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Original Article

Reference data for jumping mechanography in healthy children and adolescents aged 6-18 years

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Abstract

Objectives: To present gender-specific pediatric normative data on the main parameters of muscle function assessed using jumping mechanography. **Methods:** The study population included 796 non-selected Caucasian children and adolescents (432 girls and 364 boys) aged 6-19 years recruited from 6 primary schools and 3 high schools. Maximum peak power (P_{max}) was examined by a single two-legged jump, and maximum force (F_{max}) was examined by a multiple one-legged hopping. All measurements were performed using a portable force platform (Leonardo Mechanograph, Novotec). P_{max}, P_{max}/mass, F_{max} and F_{max}/body weight were analyzed as the main outcome parameters. LMS method was used to generate age- and weight-specific reference smooth curves. **Results:** Both P_{max} and F_{max} were strongly dependent on age and weight in both genders (all p<0.001). In prepubertal children, there was no intergender difference in P_{max} or F_{max}. Both parameters steadily increased in boys and plateaued in girls aged >13 years. Whereas P_{max}/mass was more dependent on anthropometric parameters, F_{max}/BW remained nearly constant with respect to age and weight. **Conclusions:** These reference data are intended to assist clinicians in the assessment of muscle function by jumping mechanography in pediatric patients.

Keywords: Jumping Mechanography, Muscle, Children, Power, Force

Introduction

Bone development is strongly dependent on stimulation by skeletal muscles. Indeed, many densitometric studies using both areal and volumetric techniques have shown that muscle mass as a surrogate of muscle function correlates well with bone mass as well as with other parameters of bone strength[1-4]. As formulated by Harold Frost several decades ago in his mechanostat hypothesis, muscles are the most important stimulators for a bone, which adapts to mechanical stimuli by increasing its mass and changing its geometry[5]. In other words, the increase in bone strength as a function of structural adaptation is driven by the highest bone strains, which are induced by muscle force[6]. Co-examination of bone and muscle parameters is thus of crucial importance when differentiating between primary and secondary (i.e., muscle-determined) osteoporosis[7].

Examination of muscle function is still challenging. Among the techniques used for muscle assessment in children, measurement of grip force by dynamometry is probably the most widely available test. However, this method has limited relevance for the examination of muscle force because it only assesses isometric force at the upper extremity, i.e., at the non-weight-bearing part of the body. Conversely, dynamometry does not mirror the movement patterns used in children and adolescents during their daily physical activities[8,9]. New techniques such as the portable ground reaction force plates, which are able to examine dynamic muscle function during a vertical countermovement jump test for maximal height, seem promising while representing simple and reliable methods for assessing muscle function. Jumping mechanography was designed to measure muscle force and power by deriving measurements from an individual's ground reaction forces and

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is therefore able to give a more complex picture about muscle function and body coordination compared to isometric techniques. This method is becoming widely used to analyze muscle function in children and adults[10-13].

Jumping mechanography assesses muscle function using various tests[14]. Two of them are mostly used in children: single two-legged jump (S2LJ) and multiple one-legged hopping (M1LH). S2LJ is a vertical countermovement jump aiming to achieve maximum jump height. Its results are influenced by a variety of factors, such as muscle power, coordination, balance, and jumping technique. The S2LJ test results might therefore mirror the characteristics of the daily performance of the motor system, so S2LJ regarded as a 'screening test' for anaerobic fitness. The aim of the one-legged hopping test is to achieve a maximal ground reaction force. M1LH's application is thus to evaluate the maximal force to which the tibia is exposed and thus might be used to evaluate the muscle-bone unit[15].

The clinical utility of jumping mechanography has been confirmed by a number of studies. Most importantly, Anliker et al.[16] recently described a strong correlation between the maximum force (F_{max}) performed during the M1LH test and bone mineral content (BMC) at the 14% site of the tibia measured by pQCT in children and adults and showed that F_{max} predicted 84% of the BMC, i.e., more than the calf muscle cross sectional area. These results highlight the diagnostic role of jumping mechanography in a complex evaluation of musculoskeletal health. Importantly, there is low variability in inter-day test-retest assessment of the main outcome parameters of these tests (varying from 3.4% to 7.5%) in healthy children[15], which illustrates the potential of the method to be used as a screening tool for examining muscle function in children at risk of musculoskeletal impairment.

One of the limitations of this method is the lack of pediatric reference data. The only published reference values were derived from 135 boys and 177 girls enrolled in German primary and high schools[10]. This dataset constitutes a substantial part of the corresponding section of the manufacturer's software. However, these data have significant weaknesses. First, only values of the S2LJ were published. Second, subjects were not equally distributed by age, and some age categories were represented by only a few subjects, especially in adolescents. Therefore, to enable jumping mechanography to become widely usable in clinical practice as a basic screening method for muscle function assessment, there is a need to examine a larger pediatric population and test the reproducibility of the test as administered by different investigators. The aim of our study was to create a pediatric reference data set for basic parameters assessed by jumping mechanography (S2LJ and M1LH) using the Leonardo Jumping Platform.

Materials and methods

Study population

The study population included healthy non-selected Caucasian children and adolescents recruited from 6 primary schools and 3 high schools. Six schools (4 primary schools and 2 high schools) were in Prague, and the remaining 3 schools were located in Úpice, a small city in eastern Czech Republic. The recruitment strategy was as follows: the basic information about the study was sent to all parents or guardians of pupils attending the schools via their children. All children whose parents gave informed consent and who met the inclusion criteria were included to the study. As inclusion criteria, participants had to be healthy and able to perform S2LJ and M1LH according to the recommendations for measurement by the Leonardo Mechanograph published elsewhere[15]. They were excluded if they presented with a diagnosed musculoskeletal condition or were taking any medication for muscle, bone, or cartilage. Their current health status, including medication, was reviewed using a structured questionnaire distributed to the parents together with the informed consent form up to two days before the measurement. No medication known to influence bone metabolism was given, except for thyroxin substitution for autoimmune thyroiditis in two girls, which had been long-term euthyroid before the measurement.

The children and their parents were fully informed about the purposes and risks associated with the measurements before providing written informed consent. Informed consent was obtained from all individuals and their parents if the subject was younger than 18 years. The study was approved by the Ethics Committee of the University Hospital Motol, Prague.

Anthropometry

On the day of the mechanography assessment, the height was measured by a stadiometer to the nearest 1 mm, and the weight was measured by an electronic scale to the nearest 100 g. BMI was calculated as weight (kg) divided by height squared (m^2). For these three anthropometric variables, Z-scores were calculated using the national reference data[17].

Mechanography

Dynamic muscle function was assessed using a Leonardo Mechanograph® Ground Reaction Force Plate (Novotec Medical, Pforzheim, Germany) as described in detail previously[10,15]. This is a force platform with a length of 66 cm, a width of 66 cm and a height of 7 cm. The platform is composed of two symmetrical force plates that separate the platform into a left and a right half. The force plate has eight sensors (four per half), with each sensor recording force at a sampling frequency of 800 Hz. Force is detected by a deformation of the detector that is proportional to the applied force. The detector changes its electrical resistance proportionally to the deformation, the change of force measured over time is recorded by the computer. For the detection, storage, and calculation of data, we used the manufacturer's software (Leonardo Mechanography GRFP version 4.2, Novotec, Pforzheim, Germany). The tests were performed at each school on one occasion during the regular hours of physical education, with the child dressed in light clothing without shoes.

