Association of Plasma Carotenoid and Malondialdehyde Levels with Physical Performance in Korean Adolescents

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Research Article

Keywords: malondialdehyde, carotenoid, physical performance, antioxidant, adolescent, effect modifier

Posted Date: November 17th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1080957/v1

Version of Record: A version of this preprint was published at International Journal of Environmental Research and Public Health on April 3rd, 2022. See the published version at https://doi.org/10.3390/ijerph19074296.

Abstract

Background

Increased oxidative stress has been shown to lead to muscle damage and reduced physical performance. The antioxidant mechanism is most likely to reduce these relationships, but in the context of the action of carotenoids, more research is needed. This cross-sectional study aims to investigate whether carotenoids modify the association between plasma malondialdehyde (MDA) and physical performance in Korean adolescents.

Methods

The study sample consisted of 381 participants (164 boys, 217 girls) aged 13–18, who participated in the 2018 National Fitness Award Project. We quantified *α*-carotene, *β*-carotene, *β*-cryptoxanthin, lutein, zeaxanthin, lycopene, and MDA levels in plasma using HPLC with photodiode array detection. Physical performance was measured by determining the absolute and relative hand grip strength, 20-m progressive aerobic cardiovascular endurance run, estimated maximal oxygen consumption, curl-up, and sit-and-reach.

Results

In boys, the multiple linear regression model adjusted for age, BMI, smoking, drinking, and physical activity showed that the MDA level was negatively associated with absolute hand grip strength; this association was observed only in groups with *α*-carotene, *β*-cryptoxanthin, zeaxanthin, and total carotenoid values below the median.

Conclusion

These results suggest that carotenoids may act as an effect modifier of the association between MDA and physical performance in Korean male adolescents.

Background

Physical performance (or fitness) is a measure of physical activity that requires cardiorespiratory endurance, neuromuscular skeletal endurance and strength, and flexibility [1, 2].An individual's physical performance state is mainly determined by lifestyle factors, including physical activity, as well as genetically inherited ability. Oxidative stress status is considered one of the most important factors related to physical performance [3, 4].

Malondialdehyde (MDA) is one of the most common biomarkers of oxidative stress as an end product of lipid peroxidation [5]. A number of clinical [6, 7] and epidemiological [8, 9] studies have evaluated the degree of oxidative stress/oxidative damage by measuring MDA contents in humans. A recent study indicated that an elevated MDA level was associated with a higher risk of low hand grip strength in the non-paretic limbs of stroke patients [10].

Carotenoids are natural pigments responsible for the yellow, orange, and red colors of various fruits and vegetables [11]. Human organisms cannot synthesize carotenoids; therefore, these compounds must be supplied with the diet. Among the various carotenoids supplied through the diet, *α*-carotene, *β*-carotene, *β*-cryptoxanthin, lutein, zeaxanthin, and lycopene are the six main carotenoids found in human blood serum [12]. Carotenoid status has been associated with various health benefits. Findings have linked the importance of carotenoids to human health with their antioxidant activity, protecting cells and tissues from oxidative damage [13].

Some observational evidence suggests that carotenoids are positively associated with physical performance [14–16]. Our previous study observed that blood carotenoid levels might be positively associated with physical performance in Korean adolescents [17]. It could be that the protective effect of carotenoids against oxidative damage promotes health and nutrition to elevate physical performance. To the best of our knowledge, no current literature studies have investigated the association between blood carotenoids, MDA, and physical performance. There have also been few studies examining such associations during adolescence, a critical period considering that the physical performance level in adolescence can affect diseases in adulthood. Therefore, the aim of this study is to determine whether carotenoid levels modify the association between the blood MDA level and physical performance in Korean adolescents aged 13–18 years.

Methods

Study participants

The subjects were adolescents who participated in the Korean National Fitness Award Project in 2018. This large-scale national project is currently managed by 21 centers [18]. Among the 450 adolescents in our previous study, which reported associations between carotenoids and physical performance [17], we excluded participants for whom we were unable to analyze MDA concentration due to insufficient blood samples (n = 65). As a result, 381 participants (164 boys, 217 girls) aged 13-18 years were included in this study. This study was approved by the Institutional Review Board (IRB) of the Korea Institute of Sport Science, and Ewha Womans University. Informed consent of all participants was obtained before enrollment.

