

University of Groningen

Grip strength is strongly associated with height, weight and gender in childhood

Ploegmakers, Joris J. W.; Hepping, Ann M.; Geertzen, Jan H. B.; Bulstra, Sjoerd K.; Stevens, Martin

Published in:
Journal of Physiotherapy

DOI:
[10.1016/S1836-9553\(13\)70202-9](https://doi.org/10.1016/S1836-9553(13)70202-9)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2013

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Ploegmakers, J. J. W., Hepping, A. M., Geertzen, J. H. B., Bulstra, S. K., & Stevens, M. (2013). Grip strength is strongly associated with height, weight and gender in childhood: a cross sectional study of 2241 children and adolescents providing reference values. *Journal of Physiotherapy*, 59(4), 255-261. [https://doi.org/10.1016/S1836-9553\(13\)70202-9](https://doi.org/10.1016/S1836-9553(13)70202-9)

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Grip strength is strongly associated with height, weight and gender in childhood: a cross sectional study of 2241 children and adolescents providing reference values

Joris JW Ploegmakers¹, Ann M Hepping², Jan HB Geertzen², Sjoerd K Bulstra¹ and Martin Stevens¹

¹Department of Orthopaedics, ²Department of Rehabilitation Medicine
University of Groningen, University Medical Center Groningen
The Netherlands

Question: What are reference values for grip strength in children and adolescents based on a large and heterogeneous study population? What is the association of grip strength with age, gender, weight, and height in this population? **Design:** Cross-sectional study. **Participants:** Participants were recruited from schools in the northern provinces of the Netherlands. The study included healthy children and adolescents ranging in age from 4 to 15 years. **Outcome measures:** All children had their height (cm) and weight (kg) measured and were allowed a total of four attempts using the Jamar hand dynamometer: twice with each hand. Grip strength scores (kg) were recorded for the dominant and non-dominant hands. **Results:** The study population comprised 2241 children and adolescents. Reference values for both genders are provided according to age and dominance. Grip strength shows a linear and parallel progression for both genders until the age of 11 or 12, after which grip strength development shows an acceleration that is more prominent in boys. **Conclusion:** There is a significant difference in grip strength with each ascending year of age in favour of the older group, as well as a trend for boys to be stronger than girls in all age groups between 4 and 15 years. Weight and especially height have a strong association with grip strength in children. [Ploegmakers JJW, Hepping AM, Geertzen JHB, Bulstra SK, Stevens M (2013) Grip strength is strongly associated with height, weight and gender in childhood: a cross sectional study of 2241 children and adolescents providing reference values. *Journal of Physiotherapy* 59: 255–261]

Key words: Grip strength, Children, Jamar hand dynamometer, Reference values, Physiotherapy

Introduction

Grip strength is used extensively in the assessment of hand function. Because it is directly affected by the neural, muscular and skeletal systems, grip strength is used in the evaluation of patients with a large range of pathologies that impair the upper extremities, including rheumatoid arthritis, osteoarthritis, muscular dystrophy, tenosynovitis, stroke, and congenital malformations. Grip strength measurements also have an established role in determining treatment efficacy, such as in the evaluation of different wrist orthoses, the effect of hand exercises in rheumatoid arthritis, and recovery after trauma. Also, they are used as an outcome measure after many different surgical interventions. Grip strength measurements provide a well established and objective score that is reflective of hand function and that is easily and quickly obtainable by a range of different health professionals.

Since comparison to normative data is important when making statements about specific patient groups or treatments, obtaining normative data for grip strength in adults has been the subject of many studies. In contrast, normative data for children is far less readily available. To identify studies on this topic we searched PubMed, MEDLINE and EMBASE using combinations of the search terms: children, adolescents, grip strength, dynamometer, Jamar hand dynamometer, JHD, normative data and reference values. Reference lists of relevant articles were then screened to identify additional articles that might not

have shown up in the search. Although we found several studies focusing specifically on grip strength in children, most of them had not assessed height and weight as factors of influence (Ager et al 1984, Bear-Lehman et al 2002, Butterfield et al 2009, De Smet and Vercammen 2001, Mathiowetz et al 1986). This is remarkable in the case of growing children, especially when weight and height are known to correlate with strength in children (Rauch 2002, Häger-Ross and Rösblad 2002, Newman et al 1984). Moreover, although some of these studies included a large number of children in total (with exception of Newman

What is already known on this topic: Grip strength is used widely in clinical practice and research to assess the impact of a variety of disorders on hand function. Although robust data exist for predicting grip strength in adults, the few studies that have generated normative data in children and adolescents either had a limited sample size, used a measurement device that is no longer used in clinical practice, or did not analyse factors such as hand dominance, height, or weight.

