Application of a wireless BSN for gait and balance assessment in the elderly

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***Abstract*— In developed countries, sedentary lifestyle is a major health risk factor. In elderly people, such mobility limitation is worsened by the reduced self-confidence and the fear of falling, leading to a further motor deterioration. This work presents an application of a wireless Body Sensor Network as a simple and easy-to-use individual motor function assessment tool for elderly. The wearable nodes have been exploited to monitor the body during the Six-Minute Walk Test and a set of stability tests. During the exercises, wearable sensors inertial data, along with the real-time orientation of the platforms, have been exploited to obtain gold-standard indicators (such as total distance) and some additional gait parameters. Stability tests consist of a series of single and double stance exercises aimed to assess the balance of the subject. This paper presents the system, the processing and the preliminary results on two subjects groups of different ages (31±6 and 70.8±7).**

Keywords—elderly; 6MWT; balance; stability; AHRS

I. Introduction

Insufficient physical activity is the 4th leading global risk for mortality in the world [1]. It is estimated to be responsible for 6% of deaths globally, after high blood pressure (13%), tobacco use (9%), high blood glucose (6%) and right before overweight and obesity (5%). As life expectancies increase and the major causes of death shift to the chronic and noncommunicable diseases (NCDs), populations are facing modern risks due to sedentary lifestyle. Moreover, the increase in the elderly population has in turn rapidly increased fall-induced injuries, which are major issues for health and social care providers in the world [2]. Falls are the most serious and frequent home accident among older people. As a matter of fact, they are the major reason for admission to hospital or a residential care setting, even when no serious injury has occurred: Heinrich et al. reported the evidence of the economic burden of falls on society [3]. The safety of walking as well as coordinating abilities depend on the single stance stability of the subject [4]. In fact, in elderly people a single stance instability situation leads to a deterioration of motor experience: the risk associated to this condition induces a lack of self-confidence in the subject, which will reduce their motor habits and change their lifestyle becoming more hypokinetic. Also, there is observational evidence that mid-life and older adults who participate in regular physical activity have reduced risk of moderate and severe functional limitations and role limitations [5]. In some cases the evidence of health benefits is strongest in older adults because the outcomes related to inactivity are more common in older adults. Pahor et al. [6] have demonstrated the potential for structured physical activity as a feasible and effective intervention to reduce the burden of disability among vulnerable older people, in spite of functional decline in late life. Furthermore, improving physical conditions and motor abilities of elderly contributes to the abatement of health and hospitalization costs. In order to prevent disability and fall-induced injuries, physical activity has to be considered as a therapeutic tool prescribed by doctors on the basis of diagnostic assessments on the patient. Such activity will have the goal to maintain and improve the motor condition of the subject, including coordination, balance, proprioception and reaction time. In this paper, a network of wearable Attitude and Heading Reference Systems (AHRS) has been exploited as a quantitative tool to assess motor performance in elderly people. Patients of different ages have been monitored during the execution of two exercises, the so-called Six-Minute Walk Test (6MWT) and a set of stability tests, in order to evaluate some gait key parameters and the balance respectively. The work reports the preliminary results of the system on two groups of subjects of different ages.

II. Assessments descprition

Inactive adults of the 65 years and above age group, including those with NCDs, are likely to gain health benefits by increasing their level of physical activity. International guidelines for elderly physical activity prescription in elderly suggest to include a set of exercises aimed to improve stability. In fact, the physiological functional regression involving this category is the reason of the increase of falls, which deeply change subject's behavior even when there are no consequences. Before starting any physical exercise program, it is necessary to establish reliable methods for subjects motor assessment. Steffen et al. [7] reported reliability, validity and reference data of 4 common clinical tests, i.e. Six-Minute Walk Test, Berg Balance Scale (BBS), Timed Up & Go (TUG) and Comfortable and Fast Gait Speeds (CGS and FGS). Langley and Mackintosh provided a systematic review of published literature relevant to 17 functional balance tests [8]. In order to define a proper therapeutic set of exercises aimed to maintain and improve functional abilities, two of those assessments have been selected as diagnostic tools to evaluate motor conditions in elderly people: the 6MWT and a set of balance tests.

