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Approximation of Cognitive Performance Using an Elastic Net Regression Model Trained on Gait, Visual, Auditory, Postural, and Olfactory Function Features

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Abstract: When dementia is diagnosed, it is most often already past the point of irreversible neuronal deterioration. Neuropsychological tests are frequently used in clinical settings; however, they must be administered properly and are oftentimes conducted after cognitive impairment becomes apparent or is raised as a concern by the patient or a family member. It would be beneficial to develop a non-invasive system for approximating cognitive scores which can be utilized by a general practitioner without the need for cognitive testing. To this end, gait, visual, auditory, postural, and olfactory function parameters, reported history of illness, and personal habits were used to train an elastic-net regression model in predicting the cognitive score. Community-dwelling men (N = 104) above the age of sixty-five participated in the current study. Both individual variables and principal components of the motor and sensory functions were included in the elastic-net regression model, which was trained on 70% of the dataset. The years of education, limits of stability testing time, regular ophthalmological exams, postural testing time principal component, better ear score on the sentence recognition test, and olfactory discrimination score largely contributed to explaining over 40% of the variance in the cognitive score.

Keywords: cognitive function; elastic-net regression; gait; posture; vision; hearing; olfaction

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1. Introduction

The World Health Organization (WHO) estimates that by 2050, 2.1 billion people will be over the age of 60 [1]. With more and more people reaching this age category, the incidence of geriatric diseases, such as dementia, is expected to rise exponentially. With no existing cure for dementia, the best course of action is prevention, and up to 40% of dementia cases can be prevented or delayed simply by addressing the 12 risk factors stated in the 2020 Lancet report on dementia prevention [2]. Additionally, according to the 2023 World Alzheimer Report, slowing down or halting the progression of dementia even after a diagnosis is important in lessening both the societal and individual burden of dementia [3]. For effective risk reduction, it is beneficial to detect cognitive changes as early as possible; therefore, the first step towards detection of cognitive impairment is the most important, and screening for early signs of dementia should be performed routinely in older individuals.

Current clinical practices use neuropsychological tests, such as the Montreal Cognitive Assessment (MoCA) [4], as an initial assessment which is followed by further testing. However, proper training is necessary to be able to perform cognitive assessments. Additionally, these tests are usually performed only after cognitive decline is presented as a concern by the patient or a caregiver. This results in fewer patients being screened for cognitive decline and a diagnosis in the mild or moderate stage of the disease, by which time a significant amount of neuronal injury has occurred [5].

Developing a non-invasive system that can approximate a cognitive score without the use of neuropsychological testing could allow practitioners to assess their patients quickly and refer them for further testing if needed. To achieve this, it is necessary to investigate possible biomarkers that can be obtained using non-invasive methods that are sensitive to differences in cognitive functioning. One possible method is the use of motor and cognitive function features, such as gait, visual, auditory, postural, and olfactory function features, as previous research has identified the existence of robust correlations between these functions and cognitive performance.

Gait function and its relation to mild cognitive impairment and dementia have been investigated by numerous studies. The majority of the studies investigated spatiotemporal parameters and gait variability in single- and double-task settings [6]. Many studies reported gait speed and step and stride lengths as differentiating factors between AD and normal cognition or between AD and MCI [7–10]. Some studies determined that there is a potential for detecting AD and MCI using continuous gait monitoring [11] or by training machine learning models on gait data [12]. Compared to the studies regarding gait and cognition, there are much fewer studies regarding the relationship between cognition and postural control and it has been noted that further investigation is necessary [13]. The few existing studies reported significant correlations between cognitive performance and postural parameters [14,15]. Various sensory parameters have also been shown to have a robust relationship with cognition. A recent study concluded that all types of measured visual impairment were associated with a higher dementia prevalence [16], and meta-analysis research confirmed the consistency of the association [17]. Additionally, a 9-year longitudinal study found better visual ability to be associated with better cognitive performance and slower rates of decline on both vision-dependent and vision-independent cognitive tests [18]. In the case of auditory ability, hearing loss was identified as a risk factor for dementia [19,20]. Alongside vision and hearing, sensory loss in olfaction is also considered a risk factor for developing dementia [21], and impaired olfaction was determined to have an association with cognitive decline and neurodegeneration in the brain [22,23], which is why some studies have attempted to detect dementia using olfactory function parameters [24–26].

The research mentioned previously has utilized motor or sensory variables to explore the possibility of detecting cognitive impairment; however, the majority of the research relied on neuropsychological testing results to enhance the performance of the functional parameters. Additionally, most research did not consider evaluating principal components of the motor and sensory functions, which may be necessary to determine the role of specific motor and sensory abilities in regard to cognition. To investigate the possibility of an alternative method for estimating cognition without the need for neuropsychological testing, the present study (1) obtained the participants' history of illness, information regarding daily habits and motor and sensory function parameters, (2) evaluated individual correlations between the K-MoCA scores and motor and sensory parameters and principal components (PCs), and (3) assessed an elastic net regression model performance in approximating the cognitive score.

2. Materials and Methods

2.1. Participants

Older men with no history of neurological disorders were recruited for participation in the study. The participants attended two consecutive sessions in the period between 2022 and 2023. Inclusion criteria were a biological age over 65 years, the ability to independently participate in the study, and written informed consent. Exclusion criteria were severe motor or sensory impairments and a MoCA score below 18 points. Cognitive assessment battery and level walking assessments were performed during the first session. Visual, postural, auditory, and olfactory functions were tested during the second session. Participants received all the relevant information regarding the study and were given the opportunity to ask questions regarding the experiments. All of the participants read and signed the informed consent agreement.