What this study adds: Normative equations and graphs were generated using data from 2241 children and adolescents. Grip strength increases with age, with a trend for boys to be stronger than girls in all age groups between 4 and 15 years. Weight and height have a strong association with grip strength in children and adolescents.

et al 1984, varying between 81 and 736), the number of children in each age group and/or the range of age groups is often limited and relatively small for establishing reference values. Also, a variety of methods and instruments was used. For example, some studies did not differentiate between scores of the dominant and non-dominant hand, used a device that is no longer used in clinical practice, or scored the maximum instead of the mean of attempts. Therefore, it can be concluded that there is a need for a study that assesses the development of grip strength in children, based on large groups according to age and gender and performed according to current standardised methods regarding measurement of grip strength.

The primary aim of this study was to provide reference values for grip strength in children and to present these data graphically to allow easy comparison with patient outcomes by a range of clinicians in daily practice. Therefore the research questions were:

1. What are the reference values for grip strength in children aged 4–15 years according to age, gender and dominance based on a large, heterogeneous study population?
2. What is the association of gender, height, and weight with grip strength in children?

Method

Design

This cross-sectional study measured grip strength in a cohort of healthy children and adolescents. The data were used to generate normative values for grip strength.

Participants

Children and adolescents ranging in age from 4 to 15 years were included. Participants were recruited by approaching schools in the four northern provinces of The Netherlands. All children of participating school classes were invited to take part. Exclusion criteria were: pain or restriction of movement of a hand or arm, neuromuscular disease, generalised bone disease, aneuploidy, any condition that severely interfered with normal growth or required hormonal supplementation, and children who could not be instructed in how to use the dynamometer.

All included subjects were assigned to a group based on their calendar age at the time of the assessment, thereby creating nine subgroups in total. The study aimed to include at least 200 children in each age group, with a near to equal representation of boys and girls.

Outcome measures

Each measurement session started with a short lecture by the researchers to introduce themselves to the school class and to explain the procedures and the purpose of the study. A demonstration of the use of the dynamometer was given, using the teacher as an example. Individually, dominance was determined by asking which hand was used to write or, in the case of young children, used to perform activities such as cutting or painting. Children aged 4 and 5 years, in whom hand dominance is not yet fully established, and any older children who displayed uncertainty regarding hand dominance, were asked to draw a circle. To avoid suggestion by the researcher, these participants had to pick up the pencil from the table themselves. The hand used to draw the shape was then scored as the dominant hand. The

height (in cm) and weight (in kg) of each participating child were then measured.

Grip strength was measured using the Jamar® hydraulic hand dynamometer^a. A total of six calibrated dynamometers were at the researchers' disposal. The devices were replaced twice, at subsequent time intervals, with two used devices exchanged for two non-used devices after approximately one-third, and again after two-thirds of the total number of children we aimed to recruit had been assessed. The following standardised testing position for measuring grip strength was used, as advocated by the American Society of Hand Therapists (ASHT): the participant is seated with shoulders adducted and neutrally rotated, elbow flexed at 90 deg, wrist between 0 and 30 deg extension, and between 0 and 15 deg ulnar deviation (Balogun et al 1985, Fess 1992). The handle of the device was set to the second position for all participants, with the exception of 4 and 5 year olds, for whom the bar was set to the first position, and who were allowed to manually support the arm with the other hand. Participants were allowed four attempts using the dynamometer, two with each hand, and each individual attempt was scored. The starting hand was alternated between subjects and a 10-sec break was allowed between attempts. A Dutch translation of the Southampton grip strength measurement protocol was used as verbal encouragement (Roberts et al 2011). Encouragement was kept as consistent as possible for every participant in volume and tone, counting down from 3 to 0, followed by 'squeeze as hard as you can ... squeeze and let go'.

Data analysis

Descriptive statistics were used to describe the main characteristics of the participants. The Mann-Whitney U test was used to compare grip strength between genders. In order to establish the correlation of gender, age, height, and weight with grip strength in more detail, we performed a multilevel analysis adding them as fixed factors. As intercept, the school the child attended was added. Results were accepted to be significant when the *p* value was < 0.05.