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A. Six-Minute Walk Test

Functional endurance is necessary for individuals to live independently without accommodation in community settings. The 6MWT is a simple and inexpensive method of indirectly assessing physical capacity that is widely available and commonly used. Such test measures the distance that a patient can quickly walk on a flat, hard surface in a period of 6 minutes. Although it was originally developed to assess cardiorespiratory and cardiovascular endurance, the distance covered during the 6MWT (6MWD) has been shown to be a sensitive measure of the severity of heart disease, according to the New York Heart Association (NYHA) functional classification. According to the official statement of the American Thoracic Society (ATS) [9], practical guidelines for the 6MWT are as follows:

- The test should be performed indoors, along a long, flat, straight, enclosed corridor with a hard surface.
- The patient has to walk back and forth in such corridor as far as possible for 6 minutes.
- The walking course must be 30 m in length, and turnaround points should be marked with cones.
- The patient is permitted to slow down, to stop and to rest if necessary, but they have to resume walking as soon as they are able.

The self-paced 6MWT assesses the submaximal level of functional capacity. Most patients do not achieve maximal exercise capacity during the 6MWT; instead, they choose their own intensity of exercise and are allowed to stop and rest during the test. However, because most activities of daily living are performed at submaximal levels of exertion, the 6MWD may better reflect the functional exercise level for daily physical activities. In recent decades, the 6MWD has been validated as a general indicator of overall physical performance and mobility for older people [10]. Optimal reference equations from healthy population-based samples using standardized 6MWT methods are not yet available. In one study, the median 6MWD was approximately 580 m for 117 healthy men and 500 m for 173 healthy women [11]. A mean 6MWD of 630 m was reported by another study of 51 healthy older adults [12]. Camarri et al. [13] demonstrated an average distance of 659 m in 70 healthy subjects aged 55-75 years. Usually, a 6MWD of 300 m or less is considered to be an indicator of high mortality risk.

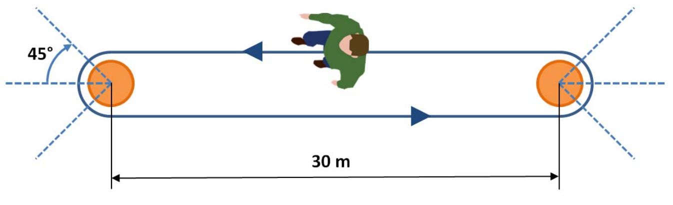

Fig. 1. Top view representation of the 6MWT.

B. Balance tests

Unstable balance, falls, and loss of independence in the older population are a growing problem in the developed countries. The safety of walking and balance are indispensable requirements to prevent falls and loss of independence. The afferent visual, vestibular and proprioceptive systems represent the base of safe mobility as they offer the patient vital information for postural control. They determine, respectively, three behavioral strategies. Using posturography or stabilometry, it is possible to distinguish and to evaluate the functional levels of the strategy used by each subject [4]. A posturographic system should be able to analyze the postural oscillations and the strategy used to maintain control of an upright stance, offer the possibility to analyze several parameters and provide comparable data. The balance is evaluated considering the average value and the standard deviation of the center of gravity in different conditions. Among several balance tests, the static double-leg stance (stabilometric) and the static single-leg stance (static propedeutic) tests provide a quantification of the postural control [14]. The former test assesses the stability in bipodalic stance during different sensory conditions (open eyes, closed eyes, hyperextended head and on rubber). The comparison among the data of the different tests underlines the presence of visual dependence, visual effect paradox and vestibular effect paradox. On the other hand, the static propedeutic test has the goal to evaluate the risk of fall and if the walking stability of the subject depends on the visual information. Thanks to the comparison of a simple static test performed in monopodalic stance in two different sensory conditions (Eyes Open and Eyes Closed) it is possible to assess:

- The precaution strategy, that comes into play when the subject is not able to manage the static monopodalic stance without the help of an external support (sensor-bar).
- The visual strategy that allows a quantification of the visual dependence that is how much the stability of the subject depends on the visual information.
- The intervention of the proprioceptive strategy that is the base of the postural control.
- The intervention of the vestibular strategy (ability to manage the emergency situations).