General characteristics and anthropometric measurement

Skilled interviewers surveyed the study participants' smoking, drinking, physical activity, and eating habits to obtain general information on their health-related behaviors. We defined "current smoker" as a participant who reported smoking at least one cigarette in the last 30 days and "current drinker" as a participant who reported drinking at least one cup of alcohol in the last 30 days. We defined "physical activity" as being involved in at least one of four intensity levels (high, moderate, cardio-intensive, and strength-intensive) at least once a week. Questions related to eating habits consisted of breakfast frequency in the last week, fruits, fast foods, and carbonated drink consumption, and the number of late-night snacks in the last 30 days.

Height was measured in units of 0.1 cm using a stadiometer (Seca, Seca Corporation, Columbia, MD, USA). Body weight was measured in units of 0.1 kg using an electronic weight scale (Inbody 720, Biospace, Seoul, Korea). Body mass index (BMI) was calculated as weight divided by height squared (kg/m^2). All parameters were measured by skilled medical staff.

Plasma MDA measurements

We used an approved high-performance liquid chromatography (HPLC) method to quantify plasma MDA based on its reaction with 2-thiobarbituric acid (TBA). The HPLC instrument (Shiseido Co., Ltd., Tokyo, Japan) was equipped with an analytical column (4.6 mm id × 250 mm; Shiseido Co., Ltd.) for MDA separation and a fluorescence detector (excitation length = 527 nm, emission length = 551 nm) for MDA detection. The mobile phase consisted of 50 mM potassium phosphate buffer (pH 6.8) and methanol (7:3, v/v). The flow rate was 1.0 mL/min at 40°C. For the peak calibration of the MDA-TBA adduct, a 1,1,3,3-tetra-ethoxypropane solution was used [19].

Before the analysis, plasma samples were mixed with 0.44 M phosphoric acid and a 42 mM phosphoric acid solution for deproteinization. Then, they were heated at 95°C for 1 h, cooled at 4°C for 1 h, and centrifuged (2,500×*g* at 4°C for 3 min). The resultant supernatants were filtered through a 0.45-μm PTFE syringe filter.

Plasma carotenoids measurements

Blood samples were taken after participants fasted for 8 h. Plasma was obtained by immediate centrifugation of the blood samples at 3000 rpm for 3 min. Plasma carotenoid levels were determined on an HPLC instrument (Shiseido Co., Ltd.) equipped with a YMC C30 column (5 μm, 4.6 × 250 mm; YMC Europe GmbH, Dinslaken, Germany) and a photodiode array detector (Shiseido Co., Ltd.). We quantified α-carotene, β-carotene, β-cryptoxanthin, lutein, zeaxanthin, and lycopene, and total carotenoids were calculated as the sum of the six individual carotenoids.

Physical performance measurements

Physical performance was assessed by determining muscular strength (absolute and relative hand grip strength test), muscular endurance (curl-up test), aerobic capacity (20-m Progressive Aerobic Cardiovascular Endurance Run: 20-m PACER test, estimated maximal oxygen consumption: VO_{2max}), and flexibility (sit-and-reach test). The National Fitness Award project test items for Korean adolescents showed a high consistency, with reliability ranging from 0.87 to 0.99 [20]. All physical performance assessments were conducted by trained experts, and the detailed evaluation methods are as follows:

Muscular strength

To assess the absolute hand grip strength (kg, %), the participants first extended both feet shoulder-width apart in an upright position. A hand dynamometer (GRIP-D 5101, Takei, Niigata, Japan) was adjusted to the second finger of the participants. Then, the arms of the participant were straightened down and kept 15° apart from the torso. At the signal "start," the participant exerted maximum strength to hold the hand dynamometer for 5 s. The maximum value was recorded to the nearest 0.1 kg for the left then right hand. The relative hand grip strength (kg, %) was calculated using the formula: [absolute hand grip strength (kg) / body weight (kg)] × 100.

