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External skeletal robusticity of children and adolescents – European references from birth to adulthood and international comparisons

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With 2 figures and 3 tables

Abstract: *Background:* In our modern world, the way of life in nutritional and activity behaviour has changed. As a consequence, parallel trends of an epidemic of overweight and a decline in external skeletal robusticity are observed in children and adolescents. *Aim:* We aim to develop reference centiles for external skeletal robusticity of European girls and boys aged 0 to 18 years using the Frame Index as an indicator and identify population specific age-related patterns. *Methods:* We analysed cross-sectional & longitudinal data on body height and elbow breadth of boys and girls from Europe (0–18 years, n = 41.679), India (7–18 years, n = 3.297) and South Africa (3–18 years, n = 4.346). As an indicator of external skeletal robusticity Frame Index after Frisancho (1990) was used. We developed centiles for boys and girls using the LMS-method and its extension. *Results:* Boys have greater external skeletal robusticity than girls. Whereas in girls Frame Index decreases continuously during growth, an increase of Frame Index from 12 to 16 years in European boys can be observed. Indian and South African boys are almost similar in Frame Index to European boys. In girls, the pattern is slightly different. Whereas South African girls are similar to European girls, Indian girls show a lesser external skeletal robusticity. *Conclusion:* Accurate references for external skeletal robusticity are needed to evaluate if skeletal development is adequate per age. They should be used to monitor effects of changes in way of life and physical activity levels in children and adolescents to avoid negative health outcomes like osteoporosis and arthrosis.

Introduction

In our modern world, the way of life has changed, particularly in nutritional and activity behavior. As a consequence, the prevalence of overweight has increased enormously and the world is experiencing a severe epidemic of overweight and obesity, through all age groups (NCD Risk Factor Collaboration 2017). In Europe the prevalence of overweight and obesity ranges from 10% to 40% in children and adolescents with girls being more affected than boys (Ahrens et al. 2014). For example, in Germany 26% of all boys and girls aged 5 to 19 years were overweight or obese (WHO 2017).

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Prevalence is smaller in South-East Asia (13.4%) and Africa (17%), whereas countries within a region differ a lot (WHO 2017). For instance, children living in India have, depending on the data source, either a smaller or higher risk of being overweight or obese than German children (15% to 50%; (Ramachandran et al. 2002; Kotian et al. 2010; Schönfeld Janewa et al. 2012). Further, the prevalence of overweight in South African boys and girls varies from 4% to 25% (Kruger et al. 2006; Kimani-Murage et al. 2010), depending on age, sex and region. WHO recently reported a prevalence of 24.7% (WHO 2017). Besides high risk for cardiovascular diseases and diabetes, overweight is also associated with arthrosis, in particular in adulthood (Anderson & Felson 1988; Sandmark et al. 1999; Stürmer et al. 2000).

As a parallel trend to the increase in overweight and obesity, a decline in external skeletal robusticity in school children and young adolescents was observed in the last 20 years, e.g. in Germany (Scheffler 2011; Rietsch et al. 2013a; Scheffler & Hermanussen 2014) and Russia (Rietsch et al. 2013b). As a main reason lack of activity, in particular daily physical activity, is assumed (Rietsch et al. 2013a). As an indicator for external skeletal robusticity the Frame Index by Frisancho (1990), which reflects elbow breadth in relation to body height, is commonly used. A low external skeletal robusticity during childhood and adolescence might have severe negative health outcomes e.g. high risk of bone fractures or osteoporosis in later life. To minimize the risk factors and negative health outcomes, children's and adolescents' skeletal robusticity should be analysed and monitored. Under average physical activity, bone tissue is mainly build during growth periods in childhood and adolescence (Matkovic et al. 1994). Young adults aged 19–25 years have achieved the highest bone mineral density (BMD) and bone mass (BM) levels of their life span, followed by a constant decrease to a variable extent (Berger et al. 2010). In females, 85–90% of the BM is reached at an age of 18 years, and in males at an age of 20 years (Heaney et al. 2000). Bone remodelling, replace of mature bone tissue by new bone tissue takes place during the whole life span. However, after the peak in BMD and BM, removal rate of mature bone tissue is higher than build-up rate of new bone tissue, leading to a reduction in BMD and BM throughout life (Grupe 2005). Exceptions can be observed in individuals with very high physical activity levels, e.g. participants of competitive sports like tennis (Kannus et al. 1995; Haapasalo et al. 1998). Due to the high physical strain and load on the bones, build-up rates are higher than removal rates of bone tissue. As a consequence, BMD and BM are increased even in adulthood. However, for the majority of a population, which has average physical activity levels, continuous decrease of BMD and BM during adulthood can be assumed. This decrease is a function of what was cumulated during growth and what was lost thereafter (Schönau 2004). The external skeletal robusticity can also be seen as an estimator for bone mass as it is highly correlated with bone width and body height (Schönau 2004). Children and adolescents with low external skeletal robusticity, and therefore low bone mass, have a higher risk of low bone density in adulthood and, as a consequence, diseases like osteoporosis. Furthermore, the parallel trend of an increase in body mass (due to overweight) and a decrease of external skeletal robustness, raises the risk of arthrosis (Seidell et al. 1986;Heliövaara et al. 2009) due to a higher compression (weight) on low dense bones.