Single two-legged jump (S2LJ)

The aim of this jump is to achieve maximum jump height. The individual stood on the plate, and each foot was placed on

	Total (N = 796)	Girls (N = 432)	Boys (N = 364)
Age (yr)	11.8±3.5	12.0±3.7	11.6±3.2
Height (cm)	149.0±18.0	147.69±17.23	150.62±18.88
Height (Z-score)	-0.24±0.97***	-0.32±1.01***	-0.14±0.91**
Weight (kg)	43.2±15.5	42.69±14.8	43.87±16.3
Weight (Z-score)	0.13±1.03***	0.07±1.06	0.2±0.99***
BMI (kg/m²)	18.9±3.2	18.99±3.25	18.79±3.17
BMI (Z-score)	0.25±1.04***	0.25±1.03***	0.25±1.06***

*Mean ± SD values are given. The Z-scores were calculated using the national reference data. BMI=body mass index. Asterisks indicate differences between the study group and reference data (*p<0.05 **p<0.01 ***p<0.001).*

Table 1. Anthropometric characteristics of the entire study group.

one section of the jumping platform. The jump was performed as a counter-movement jump with freely moving arms, and the subjects were instructed to jump as high as possible with the head and chest. Subjects jumped using both feet and landed on both feet. All children performed three jumps, and the highest jump of the three recordings was selected for further calculations. Parameters used for analysis were maximal peak power (P_{max}; both legs together; W), P_{max}/mass (W/kg) and maximum height (H_{max}). Body mass was calculated by software using the principle of Cavagna as described elsewhere[15].

Multiple one-legged hopping (M1LH)

M1LH aims to achieve maximum voluntary forefoot ground reaction force during landing. One possible application of this test is to evaluate the maximal force to which the tibia is exposed, and thus it might serve to evaluate the muscle-bone unit[15,18]. Children started from an upright standing position with feet positioned hip-wide. To start the maneuver, they lifted the non-dominant-side foot off the force plate and started to jump repeatedly (approximately fifteen jumps comparable to hopping during rope skipping) on the forefoot of their dominant leg with a stiff knee. During the first few jumps, children were instructed to jump as fast as possible, whereas the subsequent jumps (about ten) were accomplished as high as possible. Importantly, they were advised never to touch the ground with their heels during the jumping maneuver. Any jumps with heel contact were excluded from the analysis. Heel contact was controlled visually during the jumping maneuver and/or detected by the manufacturer's software. The M1LH was performed with freely moving arms. For M1LH, we present the results of maximum force (F_{max}) and F_{max}/body weight (F_{max}/BW, no unit).

Statistical analysis

The Z-scores for anthropometrical parameters were compared with the healthy population using a one-sample t-test.

Reference curves were generated using the Cole's LMS method[19] that is widely used to derive non-linear age-, weight and sex-dependent data[20,21]. The LMS method fits 3 parameters (LMS) as smooth functions of age or weight, calculated separately for each gender, by using nonparametric regression techniques. The LMS parameters are the median (M), the generalized coefficient of variation (S), and the power in the Box-Cox transformation (L). At first, we calculated L, M, and S for each age- and weight-category . Using these tables, we have decided to fix a single value of L for each of the parameters (see Tables 2-12). Next, we fit the conditional mean and the conditional variance function of each anthropometrical parameter by using a nonparametric local polynomial kernel smoother[22] with the bandwidth parameter chosen automatically by AIC[23]. For L=0, the conditional mean and the conditional variance functions is calculated from logarithms of measurements. For L=0.5, both functions are estimated from square roots of measurements. More precisely, the conditional mean function is estimated as a convex combination of locally linear and locally constant kernel regression estimators with weights of the locally linear smoother changing linearly from 1 to 0 from the youngest to the oldest subject.This simple weighting scheme allows to correct the boundary effects of the purely locally constant or purely locally linear kernel regression estimators and to capture the approximately linearly increasing trend observed in the youngest subjects and, at the same time, to model the plateauing effect observed in the oldest subjects. The conditional variance function is estimated by applying a locally constant kernel regression estimator to squared residuals. Mostly for numerical reasons, we have considered weight on logarithmic scale for the purpose of this analysis.

For L=0, the parameter M is calculated as the exponential of the conditional mean of logarithms and the parameter S is defined as the square root of the corresponding estimated conditional variance. In this situation, the Z-score (Z) for a given measurement (X) may be calculated as:

$Z = \ln(X/M)/S$

For L=0.5, the parameter M is calculated as the square of the conditional mean of square roots and the parameter LS as the ratio of the square root of the corresponding conditional variance (i.e., the conditional standard deviation) and the conditional mean. It follows that the Z-score may be calculated as:

$Z = [(X/M)^L) – 1]/ LS$

Standard two-sample t-test with Welch approximation to degrees of freedom is used to compare the means observed for boys and girls in each age and weight category. A quadratic regression model was used as a simple parametric model describing its dependence on age and weight. The gender effect was modeled by interaction terms that allowed us to fit separate quadratic regressions for both genders within one linear model and that were also used to test the regression submodel corresponding to the hypothesis of no gender effect. All statistical analyses were performed using the statistical computing environment R[24].

Results

S2LJ results were available for 796 healthy non-selected Caucasian children and adolescents (432 girls and 364 boys) aged 6-19 years (median age was 11.6 years; IQR 9.0-14.5 years). Characteristics of the study group are shown in Table 1. M1LH was performed in a subgroup of 376 children (194 girls and 182 boys) who did not differ from the entire group in any anthropometric characteristic.

The age- and weight-dependent reference curves for P_{max} , P_{max}/mass and H_{max} obtained by the S2LJ, and for F_{max} and F_{max}/BW obtained by the M1LH are presented in Figures 1-5. Figures 1 and 2 show the scatter plot of individual values with the mean and 2 standard deviations, Figures 3-5 illustrate the smoothed percentile graphs for these variables. The L, M and S parameters and percentile distributions are presented in Tables 2-10. Differences between genders are depicted in Tables 11 and 12 (Annex).

Single two-legged jump

As expected, P_{max} depended strongly on age and weight in both genders, as shown by high coefficients of determination (R^2=0.76 and 0.85, respectively, in girls and 0.84 and 0.86, respectively, in boys). Similar to F_{max}, the age-dependent reference curves for P_{max} flattened significantly in late adolescence in girls, whereas there was no intergender difference in prepubertal children. P_{max} started to differ significantly between girls and boys after the age of 13 years and in children heavier than 50 kg (Table 11). Correspondingly, tests of equality of regression lines showed significant differences in P_{max} between girls and boys whether assessed by age or weight ($p<0.001$ for all predictors).

