Optimized scoring tool to quantify the functional performance during the sit-to-stand transition with a magneto-inertial measurement unit

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ABSTRACT

Background: Sit-to-stand is used as a qualitative test to evaluate functional performance, especially to detect fall risks and frail individuals. The use of various quantitative criteria would enable a better understanding of musculoskeletal deficits and movement strategy modifications. This quantification was proven possible with a magneto-inertial unit which provides a compatible wearable device for clinical routine motion analysis.

Methods: Sit-to-stand movements were recorded using a single magneto-inertial measurement unit fixed on the chest for 74 subjects in three groups healthy young, healthy senior and frail. MIMU data was used to compute 15 spatiotemporal, kinematic and energetic parameters. Nonparametric statistical test showed a significant influence of age and frailness. After reducing the number of parameters by a principal component analysis, an AgingScore and a FrailtyScore were computed.

Findings: The fraction of variance explained by the first principal component was 77.48±2.80% for principal component analysis with healthy young and healthy senior groups, and 74.94±2.24% with healthy and frail senior groups. By receiver operating characteristic curve analysis of this score, we were able to refine the analysis to differentiate between healthy young and healthy senior subjects as well as healthy senior and frail subjects. By radar plot of the most discriminate parameters, the motion’s strategy could be characterized and be used to detect premature functional deficit or frail subjects.

Interpretation: Sit-to-stand measured by a single magneto-inertial unit and dedicated post processing is able to quantify subject's musculoskeletal performance and will allow longitudinal investigation of aging population.

Keywords: sit-to-stand; magneto-inertial measurement unit; frailty; age; biomechanics

1. INTRODUCTION

The sit-to-stand (STS) movement is one of the most commonly performed daily tasks (Nuzik et al., 1986). This postural transition requires coordination, balance, strength and muscle power (Millor et al., 2014) which become difficult with age (Alexander et al., 1991). Mobility is reduced with age due to illness, trauma, or progressive deconditioning i.e. sarcopenia, osteoporosis (Millor et al., 2014). The STS transition is often used to monitor the seniors and evaluate physical performance (Mijnarends et al., 2013). In practice, the clinical evaluation of the STS is based on motion description to investigate motor strategy modification (Millington et al., 1992). As quantification, the task duration is classically used as a descriptor of the STS transition performance (Beauchet et al., 2011; Millor et al., 2014). However this parameter is global, and not specific enough to quantify deficit in seniors (Lepetit et al. 2018).

The recent development of wearable magneto-inertial measurement unit (MIMU) has led to new opportunities for clinical assessment of STS performance (Howcroft et al., 2013; Lepetit et al., 2018; Millor et al., 2013; Sun & Sosnoff, 2018) with the advantage to be intended for clinical routine use

(Marin et al. 2015) . For instance, STS metrics deduced from MIMU data were already investigated to diagnostic frailty (Mugueta-Aguinaga & Garcia-Zapirain, 2017) or estimate fall risks (Howcroft et al., 2013; Sun & Sosnoff, 2018). However, these studies focused on populations with diagnosed pathologies. In aging populations with risk for sarcopenia, the loss of tonicity or sedentariness should be monitored early to detect the firsts signs indicating a significant weakness of the subject (Cruz-Jentoft et al. 2019).

The use of a MIMU during the STS has be demonstrated to be relevant (Millor et al., 2014) and results showed an increase of task duration and a decrease of flexion angular velocity and coefficient of variations (i.e. ratio between standard deviation and mean durations) with age (R. C. Van Lummel et al., 2013). However, few parameters take into account the subject's morphology in the STS performance (Ganea et al., 2011; Zijlstra et al., 2010). In addition, it may be relevant to combine significant parameters in order to create a score that classifies individuals according to their mobility health status (Millor et al., 2014).

The aim of this study is to design a diagnostic tool to detect functional deficit based on a single MIMU during the STS. Investigations will focus on age and frailty effects on kinematic and kinetic parameters extracted from data of a MIMU fixed on the chest during the STS postural transition to deduce a functional score which enable to differentiate frail from healthy senior individuals and healthy senior from young subjects.

