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

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

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33 **ABSTRACT**

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

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

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

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

54

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

56

## 57 1. INTRODUCTION

58 The sit-to-stand (STS) movement is one of the most commonly performed daily tasks (Nuzik et al.,  
59 1986). This postural transition requires coordination, balance, strength and muscle power (Millor et  
60 al., 2014) which become difficult with age (Alexander et al., 1991). Mobility is reduced with age due to  
61 illness, trauma, or progressive deconditioning i.e. sarcopenia, osteoporosis (Millor et al., 2014). The  
62 STS transition is often used to monitor the seniors and evaluate physical performance (Mijnarends et  
63 al., 2013). In practice, the clinical evaluation of the STS is based on motion description to investigate  
64 motor strategy modification (Millington et al., 1992). As quantification, the task duration is classically  
65 used as a descriptor of the STS transition performance (Beauchet et al., 2011; Millor et al., 2014).  
66 However this parameter is global, and not specific enough to quantify deficit in seniors (Lepetit et al.  
67 2018).

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

71 (Marin et al. 2015) . For instance, STS metrics deduced from MIMU data were already investigated to  
72 diagnostic frailty (Mugueta-Aguinaga & Garcia-Zapirain, 2017) or estimate fall risks (Howcroft et al.,  
73 2013; Sun & Sosnoff, 2018). However, these studies focused on populations with diagnosed  
74 pathologies. In aging populations with risk for sarcopenia, the loss of tonicity or sedentariness should  
75 be monitored early to detect the firsts signs indicating a significant weakness of the subject (Cruz-  
76 Jentoft et al. 2019).

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

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

89

## 90 2. MATERIALS AND METHODS

### 91 2.1. Subjects

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

101 *Insert table 1*

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

### 105 2.2. Instrumentation

106 Participants were instrumented with a MIMU (APDM, Opal, Portland, USA) fixed, with an elastic strap,  
107 on their chest at approximately two thirds of the breastbone. The MIMU was composed of a 3D

108 gyroscope, a 3D accelerometer and a 3D magnetometer. The height of the chair used for this study  
109 was standard (45cm). The signals of the MIMU data were sampled at 128Hz.

### 110 2.3. Data collection

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

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

### 117 2.4. Sit-to-Stand (STS) parameters

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

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



126 ( $\mathcal{J}$ ) as  $\mathbf{a}_{\mathcal{J},t} = [a_t^{PD} \quad a_t^{ML} \quad a_t^{AP}]$ . By the same procedure, the angular velocity of the trunk was

127 deduced in the torso frame as  $\boldsymbol{\omega}_{\mathcal{J},t} = [\omega_t^{PD} \quad \omega_t^{ML} \quad \omega_t^{AP}]$ .

128 The inclination angle of the torso  $\theta_t$  was computed as the angle between the axis of the torso and the

129 vertical axis. Then, the STS beginning time  $t_b$ , the STS end time  $t_f$ , the velocity of the torso center of

130 mass ( $\mathbf{VG}_{\mathcal{J},t}$ ) and the kinetic energy ( $\mathbf{EK}_t$ ) of the torso were computed (Lepetit et al., 2018).

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

132 trials as follows:

133 - TD: the STS task duration such as  $TD = t_f - t_b$ ;

134 - mAcc and maxAcc: the mean and maximal values of the norm of  $\mathbf{a}_{\mathcal{E},t}$ ;

135 - mAz and maxAz: the mean and maximal values of the absolute value of  $\mathbf{a}_{\mathcal{E},t}$  along the vertical  
136 axis  $|a_t^u|$ ;

137 - mAxy and maxAxy: the mean and maximal values of the norm of  $\mathbf{a}_{\mathcal{E},t}$  in the horizontal plane

138  $\sqrt{a_t^{n^2} + a_t^{w^2}}$ ;

139 - AUCml: the area under the curve of the medio-lateral acceleration  $a_t^{ML}$  as a quantification of

140 lateral sway (W. Janssen et al., 2008) ( $AUCml = \int_{t_b}^{t_f} |a_t^{ML}| dt$ );

141 - mVG and maxVG: the mean and maximal values of the norm of the torso COM velocity  $\mathbf{VG}_{\mathcal{J},t}$ ;

142 - mEK and maxEK: the mean and maximal values of the norm of the torso kinetic energy  $\mathbf{EK}_t$ ;

143 - mOmega and maxOmega: the mean and maximal values of the norm of the trunk angular

144 velocity  $\boldsymbol{\omega}_{\mathcal{J},t}$ ;

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

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

150

### 151 2.3. Scores computation and statistical analysis

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

153

#### 154 i. Aging score (*AgingScore*) computation

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

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

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

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

174

175 ii. Frailty score (*FrailtyScore*) computation

176 The same procedure was implemented to assess the *FrailtyScore* based on the *f*-length vectors with  
177  $1 \leq f \leq k$  of the FS and HS subjects. Finally, the parameters of the *f*-length vectors associated to the  
178 *FrailtyScore* identified the parameters related to frailty.

