J Musculoskelet Neuronal Interact 2026; 26(3):339-354

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Height-Specific Reference Centiles for Jumping Mechanography in Children: Retrospective Analysis of the DONALD Study Cohort

Maja Zimmermann[1,2], Jonathan Buggisch[1], Karoline Spiess[2], Eckhard Schönau[2], Ute Alexy[#3], Ibrahim Duran[#1,2]

[1]University of Cologne, Faculty of Medicine and University Hospital Cologne, Department of Pediatrics, Cologne, Germany;
[2]University of Cologne, Faculty of Medicine and University Hospital Cologne, Center of Prevention and Rehabilitation, UniReha, Cologne, Germany;
[3]Germany Department of Nutritional Epidemiology, Institute of Nutritional and Food Science, University of Bonn, Bonn, Germany
[#]Equal Contribution

Abstract

Objectives: Jumping mechanography is a common method to analyze muscle function. To date, mainly age- or weight-specific pediatric reference centiles for jumping mechanography have been published. The use of age-related references in children with small stature (defined as height below the age-specific third centile) might lead to misinterpretation of actual jumping performance. Thus, the study aim was the development of height-specific mechanography reference centiles of healthy children and show application in children with small stature. **Methods**: Data from 882 children (aged 6-18 years; height 100-200cm) from the DONALD cohort was analyzed using the LMS (lambda-mu-sigma)-method. Sex-specific centiles were calculated for maximal velocity (Vmax), Nerve–Muscle Index (NMI), maximal power (Pmax) and maximal force (Fmax), both related to body mass. Age- and height-specific jumping parameters were individually compared in healthy children with small stature. **Results**: Vmax, Pmax and NMI increased with higher stature until a plateau was reached. Fmax stayed rather stable over time. Age-specific z-scores of Vmax, Pmax and NMI in children with small stature were lower than the height-specific z-scores. **Conclusions**: In this article first height- and sex-specific reference centiles for jumping mechanography in healthy German children are presented. This study highlights the beneficial application of height-specific reference centiles for interpretation of jumping performance in children with small stature.

Keywords: DONALD, Growth, Physical Fitness, Reference Centiles Children

Introduction

Physical fitness in patients is regularly evaluated via jumping mechanography as a measure for dynamic muscle function of the lower limbs[1,2]. This procedure has been applied in sports science and used to evaluate rehabilitation outcomes and possible treatment effects in children and adults with various disabilities. Age- and sex-specific reference centiles for jumping mechanography were published for Canadian, Indian, German and Czech children and adolescents[3–9]. Jumping performance seems to increase with age, especially until puberty is reached. Further, influence of body height and mass on jumping force and power in healthy children and healthy adults have been addressed[1,10,11]. Sumnik et al.[9] have also

The authors have no conflict of interest.

Corresponding author: Ibrahim Duran, University of Cologne, Faculty of Medicine and University Hospital Cologne, Department of Pediatrics, Kerpener Strasse 62, 50937 Cologne, Germany and University of Cologne, Faculty of Medicine and University Hospital Cologne, Center of Prevention and Rehabilitation, UniReha, Lindenburger Allee 44, 50931 Cologne, Germany
E-mail: ibrahim.duran@uk-koeln.de

Edited by: G. Lyritis
Accepted 14 March 2026

Table 1. Sample characteristics of 882 DONALD study participants.

	Females	Males	Total
Participants, n	431	461	882
S2LJ, n	1445	1617	3062
S2LJ per individual, median (range)	3 (1–7)	3 (1–7)	3 (1–7)
Age, years	11.4 (3.9)	11.4 (3.8)	11.4 (3.9)
Body height, cm	148.2 (19.3)	151.7 (23.0)	150.0 (21.4)
Height, z-score	0.37 (0.95)	0.36 (1.02)	0.36 (0.99)
Body mass, kg	43.1 (17.1)	46.1 (21.4)	44.7 (19.5)
Body mass, z-score	0.12 (0.87)	0.15 (0.91)	0.14 (0.89)
Body mass index (BMI), kg/m^2	18.7 (3.5)	18.8 (4.0)	18.8 (3.8)
BMI, z-Score	-0.05 (0.88)	-0.03 (0.96)	-0.04 (0.92

BMI: Body Mass Index; S2LJ: single two-legged jump. Z-scores were calculated with the reference centiles of the KIGGS study[19]. All values are mean (SD), if not otherwise stated.

published weight-specific reference centiles for jumping mechanography. They found a greater correlation between maximum power and maximum force and weight than with age and recommended using weight-specific reference centiles for children who are heavy- or thin-for-age. However, other authors often use relative maximum power (maximum power/body mass) and relative maximum force (maximum force/body mass) in combination with age-specific reference centiles due to this correlation.

When patients with small stature (defined as height below the age-specific the third centile) perform mechanography, they tend to show a lower jumping performance than their age-matched peers, as shown by Schweizer et al.[12]. The usage of age-related reference centiles in children with small stature might not only lead to underestimation but even misinterpretation of jumping performance and physical fitness. This might result in inadequate evaluation of muscle function and monitoring of rehabilitation, training and intervention outcomes. Hence, height-specific reference data for jumping mechanography is needed to overcome this problem.

Regarding output measures, jumping mechanography yielded reproducible results for velocity, force and power[1,4,8,9,13]. To evaluate jumping efficiency, the Esslinger Fitness Index (in %), which is the maximal power/body mass in relation to the average of age- and sex-matched references, was used previously[4,14–16]. Further, the Nerve-Muscle-Index (NMI), the ratio of maximal velocity to relative force, was presented by our colleagues as an additional, surrogate parameter for motor efficiency[8]. The NMI was defined as

$$1000 * \frac{maximumvelocity\left(\frac{m}{s}\right)}{\frac{maximumforce(N)}{bodymass(kg)}}.$$

The advantage of the NMI is the relationship of coordinated nerve-muscle interaction (referred to as Vmax) to muscular strength (Fmax/mass), especially in conditions such as obesity[8]. The NMI has not yet been widely used in the literature, however Kasture et al. also showed that the NMI increased until puberty and even decreased during puberty[3]. The author stated, that jumping efficiency might be reduced during puberty to due reduced physical activity[3].

Besides varying jumping parameters that were analyzed in the literature, different techniques, such as countermovement jump, squat jump, single two-legged jump (S2LJ) and multiple one-legged jump have been published. In addition to that, individual factors such as anthropometric parameters, neuromuscular function as well as comprehension of the task may lead to differences in presented results[17].

To the best of our knowledge, no pediatric height-specific reference centiles exist which is necessary to interpret jumping performance, especially in children with small stature. In this study, it was aimed to generate height- and sex-specific reference centiles for jumping parameters in healthy children and to demonstrate its meaningful use in practice.

Materials and Methods

Subjects

In this retrospective observational study, data of the open cohort DOrtmund Nutritional and Anthropometric Longitudinally Designed (DONALD) study, collected between 2004-2021 (median test date was 2013, IQR 8.8 years) was used to calculate reference centiles[18]. The DONALD study was registered at the German Clinical Trial Register (DRKS00029092, 09.06.2022). Since 2012, the study has been affiliated with the Department of Nutritional Epidemiology at the Institute for Nutrition and Food Sciences (IEL), Rheinische Friedrich-Wilhelms University of Bonn. Ethical approval was granted by the Medical Faculty of the University of Bonn (No. 205/03, January 20, 2004). Written parental consent for usage of collected data was obtained from all study participants. A total of 3062 jumping measurements, conducted by 882 children were analyzed from the DONALD cohort. At each study visits, up to 3 jumps were performed. Detailed patient characteristics can be found in Table 1.

Inclusion criteria of study cohorts were physical ability to perform at least one jump and availability of data regarding age at jump, body mass and height.