References for external skeletal robusticity for European children and adolescents from birth to adulthood are so far missing. Published information either includes (1) only elbow breadth, but no Frame Index e.g. (Frisancho 1990), (2) only mean and standard deviation but no centiles (Stolzenberg et al. 2007) or (3) only specific age groups (Rietsch et al. 2013b; Hesse et al. 2016). In particular, information for pre-school children (under the age of 6) is rarely available.

In this study, we aim to develop reference centiles for external skeletal robusticity of European girls and boys aged 0 to 18 years using the Frame Index as an indicator. Further, we aim to investigate if population specific age-related patterns of external skeletal robusticity exist.

Samples and methods

Samples

We analysed cross-sectional & longitudinal data on body height and elbow breadth of boys and girls from Europe (0–18 years, n = 41,679), India (7–18 years, n = 3,297) and South Africa (3–18 years, n = 4,346). European dataset includes data from Germany (n = 20,337), Poland (n = 19,157), Czech Republic (n = 930) and Russia (n = 2,342). Data of children and adolescents from different European countries were pooled as they do not differ significantly in body height and elbow breadth per age and sex. Data from India and South Africa was used for an international comparison. Children and adolescents have been measured between 1986 and 2017. Details on datasets have been published elsewhere (Germany: Schilitz 2001; Kamtsiuris et al. 2007; Scheffler et al. 2007; Schüler 2009; Rietsch et al. 2013a; Hesse et al. 2016. Russia: Rietsch et al. 2013b. Poland: Gomula et al. 2015; Nowak-Szczepanska et al. 2016; Suder et al. 2017. Czech Republic: Sedlak et al. 2015. India: Das et al. 2016. South Africa: Mumm et al., unpubl.; Henneberg & Louw 1998). Datasets include information on body height, elbow breadth, sex and age in years. Age in days was available for European children and adolescents and a part of South African 3 to 14-year-olds. For data from India and South Africa (5 to 18 years) age was available in completed years. Table 1 shows sample size per sex and age group of the studied samples.

Table 1. Sample size per sex and age group.

	Europe		India		South Africa	
age	**girls**	**boys**	**girls**	**boys**	**girls**	**boys**
0	643	763				
1	135	165				
2	161	180				
3	286	295			23	18
4	461	483			29	34
5	492	573			52	47
6	1060	1214			154	142
7	1543	1480	153	123	209	184
8	1534	1378	152	124	208	194
9	1644	1556	146	129	168	175
10	1630	1550	156	116	140	168
11	1699	1581	142	123	144	134
12	1642	1535	140	146	151	119
13	1471	1532	136	158	234	190
14	1496	1536	137	137	209	153
15	1803	1839	144	126	193	173
16	1677	1594	132	138	182	141
17	1278	1214	137	142	139	104
18	317	232	132	128	61	65

Statistics

We used the Frame Index as an indicator of external skeletal robusticity. Frame Index was calculated after Frisancho (1990) as: Frame Index = elbow breadth (in mm)/body height (in cm)*100.

