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Brain Structural Changes are Associated with Motor Function: A Study of Healthy Young Adults from the Human Connectome Project

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Abstract

Purpose: There is a known decline in brain volume with age, impacting cognitive health and increasing the risk of diseases such as dementia and Alzheimer's. Physical activity has been shown to have positive effects on brain structure and cognitive function with aging. Still, the association between motor function and brain volume in young adults remains unclear.

Materials and Methods: This study utilized high-resolution T1-weighted MRI images and motor function test results from 1082 healthy young adults aged 22-37, sourced from the Human Connectome Project Young Adult (HCP-YA). Motor functions were assessed using four tests: Endurance, Gait Speed, Dexterity, and Strength. Correlation analysis and multiple linear regression models were used to evaluate the association between motor functions and brain volumes, adjusting for demographic variables and Body Mass Index (BMI).

Results: Significant positive correlations were found between Endurance and Strength tests with multiple brain volumes. In contrast, the Dexterity test showed negative correlations reflecting intricate patterns of neural connectivity and plasticity, which may not directly correlate to brain volumes. No significant correlations were observed for the Gait Speed test, indicating that it may not be a sensitive indicator of brain health in younger adults. Multiple linear regression analyses revealed that total brain (β = 0.045, SE = 0.020), total gray matter (GM) (β = 0.035, SE = 0.016), left white matter (WM) (β = 0.058, SE = 0.025), right WM (β = 0.056, SE = 0.025), total WM (β = 0.057, SE = 0.025), and left accumbens (β = -0.072, SE = 0.031) volumes were significantly associated with motor function scores ($p < 0.05$).

Conclusion: Physical fitness, as measured by motor function tests, is significantly associated with brain structural integrity in young adults. These findings highlight the potential importance of physical activity in maintaining brain health, which could inform strategies to promote active lifestyles and prevent neurodegenerative diseases.

Keywords: Brain Structure; Motor Function; Physical Fitness; Magnetic Resonance Imaging; Cognitive Health.

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1. Introduction

There is a decline in gray and white matter volumes as well as an increase in the size of the ventricles in the brain as we age [1]. Also, there is an increased risk of multiple diseases and disorders as a result of brain atrophy, including mild cognitive impairment, dementia, and Alzheimer's disease [2, 3]. Therefore, efforts should be made to control and even prevent these cognitive problems. These efforts have recently been aimed at changing health behaviors, especially increasing physical activity levels, to improve health outcomes [4, 5]. An activity can be defined as the movement of skeletal muscles that involves the release of energy, resulting in excess energy consumption [6]. Physical activity, according to health professionals, can be divided into a variety of activities such as sports, physical exercises, leisure time walking, and so on.

There has been a growing body of evidence that shows the association between physical activity and health-related characteristics like morphological and motor functions [7]. On the other hand, there is some evidence that indicates motor functions resulting in physical fitness may have positive effects on cognitive health across a lifetime [8, 9]. Additionally, through the use of experimental studies, it has been demonstrated that physical fitness has a positive effect on a number of mental health-related functions like executive function and attention [10, 11]. There is evidence that 12 months of aerobic exercise resulted in an increment in hippocampal volume and an improvement in memory in the elderly population [12]. There has also been evidence that performing sports activities for more than one hour per week has an additive effect on gray matter volume in the dorsomedial frontal lobe, superior parietal lobe, and precuneus/cuneus, showing a greater degree of reliability in older individuals [13]. Alternatively, studies on physical activity across a wide variety of changes in the volume of the brain in older adults have revealed that moderate and vigorous physical activity has a meaningful effect on preserving the volume of a variety of parts of the brain [14].

Physical activity and, therefore, physical fitness can be measured directly and over time by motor function tests. Many motor function tests, including strength tests, dexterity tests, and endurance tests, are already available clinically as standard motor assessment tests, and they are also available as part of some publicly available databases as well [15, 16]. It has been established that among the different imaging modalities available, Magnetic Resonance Imaging (MRI) has shown the highest sensitivity as a tool for estimating different brain volumes, especially since the development of fast and three-dimensional sequences for MRI [17]. Among the different MRI techniques, most of the recent brain volumetric studies have used three-Dimensional (3D) and high-resolution T1w MRI because of the highly sensitive structural information and the availability of the technique [18].

The association between physical activity and brain structural changes has already been reported in the literature; however, the results are often contradictory, and most of them have been focused on the elderly population and self-reported physical activity assessments [18-20]. Therefore, the current study aims to evaluate the impact of motor function tasks, as direct representations of physical fitness, on multiple cortical and subcortical brain volumes extracted from structural MRI in a retrospective approach and on a large cohort of young individuals who participated in the Human Connectome Project Young Adult (HCP-YA) database. The HCP-YA is an extensive research initiative aimed at mapping the neural pathways that underlie brain function and behavior in healthy adults. The HCP-YA data set includes high-resolution structural and functional MRI scans, as well as comprehensive behavioral and demographic information from a large cohort of participants. This rich data source allows for detailed investigation of the relationships between brain structure, function, and a wide range of behavioral measures, including motor functions [21].

