-stand-to-sit cycles and their main phases (impulse, stand-up and sit-down) [108] were determined using the X-orientation as well as the Z-acceleration, Z-velocity and Z-position. The Z-position signal was used as an indicator of changes in the vertical position of the MTx unit, making it possible to automatically obtain the number of completed cycles (the current standard measurement from the 30-s CST). The X-orientation informs about the body's sway movements (i.e., forward and backward trunk leans), while the Z-acceleration gives information about the up and down body forces exerted to complete the cycles. The combination of these two signals with the Z-position provides enough markers to clearly detect stand-up and sit-down transitions, as well as failed attempts. A failed cycle was defined as an attempt performed by a subject who did not reach the upright position. In the algorithm, these situations were automatically detected based on a threshold applied to both the time elapsed between a maximum and a minimum of the Z-position and to their difference. The Z-velocity signal was used to establish whether a transition was SitTS or StandTS, (Figure 5.1), [108].

Finally, to quantify the potential differences between subjects, specific movement-related parameters were derived based on the raw MTx acceleration and orientation signals, as well as additional values obtained after data analysis (i.e., the duration, velocity, and position).

An analysis was performed on the X-orientation and Z-acceleration signals. The X-orientation was selected because it contains information about the way the subjects manage their body (the trunk's forward and backward tilt), while the Z-acceleration was related to the impulse required to reach the upright position. To evaluate each parameter, the data were first divided into cycles; then, each cycle was separated into its corresponding phases. Therefore, kinematic parameters could be defined in each phase of the performed cycles for any subject. The overall value of a parameter for a subject was obtained by computing its mean value across the subject's cycles. These parameters describe the subject's movement performance in terms of the mean, standard deviation, maximum, minimum and range of several features of the subtasks, including the duration of the phases and the orientation, position and acceleration signals. The parameters described below (A, B, and C) were also obtained from our analysis:

A. X-orientation range

Four parameters were defined to characterize the amount of forward and backward trunk tilt occurring during each cycle, (Figure 5.2, blue line).

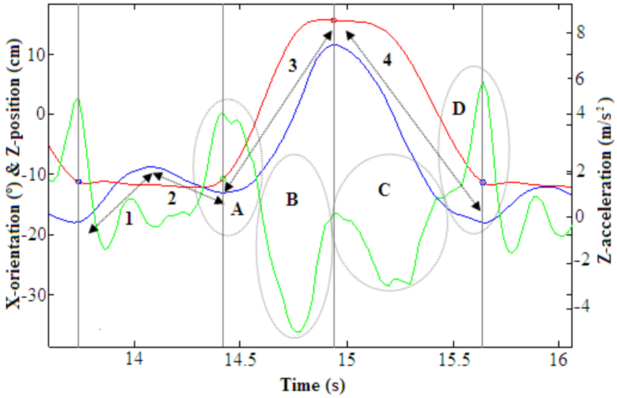

Figure 5.2: *Explanation of the impulse (A-D) or body management (1-4) parameters. Numbers 1 to 4 outline the maximum lean backwards and forwards to sit-down and stand-up: "TurnB_Sit", "TurnF_Sit", "TurnB_Up", and "TurnF_Up". Capital letters refers to the active and passive impulse to achieve the standing and corresponding sitting positions: "+" and "-" up "modified impulses" and "+" and "-" Down "modified impulses". Signals are raw MTx ones during the test performed by a pre-frail subject: Z-position (red), Z-acceleration (green) and X-orientation (blue).*

These parameters were evaluated not according to the phases of the cycles but instead to the trunk movements of the subjects performing SitTS and StandTS transitions. Considering that the cycle starts with the impulse phase, we assumed that the subject was initially in the upright position to define the following ranges of movement:

- TurnB_Sit is a backward trunk lean while the subject is sitting down that is generally produced to accommodate the weight into the chair, (Figure 5.2, blue line, "1").
- TurnF_Sit is a forward trunk lean in the seated position to start the next standing-up (Figure 5.2, blue line, "2").
- TurnB_Up is a backward trunk lean that occurs while the subject is standing-up until he reaches the upright position (Figure 5.2, blue line, "3").

- TurnF_Up is a forward trunk lean in the standing position while the subject is descending that is normally generated to improve balance control (Figure 5.2, blue line, "4").