Centiles for boys and girls were calculated combining the LMS-method by Cole (1990) and Cole & Green (1992) and its extension by Rigby & Stasinopoulos (2004; 2016). The R package 'gamlss' of the statistical software R was modified and adapted to the datasets to create reference centiles for European and centiles for Indian and South African boys and girls as sample sizes were too small to be representative for individual countries. European references centiles were compared with calculated centiles of India and South Africa.

Results

In all studied samples Frame Index decreases with age in boys and in girls, indicating a greater increase in height than in skeletal width with age (Fig. 1 and Fig. 2). Girls and boys differ in absolute values of Frame Index; boys have greater external skeletal robusticity than girls. However, whereas in girls Frame Index decreases continuously during growth, a small increase of Frame Index from 12 to 16 years with a maximum at 14 years in European boys can be observed. Indian and South African boys are similar in pattern and absolute values of Frame Index to European boys in all centiles, except for the described small increase during puberty. The Frame Index of Indian and South African boys decreases from childhood during adolescences until adulthood. Male adolescents from India and South Africa might either lack the puberty-related change in external skeletal robusticity or show a methodological artefact due to missing exact ages.

In girls, the pattern of Frame Index is slightly different. South African girls are similar in external skeletal robusticity, measured as absolute values and centiles of Frame Index, to European girls in all age groups. In contrast, Indian girls differ considerably in Frame Index from European and South African females. During the age period from 7 to 18 years, Indian females show smaller Frame Index values in all centiles, and therefore a lesser external skeletal robusticity. As an example, the 10th centile of Indian girls is below the 3rd centile of European and South African girls. As the centiles are almost equally spaced, this pattern continues through the centiles, so that e.g. the 97th centile of Indian females is below the 90th centile of European and South African girls.

Reference centiles and L, M and S values for Europe are presented in Table 2 (boys) and Table 3 (girls). Corresponding centiles and L, M and S values for South Africa and India are available on enquiry.

Discussion

Independent of sample (origin and population) the Frame Index, an indicator of external skeletal robusticity, decreases with age in boys and girls from childhood to adulthood. This decline of external skeletal robusticity is basically a change of proportions during human development. Humans experience a greater linear growth, reflected in body height, than a growth in skeletal breadth. Our analysed samples from Europe, India and South Africa support the so far published trend in school children and young adolescents seen in Germany, Russia (Rietsch et al. 2013b), and United States of America (Frisancho 1990).

Although the general age-related decline of external skeletal robusticity is similar in females and males, sex-specific differences occur for absolute values and trend of Frame Index. In particular, Frame Index of boys remains slightly increases during adolescent growth spurt, whereas it is decreasing further in girls. During adolescent growth spurt sex-specific hormone levels, e.g. testosterone and oestrogen, are known to influence growth in boys and girls and result in slightly sexually different growth patterns (August et al. 1972; Klein et al. 1996). Whereas oestrogen is involved in linear skeletal growth in prepubertal boys, testosterone promotes bone density and linear growth in adolescent boys. In girls, however, oestrogen is involved in both, linear growth and skeletal mineralization during the whole growth period. However, testosterone is not correlated with bone density in girls (Yilmaz et al. 2005). Low testosterone level in boys in