Additionally, the participants completed a questionnaire that included standard history of illness questions about illnesses most commonly correlated with dementia [27,28] and questions regarding the participants' habits. Apart from the questions most commonly asked during a general practice check-up, the participants were asked whether they receive ophthalmological and auditory exams regularly, based on the recommendations for older adults. Detailed characteristics of participants are listed in Tables 1 and 2 in the results section. This study was approved by the Institutional Review Board of Jeonbuk National University (JBNU IRB File No. 2022-04-017-003). All experiments were performed per relevant guidelines and regulations.

Table 1. Participants' demographic and cognitive characteristics.

Parameter	MEAN (SD)	R^2	*p*-Value
Age (years) *	75.3 (4.1)	0.058	0.001
BMI (kg/m^2)	24.2 (2.4)	<0.001	0.921
Years of education *	13.4 (3.7)	0.156	<0.001
K-MoCA score	24.4 (2.8)	-	-
SMCQ score	2.8 (2.8)	<0.001	0.947

SD, standard deviation; BMI, body mass index; K-MoCA, the Korean version of the Montreal Cognitive Assessment; SMCQ, Subjective Memory Complaints Questionnaire; * significant correlation with the K-MoCA score.

Table 2. History of illness and habits assessment.

Q		YES (*n*/%)	*p*-Value
Diabetes mellitus		35/33.7	0.319
Hypertension		41/39.4	0.960
Cardiovascular disease		16/15.4	0.488
Neurovascular disease *		6/5.8	0.024
Smoking	Never	42/40.4	0.769
	Previous	54/51.9	
	Current	8/7.7	
Drinking *	Never	37/35.6	0.023
	Occasionally	61/58.7	
	Daily	6/5.8	
Physical activity		101/97.1	0.898
Regular ophthalmological exam *		83/79.8	0.001
Regular audiological exam		69/66.3	0.732

* significant correlation with the K-MoCA score.

2.2. Cognitive Testing

The participants completed a Subjective Memory Complaints Questionnaire (SMCQ) to assess their perceived cognitive state and the Montreal Cognitive Assessment (MoCA) in Korean to assess their objective cognitive function. SMCQ consists of 14 items that reflect both general and specific cognitive aspects [29] and a higher score indicates more subjective memory complaints. MoCA is used for quick screening of the global cognitive function [4] with scores ranging from 0 to 30 points. The MoCA in Korean (K-MoCA) is a validated alternative-form MoCA test suited for testing the Korean population and was used to quantify the global cognition of the study's participants.

2.3. Gait Function

During level walking assessment, participants completed 3 trials at a comfortable speed along a 10 m walkway and the ensemble average was used to represent the gait function. To collect the anthropometric data, 17 active markers were placed on the lower body and their placement in three-dimensional space was captured using the gold standard motion sensor system, Optotrak (Northern Digital Inc., Waterloo, ON, Canada). The gait parameters were extracted via Software for Interactive Musculoskeletal Modeling (SIMM) version 7.0 (Motion Analysis Corp., Rohnert Park, CA, USA). The gait function parameters were obtained for a full gait cycle starting from the left foot heel strike. The coefficient of variation (CoV) for the aforementioned variables, calculated as (SD/MEAN) $\times$ 100, was also included in the analysis.

2.4. Visual Ability

To assess the visual function of the participants, depending on target size and contrast, both visual acuity and contrast sensitivity were measured. The best eye-uncorrected (VAUC) and best eye-corrected (VABC) visual acuity were assessed using the Korean standard vision chart. The uncorrected (CSU) and corrected (CSC) contrast sensitivity was assessed as how many numbers from a Lea Numbers chart (Lea test intl. LLC, Helsinki, Finland) the participant read correctly. The chart includes 5 numbers for each of the 25%, 10%, 5%, 2.5% and 1.5% contrasts. The contrast sensitivity was tested from four distances (4 m, 3 m, 2 m, and 1.6 m).

2.5. Auditory Function

A clinical audiometer (Grason-Stadler, Copenhagen, Denmark) was used to measure pure tone audiometry (PTA). The measurements were recorded for both ears in the frequency range of 0.125 and 8 kHz in octave and semi-octave steps. The scores were averaged over three frequencies (0.5, 1, and 2 kHz) and the average of both ears and the better ear score were included in further analysis.

Korean speech audiometry tests were used to assess the speech recognition threshold (SRT) and speech intelligibility based on word (WR) or sentence recognition of target words (SRW) and whole sentences (SRS). The average of both ears and the better score on each of the tests were included in further analysis.

2.6. Postural Stability

The ability to maintain equilibrium under dynamic and static conditions is complex and as such requires testing in conditions with mechanical, sensory, or cognitive disturbances in addition to static testing. For this reason, the participants completed four postural stability tests, three of which are included in the Biodex SD (Biodex Medical System. Inc., Shirley, NY, USA) system. The first assessment was a tandem Romberg test under two conditions: eyes open and eyes closed. The time of maintaining the pose was recorded as a variable, with the maximum being 60 s. The second assessment was used to obtain the mediolateral (MLSI), anteroposterior (APSI), and overall postural stability (OSI) indexes under two conditions: eyes open and eyes closed. The higher value of the indexes indicates lower postural stability. The third assessment was a fall risk assessment from which a fall risk index (FRI) was obtained. Higher values of this index indicate a greater risk of falling. The last assessment was used to test the participants' limits of stability (LOS). The time for completing the test was recorded as a variable. The testing performed using the Biodex SD system was performed following the product manual [30].

