

**This is a self-archived version of an original article. This version may differ from the original in pagination and typographic details.**

**Author(s):** Narimani, Mohammad; Esmaeilzadeh, Samad; Pesola, Arto J.; Haapala, Eero A.; Heidari, Behrouz; Azevedo, Liane B.

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

**Year:** 2020

**Version:** Accepted version (Final draft)

**Copyright:** © 2020 EDIZIONI MINERVA MEDICA

**Rights:** In Copyright

**Rights url:** <http://rightsstatements.org/page/InC/1.0/?language=en>

**Please cite the original version:**

Narimani, M., Esmaeilzadeh, S., Pesola, A. J., Haapala, E. A., Heidari, B., & Azevedo, L. B. (2020). Allometrically scaled explosive strength, but not static strength or maximal oxygen uptake is associated with better central processing time in young males. *Journal of Sports Medicine and Physical Fitness*, 60(7), 947-956. <https://doi.org/10.23736/S0022-4707.20.10273-1>

# **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

Mohammad NARIMANI\*<sup>1</sup>, Samad ESMAEILZADEH<sup>1,2</sup>, Arto J. PESOLA<sup>2</sup>, Eero A. HAAPALA<sup>3</sup>, Behrouz HEIDARI<sup>1</sup>, Liane B. AZEVEDO<sup>4</sup>

<sup>1</sup>University of Mohaghegh Ardabili; Department of Psychology, Ardabil; Iran; <sup>2</sup>Active Life Lab, South-Eastern Finland University of Applied Sciences, Mikkeli, Finland; <sup>3</sup>Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland. Physiology, Institute of Biomedicine, School of Medicine, University of Eastern Finland, Kuopio, Finland; <sup>4</sup> School of Human and Health Sciences, University of Huddersfield

1- \*Corresponding author:”University of Mohaghegh Ardabili, Department of Psychology, Ardabil, Iran. E-mail: [narimani@uma.ac.ir](mailto:narimani@uma.ac.ir)

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

## **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.

**Keywords:** allometric scaling - cardiorespiratory fitness - cognitive function – electromyography - grip strength - Sargent jump test

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.<sup>1,2</sup> 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.<sup>3</sup> A body of evidence suggests they are also associated with cognitive function in adults.<sup>4-7</sup> 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.<sup>8-12</sup> 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 these independent associations.

Several studies have shown that CRF is directly associated with cognition in prepubertal children and older adults.<sup>4,13</sup> However, the association between CRF and cognitive function in adolescents and young adults (18-35 years), when the brain is in its peak development,<sup>14,15</sup> has been less explored and findings are inconsistent.<sup>14-17</sup> 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.<sup>14,18,19</sup>

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,<sup>5,6</sup> previous studies have failed to observe this in young participants.<sup>19-21</sup> 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.<sup>7,19</sup> 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.<sup>8-10</sup> 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.<sup>22</sup> The time between the onset or offset of the response signal in relation to the initial or terminal EMG activity can determine PMT.<sup>22</sup> 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.<sup>23-26</sup>

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

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).<sup>4,13,17,27</sup> 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.<sup>28-30</sup> 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.<sup>28-31</sup>

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 characteristics 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 to 14.30-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 ( $\text{kg}/\text{m}^2$ ).

### *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.<sup>32</sup> Gas exchange measurement during the GXT was performed breath-by-breath using the Ergo-Spirometry analyzer (Ganshorn, Medizin Electronic, GmbH, PowerCube system, Germany).  $\text{VO}_{2\text{max}}$  was recorded as the greatest mean value determined breath-by-breath during 10 consecutive seconds and confirmed if two of three criteria of  $\text{VO}_{2\text{max}}$  were met.<sup>33</sup>

### *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  $0.890$ ).<sup>34</sup> Grip strength test was measured in a sitting position with shoulder adduction, wrist and forearm in a neutral position and elbow at  $90^\circ$  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.<sup>35,36</sup> Reliability studies have indicated high correlation coefficients for the Sargent Jump test ( $r = 0.93$ ).<sup>37</sup>