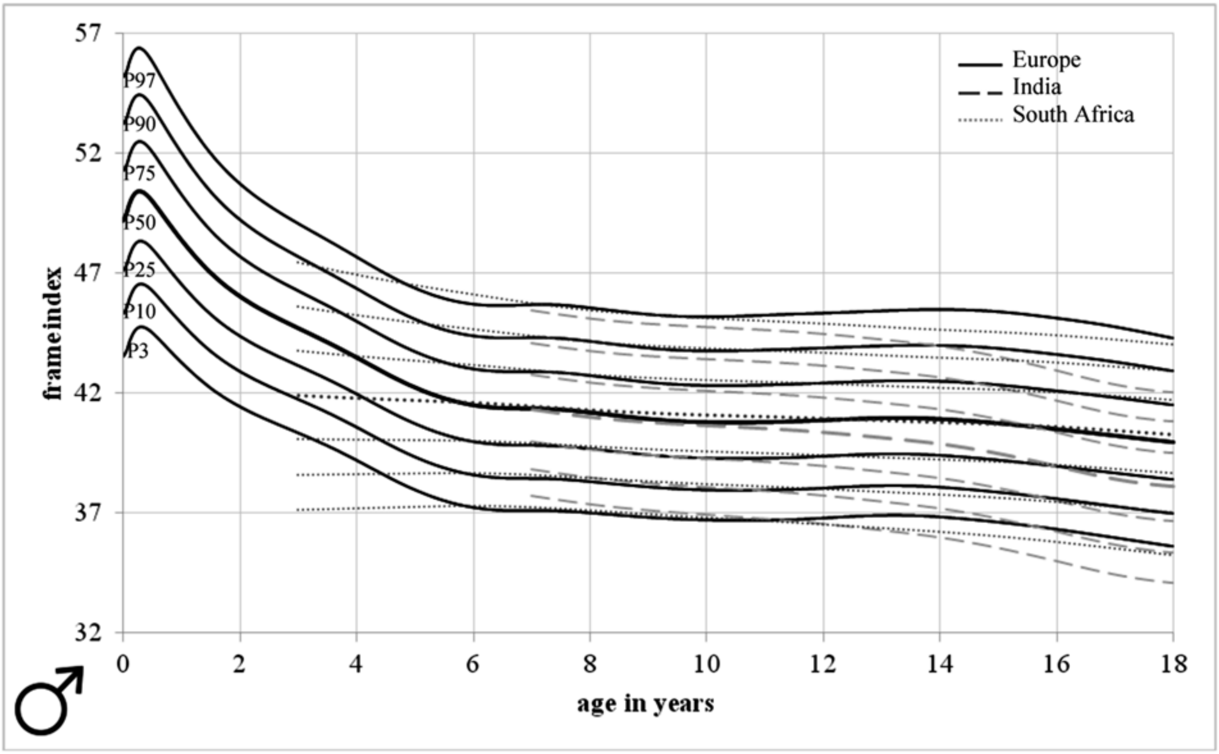

Fig. 1. Boys. Centiles of frame index for Europe, South Africa and India.