While much of the existing research has focused on older adults to understand the effects of physical activity on brain health, examining younger adults provides unique insights into early preventive measures. Young adulthood is a crucial period for establishing lifelong habits that can influence long-term brain health. By investigating the relationship between motor functions and brain structural volumes in healthy young adults, this study aims to emphasize the significance of physical fitness from an early age. Promoting physical activity during young adulthood may not only support immediate cognitive and structural brain benefits but also serve as a foundation for reducing the risk of cognitive decline and neurodegenerative diseases later in life.

2. Materials and Methods

2.1. Participants

High-resolution T1-w MRI images along with demographic and physical activity assessments were obtained from the March 2017 public data release from the HCP-YA from the Washington University-University of Minnesota Consortium, which consists of healthy participants (n=1206) aged between 22 and 37. The inclusion and exclusion criteria for this database are detailed elsewhere [22].

Briefly, participants who were healthy and between the ages of 22 and 37, without any history of certain illnesses such as cardiovascular disease, were selected in this study by screening interviews. Then, participants whose motor function test results were not complete were excluded. Finally, 1082 participants were included in this study for further analysis.

2.2. Demographics and Physical Fitness

Age, gender, race, and ethnicity were self-reported. Four motor function tests as representations of physical fitness were included in the NIH Toolbox for Assessment of Neurological and Behavioral Function (NIH Toolbox) [23], which hosts cognition and behavior psychometric measurements, implemented within the HCP-YA database [15].

The four motor function tests were the 2-Minute Walk Endurance Test, 4-Meter Walk Gait Speed Test, 9-Hole Pegboard Dexterity Test, and Grip Strength Test. Two-Minute Walk Endurance is a 4-minute evaluation of a person's level of physical fitness and endurance for ages 3 and above. This test involves participants walking on a flat surface at a normal speed for two minutes. The 4-Meter Walk Gait Speed is a 3-minute test for ages 7 and above that measures locomotion. In order to complete this test, participants will be asked to walk 4 meters on a flat surface at a normal speed. The 9-Hole Pegboard Dexterity Test consists of participants placing 9 pegs into nine holes and then removing them as quickly as possible with one hand each time. This is a 4-minute test for ages 3 and above, which measures fine motor dexterity. In the Grip Strength Test, participants squeeze a hand dynamometer as hard as they can with one hand each time. This is a 3-minute test for ages 3 and above, which measures the upper extremity strength.

2.3. Structural MRI Data Acquisition and Processing

A 3 Tesla Siemens scanner with a 32-channel head coil was implemented to acquire high-resolution T1-weighted structural images with a resolution of 0.7mm^3 isotropic and using the 3D MPRAGE sequence. The scan parameters were TR=2400 msec, TE=2.14 msec, TI= 1000 msec, flip angle= 8 degrees, FOV=224*224 mm, voxel size= 0.7 mm isotropic, BW=210 Hz/Px, acquisition time (min: sec) =7:40. Quality control checks and procedures to ensure high-quality data were performed before the data release, as reported previously [22].

We used an image processing procedure conducted by the HCP-YA research team. The details of the imaging analysis protocol could be found elsewhere [21, 24]. Briefly, a quality checking procedure was first conducted to ensure the high quality of input images. Then, the selected images were imported to FreeSurfer Image Analysis Suite version 5.3 (http://surfer.nmr.mgh.harva) for reconstruction and preprocessing. Processing steps included spatial and intensity normalization and skull stripping. The volumes were segmented into gray matter, white matter, and Cerebrospinal Fluid (CSF). The automatic subcortical segmentation of brain volume was conducted considering an atlas of probabilistic information on the structural locations. Cortical and subcortical volumes were extracted from 24 regions of interest (ROIs) including total brain, total gray matter (GM), total cortical GM, left & right cortical gray matter, subcortical GM, total White Matter (WM), left & right WM, left & right thalamus, left & right caudate, left & right putamen, left & right pallidum, left & right hippocampus, left & right amygdala, left & right accumbens, and CSF volumes.

2.4. Statistical Analysis

In the first step of the analysis, the presence or absence of a correlation between each brain volume and motor function test was determined using the

Spearman correlation coefficient analysis. A p-value<0.05 was set as a statistically significant level.

In the second step, in order to investigate the association of motor functions with brain volume changes, multiple linear regression analyses (adjusted for total intracranial volume (TIV), sex, age, race, education, and BMI) were conducted, considering brain volumes as dependent variables and the four motor function test results as independent variables. All motor function measures were included in the same regression model to independently associate them with the neuroimaging outcomes. All variables except for gender and race were standardized to Z-values before entering the model. Two-tailed hypothesis testing with an alpha level = 0.05 was considered statistically significant. SPSS 27.0 statistical software (SPSS Inc., Chicago, IL, USA) and GraphPad Prism 9.0 (GraphPad Software, San Diego, California, USA) were used to analyze and graph the data.