Anthropometric measurements were taken during every visit to the study centers. Body height was measured with a digital telescopic wall-mounted stadiometer to the nearest of 0.1 cm (Harpenden, Rappenswil, Switzerland). Body mass was recorded with an electronic scale in all patients with a precision of 0.1 kg (Model 753 E, Seca, Hamburg, Germany). For determination of body mass, height and BMI z-scores the KIGGS survey was used as reference[19].

Mechanography

For the S2LJ, all patients were instructed by a study nurse (pediatric nurse, physician assistant or sports scientist) to perform at least one to three vertical, countermovement jump, standing upright allowing slight bending of the knees (angle not measured), with freely moving arms and aiming for maximal height. There was no defined resting interval between jumps, rather the connected software determined the end of the first and possible start of the next jump. Measurement was performed without shoes and with each foot placed on one of the two separate sections of a Ground Reaction Force Plate (GRFP, Leonardo Mechanograph®, NOVOTEC Medical GmbH, Pforzheim, Germany). Each force plate measured deformation of the plate and sampled data at a frequency of 800/second, without signal processing or filtering procedures. The Leonardo software used was LEONARD MECHANOGRAPH® v4.1.18. The parameters analyzed were maximal velocity (Vmax in m/s), maximal power (Pmax in Watt), maximal force (Fmax in Newton). For inter-individual comparison, reference centiles for Pmax and Fmax were calculated in relation to body mass (kg) (relative Pmax and Fmax). Holding true for all patients, if more than one jump was performed at one visit, only jumping measurements with the highest jump were included. The height of the jump was calculated by the Leonardo Mechanograph®.

Statistical Analysis

For the analysis, R Studio (Version 2022.07.2 Build 576), R version 4.5.0 and the gamlss R-package, version 5.4–12 was used. Descriptive statistics primarily included auxological and jumping parameters, as well as demographic data.

To develop the centile curves, the LMS (lamb-da-mu-sigma) method was applied[20–22]. The LMS method models growth-related data by estimating three age/growth dependent curves: L (skewness), M (median), and S (coefficient of variation). In gamlss, these three parameters are fitted as smooth functions of e.g. age or height, allowing flexible calculation of centiles and z-scores even when the data are skewed or heteroscedastic. For this, the Box-Cox Cole and Green distribution was employed to estimate M, S, and L. The model's fit is assessed using diagnostic tools such as the Q-test and the worm plot, and refined by adjusting the degrees of freedom of the three LMS parameters (in this case for M 1.7-3.5, for S 0.5-1.5, and for L 0.5-1.0, Suppl. Table 9). Although the LMS method, as implemented in GAMLSS, was originally developed for cross-sectional data, it can also be applied to longitudinal datasets when the number of repeated measurements per individual is small relative to the number of subjects. This approach has been used, for example, in the development of the WHO Child Growth Standards (2006)[23]. For the sensitivity analysis, reference percentiles were also created, in which only the first measurement value per test subject was included in the calculation. This means that each test subject is only included in the calculation once. For further information, please refer to the cited literature.

Results

Sample Characteristics

The characteristics of the study sample used for the reference centile calculation are presented in Table 1. Of 3062 measurements, 1445 were taken by girls and 1617 by boys aged 6 to 18 years. The mean height was 148.2 cm for girls and 151.7 cm for boys. The mean BMI was 18.7 kg/m^2 for girls and 18.8 kg/m^2 for boys.

Reference Centiles for S2LJ According to Body Height

In Figures 1 and 2 reference centiles for Pmax/mass, Fmax/mass, Vmax and NMI for females and males according to body height are shown. Detailed z-scores for centile calculation can be found in the Supplement (Suppl.) Tables 1-8. The exact specifications of the settings used to generate the GAMLSS models can be found in Suppl. Table 9. Suppl. Table 10 shows the exact number of assessments per specific height interval in both sexes.

Overall, jumping parameters at smallest heights were similar in both sexes (statistically not tested). With increasing height, values for relative Pmax and Vmax increased up until a height of 160 cm in girls and 180 cm in boys. The steepest increase in jumping parameters with height was seen in Vmax in boys. The NMI likewise increased with height in both sexes, suggesting a plateau in girls after a height of 140 cm. Relative Fmax remained relatively stable after a height of 140 cm in boys and slightly decreased in girls with a height over 160 cm. At heights between 100-140cm, relative Fmax was slightly higher in girls than in boys.

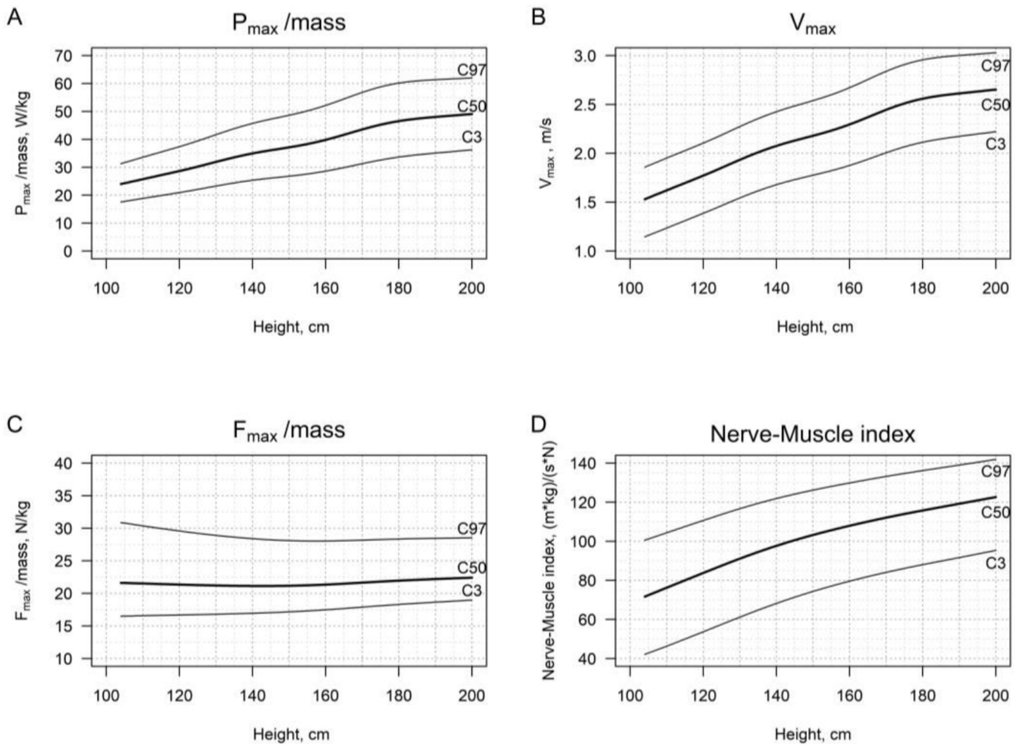


Figure 1. Reference centiles of single two-legged jump parameters according to body height in healthy boys aged 6-18 years. A) Pmax/mass, B) Vmax, C) Fmax/mass D) Nerve-Muscle-Index. Fmax: maximal force; N: Newton; Pmax: maximal power; s: second; Vmax: maximal velocity; W: Watt.

