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Allometrically scaled explosive strength, but not static strength or maximal oxygen uptake is associated with better central processing time in young males

Short title: Physical fitness in relation to cognition

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ABSTRACT

BACKGROUND: We aimed to examine the associations of cardiorespiratory fitness (CRF), static strength and explosive strength with cognitive functions in young males.

METHODS: Eighty-six young males (age 16–24 years) participated in the study and took part in a number of tests including: static strength (grip strength test), explosive strength (Sargent jump test), and CRF (via direct measure of maximal oxygen uptake (VO_{2max})). Static strength and explosive strength were scaled by allometrically modeled skeletal muscle mass (SMM) and height while VO_{2max} was scaled by SMM and body mass (BM). Cognition was assessed by inhibitory control, simple and choice reaction time tasks using computerized Cambridge Neuropsychological

Test Battery (CANTAB). Central processing time was measured by surface electromyography changes in isometric contraction response to an audio stimulus.

RESULTS: VO_{2max} scaled by BM (but not SMM), was associated with better central processing time and stop-signal reaction time (SSRT). Explosive strength was also associated with better central processing time independent of VO_{2max}. However, static strength was not associated with cognition.

CONCLUSION: The results suggest that explosive strength is a better predictor of central processing than static strength or VO_{2max} in young males. Longitudinal studies are needed to examine whether explosive strength training in youth would improve central processing time.

Physical fitness is as a powerful marker of health related outcomes and a prospective determinant of current and future health status both in childhood and adulthood.[1,2] Likewise, there is evidence that physical fitness components including cardiorespiratory fitness (CRF) and muscular strength are independently associated with cardio-metabolic health in young people.[3] A body of evidence suggests they are also associated with cognitive function in adults.[4-7] Cognitive function, like being able to inhibit impulsive behavior or to process information quickly, are prerequisites for academic achievement and independent living at old ages.[8-12] Better understanding of how different components of fitness are associated with cognitive abilities is needed to support individual development at young ages. However until now, no study has investigated theses independent associations.

Several studies have shown that CRF is directly associated with cognition in prepubertal children and older adults.[4,13] However, the association between CRF and cognitive function in adolescents and young adults (18-35 years), when the brain is in its peak development,[14,15] has been less explored and findings are inconsistent.[14-17] Methodological reasons for this inconsistency may include small sample size, indirect measures or self-reported CRF, or failing to control for potential covariates in the analysis.[14,18,19]

Similarly, there is uncertainty concerning the association between muscular strength and cognitive function. Although static strength (measured by grip strength) is associated with cognitive functioning in middle aged and older people, [5,6] previous studies have failed to observe this in young participants. [19-21] Instead, explosive strength seems to be a stronger predictor of both simple and higher-level cognitive functioning tasks (e.g. RT and inhibitory control) compared to static strength. [7,19] Therefore, different muscular fitness variables might vary in importance concerning cognitive functioning at youth and should be investigated further.

Different cognitive tasks can be used to assess cognitive processing capabilities. RT is a cognitively simple test depicting an individual's information processing speed. [8-10] RT can be further divided into two fractionated parts including, central visuomotor (premotor or central processing time) and peripheral motor processes (motor time). The central processing time or premotor time (PMT) can be measured by recording surface electromyography (EMG) signal during isometric contraction in response to a stimulus. [22] The time between the onset or offset of the response signal in relation to the initial or terminal EMG activity can determine PMT. [22] PMT is a more sensitive measure of RT than the overall RT, since it is a direct measurement of the central processing time and provides more information of processing speed. [23-26]

Inhibitory control is a higher-level cognitive functioning task, which depicts a capacity to prevent dominant or habitual responses to a stimulus. [11] Stopping at traffic lights or avoiding impulsive behavior are examples of inhibitory control that are needed in everyday life. [12]

CRF is strongly associated with tasks requiring higher level of cognition such as inhibitory control, as compared to cognitively less demanding tasks such as reaction time (RT). [4,13,17,27] However, it is unclear if CRF is associated with the different components of RT (i.e. PMT).

One important consideration when exploring the association between physical fitness and cognitive function is normalizing fitness records using body size and composition. [28-30] Scaling CRF and muscular strength inappropriately have obscured our understanding of the relationship between fitness and cognition. For example, normalizing maximal oxygen uptake (VO_{2max}) or muscle strength with body mass (BM) introduces bias, as such approach is confounded by body size and composition. [28-31]

Considering these methodological aspects improves our understanding of how specific fitness components are associated and can be potentially used to improve, some aspects of cognitive processing already at a young age.

The present study has two aims; the first is to examine the independent associations between CRF, static strength and explosive strength with cognitive function after adjustment of covariates (i.e. age, socioeconomic status, adiposity, daily physical activity, and depression). The secondary aim is to examine whether tasks requiring a different degree of cognitive processing and sensitivity are associated with CRF, static strength or explosive strength in young males. Since these variables are influenced by body size and composition, we used several statistically sound allometric scaling procedures.