2. MATERIALS AND METHODS

2.1. Subjects

Seventy-four subjects were enrolled in this study (table 1). They were divided into three groups: healthy young (HY), healthy senior (HS) and frail senior (FS). To be eligible, healthy young subjects had to be asymptomatic between 18 and 30 years old. Healthy senior subjects had to be over 65 years old and asymptomatic after examination by a medical doctor. The study also included 11 frail senior subjects after examination of a geriatrician. Geriatricians define frailty as a biologic syndrome of decreased reserve and resistance to stressors, resulting from cumulative declines across multiple physiologic systems, and causing vulnerability to adverse outcomes (Fried et al., 2001). Frail subjects had to be over 65 years old and have a degree of frailty greater than 5 according to Rockwood index (Rockwood et al., 2005).

Insert table 1

All the volunteers gave their free and written consent for these experiments. The protocol was approved by the ethical committee of Nord-Ouest II number 2016-A00534-47 and ethical committee of Ile-de-France VI in 2016.

2.2. Instrumentation

Participants were instrumented with a MIMU (APDM, Opal, Portland, USA) fixed, with an elastic strap, on their chest at approximately two thirds of the breastbone. The MIMU was composed of a 3D gyroscope, a 3D accelerometer and a 3D magnetometer. The height of the chair used for this study was standard (45cm). The signals of the MIMU data were sampled at 128Hz.

2.3. Data collection

After a static sitting pose, the subjects were asked to stand up at self-pace without assistance and without using their hands. Each participant performed three to five STS transitions according to their physical conditions. Each transition was recorded separately. A 1-minute rest period was done between each test.

After the session, the weight and height of each subject were measured using a weighing scale and a measuring stick.

2.4. Sit-to-Stand (STS) parameters

Based on fusion algorithm, MIMU provided in the MIMU local frame ($\mathcal{M}$), at each time t, the acceleration, the angular velocity and the orientation relative to the earth reference frame ($\mathcal{E}$) (north, west, up) (Sabatini, 2011). The STS movement beginning (t_b) and the STS movement ending (t_f) were assessed by a motion detection algorithm and defined the STS time window (Lepetit et al., 2018). The acceleration in the earth frame $\mathcal{E}$ is: $\boldsymbol{a}_{\mathcal{E},\boldsymbol{t}} = [a_t^n \quad a_t^w \quad a_t^u]$.

A technical calibration as proposed by (Bouvier et al., 2015) was performed to register the local frame of the MIMU ($\mathcal{M}$) with the anatomical axes of the trunk (i.e. proximal-distal (PD) , medio-lateral (ML), antero-posterior (AP) axes). Thus, the linear acceleration was deduced in the trunk reference frame

($\mathcal{T}$) as $\boldsymbol{a}_{\mathcal{T},t} = [a_t^{PD} \quad a_t^{ML} \quad a_t^{AP}]$. By the same procedure, the angular velocity of the trunk was deduced in the torso frame as $\boldsymbol{\omega}_{\mathcal{T},t} = [\omega_t^{PD} \quad \omega_t^{ML} \quad \omega_t^{AP}]$.

The inclination angle of the torso θ_t was computed as the angle between the axis of the torso and the vertical axis. Then, the STS beginning time t_b, the STS end time t_f, the velocity of the torso center of mass ($\boldsymbol{VG}_{\mathcal{T},t}$) and the kinetic energy ($\boldsymbol{EK}_t$) of the torso were computed (Lepetit et al., 2018).

In the STS time window, for each subject, 15 parameters were computed as the average value of all trials as follows:

- TD: the STS task duration such as $\mathrm{TD} = t_f - t_b$;
- mAcc and maxAcc: the mean and maximal values of the norm of $\boldsymbol{a}_{\mathcal{E},t}$;
- mAz and maxAz: the mean and maximal values of the absolute value of $\boldsymbol{a}_{\mathcal{E},t}$ along the vertical axis $|a_t^u|$;
- mAxy and maxAxy: the mean and maximal values of the norm of $\boldsymbol{a}_{\mathcal{E},t}$ in the horizontal plane $\sqrt{{a_t^n}^2 + {a_t^w}^2}$;
- AUCml: the area under the curve of the medio-lateral acceleration a_t^{ML} as a quantification of lateral sway (W. Janssen et al., 2008) ($AUCml = \int_{t_b}^{t_f} |a_t^{ML}| dt$);
- mVG and maxVG: the mean and maximal values of the norm of the torso COM velocity $\boldsymbol{VG}_{\mathcal{T},t}$;
- mEK and maxEK: the mean and maximal values of the norm of the torso kinetic energy $\boldsymbol{EK}_t$;
- mOmega and maxOmega: the mean and maximal values of the norm of the trunk angular velocity $\boldsymbol{\omega}_{\mathcal{T},t}$;

- Incl: the maximal inclination angle of the torso as the maximal absolute value of θ_t ($Incl = \max(|\theta_t|)$).