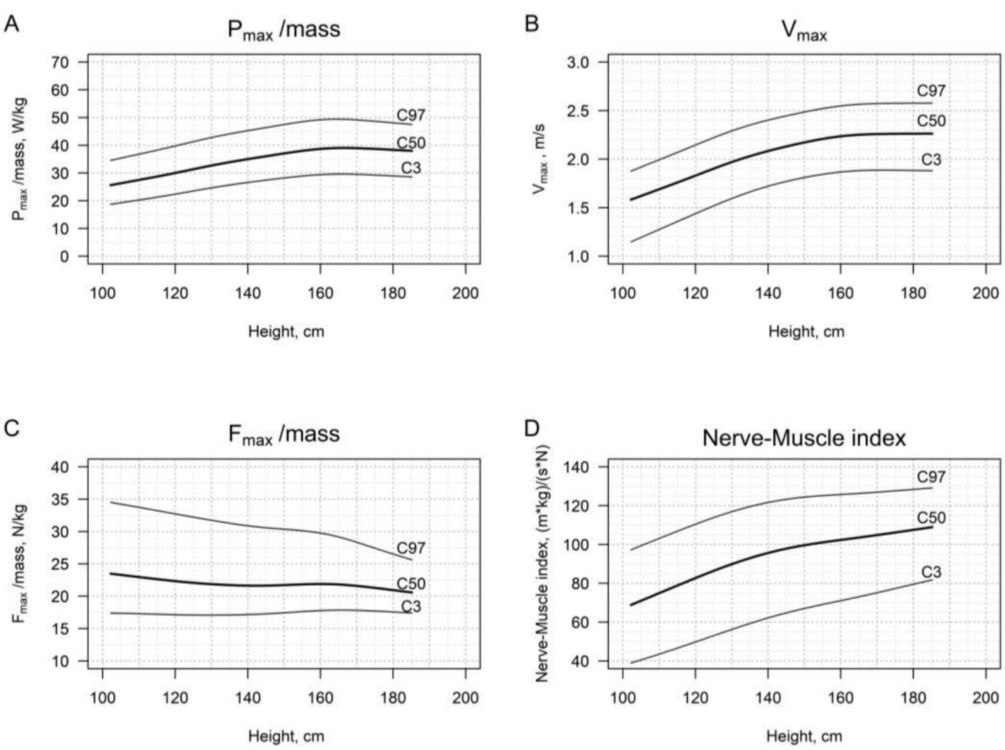


Figure 2. Reference centiles of single two-legged jump parameters according to body height in healthy girls aged 6-18 years. A) Pmax/mass, B) Vmax, C) Fmax/mass D) Nerve-Muscle-Index). Fmax: maximal force; N: Newton; Pmax: maximal power; s: second; Vmax: maximal velocity; W: Watt.

Table 2. Jumping performance of healthy children from the DONALD study with an age-specific z-score for height below third centile.

Patient no.	Age, years	Sex	Height	Age-specific z-scores for				Height-specific z-scores for			
				Vmax	rel. Pmax	rel. Fmax	NMI	Vmax	rel. Pmax	rel. Fmax	NMI
1	15.0	F	-2.45	-1.49	-0.40	1.88	-1.85	-1.07	0.09	1.82	-1.92
2	12.9	F	-1.90	-0.62	-0.07	0.29	-0.56	-0.10	0.39	0.35	-0.34
3	11.9	M	-2.10	-1.23	-0.64	0.50	-1.26	-0.12	0.28	0.47	-0.46
4	9.9	M	-2.17	-1.84	-1.78	-1.37	-0.23	-0.83	-0.97	-1.28	0.49
5	8.0	F	-2.14	-0.37	-0.21	0.05	-0.23	0.60	0.50	-0.10	0.34
6	6.0	F	-2.55	-0.44	-0.58	-0.33	-0.06	0.41	0.08	-0.53	0.55
7	14.1	M	-2.14	-0.55	-0.42	-0.32	-0.11	0.71	0.61	-0.07	0.56
8	10.0	F	-1.98	-0.35	0.48	0.49	-0.55	0.59	1.14	0.38	-0.04
9	12.1	F	-1.99	-0.33	-0.65	-0.82	0.61	0.34	-0.11	-0.71	0.94
10	5.9	M	-2.01	1.54	0.67	0.32	0.39	2.24	1.43	0.24	0.90
11	6.0	M	-1.93	-0.04	-0.14	-0.59	0.42	0.79	0.57	-0.61	0.90
12	8.2	F	-1.90	-0.60	0.79	2.11	-1.78	0.27	1.35	2.01	-1.58
13	5.8	M	-2.70	-2.22	-1.18	1.83	-2.17	-1.49	-0.21	1.64	-1.88
14	6.0	F	-3.17	-0.14	0.10	0.53	-0.59	0.99	0.85	0.28	0.13
15	5.9	M	-2.53	-1.48	-1.85	0.47	-1.18	-0.56	-1.12	0.36	-0.63
16	6.0	F	-1.97	-1.08	0.43	1.57	-1.54	-0.44	0.82	1.48	-1.38
17	8.3	M	-1.91	-1.19	-1.01	0.08	-0.77	-0.29	-0.29	0.01	-0.23
18	7.4	M	-2.53	0.23	0.83	1.53	-1.13	1.38	1.80	1.35	-0.51
19	6.2	F	-2.02	-1.33	-0.42	0.62	-1.09	-0.65	0.09	0.46	-0.76
20	7.1	M	-2.83	1.23	0.47	-1.00	1.72	2.44	1.54	-0.98	2.26

*F: female; rel. Fmax: maximum force/body weight (N/kg); No.: Number; NMI: nerve-muscle index ((m*kg)/(s*N)); M: male; rel. Pmax: maximum power/body weight (W/kg); Vmax: maximum velocity (m/s).*

In Supplement Figures 1 and 2, the reference percentiles are compared with those in which only the first measurement per subject is taken into account. Both methods yield very similar reference percentiles.

Application of the height-specific reference centiles to the healthy children from the DONALD study with an age-specific z-score for height below the third centile

To demonstrate the clinical application of height-specific reference percentiles, the age-specific z-scores for the S2LJ parameters were compared with the height-specific z-scores for healthy children from the DONALD study who had an age-specific z-score for body height below the 3rd percentile. The results are shown in Table 2.

Figure 3 shows the comparison of the age-specific z-scores of children with small stature with the height-specific z-scores of the four parameters considered in S2LJ. For Fmax/mass (C), both z-scores are very comparable. For Pmax/mass (A), Vmax (B), and nerve-muscle index (D), the height-specific z-scores are mostly greater than the age-specific z-scores.

Discussion

This is the first study to present height- and sex-specific reference centiles for mechanographic parameters in healthy German children aged 6-18 years. The presented height-specific reference centiles seem to be similar between both sexes at shorter heights (Figures 1 and 2). Thereafter an increase of Vmax, relative Pmax and NMI was observed with increasing body height until a plateau was reached. Relative Fmax did not show substantial variation with increasing height in both sexes. Descriptively, relative Fmax in girls seemed to be slightly higher at shorter stature and minimally decreased after a height of 160 cm compared to boys.

The first studies that pointed out the influence of body height on jumping performance (jumping height, force and power) were the ones from Gieysztor et al. and Fricke et al[1,11]. Gieysztor used a similar jumping method (CMJ with arm thrust) but studied different outcome measures (except Vmax) on a distinct platform. Fricke stated that jumping force and power were rather dependent on body height than age and body mass[1]. However, no height-specific reference centiles were published so far,