Materials and methods

Participants and Procedures

Eighty-six young males (age 16–24 years) participated in the study. To ensure the inclusion of subjects with a broad range of CRF levels participants were recruited from general participant's pools (i.e., public libraries, public high schools, and University of Mohaghegh Ardabili, Ardabil, Iran). Two participants were excluded from the study due to failure to meet inclusion criteria (e.g., reporting musculoskeletal problems or chronic diseases, heart or lung diseases, using medications, smoked more than half a pack of cigarettes per day or not interested in participating). One participant was excluded from the data analysis due to failure to meet criteria for valid VO_{2max} and EMG RT data. Three participants were excluded at the data analysis stage due to inappropriate EMG signal, misses, or anticipations. The final sample included 80 young males aged 16-24 years. Participants charactheristics are presented in Table 1. Participants provided written informed consent, and the study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Mohaghegh Ardabili University.

Data were collected between June-July 2018 in the course of 6 weeks in a physiological test lab at the University of Mohaghegh Ardabili. Each participant visited the lab twice. During the first visit (9-a.m to14.30-p.m) participants were familiarised with the procedures of the study and participants'demographic characteristics, blood pressure (BP) and body composition data were

recorded. Participants were instructed to shave for EMG electrode placement. Furthermore, they were requested to avoid food and caffeine-containing beverages 3-4 hours before the measurements. They were also recommended to avoid vigorous PA at least 24 hours before the measurements, and to wear appropriate clothing (e.g., shorts or pants and running shoes) for the physical tests on the second visit. Data collection of cognitive tests, surface EMG analysis of RT (EMG RT), muscle strength and CRF were performed on the second visit (24 hours later from the first visit).

Anthropometry

Height was measured barefoot in the Frankfurt horizontal plane with a telescopic height measuring instrument (Type SECA 225) to the nearest 1 mm. BM, skeletal muscle mass (SMM) and body fat percentage (BF%) were measured by using an X-Contact 356 body composition analyzer (Jawon Medical, South Korea). Body mass index (BMI) was calculated as body weight in kilograms divided by the square of height in meters (kg/m^2).

Cardiorespiratory Fitness (CRF) Test

CRF was measured using a maximal graded exercise running test (GXT). The test was performed on a treadmill (hp/cosmos, Mercury Med, Germany) using the modified Bruce ramp protocol. [32] Gas exchange measurement during the GXT was performed breath-by-breath using the Ergo-Spirometry analyzer (Ganshorn, Medizin Electronic, GmbH, PowerCube system, Germany). VO_{2max} was recorded as the greatest mean value determined breath-by-breath during 10 consecutive seconds and confirmed if two of three criteria of VO_{2max} were met. [33]

Static strength

Static strength was assessed by the handgrip strength test using a digital hand dynamometer (Saehan, DHD-3, SH1003, Korea) with an electronic zero calibration system. The test has been validated and has a strong positive correlation with upper and lower body static strength ($r = 0.736$ to 0.890). [34] Grip strength test was measured in a sitting position with shoulder adduction, wrist and forearm in a neutral position and elbow at 90° flexion. Participants were asked to squeeze the dynamometer as forcefully as possible and performed the test twice for each hand with one minute rest time between trials. The best scores of the right and left hands were recorded and averaged.

Explosive strength

The vertical jump (VJ) or Sargent Jump was used to measure explosive strength. This test has been shown as a reliable field-based test to measure explosive strength in the young. [35,36] Reliability studies have indicated high correlation coefficients for the Sargent Jump test (r= 0.93). [37]

Participants were asked to stand next to a wall with a right upper arm extended upwards above the head. First, the highest reaching point was marked with chalk powder. Secondly, participants were asked to jump as high as possible and mark another chalk mark to the wall. Before the jump participants were requested to keep their arms straight and on their sides. The score was recorded as a difference between the first mark and the second mark in centimeters. The test was performed three to four times and included a 1 min rest after each trial and the highest jump was retained (in cm).

Allometric scaling of physical fitness

Allometric scaling of physical fitness was performed using the log-linear regression model with age and log-transformed SMM or height as the independent variables and log-transformed absolute fitness record (VO_{2max}, static or explosive strength) as the dependent variable. [28-31] Allometrically scaled VO_{2max} using SMM is considered the gold standard measure. [29,31] However, for static and explosive strength not only SMM, but also height was used for scaling. [28,30] The following allometric equation [Fitness= Y/Xb], where "b" is the scaling exponent, and "X" is the anthropometric scaling variable (height or SMM).

1) Allometric scaling of VO_{2max}: Weak and negligible association was observed between VO_{2max} (ml kg SMM^{-1} Min^{-1}) with SMM (β=-0.01, p=0.94), showing the validity of SMM in scaling VO_{2max}.

2) Allometric scaling of static strength: Weak association was observed between grip strength (cm $height^{-1}$) with height (β= 0.06, *p*=0.56), showing the validity of height in scaling of grip strength. A negative association was observed between grip strength (kg SMM^{-1}) with SMM (β= -0.22, *p*=0.05), showing the inability of ratio scaling by SMM to remove the effect of SMM on grip strength. The scaling exponent for SMM was found to be 0.72. The determined allometric model was able to disappear the relationship between grip strength (kg $SMM^{-0.72}$) and SMM (β= -0.02, *p*=0.84), which show its validity in scaling static strength.