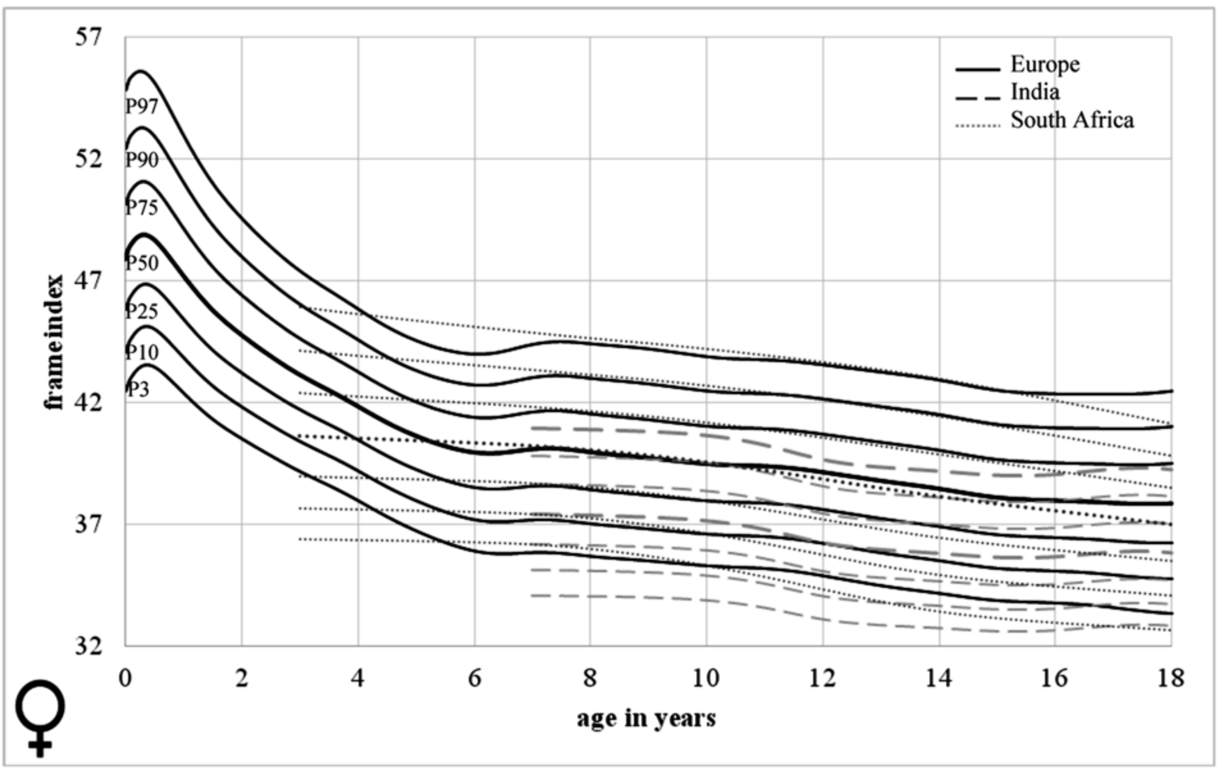

Fig. 2. Girls. Centiles of frame index for Europe, South Africa and India.

Table 2. European boys. Centiles for frame index, sample size (n) and L. M and S values.

age	n	L	S	P3	P10	P25	P50(M)	P75	P90	P97
0	574	0.499	0.063	43.57	45.33	47.15	49.21	51.32	53.26	55.21
0.5	189	0.586	0.060	44.52	46.24	48.02	50.02	52.06	53.93	55.79
1	88	0.678	0.057	43.28	44.89	46.55	48.41	50.29	52.01	53.72
1.5	77	0.776	0.055	42.21	43.74	45.30	47.04	48.80	50.40	51.98
2	79	0.878	0.054	41.44	42.91	44.40	46.06	47.73	49.24	50.74
2.5	101	0.988	0.053	40.86	42.29	43.73	45.34	46.95	48.39	49.82
3	155	1.102	0.052	40.35	41.75	43.17	44.74	46.30	47.70	49.08
3.5	140	1.217	0.052	39.81	41.20	42.60	44.15	45.68	47.05	48.39
4	239	1.315	0.052	39.21	40.59	41.99	43.51	45.03	46.37	47.69
4.5	244	1.382	0.052	38.56	39.95	41.34	42.86	44.36	45.69	46.99
5	259	1.395	0.053	37.97	39.36	40.75	42.27	43.77	45.10	46.40
5.5	314	1.335	0.054	37.52	38.91	40.30	41.82	43.32	44.66	45.97
6	560	1.213	0.054	37.24	38.62	40.00	41.53	43.05	44.40	45.73
6.5	654	1.056	0.055	37.12	38.49	39.87	41.41	42.94	44.31	45.67
7	760	0.898	0.055	37.11	38.47	39.85	41.39	42.93	44.33	45.71
7.5	720	0.770	0.055	37.09	38.44	39.81	41.34	42.89	44.30	45.70
8	653	0.679	0.055	37.01	38.34	39.70	41.23	42.77	44.18	45.58
8.5	725	0.589	0.055	36.92	38.23	39.57	41.09	42.63	44.03	45.44
9	783	0.499	0.055	36.83	38.12	39.45	40.96	42.49	43.90	45.31
9.5	773	0.421	0.055	36.76	38.04	39.36	40.86	42.40	43.81	45.22
10	768	0.347	0.055	36.72	37.99	39.31	40.82	42.35	43.77	45.20
10.5	782	0.284	0.055	36.70	37.98	39.30	40.80	42.35	43.78	45.22
11	826	0.249	0.056	36.71	37.98	39.31	40.82	42.38	43.81	45.27
11.5	755	0.241	0.056	36.74	38.01	39.34	40.86	42.41	43.86	45.31
12	745	0.230	0.056	36.80	38.07	39.39	40.90	42.46	43.90	45.35
12.5	790	0.192	0.055	36.86	38.13	39.45	40.95	42.51	43.94	45.40
13	782	0.132	0.055	36.91	38.17	39.48	40.99	42.54	43.98	45.45
13.5	750	0.069	0.056	36.90	38.16	39.48	40.99	42.55	44.01	45.49
14	703	0.017	0.056	36.85	38.11	39.43	40.95	42.53	44.00	45.51
14.5	833	-0.024	0.057	36.75	38.02	39.34	40.88	42.47	43.96	45.48
15	983	-0.040	0.057	36.63	37.90	39.24	40.78	42.38	43.88	45.42
15.5	856	0.006	0.057	36.49	37.77	39.11	40.66	42.26	43.76	45.30
16	873	0.103	0.058	36.33	37.63	38.98	40.53	42.13	43.63	45.15
16.5	721	0.265	0.058	36.16	37.47	38.84	40.39	42.00	43.48	44.99
17	681	0.489	0.058	35.98	37.32	38.70	40.26	41.85	43.32	44.79
17.5	533	0.768	0.058	35.80	37.16	38.56	40.12	41.70	43.13	44.56
18	170	1.081	0.058	35.62	37.01	38.42	39.99	41.54	42.94	44.32