3. Results

The summary of study population characteristics can be found in Table 1.

3.1. The Correlation between Brain Volumes and Motor Functions

The results of the first step of the study showed that most of the investigated brain volumes had a significant correlation with the motor function scores, except for the Gait speed test. Figure 1 shows the heatmap of these correlations.

In the case of the Endurance test, all of the 24 investigated brain volumes showed a significant positive correlation with the motor function scores ($p < 0.0001$). The highest correlation was found between total GM volume and the Endurance scores ($r = 0.3093$, $p < 0.0001$, Figure 2A).

When assessing the Gait speed test, there was no significant correlation between most of the brain volumes and the test scores ($p > 0.05$). Left pallidum, left accumbens, and right accumbens were the only brain volumes with a significant negative correlation with the Gait speed scores, with right accumbens volume showing the highest correlation ($r = -0.06947$, $p = 0.0223$, Figure 2B).

By investigating the Dexterity test, all of the brain volumes had a significant negative correlation with the test scores ($p < 0.05$), except for the five volumes of left caudate, left putamen, left pallidum, left accumbens, and right putamen. Total brain volume showed the highest correlation with Dexterity test scores ($r = -0.1035$, $p = 0.0006$, Figure 2C).

In the case of the Strength test scores, all of the 24 investigated brain volumes had a significant positive correlation with the test scores ($p < 0.0001$). The highest correlation was found between total brain volume and the Strength scores ($r = 0.5495$, $p < 0.0001$, Figure 2D).

Table 2 indicates the detailed information on the correlation between motor function scores and brain structure volumes

Table 1. Descriptive information on the total sample

Variable	
Sample size	1082
Age, years [mean (SD)]	28.78 (3.68)
Sex, male (%)	495 (45.7)
Race (%)	
White	814 (75.2)
Others	268 (24.8)
Education, years [mean (SD)]	14.95 (1.78)
BMI [mean (SD)]	26.48 (5.13)
Endurance [mean (SD)]	110.31 (11.95)
Gait speed, meters per second [mean (SD)]	1.31 (0.196)
Dexterity [mean (SD)]	112.61 (10.72)
Grip strength [mean (SD)]	116.61 (11.20)