B. Standing-up and sitting-down "modified-impulses"

The AUC_{Zacc} parameter was defined as the area under the curve of the acceleration for the duration of the movement (Equation 5.1). It was related to the necessary impulse to stand upright and to return to the seat. As previously defined in [108], the AUC was divided into positive and negative components, according to the direction of the displacement. AUC^{+}_{Zacc} referred to the active "modified impulse" used to perform the transition upward, whereas AUC^{-}_{Zacc} referred to the passive transition back to the chair (Figure 5.2).

$$AUC_{Zacc} = \int_{t_i}^{t_j} a_Z(t)\, dt \quad \text{(Equation 5.1)}$$

C. Maximum peaks of standing-up and sitting-down velocities

Drift-effect cancellation, which has been previously described, was required to obtain the 3-axis velocity from the corresponding acceleration signals. For simplicity, only the Z-velocity and the Y-velocity were evaluated because these parameters have greater relevance for the transitions. The Z-velocity refers to the vertical movements of each cycle of the 30-s CST, while the Y-velocity is the forward and backward speed when standing-up and sitting-down.

Finally, standard statistical methods were used to calculate the mean and standard deviation (SD) of each phase parameter across both cycles and subjects.

5.3.4 Statistical analysis

The differences among the three groups (frail, pre-frail and healthy) were determined using a one-way analysis of variance (ANOVA) with Newman-Keuls post-hoc comparisons. When the normality test failed ($p < 0.05$), the Mann–Whitney rank sum test was employed. A "$p < 0.01$" criterion was used to establish statistical significance. Box plots of each parameter for the different movement phases were used to graphically display the variable's location. The box itself contained the middle 50% of the data. The upper and lower edges of the box indicated the 75th and 25th percentiles, respectively, and the central line was the median value of the data. The ends of the vertical lines, or "wiskers", were the minimum and maximum data values, and any points outside the whisker ends represented outliers.

5.4 RESULTS

5.4.1 Overall 30-s CST outcomes

Healthy subjects performed a significantly ($p \leq 0.001$) greater number of sit-to-stand cycles (22 ± 7) during the test duration than did either the pre-frail (15 ± 5) or frail subjects (6 ± 1).

5.4.2 Time domain analysis

The following list outlines the primary parameters analyzed in the time domain. They are categorized based on the information obtained.

A. Phase duration

The duration of the impulse phases was significantly greater ($p \leq 0.001$) for frail subjects than for pre-frail and healthy subjects. Other significant differences were also found between pre-frail and healthy subjects (Figure 5.3 (a)). When the impulse phase duration was normalized to the mean length of the entire cycle, the duration of all phases were significantly smaller ($p \leq 0.001$) for the healthy subjects than for pre-frail and frail subjects. However, the differences found between the pre-frail and frail subjects were not significant.

B. X-orientation

Significant differences were observed among the three groups in the X-orientation range found during the impulse phase (Figure 5.3 (a)). This value, indicating the subject's sway, was significantly greater for the frail subjects than for the pre-frail and healthy subjects ($p \leq 0.001$).

The frail subjects had a greater X-orientation range during the stand-up phase than did the healthy and pre-frail subjects ($p \leq 0.001$), whereas the differences between the ranges of the pre-frail and healthy subjects were not significant.

C. Linear Z-acceleration

The minimum Z-acceleration values when standing-up and sitting-down were significantly greater for the healthy subjects than for the pre-frail and frail subjects. In addition, these values were significantly ($p \leq 0.001$) greater in the pre-frail subjects than in the frail subjects (Figure 5.3 (b)). However, the maximum Z-acceleration values for the stand-up and sit-down phases only differentiate healthy from frail and pre-frail subjects.

The Z-acceleration "modified impulses" (positive, negative and total) required for the standing-up transition were significantly greater in the healthy subjects than in the pre-frail and frail subgroups. These parameters were also significantly greater for the pre-frail subjects than for the frail (Figure 5.3 (c)). During the sitting-down transition, the positive impulse was greater in the healthy subjects than in the pre-frail and frail groups. Moreover, this impulse was greater in the pre-frail subjects than in the frail group, while no differences were found between these groups for the negative and total impulses.

D. Linear Z-velocity

The minimum Z-acceleration values when standing-up and sitting-down were significantly greater for the healthy subjects than for the pre-frail and frail subjects. In addition, these values were significantly ($p \leq 0.001$) greater in the pre-frail subjects than in the frail subjects (Figure 5.3 (b)). However, the maximum Z-acceleration values for the stand-up and sit-down phases only differentiate healthy from frail and pre-frail subjects.