3) Allometric scaling of VJ: Weak association was observed between VJ (cm $height^{-1}$) with height (β= 0.02, *p*=0.86), showing the validity of height in scaling of VJ. However, a strong

negative association was observed between VJ (cm SMM^{-1}) with SMM (β= -0.59, p< 0.001), showing the inability of ratio scaling by SMM to remove the effect of SMM on VJ. The scaling component for SMM was found -0.20. The determined allometric model was able to disappear the relationship between VJ (cm $SMM^{0.20}$) with SMM (β= -0.02, p=0.83), which shows its validity in scaling VJ.

Assessment of computerized RT and inhibitory control tests

Computerized RT and inhibitory control were assessed using the Cambridge Neuropsychological Test Battery (CANTAB) [38] in a touch screen PC (ASUS, ET2012EUTS - 20.1 inches). The following parameters were measured: 1) Motor Screening Task (MST), 2) Simple and five-choice RT (SRT and 5-CRT, respectively) (performed using the touch screen), and 3) Two-choice RT (performed using keyboard buttons) 4) Stop Signal task (SST) for measuring inhibitory control. The tests lasted approximately 40 minutes and had a 2 min break between.

1) Motor screening test: The motor screening test as an introductory task to familiarize participants with the study procedures. In the MST a pink cross appeared on a black touch screen and participants were requested to touch the centre of the cross with the dominant hand.

2) Simple and five choices RT: Participants must hold their fingers in a rectangle in the touch screen until the yellow circle appears on the screen above the rectangle. The stimulus (yellow circle) appears in either a single (SRT) or one of five possible locations (5-CRT). Then, participants must release their fingers upon detecting the yellow circle presentation and immediately afterwards touch the screen where the yellow circle appeared. Single stimulus (SRT) condition is identified first, and five stimuli (5-CRT) is identified in the second condition.

3) Two-choice RT (2-CRT): The test has two possible stimuli (left and right), and participants need to respond with two possible options (left and right buttons). They must press the right button (i.e., F8) on the keyboard when the stimuli (an arrow-shaped) is displayed on the right-hand side of the screen; and press the left button (i.e., F7) on the keyboard when the stimuli are displayed on the left-hand side of the screen.

4) Stop Signal Task (SST): Response inhibition was measured by the SST, a unique version of a classic approach to measuring response inhibition. A two-choice button box was presented on the screen and participants were requested to respond to an arrow stimulus, by touching one of

the two boxes depending on the direction in which the arrow points. In this regard, participants touched the right box on the touch screen as quick as possible with his index finger of the right hand when showed with a right-pointing arrow and vice versa for a left-pointing arrow with his index finger of the left hand. However, for 25% of trials participants were presented with an auditory stop signal after showing the arrow (go signal) and instructed to respond as quickly as possible except for those trials containing the auditory stop signal (a beep sound) in which they were required to stop to response. Each participant completed five blocks and a feedback screen presented of their performance. The analyzed measures included: the mean stop signal reaction time (SSRT) which is the mean time in which a person is able to inhibit the pre-potent response successfully; and the mean reaction time on go trials (Go RT) which is the mean time passed until a person touch the related button box on the screen when there is no stop signal.

Electromyographic analysis of RT (EMG RT) for measuring premotor time (PMT)

Extensor carpi radialis electromyographic activity was used for measuring RT in initiation and termination during isometric contraction. Surface EMG electrodes were placed over the belly of the extensor carpi radialis to record isometric wrist extension. Participants dominant forearm and hand were placed on an armchair (special $60 \times 12cm$ wooden arms) and fixed with belts (to stabilize wrist). All participants performed wrist extension with a total time of one min. EMG activity was recorded with portable wireless surface EMG sensor, Biometrics Ltd., LE230, UK Before starting, participants were requested to do wrist extension as quickly and forcefully as possible against the confinement of the devices in response to an audible beep and to relax their muscle as fast as possible as soon as the beep sound finished. The auditory beep signal comprised a total of six audio signals consisting of three trials of 3-second contractions and three trials of 6-second contractions. To minimize the participants' anticipation, the auditory beep signals were introduced as follows: 1) the sounds were presented in a balanced random order 2) the time between sounds (beep) was also randomized to be either 3, 5 or 6 seconds. The audio beep signals were presented with the same sound volume for all participants to remove the confounding effects of intensity. [39] The recorded EMG activities were saved in the personal computer for visual detection of the delay in initiation or termination of contraction. Visual detection has been shown to correlate very highly with computer-based techniques (r= 0.999); however, with higher reliability. [40] In this method, delay in initiation or termination of the EMG signal was defined as the time interval between the onset or offset of the auditory beep signal and onset or offset of the

EMG signal. The EMG signal was sampled at 1000-Hz, and band-pass filtered between 10-490 HZ, and amplified (common-mode rejection ratio higher than 96dB at 60Hz, and total gain=1000), and was processed through Lab View software (2015v15.0). The analyzed measures included 12 onsets and offset RT which by averaging were decreased to four onsets and offset RTs as follows: 1) Mean RT in initiation of 3 second contractions (Onset3), 2) Mean RT in termination of 3 seconds contractions (Offset3), 3) Mean RT in initiation of 6 second contractions (Onset6), 4) Mean RT in termination of 6 second contractions (Offset6).