Results

In total 19 schools participated, located in 12 towns and cities. Thirteen children were ineligible for participation in the study. Two children were excluded because of Down syndrome, two children because they suffered from active juvenile arthritis, four because they had pre-existing pain of a hand or arm, and one because she received hormonal therapy to improve growth. Another four children were excluded because they did not meet the inclusion criteria, but no specific reason was recorded. Nine eligible children were excluded because the form on which measurements were written was not filled in completely. In order to get an impression of how many children refused to participate we randomly recorded the number of children that refused to participate at half of the schools visited. Based on this registration it can be estimated that about 1% of invited children did not participate in the study. The reasons cited most commonly were unfamiliarity (children who just started school), problems with (self-perceived) body weight, or simply 'not feeling like it'.

The final study population comprised 2241 children and adolescents (1112 boys and 1129 girls) ranging in age from 4 to 15 years. Values for grip strength according to age,

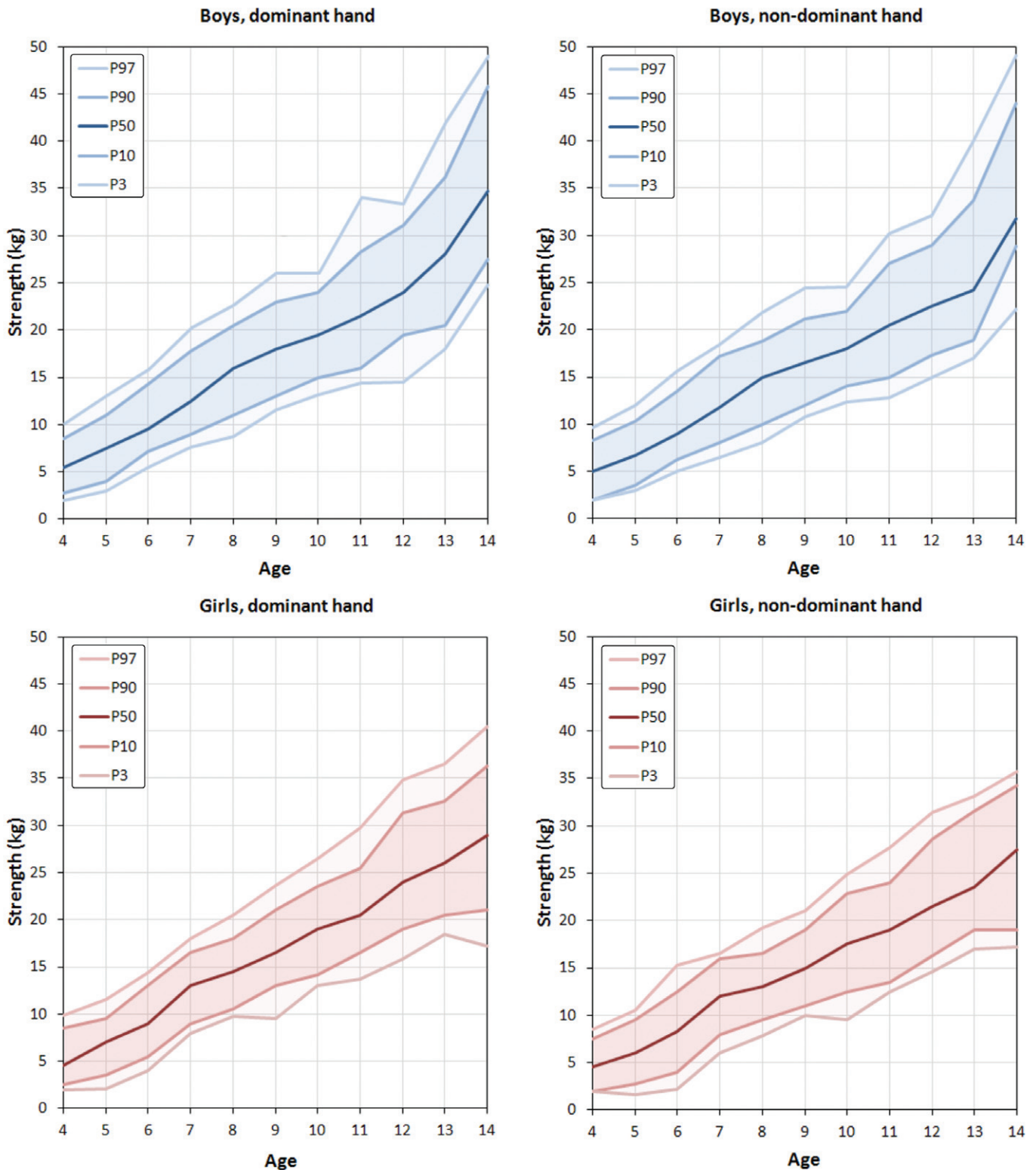


Figure 1. Reference values for grip strength according to gender, dominance, and age. Scores are plotted as percentiles 3, 10, 50, 90, and 97. The upper and lower limits indicate the borders of reference values for strength at the corresponding age. The darker shaded areas represent the centralised 80% of scores.