III. Hardware Description

The wearable platform dedicated to this work is derived from neMEMSi, a miniaturized multi-sensor hub presented in a previous paper [15]. The new platform, named neMEMSi-Smart, has been designed in order to add functionalities capable for enhancing its operation, without incrementing the cost and the external volume. neMEMSi-Smart comes in a 25 mm x 25 mm form factor PCB and embeds sensing, processing, storage and communication units. The platform exploit the latest technologies in sensing and processing capabilities and power consumption: a 32 bit microcontroller, a 3D geomagnetic System-in-Package (SiP), a pressure sensor have been combined with a 128 Mbit high-capacity serial NOR Flash memory, providing hours of continuous data log without the need of an active radio connection.

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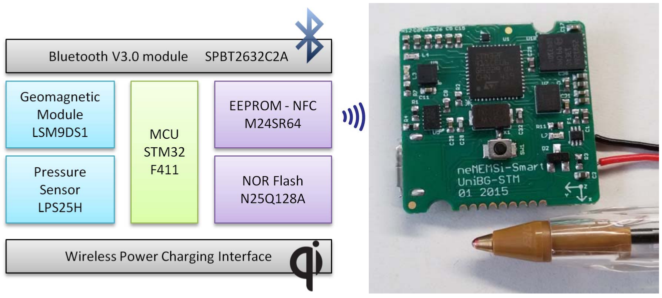

Fig. 2. neMEMSi Smart Block diagram (left) and assembled PCB (right).

The processing core of neMEMSi-Smart platform is the STM32F411 high-performance Cortex-M4 microcontroller by STMicroelectronics. It features a current consumption per MHz down to 100 uA/MHz with a floating point unit (FPU) core scalable at a frequency up to 100 MHz. neMEMSi-Smart integrates the second generation of System-in-Package (SiP) LSM9DS1 geomagnetic module, manufactured by STMicroelectronics. The LSM9DS1 embeds a ±8g (g-force) 3D accelerometer, a ±16 Gauss 3D magnetometer and a ±2000 dps gyroscope in a 3.5 mm x 3 mm package. In order to achieve a data logger, a non-volatile NOR memory has been used as a primary storage. The memory is a N25Q128 by Micron Technology, a 128 Mbit serial NOR flash in a 5 mm x 6 mm package. As far as the wireless communication is concerned, the standard Bluetooth technology for short distances data communication has been chosen. The SPBT2632C2A micro-sized Bluetooth V3.0 module provided by STMicroelectronics is a highly integrated solution for Bluetooth applications using the Serial Port Profile (SPP). It ensures communication interoperability with any kind of Bluetooth enabled platforms and Windows, Linux, MacOS or Android based devices.

IV. Methods

In order to collect data from the BSN nodes, a C#-based software has been developed. This software allows to associate each module of the network to the limb on which they are mounted, establish and test connections and finally start simultaneous transmissions from the devices. Two neMEMSi-Smart modules were used for the preliminary measurement campaign; providing adjustable straps the modules were mounted on the trunk and the other one on the forearm as concerns the stability tests, on the ankle for the 6MWT. The measured subjects were instructed before the exercise and all of them followed the test protocol hereafter explained. The study was approved by the Brescia Province Ethics Committee as project SCN00442.