Covariates

The following covariates were considered: blood pressure, socioeconomic status (SES), daily physical activity (PA) and depressive symptoms. Blood pressure (BP) was measured using standard mercury sphygmomanometers (Model 1002/Presameter, Riester, Germany) three times and averaged. SES was computed from parents' educational and occupational status using a questionnaire [41]. Long form International Physical Activity Questionnaire (IPAQ) was used as a standardized measure for measuring PA in the previous week across several lifestyle domains. [42] The Beck Depression Inventory-II (BDI-II) was used as a valid measure of depressive symptoms. [43]

Statistical analyses

Data were checked for normality and outliers by using the Kolmogorov–Smirnov test and boxplots and histogram. All independent values except for total-PA showed normal distribution, therefore, natural log transformation data of total-PA was applied. Furthermore, although Offset3, SRT, and 5-CRT showed non-normal distribution, none of them showed substantial skewness and kurtosis (i.e., >+2 or <-2), and according to Tabachnick & Fidell, [44] the variables could be included in the factor analysis with the other variables.

Factor analysis was used to decrease the numbers of dependent variables. Computerized RT (SRT; 5-CRT; 2-CRT), and EMG RT (onset3; offset3; onset6; offset6) yielded a total of two factors including: 1) PMT and 2) RT with Varimax rotation and principal components analysis (Table 2).

Cognitive function were compared between fitness groups categorized according to median. Therefore, participants were divided into "unfit" or "fit" group according to the median scores of the CRF, static strength or explosive strength data ("fit"= fitness record >50% or "unfit"= fitness

record ≤50%). Multivariate analysis of covariance (MANCOVA) by adjusting for age, blood pressure, SES, depressive symptoms, BF%, and total-PA was conducted for comparison of cognitive functioning tasks between the CRF groups. Independent association between static or explosive strength with cognitive function was analyzed using MANCOVA and adjusted for age, blood pressure, SES, depressive symptoms, BF%, total-PA and VO_{2max} (ml kg SMM^{-1} min^{-1}). LSD post hoc test was used for multiple comparisons. Cohen's [45] d (i.e. negligible for $|d| < 0.2$; small for $0.2 \leq |d| < 0.5$; medium for $0.5 \leq |d| < 0.8$; and large for $|d| \geq 0.8$) was calculated based on the partial η^2 statistics to interpret the magnitude of the effect size. Assuming a power of 0.80, and an alpha of 0.05, it was estimated that a sample of 80 was required for comparison with four groups. [46] All calculations were performed using SPSS v.21.0 software for Windows (IBM, Corp., Armonk, NY, USA). Statistical significance was set at $p \leq .05$.

Table 1. Characteristics of the participants (n=80)

Variables		Mean (SD)
Demographics and physiological	Age (year)	19.2 (3.3)
	SES (score)	11.3 (4.1)
	Height (cm)	179.3 (6.5)
	BM (kg)	75.1 (15.9)
	BMI (kg/m^2)	23.2 (5.1)
	BF%	16.9 (8.4)
	SMM (kg)	
	Systolic blood pressure (mm Hg)	113.3 (13.2)
	Diastolic blood pressure (mm Hg)	74.1 (10.4)
	Total PA (MET-min/week)	7375.0 (4245.7)
	BDI-II (score)	10.1 (7.4)
Raw and allometric scaling of physical fitness	VO_{2max} (ml kg BM^{-1} min^{-1})	39.6 (5.9)
	VO_{2max} (ml kg SMM^{-1} min^{-1})	85.1 (9.1)
	Grip strength (kg)	47.2 (8.7)
	Grip strength (kg. $SMM^{-0.72}$)	3.7 (0.63)
	VJ (cm)	48.0 (9.1)
	VJ (cm. $SMM^{0.20}$)	97.1 (18.4)
	VJ (cm .$height^{-1}$)	0.27 (0.05)
EMG muscle onset and offset RT	RT-Onset3 (ms)	154.8 (58.7)
	RT-Offset3 (ms)	279.8 (100.9)
	RT-Onset6 (ms)	224.7 (69.1)
	RT-Offset6 (ms)	257.0 (82.0)
Computerized RT	SRT (ms)	287.4 (31.0)
	5-CRT (ms)	312.6 (28.1)
	2-CRT (ms)	315.1 (36.0)

| Stop signal task | Go RT (ms) | 680.3 (166.3) |
| | SSRT (ms) | 226.3 (42.2) |

BDI-II: Beck Depression Inventory-II**; BM:** body mass; **RT-Onset3**: Mean RT delay in initiation of 3 seconds contractions; **RT-Offset3**: Mean RT delay in termination of 3 seconds contractions; **RT-Onset6**: Mean RT delay in initiation of 6 second contractions; **RT-Offset6**: Mean RT delay in termination of 6 second contractions; **SRT**: simple reaction time; **5-CRT**: five choice reaction time; **2-CRT**: two choice reaction time; **SSRT**: stop signal reaction time; **SMM**: skeletal muscle mass; **VJ**: vertical jump

Results

Participants characteristics are presented in Table 1. Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was found 0.66, which shows the sample size is adequate.

The results of factor analysis (Table 2) shows that computerised RT and EMG RT accounted for 65.30% of the total variance.