Note: SD, standard deviation; BMI, body mass index

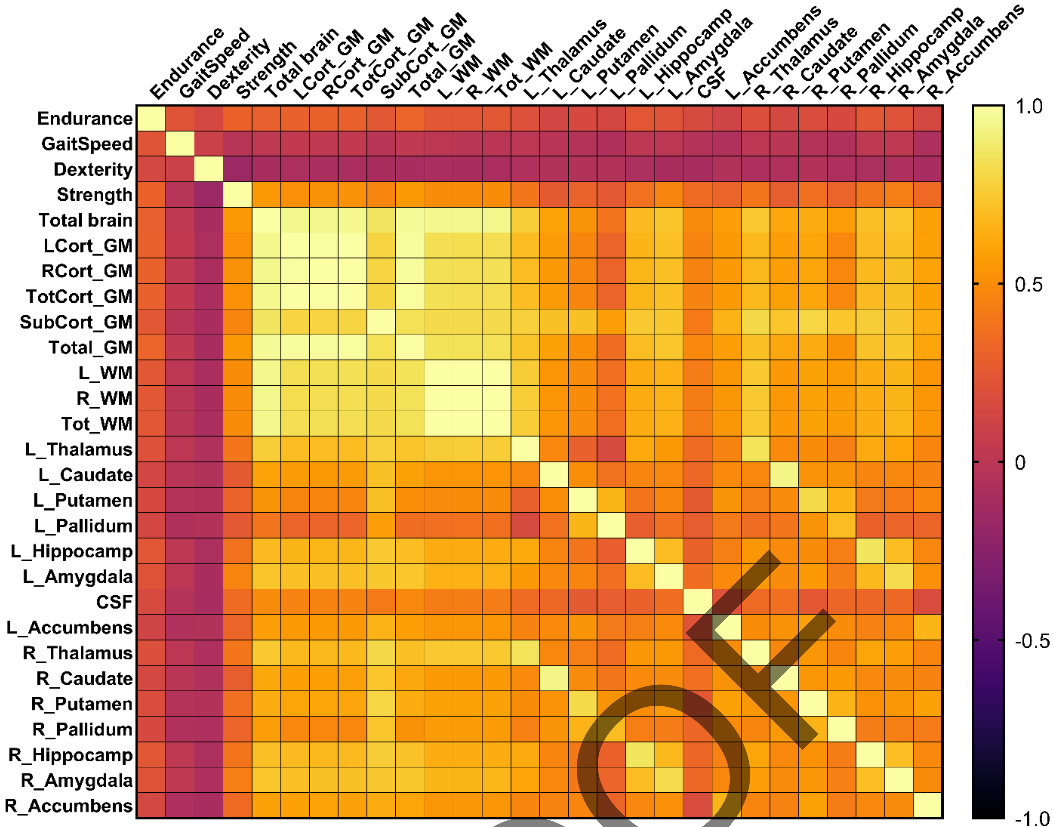

Figure 1. Heatmap of correlation between motor functions and brain structures

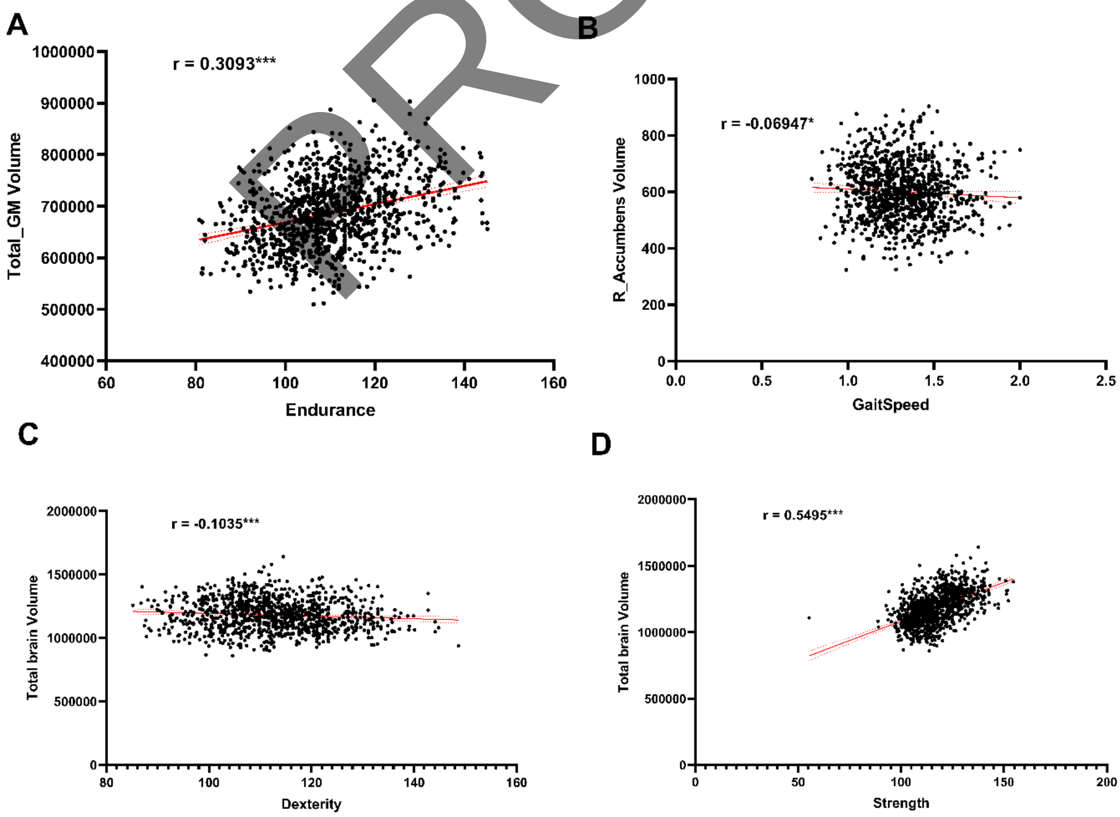

Figure 2. Scatterplots of the correlations between (A) Endurance and total gray matter volume, (B) Gait speed and right accumbens volume, (C) Dexterity and total brain volume, and (D) Strength and total brain volume

Table 2. Correlation of various brain structures' volume with motor function scores (endurance, gait speed, dexterity, and strength) across the subjects, n=1082