Muscular endurance

The curl-up test (number of times) was performed to assess muscular endurance. First, the participant was instructed to lay down with their knees bent, and their feet fixed to the floor about 30 cm away from their hips. At the signal "start," the participant extended their arms forward until their fingertips touched their knees and downed their head to the floor. This movement was regarded as one curl-up. Each participant repeated this process. The number of curl-ups was measured and recorded.

Aerobic capacity

To perform the 20-m PACER test (number of times), the experts divided each lane into a 20-m course and drew a line with tape at the end. The experts shout "start" 5 s after the "ready" command, at which point the participants start to run across 20 m. If they reach the opposite line before the beep, they must wait until the second beep before again running toward the end of the opposite line. If participants do not reach the line before the first beep, they can run in a different direction at the second beep. However, if they cannot reach the line before the second beep, they are eliminated. In this way, participants must continue until the line is not reached before the second beep, and the eliminator must stay clear of the line. The maximum number of repetitions was recorded.

Another effective aerobic capacity measurement index is VO_{2max}. However, it is costly and hard to measure VO_{2max} directly. Instead, VO_{2max} was estimated by the 20-m PACER using the quadratic model developed by Mahar et al. [21] to estimate VO_{2max} (mL/kg·min) in adolescents.

Flexibility

The sit-and-reach test (cm) was performed to assess flexibility. First, the participants were instructed to take off their shoes and sit correctly with their knees extended so that the soles of both feet touched the vertical surface of the measuring instrument; the distance between the feet should not exceed 5 cm. The participant was then asked to stretch their arms without bending their knees and bend their upper body as far forward as possible with their fingertips touching the measuring instrument. This process was performed twice, and the highest measurement was recorded to the nearest 0.1 cm.

Statistical analysis

General characteristics were presented as mean ± standard deviation for continuous variables and as numbers and percentages for categorical variables. The differences in the mean general characteristics, blood carotenoids and plasma MDA levels, and physical performances between the groups below the median and above the median were analyzed through the Student's *t*-test. In addition, the differences in the distribution of categorical variables, such as smoking, drinking, and physical activity, between the groups below the median and above the median were analyzed by the Chi-square test. To determine whether the carotenoid modifies the association between plasma MDA levels and physical performances, multiple linear regression analysis was used after adjusting for age, BMI, smoking, drinking, and physical activity. All analyses were performed using the SAS software (version 9.4; SAS Institute, Inc., Cary, NC, USA). Significance was defined as a value of $p < 0.05$.

Results

General characteristics and blood carotenoids

The general characteristics and blood carotenoid levels of the groups by the total carotenoids median value are summarized in Table 1. In boys, the mean age, weight, and BMI were significantly higher in the group below the median than above the median. However, all the median levels of general characteristics in girls were not significantly different between the groups below the median and above the median. All carotenoids mean levels (α-carotene, *β*-carotene, *β*-cryptoxanthin, lutein, zeaxanthin, lycopene, and total carotenoids) were significantly higher ($p < 0.01$) in the group above the median than the group below the median in both boys and girls.

Table 1
General characteristics and blood carotenoid levels of Korean adolescents by total carotenoids median 1