Table 2. Summary of principal component factor analysis

Factors		Variables	Factor loading
EMG RT	1- PMT	Onset3	0.76
		Offset3	0.81
		Onset6	0.82
		Offset6	0.79
Computerized RT	2- RT	SRT	0.86
		5-CRT	0.87
		2-CRT	0.65

Table shows the Varimax rotated factor loading
EMG RT: electromyography reaction time; **PMT:** premotor time which was measured using RT on initiation and termination of upper extremities contraction against audio signal; **RT:** total computerized reaction time

Cognitive tasks between "unfit" or "fit" groups

Results of Levene's test of equality of error variance was found non-significant for all the dependent variables ($p>0.05$).
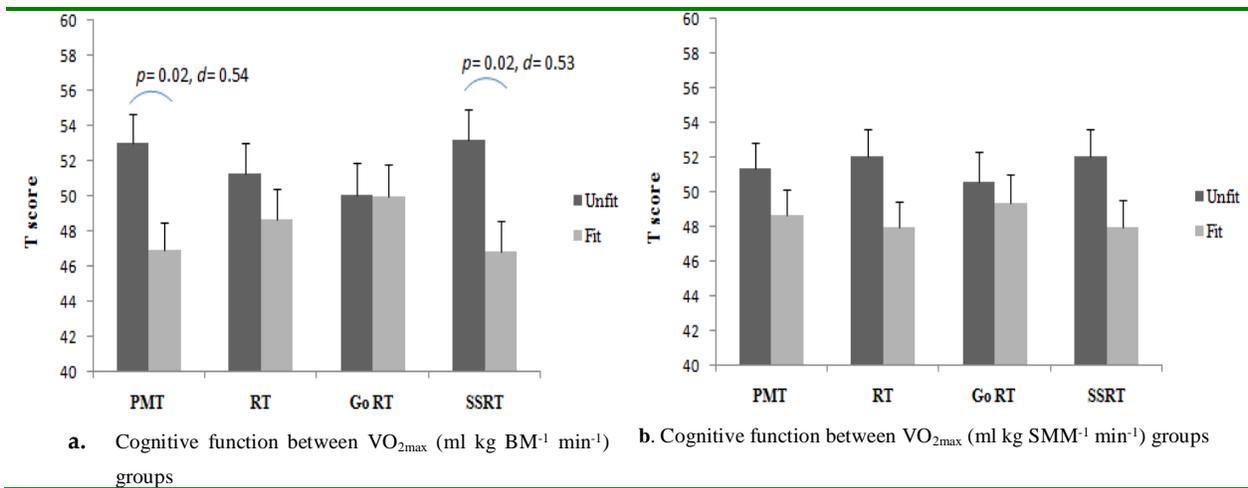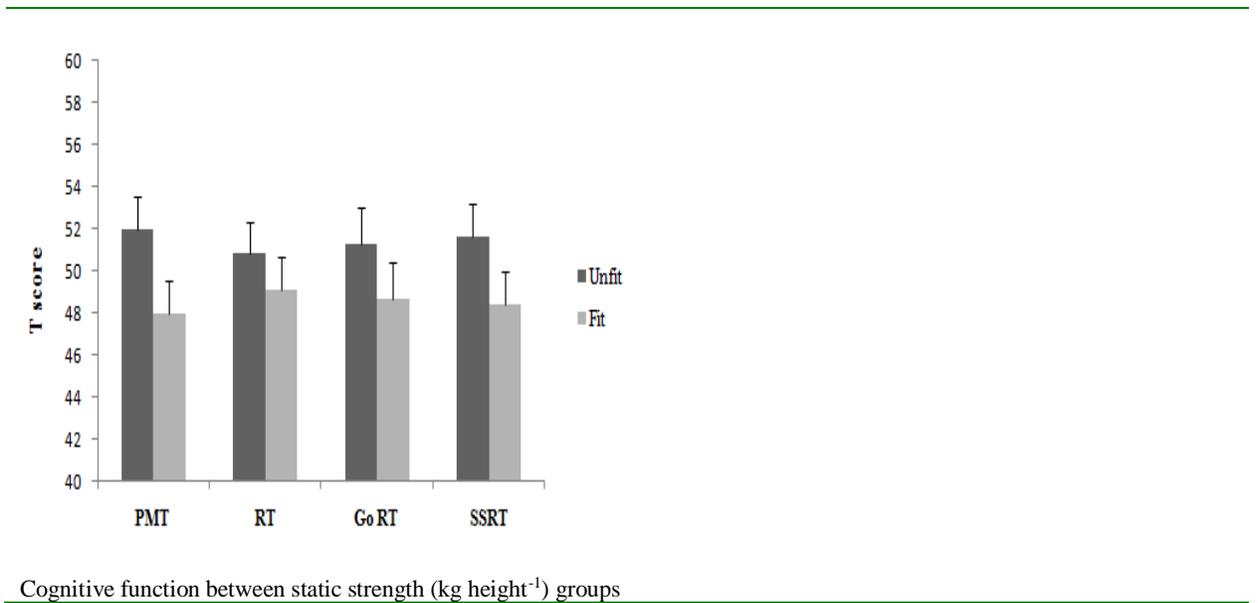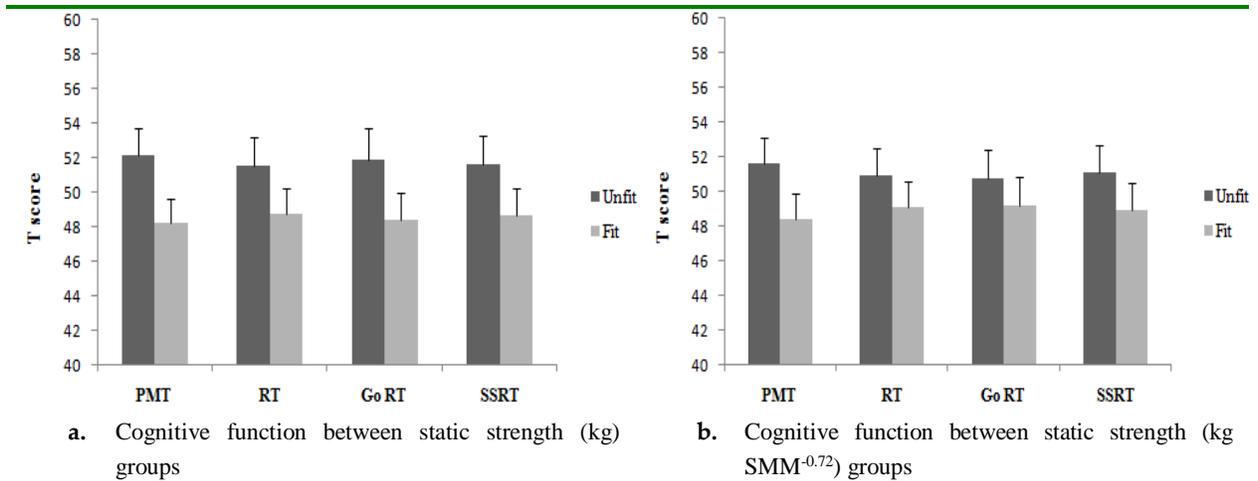
a. Cognitive function between VO_{2max} (ml kg BM^{-1} min^{-1}) groups