A. 6MWT

Measurements were performed in a corridor, using two cones at 30 m distance as depicted in Fig. 1. At operator start, subjects walked at maximum speed for 6 minutes, being advised each minute, with a countdown the last 5 seconds. At operator stop the last segment length has been measured by means of a measuring tape.

B. Balance Tests

The performed balance assessment is composed by 8 consecutive tests, of 10’’ duration each, with a pause of about 10’’ between them. At the end of each single test, which was given by an operator vocal command, the subjects had to raise the arm with the sensor in order to permit in the post-processing to easily extract the data subsets. The stabilometric test has been performed on ground and on an exercise mat with eyes open (EO) and closed (EC). The static Riva test was performed in monopodalic stance, in both EO and EC conditions.

C. Subjects

The measured subjects, whose parameters are summarized in Table I, have been classified in two groups, A and B; group A (mean age 31±6) is composed by 5 adults with no pathologies and different levels of training. Group B (mean age 70.8±7) is composed by elderly following the prescription of physical activity in the hospital gym.

TABLE I. SUBJECTS PARAMETERS

Subject	Age	Sex	Weight [kg]	Height [m]	Notes
A.1	39	M	74	1.79	-
A.2	28	M	66	1.75	-
A.3	26	F	63	1.70	-
A.4	35	M	70	1.78	-
A.5	27	F	49	1.58	-
B.1	76	M	67	1.62	diabetes type 2, Physical activity from 2012
B.2	62	M	92	1.72	diabetes type 2, Physical activity from Feb 2015
B.3	77	M	81	1.72	diabetes type 2, Physical activity from Sept 2013
B.4	68	F	87	1.60	Physical activity from Sept 2013

V. Results and Discussion

The saved data for each sensor platform include 3D orientation and raw data, namely 3D accelerometer, 3D angular velocities and 3D compass measurements. The output data rate was set to 50 Hz for the Six-Minute Walk Test and to 25 Hz for balance tests. The orientation of each platform with respect to the reference system of the subject has been calculated by means of the procedure reported in [15]. The rotation between the earth reference system and the direction of the execution has been collected before test sessions started, once for the 6MWT and once for balance tests. Each orientation has been converted to Euler angles, namely roll, pitch and yaw, in order to represent the rotation around x, y and z axis of the body reference system.

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A. 6MWT Analysis

The 6MWT has been analyzed in terms of trunk yaw angles for determining the number of segments fully walked between cones and in terms of raw data for determining the gait parameters and the residual distance of the last segment. Steps are identified by applying a version of the Todd-Andrews algorithm to the magnitude of the acceleration measured by the node mounted on the ankle. The algorithm has been modified in order to include an adaptive threshold: in this way, the system is independent from the speed and the style of the walk, as depicted in Fig. 3.

In order to split the exercise, a threshold for the yaw of the trunk has been selected: the subject is walking straight if the absolute value of the yaw is less than 45 degrees or greater than 135 degrees, otherwise the subject is turning around one of the two cones. In this way, it is possible to identify the start and the end of each turning, and so the turning time and the number of straight segments. The distance can now be expressed as the number of straight segments times the measure of the cone-to-cone distance (see Fig. 4). This measure lacks the meters between the last turning point and the position the subject ends the exercise. In order to include this additional distance, the mean stride length is calculated on the basis of the steps taken from the start to the last turning point and the distance previously obtained: then, such mean stride length is multiplied by the number of steps from the last turning point.

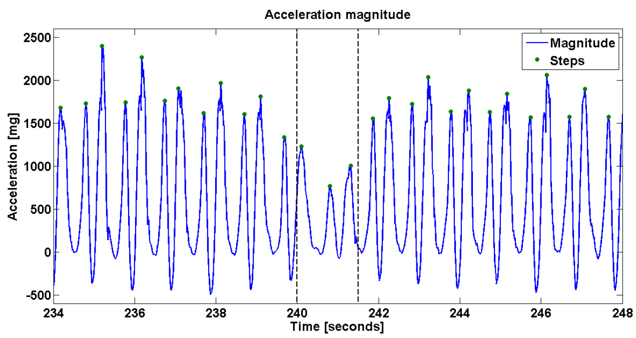


Fig. 3. 6MWT steps identification in proximity of the turning. The deceleration before turning segments and the subsequent acceleration of the gait are clearly visible.