	Total (*n* = 381)	**Boys (*n* = 164)**			**Girls (*n* = 217)**		
		Below the median (*n* = 82)	Above the median (*n* = 82)	*p*	Below the median (*n* = 109)	Above the median (*n* = 108)	*p*
General characteristics							
Age (years)	15.26 ± 2.02	15.87 ± 2.05	15.22 ± 1.88	0.04	15.28 ± 2.16	14.81 ± 1.86	NS
Height (cm)	164.89 ± 7.59	170.3 ± 6.4	169.7 ± 7.68	NS	161.5 ± 5.63	160.5 ± 5.09	NS
Weight (kg)	57.48 ± 11.81	65.90 ± 13.37	59.63 ± 10.78	0.001	54.66 ± 9.97	52.31 ± 8.86	NS
BMI (kg/m^2)	21.02 ± 3.45	22.65 ± 4.16	20.62 ± 3.05	0.001	20.88 ± 3.21	20.24 ± 2.98	NS
Current smoker (*n*, %)	11 (2.9)	3 (3.7)	5 (6.1)	NS	1 (0.9)	2 (1.9)	NS
Current drinker (*n*, %)	38 (10.0)	8 (9.8)	12 (14.6)	NS	10 (9.17)	8 (7.4)	NS
Physical activity (*n*, %)	326 (85.6)	75 (91.5)	77 (93.9)	NS	87 (79.82)	87 (80.7)	NS
Carotenoid concentration (μmol/L)							
α-Carotene	0.16 ± 0.05	0.15 ± 0.05	0.17 ± 0.07	0.01	0.15 ± 0.05	0.17 ± 0.05	0.003
β-Carotene	0.58 ± 0.34	0.37 ± 0.15	0.75 ± 0.46	<0.0001	0.45 ± 0.18	0.73 ± 0.33	<0.0001
β-Cryptoxanthin	0.44 ± 0.25	0.30 ± 0.07	0.53 ± 0.28	<0.0001	0.35 ± 0.10	0.59 ± 0.31	<0.0001
Lutein	0.25 ± 0.10	0.20 ± 0.05	0.28 ± 0.10	<0.0001	0.20 ± 0.06	0.30 ± 0.13	<0.0001
Zeaxanthin	0.20 ± 0.07	0.17 ± 0.06	0.24 ± 0.07	<0.0001	0.17 ± 0.06	0.21 ± 0.06	<0.0001
Lycopene	0.55 ± 0.31	0.42 ± 0.22	0.70 ± 0.26	<0.0001	0.44 ± 0.23	0.63 ± 0.39	<0.0001
Total carotenoids [2]	2.17 ± 0.69	1.60 ± 0.24	2.66 ± 0.79	<0.0001	1.77 ± 0.20	2.63 ± 0.58	<0.0001

[1] Values are expressed as mean ± standard deviation or *n* (%). Current smokers indicate a participant who reported to have smoked at least one cigarette in the last 30 days. Current drinkers indicate a participant who reported drinking at least one cup of alcohol in the last 30 days. Physical activity indicates participation in at least one of the four intensities (high, moderate, cardio-intensive, and strength-intensive) at least once a week. [2] Total carotenoids: the sum of the blood levels of the six individual carotenoids. BMI, body mass index.

Plasma Mda And Physical Performances

The plasma MDA and physical performance value of the groups by total carotenoids median value are summarized in Table 2. No differences in plasma MDA mean level between the groups below the median and above the median were observed in both boys and girls. However, the mean levels of physical performance (20-m PACER, estimated VO_{2max}, and curl-up) were significantly higher ($p < 0.01$) in the group above the median than the group below the median in boys. There were no differences in the mean physical performance between the groups below the median and above the median in girls.

Table 2
Plasma MDA and physical performance levels of Korean adolescents by total carotenoids median 1

	Total (*n* = 381)	**Boys (*n* = 164)**			**Girls (*n* = 217)**		
		Below the median (*n* = 82)	Above the median (*n* = 82)	*p*	Below the median (*n* = 109)	Above the median (*n* = 108)	*p*
Plasma MDA concentration (μmol/L)	2.98 ± 1.09	3.04 ± 0.97	2.79 ± 0.98	NS	3.05 ± 1.19	2.99 ± 1.14	NS
Physical Performance							
Absolute hand grip strength (kg)	28.81 ± 8.82	36.52 ± 8.12	35.41 ± 7.26	NS	23.67 ± 4.78	23.13 ± 5.01	NS
Relative hand grip strength (%)	50.33 ± 12.45	56.50 ± 12.54	59.83 ± 9.84	NS	43.92 ± 8.79	44.90 ± 10.52	NS
20-m PACER (reps)	36.02 ± 16.70	44.48 ± 15.78	51.28 ± 15.37	0.01	26.18 ± 10.74	27.95 ± 10.43	NS
Estimated VO_{2max} (mL/kg·min)	39.57 ± 5.51	43.23 ± 4.48	45.59 ± 3.54	0.0003	35.59 ± 3.07	36.24 ± 2.89	NS
Curl-up (reps)	25.86 ± 17.44	28.61 ± 15.90	37.07 ± 18.35	0.002	19.39 ± 14.56	21.78 ± 16.08	NS
Sit-and-reach (cm)	11.11 ± 10.43	7.84 ± 10.37	8.00 ± 10.21	NS	12.71 ± 10.21	14.35 ± 9.59	NS

[1] Values are expressed as mean ± standard deviation. MDA, malondialdehyde; PACER, progressive aerobic cardiovascular endurance run; VO_{2max}, maximal oxygen uptake; NS, non-significant; Total carotenoids: the sum of the blood levels of the six individual carotenoids.

