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Review

Global and regional estimates of prevalence of refractive errors: Systematic review and meta-analysis

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Abstract

Purpose: The aim of the study was a systematic review of refractive errors across the world according to the WHO regions.
Methods: To extract articles on the prevalence of refractive errors for this meta-analysis, international databases were searched from 1990 to 2016. The results of the retrieved studies were merged using a random effect model and reported as estimated pool prevalence (EPP) with 95% confidence interval (CI).
Results: In children, the EPP of myopia, hyperopia, and astigmatism was 11.7% (95% CI: 10.5–13.0), 4.6% (95% CI: 3.9–5.2), and 14.9% (95% CI: 12.7–17.1), respectively. The EPP of myopia ranged from 4.9% (95% CI: 1.6–8.1) in South–East Asia to 18.2% (95% CI: 10.9–25.5) in the Western Pacific region, the EPP of hyperopia ranged from 2.2% (95% CI: 1.2–3.3) in South-East Asia to 14.3% (95% CI: 13.4–15.2) in the Americas, and the EPP of astigmatism ranged from 9.8% in South-East Asia to 27.2% in the Americas. In adults, the EPP of myopia, hyperopia, and astigmatism was 26.5% (95% CI: 23.4–29.6), 30.9% (95% CI: 26.2–35.6), and 40.4% (95% CI: 34.3–46.6), respectively. The EPP of myopia ranged from 16.2% (95% CI: 15.6–16.8) in the Americas to 32.9% (95% CI: 25.1–40.7) in South-East Asia, the EPP of hyperopia ranged from 23.1% (95% CI: 6.1%–40.2%) in Europe to 38.6% (95% CI: 22.4–54.8) in Africa and 37.2% (95% CI: 25.3–49) in the Americas, and the EPP of astigmatism ranged from 11.4% (95% CI: 2.1–20.7) in Africa to 45.6% (95% CI: 44.1–47.1) in the Americas and 44.8% (95% CI: 36.6–53.1) in South-East Asia. The results of meta-regression showed that the prevalence of myopia increased from 1993 (10.4%) to 2016 (34.2%) ($P = 0.097$).
Conclusion: This report showed that astigmatism was the most common refractive errors in children and adults followed by hyperopia and myopia. The highest prevalence of myopia and astigmatism was seen in South-East Asian adults. The highest prevalence of hyperopia in children and adults was seen in the Americas.

Keywords: Myopia; Hyperopia; Astigmatism; Meta-analysis

Introduction

Refractive errors are the most common ocular problem affecting all age groups. They are considered a public health challenge. Recent studies and WHO reports indicate that refractive errors are the first cause of visual impairment and the second cause of visual loss worldwide as 43% of visual

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impairments are attributed to refractive errors.[1] In a review study, Naidoo et al.[2] showed that uncorrected refractive errors were responsible for visual impairment in 101.2 million people and blindness in 6.8 million people in 2010.

Refractive errors also affect the economy of different societies.[3,4] According to a study by Smith et al.,[4] uncorrected refractive errors result in an annual economy loss of $269 billion worldwide. According to this report,[4] this index was $ 121.4 billion in individuals above 50 years.

A review of the literature and medical databases reveals that many studies have been conducted on the epidemiology of refractive errors across the world since 1990.[5,6] Although numerous studies report the prevalence of refractive errors every year, many new articles are published on the epidemiology of these errors annually due to their importance and prevalence.

Although recent studies[7,8] suggest an increase in the prevalence of myopia due to lifestyles changes, differences in ethnic groups, measurement methods, definitions of refractive errors, and age groups of the participants hinder a definite conclusion regarding the pattern of the distribution of refractive errors worldwide.

The distribution of refractive errors is not equal in different countries. A high prevalence of myopia in East Asian countries is a common finding in most previous studies.[7] However, there are some controversies regarding hyperopia. Although some studies have shown a high prevalence of hyperopia in Europe and western countries, it is difficult to make a conclusion since most of these studies were conducted on the elderly, and the high prevalence of hyperopia in this age group is a normal finding due to lens changes. Considering the diversity of the results and use of different definitions and measurement techniques, we decided to evaluate the prevalence of refractive errors across the world in this meta-analysis. Moreover, the status of refractive errors in the world is presented according to the WHO regions in this report.

Methods

The present meta-analysis was conducted according to the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.[9]

Search strategy

To extract articles from 1990 to 2016 on the prevalence of refractive errors for this meta-analysis, international databases including Medline, Scopus, Web of Sciences, Embase, CABI, CINAHL, DOAJ, and Index Medicus for Eastern Mediterranean Region-IMEMR were searched. The literature was reviewed using a combination of words like population (children, student, adult, and related MeSH terms), outcome [refractive error, myopia, hyperopia, astigmatism, spherical equivalent (SE), cylinder power], and study design (prevalence, ratio, cross-sectional, survey, descriptive, and epidemiology). A search strategy was developed for MEDLINE which then used for other databases. Table 1 presents the details of the search strategy. In addition, the reference lists of all searched studies and reviews were evaluated to find similar studies.

Table 1
Search strategy for MEDLINE (MeSH, Medical Subject Headings).

1: Refractive errors [Text Word] OR Refractive errors [MeSH Terms]
2: Myopia [Text Word] OR Myopia [MeSH Terms]
3: Hyperopia [Text Word] OR Hyperopia [MeSH Terms]
3: Astigmatism [Text Word] OR Astigmatism [MeSH Terms]
4: Spherical equivalent [Text Word] OR Spherical equivalent [MeSH Terms]
5: Cylinder power [Text Word] OR Cylinder power [MeSH Terms]
6: 1 OR 2 OR 3 OR 4 OR 5 OR 6
7: Pediatric [Text Word] OR pediatric [MeSH Terms]
8: Children [Text Word] OR children [MeSH Terms]
9: Student [Text Word] OR Student [MeSH Terms]
10: Adolescent[Text Word] OR Adolescent[MeSH Terms]
11: Adult [Text Word] OR Adult [MeSH Terms]
12: 7 OR 8 OR 9 OR 10 OR 11
13: Prevalence [Text Word] OR Prevalence [MeSH Terms]
14: Frequency [Text Word] OR Frequency [MeSH Terms]
15: Cross-Sectional [Text Word] OR Cross-Sectional [MeSH Terms]
16: Descriptive [Text Word] OR Descriptive [MeSH Terms]
17: Survey [Text Word] OR Survey [MeSH Terms]
18: 13 OR 14 OR 15 OR 16 OR 17
19: 6 AND 12 AND 18

Study selection

After an extensive search, all studies were entered into EndNote X6. Duplicate articles were identified and removed using the duplicates command. Relevant articles were selected in three phases. In phases 1 and 2, the titles and abstracts of the studies were screened, and irrelevant articles were excluded. In phase 3, the full texts of the studies were carefully evaluated. All three phases were conducted by two interviewers independently (S.M. and F.J.). It should be noted that the reviewers were blind to the process of article selection.

The two reviewers had 81% agreement in finding similar studies and 88.7% agreement in data collection. In the remaining 11.3%, the results were evaluated by a third reviewer (M.P.), and the required data were extracted.

Data extraction and assessment of study quality

The title and abstract of each article was carefully evaluated by 2 reviewers, and data such as the first author's name, publication date, study location (country), study design and characteristics, participants' characteristics (age, sex, sample volume), definitions used for the prevalence of refractive errors, and the prevalence of refractive errors (myopia, hyperopia, and astigmatism) were extracted. The quality of the selected articles was evaluated by the 2 reviewers using the STROBE checklist that contains 22 questions on the methodologic aspects of descriptive studies including the sampling method, study variables, and statistical analysis. The quality assessment results were classified into low quality (less than 15.5), moderate quality (15.5—29.5) and high quality (32—46). Low quality studies were excluded from the meta-analysis.

Eligibility criteria to select articles for meta-analysis

For studies on children under 20 years of age, only the studies that used cycloplegic refraction were selected for the meta-analysis. For studies on adults, the results of age groups above 30 years were included in the meta-analysis. For studies that were conducted on all age groups, if cycloplegic refraction was used, the first author was contacted by email to obtain the results of cycloplegic refraction in participants below 20 years of age and the results of non-cycloplegic refraction in participants above 30 years of age.

Statistical analysis

To compare the prevalence of refractive errors in the six WHO regions, we estimated the prevalence of myopia, hyperopia, and astigmatism in each region based on studies with a similar methodology and definition of refractive errors.

Statistical analysis was performed on all studies that were entered into the meta-analysis. The binomial distribution formula was used to calculate the variance and estimated pooled prevalence. The Q statistic with a significance level of 10% was used to evaluate the presence of heterogeneity, and I^2 was used to determine the amount of heterogeneity among studies. To merge the studies, the random effect model was used if there was heterogeneity, and the fix model was used if there was no heterogeneity. The estimated pool prevalence (EPP) was reported for children and adults separately according to WHO regions.

In this study, the WHO regions according to the most recent classification were African Region, Region of the Americas, South-East Asia, Europe, Eastern Mediterranean region, and Western Pacific region.

The forest plot was used to show the total and specific prevalence of refractive errors. Finally, meta-regression analysis was used to evaluate the trend of the prevalence of refractive error with the study year and sample size. It should be mentioned that all analyses were performed with the STATA software version 11.2.