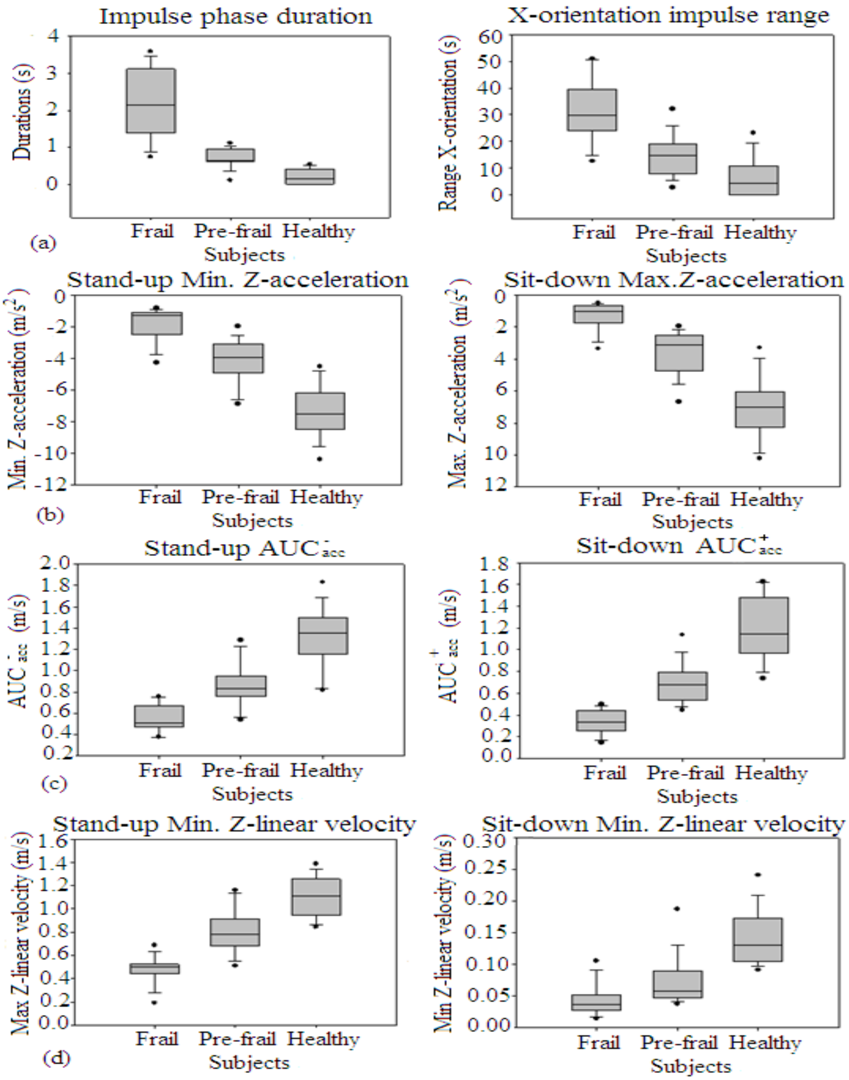

Figure 5.3: *Box plots of the accelerometer-derived parameters which differentiate between groups for the pair wise comparisons. The time invested for the impulse phase, left side, and the X-orientation range during the impulse phase, right side, (a). The Z-acceleration AUC for the negative and positive impulse when standing-up and sitting-down, (b). Finally, the maximum and minimum Z-velocity peaks during the stand-up and sit-down, (d).*

5.4.3 Analysis of the pre-frail and healthy subjects with matching cycles

The two groups chosen for their matching cycle number were similar with respect to the duration of their phases. Nonetheless, a few of the orientation- and acceleration-derived magnitudes that were able to differentiate frailty groups in the previous analysis could also differentiate the new sub-groups. For example, the maximum Z-velocity during the standing-up phase was greater for the healthy subjects than for the other group, a relationship that was also true for the minimum Z-velocity's absolute value (Figure 5.3 (b)). Additionally, the AUC^{-}_{Zacc} when standing up and the AUC^{+}_{Zacc} when sitting down were significantly greater for the pre-frail subjects than for the healthy subjects ($p \leq 0.001$) (Figure 5.3 (c)).

5.5 DISCUSSION

Our analysis revealed that movement-related parameters such as the phase duration and the angular rate, as well as power-related magnitudes such as acceleration, velocity and AUC_{Zacc} allow us to clearly differentiate between people belonging to different frailty groups (frail, pre-frail, healthy) (Table 5.1). Moreover, the velocity and AUC_{Zacc} parameters are sensitive enough to differentiate between a pre-frail and a healthy subject when the actual outcome (number of cycles completed) could not. These results are a preliminary step toward the development of a user-friendly, simple automated tool to help clinicians assess the 30-s CST in an objective manner based on movement-related parameters.