hand dominance, and gender are presented in Figure 1. Grip strength in both hands increased with age, showing a nearly linear progression for boys until the age of 12. Above the age of 12, the increase in strength shows acceleration in the dominant hand. A similar observation can be made for the non-dominant hand after reaching the age of 13. For girls, this acceleration was less prominent but began at the earlier

age of 11 for both hands. Regardless of this acceleration, the difference in mean strength between all age groups was significant for both hands and in both genders in favour of the older group ($p < 0.01$), with exception for the values of the non-dominant hand between girls aged 13 and 14 where p was 0.02.

Table 1. Number of participants, grip strength values for the dominant and non-dominant hands, height and weight, according to age and gender.

Age (yr)	Boys				Girls					
	n	Dominant (kg)	Non-dominant (kg)	Height (cm) range	Weight (kg)	n	Dominant (kg)	Non-dominant (kg)	Height (cm) range	Weight (kg)
4	124	5.7 (2) 1 to 12	5.3 (2) 2 to 10	111 (5) 100 to 126	19 (3) 15 to 26	109	5.1 (2) 1 to 11	4.7 (2) 2 to 10	111 (5) 100 to 126	19 (3) 13 to 29
5	102	7.5 (3) 2 to 14	6.8 (3) 3 to 14	117 (6) 103 to 138	22 (3) 15 to 30	105	6.7 (2) 2 to 15	6.0 (2) 1 to 12	118 (6) 102 to 131	22 (3) 15 to 32
6	123	10.2 (3) 5 to 18	9.4 (3) 4 to 17	125 (5) 111 to 139	25 (4) 17 to 44	108	9.0 (3) 3 to 18	8.3 (3) 2 to 16	124 (6) 100 to 137	25 (4) 16 to 39
7	104	13.0 (4) 7 to 21	12.0 (3) 5 to 19	131 (6) 116 to 145	28 (5) 20 to 54	98	12.9 (3) 7 to 21	11.9 (3) 5 to 18	131 (6) 113 to 141	29 (5) 17 to 40
8	113	15.9 (4) 8 to 25	14.6 (3) 8 to 23	139 (6) 124 to 155	32 (6) 23 to 55	118	14.4 (3) 8 to 22	13.1 (3) 7 to 21	136 (6) 122 to 151	31 (6) 20 to 49
9	116	18.2 (4) 10 to 29	16.8 (4) 8 to 33	142 (6) 126 to 162	36 (7) 25 to 60	119	16.7 (3) 9 to 26	15.1 (3) 7 to 23	141 (5) 126 to 154	35 (7) 24 to 53
10	109	19.6 (2) 12 to 29	18.1 (3) 9 to 28	147 (7) 129 to 161	38 (7) 26 to 65	103	19.1 (4) 9 to 29	17.2 (4) 8 to 29	149 (7) 132 to 167	41 (8) 25 to 63
11	113	22.0 (5) 9 to 35	20.6 (4) 8 to 33	154 (8) 134 to 172	43 (10) 27 to 74	113	20.6 (4) 10 to 35	19.1 (4) 11 to 30	154 (8) 135 to 181	44 (9) 28 to 79
12	96	24.7 (5) 13 to 36	22.9 (5) 13 to 35	159 (9) 140 to 180	48 (10) 30 to 73	106	24.2 (5) 15 to 39	22.3 (4) 13 to 33	160 (6) 144 to 178	48 (11) 32 to 110
13	66	28.2 (6) 17 to 45	25.8 (6) 17 to 42	166 (9) 150 to 189	52 (10) 39 to 85	97	26.4 (5) 14 to 39	24.5 (4) 17 to 36	163 (7) 138 to 176	49 (8) 33 to 89
14	46	36.0 (7) 24 to 51	33.5 (7) 22 to 51	175 (8) 155 to 193	60 (11) 38 to 89	53	29.1 (5) 16 to 43	26.6 (5) 15 to 36	169 (6) 157 to 183	55 (10) 42 to 103