To investigate the age effect on each parameter, a Mann-Whitney U-test was realized between the parameters of HY and HS groups. Likewise, the influence of frailty was analyzed with a Mann-Whitney U-test realized between HS and frail groups. The significance level was set to 0.01 for all comparisons.

2.3. Scores computation and statistical analysis

Each subject of each group (HS, HY, and FS) was characterized with a *k*-length vector with *k*=15.

i. Aging score (*AgingScore*) computation

To assess the discrimination performance of each parameter between HY and HS, the area under the curve (AUC) of a receiver operating characteristic (ROC) was computed (Zweig & Campbell, 1993).

The aim of the *AgingScore* is to reduce the *k*-length vector to a scalar based on an iterative principal component analysis (PCA) procedure as follows. First, from the *k*-length vectors of the HS and HY subjects, an *a*-length sub-vectors of the *a* most discriminative parameters according to the PCA ($1 \leq a \leq k$) were extracted (Jackson, 1991). At this stage, each subject is now characterized by an *a*-length vector. Secondly, the *a*-length vectors of HY and HS subjects were randomly divided into equal training (t) and test (s) subgroups as HY_t, HY_s, HS_t and HS_s, respectively. Then, a PCA with standardized correlation matrix was performed with the *a*-length vectors of the training data (HY_t and HS_t)

(Jolliffe, 2002). The first principal component PC1, which maximizes the variance in one dimension and has the highest potential in terms of classification accuracy (Nikas & Low, 2011), was computed for HY_s and HS_s subjects and was defined as the temporary aging score named *AgingScore-tmp.*. At this stage, each subject in the test group is now characterized by a single parameter. The classification performance according to the *AgingScore-tmp* was evaluated with the AUC of a ROC curve, denoted by *AUC-tmp*. This randomization process (i.e. division between equal training and test subgroups to AUC-tmp computation) was performed 1000 times. The mean value of *AUC-tmp* was considered and defined as *AUC-a*.

Finally, the value *a* was chosen in order to maximize the classification performance *AUC-a*. In addition, the *a*-length vector associated to the AgingScore identified the parameters related with age.

ii. Frailty score (*FrailtyScore*) computation

The same procedure was implemented to assess the *FrailtyScore* based on the *f*-length vectors with $1 \leq f \leq k$ of the FS and HS subjects. Finally, the parameters of the *f*-length vectors associated to the *FrailtyScore* identified the parameters related to frailty.

iii. Sit-to-Stand strategy plot

The STS strategy was also investigated on the base of the two previous computations. Parameters of the *a*-length vectors from the *AgingScore* and *f*-length vectors from the *FrailtyScore* were kept to deduce a s-length vector with $max(a, f) \leq s \leq a + f$. The vector of the s unique parameters was normalized by the mean values of the HY group. For each group, the mean and standard deviation values of each parameter were displayed in a radar plot. For each subject, the STS strategy was quantified by computing the circularity ratio ($\frac{perimeter^2}{4\pi.area}$) of the polygon in the radar plot. The significance of the evolution of the circularity ratio between groups was quantified with a Mann-Whitney U-test. Data are presented as mean and standard deviation. The significance level was set to 0.01.

3. RESULTS

The mean and standard deviation for each of the 15 parameters for each group are presented in table 2. The p-values of Mann-Whitney U-tests are also given. A significant difference between HY and HS subjects has been found for maxVG, maxOmega, maxAcc, maxAz, while between HS and FS subjects, significant differences were highlighted for maxAxy, mVG, maxVG, mOmega, TD, Incl, mAcc, mAz, mAxy, AUCml, mEK and maxEK.

By the value of AUC of the ROC analysis, it was demonstrated that maxAcc was the most discriminative for HY and HS groups (AUC=0.763), and mVG was the most discriminative for HS and FS groups (AUC=0.972).

The *a*-vector of parameters which maximized the AgingScore discrimination performance was [maxAcc, maxAz, maxAxy, maxVG, maxOmega] with a=5. For the FrailtyScore, the *f*-vector of parameters which maximized the discrimination performance was [mVG, mEK, TD, mAz, maxEK, mAcc, AUCml] (*f*=7) (table 2).