Compared to F_{max}/BW (see below in detail), P_{max}/mass was more dependent on anthropological parameters, as illustrated by moderate coefficients of determination. Especially in boys, we observed a continuous, significant increase of P_{max}/mass with age and weight (R^2=0.27 and 0.18, respectively, in girls and 0.56 and 0.33, respectively, in boys) (Figures 3 and 4, Tables 3 and 7). Similar to P_{max}, P_{max}/mass was higher in older boys than older girls (Table 3).

Multiple one-legged hopping

The shapes of the curves for F_{max} were similar to P_{max}, showing tight correlations with age and weight. Especially weight best predicted (almost linearly) maximum force, with coefficients of determination R^2 of 0.81 and 0.86 for girls and boys, respectively. However, F_{max} was still well predicted by age in both sexes but with lower R^2 of 0.64 in girls and 0.69 in boys. The curve showing the age-dependency of F_{max} (Figure 3) has a quadratic shape in girls, with a clear flattening in adolescence, which is in contrast to boys, in whom the F_{max} increased continuously with age. A test of the equality of the mean regression lines for girls and boys showed significant inter-gender differences for F_{max} vs. age ($p<0.001$), but not for F_{max} vs. weight.

The shapes of the mean regression lines for F_{max}/BW differed markedly from the P_{max}/mass curves. As illustrated by Figures 3 and 4, the relationships between F_{max}/BW and age and weight were close to constant, especially in girls. In boys, there was a tendency toward an increase in F_{max}/BW in adolescence, but the difference reached significance only in individuals older than 18 years (Table 12). The stability of this parameter is well illustrated by the very low coefficients of determination with respect to age and weight (R^2= 0.02 and 0.04, respectively, in girls and 0.04 and 0.01, respectively, in boys).

Discussion

This cross-sectional study presents smoothed gender-specific normative pediatric data on the main parameters assessed using jumping mechanography, i.e., maximum peak power P_{max} produced by a S2LJ and maximum force F_{max} produced by M1JH. To our knowledge, this is the largest study (796 children and adolescents) on reference data for Leonardo jumping mechanography.

The use and correct interpretation of any method in children and adolescents relies on the availability of appropriate reference data matched by sex, age and weight. In spite of the fact that jumping mechanography has been used clinically for years, only one study has been published with pediatric reference data on P_{max} in S2LJ[10], whose results have been included in the manufacturer´s normative data that are routinely used in most cases. Alternatively, locally derived data from a small number of participants serves as a control group in clinical studies. Our reference data are intended to assist clinicians in the assessment of muscle function by jumping mechanography in pediatric patients.

It is not surprising that the development of muscle function during growth is strongly dependent on age and anthropometric parameters. Interestingly, the shapes of the curves for P_{max} and F_{max} had similar patterns, showing a linear increase with age in prepubertal children followed by plateau in adolescent girls and a steady increase throughout childhood in boys. In contrast, we observed a continuous increase of both muscle power and force as weight increased in both genders. These differences are most likely caused by two main factors: 1) earlier termination of growth in girls: as muscle function is a function of height and boys' growth plates close later, higher absolute power and force could be expected in older boys; and 2) different actions of estrogens and testosterone on muscle: whereas testosterone has a powerful anabolic effect on muscles, mediated by various mechanisms and pathways[25], the actions of estrogens on skeletal muscles are less conclusive.

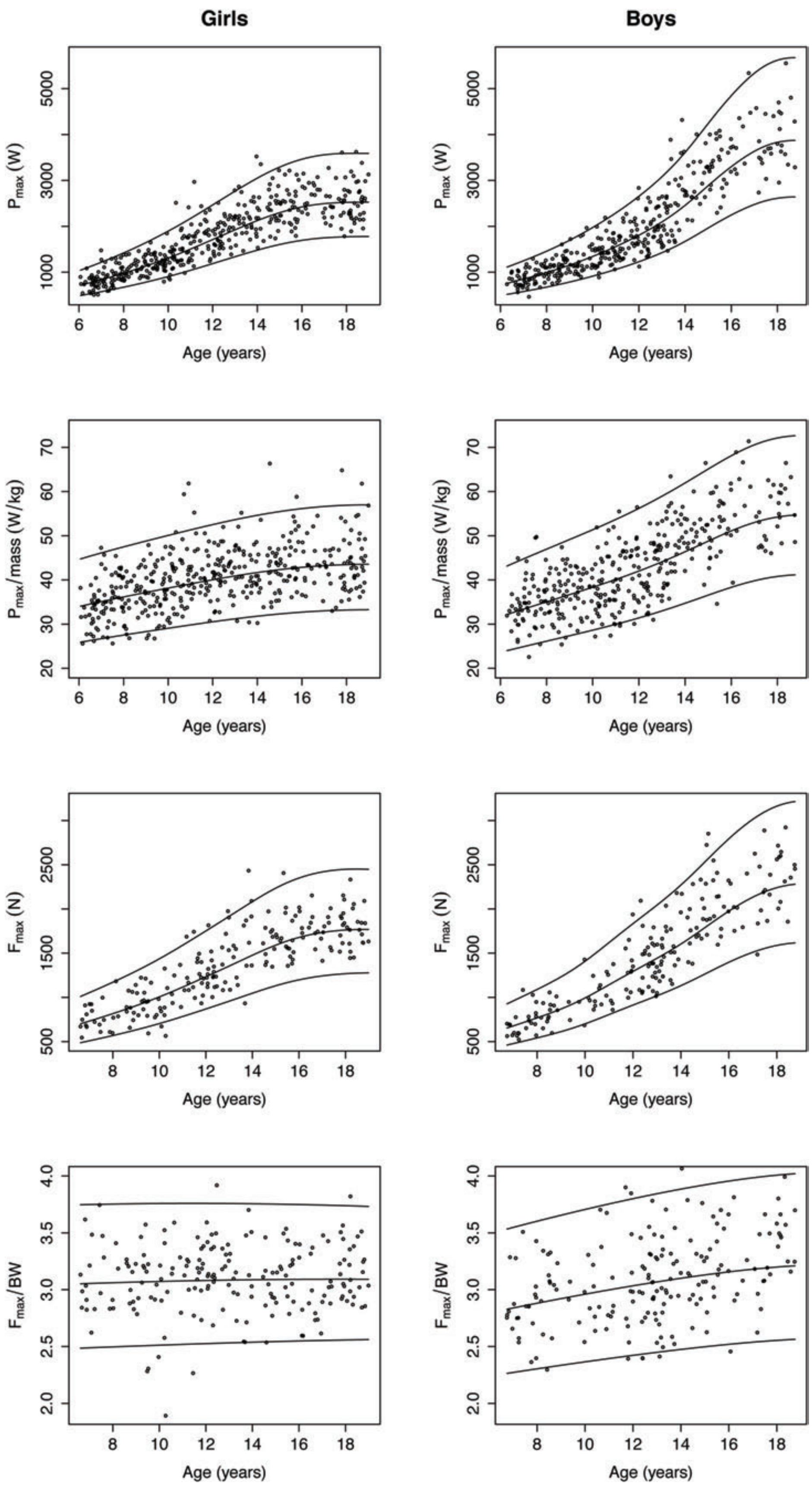

Figure 1. Age-dependent reference curves for mechanography parameters with individual values and the curves for mean and the range of 2 standard deviations.