179

180 iii. Sit-to-Stand strategy plot

181 The STS strategy was also investigated on the base of the two previous computations. Parameters of  
182 the *a*-length vectors from the *AgingScore* and *f*-length vectors from the *FrailtyScore* were kept to

183 deduce a  $s$ -length vector with  $\max(a, f) \leq s \leq a + f$ . The vector of the  $s$  unique parameters was  
184 normalized by the mean values of the HY group. For each group, the mean and standard deviation  
185 values of each parameter were displayed in a radar plot. For each subject, the STS strategy was  
186 quantified by computing the circularity ratio ( $\frac{perimeter^2}{4\pi \cdot area}$ ) of the polygon in the radar plot. The  
187 significance of the evolution of the circularity ratio between groups was quantified with a Mann-  
188 Whitney U-test. Data are presented as mean and standard deviation. The significance level was set to  
189 0.01.

### 190 3. RESULTS

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

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

199 The  $a$ -vector of parameters which maximized the AgingScore discrimination performance was  
200 [maxAcc, maxAz, maxAxy, maxVG, maxOmega] with  $a=5$ . For the FrailtyScore, the  $f$ -vector of

201 parameters which maximized the discrimination performance was [mVG, mEK, TD, mAz, maxEK, mAcc,  
202 AUCml] ( $f=7$ ) (table 2).

203 *Insert table 2*

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

207 *Insert figure 1*

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

212 *Insert figure 2*

213 *Insert figure 3*

214

## 215 4. DISCUSSION

216 The quantification of the STS postural transition with a single MIMU fixed on the trunk enabled the  
217 classification of the subjects according to two different scores. Moreover, the present study has  
218 evidenced that the analysis based on 12 parameters was able to quantify the strategy of the STS

219 motion. The influence of age and frailty on the STS movement through several parameters was  
220 demonstrated. The results also validated that the STS motion strategy was significantly modified for  
221 few frail subjects.

222 Classically, the task duration (TD) is the only parameter analysed during single STS transition. The mean  
223 TD values for healthy subjects were between 1.57s and 2.42s (Cerrito et al., 2015; Galli et al., 2008;  
224 Grimm & Bolink, 2016; Moufawad el Achkar et al., 2018; R. C. Van Lummel et al., 2013). Several studies  
225 showed that TD increases with frailty (Ganea et al., 2011; Millor et al., 2013; R. C. Van Lummel et al.,  
226 2013). However, there is no consensus for the influence of age. Studies showed that the subject's age  
227 may influence (R. C. Van Lummel et al., 2013) or not (Hurley, 2013) this parameter during the STS  
228 motion. This could be explained by the different methodological approaches used to determinate  $t_b$   
229 and  $t_f$ . Hurley used a marker-based motion capture device in his study which is known to be more  
230 reliable than magneto-inertial units used by (R. C. Van Lummel et al., 2013).

231 In our study, we noticed that other parameters, which quantified the STS performance, showed  
232 heterogeneities according to age and frailty. For instance, the maximal value of the trunk CoM velocity  
233 (maxVG) was the only parameter which was significantly influenced by age and frailty. The inclination  
234 angle (Incl) did not evolve significantly with the age but raised with frailty. Although the mean value  
235 increased for FS subjects, the range of values was wider (standard deviation=20.70°). However, the  
236 inclination angle was similar between HY and HS subjects and in agreement with a previous study  
237 (Hurley, 2013). Also, AUCml which is linked to the acceleration and TD did not evolve between HY and  
238 HS subjects but increased significantly for FS persons. Our study confirmed that the quantification of

239 the STS performance evaluate by single parameter would not enough be accurate ,and consequently,  
240 the use of a composite parameter, i.e. a score, as an image of multidimensional parameters, is more  
241 relevant (W. G. M. Janssen et al., 2008).