2.7. Olfactory Function

Participants' olfactory function was assessed using the Snap & Sniff olfactory testing kit (Sensonics Inc., Hadden Heights, NJ, USA). The kit includes an odor threshold test and two suprathreshold tests (odor discrimination and odor identification). The threshold test includes five blank-odor pens and 15 odorant pens and employs a so-called "staircase testing paradigm" to determine the odor concentration for which the participant can distinguish between the blank and odor pens without error. The threshold ranges from 2 to 9, with 9 representing high sensitivity and 2 representing low sensitivity. For any participant whose sensitivity was below 2, a value of 1 was recorded. The odor discrimination test consists of 22 questions. For each question, a triplet of odors, two of which are the same and one that differs, are presented to the participant. Therefore, the odor discrimination score can range between 0 and 22, with the higher number representing better discrimination. Lastly, the odor identification test consists of 16 multiple-choice questions. For this test, a participant would be presented with an odor and consequently choose an answer among 4 choices represented by both image and text. All olfactory testing was performed in accordance with previous studies [31] and the relevant manuals.

2.8. Statistical Analysis

To explore which motor and sensory parameters significantly correlate to global cognition, and to what extent both original variables and PCs were examined. The correlation between the cognitive score and each variable/PC was determined using Pearson, Spearman, or Kendal–Tau correlation analysis, depending on the normality of the parameters. The PCs were extracted using the quartimax method and only the components with eigenvalues greater than one were included in further analysis. The descriptive statistics of the original variables, factor loadings for the principal components and the R^2 and p-values of all the correlation analyses are reported in the results.

For the purpose of the study, a regression model with K-MoCA score as the dependent variable was trained and evaluated. Elastic net resolves the issue of collinearity by adjusting the model coefficients through the use of a penalty, which allows automatic predictor selection in cases where there are many predictors. Performance metrics of the model (i.e., root-mean-square error (RMSE), correlation coefficient, and standardized coefficients (R^2)) are reported in the results section.

Statistical Package for the Social Sciences (SPSS) version 26.0.0 (IBM Corp, New York, NY, USA) and Statistical Software for Excel (XLSTAT) version 2023.1.2 (Addinsoft, Paris, France) were used for all the statistical analyses.

3. Results

3.1. Demographics, Cognitive Function, and the History of Illness

The cognitive scores and demographic data of the participants (N = 104) are presented in Table 1. The majority of the participant's BMI fell in the healthy range for older individuals [32]. The years of education ranged between 3 and 21 years, with 48% of participants having received higher education. A significant linear correlation to the K-MoCA score was observed in the case of age and years of education.

The results of the questionnaire can be found in Table 2. The participants with a history of neurovascular disease had a significantly lower cognitive score than the rest; however, no significant differences were found in the case of any other illness. Regarding personal habits, a significant difference in cognition was observed only in the case of regular ophthalmological exams. The participants who did not receive regular exams had significantly lower cognitive scores.

Additionally, the participants who reported drinking alcohol on a daily basis were found to have higher cognitive scores than those who did not consume or occasionally consumed alcohol.

3.2. Gait Assessment

The gait function parameters' descriptive statistics and the K-MoCA correlation results are presented on the left side of Table 3. The factor loadings respective to the parameters that make up gait PCs, and their K-MoCA correlation results, are presented on the right side of Table 3. Among all of the gait variables, only the stride length, stance duration CoV, and the variability of the loading response portion of the gait cycle (LR CoV) were significantly correlated to the cognitive score. Stride length was positively correlated with the cognitive score. For both stance duration and LR, more intra-participant variation was correlated with lower MoCA scores.

Table 3. Participants' gait function characteristics.

Parameter	MEAN (SD)	R^2 (*p*-Value)	PC	Loading	R^2 (*p*-Value)
DLS (%)	21.6 (2.3)	0.004 (0.370)	Gait cycle	0.963	0.001 (0.661)
PS (%)	11.1 (1.4)	0.004 (0.378)		0.902	
SLS (%)	39.5 (1.3)	0.001 (0.583)		−0.832	
LR (%)	10.5 (1.2)	0.006 (0.283)		0.827	
SW (%)	38.9 (1.5)	0.003 (0.420)		−0.754	
DLS CoV	4.2 (5.6)	0.007 (0.217)	Gait cycle variation	0.970	0.012 (0.114)
PS CoV	5.4 (8.2)	<0.001 (0.810)		0.931	
LR CoV *	5.6 (4.1)	0.022 (0.034)		0.852	
SLS CoV	2.0 (1.8)	0.004 (0.358)		0.829	
SW CoV	2.1 (2.6)	0.009 (0.163)		0.538	
Swing duration CoV	2.6 (2.9)	0.002 (0.481)	-	-	-
Swing duration (ms)	417.4 (25.0)	0.007 (0.264)	Gait rhythm	0.929	0.003 (0.447)
Stride duration (ms)	1075. 8 (82.7)	0.011 (0.138)		0.886	
Cadence (steps/min)	112.2 (8.2)	0.011 (0.136)		−0.879	
Stance duration (ms)	658.5 (62.6)	0.012 (0.118)		0.804	
Stride duration CoV	1.9 (1.4)	0.017 (0.064)	Gait rhythm variation	0.943	0.001 (0.660)
Cadence CoV	1.5 (1.1)	0.017 (0.062)		0.941	
Stance duration CoV *	2.5 (1.9)	0.027 (0.019)		0.861	
Velocity CoV	2.6 (2.0)	<0.001 (0.819)		0.722	
Step Length (cm)	64.7 (7.0)	0.033 (0.066)	Gait pace	0.884	0.016 (0.073)
Stride Length (cm) *	127.0 (12.7)	0.040 (0.041)		0.877	
Velocity (cm/s)	119.1 (17.0)	0.033 (0.065)		0.685	
Step Length CoV	2.3 (1.3)	0.001 (0.653)	Gait pace variation	0.828	0.001 (0.617)
Stride Length CoV	1.8 (1.2)	0.002 (0.521)		0.767	
TS (%)	19.1 (2.4)	0.007 (0.235)	Midstance	0.951	0.006 (0.266)
MS (%)	20.5 (2.5)	0.007 (0.235)		−0.936	
MS CoV	10.3 (6.2)	0.003 (0.437)	Midstance variation	0.884	<0.001 (0.767)
TS CoV	11.3 (7.5)	<0.001 (0.749)		0.857	