A more extensive overview of all the results, including additional details regarding the study population, is presented in Table 1. Boys were significantly stronger than girls with the dominant hand at ages 4 ($p = 0.02$), 5 ($p = 0.04$), 6 ($p = 0.003$), 8 ($p = 0.001$), 9 ($p = 0.001$), and 14 ($p < 0.001$). For the non-dominant hand this was true at ages 4 ($p = 0.03$), 6 ($p = 0.02$), 8 ($p < 0.001$), 9 ($p < 0.001$), 11 ($p = 0.01$), and 14 ($p < 0.001$). With the exception of the dominant hand at age 7, where both genders scored equal, there was a trend for boys to score higher than girls with both their dominant and non-dominant hand in all age groups. The percentage difference in grip strength in favour

of boys fluctuated, from 0–14% at ages 4 to 13, rising to 26% at age 14.

In order to establish the association of gender, age, height, and weight with grip strength in more detail, we performed a multilevel analysis adding them as fixed factors. Adding the school the child attended as an intercept resulted in a better fit of the model for both the dominant and the non-dominant hand data. For both the dominant and the non-dominant hand, the variables age, height, weight, and gender had a significant association with grip strength ($p = < 0.001$), resulting in the following predictive equations:

Table 2. Multilevel analysis of grip strength data.

Hand Parameter	Estimate	SE	DF	t	Wald Z	p	95% CI	
							Lower	Upper
Dominant								
Intercept	-20.59	1.16	1707.65	-17.80		0.00	-22.85	-18.32
Male	1.09	0.14	2224.61	8.00		0.00	0.83	1.36
Height	0.17	0.13	2231.36	13.72		0.00	0.15	0.20
Weight	0.14	0.12	2231.41	11.78		0.00	0.12	0.16
Age	0.85	0.07	2172.38	12.05		0.00	0.71	0.99
Covariance								
Residual	10.23	0.31			33.30	0.00	9.64	10.85
Intercept school	1.11	0.42			2.64	0.01	0.53	2.33
Non-dominant								
Intercept	-19.52	1.15	1832.86	-16.92		0.00	-21.78	-17.25
Male	1.17	0.14	2226.23	8.58		0.00	0.91	1.44
Height	0.16	0.13	2233.39	12.90		0.00	0.14	0.19
Weight	0.12	0.12	2233.49	10.47		0.00	0.10	0.15
Age	0.79	0.07	2130.14	11.21		0.00	0.65	0.93
Covariance								
Residual	10.29	0.31			33.30	0.00	9.70	10.91
Intercept school	0.87	0.34			2.60	0.01	0.41	1.86

Dominant hand = $-20.59 + 1.09 \text{ if male} + 0.85 * \text{age (yr)} + 0.17 * \text{height (cm)} + 0.14 * \text{weight (kg)}$

Non-dominant hand = $-19.52 + 1.17 \text{ if male} + 0.79 * \text{age (yr)} + 0.16 * \text{height (cm)} + 0.12 * \text{weight (kg)}$

A more extensive overview of these results is presented in Table 2.

Discussion

To our knowledge, this is the largest study to generate normative values of grip strength in children. Although other studies have provided normative data, the subgroups according to age and gender in most studies were small for establishing reference values (Ager et al 1984, De Smet and Vercammen 2001, Molenaar et al 2010, Newman et al 1984). Samples for normative data should be 'large, random, and representative of the population's heterogeneity' (Portney and Watkins 1993, Innes 1999). This study was designed to meet these criteria not only by including a large number of children, but also by ensuring that each subgroup when broken down according to age and gender included a sufficient number of children. The results of this study show a significant difference in strength with each ascending year of age in favor of the older group, as well as a trend for boys to be stronger than girls in all age groups between 4 and 15 years. In addition, weight and height were strongly associated with grip strength in children.

The described curve of grip strength in boys – higher yet parallel to those of girls until the age of 12 – is consistent with other studies, as is the acceleration of grip strength specifically for boys after the age of 12 (Ager et al 1984, Butterfield et al 2009, Mathiowetz et al 1986, Newman et al 1984). Considering the strong correlation of height with strength, this is probably a result of the growth spurt. This would also explain why the acceleration described in girls