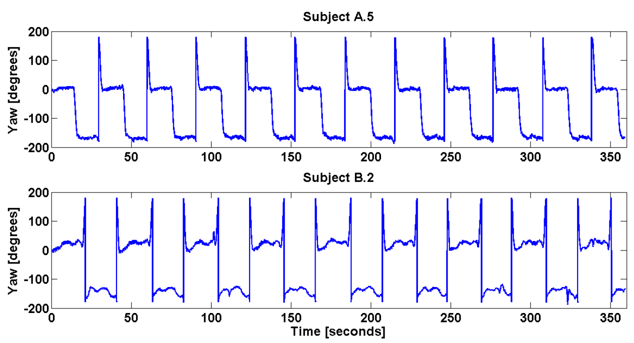


Fig. 4. Trunk yaw of two subjects during the whole 6MWT. Straight segments are clearly visible (23 for subject A.5, 17 for subject B.2).

Table II summarizes the results, showing that group A performed on average 122 meters more with respect to group B: in consequence of that, the stride length and gait velocity are different, while the turning times are comparable. The average absolute error of the automatically estimated distance with respect to the distance obtained with the measuring tape is 1.8 m in group A and 0.5 m in group B.

TABLE II. 6MWT RESULTS

Subject	6MWT					
	Distance [m]	***Steps#***	***Mean Stride Length [m]***	***Mean Speed [m/s]***	***Mean Straight Speed [m/s]***	***Mean Turning Time [s]***
A.1	660	779	0.85	1.83	1.94	0.84
A.2	599	742	0.81	1.66	1.75	0.78
A.3	612	739	0.83	1.7	1.8	0.86
A.4	696	784	0.89	1.93	2.06	0.89
A.5	710	752	0.94	1.97	2.04	0.44
Mean	*655.40*	*759.20*	*0.86*	*1.82*	*1.92*	*0.76*
ST Dev	*49.28*	*20.99*	*0.05*	*0.14*	*0.14*	*0.18*
B.1	521	750	0.69	1.45	1.49	0.52
B.2	523	724	0.72	1.45	1.55	0.95
B.3	544	735	0.74	1.51	1.56	0.54
B.4	545	796	0.68	1.51	1.57	0.72
Mean	*533.25*	*751.25*	*0.71*	*1.48*	*1.54*	*0.68*
ST Dev	*13.02*	*31.68*	*0.03*	*0.03*	*0.04*	*0.20*

Fig. 5 depicts the ankle raw data collected during a portion of a 6MWT straight segment; from the analysis of the accelerometer and the gyroscope main components (a_y and ω_z) it is possible to detect the different step segmentation and thus perform gait quality evaluation. The typical pattern is composed by a peak in angular velocity, corresponding to the forward rotation of the foot, followed by a peak in acceleration, corresponding to the foot stance [16].

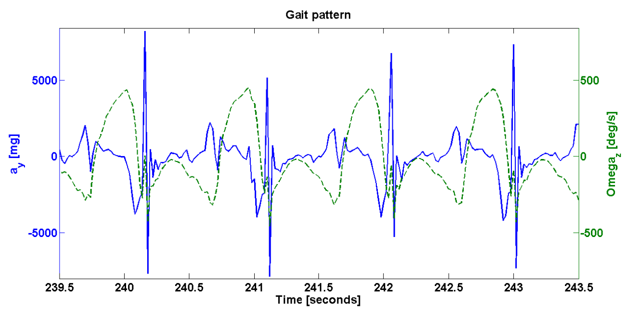


Fig. 5. Visualization of 4 steps during a 6MWT in terms of accelerometer and gyroscope main components.