TABLE 5.1: PARAMETERS THAT DIFFERENTIATE FRAILTY LEVELS

PARAMETERS	Frail Vs Pre-Frail	Frail Vs Healthy	Pre-Frail Vs Healthy	Cycles-matched
Cycles number	YES	YES	YES	NO
IMPULSE PHASE				
Duration	YES	YES	YES	NO
Normalized duration	NO	YES	YES	NO
X-orientation range	YES	YES	YES	NO
STAND-UP PHASE				
X-orientation range	YES	YES	NO	YES
Minimum Z-acc. peak	YES	YES	YES	NO
Maximum Z-acc. peak	NO	YES	YES	NO
AUC^{+}_{Zacc}	YES	YES	YES	NO
AUC^{-}_{Zacc}	YES	YES	YES	YES
AUC^{T}_{Zacc}	NO	YES	YES	NO
Maximum Z-veloc. peak	YES	YES	YES	YES
Minimum Z-veloc. peak	YES	YES	YES	YES
SIT-TO-STAND PHASE				
Minimum Z-acc. peak	YES	YES	YES	YES
Maximum Z-acc. peak	NO	YES	YES	NO
AUC^{+}_{Zacc}	YES	YES	YES	YES
AUC^{-}_{Zacc}	NO	YES	YES	NO
AUC^{T}_{Zacc}	NO	YES	YES	NO
Maximum Z-veloc. peak	NO	YES	YES	NO
Minimum Z-veloc. peak	YES	YES	YES	YES

Z-acc and the subindex Zacc refers to the Z-axis acceleration
Veloc. Referes to the term velocity

5.5.1 Added information from the instrumented 30-s CST

Our hypothesis was that subjects with different frailty levels not only differ in the number of the performed cycles during the 30-s CST but also in their movement pattern, which is constrained by their functional capacity. IUs were presented as a suitable tool to evaluate each cycle and its constituent phases (impulse, stand-up, and sit-down) and from these IUs, the corresponding kinematic information could be obtained.

As Ganea et al. showed in a previous study [73], frailty was related to an increased duration of the impulse phase as well as a greater X-orientation range during this phase. This idea is consistent with our results, as it indicates that frail subjects require extra forward and backward leaning to connect one cycle with the next (Figure 5.4). Moreover, Gross et al. [54] suggested that this extra movement may result from arranging the body to enhance stability or to meet the strength demands of the task. Thus, our hypothesis that different frailty levels lead to different methods of performing movements was corroborated.

Other studies define consecutive sit-stand-sit cycles by a double flexion and extension movement [112;130;224]. Our research showed that this specific movement does not always occur; the X-orientation range we found during the impulse phase revealed that healthy subjects do not perform double flexion and extension. Rather, they are healthy and strong enough to produce the power output with only their lower muscles, so there is no need for any compensatory movement or control strategy. Furthermore, the range of X-orientations during the stand-up and sit-down phases of the frail subjects differed from those of the pre-frail and healthy subjects. Indeed, a frail subject used increased range when leaning backward to sit down and when leaning forward to stand up. No differences in this value were found between healthy and pre-frail subjects.

Frail subjects obtained lower velocity and acceleration peaks as well as reduced impulses (AUC_{Zacc}) than did the pre-frail and healthy groups during the stand-up and sit-down phases. Therefore, this frailty group has less physical capacity to perform the different phases of the cycles in the 30-s CST. This finding might be explained by the fact that frail subjects have reduced power in their lower extremities, leading to a restricted and cautious strategy for transitions performance [54;225].

Another interesting and promising result was that our method is sensitive enough to detect different frailty levels among groups of subjects with the same number of performed cycles. This finding is especially important because it reveals that other parameters related to the 30-s CST are more sensitive to frailty. In particular, the maximum linear Z-velocity peak during the stand-up phase and the minimum during the sit-down phase, appear to be highly related to frailty. Moreover, the negative "modified-impulse", AUC^{-}_{Zacc} that occurs when standing-up (related to the negative acceleration required to reach the upright position), as well as the positive "modified impulse", AUC^{+}_{Zacc}, that occurs when sitting down (related to the positive acceleration required to reach the seat), can differentiate pre-frail subjects from healthy ones. This idea could lead to an accurate definition of the frailty syndrome that considers parameters obtained from an IU and is directly related to the movement performance.