Brain volumes	Endurance		Gait Speed		Dexterity		Strength	
	r	p-value	r	p-value	r	p-value	r	p-value
Total brain	0.2860	**<0.0001**	0.01554	0.6096	-0.1035	**0.0006**	0.5495	**<0.0001**
Left cortical GM	0.2863	**<0.0001**	0.03269	0.2827	-0.08094	**0.0077**	0.5130	**<0.0001**
Right cortical GM	0.2914	**<0.0001**	0.02356	0.4389	-0.08453	**0.0054**	0.5182	**<0.0001**
Total cortical GM	0.2877	**<0.0001**	0.02890	0.3423	-0.08377	**0.0058**	0.5163	**<0.0001**
Subcortical GM	0.2372	**<0.0001**	-0.01753	0.5646	-0.09724	**0.0014**	0.4627	**<0.0001**
Total GM	0.3093	**<0.0001**	0.02502	0.4110	-0.1001	**0.0010**	0.5469	**<0.0001**
Left WM	0.2318	**<0.0001**	-0.003731	0.9024	-0.08845	**0.0036**	0.4992	**<0.0001**
Right WM	0.2329	**<0.0001**	-0.005355	0.8603	-0.09031	**0.0029**	0.4995	**<0.0001**
Total WM	0.2325	**<0.0001**	-0.004455	0.8836	-0.08965	**0.0032**	0.4995	**<0.0001**
Left thalamus	0.1988	**<0.0001**	0.001273	0.9666	-0.06057	**0.0464**	0.3982	**<0.0001**
Left caudate	0.1271	**<0.0001**	-0.01411	0.6428	-0.05257	0.0839	0.2531	**<0.0001**
Left putamen	0.1475	**<0.0001**	-0.03916	0.1980	-0.04807	0.1140	0.3015	**<0.0001**
Left pallidum	0.1356	**<0.0001**	-0.06594	**0.0301**	-0.05025	0.0985	0.2451	**<0.0001**
Left hippocampus	0.2303	**<0.0001**	0.01121	0.7125	-0.08223	**0.0068**	0.3732	**<0.0001**
Left amygdala	0.2062	**<0.0001**	0.001952	0.9489	-0.09324	**0.0021**	0.4609	**<0.0001**
CSF	0.1557	**<0.0001**	-0.04100	0.1778	-0.1008	**0.0009**	0.3420	**<0.0001**
Left accumbens	0.1078	**0.0004**	-0.06140	**0.0435**	-0.05688	0.0614	0.3115	**<0.0001**
Right thalamus	0.1853	**<0.0001**	0.002983	0.9219	-0.06939	**0.0224**	0.3944	**<0.0001**
Right caudate	0.1376	**<0.0001**	-0.007020	0.8176	-0.06125	**0.0440**	0.2711	**<0.0001**
Right putamen	0.1703	**<0.0001**	-0.03564	0.2415	-0.05089	0.0943	0.3574	**<0.0001**
Right pallidum	0.1478	**<0.0001**	-0.05946	0.0505	-0.07346	**0.0156**	0.3041	**<0.0001**
Right hippocampus	0.2379	**<0.0001**	0.01544	0.6120	-0.08065	**0.0080**	0.3918	**<0.0001**
Right amygdala	0.2027	**<0.0001**	0.01203	0.6926	-0.07188	**0.0180**	0.4282	**<0.0001**
Right accumbens	0.1441	**<0.0001**	-0.06947	**0.0223**	-0.09819	**0.0012**	0.3387	**<0.0001**

Note: GM, gray matter; WM, white matter; CSF, cerebrospinal fluid; **Bold values indicate statistically significant**

3.2. The Impact of Motor Functions on Brain Structures

In the second step of the study, we investigated how different motor functions independently impact the brain structure volume changes by employing linear regression models. The motor functions that showed a significant correlation in the previous step were selected as inputs of the regression models. Due to the nonsignificant correlation between the Gait speed scores and volumes in most brain structures, this motor function test was excluded from further analysis. Therefore, the scores of the three motor functions of Endurance, Dexterity, and Strength were imported to the models.

Three models were developed to assess the association of motor functions and brain structure changes. In the first model (Model 1), endurance, dexterity, and strength scores were imported to the model as independent variables, and each brain volume was considered as the dependent variable. Also, Model 1 was adjusted for TIV to minimize the impact of different skull sizes of the population. For the second model (Model 2), the variables age, sex, race, and education were also added to the model as covariates, and the results were adjusted for them. The last model (Model 3) was further adjusted for the variable BMI to investigate whether the difference in BMI in the population can have a significant impact on motor function scores and their association with brain structure changes.

By considering the endurance test, there were significant associations between the test scores and total brain ($\beta = 0.042$, standard error (SE) = 0.014, $p < 0.01$), left cortical GM ($\beta = 0.060$, SE = 0.018, $p < 0.001$), right cortical GM ($\beta = 0.066$, SE = 0.017, $p < 0.001$), total cortical GM ($\beta = 0.063$, SE = 0.017, $p < 0.0001$), total GM ($\beta = 0.076$, SE = 0.015, $p < 0.0001$), left hippocampus ($\beta = 0.055$, SE = 0.026, $p < 0.05$), and right hippocampus ($\beta = 0.065$, SE = 0.025, $p < 0.01$) volumes. However, when adjusting for other covariates, only total GM volume ($\beta = 0.036$, SE = 0.016, $p < 0.05$ and $\beta = 0.035$, SE = 0.016, $p < 0.05$ for models 2 and 3, respectively) remained significant. Surprisingly, there was no significant association with left accumbens in the first model, but when adjusting for other covariates in models 2 and 3, the association was negatively significant (β = -0.060, SE = 0.030, p < 0.05 and β = -0.072, SE = 0.031, p < 0.05 for models 2 and 3, respectively).