B. Balance Tests

The orientation of the node mounted on the trunk of subjects has been reported to the body reference system and converted to Euler angles. In particular, only two of the three angles have been considered in order to evaluate the balance, i.e. roll and pitch. The following convention has been adopted:

- Positive values of the roll represent rotations toward the right side of the subject.
- Positive values of the pitch represent backward rotations of the trunk.

The stability parameters assessment has been performed in accordance to the procedure described by Riva in [4]. The present system limitation is the lack of information of hand contact with the wall, in order to prevent fall. The average radius of the postural cone of instability *PIxy* and the stability index *SI* were calculated as follows:

$$PIxy = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(\alpha(i)-\alpha_a)^2 + (\beta(i)-\beta_a)^2} \quad (1)$$

$$SI = \frac{100}{n}\sum_{i=1}^{n} spv(i) \quad (2)$$

where $\alpha(i)$ and $\beta(i)$ represent the ith roll and pitch respectively, α_a and β_a the average position coordinates, and *spv(i)* the performance value of the ith sample determined on the basis of the absolute instant deviation from the average axis. The latter value estimation depends on whether the hand contact is present or not; because of that, the stability index is overestimated for the tests in which hand contact events have been marked. In addition to the above mentioned parameters, the visual dependency has been evaluated by subtracting the stability index with EC condition from the stability index with EO condition only for propedeutic tests. This parameter gives a quantification of how much the subject relies on visual information to correct the balance.

Stabilometric tests results showed a good balance control for both groups (Fig. 6), obtaining an average COM within ±4 degrees and very low *PIxy* values (0.35 degrees for group A, 0.43 degrees for group B). No significant deterioration has been registered using the exercise mat with respect to ground.

Propedeutic tests results are depicted in Fig. 7-8; hand contacts to prevent fall during test execution have been marked with asterisks on the relative histogram columns. The average *SI* is 87.7% (with 2 hand contact events) in group A and 81.7% (with 7 hand contact events) in group B. The average visual dependence index of group A (11.54%) is lower than the group B one (17.86%), indicating a better intervention of proprioceptive and vestibular strategy. Moreover, the visual dependence of group B should be higher considering the hand contact events occurred.

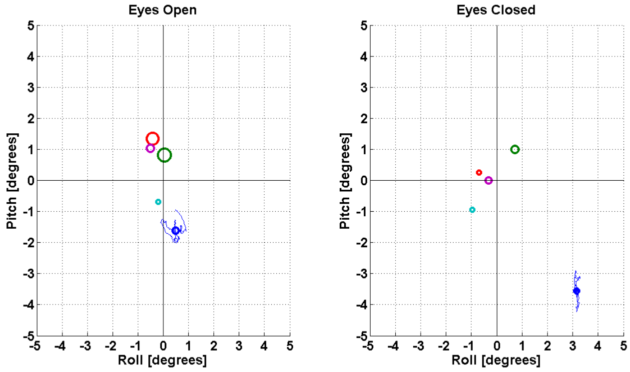


Fig. 6. Stabilometric on ground-test results for group A; the center of each circle is a subject COM, whereas the diameter is the SD during the exercise. In one case, the full 10'' acquisition is represented.