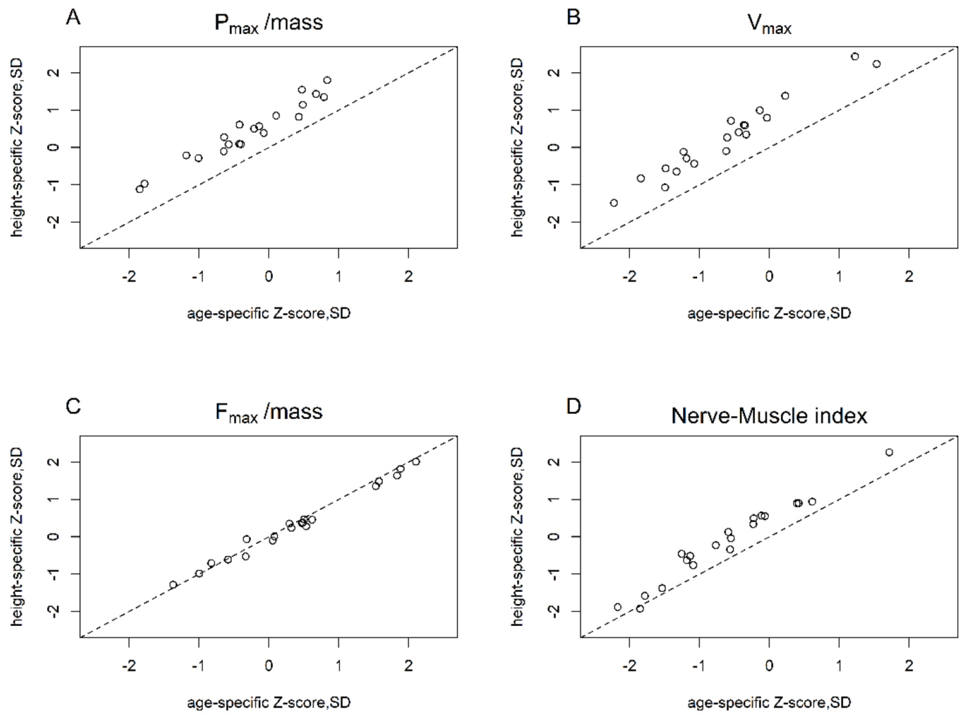


Figure 3. Comparison of age- and height-specific z-scores of children with short stature. Dotted line: represents the identity line. Fmax: maximal force; Pmax: maximal power; SD standard deviation; Vmax: maximal velocity.

making validation of our results difficult. In general, as age increases, also height increases in growth spurts explaining the general observation of increasing jumping variables with body height.

In contrast, a variety of published age-specific reference centiles provided insights into jumping performance during childhood. All of them showed increasing variables, such as Vmax, jumping efficiency and (relative) Pmax with age or with increasing body mass until puberty in girls (aged 12-14 years)[4,6–10,17,24,25]. Likewise analyzing the DONALD cohort, our colleagues showed an increase in Vmax, Pmax and NMI centiles with increasing age until puberty in the same range as our values[8]. Very recently, Li superimposed the previously published age centiles from our group and other references with their study cohort. Relative Pmax and Vmax centiles were very similar[7]. Hence it is assumed, that also the presented height-specific centiles are comparable with other Caucasian populations. However, ethnic differences in body size, muscle mass and composition, as presented in an Indian cohort, might contribute to lower jumping results[3]. Thus, multicenter cohorts across nations are needed to generate international applicability of height-specific reference centiles.

Regarding the observed plateau in age-specific and height-specific reference centiles, it is hypothesized that the flattening at certain body heights starts around the age of puberty. The marked stagnation in jumping performance in girls rather than boys, might be explained by the lower increase in muscle mass and bone length in favor of higher body fat due to lower androgenic hormones[1,4,25–28]. Additionally, girls reach puberty earlier than boys which might explain the plateau at lower heights in girls than boys, likely to correspond to a younger age.

Regarding jumping efficiency, it is not surprising that the NMI did not approach a plateau in males with increasing Vmax and relatively consistent Fmax/mass at higher stature. However, besides muscle strength and muscle coordination, other factors might influence jumping efficiency. These might be the extent of muscle-bone as well as neurocognitive function and task comprehension, which need to be studied further.

The stability in body mass-related Fmax around 2.5g (equivalent to 25 N/kg in this study) in both sexes is in line with previous studies[6,8–10,28]. Especially Sumnik et al. presented low coefficients of determination with respect to age and mass for Fmax/body mass[9]. The reason why most studies showed a relatively stable Fmax/mass has not been understood so far. It could be conjectured that force/mass might be somewhat like a constant that is rather independent on anthropological parameters. One hypothesis could be that there might be a mechanism for protection against tissue damage by limiting the body to a certain amount of force production.

In healthy children with short stature (defined as age-specific z-score for height below the third centile), considering only age-specific z-scores for jumping parameters can lead to incorrect assessment. For example, one healthy boy from this cohort (number 13, aged 5.8 years, height z-score -2.7, Table 2) has a noticeable finding with regard to Vmax (-2.22 z-score) and NMI (-2.17 z-score; -1.9 z-score corresponds to third centile) if only age-dependent z-scores are considered. Since he has a short stature, it makes sense to determine the height-specific z-scores for these parameters. These result in a z-score of -1.49 for Vmax and -1.88 for NMI, which is still within the normal range. The z-score for relative Pmax also increases from -1.18 (age-specific) to -0.21 (height-specific). This example also shows that the z-score for relative Fmax does not change relevantly when considering the height-specific z-score (1.83 vs. 1.64). Overall, when considering height-specific z-scores for this healthy boy, it can be seen that his jumping performance is within the normal range when taking his small stature into account.

Other cases in Table 2 also show that Vmax and rel. Pmax underestimate the jumping performance of children and adolescents with small stature. Figure 3 illustrates this relationship graphically for all children with small stature. In particular, the height-specific z-scores for Vmax and rel. Pmax are greater than the corresponding age-specific z-scores. Except for relative Fmax, the jumping performance of children with short stature is consistently underestimated by age-specific z-scores.

There is a wide applicability of pediatric reference centiles in different areas of interest, such as physiotherapy practice, rehabilitation centers, sports science as well as endocrinologic departments to track physical health and training outcomes. As jumping mechanography is often used to evaluate muscle strength and indirectly bone health in children, e.g. in treatment studies, it is crucial to interpret results correctly. Further, determination of muscle function by jumping mechanography is used to anticipate the risk for disability and cardiometabolic diseases in adult life. Our results show that applying age-related reference centiles for children with small stature might lead to misinterpretation of jumping performance. Thus, it is recommended to take the presented height-specific reference centiles in addition to age-specific reference centiles into account when jumping data from children with small stature are analyzed.

Strengths and Limitations

Some strengths and limitations of this study have to be discussed. A major strength was the use of a large study cohort with 3062 jumping measurements and anthropometric data from childhood until adolescence to create height-specific centiles. However, the DONALD Study design is a select population with high educational attainment and socioeconomic status. It can only be speculated that the DONALD cohort may differ from the general population in terms of dietary and physical activity patterns. The exact effect of this selection on the distribution of the percentiles cannot be calculated with the data available to us, but a bias toward higher percentiles may be conceivable. However, the mean age-specific z-scores for height and BMI are very close to zero, indicating that the study population does not differ relevantly from the general pediatric population in these parameters.

The presented reference centiles show no data of patients below 100 cm body height and include very few patients with body height of 100–109 cm. Additionally, limited female data with height >180 cm was available. Hence, our reference centiles might not be valid for patients with heights at the outer edges of the centiles.

This study did not take contributing factors like fatigue or training effect due to repeated jumps into account as no standardized resting time between jumps was carried out. Thus, interpreting jumping results of this study should be done with care.

Additionally, larger multicenter investigations on jumping performance and especially applicability of the NMI could add important value regarding international comparability as well reproducibility of results. Moreover, studies using muscle cross-sectional area and motor coordination measurements might further contribute to interpret jumping performance in children with small stature.

Conclusions

The first height-specific reference centiles for jumping mechanography for healthy German children were presented here. They could assist in combination with existing age-specific reference percentiles to improve interpretation of jumping performance and thus physical health in children with small stature. Whether height-specific reference centiles are applicable internationally, remains to be studied.

Ethics Approval

The study was conducted in accordance with the 1964 Declaration of Helsinki and its subsequent amendments and was approved by the Ethics Committee of the University of Bonn, Germany (approval no. 205/03, January 20, 2004).

Consent to Participate

Informed consent was obtained from all subjects involved in the DONALD study.