Associations between plasma MDA and physical performance by the carotenoid median

The association between plasma MDA and physical performances by the carotenoid median resulting from multiple logistic regression analyses adjusted for age, BMI, smoking, drinking, and physical activity is shown in Table 3. In boys, the MDA level was negatively associated with absolute hand grip strength; this association was observed only in groups with α-carotene (β = -1.497, p = 0.015), β-cryptoxanthin (β = -1.829, p = 0.028), zeaxanthin (β = -1.841, p = 0.016), and total carotenoid (β = -1.825, p = 0.042) values below the median. No significant associations between plasma MDA and physical performances according to the carotenoid median were observed in girls.

Table 3

Multiple linear regression analysis for the association between plasma MDA levels and physical performance in Korean adolescents by the c

			Absolute Hand Grip Strength			Relative Hand Grip Strength			20-m PACER			Estimated VO_{2max}			Curl-up	
			β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE
Boys (n = 164)	**Median**															
α-Carotene	0.194	Below the median	-1.497	0.603	0.015	-1.257	0.853	NS	-1.247	1.377	NS	-0.245	0.270	NS	-2.404	1.52
		Above the median	0.585	0.968	NS	1.397	1.296	NS	1.380	2.571	NS	0.270	0.504	NS	1.766	2.84
β-Carotene	0.465	Below the median	-1.321	0.920	NS	-0.892	1.168	NS	0.476	1.991	NS	0.093	0.390	NS	-0.578	2.20
		Above the median	-0.341	0.648	NS	-0.161	0.956	NS	-0.369	1.703	NS	-0.072	0.334	NS	-1.626	1.94
β-Cryptoxanthin	0.347	Below the median	-1.829	0.816	0.028	-1.514	1.067	NS	0.363	1.886	NS	0.071	0.370	NS	-1.800	1.92
		Above the median	-0.274	0.698	NS	-0.050	0.961	NS	-0.157	1.791	NS	-0.031	0.351	NS	-0.130	2.09
Lutein	0.239	Below the median	-1.378	0.745	NS	-0.619	0.980	NS	-0.697	1.896	NS	-0.137	0.372	NS	0.380	1.89
		Above the median	-0.176	0.854	NS	-0.081	1.171	NS	1.233	1.993	NS	0.242	0.391	NS	-1.154	2.38
Zeaxanthin	0.225	Below the median	-1.841	0.750	0.016	-1.577	1.027	NS	-0.722	1.658	NS	-0.142	0.325	NS	-0.841	1.68
		Above the median	0.146	0.809	NS	0.458	1.070	NS	1.427	2.238	NS	0.280	0.439	NS	-1.264	2.53
Lycopene	0.547	Below the median	-1.406	0.912	NS	-0.728	1.266	NS	0.433	2.127	NS	0.085	0.417	NS	-2.047	2.38
		Above the median	-0.659	0.630	NS	-0.436	0.846	NS	-0.684	1.612	NS	-0.134	0.316	NS	-0.228	1.80
Total carotenoids [2]	1.962	Below the median	-1.825	0.884	0.042	-1.381	1.191	NS	1.077	1.839	NS	0.211	0.360	NS	-1.038	1.89
		Above the median	-0.250	0.662	NS	-0.130	0.900	NS	-0.476	1.793	NS	-0.093	0.351	NS	-0.466	2.17
Girls (n = 217)																
α-Carotene	0.139	Below the median	-0.411	0.359	NS	-0.151	0.627	NS	-0.420	1.100	NS	-0.082	0.216	NS	-1.802	1.42
		Above the median	0.228	0.419	NS	0.167	0.846	NS	-0.483	0.729	NS	-0.095	0.143	NS	0.155	1.27
β-Carotene	0.510	Below the median	0.160	0.361	NS	0.453	0.670	NS	-0.798	0.752	NS	-0.156	0.147	NS	0.534	0.94
		Above the median	-0.071	0.418	NS	-0.278	0.843	NS	0.129	0.949	NS	0.025	0.186	NS	-0.967	1.58