By assessing the dexterity test, there were no significant associations between the test scores and any of the brain volumes. On the other hand, when considering the strength test, there were significant associations between the test scores and total brain (β = 0.099, SE = 0.015, p < 0.001), left cortical GM (β = 0.078, SE = 0.019, p < 0.001), right cortical GM (β = 0.081, SE = 0.019, p < 0.001), total cortical GM (β = 0.080, SE = 0.019, p < 0.001), subcortical GM (β = 0.071, SE = 0.022, p < 0.01), total GM (β = 0.092 SE = 0.017, p < 0.001), left WM (β = 0.103, SE = 0.020, p < 0.001), right WM (β = 0.104, SE = 0.020, p < 0.001), total WM (β = 0.103, SE = 0.020, p < 0.001), left thalamus (β = 0.083, SE = 0.027, p < 0.01), left putamen (β = 0.073, SE = 0.032, p < 0.05), left hippocampus (β = 0.063, SE = 0.029, p < 0.05), left amygdala (β = 0.142, SE = 0.027, p < 0.001), CSF (β = 0.061, SE = 0.030, p < 0.05), left accumbens (β = 0.092, SE = 0.032, p < 0.01), right thalamus (β = 0.081, SE = 0.027, p < 0.01), right putamen (β = 0.093, SE = 0.030, p < 0.01), right hippocampus (β = 0.062, SE = 0.028, p < 0.05), right amygdala (β = 0.083, SE = 0.028, p < 0.01), and right accumbens (β = 0.104, SE = 0.032, p < 0.01) volumes. However, when adjusting for other covariates, only the volumes total brain (β = 0.043, SE = 0.019, p < 0.05 and β = 0.045, SE = 0.020, p < 0.05 for models 2 and 3, respectively), left WM (β = 0.055, SE = 0.024, p < 0.05 and β = 0.058, SE = 0.025, p < 0.05 for models 2 and 3, respectively), right WM (β = 0.053, SE = 0.024, p < 0.05 and β = 0.056, SE = 0.025, p < 0.05 for models 2 and 3, respectively), and total WM (β = 0.054, SE = 0.024, p < 0.05 and β = 0.057, SE = 0.025, p < 0.05 for models 2 and 3, respectively) remained significant.

Overall, the six volumes of total brain, total GM, left WM, right WM, total WM, and left accumbens were found to be significantly associated with motor functions even after adjusting for all other covariates. Table 3 includes the detailed information on the association between motor function scores and brain structure volume changes.

4. Discussion

This study aimed to investigate the relationship between motor functions, measured through endurance, dexterity, and strength tests, and brain structural volumes in a large number of healthy young adults. The results revealed significant associations between motor functions and cortical as well as subcortical brain volumes, with endurance and strength showing the most notable correlations. These findings provide insight into the role of physical fitness in supporting brain health, even in young adulthood.

Previous research has often focused on the effects of physical activity on brain structure in older adults, primarily to prevent or delay neurodegenerative diseases such as Alzheimer's and dementia [1, 25]. Our study, however, shifts this focus to a younger population, showing that motor functions related to physical fitness can also influence brain volumes at an earlier age. This suggests that promoting physical fitness in young adulthood may be beneficial for brain health over the long term, potentially slowing brain aging or reducing the risk of cognitive decline later in life [4].

The significant positive correlations we observed between endurance and strength test scores with total GM and WM volumes align with earlier studies showing that physical activity is associated with larger brain volumes, particularly in regions critical for memory and cognitive function, such as the hippocampus [12]. This finding supports the hypothesis that higher levels of physical fitness might maintain brain structure, reinforcing the importance of physical activity as a means to improve overall brain health, even outside the context of aging populations [20].

Our study also showed that gait speed, a common marker of motor function in older populations, did not correlate significantly with brain volumes in our young cohort. This could suggest that gait speed, while valuable in predicting age-related decline, may not be a sensitive indicator of brain health in younger adults. The lack of significant findings for the gait speed test might be expected given the young age of the participants, who typically do not exhibit the gait impairments seen in older adults. This is consistent

Table 3. Association between brain structures volume and motor function scores, n=1082