Authors' Contributions

Conceptualization, M.Z., U.A., E.S. and I.D.; methodology, I.D., U.A., M.Z., E.S.; software, I.D., M.Z..; validation, I.D., J.B., E.S.; formal analysis, I.D., M.Z.; investigation, I.D., M.Z., U.A.; resources, *U.A., I.D., E.S.; data curation, I.D., U.A., M.Z.; writing—original draft preparation, M.Z., I.D.; writing—review and editing, M.Z., J.B., K.S., U.A., E.S. and I.D.; visualization, I.D., M.Z.; supervision, I.D., E.S.; project administration, U.A., E.S.; funding acquisition, U.A., All authors have read and approved the final version of the manuscript.*

Funding

The DONALD study is funded by the state of Northrhine Westfalia.

Acknowledgements

We would like to thank all participants and families for contribution to this study.

References

1. Fricke O, Weidler J, Tutlewski B, Schoenau E. Mechanography--a new device for the assessment of muscle function in pediatrics. Pediatr Res 2006; 59: 46–49.
2. Blaschek A, Rodrigues M, Rawer R, Müller C, Ille L, Schröder S, Idriess M, Müller-Felber W, Vill K. Jumping Mechanography is a Suitable Complementary Method to Assess Motor Function in Ambulatory Boys with Duchenne Muscular Dystrophy. Neuropediatrics 2021; 52: 455–461.
3. Kasture S, Khadilkar V, Patwardhan V, Khadilkar A. Gender-specific Indian Paediatric and Adult Reference Data for Muscle Function Parameters Assessed Using Jumping Mechanography. J Musculoskelet Neuronal Interact 2024; 24: 243–258.
4. Busche P, Rawer R, Rakhimi N, Lang I, Martin DD. Mechanography in childhood: References for force and power in counter movement jumps and chair rising tests. J Musculoskelet Neuronal Interact 2013; 13: 213–226.
5. Hoffmann MD, Colley RC, Doyon CY, Wong SL, Tomkinson GR, Lang JJ. Normative-referenced percentile values for physical fitness among Canadians. Health Rep 2019; 30: 14–22.
6. Gabel L, Macdonald HM, Nettlefold L, Race D, McKay HA. Reference data for jumping mechanography in Canadian children, adolescents and young adults. J Musculoskelet Neuronal Interact 2016; 16: 283–295.
7. Li O, Ward LM, Griffith LE, Anderson LN, Wong AKO, Adachi JD, Ma J, Rauch F. Jumping mechanography reference data in Canadian children and adolescents aged 6 to 20 years. Osteoporos Int 2025.
8. Martakis K, Alexy U, Stark C, Hahn A, Rawer R, Duran I, Schönau E. Jumping Mechanography: Reference Centiles in Childhood and Introduction of the Nerve-Muscle Index to Quantify Motor Efficiency. J Clin Med 2023; 12.
9. Sumnik Z, Matyskova J, Hlavka Z, Durdilova L, Soucek O, Zemkova D. Reference data for jumping mechanography in healthy children and adolescents aged 6-18 years. J Musculoskelet Neuronal Interact 2013; 13: 297–311.
10. Markovic S, Mirkov DM, Nedeljkovic A, Jaric S. Body size and countermovement depth confound relationship between muscle power output and jumping performance. Hum Mov Sci 2014; 33: 203–210.
11. Gieysztor E, Dawidziak A, Kowal M, Paprocka-Borowicz M. Jumping Motor Skills in Typically Developing Preschool Children Assessed Using a Battery of Tests. Sensors (Basel) 2024; 24.
12. Schweizer R, Martin DD, Binder G. Increase of jump performance during GH treatment in short children born SGA. Front. Endocrinol. (Lausanne) 2023; 14: 1122287.
13. Duran I, Martakis K, Stark C, Alberg E, Bossier C, Semler O, Schoenau E. Experience with jumping mechanography in children with cerebral palsy. J Musculoskelet Neuronal Interact 2017; 17: 237–245.
14. Runge M, Rittweger J, Russo CR, Schiessl H, Felsenberg D. Is muscle power output a key factor in the age-related decline in physical performance? A comparison of muscle cross section, chair-rising test and jumping power. Clin Physiol Funct Imaging 2004; 24: 335–340.
15. Tsubaki A, Kubo M, Kobayashi R J H, Takahashi HE. Normative values for maximum power during motor function assessment of jumping among physically active Japanese. J Musculoskelet Neuronal Interact 2009; 9: 263–267.
16. Ward KA, Das G, Berry JL, Roberts SA, Rawer R, Adams JE, Mughal Z. Vitamin D status and muscle function in post-menarchal adolescent girls. J Clin Endocrinol Metab 2009; 94: 559–563.
17. Ullrich B, Pelzer T, Pfeiffer M. Neuromuscular Effects to 6 Weeks of Loaded Countermovement Jumping With Traditional and Daily Undulating Periodization. J Strength Cond Res 2018; 32: 660–674.
18. Kroke A, Manz F, Kersting M, Remer T, Sichert-Hellert W, Alexy U, Lentze MJ. The DONALD Study. History, current status and future perspectives. Eur J Nutr 2004; 43: 45–54.
19. Schienkiewitz A, Ed. Referenzperzentile für anthropometrische Maßzahlen und Blutdruck aus der Studie zur Gesundheit von Kindern und Jugendlichen in Deutschland (KiGGS); Robert-Koch-Inst: Berlin 2011, ISBN 9783896062109.
20. Cole TJ, Presenting information on growth distance and conditional velocity in one chart: Practical issues of chart design. Statist Med 1998; 17: 2697–2707.
21. Cole TJ, Green PJ. Smoothing reference centile curves: The LMS method and penalized likelihood. Statist Med 1992; 11: 1305–1319.
22. Vogel M, Kirsten T, Kratzsch J, Engel C, Kiess W. A combined approach to generate laboratory reference intervals using unbalanced longitudinal data. J Pediatr Endocrinol Metab 2017; 30: 767–773.
23. WHO Multicentre Growth Reference Study Group. WHO Child Growth Standards based on length/height,

weight and age. Acta Paediatr Suppl 2006; 450: 76-85, ISBN 924154693X
24. Jones CM, McNarry MA, Owen NJ. The effect of body size on countermovement jump kinetics in children aged 7-11 years. Eur J Sport Sci 2020; 20: 174–181.
25. Temfemo A, Hugues J, Chardon K, Mandengue SH, Ahmaidi S. Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. Eur J Pediatr 2009; 168: 457–464.
26. Round JM, Jones DA, Honour JW, Nevill AM. Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. Ann Hum Biol 1999; 26: 49–62.
27. Schoenau E, Neu CM, Mokov E, Wassmer G, Manz F. Influence of puberty on muscle area and cortical bone area of the forearm in boys and girls. J Clin Endocrinol Metab. 2000; 85: 1095–1098.
28. Focke A, Strutzenberger G, Jekauc D, Worth A, Woll A, Schwameder H. Effects of age, sex and activity level on counter-movement jump performance in children and adolescents. Eur J Sport Sci 2013; 13: 518–526.