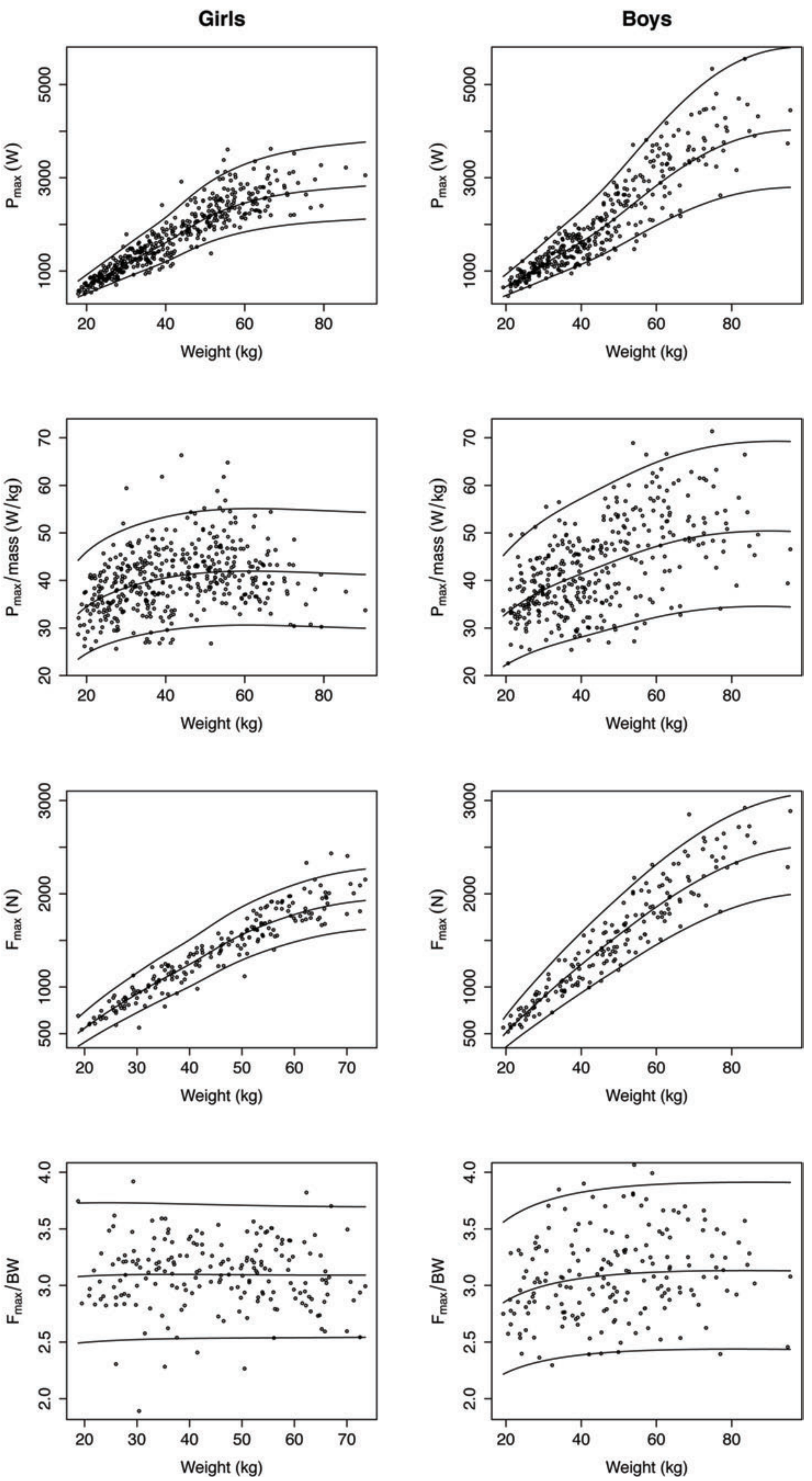

Figure 2. Weight-dependent reference curves for mechanography parameters with individual values and the curves for mean and the range of 2 standard deviations.

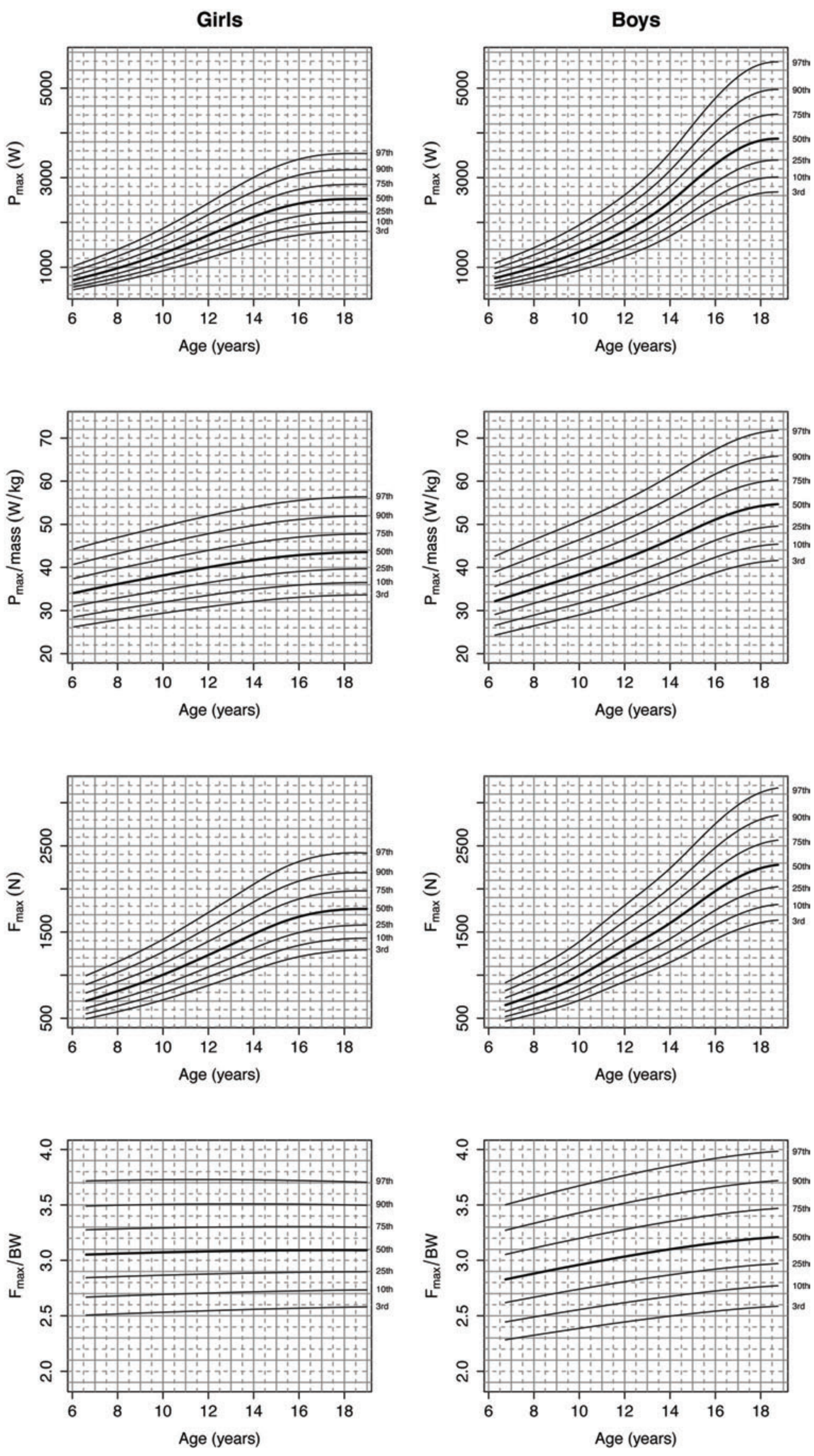

Figure 3. Age-dependent smoothed percentile graphs for mechanography parameters.