Results

A total of 9334 articles were identified in this study. After excluding duplicate studies, the titles or abstracts of 4629 articles were reviewed. Then 4326 articles were excluded after reading their abstracts with regards to the inclusion criteria of the study, and 140 articles were excluded after reading their full texts because the required data could not be extracted. Finally, 163 articles were used for the final analysis. However, the number of articles was different for the meta-analysis of myopia, hyperopia, and astigmatism, which is explained in detail in the following sections. Fig. 1 shows the phases of article selection.

Table 2 presents a summary of the results of the studies according to the WHO regions. It should be noted that not all the studies were used in our study, and only the studies that met the criteria were included in the meta-analysis. Table 3 shows the results of meta-analysis for different refractive errors according to the age group and WHO region.

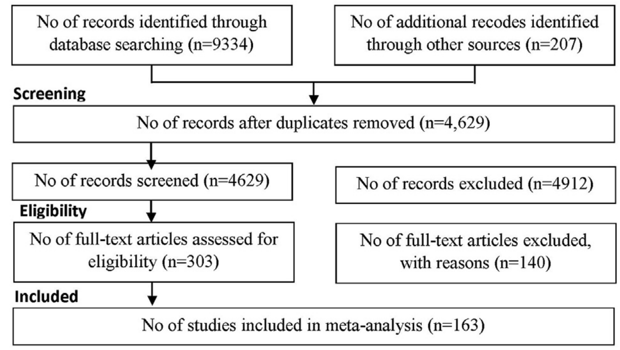

Fig. 1. Flow of information through the different phases of the systematic review.

Prevalence of myopia

We evaluated 157 studies for myopia. A review of the literature showed different definitions of myopia. Of 157 articles, 130 defined myopia based on a cut point of SE ≤ -0.5 diopter (D) or SE < -0.5 D, of which 67 were conducted on children, and 63 were conducted on adults. Of 67 articles on children, 49 (73.1%) used the cut point of SE ≤ -0.5 D and of 63 articles on adults, 50 (79.4%) used the cut point of SE < -0.5 D, which showed a significant difference ($P < 0.001$). Therefore, we used the cut point of SE ≤ -0.5 D in children and SE < -0.5 D in adults for myopia in our meta-analysis.

The total sample size of the 49 articles on children that were included in the meta-analysis was 606,155 children. As shown in Fig. 2 and Table 3, the EPP of myopia was 11.7% [95% confidence interval (CI): 10.5–13.0] in all children based on SE ≤ -0.5 D. As seen in Fig. 2, according to the WHO regions, the EPP of myopia in children ranged from 4.9% in South-East Asia to 18.2% in the Western Pacific region.

The total sample size of the 50 studies on adults that were included in the meta-analysis was 233,025 participants. The results of meta-analysis based on SE < -0.5 D showed that the EPP of myopia was 26.5% (95% CI: 23.4–29.6) in adults. Myanmar had the highest prevalence (51.0%), and India had the lowest prevalence (4.4%). According to Fig. 3 and Table 3, South-East Asia and the Americas had the highest and lowest EPP of myopia, respectively (32.9% vs. 16.2%). Fig. 4 shows the trend of myopia from 1993 to 2016. The results of meta-regression showed that the prevalence of myopia increased from 1993 (10.4% 95% CI: 7.5–13.6) to 2016 (34.2%: 27.6–40.7) (coefficient = 0.004, 95% CI: −0.001–0.009, $P = 0.097$).

Prevalence of hyperopia

The prevalence of hyperopia was reported in 146 articles. Although there were different cut points to define hyperopia, a

Table 2
Summary of studies according refractive errors in worldwide.

Country	Size	Place	Age	Refraction	Myopia		Hyperopia			Astigmatism	
					<−0.5	≤−0.5	≥2	>0.5	≥0.5	≥0.75	≥0.5
USA[10]	11,260	Los Angeles	3−5	Non-cycloplegic		21%			58%		
China[11]	1839	Anyang of Henan	12.9−17.6	Cycloplegic		82.7%			7.5%		
Norway[12]	224	Trondheim	Mean 20.6	Cycloplegic					47%		
China[13]	1565	Inner Mongolia	6−21 Y	Cycloplegic	54.1%			15.5%			
USA[14]	4144	Monterey Park	>50	Non-cycloplegic	35.1%			40.2%		45.6%	
Korea[15]	33,355	Seoul	≥5 Y	Non-cycloplegic	51.9%			13.4%			
China[16]	1415	Harbin	≥40 Y	Non-cycloplegic	38.5%			19.9%			
New York[17]	4709	New York	40−84Y	Non-cycloplegic	21.9%			46.9%			
Puerto Rico[18]	784	Puerto Rico	≥40 Y	Non-cycloplegic	14.7%			51.5%			
Netherlands[19]	520	Dutch	11−13 Y	Non-cycloplegic	28%			8%			
Netherlands[19]	444	Dutch	17−60 Y	Non-cycloplegic	30%			10%			
Bangladesh[20]	11,624	National	≥30 Y	Non-cycloplegic	22.1			20.6%		32.4	
India[21]	1414	Tamil Nadu	>40 Y	Non-cycloplegic	19.4%			39.7%			
Australia[22]	148	Adelaide	44.8 ± 14.5 Y	Non-cycloplegic	31.1%			33.1%			
India[23]	11,786	Hyderabad	≤15 Y	Cycloplegic	3.19%			62.62%			
India[24]	3509	Chennai	>39 Y	Non-cycloplegic		27%		18.7%			54.8%
India[24]	3513	Chennai	>39 Y	Non-cycloplegic		16.8%		52.3%			53%
China[25]	8398	Shanghai	3−10 Y	Cycloplegic		20.1%	17.8%				
California[26]	1501 NHW	Los Angeles and Riverside	6−72 M	Cycloplegic	1.2%[a]		25.65%				
California[26]	1507 Asian	Los Angeles and Riverside	6−72 M	Cycloplegic	3.98%[a]		13.47%				
California[27]	2994	Los Angeles	6−72 M	Cycloplegic			20.8%				
California[27]	3030	Los Angeles	6−72 M	Cycloplegic			26.9%				
Australia[28]	1765	Sydney	6	Cycloplegic			13.2%				
Australia[28]	2353	Sydney	12	Cycloplegic			5.0%				
Brazil[29]	1032	Pelotas	7−15	Non-cycloplegic			13.4%				
India[30]	4074	Hyderabad	7−15 Y	Cycloplegic		4.1%	0.8%			6.30%	
China[31]	5884	Beijing	5−15	Cycloplegic		14.9%	2.6%				
Malaysia[32]	4634	Selangor	7−15 Y	Non-cycloplegic	20.7%					21.3%	
China[33]	2749	Anyang	7.1 Y	Cycloplegic	3.9%		23.3%			25.6	
China[33]	2112	Anyang	12.7 Y	Non-cycloplegic	67.3%		1.2%			28.3	
India[34]	1789	Hyderabad	7−15 Y	Cycloplegic	51.4%		3.3%				
India[34]	1525	Hyderabad	7−15 Y	Cycloplegic	16.7%		3.1%				
Australia[35]	1816	Sydney	6−72 M	Cycloplegic	10.5%		28.9%				
South Africa[36]	1939	Durban	35−90 Y	Non-cycloplegic				37.7%			25.7%
Equatorial Guinea[37]	425	Malabo	6−16 Y	Cycloplegic		10.4%	U(3.1%)			U(32.5%)	
Rwanda[38]	634	Nyarugenge	11−37 Y	Cycloplegic		10.2%			4.3%		4.4%
Ethiopia[39]	4238	Butajira	7−18 Y	Non-cycloplegic		6.0%	0.33%				2.17
Ghana[40]	2435	Ashanti region	12−15 Y	Cycloplegic		3.2%	0.3%				
Kenya[41]	4414	Nakuru	≥50 Y	Non-cycloplegic				27.4%			
Nigeria[42]	13,599	Across the country	≥40 Y	Non-cycloplegic	16.2%			50.7%		63.0%	
Morocco[43]	545	Morocco	6−16 Y	Cycloplegic		6.1%	18.3%.			23.5%	
Benin[44]	1057	Cotonou	4−16 Y	Non-cycloplegic						91.9%	
South Africa[45]	4890	Durban	5−15 Y	Cycloplegic		4.0%	2.6%			9.6	
Uganda[46]	623	Kampala	6 and 9	Cycloplegic		11%	37%			52%	
Ethiopia[47]	811	Gondar	6−16 Y	Non-cycloplegic		4.8%	1.6%				0.4%
South Africa[36]	520 (male)	Durban	20−75 Y	Non-cycloplegic		1.9%					5.8%
Ethiopia[48]	420	Debre Markos	7−15 Y	Non-cycloplegic		5.47%	1.4%				1.9%
Ethiopia[49]	1852	Gondar	4−24 Y	Non-cycloplegic		2.3%				1.3%	
Brazil[50]	7654	Sao Paulo	>1 Y	Cycloplegic		25.3%			33.8%		59.7%
Brazil[51]	2454	Botucatu	1−91 Y	Non-cycloplegic				33.8%			59.7%
Brazil[52]	1608	Rio Grande do Sul	7−10 Y	Non-cycloplegic							
Mexico[53]	317	Toluca	6−12 Y	Cycloplegic		9.7%			5.4%		
Brazil[54]	1024	Natal	5−46 Y	Cycloplegic							
Chile[55]	5303	La Florida	5−15 Y	Cycloplegic		5.8%.	14.5%			27.2%	
Wisconsin[56]	4275	Beaver Dam	43−84 Y	Non-cycloplegic				49.0%			
California[57]	431	Los Angeles	>55 Y	Non-cycloplegic		10.4%			24.8%		31.8%
China[58]	3070	Yongchuan	6−15 Y	Cycloplegic		13.75%					3.75%
Malaysia[59]	705	Kota Bharu	6−12 Y	Non-cycloplegic		5.4%	1.0%			0.6%	
Singapore[60]	946	Singapore	15−19 Y	Non-cycloplegic		73.9%			1.5%		58.7%