SD, Standard Deviation; LR, Loading Response; MS, Mid-Stance; TS, Terminal Stance; PS, Pre-Swing; SLS, Single Limb Support; DLS, Double Limb Support; SW, SWing; CoV, Coefficient of Variance; PC, Principal Component; * significant correlation with the K-MoCA score.

The PCA yielded a total of eight PCs related to gait: Gait cycle (consisting of LR, PS, SLS, DLS, SW), Gait pace (consisting of stride length, step length, and gait velocity), Gait rhythm (consisting of stance duration, swing duration, stride duration, and cadence), Midstance (consisting of MS and TS), Gait cycle variation (consisting of LR CoV, PS CoV, SLS CoV and DLS CoV), Gait pace variation (consisting of step and stride length CoVs), Gait rhythm variation (consisting of gait velocity CoV, cadence CoV, stance duration CoV and stride duration CoV), and Midstance variation (consisting of MS and TS CoVs). None of these components were significantly correlated with the K-MoCA score.

3.3. Visual Function

The visual function parameters' descriptive statistics and the K-MoCA correlation results are presented on the left side of Table 4. The factor loadings respective to the parameters that make up visual PCs, and their K-MoCA correlation results, are presented on the right side of Table 4. Apart from the CSC at a 3 m distance, none of the variables were significantly correlated to the cognitive score.

Table 4. Participants' visual function characteristics.

Parameter	MEAN (SD)	R^2 (*p*-Value)	PC	Loading	R^2 (*p*-Value)
CSC at 3 m *	16.2 (5.6)	0.021 (0.045)	Corrected vision *	0.929	0.023 (0.028)
CSC at 4 m	11.7 (6.2)	0.017 (0.067)		0.907	
CSC at 2 m	20.8 (4.6)	0.011 (0.151)		0.901	
CSC at 1.6 m	22.8 (3.6)	0.009 (0.214)		0.853	
VABC	0.8 (0.3)	0.009 (0.206)		0.837	
CSU at 2 m	21.4 (5.4)	<0.001 (0.958)	Uncorrected vision	0.869	<0.001 (0.821)
CSU at 1.6 m	18.8 (6.6)	0.001 (0.642)		0.866	
CSU at 3 m	14.1 (6.6)	<0.001 (0.770)		0.824	
CSU at 4 m	9.5 (6.8)	<0.001 (0.925)		0.714	
VABU	0.7 (0.3)	<0.001 (0.952)		0.665	

SD, Standard Deviation; VABU, Visual Acuity Best Uncorrected; VABC, Visual Acuity Best Corrected; CSU, Contrast Sensitivity Uncorrected; CSC, Contrast Sensitivity Corrected; PC, Principal Component; * significant correlation with the K-MoCA score.

After performing PCA, two distinct visual components were derived: uncorrected and corrected visual ability. The uncorrected visual ability was found to not correlate with cognition, while higher corrected visual ability was significantly correlated with higher cognitive performance.

3.4. Auditory Function

The auditory function parameters' descriptive statistics and the K-MoCA correlation results are presented on the left side of Table 5. The factor loadings respective to the parameters that make up auditory PCs, and their K-MoCA correlation results, are presented on the right side of Table 5. The sentence recognition results were highly correlated with the cognitive score, with the highest correlation coefficient observed in the case of SRS of the better ear. None of the other parameters were significantly correlated with the K-MoCA score. PCA resulted in three auditory components, one for overall hearing level (including PTA and SRT results), one for word recognition (including WR better, WR average, and WR total number of mistakes), and one for sentence recognition (including all the SR results). The sentence recognition component was the only component significantly correlated with the MoCA score.

Table 5. Participants' auditory function characteristics.