Insert table 2

The fraction of variance explained by the first principal component was 77.48±2.80% for PCA with HY and HS groups and 74.94±2.24% for PCA with HS and FS groups. The average ROC curve and AUC for both classifications with *AgingScore* and *FrailtyScore* are displayed in figure 1.

Insert figure 1

The STS strategies displayed in a radar plot are presented in figure 2. Only the 12 different parameters which were retained in both score computations are displayed. The circularity ratio for each group is summarized in boxplots in figure 3. According to the Mann-Whitney U-tests, the evolution was significative only for FS subjects.

Insert figure 2

Insert figure 3

4. DISCUSSION

The quantification of the STS postural transition with a single MIMU fixed on the trunk enabled the classification of the subjects according to two different scores. Moreover, the present study has evidenced that the analysis based on 12 parameters was able to quantify the strategy of the STS motion. The influence of age and frailty on the STS movement through several parameters was demonstrated. The results also validated that the STS motion strategy was significantly modified for few frail subjects.

Classically, the task duration (TD) is the only parameter analysed during single STS transition. The mean TD values for healthy subjects were between 1.57s and 2.42s (Cerrito et al., 2015; Galli et al., 2008; Grimm & Bolink, 2016; Moufawad el Achkar et al., 2018; R. C. Van Lummel et al., 2013). Several studies showed that TD increases with frailty (Ganea et al., 2011; Millor et al., 2013; R. C. Van Lummel et al., 2013). However, there is no consensus for the influence of age. Studies showed that the subject's age may influence (R. C. Van Lummel et al., 2013) or not (Hurley, 2013) this parameter during the STS motion. This could be explained by the different methodological approaches used to determinate t_b and t_f. Hurley used a marker-based motion capture device in his study which is known to be more reliable than magneto-inertial units used by (R. C. Van Lummel et al., 2013).

In our study, we noticed that other parameters, which quantified the STS performance, showed heterogeneities according to age and frailty. For instance, the maximal value of the trunk CoM velocity (maxVG) was the only parameter which was significantly influenced by age and frailty. The inclination angle (Incl) did not evolve significantly with the age but raised with frailty. Although the mean value increased for FS subjects, the range of values was wider (standard deviation=20.70°). However, the inclination angle was similar between HY and HS subjects and in agreement with a previous study (Hurley, 2013). Also, AUCml which is linked to the acceleration and TD did not evolve between HY and HS subjects but increased significantly for FS persons. Our study confirmed that the quantification of the STS performance evaluate by single parameter would not enough be accurate ,and consequently, the use of a composite parameter, i.e. a score, as an image of multidimensional parameters, is more relevant (W. G. M. Janssen et al., 2008).

In the present study, a multifactorial analyze of several parameters was reduced into a unique quantitative score using the first principal component of a PCA. The classification performance of these scores were quantified with a ROC analysis. In both cases, the AUC which represents the classification performance of the scores was better than with any other single parameter (figure 1 and table 2). The *FrailtyScore* enabled a reliable classification (meanAUC>0.98, figure 1). This result was improved in comparison to previous studies which generally used only one parameter such as TD (Millor et al., 2014). The *AgingScore* enabled to classify HS and HY subjects (meanAUC>0.77, figure 1). Van Lummel (R. Van Lummel, 2017) proposed a score to evaluate the 5 times repeated STS. Their method was based on an exploratory factor analysis of 24 parameters of three different types: durations, kinematics and coefficients of variation. However, the discrimination power between young and old individuals was not documented because they did not include young subjects in their study.

The age is known to influence the STS motion performance (Cruz-Jentoft et al. 2019). The results showed that except for maxEK, all the maximal values of the other parameters decreased significantly with age. These results could be explained by a reduction of muscles and tendons capacities. Indeed, the relationship between muscle strength and STS performance was already demonstrated (Bohannon et al., 2010). On other hand, the circularity ratio analysis demonstrated that the STS strategy is not significantly influenced with age (p-value=0.221) for the healthy subjects. This result agreed with a previous study which highlighted quantitative reduction but similar qualitative kinematic and kinetic parameters between HY and HS subjects (Hurley, 2013; Marin et al., 1999; Steffen et al., 2013). On the contrary, frailty influences significantly the STS strategy (p-value<0.01). We found that all the mean-based parameters (mVG, mAcc, mAz, mAxy, mEK), max EK and maxVG decreased significantly for FS subjects as compared with HS and HY groups. These observations could be a marker of frailness for further longitudinal investigation.