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.<sup>28-31</sup> Allometrically scaled  $VO_{2max}$  using SMM is considered the gold standard measure.<sup>29,31</sup> However, for static and explosive strength not only SMM, but also height was used for scaling.<sup>28,30</sup> The following allometric equation [Fitness=  $Y/X^b$ ], 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 ( $\beta=-0.01, p=0.94$ ), 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 ( $\beta= 0.06, p=0.56$ ), showing the validity of height in scaling of grip strength. A negative association was observed between grip strength ( $kg\ SMM^{-1}$ ) with SMM ( $\beta= -0.22, p=0.05$ ), 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 ( $\beta= -0.02, p=0.84$ ), which show its validity in scaling static strength.
- 3) Allometric scaling of VJ: Weak association was observed between VJ ( $cm\ height^{-1}$ ) with height ( $\beta= 0.02, p=0.86$ ), showing the validity of height in scaling of VJ. However, a strong negative association was observed between VJ ( $cm\ SMM^{-1}$ ) with SMM ( $\beta= -0.59, p< 0.001$ ), 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<sup>0.20</sup>) with SMM ( $\beta = -0.02, p = 0.83$ ), 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)<sup>38</sup> 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 × 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.<sup>39</sup> 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.<sup>40</sup> 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 <sup>41</sup>. Long form International Physical Activity Questionnaire (IPAQ) was used as a standardized measure for measuring PA in the previous week across several lifestyle domains. <sup>42</sup> The Beck Depression Inventory-II (BDI-II) was used as a valid measure of depressive symptoms.

<sup>43</sup>

### *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, <sup>44</sup> 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  $\leq 50\%$ ). 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<sup>-1</sup> min<sup>-1</sup>). LSD post hoc test was used for multiple comparisons. Cohen's <sup>45</sup>  $d$  (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  $\eta^2$  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. <sup>46</sup> 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)
<b>Demographics and physiological</b>	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 <sup>2</sup> )	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)	
<b>Raw and allometric scaling of physical fitness</b>	$VO_{2max}$ (ml kg BM <sup>-1</sup> min <sup>-1</sup> )	39.6 (5.9)
	$VO_{2max}$ (ml kg SMM <sup>-1</sup> min <sup>-1</sup> )	85.1 (9.1)
	Grip strength (kg)	47.2 (8.7)
	Grip strength (kg. SMM <sup>-0.72</sup> )	3.7 (0.63)
	VJ (cm)	48.0 (9.1)
	VJ (cm. SMM <sup>0.20</sup> )	97.1 (18.4)
	VJ (cm .height <sup>-1</sup> )	0.27 (0.05)
<b>EMG muscle onset and offset RT</b>	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)
<b>Computerized RT</b>	SRT (ms)	287.4 (31.0)
	5-CRT (ms)	312.6 (28.1)
	2-CRT (ms)	315.1 (36.0)
<b>Stop signal task</b>	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

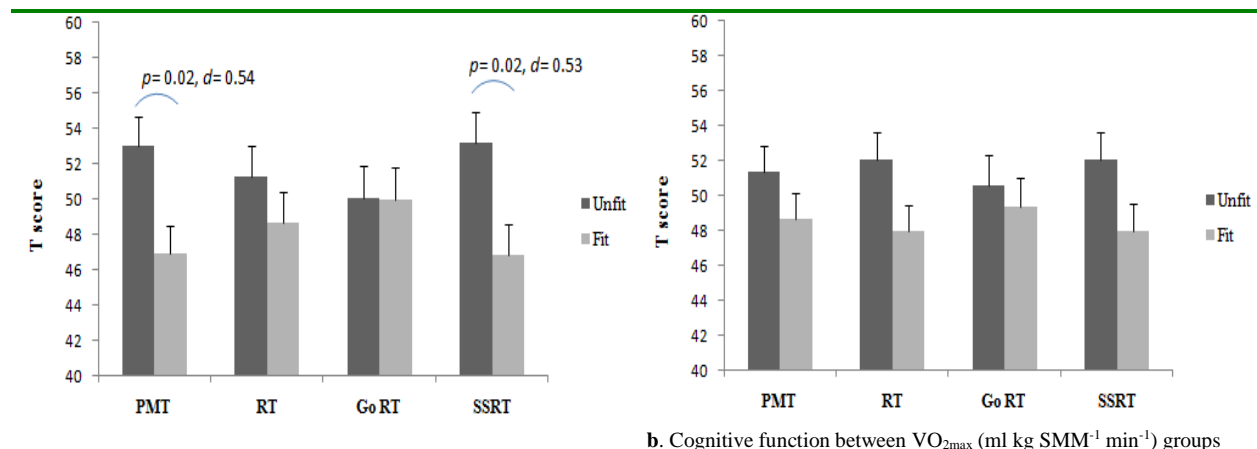
Factors	Variables	Factor loading
<b>EMG RT</b>	<b>1- PMT</b>	
	Onset3	0.76
	Offset3	0.81
	Onset6	0.82
<b>Computerized RT</b>	<b>2- RT</b>	
	Offset6	0.79
	SRT	0.86
	5-CRT	0.87
	2-CRT	0.65