Parameter	MEAN (SD)	R^2 (*p*-Value)	PC	Loading	R^2 (*p*-Value)
SRW total number of mistakes *	1.9 (2.0)	0.084 (<0.001)	Sentence Recognition *	−0.946	0.069 (<0.001)
SRW average *	97.6 (2.4)	0.084 (<0.001)		0.946	
SRS total number of mistakes *	1.9 (1.8)	0.085 (<0.001)		−0.939	
SRS average *	90.3 (9.1)	0.085 (<0.001)		0.939	
SRS better *	94.9 (8.4)	0.106 (<0.001)		0.933	
SRW better *	99.0 (1.8)	0.077(0.001)		0.898	
SRT average	24.2 (12.3)	0.011 (0.152)	Hearing level	0.952	0.007 (0.232)
SRT better	19.8 (11.2)	0.008 (0.240)		0.923	
PTA average	25.0 (11.9)	0.017 (0.058)		0.910	
PTA better	20.9 (10.5)	0.014 (0.094)		0.897	
WR better	82.2 (12.6)	0.009 (0.188)	Word recognition	0.900	0.001 (0.690)
WR total number of mistakes	11.2 (6.4)	0.015 (0.084)		−0.898	
WR average	77.5 (12.8)	0.014 (0.099)		0.898	

SD, Standard Deviation; PTA, Pure Tone Audiometry; SRT, Speech Recognition Threshold; WR, Word Recognition; SRW, Sentence Recognition of target Words; SRS, Sentence Recognition of whole Sentence; PC, Principal Component; * significant correlation with the K-MoCA score.

3.5. Postural Stability

The postural stability parameters' descriptive statistics and the K-MoCA correlation results are presented on the left side of Table 6. The factor loadings respective to the parameters that make up postural stability PCs, and their K-MoCA correlation results, are presented on the right side of Table 6. The only variable significantly correlated with the cognitive score was LOS time. The longer it took the participants to complete the test, the lower their MoCA score was.

Table 6. Participants' postural stability characteristics.

Parameter	MEAN (SD)	R^2 (p-Value)	PC	Loading	R^2 (p-Value)
OSI EO	0.5 (0.2)	0.016 (0.095)	Eyes open postural stability	0.929	0.006 (0.252)
MLSI EO	0.2 (0.1)	0.013 (0.135)		0.850	
APSI EO	0.4 (0.2)	0.014 (0.135)		0.803	
FRI	1.1 (0.4)	0.011 (0.146)	-	-	-
APSI EC	1.2 (0.6)	0.002 (0.570)	Eyes closed postural stability	0.926	0.001 (0.674)
OSI EC	1.5 (0.7)	0.002 (0.500)		0.826	
MLSI EC	0.6 (0.4)	0.001 (0.662)		0.762	
RT EC (s)	8.1 (13.5)	0.014 (0.100)	PS testing time *	0.799	0.044 (0.003)
RT EO (s)	40.2 (24.3)	0.006 (0.310)		0.699	
LOS time (s) *	55.4 (14.1)	0.048 (0.001)		−0.587	

SD, Standard Deviation; RT, Romberg Tandem; EO, Eyes Open; EC, Eyes Closed; OSI, Overall Stability Index; MLSI, MedioLateral Stability Index; APSI, AnteroPosterior Stability Index; FRI, Fall Risk Index; LOS, Limits Of Stability; PS, Postural Stability; PC, Principal Component; * significant correlation with the K-MoCA score.

Three PCs represented postural stability: eyes open postural stability (consisting of OSI, MLSI, APSI under eyes open condition); eyes closed postural stability (consisting of OSI, MLSI, APSI under eyes closed condition) and PS testing time (consisting of RT EO, RT EC and to an extent, the LOS time). Among them, the testing time component displayed a significant correlation to the cognitive score.

3.6. Olfactory Function

The olfactory function parameters' descriptive statistics and the K-MoCA correlation results are presented on the left side of Table 7. The factor loadings respective to the parameters that make up olfactory PCs, and their K-MoCA correlation results are presented on the right side of Table 7. Among the 104 participants, 3 refused to complete the olfactory identification test. The results of said test shown in Table 7 refer to the 101 participants who completed it. The olfaction threshold and olfactory identification score were not correlated with the K-MoCA score. The only variable with a significant correlation to the cognitive score was the olfactory discrimination score.

Table 7. Participants' olfactory function characteristics.

Parameter	MEAN (SD)	R^2 (p-Value)	PC	Loading	R^2 (p-Value)
Olfaction threshold	3.8 (2.0)	<0.001 (0.964)	Sense of smell	0.799	0.014 (0.087)
Olfactory discrimination *	12.5 (3.3)	0.033 (0.011)		0.799	
Olfactory identification †	8.2 (2.3)	0.003 (0.447)	-	-	-

SD, Standard Deviation; PC, Principal Component; * significant correlation with the K-MoCA score; † results refer to n = 101.

Due to the missing values, the olfactory identification score was omitted from the PCA. The olfaction threshold and discrimination score were combined into one component, which did not correlate with the cognitive score.

3.7. Regression Model Parameters and Coefficients

The dataset consisting of demographic data, standardized functional parameters, and PCs was randomly divided into train and test data in a 70:30 ratio, with no repeating samples. The training dataset was used to train an elastic-net regression model and the model parameters for the train and test datasets are presented in Table 8. There were no large discrepancies between the results of the two datasets regarding RMSE, R^2, or the correlation of the predicted values with the actual cognitive score.

Table 8. Elastic-net regression model.

Dataset	RMSE	R^2	K-MoCA Correlation Coefficient	Lambda	Alpha
Train	2.119	0.493	0.569	0.593	0.515
Test	2.017	0.420	0.524		

RMSE, root-mean-square error.