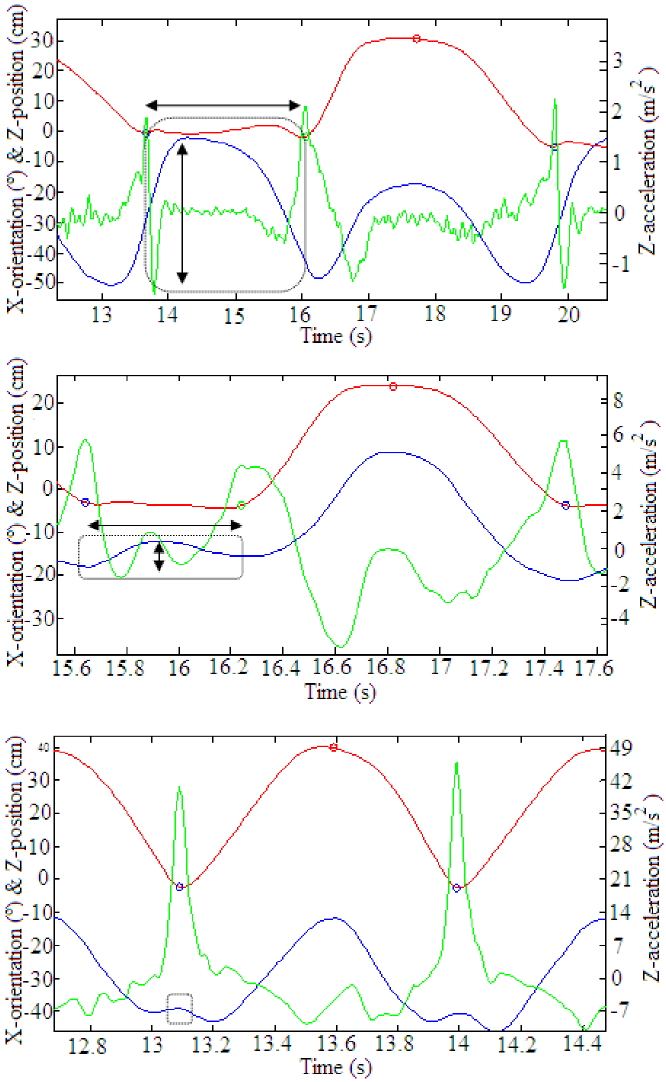

Figure 5.4: *Movement patterns of raw MTx signals (Z-position, X-orientation, Z-acceleration) for frail (a), pre-frail (b) and healthy subjects (c). The circle outlines the extra forward and backward lean for more frail subjects and the arrows features the time duration and X-orientation range.*

In summary, differences in the frailty level of a subject can be found by evaluating the specific way the 30-s CST cycles are carried out. This study highlights the additional backward and forward lean that is produced during the impulse phase for frail subjects, as well as the differences in the forces required to achieve the upward position and to subsequently return to the chair (i.e., decreased Z-acceleration peaks and AUC_{Zacc}). Furthermore, the velocities seen in the different phases of each cycle, particularly the Z-velocity peaks of the stand-up and sit-down phases are of special interest because they can differentiate subjects with different levels of frailty that performed the same number of cycles during the 30-s CST.

The present findings motivate future investigations into these topics. For instance, an additional assessment is required to explore the spectral edge frequency information found in the phases of each cycle of the 30-s CST. This manuscript shows that using IUs in the 30-s CST provides kinematic information while maintaining tests simplicity and requiring no additional time for data acquisition. Until now, measurements were based on the quantity of cycles, and there was no information about the quality of the movement performance. Furthermore, there is currently no gold standard based on IU data for the assessment of the SitTS and StandTS transitions. The automated approach described in this study may improve doctors' ability to detect high-risk frailty levels, provide a finer scale for frailty levels, document progression of aging in the elderly, and assess subject responses to exercise programs or other types of interventions in an objective and sensitive manner based on kinematic parameters. However, further research is required to evaluate the association between kinematic 30-s CST variables and other age-related processes in a larger group of subjects.

5.6 CONCLUSSION

The aim of this work is to improve the information gathered with the 30-s CST by defining kinematic parameters that can be gathered from IU data. These parameters could lead to a more precise and reliable determination of a subject's frailty level (frail, pre-frail, or healthy). This study provides evidence that some of the proposed parameters are more sensitive to the frailty level than the current standard 30-s CST outcome of completed cycles. Positive Z-velocity peaks during the stand-up and sit-down phases, as well as the so-called "modified impulses" stand out as the most promising parameters for the classification task. Therefore, this work offers clinicians a possible method for the early detection of frailty syndrome so that an appropriate treatment can be applied to avoid further decline.

CHAPTER 6:

Conclusions and Future Work

Conclusiones y Trabajo Futuro

6.1 CONCLUSSIONS

The aim of this thesis was to assess one functional test such as the 30-s CST, under the signal analysis point of view, by using a kinematic unit in an elderly population with different frailty levels. The main conclusion of the overall work is that the obtained kinematic information can indeed outperform functional test such as the 30-s CST. This kind of parameters is able to distinguish patients with different frailty levels even with the same actual outcome, the number of performed cycles. The relevance of this kind of measures is that they are not only able to quantify a movement but also to qualify the way it has been performed. Clinicians will take advantage of this new procedure since there is a current lack of objective parameters to use in their diagnostics when dealing with movement assessment. Therefore, clinicians in special geriatricians as well as physiotherapist will be provided by portable and meaningful tools to deal with diseases difficult to diagnose in its early stages such as the frailty syndrome.