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<sup>-1</sup> min<sup>-1</sup>) 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

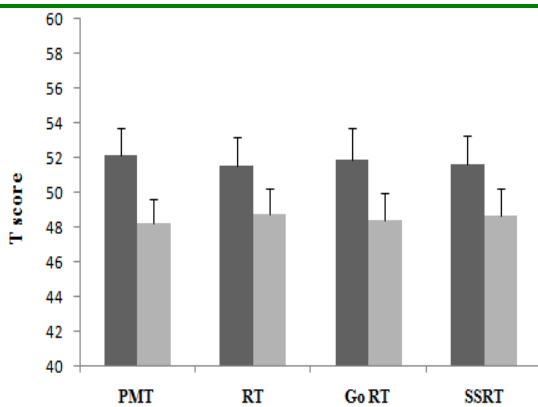
**Note:** Values are reported after adjustment for age, SES, depressive symptoms, total PA, blood pressure, and BF%

Note: Median score for  $VO_{2max}$  (ml kg BM<sup>-1</sup> min<sup>-1</sup>) is 39.65 (max-min: 26.2 – 51.9); Median score for  $VO_{2max}$  (ml kg SMM<sup>-1</sup> min<sup>-1</sup>) is 85.00 (max-min: 66.3 – 108.9).

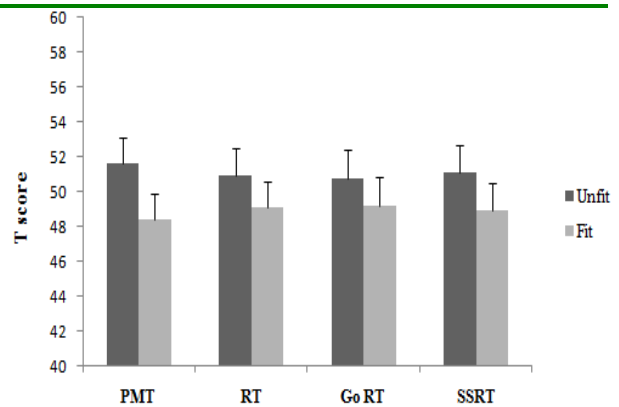
A shorter PMT and SSRT were observed for participants with higher  $VO_{2max}$  (ml. kg BM<sup>-1</sup> min<sup>-1</sup>) compared to their peers with lower  $VO_{2max}$  (ml kg BM<sup>-1</sup> min<sup>-1</sup>) (Fig 1a). However, no significant differences were observed for any of the cognitive performances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

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

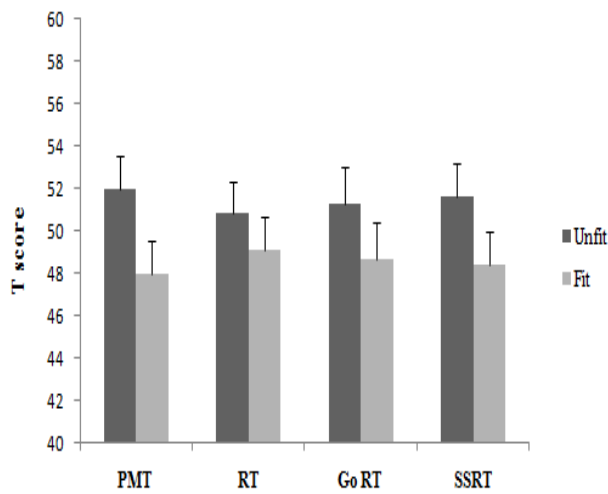
Participants with a higher explosive strength had a shorter PMT than those with poorer explosive strength performance with all scaling scenarios. No differences were observed for RT, Go RT and SSRT between participants categorized according to their explosive strength independent of the scaling scenarios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