[1] Adjusted for age, BMI, smoking, drinking, and physical activity. [2] Total carotenoids: the sum of the blood levels of the six individual carotenoids. MDA, malo aerobic cardiovascular endurance run; VO_{2max}, maximal oxygen uptake; SE, standard error; NS, non-significant.

			Absolute Hand Grip Strength			Relative Hand Grip Strength			20-m PACER			Estimated VO_{2max}			Curl-up	
β-Cryptoxanthin	0.388	Below the median	0.331	0.446	NS	0.618	0.870	NS	-0.429	0.875	NS	-0.084	0.171	NS	0.422	1.49
		Above the median	-0.083	0.368	NS	-0.130	0.720	NS	-0.153	0.889	NS	-0.030	0.174	NS	-0.446	1.19
Lutein	0.240	Below the median	-0.537	0.371	NS	-0.426	0.656	NS	-1.067	1.066	NS	-0.209	0.209	NS	-0.399	1.39
		Above the median	0.359	0.403	NS	0.240	0.818	NS	0.055	0.746	NS	0.011	0.146	NS	0.261	1.22
Zeaxanthin	0.188	Below the median	-0.568	0.410	NS	-0.304	0.744	NS	-0.081	1.146	NS	-0.016	0.225	NS	-0.443	1.58
		Above the median	0.275	0.380	NS	0.161	0.766	NS	-0.485	0.708	NS	-0.095	0.139	NS	-0.218	1.16
Lycopene	0.516	Below the median	0.386	0.381	NS	0.536	0.711	NS	-0.307	0.814	NS	-0.060	0.159	NS	0.502	1.26
		Above the median	-0.581	0.397	NS	-0.725	0.813	NS	-0.515	0.924	NS	-0.101	0.181	NS	-1.589	1.35
Total carotenoids [2]	2.092	Below the median	0.081	0.373	NS	0.256	0.685	NS	-0.697	0.852	NS	-0.137	0.167	NS	1.135	1.19
		Above the median	0.060	0.414	NS	-0.051	0.844	NS	-0.318	0.877	NS	-0.062	0.172	NS	-1.497	1.40

[1] Adjusted for age, BMI, smoking, drinking, and physical activity. [2] Total carotenoids: the sum of the blood levels of the six individual carotenoids. MDA, malo aerobic cardiovascular endurance run; VO_{2max}, maximal oxygen uptake; SE, standard error; NS, non-significant.

Discussion

To our knowledge, no current literature studies have demonstrated the association between plasma carotenoids and plasma MDA with physical performance. In this study, we found the association between plasma MDA and absolute hand grip strength only in Korean male adolescents with α-carotene, β-cryptoxanthin, zeaxanthin, and total carotenoid values lower than the corresponding median values.

Although it is difficult to explain the exact mechanism for the results of this study, the role of carotenoids as effect modifiers in the association between MDA and hand grip strength could be linked to the role of carotenoids as part of the antioxidant defense system in humans. High levels of oxidative stress in the blood indicate the presence of many reactive oxygen species (ROS), which can cause muscle damage [22–24] and eventually lead to physical performance loss [25, 26]. Carotenoids are well known to be effective lipophilic antioxidants that quench singlet oxygen [27] and scavenge other ROS [28]. Many studies of adults, including older adults, have reported that carotenoid levels are positively related to physical performance [29, 30]. Moreover, a previous study on Korean adolescents reported that blood carotenoid levels were positively related to physical performance [17].