Brain Volumes *(Dependent)*	**Motor Functions** *(Independent)*	**Model 1**	**Model 2**	**Model 3**
		Beta Coefficient ***(SE)***	**Beta Coefficient** ***(SE)***	**Beta Coefficient** ***(SE)***
Total brain	Endurance	**0.042 (0.014)****	0.022 (0.015)	0.020 (0.015)
	Dexterity	0.003 (0.013)	0.015 (0.014)	0.014 (0.014)
	Strength	**0.099 (0.015)*****	**0.043 (0.019)***	**0.045 (0.020)***
Left cortical GM	Endurance	**0.060 (0.018)*****	0.027 (0.018)	0.027 (0.019)
	Dexterity	0.008 (0.017)	0.011 (0.017)	0.012 (0.017)
	Strength	**0.078 (0.019)*****	0.037 (0.024)	0.037 (0.024)
Right cortical GM	Endurance	**0.066 (0.017)*****	0.031 (0.018)	0.032 (0.019)
	Dexterity	0.005 (0.017)	0.010 (0.016)	0.011 (0.017)
	Strength	**0.081 (0.019)*****	0.034 (0.023)	0.033 (0.024)
Total cortical GM	Endurance	**0.063 (0.017)*****	0.029 (0.018)	0.029 (0.019)
	Dexterity	0.006 (0.017)	0.011 (0.016)	0.011 (0.017)
	Strength	**0.080 (0.019)*****	0.036 (0.023)	0.035 (0.024)
Subcortical GM	Endurance	0.029 (0.020)	0.005 (0.021)	0.005 (0.022)
	Dexterity	0.001 (0.019)	0.013 (0.019)	0.014 (0.020)
	Strength	**0.071 (0.022)****	- 0.003 (0.028)	- 0.003 (0.028)
Total GM	Endurance	**0.076 (0.015)*****	**0.036 (0.016)***	**0.035 (0.016)***
	Dexterity	- 0.001 (0.015)	0.005 (0.014)	0.005 (0.015)
	Strength	**0.092 (0.017)*****	0.038 (0.021)	0.039 (0.021)
Left WM	Endurance	- 0.002 (0.018)	0.002 (0.018)	- 0.002 (0.019)
	Dexterity	0.016 (0.017)	0.030 (0.017)	0.029 (0.017)
	Strength	**0.103 (0.020)*****	**0.055 (0.024)***	**0.058 (0.025)***
Right WM	Endurance	- 0.001 (0.018)	0.003 (0.019)	0.000 (0.019)
	Dexterity	0.016 (0.017)	0.030 (0.017)	0.029 (0.017)
	Strength	**0.104 (0.020)*****	**0.053 (0.024)***	**0.056 (0.025)***
Total WM	Endurance	- 0.002 (0.018)	0.002 (0.018)	- 0.001 (0.019)
	Dexterity	0.016 (0.017)	0.030 (0.017)	0.029 (0.017)
	Strength	**0.103 (0.020)*****	**0.054 (0.024)***	**0.057 (0.025)***
Left thalamus	Endurance	0.002 (0.024)	- 0.007 (0.025)	- 0.007 (0.027)
	Dexterity	0.024 (0.023)	0.026 (0.024)	0.026 (0.024)
	Strength	**0.083 (0.027)****	0.062 (0.033)	0.061 (0.034)
Left caudate	Endurance	- 0.006 (0.027)	- 0.016 (0.028)	- 0.003 (0.030)
	Dexterity	0.015 (0.026)	0.012 (0.026)	0.016 (0.026)
	Strength	- 0.042 (0.030)	- 0.035 (0.037)	- 0.046 (0.038)
Left putamen	Endurance	0.010 (0.029)	0.003 (0.030)	0.004 (0.031)
	Dexterity	0.002 (0.027)	0.020 (0.028)	0.021 (0.028)
	Strength	**0.073 (0.032)***	- 0.018 (0.039)	- 0.018 (0.040)
Left pallidum	Endurance	0.023 (0.030)	0.028 (0.031)	0.030 (0.033)
	Dexterity	0.002 (0.029)	0.021 (0.029)	0.021 (0.029)
	Strength	0.045 (0.033)	- 0.039 (0.041)	- 0.040 (0.042)
Left hippocampus	Endurance	**0.055 (0.026)***	0.008 (0.027)	0.008 (0.029)
	Dexterity	- 0.007 (0.025)	- 0.001 (0.025)	0.000 (0.025)
	Strength	**0.063 (0.029)***	0.010 (0.036)	0.011 (0.037)
Left amygdala	Endurance	0.020 (0.024)	- 0.023 (0.025)	- 0.016 (0.026)
	Dexterity	- 0.008 (0.023)	0.020 (0.023)	0.023 (0.023)
	Strength	**0.142 (0.027)*****	- 0.009 (0.033)	- 0.014 (0.033)
CSF	Endurance	- 0.005 (0.027)	- 0.019 (0.029)	- 0.004 (0.030)
	Dexterity	- 0.026 (0.026)	- 0.017 (0.027)	- 0.013 (0.027)
	Strength	**0.061 (0.030)***	0.006 (0.038)	- 0.006 (0.038)
Left accumbens	Endurance	- 0.018 (0.029)	**- 0.060 (0.030)***	**- 0.072 (0.031)***
	Dexterity	0.006 (0.027)	0.012 (0.028)	0.008 (0.028)
	Strength	**0.092 (0.032)****	0.033 (0.039)	0.044 (0.040)