a. Cognitive function between static strength (kg) groups



b. Cognitive function between static strength (kg SMM<sup>-0.72</sup>) groups



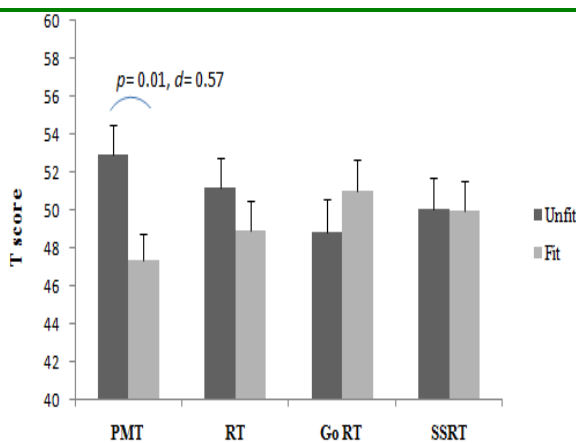
Cognitive function between static strength (kg height<sup>-1</sup>) groups

**Figure 2.** Cognitive function between “fit” and “unfit” groups categorized according to static strength

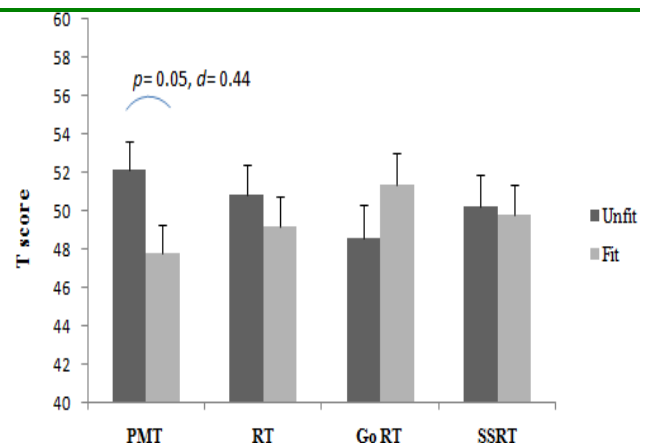
**Note:** Abbreviations are explained under Figure 1 and Table 1

**Note:** Values are reported after adjustment for age, SES, depressive symptoms, total PA, blood pressure, BF% and VO<sub>2max</sub> (ml. kg SMM<sup>-1</sup> .min<sup>-1</sup>)

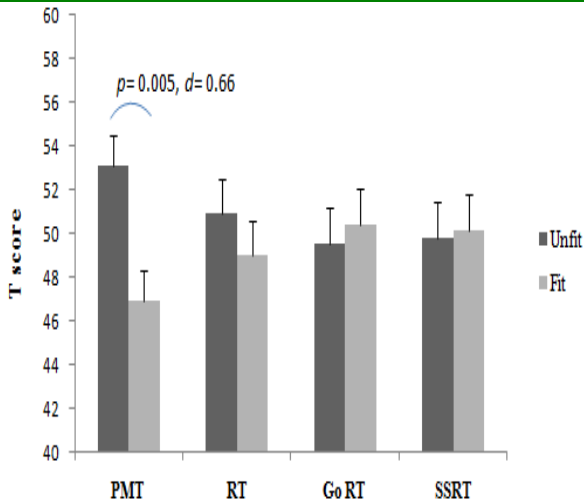
Note: Median score for static strength (kg) is 47.00 (max-min: 25.0 – 66.5); Median score for static strength (kg SMM<sup>-0.72</sup>) is 3.70 (max-min: 2.2 – 5.3); Median score for static strength (kg height<sup>-1</sup>) is 0.27 (max-min: 0.15 – 0.38).



a. Cognitive function between explosive strength (cm) groups



b. Cognitive function between explosive strength (cm SMM<sup>0.20</sup>) groups



c. Cognitive function between explosive strength (cm height<sup>-1</sup>) 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<sub>2max</sub> (ml. kg SMM<sup>-1</sup> .min<sup>-1</sup>)

**Note:** Median score for explosive strength (kg) is 49.00 (max-min: 22.0 – 66.5); Median score for explosive strength (cm SMM<sup>0.20</sup>) is 99.01 (max-min: 47.1 – 133.6); Median score for explosive strength (cm height<sup>-1</sup>) 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<sub>2max</sub> (ml kg BM<sup>-1</sup> min<sup>-1</sup>) and executive function in young adults, and

suggested that this relationship emerges mainly after early adulthood,<sup>14,15</sup> whereas, others have found a positive association between  $\text{VO}_{2\text{max}}$  ( $\text{ml kg BM}^{-1} \text{ min}^{-1}$ ) and executive function in young adult populations<sup>16,17</sup> and some suggested that higher CRF would benefit cognitive function in all age groups, including young adults.<sup>17</sup>