early puberty promoting height, and high testosterone level in late puberty promoting external skeletal robusticity, might lead to a greater increase in external skeletal robusticity in boys during growth spurt than in girls.

A comparison of our samples revealed a slightly diverse pattern in absolute values and trend of Frame Index in Europe, India and South Africa. Indian and South African boys are similar in absolute values to European boys but do not show a small increase in external skeletal robusticity during puberty. This is either a population specific pattern which needs further investigation or a methodological problem. Growth spurts and developmental tempo are unique for any individual and highly diverse (Hermanussen 2013), particularly during puberty. Therefore, variability of anthropometric

Table 3. European girls. Centiles for frame index, sample size (n) and L. M and S values.

age	n	L	S	P3	P10	P25	P50(M)	P75	P90	P97
0	500	–0.958	0.067	42.51	44.10	45.82	47.91	50.19	52.42	54.83
0.5	143	–0.748	0.063	43.49	45.04	46.71	48.70	50.84	52.91	55.11
1	74	–0.534	0.059	42.41	43.86	45.41	47.23	49.16	51.01	52.94
1.5	61	–0.315	0.056	41.33	42.70	44.15	45.83	47.60	49.26	50.99
2	73	–0.088	0.053	40.54	41.85	43.22	44.80	46.45	47.98	49.56
2.5	88	0.148	0.052	39.84	41.11	42.43	43.94	45.49	46.93	48.39
3	133	0.381	0.051	39.19	40.43	41.72	43.18	44.67	46.03	47.41
3.5	153	0.613	0.050	38.61	39.85	41.11	42.54	43.98	45.30	46.61
4	210	0.818	0.050	37.99	39.22	40.48	41.89	43.30	44.58	45.85
4.5	251	0.989	0.050	37.33	38.57	39.82	41.22	42.62	43.88	45.12
5	232	1.105	0.051	36.75	38.00	39.27	40.67	42.07	43.33	44.56
5.5	260	1.159	0.052	36.27	37.54	38.83	40.26	41.67	42.94	44.18
6	501	1.153	0.054	35.92	37.23	38.54	40.00	41.44	42.74	44.01
6.5	559	1.092	0.055	35.81	37.14	38.49	39.99	41.48	42.81	44.13
7	773	0.991	0.057	35.86	37.22	38.60	40.13	41.66	43.04	44.41
7.5	770	0.868	0.058	35.83	37.19	38.59	40.14	41.70	43.12	44.52
8	759	0.747	0.058	35.70	37.06	38.45	40.01	41.58	43.01	44.43
8.5	775	0.641	0.058	35.61	36.95	38.33	39.88	41.46	42.90	44.33
9	864	0.584	0.058	35.51	36.85	38.22	39.77	41.34	42.78	44.22
9.5	780	0.589	0.058	35.41	36.74	38.10	39.64	41.21	42.64	44.07
10	833	0.648	0.058	35.31	36.64	38.00	39.53	41.08	42.49	43.91
10.5	797	0.718	0.058	35.25	36.58	37.94	39.47	41.01	42.42	43.81
11	841	0.763	0.058	35.20	36.54	37.90	39.43	40.98	42.38	43.78
11.5	858	0.788	0.058	35.08	36.43	37.80	39.34	40.89	42.30	43.70
12	869	0.805	0.059	34.90	36.26	37.64	39.19	40.75	42.16	43.57
12.5	773	0.812	0.060	34.69	36.06	37.45	39.01	40.58	42.01	43.42
13	725	0.813	0.060	34.49	35.87	37.27	38.84	40.42	41.85	43.27
13.5	746	0.807	0.060	34.33	35.70	37.11	38.68	40.26	41.70	43.12
14	722	0.800	0.061	34.18	35.54	36.94	38.51	40.09	41.52	42.94
14.5	774	0.800	0.060	34.01	35.37	36.76	38.31	39.88	41.30	42.72
15	926	0.797	0.060	33.88	35.23	36.61	38.15	39.71	41.12	42.52
15.5	877	0.783	0.060	33.82	35.16	36.54	38.07	39.62	41.03	42.42
16	829	0.772	0.060	33.78	35.12	36.49	38.02	39.57	40.98	42.38
16.5	848	0.780	0.061	33.71	35.06	36.44	37.98	39.54	40.96	42.36
17	745	0.822	0.062	33.59	34.96	36.36	37.93	39.51	40.94	42.36
17.5	533	0.888	0.063	33.45	34.86	36.29	37.89	39.50	40.95	42.39
18	242	0.971	0.064	33.35	34.80	36.27	37.91	39.55	41.03	42.50