Supplementary Material

Suppl. Table 1. Reference centiles for velocity$_{max}$ (m/s) in the S2LJ in healthy German females.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	1.11	1.28	1.42	1.55	1.67	1.76	1.84	0.117	2.775
105	1.19	1.35	1.49	1.62	1.74	1.83	1.92	0.112	2.604
110	1.28	1.43	1.56	1.69	1.81	1.90	1.99	0.108	2.434
115	1.36	1.50	1.63	1.76	1.88	1.98	2.07	0.104	2.267
120	1.44	1.58	1.70	1.83	1.95	2.05	2.15	0.100	2.109
125	1.52	1.65	1.77	1.90	2.02	2.12	2.22	0.097	1.979
130	1.59	1.72	1.84	1.97	2.09	2.19	2.29	0.093	1.876
135	1.66	1.79	1.91	2.03	2.15	2.25	2.35	0.089	1.807
140	1.72	1.84	1.96	2.08	2.20	2.30	2.40	0.086	1.793
145	1.77	1.89	2.01	2.13	2.25	2.35	2.45	0.084	1.833
150	1.81	1.93	2.05	2.17	2.29	2.39	2.49	0.082	1.909
155	1.84	1.97	2.08	2.21	2.33	2.43	2.52	0.081	1.996
160	1.87	1.99	2.11	2.24	2.35	2.45	2.55	0.080	2.054
165	1.88	2.01	2.13	2.25	2.37	2.47	2.56	0.080	2.082
170	1.89	2.01	2.13	2.26	2.38	2.48	2.57	0.080	2.111
175	1.89	2.01	2.13	2.26	2.38	2.48	2.57	0.080	2.156
180	1.88	2.01	2.14	2.26	2.38	2.48	2.58	0.080	2.207

Suppl. Table 2. Reference centiles for velocity$_{max}$ (m/s) in the S2LJ in healthy German males.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	1.09	1.22	1.34	1.47	1.59	1.70	1.80	0.126	1.663
105	1.16	1.29	1.42	1.55	1.67	1.77	1.87	0.121	1.676
110	1.24	1.37	1.49	1.62	1.75	1.85	1.95	0.116	1.688
115	1.31	1.44	1.57	1.70	1.82	1.93	2.03	0.111	1.701
120	1.39	1.52	1.64	1.77	1.90	2.00	2.11	0.106	1.712
125	1.47	1.60	1.72	1.85	1.98	2.09	2.19	0.103	1.717
130	1.54	1.68	1.80	1.93	2.06	2.17	2.27	0.099	1.716
135	1.62	1.75	1.88	2.01	2.14	2.25	2.36	0.097	1.708
140	1.68	1.81	1.94	2.08	2.21	2.32	2.43	0.095	1.693
145	1.73	1.86	1.99	2.13	2.26	2.38	2.48	0.093	1.674
150	1.78	1.91	2.04	2.18	2.31	2.43	2.54	0.092	1.653
155	1.82	1.96	2.09	2.23	2.37	2.49	2.60	0.092	1.634
160	1.88	2.02	2.15	2.30	2.43	2.56	2.67	0.092	1.623
165	1.94	2.08	2.22	2.37	2.51	2.64	2.76	0.091	1.623
170	2.01	2.15	2.29	2.45	2.59	2.72	2.84	0.090	1.635
175	2.07	2.21	2.36	2.51	2.66	2.79	2.91	0.089	1.658
180	2.11	2.26	2.41	2.56	2.71	2.83	2.96	0.087	1.689
185	2.15	2.30	2.44	2.59	2.74	2.86	2.98	0.085	1.726
190	2.17	2.32	2.46	2.61	2.76	2.88	3.00	0.084	1.767
195	2.20	2.34	2.48	2.63	2.77	2.90	3.02	0.082	1.809
200	2.22	2.37	2.51	2.65	2.79	2.91	3.03	0.080	1.852

Suppl. Table 3. Reference centiles for $power_{max}$/mass (W/kg) in the S2LJ in healthy German females.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	18.3	20.3	22.5	25.1	28.0	30.9	33.9	0.164	0.181
105	19.3	21.3	23.6	26.3	29.3	32.2	35.4	0.161	0.173
110	20.3	22.4	24.7	27.5	30.6	33.6	36.8	0.158	0.164
115	21.3	23.5	25.8	28.7	31.9	35.0	38.2	0.156	0.156
120	22.4	24.6	27.1	30.0	33.2	36.4	39.8	0.153	0.151
125	23.5	25.8	28.3	31.4	34.7	37.9	41.3	0.150	0.156
130	24.6	27.0	29.6	32.7	36.1	39.3	42.8	0.147	0.173
135	25.7	28.1	30.7	33.9	37.3	40.6	44.1	0.144	0.204
140	26.6	29.1	31.8	35.0	38.5	41.8	45.3	0.141	0.247
145	27.4	30.0	32.8	36.0	39.5	42.9	46.4	0.139	0.301
150	28.2	30.9	33.7	37.1	40.6	44.0	47.5	0.138	0.367
155	28.9	31.6	34.6	38.0	41.6	45.0	48.5	0.137	0.442
160	29.4	32.2	35.2	38.7	42.3	45.7	49.2	0.136	0.522
165	29.6	32.5	35.5	39.0	42.6	46.0	49.4	0.135	0.606
170	29.5	32.4	35.5	38.9	42.5	45.8	49.1	0.134	0.693
175	29.3	32.2	35.2	38.7	42.2	45.4	48.6	0.133	0.780
180	28.9	31.9	34.9	38.4	41.8	45.0	48.1	0.133	0.865

Suppl. Table 4. Reference centiles for $power_{max}$/mass (W/kg) in the S2LJ in healthy German males.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	16.7	18.6	20.6	22.8	25.2	27.5	29.8	0.152	0.544
105	17.8	19.8	21.9	24.3	26.9	29.2	31.7	0.152	0.550
110	18.9	21.0	23.2	25.8	28.5	31.0	33.6	0.152	0.555
115	19.9	22.1	24.5	27.2	30.1	32.7	35.5	0.152	0.561
120	21.0	23.3	25.8	28.7	31.7	34.5	37.4	0.153	0.567
125	22.1	24.6	27.2	30.2	33.4	36.4	39.5	0.153	0.575
130	23.3	25.9	28.7	31.9	35.3	38.5	41.7	0.153	0.585
135	24.4	27.2	30.1	33.6	37.1	40.4	43.8	0.154	0.597
140	25.4	28.3	31.4	35.0	38.7	42.2	45.7	0.155	0.610
145	26.1	29.2	32.4	36.1	40.0	43.6	47.2	0.156	0.624
150	26.8	30.0	33.3	37.1	41.1	44.9	48.6	0.156	0.638
155	27.6	30.9	34.3	38.3	42.5	46.3	50.2	0.157	0.655
160	28.6	32.1	35.7	39.8	44.1	48.1	52.2	0.157	0.676
165	29.9	33.5	37.3	41.6	46.1	50.3	54.5	0.157	0.701
170	31.3	35.1	39.0	43.6	48.2	52.5	56.8	0.156	0.732
175	32.6	36.5	40.6	45.2	50.0	54.4	58.8	0.154	0.766
180	33.7	37.7	41.8	46.5	51.3	55.7	60.1	0.152	0.804
185	34.5	38.5	42.7	47.4	52.2	56.6	60.9	0.149	0.844
190	35.1	39.2	43.3	48.0	52.8	57.1	61.4	0.146	0.886
195	35.7	39.8	43.9	48.6	53.2	57.5	61.7	0.143	0.927
200	36,3	40,3	44,5	49,1	53,7	57,9	62,0	0,139	0,969

Suppl. Table 5. Reference centiles for F_{max}/mass (N/kg) in the S2LJ in healthy German females.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	17.43	19.07	21.03	23.63	26.82	30.38	34.73	0.180	-0.684
105	17.37	18.93	20.80	23.30	26.40	29.89	34.24	0.176	-0.801
110	17.30	18.79	20.57	22.97	25.97	29.39	33.74	0.172	-0.918
115	17.22	18.64	20.34	22.64	25.55	28.91	33.24	0.168	-1.034
120	17.14	18.49	20.12	22.33	25.15	28.43	32.73	0.164	-1.149
125	17.09	18.38	19.94	22.07	24.78	27.98	32.22	0.160	-1.256
130	17.08	18.32	19.82	21.87	24.49	27.59	31.74	0.156	-1.349
135	17.10	18.30	19.75	21.72	24.25	27.25	31.28	0.151	-1.422
140	17.16	18.33	19.73	21.64	24.09	26.99	30.88	0.147	-1.476
145	17.27	18.41	19.78	21.64	24.02	26.83	30.58	0.143	-1.516
150	17.44	18.56	19.90	21.72	24.04	26.75	30.36	0.139	-1.543
155	17.63	18.73	20.05	21.83	24.07	26.69	30.12	0.135	-1.557
160	17.79	18.87	20.16	21.88	24.04	26.53	29.75	0.130	-1.556
165	17.86	18.91	20.16	21.81	23.87	26.20	29.17	0.125	-1.540
170	17.82	18.84	20.03	21.60	23.52	25.67	28.35	0.119	-1.512
175	17.71	18.68	19.81	21.29	23.07	25.03	27.43	0.112	-1.479
180	17.57	18.50	19.57	20.95	22.60	24.38	26.53	0.106	-1.445