242 In the present study, a multifactorial analyze of several parameters was reduced into a unique  
243 quantitative score using the first principal component of a PCA. The classification performance of these  
244 scores were quantified with a ROC analysis. In both cases, the AUC which represents the classification  
245 performance of the scores was better than with any other single parameter (figure 1 and table 2). The  
246 *FrailtyScore* enabled a reliable classification (meanAUC>0.98, figure 1). This result was improved in  
247 comparison to previous studies which generally used only one parameter such as TD (Millor et al.,  
248 2014). The *AgingScore* enabled to classify HS and HY subjects (meanAUC>0.77, figure 1). Van Lummel  
249 (R. Van Lummel, 2017) proposed a score to evaluate the 5 times repeated STS. Their method was based  
250 on an exploratory factor analysis of 24 parameters of three different types: durations, kinematics and  
251 coefficients of variation. However, the discrimination power between young and old individuals was  
252 not documented because they did not include young subjects in their study.

253 The age is known to influence the STS motion performance (Cruz-Jentoft et al. 2019). The results  
254 showed that except for maxEK, all the maximal values of the other parameters decreased significantly  
255 with age. These results could be explained by a reduction of muscles and tendons capacities. Indeed,  
256 the relationship between muscle strength and STS performance was already demonstrated (Bohannon  
257 et al., 2010). On other hand, the circularity ratio analysis demonstrated that the STS strategy is not  
258 significantly influenced with age (p-value=0.221) for the healthy subjects. This result agreed with a

259 previous study which highlighted quantitative reduction but similar qualitative kinematic and kinetic  
260 parameters between HY and HS subjects (Hurley, 2013; Marin et al., 1999; Steffen et al., 2013). On  
261 the contrary, frailty influences significantly the STS strategy ( $p$ -value $<0.01$ ). We found that all the  
262 mean-based parameters (mVG, mAcc, mAz, mAxy, mEK), max EK and maxVG decreased significantly  
263 for FS subjects as compared with HS and HY groups. These observations could be a marker of frailness  
264 for further longitudinal investigation.

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

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

278



279 CONFLICT OF INTEREST STATEMENT

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

281

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285

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## Tables

	n♀	n♂	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m <sup>2</sup> )
<b>HY subjects</b>	4	20	25 (3)	178 (9.5)	72.1 (11.7)	22.8 (3.1)
<b>HS subjects</b>	5	34	70 (4)	174 (8.3)	79.4 (14.2)	26.1 (4.1)
<b>FS subjects</b>	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	<b>p &lt; 0.01</b>	<b>0.972</b>
maxVG (m/s)	0.905 (0.147)	0.784 (0.137)	0.562 (0.167)	<b>p &lt; 0.01</b>	<b>0.735</b>	<b>p &lt; 0.01</b>	0.844
mOmega (rad/s)	0.670 (0.162)	0.637 (0.165)	0.433 (0.152)	p = 0.666	0.533	<b>p &lt; 0.01</b>	0.825
maxOmega (rad/s)	1.70 (0.57)	1.36 (0.49)	1.41 (0.43)	<b>p &lt; 0.01</b>	<b>0.706</b>	p = 0.590	0.555
TD (s)	1.98 (0.41)	1.92 (0.38)	4.22 (2.02)	p = 0.392	0.565	<b>p &lt; 0.01</b>	<b>0.923</b>
Incl (°)	32.40 (9.10)	32.80 (9.87)	46.70 (18.50)	p = 0.815	0.518	<b>p &lt; 0.01</b>	0.781
mAcc (m/s <sup>2</sup> )	1.93 (0.43)	1.69 (0.41)	0.91 (0.39)	p = 0.048	0.650	<b>p &lt; 0.01</b>	<b>0.911</b>
maxAcc (m/s <sup>2</sup> )	6.69 (2.40)	4.73 (1.69)	3.48 (1.90)	<b>p &lt; 0.01</b>	<b>0.763</b>	p = 0.058	0.690
mAz (m/s <sup>2</sup> )	1.36 (0.34)	1.16 (0.33)	0.54 (0.27)	p = 0.036	0.659	<b>p &lt; 0.01</b>	<b>0.935</b>
maxAz (m/s <sup>2</sup> )	5.12 (1.44)	3.85 (1.10)	2.69 (1.43)	<b>p &lt; 0.01</b>	<b>0.757</b>	p = 0.011	0.755
mAxy (m/s <sup>2</sup> )	1.11 (0.24)	1.03 (0.23)	0.63 (0.23)	p = 0.221	0.593	<b>p &lt; 0.01</b>	0.886
maxAxy (m/s <sup>2</sup> )	4.84 (2.47)	3.29 (1.51)	2.76 (1.49)	<b>p &lt; 0.01</b>	<b>0.745</b>	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	<b>p &lt; 0.01</b>	<b>0.895</b>
mEK (J)	3.08 (1.22)	2.97 (1.24)	0.90 (0.51)	p = 0.656	0.534	<b>p &lt; 0.01</b>	<b>0.965</b>
maxEK (J)	10.00 (3.77)	8.42 (3.71)	3.35 (2.13)	p = 0.086	0.630	<b>p &lt; 0.01</b>	<b>0.921</b>

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).