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,<sup>14,18</sup> and CRF measurements through indirect methods or self-reports are other methodological constraints for some studies.<sup>14,19</sup> 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.<sup>47,48</sup> However, some studies do not make the inclusion of such covariates in the analyses,<sup>14,18</sup>

Another limitation in most of the previous studies is scaling  $\text{VO}_{2\text{max}}$  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.<sup>49</sup> It has been suggested that scaling  $\text{VO}_{2\text{max}}$  by BM is confounded by body size and composition and has no physiological or statistical rationale.<sup>29</sup> 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  $\text{VO}_{2\text{max}}$  to SMM better accounts for variance in BM in young people.<sup>29</sup> 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<sup>50</sup>.

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.<sup>4,13,27</sup> Accordingly, after rigorously controlling for known covariates, we found that participants with higher  $\text{VO}_{2\text{max}}$  ( $\text{ml kg BM}^{-1} \text{ min}^{-1}$ ) performed better in inhibitory control (i.e. SSRT). However, participants also had shorter PMT than their peers with lower  $\text{VO}_{2\text{max}}$  ( $\text{ml kg BM}^{-1} \text{ min}^{-1}$ ), 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.<sup>51</sup> 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.<sup>23-26</sup>

Although this conflicts with the previously suggested theory,<sup>4,13,27</sup> 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,<sup>5,6</sup> the present findings are in line with null findings in young adults<sup>19,21</sup> and children.<sup>20</sup> 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,<sup>52</sup> 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 Esmailzadeh et al.<sup>19</sup> 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.<sup>19</sup> Recently Steves et al.<sup>7</sup> 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.<sup>24</sup> 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<sup>53</sup> and central nervous system plays a vital role in the rate of muscle contraction.<sup>52</sup> 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.<sup>53</sup>

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.<sup>53,54</sup> 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.

### **References**

1. Ortega F, Ruiz J, Castillo M, Sjostrom M. Physical fitness in childhood and adolescence: a powerful marker of health. *Int J Obes* 2008; 32:1-11.
2. Ruiz J, Castro-Piñero J, Artero E, et al. Predictive validity of health-related fitness in youth: a systematic review. *Br J Sports Med* 2009; 43:909-923.

3. Artero EG, Ruiz JR, Ortega FB, España-Romero V, Vicente-Rodríguez G, Molnar D, et al. Muscular and cardiorespiratory fitness are independently associated with metabolic risk in adolescents: the HELENA study. *Pediatr Diabetes* 2011; 12(8):704-712.
4. Colcombe S, Kramer AF. Fitness effects on the cognitive function of older adults. a meta-analytic study. *Psychol Sci* 2003; 14:125–130.
5. Firth J, Stubbs B, Vancampfort D, Firth JA, Large M, Rosenbaum S, et al. Grip Strength Is Associated With Cognitive Performance in Schizophrenia and the General Population: A UK Biobank Study of 476 559 Participants. *Schizophr Bull* 2018; 6:44(4):728-736.
6. Fritz NE, McCarthy CJ, Adamo DE. Handgrip strength as a means of monitoring progression of cognitive decline - A scoping review. *Ageing Res Rev* 2017; 35:112-123.
7. Steves CJ, Mehta MM, Jackson SHD, Spector TD. Kicking Back Cognitive Ageing: Leg Power Predicts Cognitive Ageing after Ten Years in Older Female Twins. *Gerontology* 2016; 62(2): 138–149.
8. Kail R. Speed of Information Processing : Developmental Change and Links. *J Sch Psychol* 2000; 38:51–61.
9. Fry AF, Hale S. Processing speed, working memory and fluid intelligence: Evidence for a developmental cascade. *Psychol Sci* 1996; 7:237–241.
10. Sheppard LD, Vernon PA. Intelligence and speed of information-processing: A review of 50 years of research. *Pers Individ Dif* 2008; 44(3): 535–551.
11. Diamond, Adele. "Executive functions". *Annu Rev Psychol* 2013; 64:135–168.
12. Mostofsky SH, Simmonds DJ. Response inhibition and response selection: Two sides of the same coin. *J Cognit Neurosci* 2008; 20:751–761.
13. Hillman CH, Buck SM, Themanson JR, Pontifex MB, Castelli DM. Aerobic fitness and cognitive development: event-related brain potential and task performance indices of executive control in preadolescent children. *Dev Psychol* 2009; 45: 114.
14. Scisco JL, Leynes PA, Kang J. Cardiovascular fitness and executive control during task-switching: an ERP study. *Int J Psychophysiol* 2008; 69:52–60.
15. Hayes SM, Forman DE, Verfaellie M. Cardiorespiratory fitness is associated with cognitive performance in older but not younger adults. *J Gerontol Series B: Psychol Sci Social Sci* 2014; 71: 474–482.