b. Cognitive function between VO_{2max} (ml kg SMM^{-1} min^{-1}) groups

Figure 1. Cognitive function between "fit" and "unfit" groups categorized according to CRF
PMT: premotor time was measured using RT on initiation and termination of upper extremities contraction against audio signal;
RT: total computerized reaction time; other abbreviations are explained under Table 1
Note: In all tasks lower score is better; T scores of the cognitive tasks were used for showing all in the same figure
Note: Values are reported after adjustment for age, SES, depressive symptoms, total PA, blood pressure, and BF%
Note: Median score for VO_{2max} (ml kg BM^{-1} min^{-1}) is 39.65 (max-min: 26.2 – 51.9); Median score for VO_{2max} (ml kg SMM^{-1} min^{-1}) is 85.00 (max-min: 66.3 – 108.9).

A shorter PMT and SSRT were observed for participants with higher VO_{2max} (ml. kg BM^{-1} min^{-1}) compared to their peers with lower VO_{2max} (ml kg BM^{-1} min^{-1}) (Fig 1a). However, no significant differences were observed for any of the cognitive performances between "unfit" and "fit" groups according to VO_{2max} (ml kg SMM^{-1} min^{-1}) (Fig 1b).

No significant difference was noted for the cognitive performances according to static strength with all scaling scenarios (Fig 2a, b and c).

Participants with a higher explosive strength had a shorter PMT than those with poorer explosive strength performance with all scaling scenarios. No differences were observed for RT, Go RT and SSRT between participants categorized according to their explosive strength independent of the scaling scenarios (Fig 3a, b and c).

a. Cognitive function between static strength (kg) groups

b. Cognitive function between static strength (kg SMM$^{-0.72}$) groups

Cognitive function between static strength (kg height^{-1}) groups

Figure 2. Cognitive function between "fit" and "unfit" groups categorized according to static strength

Note: Abbreviations are explained under Figure 1 and Table 1

Note: Values are reported after adjustment for age, SES, depressive symptoms, total PA, blood pressure, BF% and VO$_{2max}$ (ml. kg SMM^{-1} .min^{-1})