The absolute values of non-zero component coefficients are presented in Figure 1 to showcase the variable importance. The two most prominent variables in the model were years of education and LOS time. Variables with medium importance were the "yes" answer regarding regular visual exams, testing time PC, SRS better, and olfactory discrimination score. Stride Length CoV, MS CoV, age, sentence recognition PC, PTA of the better ear, SRS average, PS phase of the gait cycle, stance duration, SRS total number of mistakes, and cadence were included in the model but had minimal contributions to the prediction. When the variables with minimal contribution were omitted from the prediction calculation, the remaining six variables were still able to explain approximately 46% of the K-MoCA variance. Based on the aforementioned six-variable model, the K-MoCA score can be calculated as follows:

$$\begin{aligned}\text{KMoCA}_{\text{predicted}} = {} & 24.412 + 0.855 \times \text{Years of education} - 0.509 \times \text{LOStime} + 0.342 \times \text{Ophthalmologist(YES)} \\ & + 0.277 \times \text{PS testing time PC} + 0.257 \times \text{SRS better} + 0.185 \times \text{Olfactory discrimination}\end{aligned} \quad (1)$$

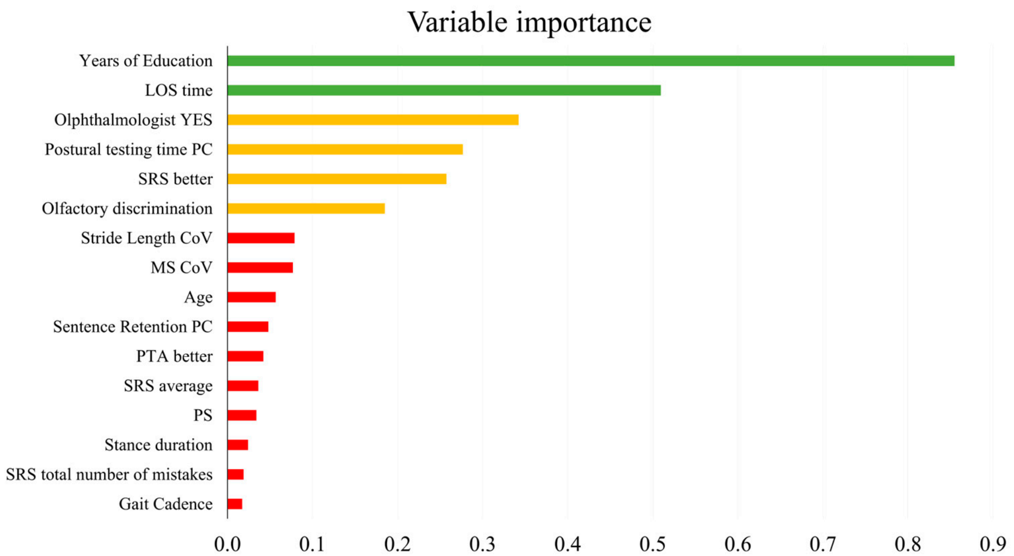

Figure 1. Variable importance of the components included in the regression model. Absolute coefficients higher than 0.5 are presented in green; absolute coefficients between 0.1 and 0.5 are presented in yellow; absolute coefficients lower than 0.1 are presented in red.

The correlations between the K-MoCA score and the five quantitative variables with substantial contributions to the prediction are presented in Figure 2. The correlation graphs for the variables which showed significant correlations to the cognitive score but were not included in the model are presented as Supplementary Material in Figures S1–S13. With the exception of LOS time, the remaining variables were positively correlated with the cognitive score. The participants with more years of education, higher sentence recognition and odor discrimination abilities, and better static and dynamic postural stability obtained higher scores on the K-MoCA test.