16. Wenggaard E, Kristoffersen M, Harris A, Gundersen H. Cardiorespiratory Fitness Is Associated with Selective Attention in Healthy Male High-School Students. *Front Hum Neurosci* 2017; 11: 330.
17. Themanson JR, Pontifex MB, Hillman CH. Fitness and action monitoring: evidence for improved cognitive flexibility in young adults. *Neuroscience* 2008; 157: 319–328.
18. Dupuy O, Gauthier CJ, Fraser SA, Desjardins-Crèpeau L, Desjardins M, Mekary S, et al. Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women. *Front Hum Neurosci* 2015; 9:66.
19. Esmaeilzadeh S, Hartman E, Farzizadeh R, Azevedo LB, Kalantari HA, Dziembowska I, et al. Association between physical fitness and cognitive performance in 19-24 year old males. *Biol Sport* 2018; 35(4): 355-362.
20. Moradi A, Sadri-Damirchi E, Narimani M, Esmaeilzadeh S, Dziembowska I, Azevedo LB, et al. Association between Physical and Motor Fitness with Cognition in Children. *Medicina* 2019; 55: 7.
21. Aberg MAI, Pedersen NL, Toren K, Svartengren M, Backstran B, Johnsson T, et al. Cardiovascular fitness is associated with cognition in young adulthood. *Proc. Nati Acad Sci* 2009; 106:20906-20911.
22. Botwinick J, Thompson LW. Premotor and motor components of reaction time. *J Exp Psychol* 1966; 71(1):9-15.
23. Chae J, Yang G, Park BK, Labatia I. Delay in initiation and termination of muscle contraction, motor impairment, and physical disability in upper limb hemiparesis. *Muscle Nerve* 2002; 25(4):568-575.
24. Chae J, Triolo R, Kilgore K, Creasey G, DiMarco AF. Functional neuromuscular stimulation. In: DeLisa J, Gans B, editors. *Physical medicine and rehabilitation: principles and practices*. Vol 2. Philadelphia: Lippincott Williams & Wilkins, 2005; 1405-1426.
25. Ballanger B, Boulinguez P. EMG as a key tool to assess motor lateralization and hand reaction time asymmetries. *J Neurosci Methods* 2009; 179(1):85-89.
26. Narimani M, Esmaeilzadeh S, Pesola AJ, Azevedo LB, Moradi A, Heidari B, et al. Impact of obesity on central processing time rather than overall reaction time in young adult men. *Eat Weight disor* 2019. [Epub ahead of print] doi: 10.1007/s40519-019-00752-2.