Table 2 (*continued*)

Country	Size	Place	Age	Refraction	Myopia		Hyperopia			Astigmatism	
					<−0.5	≤−0.5	≥2	>0.5	≥0.5	≥0.75	≥0.5
China[61]	1892	Xichang	11.4−17.1 Y	Cycloplegic			0.2%			1.7%	
China[62]	2480	Guangzhou	3−6 Y	Cycloplegic		2.5%	20%				
Nepal[63]	440	Kathmandu	7−15 Y	Cycloplegic					31.0%		
India[64]	Urban: 5021	Maharashtra	6−15	Cycloplegic	3.16%		1.06			0.16	
India[64]	Rural: 7401	Maharashtra	6−15	Cycloplegic	1.45%		0.39			0.21	
Cambodia[65]	5527	Phnom Penh	12−14 Y	Cycloplegic		5.8%			0.7%	3.76%	
Singapore[66]	1232	Tanjong Pagar district	40−79 Y	Non-cycloplegic	38.7%			28.4%			
Myanmar[67]	2076	Meiktila district	≥40 Y	Non-cycloplegic							
Indonesia[68]	1043	Sumatra	≥21 Y	Non-cycloplegic					13.9%		
Japan[69]	3021	Tajimi	>40 Y	Non-cycloplegic	51%			27.9%			
India[70]	2522	Andhra Pradesh	40−92 Y	Non-cycloplegic				18.4%			
South Korea[71]	22,562	Knhanes	>20 Y	Non-cycloplegic	41.8%			24.2			
South Korea[72]	1079	Jeolla	8−13 Y	Non-cycloplegic		46.5%			6.2%		
China[73]	2255	Xuzhou	24−80 M	Cycloplegic	48.1						
Vietnam[74]	2238	Ba Ria − Vung Tau	12−15 Y	Cycloplegic		20.4%	0.4%			0.7%	
China[75]	1675	Heilongjiang	5−18 Y	Cycloplegic		5.0%			1.6%		
South Korea[76]	1532	Namil-myeon	≥40 Y	Non-cycloplegic			41.8%				
Nepal[77]	2000	Kathmandu	5−16Y	Cycloplegic	6.85						
India[78]	4711	Not-available	30−100 Y	Non-cycloplegic	20.5%			18.0&			
Laos[79]	2899	Vientiane	6−11 Y	Cycloplegic		0.8%	2.8%			9%	
China,[80]	2422	Bai nationality	6−15 Y	Non-cycloplegic	38.1%			22.8%			
Singapore[81]	2804	Southeast district of Singapore	55−89 Y	Non-cycloplegic	30.1		41.5[a]				
Singapore[82]	2805	Southwestern Singapore	Over 40 Y	Non-cycloplegic	22.8%			35.9%			
Thailand[83]	1100	Bangkok and Nakhonpathom	6−12 Y	Cycloplegic		11.1%	1.4%			0.3%	
China[84]	4979	Harbin	≥50 Y	Non-cycloplegic	28.0%			8.9%			
Singapore[85]	2974	Malay	40−80 Y	Non-cycloplegic				27.4%			
China[86]	4364	Guangzhou	5−15 Y	cycloplegic	9.5%		5.8%			33.6%	
China[87]	2256	Lanzhou	15−19 Y	Non-cycloplegic	35.1%		0.2%			40.8%	
China[88]	4439	Beijing	>40 Y	Cycloplegic	62.3%			19.5%			
China[89]	2515	Yangxi	13−17 Y	Cycloplegic	86.5%		1.20%			25.3%	
India[90]	1062	Kanchipuram	6−16 Y	Cycloplegic	21.4%		0.56				
India[91]	2508	Tamil Nadu	>39 Y	Non-cycloplegic	42.4%			18.70%			
India[92]	6447	New Delhi	5−15 Y	Cycloplegic		7.4%	7.7%			10.19%	
Nepal[93]	5067	Mechi zone	5−15 Y	Cycloplegic		1.2%	2.1%			3.5%	
Poland[94]	5724	Szczecin	6−18 Y	Cycloplegic		13%				4.0%	
Poland[95]	4422	Szczecin	6−18 Y	Cycloplegic		13.3%					
Sweden[96]	143	Gothenburg	4−15	Cycloplegic		6%	9%			22%	
England[97]	2495	Not available	44−46 Y	Non-cycloplegic		47.8	8.8[a]				
England[98] Northfolk	7444	Not available	48−92 Y	Non-cycloplegic		23	39.4[a]				
Norway[97]	5792	Not available	38−87 Y	Non-cycloplegic		19.4	33.7[a]				
Greece[97]	1952	Not available	60−94 Y	Non-cycloplegic		14.2	39.4[a]				
France[97]	618	Not available	73−93 Y	Non-cycloplegic		16.7	53.6[a]				
Netherlands[97]	2662	Not available	14−87 Y	Non-cycloplegic		21.2	27.4[a]				
Germany[97]	14,069	Not available	35−74 Y	Non-cycloplegic		31.9	23.9[a]				
France[97]	576	Not available	76−92 Y	Non-cycloplegic		19.1	51.1[a]				
France[97]	2315	Not available	60−93 Y	Non-cycloplegic		16.2	53[a]				
Netherlands[97]	6566	Not available	55−106 Y	Non-cycloplegic		16.4	52.3[a]				
Netherlands[97]	2579	Not available	55−99 Y	Non-cycloplegic		21.9	45.7[a]				
Netherlands[97]	3530	Not available	46−97 Y	Non-cycloplegic		32.5	28.8[a]				
UK[97]	6095	Not available	16−85 Y	Non-cycloplegic		31.4	26[a]				
Germany[97]	2372	Not available	35−84 Y	Non-cycloplegic		36.1	24[a]				
England[98]	4488	Not available	48−89 Y	Non-cycloplegic		27.8%			49.4%		
Germany[99]	13,959	Gutenberg	35−74 Y	Non-cycloplegic	35.1			31.8%		32.3	
Spain[100]	417	Segovia	40−79 Y	Non-cycloplegic		25.4%			43.6%	53.5	
Greece[101]	1500	Athens	40−77 Y	Non-cycloplegic	35.1%			14.40%			
Sweden[102]	1045	Goteborg	12−13 Y	cycloplegic		49.7%					
Turkey[103]	21,062	Diyarbakir	6−14 Y	Cycloplegic		3.2%					14.3%
Pakistan[104]	45,122	Rawalpindi	5−16 Y	Cycloplegic		1.89%					0.76%

(*continued on next page*)

Table 2 (*continued*)