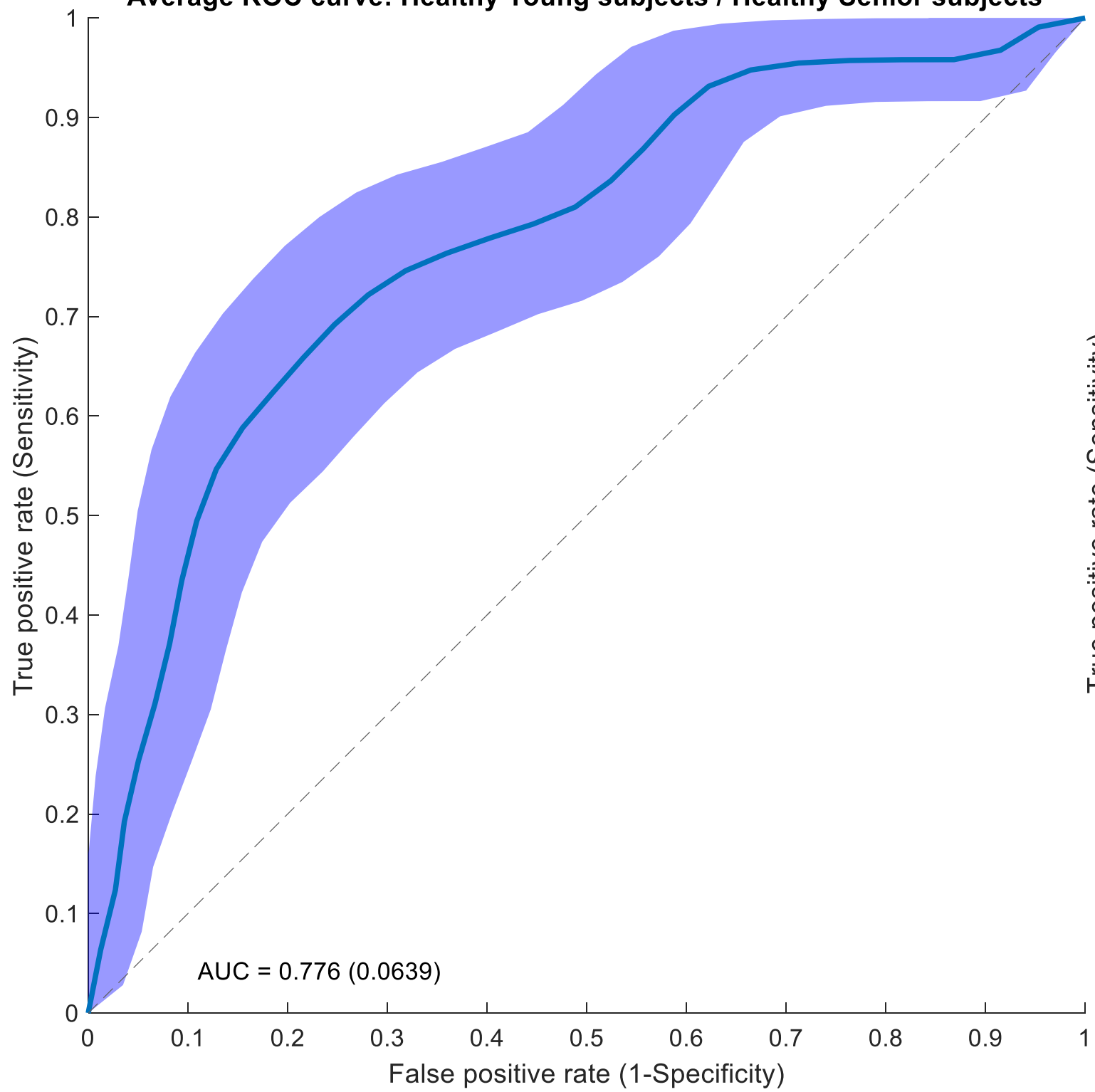
## Figure Captions

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), 1<sup>st</sup> and 3<sup>rd</sup> 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 significant between HY and FS groups and between HS and FS groups.

**Average ROC curve: Healthy Young subjects / Healthy Senior subjects**



**Average ROC curve: Healthy Senior subjects / Frail subjects**