However, this study also has some limitations. First, frail subjects were older than healthy seniors. Secondly, with our methodology, the computed variables often required the determination of t_b and t_f. In the literature, numerous methods to detect movement are proposed with MIMU data without consensus (Cerrito et al., 2015; Millor et al., 2013). In this study, the motion detection algorithm was based on a threshold of the orientation quaternions and the vertical acceleration (Lepetit et al., 2018). Moreover, the parameters based on maximum values were often more dispersed than those based on mean value (table 2). Indeed, they focused on only one specific moment and consequently, they were more subject to sensor errors. Finally, the muscle strength and activation were not evaluated, and it may be useful to add this information.

To conclude, our study proposed two quantitative scores (*AgingScore* and *FrailtyScore*) to evaluate premature functional deficit with a single MIMU during the STS transition. This setup is appropriate for clinical routines and may help clinicians to detect subject with abnormal functional capacities and monitor rehabilitation enhancements.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to report related to this study.

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Tables

	n♀	n♂	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m²)**
HY subjects	4	20	25 (3)	178 (9.5)	72.1 (11.7)	22.8 (3.1)
HS subjects	5	34	70 (4)	174 (8.3)	79.4 (14.2)	26.1 (4.1)
FS subjects	6	5	87 (6)	161 (6.0)	61.0 (11.2)	23.6 (4.9)

Table 1: Subjects' characteristics: mean value (standard deviation)

Parameter	Healthy young subjects (HY)	Healthy seniors subjects (HS)	Frail subjects (FS)	p-value (HY,HS)	ROC AUC (HY,HS)	p-value (HS,FS)	ROC AUC (HS, FS)
mVG (m/s)	0.405 (0.065)	0.390 (0.065)	0.242 (0.049)	p = 0.457	0.557	**p < 0.01**	**0.972**
maxVG (m/s)	0.905 (0.147)	0.784 (0.137)	0.562 (0.167)	**p < 0.01**	**0.735**	**p < 0.01**	0.844
mOmega (rad/s)	0.670 (0.162)	0.637 (0.165)	0.433 (0.152)	p = 0.666	0.533	**p < 0.01**	0.825
maxOmega (rad/s)	1.70 (0.57)	1.36 (0.49)	1.41 (0.43)	**p < 0.01**	**0.706**	p = 0.590	0.555
TD (s)	1.98 (0.41)	1.92 (0.38)	4.22 (2.02)	p = 0.392	0.565	**p < 0.01**	**0.923**
Incl (°)	32.40 (9.10)	32.80 (9.87)	46.70 (18.50)	p = 0.815	0.518	**p < 0.01**	0.781
mAcc (m/s²)	1.93 (0.43)	1.69 (0.41)	0.91 (0.39)	p = 0.048	0.650	**p < 0.01**	**0.911**
maxAcc (m/s²)	6.69 (2.40)	4.73 (1.69)	3.48 (1.90)	**p < 0.01**	**0.763**	p = 0.058	0.690
mAz (m/s²)	1.36 (0.34)	1.16 (0.33)	0.54 (0.27)	p = 0.036	0.659	**p < 0.01**	**0.935**
maxAz (m/s²)	5.12 (1.44)	3.85 (1.10)	2.69 (1.43)	**p < 0.01**	**0.757**	p = 0.011	0.755
mAxy (m/s²)	1.11 (0.24)	1.03 (0.23)	0.63 (0.23)	p = 0.221	0.593	**p < 0.01**	0.886
maxAxy (m/s²)	4.84 (2.47)	3.29 (1.51)	2.76 (1.49)	**p < 0.01**	**0.745**	p = 0.337	0.597
AUCml (m/s)	1.20 (0.54)	1.30 (0.70)	4.14 (2.63)	p = 0.882	0.512	**p < 0.01**	**0.895**
mEK (J)	3.08 (1.22)	2.97 (1.24)	0.90 (0.51)	p = 0.656	0.534	**p < 0.01**	**0.965**
maxEK (J)	10.00 (3.77)	8.42 (3.71)	3.35 (2.13)	p = 0.086	0.630	**p < 0.01**	**0.921**