In particular, there is a list of the main conclusions throughout this thesis:

1. Motion sensor devices are a viable technology for studying movement performance and, in particular, the complexes sit-to-stand and stand-to-sit transitions. These portable unobtrusive and low-cost systems make it possible to provide meaningful parameters through signal analysis for a more precise and quantitative assessment in clinical practice. (Chapter 2).
2. There is a lack of a gold standard to measure kinematics of the SiSt and/or StSi transitions (i.e. test nature, measurement instruments, body placement, analysis methodology, etc.) (Chapter 2).

3. Transition duration is the parameter most commonly used to measure patient's condition over time. Other time-domain kinematic parameters are also able to discriminate patients with movement disorders. However, to detect subtle differences or minor improvements additional information (i.e. dynamic, smoothness or frequency-domain parameters) should be assessed. (Chapter 2).
4. The new two-step processing method, "PB-algorithm", is able to cancel drift disturbances in Z-position estimation for periodic movements facilitating the analysis of the 30-s CST using a single inertial unit. (Chapter 3).
5. Once the drift is removed, the Z-position information obtained from IU's data is similar in quality to the one provided by expensive laboratory-fixed instruments like optical systems. (Chapter 3).
6. Z-position is the main component of the stand-up and sit-down movement so that is the best reference for cutting the whole 30-s signal into the corresponding cycles. Therefore, this approach allows for the automatic recording of the number of full stands as well as further analysis to obtain kinematic parameters. (Chapter 3).
7. The instrumented version of the 30-s CST allows for an automated control of the test even without any engineering knowledge, avoiding human errors that occur during testing. (Chapter 4).
8. A collection of meaningful kinematic variables can be gathered from the IU data of the instrumented version of the 30-s CST, while maintaining test simplicity and requiring no additional time for data acquisition. Therefore, the quality of the movement performance can be evaluated, based on this objective information. (Chapter 4).

9. Differences in the frailty level of a subject can be found by evaluating the specific way the 30-s CST cycles are carried out through the corresponding kinematic parameters. In particular, more frail subjects tend to increase the backward-forward lean during the impulse phase and decrease the forces required to achieve the upward position and subsequent return to the chair. (Chapter 4).

10. Parameters such as Z-velocity peaks during the Stand-up and Sit-down phases, as well as the so-called "modified-impulse" are more sensitive to the frailty level than the current standard 30-s CST outcome of completed cycles. (Chapter 4).

11. This automated approach of the test may improve doctor's ability to detect high-risk frailty levels, provide a finer frailty scale, document progression of aging in the elderly, and assess subject response to interventions in an objective and sensitive manner based on kinematic parameters. (Chapter 4).

6.2 FUTURE WORK

The qualitative and quantitative data provided by this new approach to evaluate the 30-s CST, by using a single inertial unit, lead to a more detailed analysis of the test. The main advantage is that successful early detection of frailty syndrome could be possible by observing pre-frail subjects. However, only two or three parameters should be selected to simplify clinical diagnostic. Therefore, more research should be done to evaluate which of the provided parameters are more related to the frailty syndrome.

On the other hand, test based on gait seem to be also of special interest in actual frailty assessment. Cross-validation should be done joint to gait parameters to obtain a global measurement of the functional status of a subject. Therefore, it could be determined which subjects have imbalances in this aspect of frailty, the one that could be corrected through the corresponding therapist actions.

In the case of exercise interventions, it should be proved if these kinematic parameters are able to detect subtle differences. Other measures such as movement smoothness or frequency-domain parameter should be tested. Thereafter, clinicians and physiotherapist could have an instrument to follow a patient during the intervention selected to correct his physical status.

Finally, these results should be introduced into a friendly to use tool, such a mobile phone application, to furnish clinicians with a real mean to evaluate patients and their progression along the time.