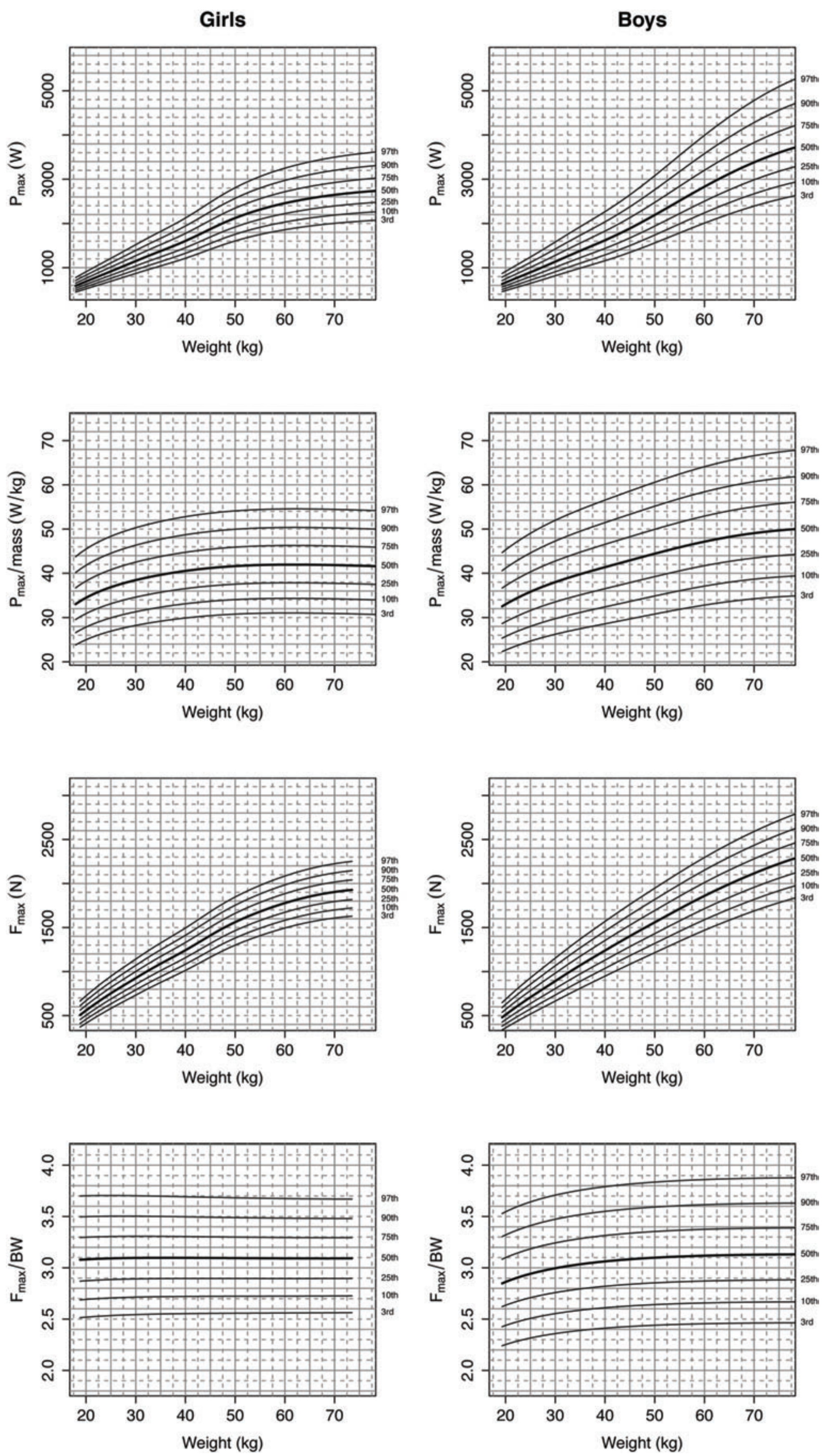

Figure 4. Weight-dependent smoothed percentile graphs for mechanography parameters.

P_{max} (W)												
Age (yr)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
6	0.20	516	579	740	946	1061	0.20	521	586	753	968	1088
7	0.19	585	656	838	1070	1200	0.20	589	662	851	1093	1229
8	0.19	684	767	978	1248	1398	0.20	687	772	993	1276	1435
9	0.19	795	891	1135	1446	1620	0.20	799	899	1155	1486	1671
10	0.19	919	1029	1310	1667	1867	0.20	929	1045	1344	1729	1944
11	0.19	1057	1183	1504	1911	2138	0.20	1077	1212	1559	2005	2256
12	0.19	1206	1349	1712	2174	2431	0.20	1248	1404	1806	2323	2613
13	0.19	1358	1517	1924	2440	2726	0.20	1449	1630	2097	2697	3034
14	0.18	1503	1678	2125	2691	3006	0.20	1698	1910	2457	3160	3555
15	0.18	1627	1816	2297	2905	3242	0.20	1995	2244	2885	3711	4174
16	0.18	1719	1918	2422	3059	3412	0.20	2282	2566	3299	4242	4771
17	0.18	1774	1978	2495	3146	3507	0.20	2515	2828	3635	4672	5254
18	0.18	1797	2002	2522	3176	3538	0.20	2652	2982	3830	4921	5533

Table 2. S and M parameters as well as percentile distribution for age-dependent reference data for P_{max}. L was set to 0.