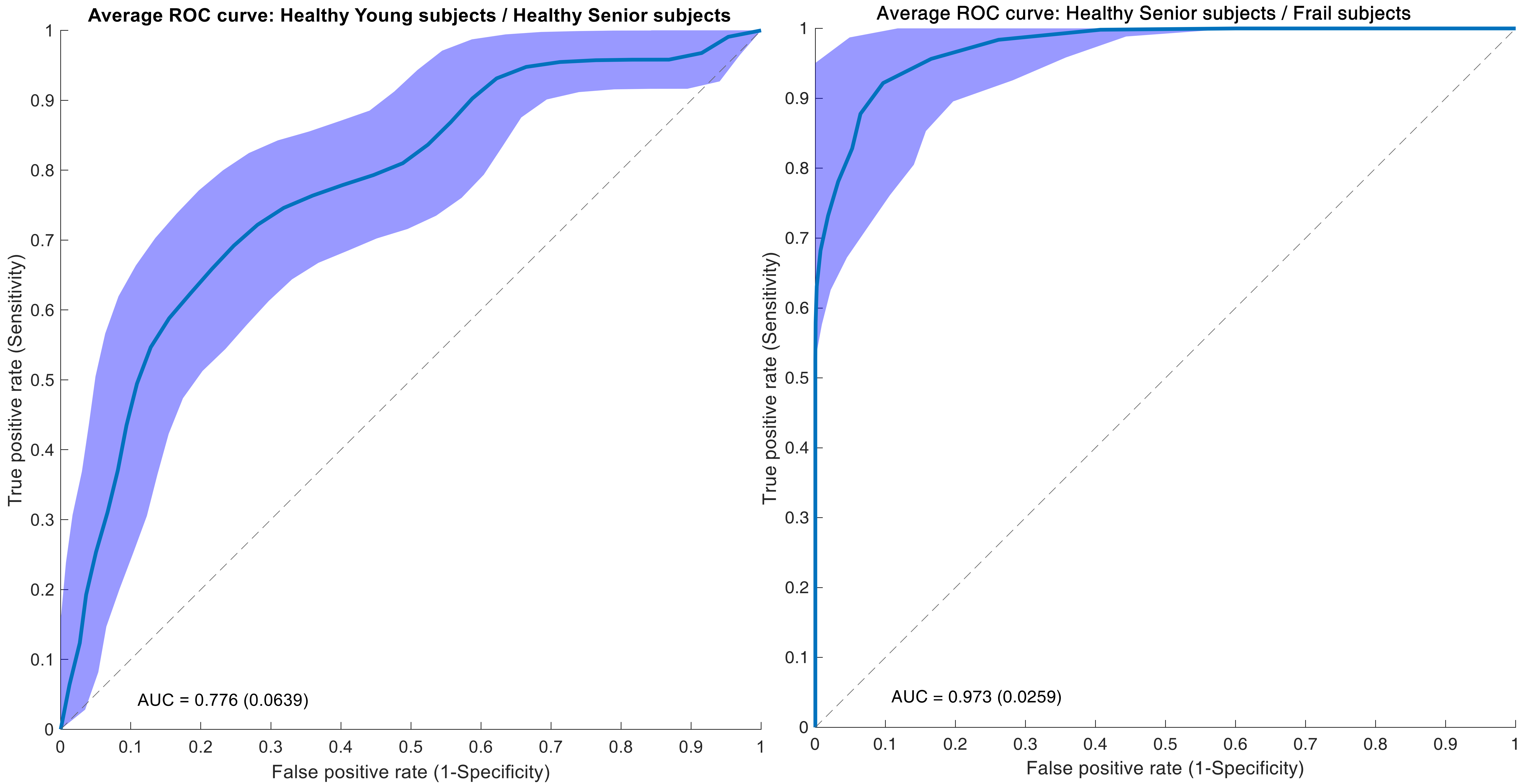
Table 2: Mean (standard deviation) for the parameters evaluating during the sit-to-stand. The Mann-Whitney p-values and ROC AUC values were assessed between healthy young subjects (HY) and healthy senior subjects (HS) and between HS subjects and frail subjects (FS).