6.1 CONCLUSIONES

El objetivo de esta tesis es estudiar en detalle el test funcional de la silla de treinta segundos, desde el punto de vista del análisis de señal. Para ello se utiliza una única unidad inercial que proporciona datos sobre el movimiento realizado. Como se pretende también dar una aplicación clínica a los resultados se eligió una población de sujetos de edad avanzada, con diferentes grados de fragilidad, para realizar el test. La conclusión principal a la que se ha llegado es que parámetros cinemáticos son capaces de mejorar la evaluación e test funcionales. De hecho, este tipo de parámetros es capaz de distinguir pacientes con diferentes niveles de fragilidad incluso cuando se ha obtenido el mismo resultado del test, el número de ciclos realizados. La importancia de este tipo de medidas es que no solo son capaces de cuantificar cierto movimiento sino que también pueden determinar el modo en el que ha sido realizado. Actualmente existe una carencia de parámetros objetivos para la valoración de la capacidad funcional de modo que el personal médico podría beneficiarse de este nuevo procedimiento para ello. Así, tanto personal relacionado con la Medicina como con la Fisioterapia podría disponer de una herramienta portátil y que proporcione datos relevantes para hacer frente a cierto tipo de enfermedades, como el síndrome de fragilidad, más difíciles de diagnosticar especialmente en sus primeras etapas.

A continuación se presenta una lista con las principales conclusiones obtenidas a lo largo de esta tesis:

1. Dispositivos como los sensores de movimiento son una tecnología totalmente viable en el estudio de la ejecución de cierto movimiento y, en particular, de las complejas transiciones de sentado a levantado y viceversa. Estos sistemas portátiles, no intrusivos y de bajo coste

permiten obtener parámetros significativos, tras un análisis de señal, para una evaluación clínica más cuantitativa y precisa (Capítulo 2).

2. No existe un procedimiento estándar para la medición cinemática de las transiciones de sentado a levantado y de levantado a sentado, ej. test utilizado, instrumento de medida, localización en el cuerpo, metodología de análisis, etc. (Capítulo 2).

3. La duración de la transición es el parámetro que más se ha utilizado para poder medir de alguna manera la condición física del paciente a lo largo del tiempo. Existen también otros parámetros cinemáticos correspondientes al dominio del tiempo que son capaces de diferenciar qué pacientes padecen ciertos trastornos del movimiento. Sin embargo, para detector diferencias más sutiles o pequeñas mejoras es necesario estudiar otro tipo de información, ej. parámetros dinámicos, de suavidad o relativos al dominio de la frecuencia, (Capítulo 2).

4. El nuevo método de procesado de dos etapas, "algoritmo PB", es capaz de cancelar las perturbaciones ocasionadas por la deriva a la hora de estimar la posición en el eje Z para movimientos periódicos, facilitando de este modo el análisis del 30-s CST mediante un único sensor inercial (Capítulo 3).

5. Una vez eliminado el efecto nocivo de la deriva, la información que nos proporciona la posición en el eje Z, obtenida de las unidades inerciales posee la misma calidad que la que nos proporciona los costosos instrumentos de laboratorio como los sistemas ópticos (Capítulo 3).

6. La posición en el eje Z es la principal componente relativa a los movimientos de levantarse y sentarse de modo que puede utilizarse como referencia para determinar los ciclos de la señal relativa a los

treinta segundos del test. Este enfoque permite obtener el número de levantadas completas así como realizar un análisis más exhaustivo para obtener parámetros cinemáticos relativos al movimiento (Capítulo 3).

7. La versión instrumentalizada del 30-s CST permite un control automático del test, incluso para aquellas personas que no posean un conocimiento tecnológico, evitando errores humanos que pueden ocurrir durante la realización del test (Capítulo 4).

8. Los datos obtenidos a partir de unidades inerciales usadas en la versión instrumentalizada del 30-s CST permiten obtener una colección de variables cinemáticas significativas, manteniendo la simplicidad de la prueba y sin otros requerimientos adicionales para la adquisición de los datos. De este modo, a partir de la información objetiva que nos proporcionan dichos parámetros, puede llegar a evaluarse la "calidad" del movimiento en cuestión (Capítulo 4).

9. Analizando los ciclos de las señales al realizar un test de la silla de treinta segundos y a partir de los parámetros inerciales pueden determinarse diferencias en el nivel de fragilidad de los sujetos. En concreto, los sujetos más frágiles tenderán a incrementar el balanceo de hacia atrás a hacia delante durante la fase del impulso y disminuir la fuerza con la que consiguen llegar a la posición erguida y el posterior retorno a la silla (Capítulo 4).

10. Parámetros tales como la velocidad en el eje Z durante las fases de levantarse y sentarse, así como el denominado "impulse modificado" son más sensible al nivel de fragilidad que la valoración actual del test mediante el número de levantadas completas (Capítulo 4).

11. Este enfoque automatizado de la prueba mejoraría la capacidad del médico para detectar el riesgo de padecer cierto nivel de fragilidad puesto que, proporciona una escala de fragilidad más fina y puede determinar la progresión de envejecimiento en las personas mayores. Por otro lado, permite evaluar la respuesta a diferentes tipos de intervenciones, de forma objetiva basada en parámetros cinemáticos (Capítulo 4).