In this study, we found that, in addition to total carotenoids, only α-carotene, β-cryptoxanthin, and zeaxanthin, among the six individual carotenoids studied, acted as effect modifiers in the association between MDA and hand grip strength. We do not know why there was no significance for β-carotene, which is recognized to have the highest antioxidant activity [31]. One possible explanation is that the bioavailability of carotenoids does not depend solely on physiological mechanisms but can be affected by many other factors, such as gender [32], dietary factors [33], and health status [34]. In support of this premise, one study of Europeans has shown that the bioavailability of α-carotene and β-cryptoxanthin with consideration of eating amount is higher compared to that of β-carotene [35]. Moreover, Britton [36] argued that zeaxanthin is a more effective antioxidant than β-carotene because of its less hydrophobic structure, which can react with free radicals not only in the inner cell membrane but also in the interior aqueous phases.

In the current study, we found significant results only for hand grip strength among the various physical performance indicators examined. Hand grip strength is the most used indicator of muscle strength [37] and has been used as a representative indicator of physical fitness [38]. Matsudo et al. [39] suggested that hand grip strength can act as a very accurate and independent predictor of physical fitness in both children and adolescents. Similarly, Gerodimos [40] suggested the reliability of hand grip strength in basketball players from childhood to adulthood. Furthermore, in the current study, the association with MDA was significant only in absolute hand grip strength and not relative hand grip strength. In this regard, one study suggested that normalized hand grip strength by weight is inferior to other normalization options [41]. The advantages and disadvantages of relative and absolute hand grip strength are still under discussion, and a compromise must be reached [42].

In our study, among the physical performance indicators, sit-and-reach showed a different pattern from the results for hand grip strength. That is, the associations between MDA and sit-and-reach in groups with lutein below the median and α-carotene above the median were positive. The sit-and-reach test is an indicator of flexibility, and flexibility is the characteristic of the musculoskeletal system that determines the range of motion without damage to the joint [43]. Several studies have argued that cardiovascular endurance and muscle strength and endurance are more closely related to athletic performance than flexibility [44–46]. It is difficult to understand the exact biochemical mechanism of flexibility, but it is expected to follow a different mechanism from other physical fitness indicators. To the best of our knowledge, there has been no study on the relationship between MDA and the sit-and-reach test. Therefore, prospective studies on this potential association are needed.

We do not know exactly why the association between MDA and physical performance by carotenoids median was confirmed only in boys. The bioactivity of carotenoids is affected by various physiological factors in men and women. A study of Europeans argued that women had higher blood carotenoid levels than men and that gender differences existed [47]. Similarly, in a study of older adults in Europe, factors related to the status of carotenoids in blood were investigated, and the total carotenoids were especially higher in women than in men [48]. Thus, the concentration of carotenoids in the blood is influenced by gender, and further studies of the concentration and bioactivity of carotenoids in men are needed.

Our study has several limitations. First, because of its cross-sectional design, we cannot determine the causal relationship between carotenoid and MDA with physical performance in our study. Second, our study only measured the blood condition of carotenoids without considering the type and amount of food intake. However, despite these limitations, our study is the first to suggest that the relationship between oxidative stress and physical performance in Korean adolescents may depend on the level of carotenoids in the blood. Our findings emphasize the importance of preventing oxidative stress in adolescents' physical performance, which can determine health in adulthood and help guide nutritional recommendations.

List Of Abbreviations

BMI: body mass index

HPLC: high-performance liquid chromatography

MDA: malondialdehyde

PACER: progressive aerobic cardiovascular endurance run

TBA: thiobarbituric acid

VO_{2max}: maximal oxygen uptake

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board (IRB) of the Korea Institute of Sport Science, and Ewha Womans University. All protocols were carried out in accordance with relevant guidelines and regulations.

Consent for publication

Not applicable.

Availability of data and materials

All datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

None.

Funding

This project was funded by the Bio-Synergy Research Project of the Ministry of Science and ICT through the National Research Foundation, grant number NRF-2012M3A9C4048761.

Author's Contributions

O.K. and H.K. designed the research; J.K. and O.K. conducted the research; H.J., J.H., and H.K. analyzed the data; H.J. and H.K. wrote the manuscript. O.K. and H.K. were primarily responsible for the final contents. All authors read and approved the final manuscript.

Acknowledgments

Not applicable.

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