Country	Size	Place	Age	Refraction	Myopia		Hyperopia			Astigmatism	
					<−0.5	≤−0.5	≥2	>0.5	≥0.5	≥0.75	≥0.5
Turkey[105]	709	Eskisehir	7–8 Y	cycloplegic		22.6%				11.0%	
Iran[106]	1367	Mashhad	>54	Non-cycloplegic	27.2%			51.6%		37.5%	
Iran[107]	1854	Shiraz	7–15	Cycloplegic		4.35%	5.04%			11.27%	
Iran[108]	201	Khaf	19–90	Non-cycloplegic	28			19.2%			14.3%
Iran[109]	1551	Bojnord	6–17	Cycloplegic		4.3%		5.4%		11.5%	
Iran[110]	937	Sari	55–87	Non-cycloplegic				39.5%			
Iran[111]	2098	Yazd	40–80	Non-cycloplegic	36.5			20.6%		53.8	
Jordan[112]	1647	Tafila	12–17 Y	Non-cycloplegic		63.5%			11.2%		
Jordan[113]	1093	Amman	17–40 Y	Non-cycloplegic	36.3%			5.67%		36.8%	
Saudi Arabia[114]	1319	Riyadh	4–6 Y	Non-cycloplegic				2.1%			
Saudi Arabia[115]	1536	Riyadh	12–13 Y	Non-cycloplegic	53.71%						
Pakistan[116]	917	Khyber Pakhtunkhwa	>30 Y	Non-cycloplegic	2.5%						
Iran[117]	4072	8 Cities	7 Y	Cycloplegic	4.5%	3.04%	6.20%				
Pakistan[118]	1644	Kohat	5–15 Y	Non-cycloplegic							
Iran[119]	2410	Tehran	7–12 Y	Cycloplegic		4.9%	3.5%			22.6%	
Iran[120]	1109	Dezful	6–15 Y	Cycloplegic	3.4%		12.9%				
Iran[121]	3675	Mashhad	4–6 Y	Non-cycloplegic							
Pakistan[122]	300	Haripur	5–20 Y	Cycloplegic	14.9%	52.6%			28.4%		
Pakistan[123]	533	Lahore	9–18 Y	Non-cycloplegic							
Iran[124]	2124	Khaf	16–65 Y	Non-cycloplegic							
Iran[125]	434	Aligoudarz	14–21 Y	Non-cycloplegic		29.3%			21.7%		
Iran[126]	1431	Mashhad	18–32 Y	Non-cycloplegic				7.8%			
Iran[127]	5020	Shahroud	40–64 Y	Non-cycloplegic							
Iran[128]	2048	Mashhad	>15 Y	Non-cycloplegic		22.36%			34.21%	25.64%	
Iran[128]	765	Mashhad	≤15 Y	Cycloplegic		3.64%	27.4%				
Iran[129]	5903	Qazvin	7–15 Y	Cycloplegic		65%,	12.46%			16.1%	
China[130]	1269	Liwan	≥50 Y	Subjective	32.3%			40.0%			
Pakistan[131]	14,490	Nationally	>30 Y	Non-cycloplegic				27.1%			
Iran[132]	5544	Dezful	7–15 Y	Cycloplegic		3.4%	16.6%			18.7%	
Pakistan[133]	2317	Kolkata	5–10 Y	Non-cycloplegic	36.5%						
Australia[134]	1936	Sydney	4–12 Y	Non-cycloplegic	14.02%		8.4%		38.4%		
Australia[135]	2535	Sydney	4–12 Y	Non-cycloplegic	3.8%	6.5%				39.25%	
Australia[136]	3654	Sydney	49–97 Y	Non-cycloplegic				57%		37%	
Singapore[137]	10,033	Singapore	>40 Y	Non-cycloplegic		38.9%		31.5%			
Iran[138]	4864	Shahroud	40–65 Y	Cycloplegic		30.2		35.6			
Argentina[139]	1518	Buenos Aires	25–65 Y	Non-cycloplegic				18.1%			
China[140]	6491	Handan	≥30 Y	Non-cycloplegic				15.9%			
Iran[141]	4354	Tehran	≥5 Y	Non-cycloplegic		21.8%		26%		29.6%	
Iran[141]	4354	Tehran	≥5 Y	Cycloplegic		17.2%		56.6%		30.3%	
China[142]	4319	Beijing	40–90 Y	Non-cycloplegic				20%			
Taiwan[143]	2045	Taipei	≥65 Y	Non-cycloplegic	19.4%			59%			
China[140]	6491	Handan	40–79 Y	Non-cycloplegic	22.9%			1.6%			
Mongolia[144]	1617	Hövsgöl and Omnögobi	≥40 Y	Non-cycloplegic	19.4%			32.9%			
Australia[145]	4744	Victoria	≥40 Y	Non-cycloplegic	19.4%			18%			
India[146]	5885	Central Maharashtra	≥30 Y	Non-cycloplegic	17.2%			18%			
Australia[147]	1884	Central Australia	>20 Y	Non-cycloplegic	17%						
Norfolk Island[148]	677	Norfolk Island	≥15 Y	Non-cycloplegic	17%						
Maryland[149]	6000	10 Cities	45–84 Y	Non-cycloplegic	11.1%						
Iran[150]	815	Shahrood	6 Y	Cycloplegic		20.5%	1.7%				
Mongolia[151]	1057	Khovd	7–17 Y	Non-cycloplegic							
India[152]	1378	Bangalore	7–15 Y	Cycloplegic		4.4%					
Mexico[153]	1035	Monterrey	12–13 Y	Cycloplegic		44%					
Iran[132]	3490	Dezful	7–15	Cycloplegic	3.4%		16.6			18.7	

Y: Year, M: Month.
[a] Spherical equivalent (SE) worse than >0.75 diopter (D).

common point in children who underwent cycloplegic refraction was the use of SE ≥ +2 D as the cut point. We also considered this cut point for children who underwent cycloplegic refraction. As for adults, since about 74% of the studies used SE > +0.5 D to define hyperopia, we also adopted this cut point for the meta-analysis of hyperopia.

A total of 91 articles were included in the meta-analysis of hyperopia, 45 of which were conducted on children (cycloplegic refraction, SE ≥ +2 D) and 46 on adults (non-cycloplegic refraction, SE > +0.5 D).

The total sample size of the 45 articles analyzed for children was 200,995 participants. The results of meta-analysis of

Table 3
Estimated pool prevalence (EPP) of myopia, hyperopia, and astigmatism in children and adult by WHO regions.

Astigmatism	Astigmatism	Hyperopia	Myopia
	%EPP(95%CI); weight	%EPP(95%CI); weight	%EPP(95%CI); weight
Children			
Africa	14.2 (9.9−18.5); 10.33	3.0 (1.8−4.3); 10.57	6.2 (4.8−7.6); 16.48
Americas	27.2 (26−28.4); 2.11	14.3 (13.4−15.2); 4.14	8.4 (4.9−12); 6.09
South-East Asia	9.8 (6.3−13.2); 16.47	2.2 (1.2−3.3); 20.89	4.9 (1.6−8.1); 8.52
Europe	12.9 (4.1−21.8); 6	9 (4.3−13.7); 1.04	14.3 (10.5−18.2); 16.04
Eastern Mediterranean	20.4 (14.5−26.3); 29.11	6.8 (4.9−8.6); 30.75	9.2 (8.1−10.4); 26.69
Western Pacific	12.1 (8.4−15.8); 35.98	3.1 (1.9−4.3); 32.59	18.2 (10.9−25.5); 26.18
All	14.9 (12.7−17.1); 100	4.6 (3.9−5.2); 100	11.7 (10.5−13.0); 100
Adult			
Africa	11.4 (2.1−20.7); 8.85	38.6 (22.4−54.8); 6.54	16.2 (15.6−16.8); 2.01
Americas	45.6 (44.1−47.1); 2.95	37.2 (25.3−49); 13.05	22 (16.4−27.7); 7.98
South-East Asia	44.8 (36.6−53.1); 17.58	28 (23.4−32.7); 21.79	32.9 (25.1−40.7); 18.02
Europe	39.7 (34.5−44.9); 8.82	23.1 (6.1−40.2); 4.36	27 (22.4−31.6); 29.99
Eastern Mediterranean	41.9 (33.6−50.2); 29.39	33 (26.9−39); 19.54	24.1 (14.2−34); 13.98
Western Pacific	44.2 (30.6−57.7); 32.41	28.5 (20.1−37); 34.73	25 (20−30.1); 28.01
All	40.4 (34.3−46.6); 100	30.9 (26.2−35.6); 100	26.5 (23.4−29.6); 100

EPP: Estimated pool prevalence.
CI: Confidence interval.

hyperopia in children are presented in Table 3 and Fig. 5. The EPP of hyperopia was 4.6% (95% CI: 3.9−5.2) in children. According to the WHO regions, the lowest and highest EPP was seen in South-East Asia (2.2%, 95% CI: 1.2−3.3) and the Americas (14.3%, 95% CI: 13.4−15.2), respectively.

The total sample size of the 46 articles analyzed for adults was 199,691 participants. The results of meta-analysis of hyperopia in adults are presented in Table 3 and Fig. 6.

The EPP of hyperopia was 30.6% (95% CI: 26.1−35.2) in adults. Based on the results of meta-analysis, Africa had the highest EPP of hyperopia (38.6%, 95% CI: 22.4−54.8) followed by the Americas (37.2%, 95% CI: 25.3−49) while Europe had the lowest EPP (23.1%, 95% CI: 6.1−40.2). The trend of hyperopia was not significant in the past three decades (coefficient: −0.005: 95% CI: −0.012 to 0.002, $P = 0.196$) (Fig. 7).

Prevalence of astigmatism

The definition of astigmatism in epidemiologic studies has less variation. The results of 135 studies on astigmatism were collected which used different cut points to define astigmatism. A cylinder power $\geq$0.5 D and a cylinder power >0.5 were more common definitions in epidemiologic studies. The most common cut point was a cylinder power >0.5 D according to which 82 out of 135 articles on astigmatism were included in the meta-analysis. Considering the changes of astigmatism with age, the articles were divided to those conducted on children and adults. For studies that evaluated age groups above 1 year of age, the data of adults and children were analyzed separately.

48 articles were included in the meta-analysis for children with a total sample size of 152,570 participants. According to Table 3 and Fig. 8, the EPP of astigmatism was 14.9% (95% CI: 12.7−17.1) in children. According to WHO regions, the lowest EPP was seen in South-East Asia (9.8%) while the highest EPP was seen in the Americas (27.2%) followed by the Eastern Mediterranean region (20.4%).

For adults, 34 articles with a total sample size of 122,436 participants were included in the meta-analysis. The results showed that 40.4% (95% CI: 34.3−46.6) of adults had astigmatism (Fig. 9). However, astigmatism showed a lot of variation in different WHO regions; the highest EPP of astigmatism was seen in the Americas, and the lowest EPP was seen in Africa (11.4% vs. 45.6). However, it should be noted only one study was conducted in the Americas. After the Americas, South-East Asia had the highest EPP of astigmatism (44.8%, 95% CI: 36.6−53.1). The trend of astigmatism was not significant in the past three decades (coefficient: 0.003: 95% CI: −0.006 to 0.011, $P = 0.559$).