Note: Median score for static strength (kg) is 47.00 (max-min: 25.0 – 66.5); Median score for static strength (kg SMM$^{-0.72}$) is 3.70 (max-min: 2.2 – 5.3); Median score for static strength (kg height^{-1}) is 0.27 (max-min: 0.15 – 0.38).
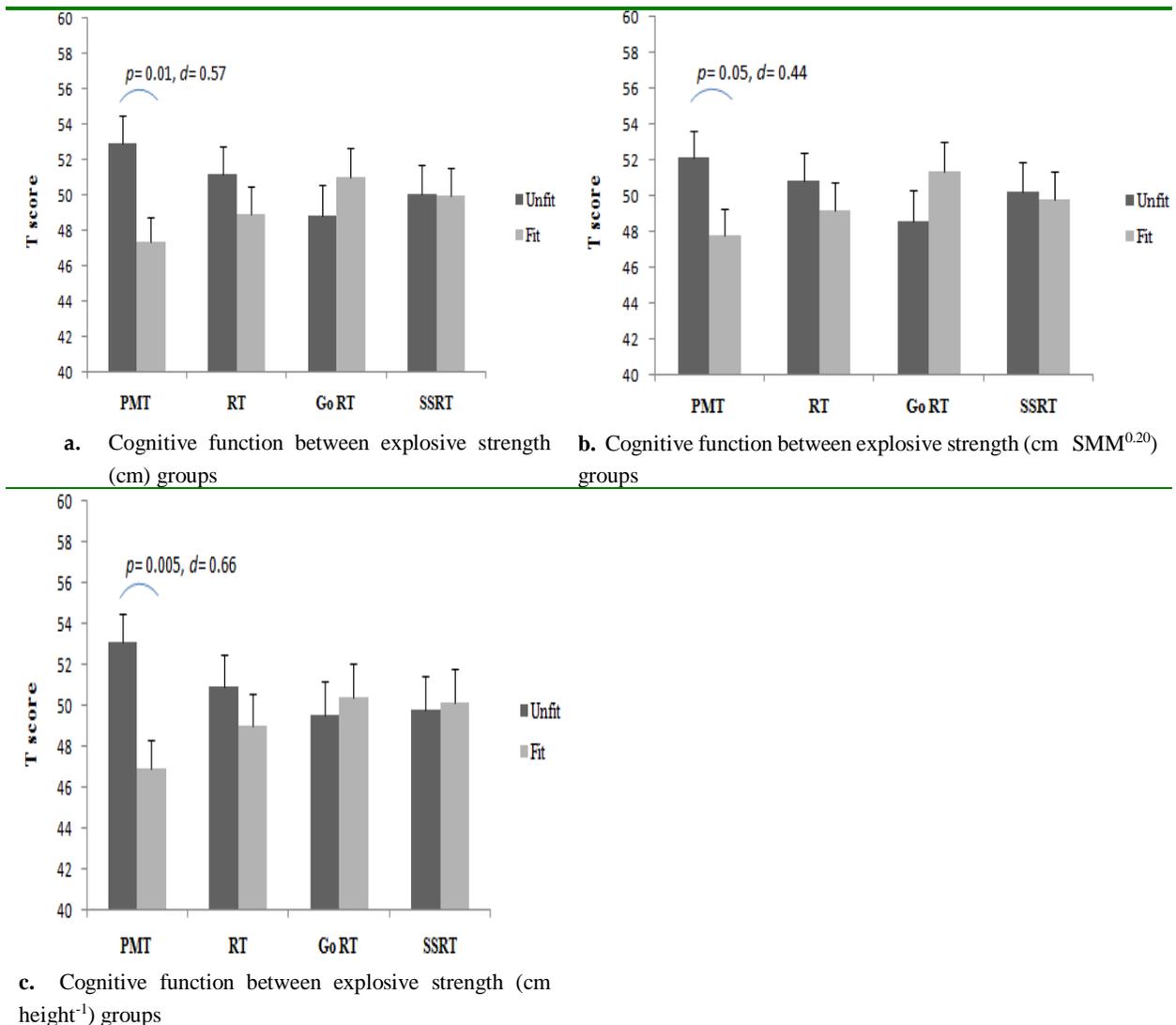
a. Cognitive function between explosive strength (cm) groups

b. Cognitive function between explosive strength (cm $SMM^{0.20}$) groups

c. Cognitive function between explosive strength (cm height^{-1}) groups

Figure 3. Cognitive function between "fit" and "unfit" groups categorized according to explosive strength

Note: Abbreviations are explained under Figure 1 and Table 1

Note: Values are reported after adjustment for age, SES, depressive symptoms, total PA, blood pressure, BF% and VO_{2max} (ml. kg SMM^{-1} .min^{-1})

Note: Median score for explosive strength (kg) is 49.00 (max-min: 22.0 – 66.5); Median score for explosive strength (cm SMM$^{0.20}$) is 99.01 (max-min: 47.1 – 133.6); Median score for explosive strength (cm height^{-1}) is 0.27 (max-min: 0.12 – 0.37).

Discussion

In the present study we aimed to examine the association between CRF, static strength and explosive strength with cognitive functioning tasks requiring different degree of cognitive processing speed and sensitivity and adjusting for covariates.

Our study revealed that aerobically fit participants performed better on PMT and SSRT when the analysis was directly scaled by participants' BM. However, the difference disappeared when the analysis were scaled according to SMM. Static strength was not related to any cognitive outcomes, but those having a better explosive strength had a better PMT with all scaling scenarios.