Suppl. Table 6. Reference centiles for F_{max}/mass (N/kg) in the S2LJ in healthy German males.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	16.46	17.84	19.49	21.69	24.40	27.44	31.22	0.166	-0.869
105	16.52	17.87	19.47	21.60	24.23	27.16	30.79	0.161	-0.896
110	16.58	17.89	19.45	21.52	24.05	26.88	30.37	0.157	-0.924
115	16.63	17.91	19.43	21.43	23.88	26.61	29.96	0.153	-0.952
120	16.68	17.93	19.41	21.35	23.72	26.35	29.58	0.148	-0.982
125	16.74	17.96	19.39	21.27	23.57	26.11	29.22	0.144	-1.015
130	16.80	17.99	19.38	21.21	23.44	25.89	28.90	0.140	-1.052
135	16.87	18.03	19.38	21.16	23.33	25.71	28.63	0.137	-1.092
140	16.95	18.08	19.40	21.14	23.24	25.56	28.40	0.133	-1.134
145	17.05	18.15	19.44	21.14	23.19	25.45	28.22	0.130	-1.179
150	17.16	18.25	19.51	21.17	23.18	25.39	28.10	0.127	-1.227
155	17.31	18.37	19.61	21.24	23.21	25.38	28.04	0.124	-1.276
160	17.48	18.53	19.75	21.35	23.28	25.42	28.03	0.122	-1.326
165	17.68	18.71	19.91	21.49	23.40	25.50	28.08	0.119	-1.380
170	17.89	18.91	20.09	21.65	23.53	25.61	28.17	0.117	-1.440
175	18.10	19.10	20.27	21.81	23.67	25.72	28.26	0.114	-1.502
180	18.30	19.29	20.44	21.95	23.79	25.83	28.34	0.112	-1.567
185	18.48	19.45	20.59	22.08	23.89	25.91	28.40	0.110	-1.633
190	18.65	19.61	20.73	22.20	23.99	25.98	28.45	0.108	-1.699
195	18.81	19.76	20.86	22.31	24.07	26.04	28.49	0.106	-1.766
200	18.98	19.91	20.99	22.42	24.16	26.10	28.53	0.104	-1.832

Suppl. Table 7. Reference centiles for Nerve-Muscle Index ((m*kg)/(s*N)) in the S2LJ in healthy German females.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	37.7	47.2	56.7	67.1	77.4	86.6	95.5	0.229	1.078
105	40.5	50.6	60.4	71.0	81.4	90.5	99.3	0.219	1.171
110	43.5	54.0	64.2	74.9	85.3	94.4	103.1	0.209	1.263
115	46.6	57.6	67.9	78.8	89.2	98.2	106.8	0.200	1.357
120	49.8	61.1	71.7	82.7	93.1	102.0	110.4	0.191	1.450
125	53.0	64.7	75.4	86.4	96.7	105.5	113.8	0.183	1.543
130	56.2	68.1	78.9	89.9	100.1	108.7	116.9	0.174	1.631
135	59.3	71.2	82.0	93.0	103.0	111.5	119.5	0.167	1.712
140	62.2	74.1	84.8	95.6	105.5	113.9	121.6	0.160	1.788
145	64.8	76.6	87.2	97.8	107.5	115.7	123.2	0.153	1.862
150	67.0	78.8	89.2	99.6	109.1	117.0	124.4	0.147	1.933
155	69.1	80.7	90.9	101.1	110.3	118.0	125.1	0.142	2.000
160	71.1	82.4	92.4	102.3	111.3	118.8	125.7	0.136	2.063
165	73.0	84.1	93.9	103.5	112.3	119.6	126.3	0.131	2.123
170	75.1	85.9	95.4	104.8	113.3	120.4	126.9	0.126	2.179
175	77.3	87.8	97.0	106.2	114.4	121.3	127.6	0.121	2.232
180	79.5	89.7	98.6	107.5	115.5	122.2	128.3	0.116	2.284

Suppl. Table 8. Reference centiles for Nerve-Muscle Index ((m*kg)/(s*N)) in the S2LJ in healthy German males.

Height, cm	C3	C10	C25	M	C75	C90	C97	S	L
100	39.5	48.7	58.2	68.7	79.2	88.6	98.0	0.227	0.992
105	42.8	52.4	62.0	72.5	82.8	92.1	101.2	0.214	1.074
110	46.4	56.1	65.8	76.3	86.5	95.6	104.4	0.201	1.156
115	50.0	59.9	69.6	80.0	90.1	99.0	107.5	0.190	1.239
120	53.7	63.8	73.5	83.8	93.7	102.4	110.7	0.179	1.325
125	57.5	67.6	77.3	87.5	97.2	105.7	113.7	0.169	1.413
130	61.2	71.4	81.0	91.1	100.7	108.9	116.7	0.159	1.504
135	64.8	75.0	84.6	94.5	103.8	111.8	119.4	0.151	1.600
140	68.2	78.4	87.9	97.7	106.8	114.5	121.9	0.143	1.698
145	71.4	81.6	91.0	100.6	109.5	117.0	124.1	0.136	1.797
150	74.4	84.5	93.8	103.2	111.9	119.3	126.2	0.130	1.895
155	77.1	87.2	96.4	105.7	114.2	121.4	128.0	0.125	1.991
160	79.6	89.7	98.8	107.9	116.3	123.3	129.8	0.120	2.086
165	81.9	92.0	101.0	110.1	118.3	125.2	131.5	0.116	2.179
170	84.1	94.2	103.1	112.1	120.2	126.9	133.2	0.112	2.272
175	86.1	96.2	105.1	114.0	122.0	128.6	134.7	0.109	2.364
180	88.0	98.1	107.0	115.7	123.6	130.1	136.1	0.106	2.457
185	89.8	100.0	108.8	117.5	125.3	131.7	137.6	0.103	2.550
190	91.7	101.8	110.6	119.2	126.9	133.2	139.0	0.101	2.642
195	93.5	103.6	112.4	120.9	128.5	134.7	140.4	0.098	2.733
200	95.3	105.5	114.2	122.6	130.1	136.3	141.9	0.096	2.824

Suppl. Table 9. Selected degree of freedom for each parameter by outcome and sex for the final LMS models.