P_{max}/mass (W/kg)												
Age (yr)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
6	0.14	26.2	28.4	34.0	40.6	44.2	0.15	23.9	26.2	31.7	38.4	42.0
7	0.14	27.0	29.4	35.1	42.0	45.6	0.15	25.2	27.6	33.4	40.4	44.2
8	0.14	27.8	30.3	36.2	43.2	47.0	0.15	26.5	28.9	35.0	42.4	46.4
9	0.14	28.6	31.1	37.2	44.4	48.3	0.15	27.7	30.3	36.7	44.4	48.6
10	0.14	29.4	31.9	38.2	45.6	49.5	0.15	29.0	31.7	38.4	46.4	50.8
11	0.14	30.2	32.8	39.1	46.7	50.8	0.15	30.3	33.2	40.1	48.5	53.1
12	0.14	30.9	33.5	40.1	47.8	52.0	0.15	31.8	34.7	42.0	50.8	55.6
13	0.14	31.6	34.3	40.9	48.8	53.1	0.15	33.4	36.5	44.1	53.3	58.3
14	0.14	32.2	34.9	41.7	49.8	54.0	0.15	35.1	38.4	46.4	56.1	61.2
15	0.14	32.7	35.5	42.3	50.5	54.9	0.15	37.0	40.4	48.8	58.9	64.3
16	0.14	33.1	35.9	42.9	51.1	55.5	0.15	38.8	42.3	51.1	61.7	67.3
17	0.14	33.4	36.3	43.2	51.6	56.0	0.15	40.3	44.0	53.0	63.9	69.8
18	0.14	33.6	36.4	43.5	51.8	56.3	0.15	41.3	45.0	54.2	65.4	71.3

Table 3. S and M parameters as well as percentile distribution for age-dependent reference data for P_{max}/mass. L was set to 0.

F_{max} (N)												
Age (yr)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
6	0.19	460	514	654	830	929	0.18	420	467	587	738	821
7	0.19	516	577	732	929	1038	0.18	483	538	676	850	945
8	0.18	576	644	815	1033	1154	0.18	549	611	768	965	1074
9	0.18	641	716	905	1145	1278	0.18	621	691	868	1092	1215
10	0.18	714	796	1005	1269	1415	0.18	710	790	993	1248	1389
11	0.18	794	885	1115	1406	1567	0.18	817	909	1142	1435	1597
12	0.18	881	980	1233	1551	1727	0.18	925	1029	1293	1625	1808
13	0.18	970	1079	1354	1699	1890	0.18	1032	1148	1442	1811	2014
14	0.18	1061	1179	1476	1849	2054	0.18	1148	1277	1603	2013	2239
15	0.17	1147	1272	1590	1986	2204	0.18	1282	1425	1788	2244	2496
16	0.17	1214	1346	1677	2091	2318	0.18	1417	1575	1975	2478	2755
17	0.17	1259	1394	1733	2155	2386	0.18	1531	1702	2133	2674	2972
18	0.17	1284	1420	1761	2184	2416	0.18	1609	1788	2240	2807	3118

Table 4. S and M parameters as well as percentile distribution for age-dependent reference data for F_{max}. L was set to 0.

F_{max}/BW												
Age (yr)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
6	0.11	2.50	2.66	3.05	3.49	3.71	0.11	2.26	2.42	2.80	3.23	3.46
7	0.10	2.51	2.67	3.06	3.49	3.72	0.11	2.29	2.45	2.84	3.29	3.52
8	0.10	2.52	2.68	3.06	3.50	3.72	0.11	2.33	2.49	2.88	3.33	3.57
9	0.10	2.53	2.69	3.07	3.50	3.73	0.11	2.36	2.52	2.92	3.38	3.62
10	0.10	2.53	2.69	3.07	3.51	3.73	0.11	2.39	2.56	2.96	3.43	3.67
11	0.10	2.54	2.70	3.08	3.51	3.73	0.11	2.42	2.59	3.00	3.47	3.72
12	0.10	2.55	2.71	3.08	3.51	3.73	0.11	2.44	2.62	3.03	3.52	3.77
13	0.10	2.55	2.71	3.09	3.51	3.73	0.12	2.47	2.65	3.07	3.56	3.81
14	0.10	2.56	2.72	3.09	3.51	3.73	0.12	2.50	2.68	3.10	3.59	3.85
15	0.10	2.56	2.72	3.09	3.51	3.72	0.12	2.52	2.70	3.13	3.63	3.89
16	0.10	2.57	2.73	3.09	3.51	3.72	0.12	2.54	2.72	3.16	3.66	3.92
17	0.10	2.57	2.73	3.09	3.51	3.72	0.12	2.56	2.74	3.18	3.69	3.95
18	0.10	2.58	2.73	3.09	3.50	3.71	0.11	2.58	2.76	3.20	3.71	3.97

Table 5. S and M parameters as well as percentile distribution for age-dependent reference data for F_{max}/BW. L was set to 0.

P_{max} (W)												
Weight (kg)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
20	0.15	522	570	688	831	908	0.17	482	534	665	827	916
30	0.15	870	951	1150	1391	1521	0.18	818	908	1137	1423	1581
40	0.15	1214	1327	1606	1943	2124	0.18	1158	1289	1621	2037	2267
50	0.15	1605	1755	2123	2569	2808	0.18	1559	1738	2191	2763	3080
60	0.15	1859	2032	2458	2974	3250	0.18	2008	2240	2831	3578	3992
70	0.15	2004	2190	2648	3201	3499	0.18	2393	2672	3382	4282	4781

Table 6. S and M parameters as well as percentile distribution for weight-dependent reference data for P_{max}. L was set to 0.

P_{max}/mass (W/kg)												
Weight (kg)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
20	0.16	25.0	27.8	34.5	41.8	45.5	0.18	22.6	25.7	33.0	41.2	45.3
30	0.15	28.2	31.3	38.5	46.4	50.3	0.18	26.2	29.7	38.0	47.3	52.0
40	0.15	29.9	33.1	40.5	48.7	52.8	0.18	28.6	32.4	41.4	51.5	56.6
50	0.15	30.8	34.1	41.6	50.0	54.1	0.18	30.8	34.9	44.4	55.2	60.6
60	0.15	31.0	34.3	42.0	50.4	54.5	0.18	32.8	37.1	47.2	58.4	64.1
70	0.15	30.9	34.2	41.9	50.3	54.4	0.18	34.2	38.7	49.1	60.7	66.6

Table 7. S and M parameters as well as percentile distribution for weight-dependent reference data for P_{max}/mass. L was set to 0.5.

F_{max} (N)												
Weight (kg)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
20	0.15	414	457	558	669	725	0.17	361	406	510	626	685
30	0.12	733	792	926	1070	1142	0.15	665	734	892	1066	1153
40	0.10	1014	1084	1243	1412	1495	0.13	948	1036	1239	1460	1569
50	0.09	1300	1381	1561	1753	1847	0.12	1214	1319	1559	1818	1947
60	0.09	1495	1582	1777	1984	2085	0.12	1469	1588	1859	2151	2295
70	0.09	1608	1700	1904	2120	2225	0.11	1688	1819	2116	2434	2591

Table 8. S and M parameters as well as percentile distribution for weight-dependent reference data for F_{max}. L was set to 0.5.

F_{max}/BW												
Weight (kg)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
20	0.10	2.52	2.69	3.08	3.50	3.70	0.12	2.25	2.44	2.86	3.32	3.55
30	0.10	2.54	2.71	3.10	3.50	3.70	0.12	2.36	2.55	3.00	3.47	3.71
40	0.10	2.55	2.72	3.10	3.50	3.69	0.12	2.41	2.61	3.06	3.55	3.79
50	0.10	2.56	2.72	3.10	3.49	3.68	0.12	2.44	2.64	3.10	3.59	3.84
60	0.10	2.56	2.72	3.09	3.48	3.68	0.12	2.46	2.66	3.12	3.62	3.86
70	0.10	2.56	2.73	3.09	3.48	3.67	0.12	2.46	2.67	3.13	3.63	3.87

Table 9. S and M parameters as well as percentile distribution for weight-dependent reference data for F_{max}/BW. L was set to 0.5.