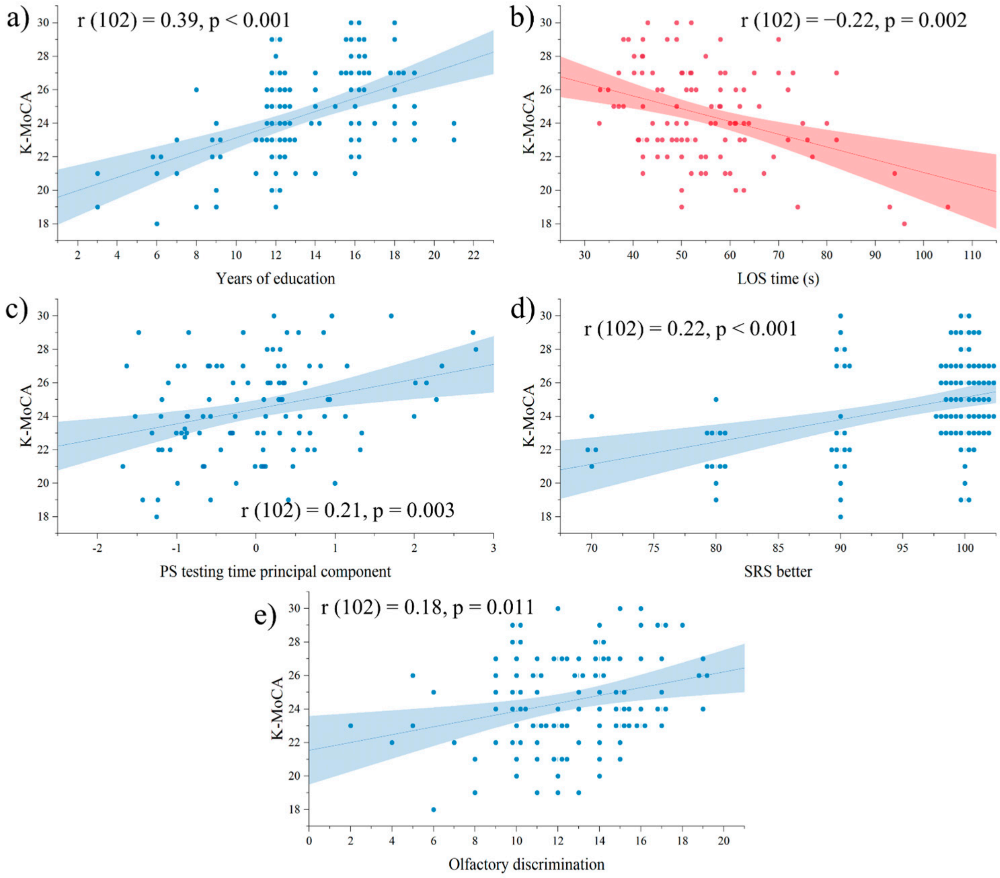

Figure 2. Correlation between K-MoCA score and (**a**) years of education, (**b**) LOS time, (**c**) postural testing time principal component, (**d**) SRS better, and (**e**) olfactory discrimination score. Positive correlations are presented in blue, and the negative correlations are presented in red.

4. Discussion

The present study explored the possibility of using motor and sensory parameters and components to predict the cognitive score of community-dwelling older Korean men. This was performed to explore an alternative to neuropsychological testing methods, which would allow early detection of cognitive deterioration.

The demographics analysis showed that age and education were highly correlated with the K-MoCA score as previous studies have consistently shown [33–35]. Age independently accounted for close to 6% of MoCA score variance, whereas years of education accounted for almost 16% of the variation. In contrast, the SMCQ score did not correlate with the cognitive score. Similar results have been previously shown by studies reporting that subjective complaints and informant reports oftentimes have inconsistent correspondence with current objective cognition [36,37].

The history of illness results showed significantly lower cognitive performance only among the people who had previously suffered a stroke. Cognitive deterioration and impairment have been reported as common occurrences after a stroke [38]. There was no significant difference in cognitive scores between participants with hypertension, diabetes mellitus or cardiovascular disease (CVD) and those without.

Regarding the participants' habits, cognitive performance was found to be higher among people who reported receiving regular ophthalmological examinations. This is in accordance with the previous research, which reported untreated poor vision as a risk factor for dementia [39] and that patients with dementia used less visual correction, had fewer ophthalmological treatments, and underwent fewer ocular surgeries [40]. Participants who reported consuming alcohol on a daily basis had higher cognitive scores than those who did not or occasionally had a drink. Upon further investigation, it was observed that the all of the six participants who consumed alcohol daily reported receiving regular ophthalmological testing and none had a history of neurovascular disease. Additionally, recent research has shown that maintaining mild to moderate daily alcohol consumption or initiating mild daily alcohol consumption was associated with decreased risk of dementia [41]. The impact of daily alcohol consumption on cognitive performance should be further investigated.

The gait variables significantly correlated with the cognitive score accounted for 2–4% of its variance. Stride length, which has been reported as a differentiating factor for cognitive status [7,8] was observed to be correlated with cognitive performance. Stance duration variability has been previously observed as directly related to central nervous system impairment which was measured using neuropsychological examinations [42]. Additionally, previous research observed a high correlation between overall gait variability and the MoCA score [43,44]. The present study observed a significant correlation only in the case of stance duration variability, which could be due to a smaller range of cognitive scores of the participants included in the study. These results present the possibility that not all of the gait disturbances reported in previous studies on dementia are present in people without severe cognitive deterioration. In the case of loading response, the objectives of this phase of the gait are limb stabilization, shock absorption, and preservation of the body's progression. During loading response, the knee flexes so that the shock from the foot falling flat on the ground can be absorbed, assuring stabilization and preparing for single limb support. Intra-individual variability of this phase could signify inconsistency in dynamic stability. The results of the present study therefore suggest that older individuals with poor cognitive performance have inconsistent dynamic stability.

In the case of visual ability, the corrected contrast sensitivity at 3 m exhibited a direct correlation with the cognitive score, with the CSC at 4 m showing a similar, but not significant, trend. These measures accounted for approximately 2% of the cognitive score variance. The contrast sensitivity test used in this study was designed so that full contrast is visible from a distance which is 10 times the visual acuity. In other words, a participant with a visual acuity of 0.4 will not be able to read numbers that are less than 100% contrast from a distance of 4 m. Table 4 shows that the minimum best corrected visual acuity of the participants is 0.25; therefore, all the participants were able to read the contrast sensitivity charts at 2 m and 1.6 m distances, but not all of them were able to do so from 3 m and 4 m distances. This indicates that visual acuity and contrast sensitivity need to be observed as a whole to accurately determine their correlation with the cognitive score, which was further confirmed by examining the PCs of the visual function. The overall corrected vision was positively correlated with K-MoCA, whereas the uncorrected vision was not, indicating that older individuals who properly receive visual stimulation in their day-to-day life, have higher cognitive ability.

Among the auditory parameters and PCs, only those representing sentence recognition ability were found to be significantly correlated with the K-MoCA score. The sentence recognition parameters accounted for up to 10% of the K-MoCA score variance. Several studies reported hearing loss (determined by PTA threshold) to be a dementia risk factor [19,20]; however, only a small effect was observed between cognition and the PTA threshold in the present study cohort. There does not appear to be a direct link between hearing loss and cognitive ability, as reported by a recent review of the literature [45]. Regarding sentence recognition, the results indicate that other factors, and not hearing loss, may be influencing the connection between cognitive ability and the ability to recognize sentences properly. Previous research has reported impaired sentence comprehension in patients with dementia [46], suggesting that an inability to comprehend sentences may be the reason for a low score when repeating said sentences.