6.2 TRABAJO FUTURO

Los datos cualitativos y cuantitativos obtenidos mediante este nuevo enfoque de evaluación del 30-s CST, usando una única unidad inercial, conducen a un análisis más detallado de esta prueba. La ventaja principal es la posibilidad de detectar los estados incipientes de fragilidad, mediante la observación de los sujetos pre-frágiles. Sin embargo, solamente dos o tres parámetros deberían seleccionarse para su uso en el diagnóstico clínico. Así, es necesario determinar cuáles de los parámetros obtenidos están más relacionados con el síndrome de fragilidad.

Por otro lado, los test basados en el análisis de la marcha parecen tener especial interés en el estudio que se realiza hoy en día de la fragilidad. De este modo, debería realizarse una validación conjunta de los parámetros obtenidos del 30-s CST y aquellos relativos a la marcha para obtener una medida global del estado funcional de un determinado sujeto. Esto permitiría determinar qué sujetos tienen ciertos déficits en los aspectos de la fragilidad relativos a la capacidad funcional, pudiendo llegar a corregirse con la correspondiente intervención terapéutica.

En el caso de tratamientos en forma de ejercicio, debería probarse si este tipo de parámetros cinemáticos son capaces de detectar diferencias más sutiles relativas a las mejoras producidas por este tipo de intervención. En caso contrario, otro tipo de medidas tales como la suavidad del movimiento o parámetros del dominio de la frecuencia deberían obtenerse para este fin. De este modo, el personal clínico podría llevar un control de las mejoras producidas en determinado paciente conforme lleva a cabo el tratamiento prescrito.

Para terminar, estos resultados deberían poder introducirse en una herramienta más amigable, como puede ser una aplicación móvil para poder proporcionar a los médicos un método real y sencillo de evaluar a sus pacientes y, especialmente, su progresión a lo largo del tiempo.

APPENDIX I

Work related to this thesis

JOURNALS

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Leocadio Rodríguez-Mañas, Francisco José García-García, Mikel Izquierdo. "*Automatic evaluation of the 30-S Chair stand test using inertial/magnetic technology in an older pre-frail population*". IEEE Journal of Biomedical and Health Informatics, July 2013, Vol. 17(4), Pag. 820-827.

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo. "*An Evaluation of the 30-s Chair Stand Test in Older Adults: Frailty Detection Based on Kinematic Parameters from a Single Inertial Unit*". Journal of NeuroEngineering and Rehabilitation, August 2013, Vol. 10, Pag. 86-95.

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo. *"Drift-Free Position Estimation for Periodic Movements Using Inertial Units"*. IEEE Journal of Biomedical and Health Informatics, July 2014, Vol. 18(4), Pag. 1131-1137.

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo. *"Kinematic Parameters to Evaluate Functional Performance of Sit-to-Stand and Stand-to-Sit Transitions Using Motor Sensor Devices: a Systematic Review"*. IEEE Transactions on Neuronal Systems and Rehabilitation (DOI: 10.1109/TNSRE.2014.2331895).

INTERNATIONAL CONFERENCES

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo. "*Kinematic and Kinetic Analysis of the 30-s Chair Stand Test with a Tri-axial Inertial Magnetic Sensor*". Proceedings of the 18th Congress of the European Biomechanics Society, July 2012, Lisboan (Portugal).

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Jon Martinikorena, Mikel Izquierdo. "*Instrumented 30-s Chair Stand Test: evaluation of an exercise program in frail nonagenarians*". Proceedings of the 2nd International Work-Conference on Bioinformatics and Biomedical Engineering (IWBBIO2014), April 2014, Granade (Spain).

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo. "*Frailty detection using the instrumented version of the instrumented version of the 30-s Chair Stand Test*". Oral presentation in the 2nd International Conference on NeuroRehabilitation, June 2014, Aalborg (Denmark).

RESEARCH PROJECTS

1. Pre-doctoral bourse from the Social Affairs, Family, Youth and Sports Department of the Government of Navarre (Regional Order 105/2010))

2. Title of the project: Thematic Network of Cooperative Research on Aging and Frailty, (RD12/0043/0002)
Funding organization: Instituto de Salud Carlos III
Principal researcher: Mikel Izquierdo Redín
Duration: 2013 – 2015
Funding: 35.401 Euros
Number of researchers: 5

3. Title of the project: Frailty and functional indicators related to aging without disability and an autonomous and independent old age, (DEP 2011-24105)
Funding organization: Ministry of Science and Innovation
Principal researcher: Mikel Izquierdo Redín
Duration: 2012 – 2015
Funding: 50.000 Euros
Number of researchers: 13

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