measures e.g. body height and elbow breadth increases during puberty. This variability may only be captured if exact chronological age at measurement is known. As for South African and Indian males, unfortunately, age is only available in completed years, and therefore variability decreases which may mask the Frame Index increase during adolescent growth spurt. However, an analysis of the European data-set using completed years (not presented) instead of exact chronological age did not show any differences. Therefore, further investigation is necessary to identify the underlying population-specific effects. In females, a similar effect, a slight increase of Frame Index in post-pubertal Indian girls, can be seen. However, whereas South African girls are similar in Frame Index over all ages, Indian girls differ – they are less robust in skeleton in all centiles. Indian females seem to have a lower external skeletal robusticity than European girls. Studies on external skeletal robusticity in relation to ethnic background are missing so far. Yet, Megyesi et al. (2011) have summarized several studies on BMD and BM of women from different ethnic origin showing that Asian women also seem to have a lower BMD compared to women of European origin (Mehta et al. 2004). However, in line with other studies, these results have to be critically reviewed as these differences are not persistent after correction for body weight and lifestyle. Then, BMD and BM are greater in Asian women than in European women (Russell-Aulet et al. 1993; Finkelstein et al. 2002; Alver et al. 2005). Thus, risk of fractures is lower in Asian than in European females (Finkelstein et al. 2002). Based on our findings, specific references for external skeletal robusticity may be needed for Asian children and adolescents, especially for girls. Further research is necessary to study the underlying mechanisms in Asian populations.

Accurate references for external skeletal robusticity are needed to evaluate if skeletal development is adequate per age. Whereas high Frame Index values indicate a high level of physical activity of populations and individuals, children and adolescents with low external skeletal robusticity, e.g. under 10th centile, can have a high risk of arthrosis and osteoporosis in adulthood. To reduce the risk and to start interventions e.g. sport programs and increased daily physical activity, these children need to be detected. Further, an early detection of low external skeletal robusticity increases the success rate of interventions.

Conclusion

The newly developed European reference centiles for external skeletal robusticity should be used to monitor effects of changes in way of life and physical activity levels in children and adolescents. If external skeletal robusticity is in critical ranges, interventions e.g. sport programs, may be considered to avoid negative health outcomes like osteoporosis and arthrosis, particularly with the ongoing increase in prevalence of overweight and obesity.

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