27. Guiney H, Machado L. Benefits of regular aerobic exercise for executive functioning in healthy populations. *Psychon Bull Rev* 2013; 20(1): 73-86.
28. Folland JP, Mc Cauley TM, Williams AG. Allometric scaling of strength measurements to body size. *Eur J Appl Physiol* 2008; 102:739–745.
29. Welsman J, Armstrong N. Interpreting Aerobic Fitness in Youth: The Fallacy of Ratio Scaling. *Pediatr Exer Sci* 2018; 31(2):184-190.
30. Maranhao Neto GA, Oliveira AJ, Pedreiro RC, Pereira-Junior PP, Machado S, Marques Neto S, Farinatti PT. Normalizing handgrip strength in older adults: An allometric approach. *Arch Gerontol Geriatr* 2017; 70:230-234.
31. Agbaje AO, Haapala EA, Lintu N, Viitasalo A, Barker AR, Takken T, et al. Peak oxygen uptake cut-points to identify children at increased cardiometabolic risk – The PANIC Study. *Scand J Med Sci Sports* 2019; 29(1):16-24.
32. American College of Sports Medicine. ACSM’s health-related physical fitness assessment manual. Philadelphia (PA): Lippincott Williams & Wilkins; 2013.
33. Kraemer WJ, Fleck SJ, Deschenes MR. Exercise physiology: integrating theory and application. Philadelphia (PA): Lippincott Williams & Wilkins; 2011.
34. Wind AE, Takken T, Helders PJ, Engelbert RH. Is grip strength a predictor for total muscle strength in healthy children, adolescents, and young adults? *Eur J Pediatr* 2010; 169: 281–287.
35. Castro-Pinero J, Ortega FB, Artero EG, Girela-Rejon MJ, Mora J, Sjostrom M, et al. Assessing muscular strength in youth: Usefulness of stand-ing long jump as a general index of muscular fitness. *J Strength Cond Res* 2010; 24(7):1810–1817.
36. Viitasalo JT. Evaluation of explosive strength for young and adult athletes. *Res Q Exerc Sport* 1988; 59(1):9–13.
37. Safrit MJ. Introduction to Measurement in Physical Education and Exercise Science. Hightown, NJ: McGraw Hill, 1995.
38. Smith PJ, Need AC, Cirulli ET, Chiba-Falek O, Attix DK. A comparison of the Cambridge Automated Neuropsychological Test Battery (CANTAB) with “traditional” neuropsychological testing instruments. *J Clin Exp Neuropsychol* 2013; 35:319–328.
39. Nissen MJ. Stimulus intensity and information processing. *Percept Psychophys* 1977; 22: 338-352.

40. Hodges PW, Bui BH. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalogr Clin Neurophysiol* 1996; 101:511–519.
41. Moradi A, Esmailzadeh S. Association between reaction time, speed and agility in schoolboys. *Sport Sci Health* 2015; 11: 251–256.
42. The International Physical Activity Questionnaire. 2005. Available at <http://www.ipaq.ki.se/>
43. Ghassemzadeh H, Mojtabai R, Karamghadiri N, Ebrahimkhani N. Psychometric properties of a Persian-language version of the Beck depression inventory-second edition: BDI-II-PERSIAN. *Depress Anxiety* 2005; 21: 185–192.
44. Tabachnick BG, Fidell LS. *Using Multivariate Statistics*. 6th ed. Pearson new international edition, 2014.
45. Cohen J. *Statistical power analysis for the behavioral sciences*. Lawrence Erlbaum: Mahwah, JH; 1988.
46. Faul F, Erdfelder E, Lang AG, Buchner A. G\*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods* 2007; 39:175–191.
47. Cox EP, O'Dwyer N, Cook R, Vetter M, Cheng HL, Rooney K, O'Connor H. Relationship between physical activity and cognitive function in apparently healthy young to middle-aged adults: A systematic review. *J Sci Med Sport* 2016; 19(8):616-28.
48. Donnelly JE, Hillman CH, Castelli D, Etnier JL, Lee S, Tomporowski P, et al. Physical Activity, Fitness, Cognitive Function, and Academic Achievement in Children: A Systematic Review. *Med Sci Sports Exerc* 2016; 48(6):1197-222.
49. Haapala EA, Lintu N, Väistö J, Tompuri T, Soininen S, Viitasalo A, et al. Longitudinal Associations of Fitness, Motor Competence, and Adiposity with Cognition. *Med Sci Sports Exerc* 2019; 51(3):465-471.
50. Giuriato M, Nevill A, Kawczynski A, Lovecchio N. Body size and shape characteristics for Cooper's 12 minutes run test in 11-13 years old Caucasian children: an allometric approach. *J Sports Med Phys Fitness* 2020. doi: 10.23736/S0022-4707.19.10282-4.
51. McMorris T. History of Research into the Acute Exercise–Cognition Interaction: A Cognitive Psychology Approach. *Exercise-Cognition Interaction*, 2016. doi:10.1016/B978-0-12-800778-5.00001-3.

52. Roebbers CM, Kauer M. Motor and cognitive control in a normative sample of 7-year-olds. *Dev Sci* 2009; 12(1):175–181.
53. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol* 2016; 116:1091–1116.
54. Tian Q, Osawa Y, Resnick SM, Ferrucci L, Studenski SA. Rate of Muscle Contraction Is Associated With Cognition in Women, Not in Men. *J Gerontol A Biol Sci Med Sci* 2018; 8.