Although there is some evidence that estrogens improve the action of myosin[26], their role in muscle force is much weaker[27]. Our observation of tighter correlations of P_{max} and F_{max} with weight than age has important implications for proper clinical interpretation of data gained from jumping mechanography: weight-related data should be preferred over age-related especially in children, who are heavy- or thin-for-age.

There are limited data on muscle function in young adults, i.e., the age category following adolescence. Anliker et al.[16] examined F_{max} using jumping mechanography in 323 children and adults aged 8-82 years and observed an increase during childhood, with peak muscle force being reached at the end of puberty. In males, this peak was followed by a plateau between 20 and 40 years of age with a subsequent decrease thereafter, whereas in females, peak muscle force was followed by a continuing decrease starting in the third decade of life. The peak F_{max} values were higher by one-third in males than in females. Similar results have been presented by studies from Greece[12] and Japan[28]. In this study, the break-out point between genders started at the age of 14, with an F_{max} difference of 15% that increased further with puberty, reaching a maximum of 37% at 18-19 years.

After correction for weight, F_{max} was nearly constant in both genders regardless of the variable used as a predictor, which makes this parameter suitable as an easy screening tool for assessing musculoskeletal health. It should be taken into account that different techniques of one-legged jumping have been used in previous studies. In contrast to the approach of our study and others[15,16] to instruct the participants to jump as high and as forcefully as possible, some other authors instructed their participants to jump as fast and hard as possible which, resulted in lower values of F_{max}/BW[11,29]. More precisely, whereas jumping high yielded F_{max}/BW values between 3.0 and 3.3 (median 3.1 in our group), jumping fast produced a F_{max}/BW of 2.7-2.8[29]. In our pilot study, we compared both techniques in a subgroup of children and found that the difference varied from 0.15 to 0.3, with a larger difference in older children and adolescents (own unpublished data). The command of jumping as high as possible is crucial to create the maximal force to which the tibia is exposed.

The strengths of this study include a large cohort of Caucasian children and measurements taken during a well-defined time period at different places thorough the country by only three technicians, one of whom (JM) was present at all measurements. Using this approach, the equality of measurement was assured during the whole study. There are also some limitations to this study. First, although our recruitment method aimed to gather a representative sample of participants, we did not use a systematic population-sampling approach, so we cannot exclude selection bias. Indeed, the children included in the study were slightly heavier (likely due to secular changes) and shorter compared to the population normative data from

2001[17]. Nevertheless, our data are presented in relation to anthropometric parameters, which decreases the necessity of having a random population-based sample. Second, we were not able to collect data on the stage of puberty because the tests were performed in schools during the regular hours of physical education, where no clinical examination could be performed, and self-assessment questionnaires were not provided. We thus cannot show any data on muscle function in relation to pubertal development, which would be crucial for our understanding of muscle physiology during pubertal catch-up growth.

The knowledge of the variability of results among different populations is mandatory for the introduction of any new method into clinical practice. Portable devices are especially inclined to technical problems due to frequent transportation and the necessity of re-positioning the machines. Moreover, different techniques of measurement implemented by different technicians could play a role in differences between measurements. That is why we compared the results of P_{max} from S2LJ derived from our children with those of 312 German children published by Fricke et al.[10] We did not observe any difference in P_{max} between these two groups of children regardless of the parameter used as a predictor. P-values for the total difference in P_{max} with respect to age and weight varied between 0.56 and 0.91. This finding favors the current method for its comparativeness to neighboring populations, which establishes a basic prerequisite for future multicenter studies using jumping mechanography.

In conclusion, this study presents gender-specific normative pediatric data on the main parameters assessed by jumping mechanography from a large cohort of children and adolescents. Our results are intended to assist clinicians in the assessment of muscle function by jumping mechanography in the pediatric patient.

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Annex

	H_{max} (m)											
Age (yr)	**Girls**						**Boys**					
	S	*3rd*	*10th*	*M 50th*	*90th*	*97th*	*S*	*3rd*	*10th*	*M 50th*	*90th*	*97th*
6	0.18	0.18	0.21	0.27	0.33	0.37	0.20	0.16	0.19	0.25	0.32	0.35
7	0.18	0.19	0.22	0.28	0.35	0.38	0.19	0.18	0.21	0.27	0.34	0.38
8	0.17	0.21	0.23	0.29	0.36	0.40	0.18	0.20	0.23	0.29	0.37	0.40
9	0.17	0.22	0.24	0.31	0.38	0.41	0.18	0.22	0.25	0.32	0.39	0.43
10	0.16	0.23	0.26	0.32	0.39	0.42	0.17	0.24	0.27	0.34	0.42	0.46
11	0.16	0.24	0.27	0.33	0.40	0.44	0.16	0.26	0.29	0.36	0.44	0.48
12	0.16	0.25	0.28	0.34	0.41	0.45	0.16	0.28	0.31	0.39	0.47	0.51
13	0.15	0.26	0.29	0.35	0.43	0.46	0.15	0.30	0.34	0.41	0.49	0.54
14	0.15	0.27	0.30	0.36	0.43	0.47	0.15	0.32	0.36	0.44	0.52	0.56
15	0.15	0.27	0.30	0.37	0.44	0.48	0.14	0.35	0.38	0.46	0.55	0.59
16	0.15	0.28	0.31	0.38	0.45	0.48	0.14	0.37	0.40	0.48	0.57	0.62
17	0.14	0.28	0.31	0.38	0.45	0.49	0.13	0.39	0.42	0.50	0.59	0.64
18	0.14	0.28	0.31	0.38	0.45	0.49	0.13	0.40	0.44	0.52	0.61	0.65

Table 10. S and M parameters as well as percentile distribution for age-dependent reference data for S2LJ H_{max}. L was set to 0.5.

	P_{max} (W)		P_{max}/mass(W/kg)	
Age (yr)	*Girls (N=432)*	*Boys (N=364)*	*Girls*	*Boys*
6	787±190 (33)	801±144 (19)	33.3±4.5	32.6±4.1
7	930±210 (43)	939±189 (38)	36.3±5.0	36.0±5.8
8	1117±180 (33)	1117±200 (38)	36.4±4.6	36.5±5.3
9	1224±205 (42)	1270±292 (29)	37.1±5.5	37.4±4.5
10	1434±353 (42)	1456±294 (45)	40.8±6.9	38.1±6.3
11	1806±399 (30)	1739±378 (37)	41.6±5.3	42.1±6.9
12	1852±327 (41)	1895±379 (40)	41.7±4.5	41.8±6.0
13	2173±409 (32)	2485±700 (36)*	42.3±5.5	47.7±7.0***
14	2379±443 (31)	2964±505 (20)***	42.0±6.8	51.0±5.5***
15	2442±379 (29)	3334±504 (26)***	45.1±5.7	52.1±6.6***
16	2701±280 (17)	3950±708 (9)***	43.7±5.6	59.2±10.0**
17	2520±418 (25)	3692±535 (13)***	43.6±6.9	52.3±5.8***
18	2557±424 (34)	4055±707 (14)***	44.5±6.2	57.1±5.3***

Table 11a. Differences between girls and boys for P_{max} and P_{max}/mass by age (S2LJ).