Discussion

Refractive errors are the most common visual problems.[1] Due to their importance, many studies have evaluated their epidemiology, etiology, and treatment methods. Numerous studies across the world have reported the prevalence of refractive errors as an index of descriptive epidemiology, and it may be the only field in refractive errors which includes reports from almost every corner of the world.[2−4,8,12,14,17−52,54−71,73−76,78−103,105−117,119−130,132−169]

The distribution of refractive errors is clear in some parts of the world according to previous studies; for example, we already know that myopia is prevalent in East Asian countries. However, despite the considerable number of studies on the prevalence of refractive errors, few studies have reviewed the epidemiology of refractive errors systematically to show the status of refractive errors across the world. Due to the importance of refractive errors and scarcity of review and meta-analysis studies in this regard, we evaluated the prevalence of refractive errors systematically in this meta-analysis.

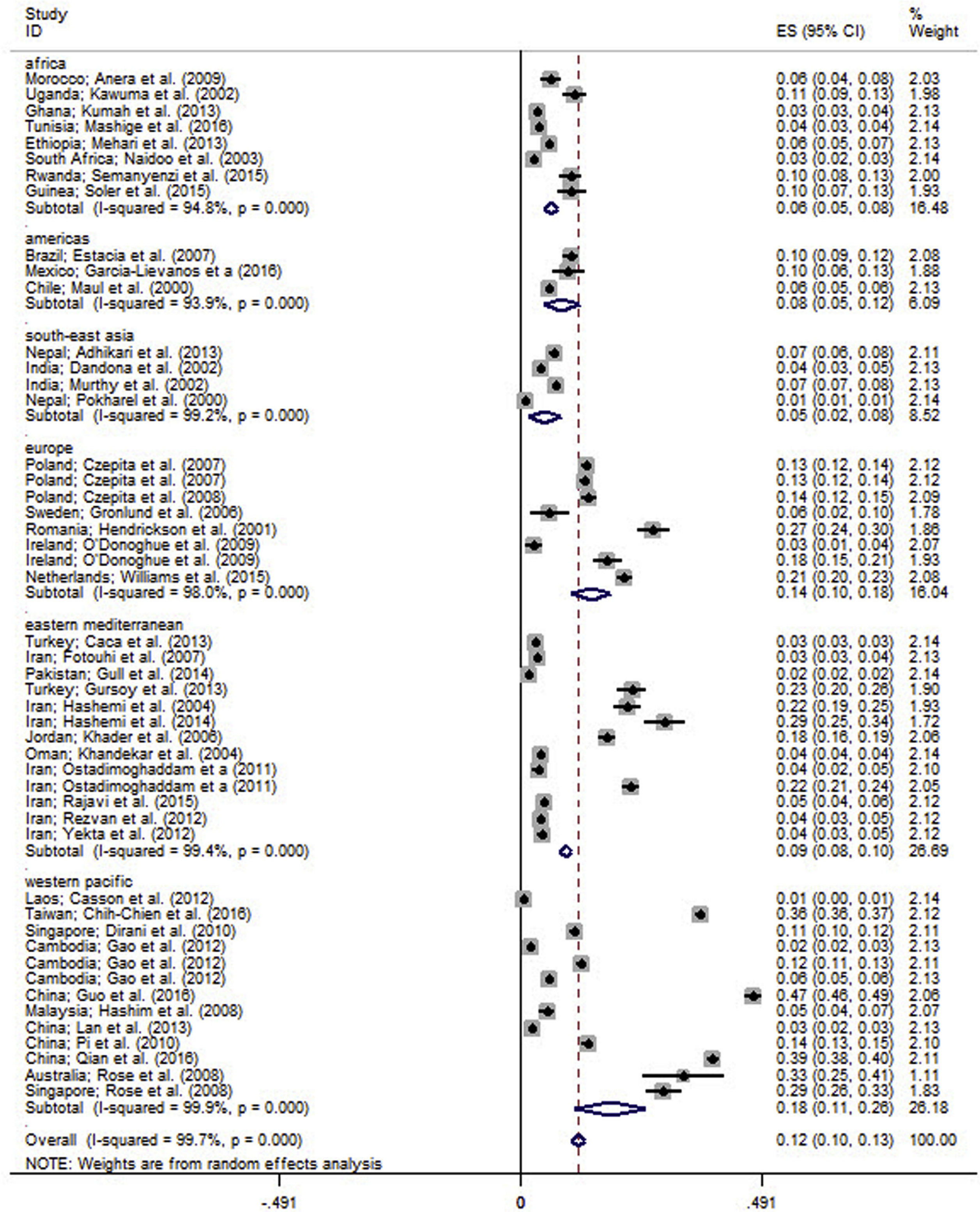

Fig. 2. Forest plot of estimated pool prevalence (EPP) of myopia [spherical equivalent (SE) ≤ −0.5] in children by WHO regions.

The results of different studies in different age groups showed that prevalence of myopia ranged from 0.8% in children aged 6−11 years in Laos[79] to 86.5% in 15−19-year-old Chinese[89] children. However, defining myopia as SE < −0.5 D in adults and SE ≤ −0.5 D in children and considering the results of cycloplegic refraction in children limited this range. The EPP of myopia was about 11.7% in children, ranging from 0.8% in Laos[79] to 47.3% in China. As mentioned earlier, the lowest prevalence of myopia was seen in South-East Asia, and the highest prevalence was seen in the Western Pacific region.

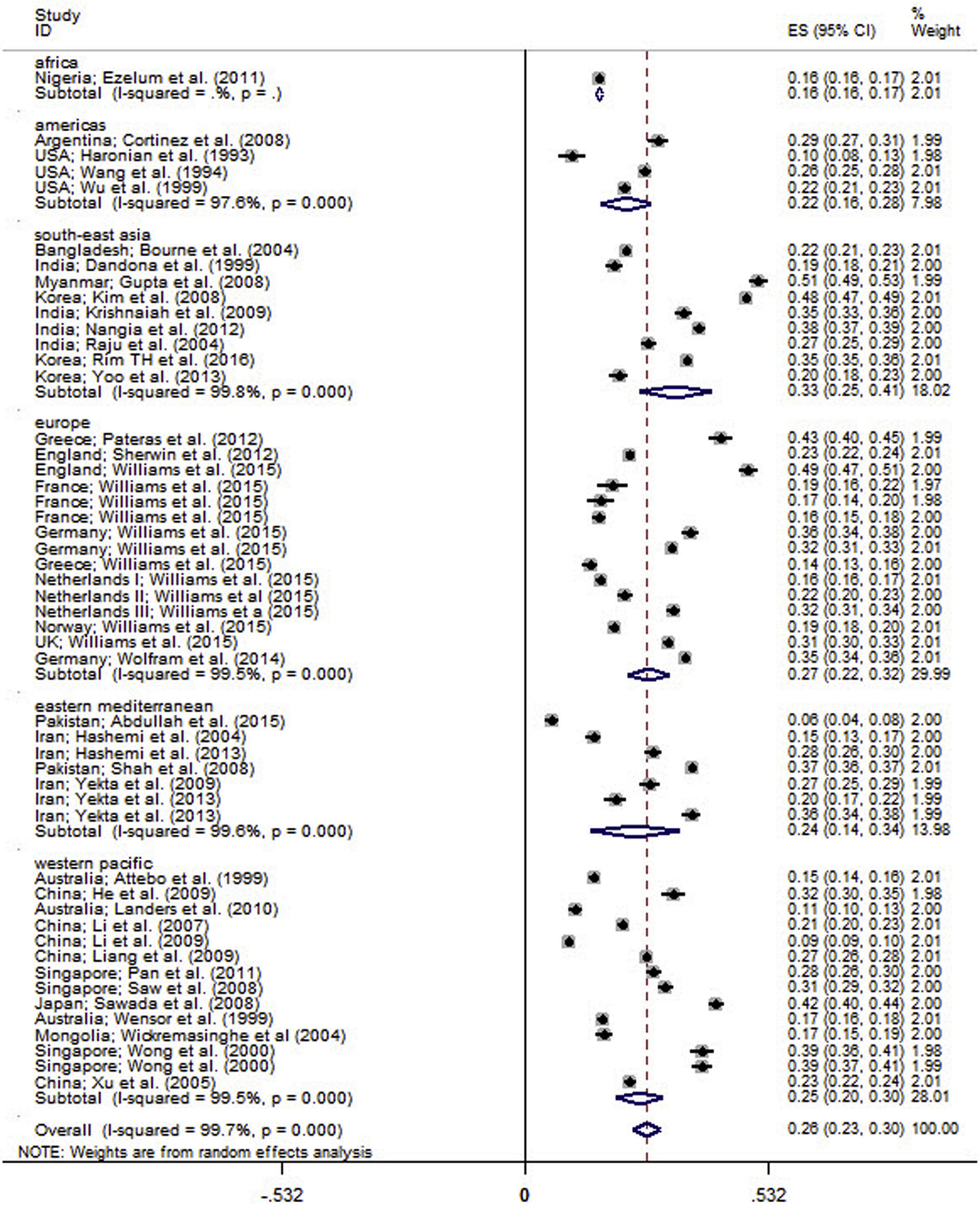

Fig. 3. Forest plot of estimated pool prevalence (EPP) of myopia [spherical equivalent (SE) ≤ −0.5] in adults by WHO regions.