Right thalamus	**Endurance**	**- 0.007 (0.024)**	**- 0.012 (0.026)**	**- 0.014 (0.027)**
	Dexterity	0.013 (0.023)	0.022 (0.024)	0.021 (0.024)
	Strength	**0.081 (0.027)****	0.040 (0.034)	0.040 (0.035)
	Strength	**0.093 (0.030)****	- 0.039 (0.037)	- 0.033 (0.037)
	Strength	**0.083 (0.028)****	- 0.047 (0.034)	- 0.045 (0.035)
Right caudate	Endurance	0.007 (0.026)	- 0.008 (0.028)	0.010 (0.029)
	Dexterity	- 0.003 (0.025)	- 0.003 (0.026)	0.003 (0.026)
	Strength	- 0.047 (0.029)	- 0.059 (0.037)	- 0.073 (0.037)
Right putamen	Endurance	0.023 (0.027)	0.000 (0.028)	- 0.007 (0.029)
	Dexterity	0.003 (0.026)	0.027 (0.028)	0.024 (0.026)
	Strength	**0.093 (0.030)****	- 0.039 (0.037)	- 0.033 (0.037)
Right pallidum	Endurance	0.004 (0.028)	0.013 (0.029)	0.018 (0.030)
	Dexterity	- 0.013 (0.027)	- 0.002 (0.027)	0.000 (0.027)
	Strength	0.037 (0.031)	- 0.008 (0.038)	- 0.012 (0.039)
Right hippocampus	Endurance	**0.065 (0.025)****	0.016 (0.026)	0.010 (0.027)
	Dexterity	- 0.004 (0.024)	0.008 (0.024)	0.006 (0.024)
	Strength	**0.062 (0.028)***	- 0.018 (0.034)	- 0.012 (0.035)
Right amygdala	Endurance	0.013 (0.025)	- 0.026 (0.026)	- 0.027 (0.027)
	Dexterity	0.004 (0.024)	0.027 (0.024)	0.027 (0.024)
	Strength	**0.083 (0.028)****	- 0.047 (0.034)	- 0.045 (0.035)
Right accumbens	Endurance	0.013 (0.029)	- 0.015 (0.030)	- 0.024 (0.031)
	Dexterity	- 0.037 (0.027)	- 0.028 (0.028)	- 0.030 (0.028)
	Strength	**0.104 (0.032)****	0.038 (0.039)	0.046 (0.040)

Note: GM, gray matter; WM, white matter; CSF, cerebrospinal fluid; SE, standard error. Model 1: adjusted for total intracranial volume. Model 2: Model 1 + age (years), sex, race, education (years). Model 3: Model 2 + body mass index (kg/m2). **Bold values indicate statistically significant (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$)**.

with previous research indicating that gait speed is more predictive of brain atrophy in elderly populations [14, 26, 27]. Young adults generally have higher and more consistent gait speeds, which may result in less variability in this measure and, consequently, less sensitivity in detecting differences in brain volumes. Additionally, the physical and cognitive demands of maintaining gait speed may be less pronounced in younger individuals compared to older adults [26]. This could mean that gait speed in young adults is not as strongly influenced by brain structural changes, which tend to be more subtle in this age group. Future longitudinal studies are needed to determine whether changes in gait speed at a younger age could predict brain volume reductions as individuals age.

Interestingly, dexterity scores were negatively correlated with brain volumes, a finding that diverges from the positive correlations seen with endurance and strength. This could be due to the complex neural circuits involved in fine motor skills, which may not directly correspond to changes in brain volume but rather reflect intricate patterns of neural connectivity and plasticity [16]. Young adults typically have more robust neural networks and less variability in brain structure compared to older adults or individuals with neurological conditions [28]. This could result in a negative correlation where higher dexterity is associated with more efficient but not necessarily larger brain volumes. Moreover, fine motor skills require precise coordination and control of small muscle groups, which involve more specialized and localized brain regions compared to gross motor skills [29]. Therefore, the negative correlation might indicate that individuals with higher dexterity have more efficient neural networks that do not necessarily translate to larger overall brain volumes. Further research is needed to explore the distinct brain mechanisms that govern fine motor skills compared to gross motor functions.

Recent studies have further emphasized the relationship between motor functions and brain structure. For instance, a review highlighted the combined use of diffusion MRI and EEG to assess structural and functional connectivity, noting that higher structural connectivity often correlates with increased event-related EEG activity [30]. Similarly, another review focused on the impact of physical activity on cognitive functioning and found that motor activity during developmental stages is crucial for physical and mental growth, suggesting that early motor activity can have long-term benefits on brain health [31]. Additionally, research on motor awareness has shown that various components of motor awareness, such as motor intention and monitoring, are supported by specific brain regions, including the parietal and insular cortices, and subcortical structures [32]. These findings align with our results, reinforcing the importance of physical fitness in maintaining brain structure and function across different age groups.

This study has limitations, most notably its cross-sectional design, which limits our ability to establish causality between motor functions and brain volume changes. Additionally, factors such as diet, sleep, and lifestyle were not controlled in our analysis and could have influenced the results. Longitudinal studies that track motor functions and brain structural changes over time would provide more definitive insights into these relationships.

5. Conclusion

In conclusion, our findings demonstrate that motor functions, particularly endurance and strength, are significantly associated with structural brain changes in healthy young adults. Promoting physical fitness in early adulthood could be key to maintaining brain health and preventing future cognitive decline. Future research should explore these relationships further and investigate the underlying mechanisms driving the observed associations.

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