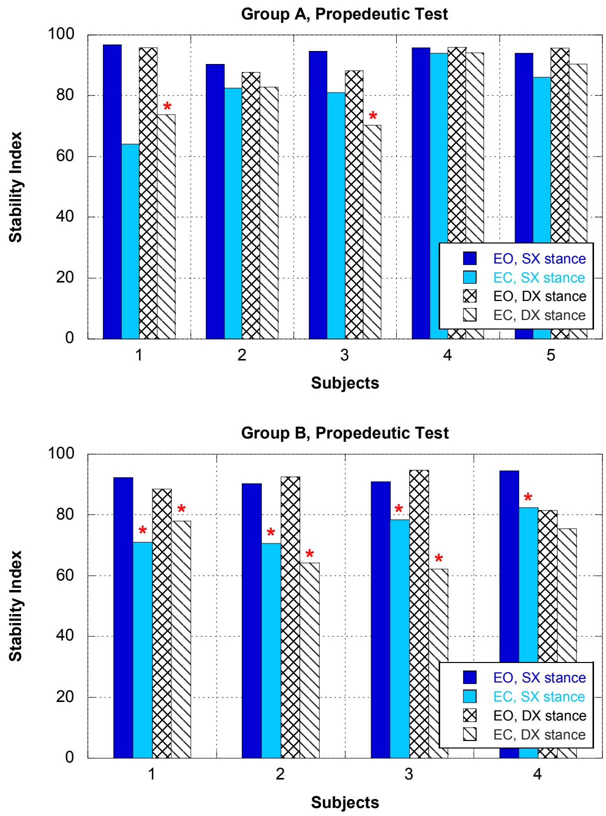
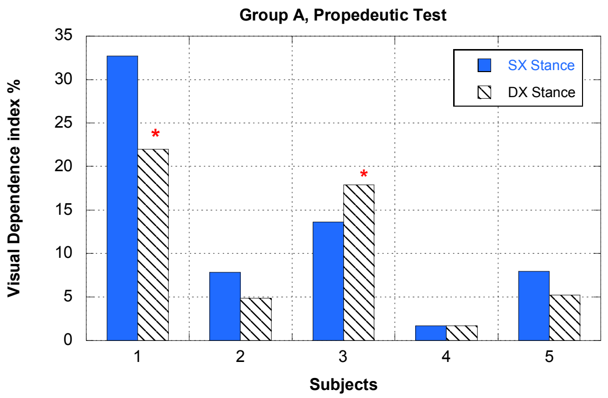


Fig. 7. Group A (top) and group B (bottom) stability indexes.



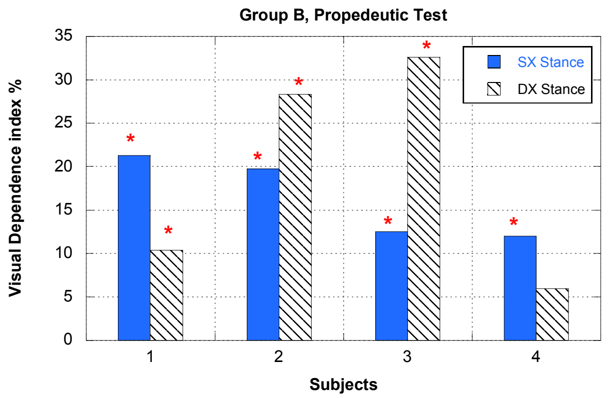


Fig. 8. Group A (top) and group B (bottom) visual dependence indexes.

VI. CONCLUSIONS

This work presented an application of a minimally intrusive BSN for motor function assessment in the elderly. The paper focused on two standard exercise dedicated to monitor and evaluate functional endurance and stability, which are key issues in older people. Different measurement procedures and data analysis have been presented in order to automatically estimate the outcomes of the 6MWT and a set of single- and double-stance balance tests. Preliminary validation has been performed on two groups of adults (group A) and trained elderly (group B). As far as the 6MWT concerns, the system provided a good correspondence in the Six-Minute total distance measurements and additional information on the stride length and velocity. The orientation collected from the trunk node used in stability tests allowed the estimation of balance parameters such as stability and visual dependence indexes, showing better motor performance in group A despite the intensive physical training and the numerous hand contact events registered in group B. In conclusion, the presented system is potentially a simple and reliable tool for motor assessment, allowing proper and individual physical exercise prescription.

ACKNOWLEDGMENT

The work is part of the Smart Aging project (SCN 00442), financed by the Italian Ministry for Education, Universities and Research (MIUR).

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