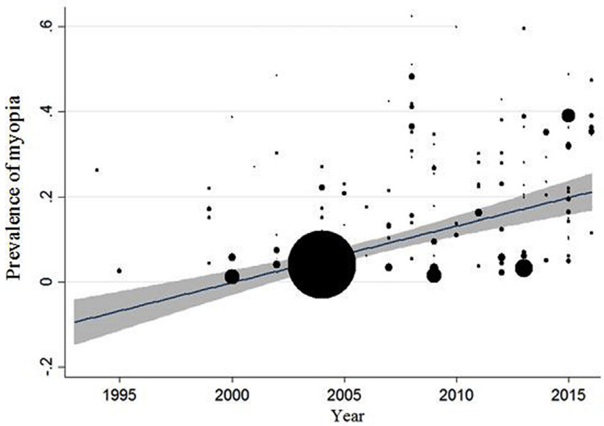

Fig. 4. Trend of myopia from 1990 to 2016.

Previous studies showed myopia aggregation in South-East Asian countries while according to this meta-analysis, myopia aggregation in children is seen in the Western Pacific region.[7] However, it is rather difficult to explain the low prevalence of myopia in South-East Asian children, but it seems that one of the reports from Nepal[63,77,93,170] with a very large sample size decreased the estimated prevalence of myopia in this region.

In adults, the prevalence of myopia ranged from 4% to 51%, and the EPP of myopia was 26.5%. The highest prevalence of myopia in adults was seen in South-East Asia, and the lowest prevalence was seen in the Africa. A comparison of the results of myopia in children and adults suggests different questions and hypotheses as to why children have the lowest and adults have the highest prevalence of myopia in South-East Asia. It seems that the limited number of studies on children in South-East Asia is one of the reasons for this finding while there is more variation in adults. On the other hand, in South-East Asia, only studies on children and adults from India were included in our meta-analysis; therefore, it may be rather difficult to make a comparison and the finding may be influenced by the Indians' race.

It seems that in countries like South-East Asian countries where the prevalence of myopia is low in children and high in adults, environmental factor have a more prominent role than genetic and ethnic factors, or the genes responsible for myopia in these individuals are expressed at higher ages.

It has been previously shown that some genes are responsible for myopia; however, it is well documented that the genes cannot cause myopia per se.[7] In 1969, a study[171] was conducted on Eskimos in northern Alaska whose living conditions were about to change. Only 2 out of 131 adults who grew up in isolated communities had myopia whereas more than half of their children and grandchildren were myopic.

Regarding this meta-analysis, we believe that countries like China and Singapore that are categorized under the Western Pacific region have genetic differences with the current South-East Asian countries because the distribution of myopia in childhood and adulthood is similar in these countries. With regards to the high prevalence of myopia in children and adults in Europe, we believe that the role of genetic and ethnic factors is more important than environmental factors.

As mentioned earlier, children in South-East Asia had the lowest and children in the Americas had the highest prevalence of hyperopia. In adults, Africans and Americans had the highest and Europeans had the lowest prevalence of hyperopia. It is a little perplexing to explain the results; however, the results of meta-analysis showed a high prevalence of hyperopia in American children and adults. Moreover, although the prevalence of hyperopia in African adults was a little higher than American adults, its prevalence was higher in American children. Emmetropization may play a role in this regard, and in addition to ethnic and genetic factors, differences in computerization and lifestyle changes may have contributed to increased prevalence of hyperopia in African and American regions as compared to other parts of the world. The role of myopization in hyperopia becomes more prominent when we consider the results of Europe where the prevalence of hyperopia is the lowest and the prevalence of myopia ranks second.

The results of our meta-analysis showed that about 15% of children and 40% of adults had astigmatism. However, the prevalence of astigmatism has a great variation in different studies, ranging from 0.3% in Thailand[83] to 91.9% in Benin.[44] The use of a cylinder power >0.5 D as the cut point in our study limited this range. Although part of the variation can be due to differences in age groups, we observed this variation in both adults and children.

As mentioned earlier, the lowest and the highest prevalence of astigmatism in children was seen in South-East Asia and the Americas, respectively. However, according to Table 3, the Eastern Mediterranean and Western Pacific regions have the highest variation in the prevalence of astigmatism. One of the limitations of the studies conducted in the Eastern Mediterranean region is that most of them are from Iran,[106–111,117,119–121,124–129,132,138,141,150,155,156,172–175] which makes conclusion difficult, although a range of 6.6–51.4% for astigmatism in Iran is also noticeable.

The highest and the lowest prevalence of astigmatism was seen in American and African adults, respectively. However, the details of the results presented in tables and figures reject this finding. After the Americas, South-East Asia followed closely by the Western Pacific region had a high prevalence of astigmatism. The only eligible study for astigmatism analysis in the Americas was conducted on Chinese people living in the USA; therefore, it is in fact related to the Western Pacific region. Ethnic and racial differences may have a more prominent role in astigmatism in comparison with myopia and hyperopia.[176]

It seems that the eyelid and palpebral fissure shape in South-East Asian and some Western Pacific countries is the major cause of high astigmatism in these people.[176] A great part of the high prevalence of astigmatism in Western Pacific countries is due to the high prevalence of astigmatism in Chinese people.

The findings of this meta-analysis provide a new perspective of the status of refractive errors across the world based on the WHO classification.

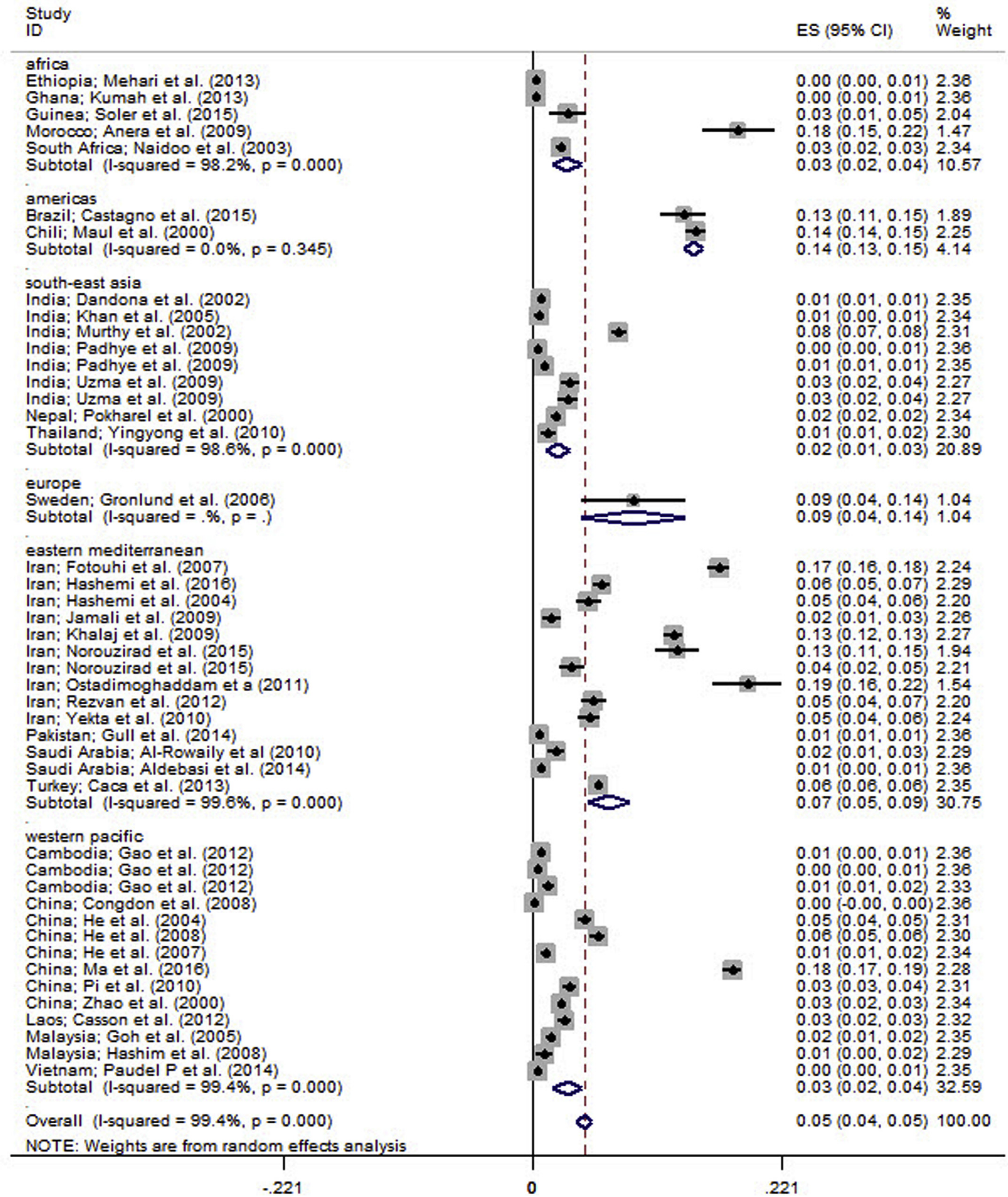

Fig. 5. Forest plot of estimated pool prevalence (EPP) of hyperopia [spherical equivalent (SE) $\geq +2$] in children by WHO regions.