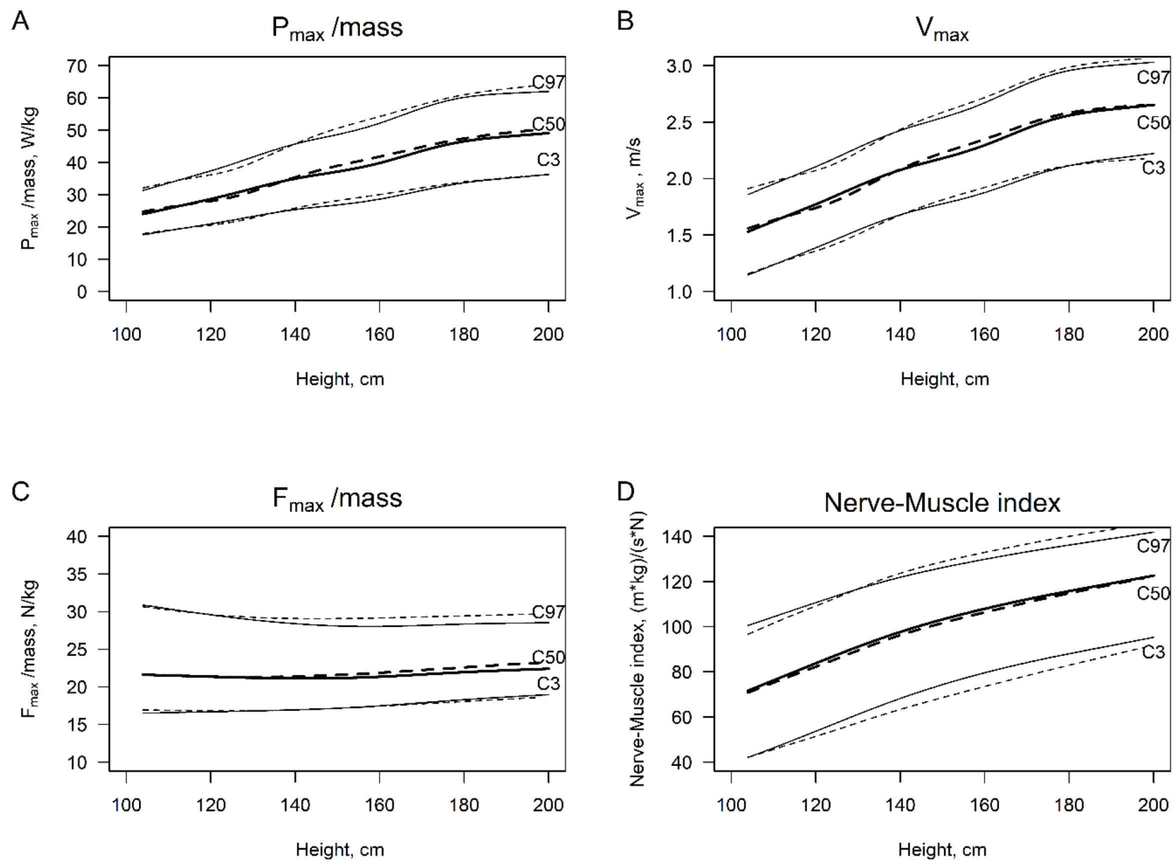
Model	Sex					
	Female			Males		
	M	S	L	M	S	L
$Velocity_{max}$	2.5	1.0	1.0	3.5	1.5	0.5
$Power_{max}$/mass	2.5	1.0	0.5	3.3	1.5	0.5
Fmax/mass	2.1	1.0	0.5	1.2	0.5	0.5
Nerve-Muscle Index	1.5	0.5	0.5	1.7	0.5	0.5

In GAMLSS, the BSCG (Box–Cox Cole and Green) distribution and the penalized cubic smoothing spline (cs() as smoothing function) were used with the function gamlss() to generated the height-specific reference centiles for the S2LJ data. M mu median, L lambda (skewness), S sigma (coefficient of variation), S2LJ single two-legged jump.

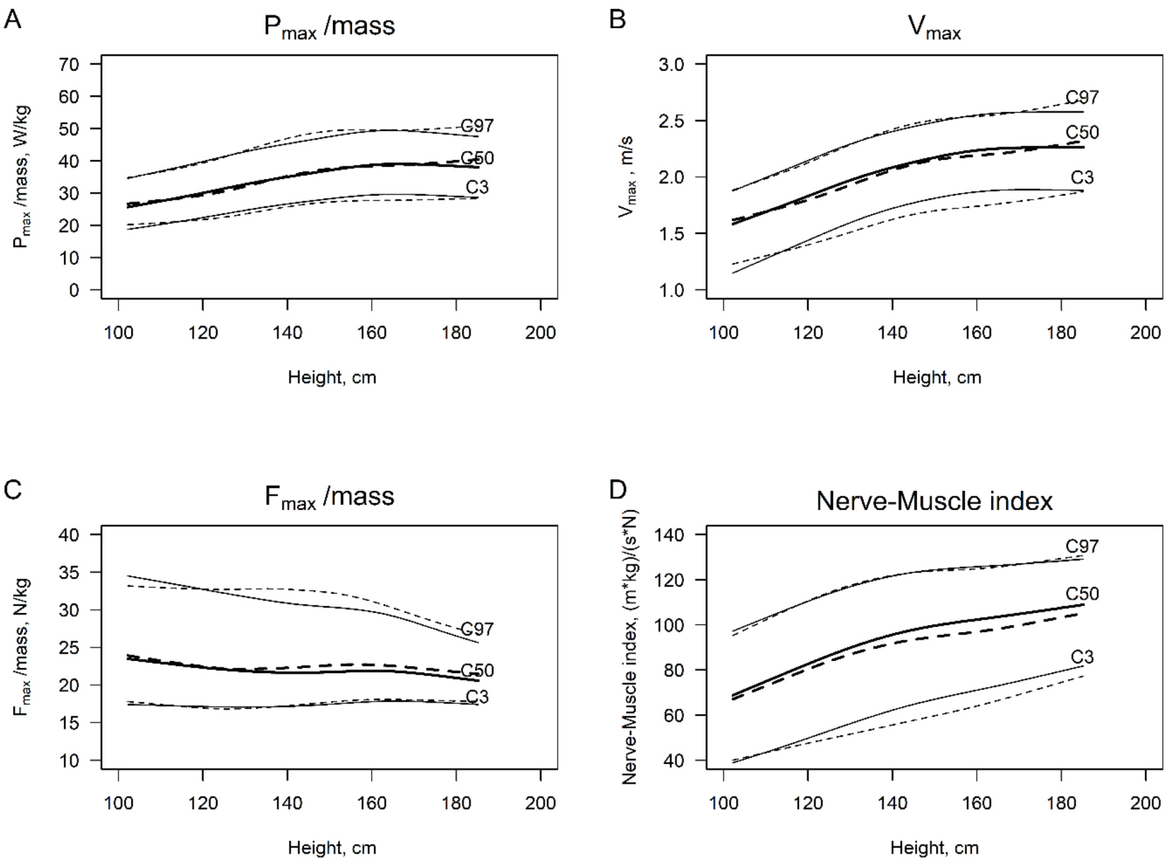
Suppl. Table 10. Number of S2LJ assessments in specific height interval by sex.

Height (cm)	Female (n)	Male (n)
100-109	7	7
110-119	150	137
120-129	173	209
130-139	202	230
140-149	186	232
150-159	168	183
160-169	373	149
170-180	173	236
>180	13	234

S2LJ single two-legged jump.



Suppl. Figure 1. Sensitivity of height-specific centiles in males. Comparison of reference percentiles of single two-legged jump parameters according to body height in healthy boys aged 6-18 years, using all measurements per subject (solid line), with those using only the first measurement per subject (dashed line). A) Pmax/mass, B) Vmax, C) Fmax/mass D) Nerve-Muscle-Index. Fmax: maximal force; N: Newton; Pmax: maximal power; s: second; Vmax: maximal velocity; W: Watt.



Suppl. Figure 2. Sensitivity of height-specific centiles in females. Comparison of reference percentiles of single two-legged jump parameters according to body height in healthy girls aged 6-18 years, using all measurements per subject (solid line), with those using only the first measurement per subject (dashed line). A) Pmax/mass, B) Vmax, C) Fmax/mass D) Nerve-Muscle-Index. Fmax: maximal force; N: New-ton; Pmax: maximal power; s: second; Vmax: maximal velocity; W: Watt.