Figure Captions

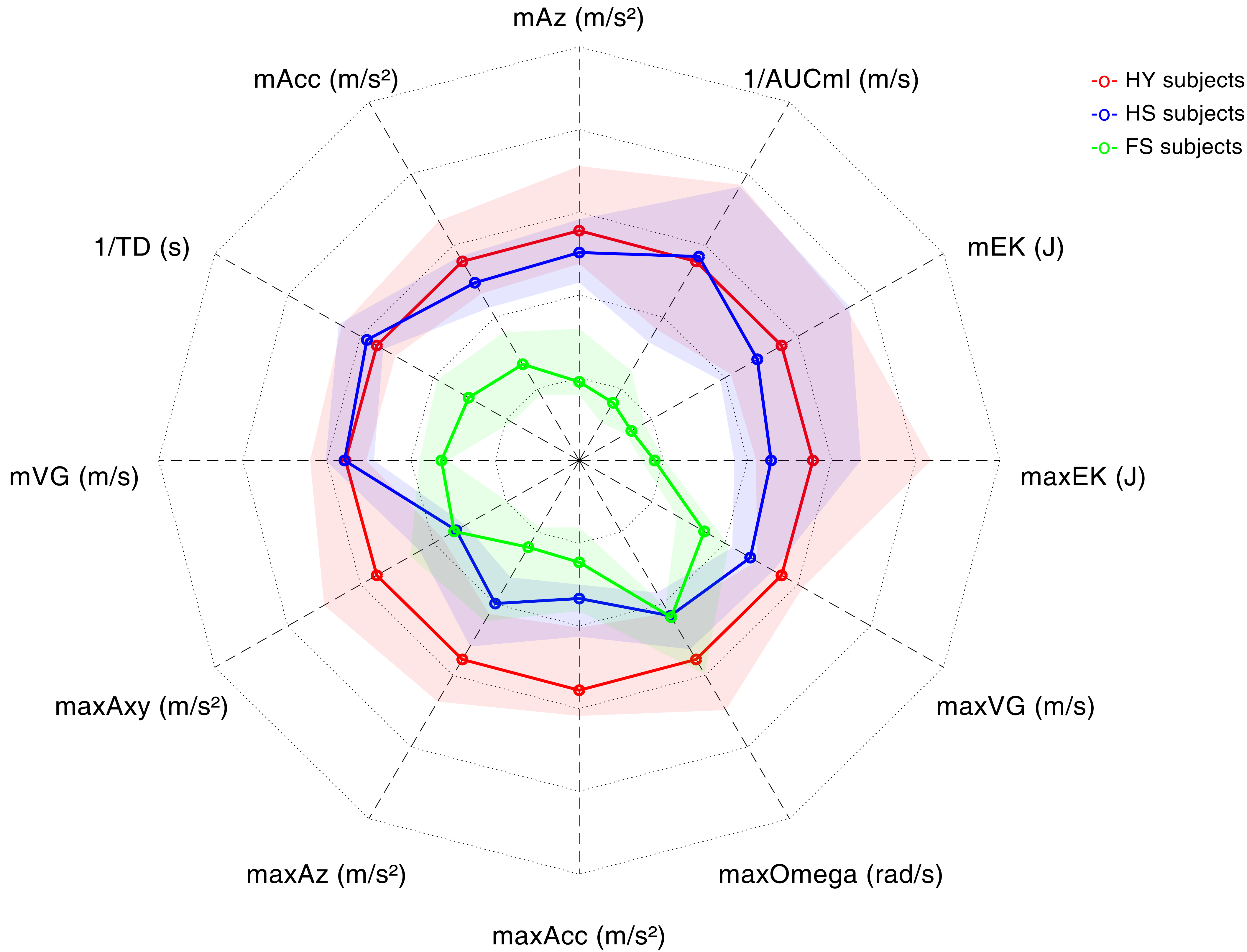
Figure 1: Average ROC curves (dark lines) and standard deviation limits (shaded areas) quantifying the classification performance of the PCA-based scores between HY and HS subjects (AgingScore, left) and between HS and FS subjects (FrailtyScore, right). The mean AUC values and their standard deviations are given for each curve.

Figure 2: Medians (dark lines), 1st and 3rd quartiles (lower and upper limits of shaded areas) of retained parameters for all groups presented in a radar plot. The data were normalized according to the median values of HY group (thus, red dark line is the unit circle).