Romberg test duration, postural stability scores, and the fall risk score were not correlated with the cognitive score. A significant negative correlation was observed only in the case of limits of stability testing (the longer the testing time the lower the cognitive score). Additionally, the principal component consisting of positively contributing Romberg test times and the negatively contributing LOS test time was significantly positively correlated to the K-MoCA score. It has been previously reported that there are significant differences in the postural stability of elderly with and without severe cognitive impairment [15]. Considering that the participants of this study were generally healthy and had no dementia diagnosis, there may be only a small effect size between cognitive function and postural stability among older individuals with normal or mildly deteriorated cognitive function. The results suggest that among people without severe cognitive impairment, only the processing time of the test, but not the postural stability scores, are correlated with the level of cognitive ability.

Regarding the olfactory function, only the odor discrimination score was significantly correlated with the cognitive score. The participants who were better at discerning which odors were different and which were the same performed better on the K-MoCA. Odor discrimination has been shown to be impaired in early cases of dementia and it deteriorates with the progression of the disease [25]. Additionally, a previous study concluded that odor discrimination is related to semantic memory and that noncognitive factors have only a minor influence on the score [47] therefore making the odor discrimination test a good measure of cognitive ability.

When combined in an elastic net regression model, among the aforementioned parameters and principal components, the years of education, LOS time, regular visual exams, postural testing time PC, SRS better ear score, and olfactory discrimination score accounted for over 40% of the variance in the MoCA score. With an RMSE of approximately 2 points, the model had consistent performance in the training and testing datasets. Because the postural testing time principal component utilizes LOS time and tandem Romberg testing time under eyes open and eyes closed conditions, there are five parameters that need to be measured to predict the cognitive score based on the presented model. These measurements require no more than 20 min to perform, similar to the K-MoCA testing time. The tandem Romberg test is being used in clinical settings, the olfactory discrimination test requires only five different odors to be administered, and the sentence recognition and limits of stability testing can be implemented in smartphones [48–50]. Therefore, the cost and difficulty of obtaining the necessary measurements can be reduced, and the tests can be included in the national health screening for older individuals. By doing so, the issue of neuropsychological testing being performed after a significant amount of neuronal injury can be addressed.

The present study has some limitations. Firstly, due to the inclusion criteria, no participants received a K-MoCA score below 18 points, which may have resulted in an underestimation of the correlation coefficients. Secondly, while olfactory threshold and olfactory discrimination tests can be performed cross-culturally, the olfactory identification test relies on the familiarity of scents and varies across cultures. For this reason, a more thorough analysis is needed to determine the magnitude of the association between cognitive performance and olfactory identification ability. Lastly, the present study included only male participants. Various factors such as longevity, biology, and gendered social roles and opportunities influence the differences in AD incidence and manifestation depending on sex [51]. Therefore, it is possible that the factors that correlate with global cognition in women are entirely different to those reported in the present study and a separate study should be designed to determine a method for approximating cognitive scores of older women.

5. Conclusions

The present study revealed that gait function parameters (stride length, stance duration CoV, and LR CoV) and sensory parameters/principal components (corrected contrast sensitivity score at a 3 m distance, corrected visual ability, SRW and SRS better and average scores, SRW and SRS total number of mistakes, LOS time, postural testing time, and the olfactory discrimination score) have a significant correlation with cognitive performance. Additionally, regular management of ocular health was positively correlated, whereas history of neurovascular disease was negatively correlated with cognitive performance.

By utilizing the years of education, LOS time, regular visual exams, testing time principal component, SRS better ear score, and olfactory discrimination score, an elastic net regression model was able to approximate the K-MoCA score, with an RMSE of 2 points in both training and testing datasets. These results showcase the use of motor and sensory parameters in approximating the cognitive score, which is a method that can be used in clinical settings to alert physicians to the possibility of early cognitive deterioration of the patient.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14052098/s1, Dataset S1: dataset.csv; Table S1: Principal component analysis of gait data: rotated component matrix; Table S2: Principal component analysis of gait data: total variance explained; Table S3: Principal component analysis of visual data: rotated component matrix; Table S4: Principal component analysis of vision data: total variance explained; Table S5: Principal component analysis of auditory data: rotated component matrix; Table S6: Principal component analysis of auditory data: total variance explained; Table S7: Principal component analysis of postural stability data: rotated component matrix; Table S8: Principal component analysis of postural stability data: total variance explained; Table S9: Principal component analysis of olfactory data: rotated component matrix; Table S10: Principal component analysis of olfactory data: total variance explained; Figure S1: Correlation between K-MoCA score and age; Figure S2: K-MoCA score depending on (a) neurovascular pathology, (b) regular ophthalmological testing, and (c) alcohol consumption; Figure S3: Correlation between K-MoCA score and stride length; Figure S4: Correlation between K-MoCA score and stance duration CoV; Figure S5: Correlation between K-MoCA score and LR CoV; Figure S6: Correlation between K-MoCA score and corrected contrast sensitivity at 3 m distance; Figure S7: Correlation between K-MoCA score and corrected vision principal component; Figure S8: Correlation between K-MoCA score and SRW better; Figure S9: Correlation between K-MoCA score and SRW average; Figure S10: Correlation between K-MoCA score and SRW total number of mistakes; Figure S11: Correlation between K-MoCA score and SRS average; Figure S12: Correlation between K-MoCA score and SRS total number of mistakes; Figure S13: Correlation between K-MoCA score and sentence recognition principal component.

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