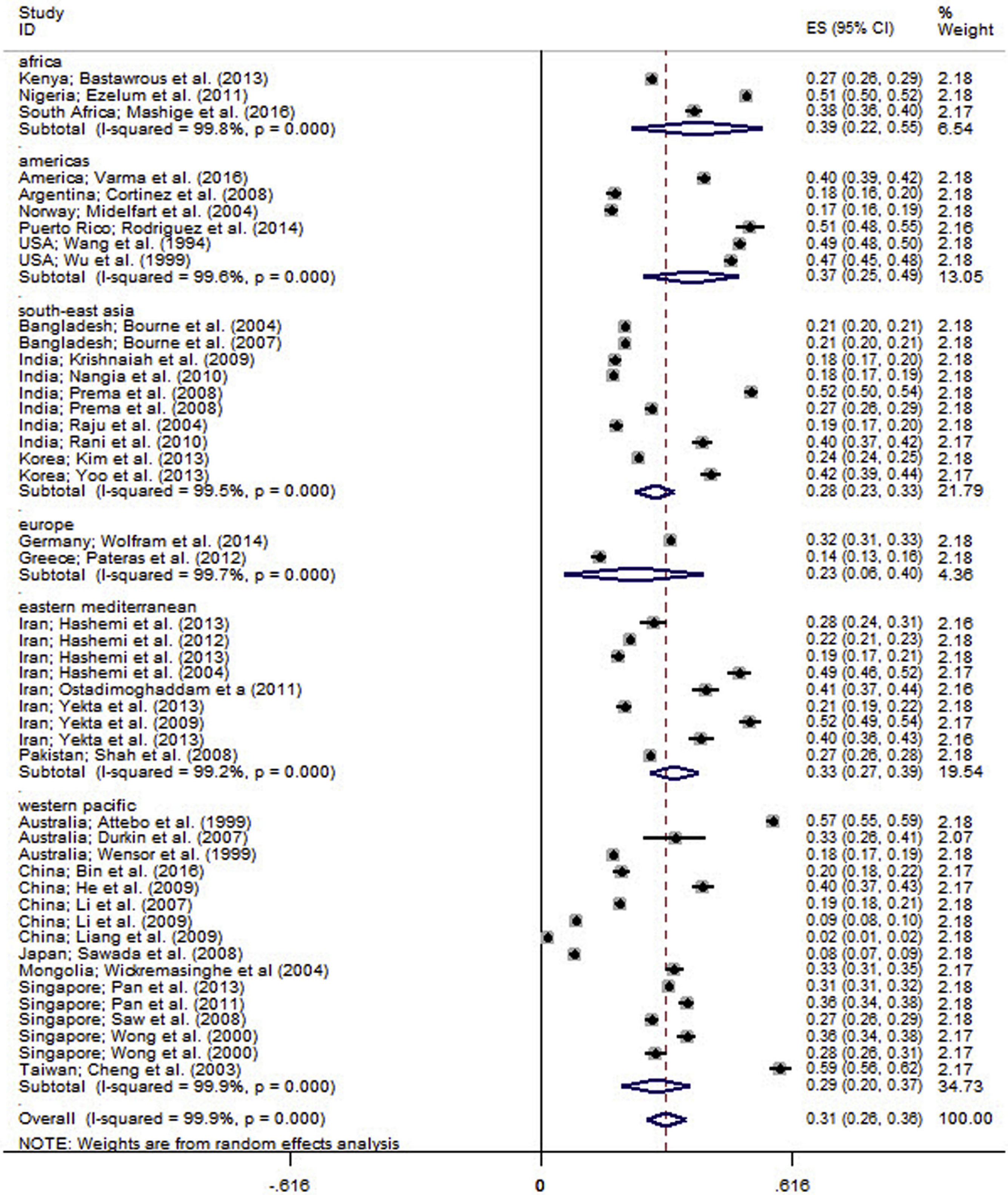

Fig. 6. Forest plot of estimated pool prevalence (EPP) of hyperopia [spherical equivalent (SE) > +0.5] in adults by WHO regions.

As mentioned earlier, the prevalence of myopia, hyperopia, and astigmatism in children was lower in South-East Asian countries in comparison with other WHO regions while in adults, the highest prevalence of myopia was seen in South-East Asia. On the other hand, the prevalence of hyperopia was high in both children and adults in American countries. Therefore, it seems that environmental factors may have a more important role in myopia since children are not myopic,

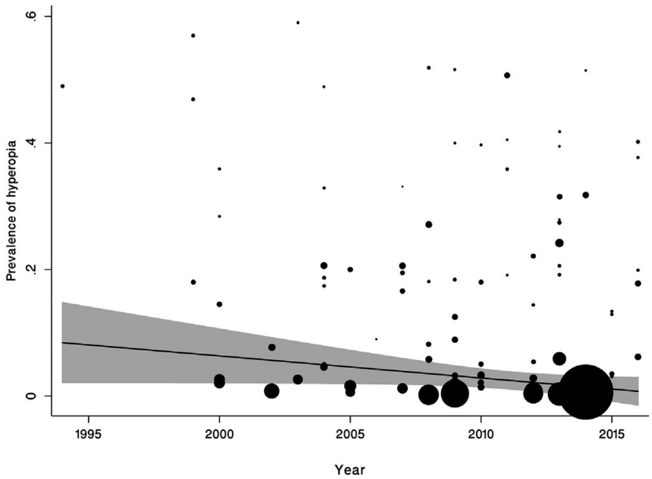

Fig. 7. Trend of hyperopia from 1990 to 2016.

and its prevalence is higher in adults in regions where near work is more common.[7] On the other hand, ethnic and genetic factors could have a more prominent role in hyperopia since the highest prevalence of hyperopia was seen in American children and adults.

The results of myopia and astigmatism in children and adults are interesting. The lowest and highest prevalence of myopia and astigmatism was seen in South-East Asian children and adults, respectively. It should be noted that common factors can cause myopia or astigmatism. The relationship between near work and myopia has been shown in different studies.[177,178] Some studies have reported that near work causes astigmatism due to incyclotorsion.[179,180] On the other hand, there are reports that 15-year-old children in some Asian countries spend more time on near work than their counterparts in some countries like UK and USA.[7] Therefore, it is possible that near work in this age group has caused astigmatism in non-astigmatic children due to incyclotorsion, manifesting the problems of astigmatism and myopia in adulthood. However, the role of ethnic, genetic, and environmental factors should be taken into account, as well.

Squinting can cause astigmatism, especially with the rule (WTR) astigmatism, in myopic patients and myopia in astigmatic patients.[181] Previous studies have shown the relationship between astigmatism and myopia.[181—183] However, the use of the SE in epidemiologic studies should not be overlooked. Considering the fact that astigmatism is part of the SE with a minus sign, this index is considered myopia in a spherically emmetropic individual due to a negative cylinder power. Therefore, part of this relationship can be due to the use of SE.

Our results showed that the prevalence of myopia had an increasing trend in the past three decades. Many studies have reported that myopia is becoming an epidemic, especially in East Asian countries, but few meta-analyses have confirmed this finding. The results of our meta-regression confirmed the increasing trend of myopia. Different reasons can be mentioned for the increase in the prevalence of myopia worldwide, including lifestyle changes and ever-increasing use of the computer and computer-related systems resulting in increased near work. Different studies have evaluated the mechanism of developing myopia following near work. Increased lens thickness and the pressure of the ciliary muscle on the globe wall increase the axial length (AL) during accommodation. Some researchers believe that optical changes during accommodation (increased accommodative lag or increased higher order aberration) can change the choroidal thickness, resulting in AL changes during near work.[184] However, it should also be noted that myopic patients are more interested in near work. In addition to the effect of near work, more and more people use computers for their daily activities as a result of computerization, and are not therefore engaged in outdoor activities.[177,181,185] The hypothesis of the effect of outdoor activity on myopia has been tested in many studies.[178,185] A recent clinical trial showed that the incidence of myopia was about 10% lower in children who were engaged in outdoor activities.[185] Other studies have confirmed this finding as well.[178,186] According to this hypothesis, the factor that prevents myopia in outdoor activity is light. Some studies[187,188] have shown the role of intense light in the prevention of myopia formation. The mechanism is that light stimulates the secretion of dopamine in the retina which in turn prevents ocular elongation during the process of ocular development and prevents myopia. Finally, the age cohort effect should not be forgotten.

According to our results, astigmatism and hyperopia did not have a significant trend in the past three decades. As mentioned earlier, although the trend of hyperopia was not significant, the prevalence of hyperopia had a decreasing trend from 1990 to 2016 with a regression coefficient similar to myopia. First, we believe that the non-significant trend of hyperopia during these three decades may be due to the lower number of studies in hyperopia analysis. Second, more variation in the results of hyperopia versus myopia during the three decades may play a role the non-significant trend of hyperopia. However, the results of this meta-analysis propose the hypothesis that the decrease in the prevalence of hyperopia may be due to the increase in the prevalence of myopia in these years.

Considering the stability of the trend of astigmatism, although an increase was expected in its trend as in myopia, it seems that the role of outdoor activity in myopia is more prominent than near work because near work was expected to have a similar effect on the trend of astigmatism as well.