The present results partly explain previous inconsistent findings regarding the association between CRF and cognitive function in young adults. For instance, some researchers observed no association between VO_{2max} (ml kg BM^{-1} min^{-1}) and executive function in young adults, and suggested that this relationship emerges mainly after early adulthood, [14,15] whereas, others have found a positive association between VO_{2max} (ml kg BM^{-1} min^{-1}) and executive function in young adult populations [16,17] and some suggested that higher CRF would benefit cognitive function in all age groups, including young adults. [17]

A large number of different definitions of executive function as well as varying measurement methods may have introduced inconsistencies in regards to the association with CRF in young adults. Low sample sizes, [14,18] and CRF measurements through indirect methods or self-reports are other methodological constraints for some studies. [14,19] Furthermore, age, SES, depression, daily-PA, and metabolic problems such as obesity, high blood pressure, diabetes, and cardiovascular disease, affect cognitive function and should be considered as covariates. [47,48] However, some studies do not make the inclusion of such covariates in the analyses, [14,18]

Another limitation in most of the previous studies is scaling VO_{2max} only by BM. In the present study, the positive association between PMT or inhibitory control with CRF (scaled to BM) disappeared when CRF was scaled by SMM, which is supported by previous findings using appropriate scaling methods. [49] It has been suggested that scaling VO_{2max} by BM is confounded by body size and composition and has no physiological or statistical rationale. [29] Therefore, differences in young people's body composition, instead of CRF per se, may have introduced bias and inconsistent conclusions in the previous studies. Instead, allometrically scaled VO_{2max} to SMM better accounts for variance in BM in young people. [29] It would be interesting and resource-wise

to republish the previous data with the suggested scaling techniques and use these techniques consistently in future studies [50].

One of the strengths of this paper is the use of tasks that differ in their cognitive demands. Previous studies have shown a stronger association between CRF and cognition in cognitively demanding tasks such as those requiring attentional ability like inhibitory control. [4,13,27] Accordingly, after rigorously controlling for known covariates, we found that participants with higher VO_{2max} (ml kg BM^{-1} min^{-1}) performed better in inhibitory control (i.e. SSRT). However, participants also had shorter PMT than their peers with lower VO_{2max} (ml kg BM^{-1} min^{-1}), and the magnitude of association was similar to that with SSRT. Information processing speed tasks such as RT are cognitively less demanding than SSRT, because the decision is made pre-presentation. [51] However, PMT is more sensitive than overall RT tasks (e.g. simple or choice RT tasks) and is able to better discriminate possible information processing problems. [23-26]

Although this conflicts with the previously suggested theory, [4,13,27] to the best of our knowledge, associations between CRF and PMT have not been studied previously. Therefore, CRF, when scaled to BM, may be beneficial for central processing time (but not overall RT). As discussed in the previous paragraph, this finding may be confounded by body composition, as evidenced by the lack of association between CRF and PMT when scaled to SMM.

In this study, we found no association between static strength and any of the cognitive outcomes. Although positive associations between grip strength and cognitive function have been observed in middle-aged and older adults, [5,6] the present findings are in line with null findings in young adults [19,21] and children. [20] These differences may suggest that reduced static muscle strength may be an early indicator of delayed nervous system processing and reduced cognitive performance during ageing, [52] but this process is not seen in young people. Instead, young people having a better explosive strength had a better PMT than their peers with lower explosive strength in all scaling scenarios, and the association persisted after adjusting for VO_{2max} (ml kg SMM^{-1} min^{-1}). This is in line with previous findings of Esmaeilzadeh et al. [19] who showed that higher explosive strength measured by standing long jump test was associated with better RT and inhibitory control in young adult males. However, aerobic fitness measured by the one-mile run test was a predictor of only inhibitory control. They observed no association between static strength measured by grip strength with any cognitive task in young adult males. [19] Recently Steves et al. [7] by including healthy female

twins and at two-time points ten years apart observed that leg power (but not maximal static strength measured by the grip strength test) predicted both global brain structure and cognitive ageing. These findings suggest that the link between explosive strength and cognition is biologically plausible and at least partly independent of genetics and early life environment.

The reason for the association between explosive but not static strength with PMT is not clear, yet some mechanisms have been suggested. PMT (a central processing time) is a measure of central functional electrical stimulation, which is the main factor controlling muscle force production. [24] For instance, multiple aspects of muscle strength such as rates of muscle contraction (or "rate coding"), which is associated with the ability to generate power or explosive strength and maximal strength, are controlled by the central nervous system. In contrast to maximal static strength, explosive strength requires a high acceleration capability by which force must be produced in minimal time [53] and central nervous system plays a vital role in the rate of muscle contraction. [52] Explosive strength is more sensitive to detect changes in neuromuscular function and is strongly related to both functional daily tasks and sport-specific task performances. [53]

Using an objective method for measuring CRF, normalizing physical fitness values for body size using either ratio standard for SMM or using allometric models and controlling for known potential covariates are strengths of this study. However, the sample was relatively small and included only young males. Therefore, our results can not be generalized to other populations. Finally, the cross-sectional nature precludes any causal interpretations.

Conclusions

Overall, in the present study, we found that CRF was associated with PMT and SSRT when VO_{2max} was scaled by BM, but not when scaled to SMM, suggesting that body composition is a confounding factor in the association between cognition and CRF. Static strength was not associated with any cognition outcomes. However, explosive strength was associated with PMT in all scaling scenarios, and the association persisted after further adjustment for CRF. Therefore, we could conclude that PMT and rates of muscle contraction may share the same physiological mechanism, which would explain the association between explosive strength, but not static strength, with cognition. [53,54] Measuring explosive strength and appropriately scaling the fitness indicators to SMM are important avenues in advancing our knowledge of the association between

fitness and cognition in young people. If confirmed in intervention studies, explosive strength training performed at a young age may improve central processing time.

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