	P_{max} (W)		P_{max}/mass (W/kg)	
Weight (kg)	*Girls (N=430)*	*Boys (N=361)*	*Girls*	*Boys*
10	612±88 (10)		32.1±4.0	
20	943±181 (100)	945±186 (86)	36.8±4.9	36.6±5.3
30	1402±244 (97)	1408±271 (94)	40.1±6.5	39.8±6.9
40	1899±363 (76)	1903±441 (72)	42.1±7.0	41.8±8.2
50	2391±374 (88)	2655±580 (44) **	43.9±6.4	48.3±9.9**
60	2633±346 (45)	3303±540 (37) ***	41.2±5.0	51.3±8.4***
70	2769±402 (14)	3938±614 (21) ***	37.6±5.7	52.6±8.4***
80		4317±746 (7)		51.3±9.0

*Mean ± SD values are given. The number of individuals is presented in parentheses and is not different between P_{max} and P_{max}/BM. Asterisks indicate the differences between girls and boys (*p<0.05, **p<0.01, ***p<0.001). N=791 in Table 11b after exclusion of 4 outliers (2 boys and 2 girls).*

Table 11b. Differences between girls and boys for P_{max} and P_{max}/mass by weight (S2LJ).

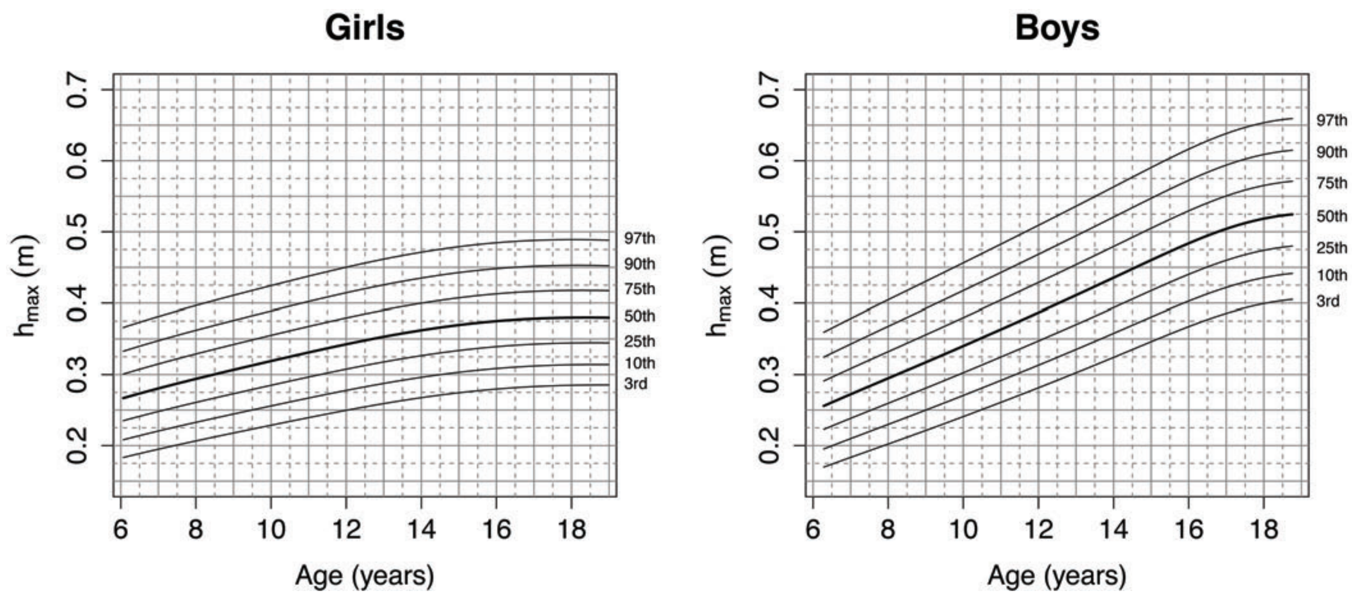

Figure 5. Age-dependent smoothed percentile graphs for H_{max} (S2LJ).

	F_{max} (N)		F_{max}/BW	
Age (yr)	*Girls (N=194)*	*Boys (N=182)*	*Girls*	*Boys*
6	718±117 (7)	645±71 (5)	3.05±0.27	2.86±0.25
7	766±147 (10)	733±165 (17)	3.14±0.36	2.86±0.32
8	904±170 (12)	833±135 (13)	3.09±0.2	2.99±0.32
9	946±173 (16)	951±292 (5)	2.98±0.38	2.84±0.21
10	965±243 (13)	1054±148 (12)	3.05±0.45	3.07±0.38
11	1267±226 (19)	1264±309 (14)	3.1±0.28	3.02±0.45
12	1364±268 (24)	1395±263 (27)	3.23±0.26	3.04±0.33*
13	1562±408 (15)	1516±288 (25)	3.05±0.35	3.0±0.36
14	1610±200 (11)	1855±285 (16)*	2.99±0.24	3.23±0.38
15	1685±264 (18)	2122±361 (18)***	3.17±0.21	3.31±0.38
16	1812±165 (13)	2045±259 (6)	2.93±0.31	3.08±0.45
17	1796±207 (18)	2192±396 (11)**	3.16±0.23	3.16±0.3
18	1775±235 (18)	2430±303 (13)***	3.16±0.27	3.52±0.24***

Table 12a. Differences between girls and boys for F_{max} and F_{max}/BW by age (M1LH).

	F_{max} (N)		F_{max}/BW	
Weight (kg)	*Girls (N=192)*	*Boys (N=179)*	*Girls*	*Boys*
20	796±125 (34)	729±120 (32)*	3.09±0.3	2.92±0.3*
30	1072±149 (41)	1065±145 (32)	3.09±0.35	3.06±0.36
40	1380±129 (34)	1374±180 (35)	3.12±0.24	3.04±0.38
50	1688±178 (50)	1744±258 (30)	3.15±0.27	3.23±0.44
60	1896±197 (27)	2023±281 (29)	3.01±0.31	3.2±0.38*
70	2096±194 (6)	2329±264 (15) *	2.98±0.31	3.16±0.36
80		2645±198 (6)		3.23±0.24

*Mean ± SD values are given. The number of individuals is presented in parentheses and is not different between F_{max} and F_{max}/BW. Asterisks indicate differences between girls and boys (*p<0.05, **p<0.01, ***p<0.001). N=371 in Table 12b after exclusion of 3 boys and 2 girls as outliers.*

Table 12b. Differences between girls and boys for F_{max} and F_{max}/BW by weight (M1LH).