Lack of studies in many countries and lack of studies in each year in many countries were among the limitations of our study. Many studies were not included in the final analysis because they used different criteria for the detection of refractive errors or because we only analyzed the studies published in English. An important limitation of many studies was that they did not use cycloplegic refraction in children which caused us limitations in the analysis of refractive errors in individuals under 20 years of age. Although we tried to include studies with similar criteria in the analysis, these exclusion criteria may have biased the results. We did not evaluate different categories of refractive errors as low, moderate, or high myopia or hyperopia. Although there was great

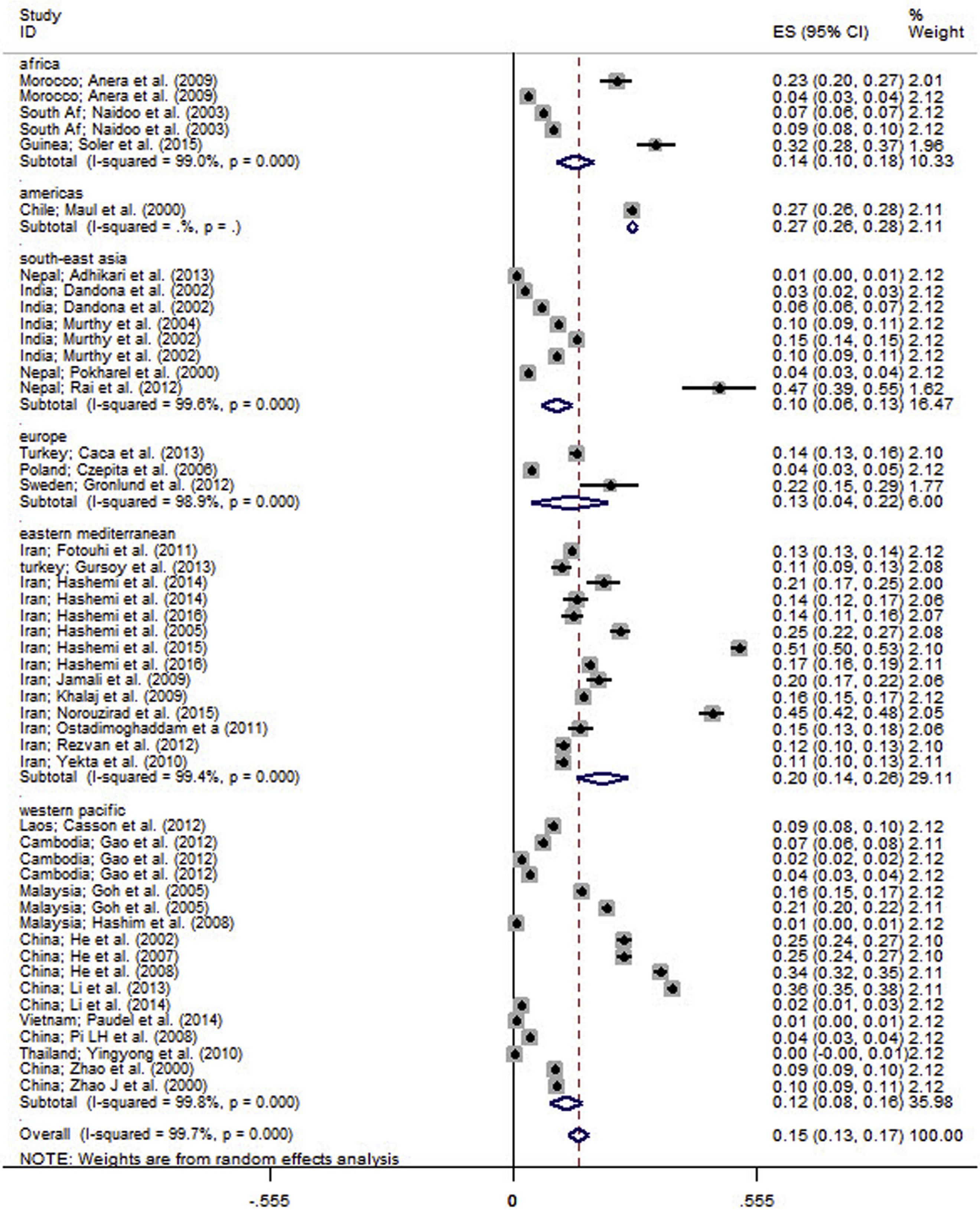

Fig. 8. Forest plot of estimated pool prevalence (EPP) of astigmatism (cylinder power >0.5) in children by WHO regions.

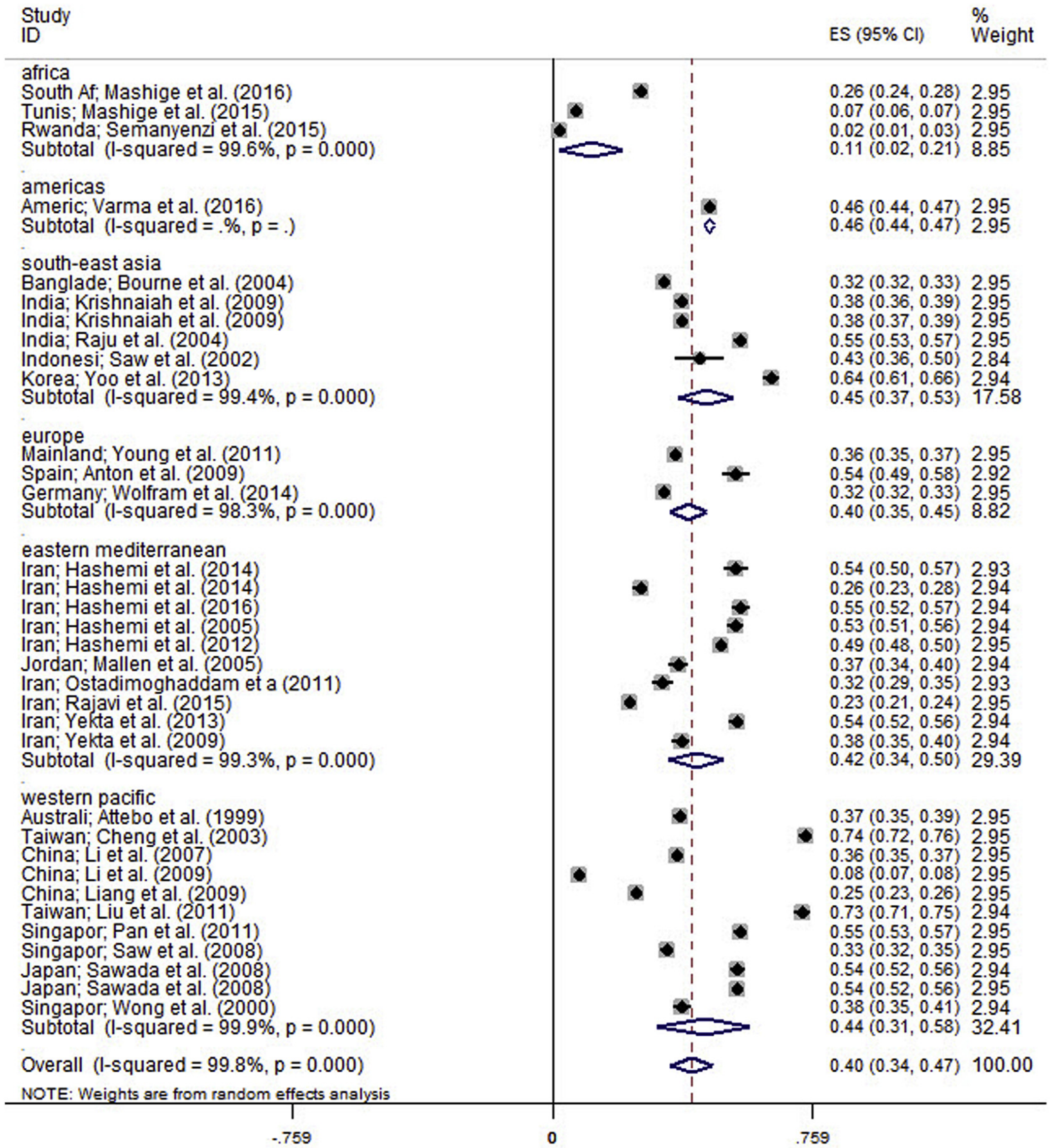

Fig. 9. Forest plot of estimated pool prevalence (EPP) of astigmatism (cylinder power >0.5) in adults by WHO regions.

heterogeneity in the results of the studies, we tried to address the differences among studies through subgroup analysis and using a random effects model. Despite the above limitations, this is the first study to show the overall prevalence of refractive errors according to WHO regions regardless of any categorization, which can be considered the most important advantage of the study.

In conclusion, this meta-analysis showed the prevalence of myopia, hyperopia, and astigmatism in children and adults separately according to WHO regions for the first time. The results showed that astigmatism, hyperopia, and myopia were the most common refractive errors in children and adults in the mentioned order. Children in South-East Asia had the lowest prevalence of astigmatism, hyperopia, and myopia as compared to other WHO regions, while the highest prevalence of myopia and astigmatism was seen in South-East Asian adults. The highest prevalence of hyperopia in children and adults was seen in the Americas. A direct correlation was found between the prevalence of myopia and astigmatism in most WHO regions. The trend of myopia has increased linearly in the past three decades, maybe as a result of increased indoor activity due to computerization in recent years.

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