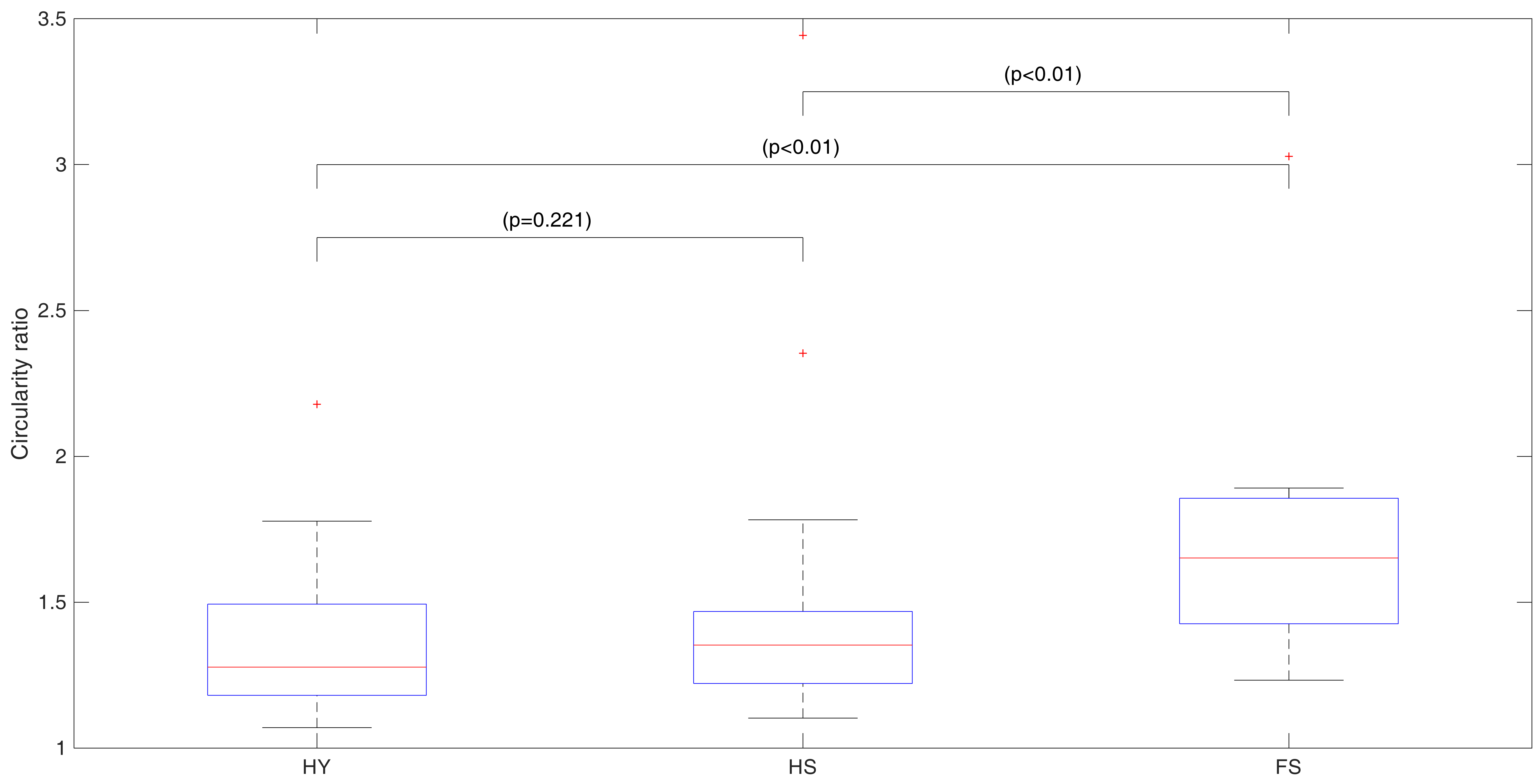
Figure 3: The circularity ratio of each group is presented in a boxplot. The evolution between groups was investigated with Mann-Whitney U-tests. The evolution was significative between HY and FS groups and between HS and FS groups.



Average ROC curve: Healthy Young subjects / Healthy Senior subjects
True positive rate (Sensitivity)
False positive rate (1-Specificity)
AUC = 0.776 (0.0639)
Average ROC curve: Healthy Senior subjects / Frail subjects
True positive rate (Sensitivity)
False positive rate (1-Specificity)
AUC = 0.973 (0.0259)



mAz (m/s²)
1/AUCml (m/s)
mEK (J)
maxEK (J)
maxVG (m/s)
maxOmega (rad/s)
maxAcc (m/s²)
maxAz (m/s²)
maxAxy (m/s²)
mVG (m/s)
1/TD (s)
mAcc (m/s²)
-o- HY subjects
-o- HS subjects
-o- FS subjects



Circularity ratio
3.5
3
2.5
2
1.5
1
(p<0.01)
(p<0.01)
(p=0.221)
HY
HS
FS