sets in earlier, but is less prominent. At the age of 12 the curves of height and weight according to gender also show a separation in favour of boys. In contrast, the height curve of females is showing a flattening slope from that age onwards – patterns consistent with those of the national growth study (TNO/LUMC 1998). Therefore, the authors predict that the grip strength of girls above the age covered in this study will not increase much further since their average increase in growth after the age of 14 is only 5 cm, and their estimated gain in weight around 5 kg until the age of 21 (TNO/LUMC 1998). This theory is supported by the data of Newman et al (1984), which showed no further increase in strength of girls after the age of 13. This is in agreement with data retrieved from a literature review regarding grip strength in adults, which showed that norms for females aged 20 in six different studies varied from 28.3 to 35.6 kilograms for the dominant hand, and from 24.2 to 32.7 kilograms for the non-dominant hand (Innes 1999). For females aged 40 results varied from 28.3 to 35.3 kilograms for the dominant hand, and from 21.9 to 33.2 kilograms for the non-dominant hand. The 14 year old girls in our study scored 29.1 and 26.6 kilograms respectively. In both cases these scores fall within these ranges for adults. For boys, no reliable prediction of grip strength above the age of 14 can be made, as on average they are expected to grow around 16 centimetres taller and gain 14 kilograms before reaching the age of 21 (TNO/LUMC 1998).

Comparing grip strength results with former studies in more detail proved to be difficult, due to differences in methods between studies. For example, the study by Newman et al (1984) contained relatively large subgroups, but it was performed with a different device that is no longer commonly used. The study of Ager et al (1984) reported scores according to the right or left hand, and not according to dominance. Where comparison was possible, the results of the current study were relatively high: 4–12% higher

than those of De Smet et al (2001) who allowed only one attempt with each hand, and 8–14% higher than those of Molenaar et al (2010) where three attempts were allowed. The study by Butterfield et al (2009) reported 4% lower to 6% higher scores. Besides differences in methods, the higher results may be a consequence of the ongoing trend in the Netherlands, ie, height is still increasing over the decades (Fredriks et al 2000). This is supported by data from Statistics Netherlands (Frenken 2007). Another factor that must be taken into consideration is that the Dutch population, and in particular those in the three most northern provinces, is known to be relatively tall (Frenken 2007).

Besides including a large number of children, a relatively large geographical area was covered and both rural and urban schools were included to ensure a broad diversity and heterogeneity of participants. A vast number of different instruments are available to measure grip strength. The Jamar hand dynamometer was selected because most normative studies have used this device and therefore it allows data to be compared with other (and future) studies (Innes 1999, Roberts et al 2011). Moreover, besides having a high test-retest and inter-investigator reliability, it also has high reproducibility when used by children (Lindstrom-Hazel et al 2009, Mathiowetz et al 1984, Roberts et al 2011, Van den Beld et al 2006). To ensure all children were measured in the same manner, and again to follow standardised methods, participants were measured according to the ASHT protocol (Innes 1999, Roberts et al 2011). However, we implemented three exceptions. First, for the 4 and 5 year olds, the handle of the device was set to the first setting, which is considered to be less accurate than the second (Bechtol 1954, Boadella et al 2005, Firrell and Crain 1996, Hamilton et al 1994). These findings result from studies that focus on adults, and young children obviously have smaller hands. Therefore the distance to the handle of the device (3.8 cm) is relatively large compared to their average hand size (Bear-Lehman et al 2002). In practice, they could not reach the second setting adequately, and the first setting has also been used for adults with small hands (Ruiz-Ruiz et al 2002). Second, it is preferred to use the mean of three attempts (MacDermid et al 1994, Mathiowetz et al 1984). However, other studies showed that scoring fewer attempts, taking fewer attempts into consideration, or even using the maximum attempt, does not lead to significant differences compared with the mean of three attempts (Coldham et al 2006, Crosby and Wehbé 1994, Haidar et al 2004). Additionally, although fatigue does not seem to influence grip strength measurement in adults, we could not find any studies regarding this matter in children. Considering these factors we chose to allow two attempts with each hand. Finally, the ASHT-protocol does not provide details regarding encouragement. Verbal encouragement was given to stimulate children to attempt their very best. The content of encouragement was the same for all children, and the type and volume was kept as consistent as possible. Unfortunately, the goal of including 200 children for each age group was not achieved in the two oldest groups, owing mainly to the fact that participation of high schools was difficult to arrange. Also, we did not systematically record exactly how many children refused to participate. However, the available data indicate that only a marginal proportion of children refused, which makes the data highly representative. Other limitations are a direct

result of the exclusion criteria, meaning results can only be applied to the healthy population and cannot be extrapolated to other age groups.

In summary, this study presents reference values for grip strength in children. These reference values for both the dominant and the non-dominant hand are provided graphically according to gender and age, to facilitate comparison to patients' values. These graphics also allow monitoring of progression over time. In addition the results of this study show that gender, age, height, and weight are strongly associated with the development of grip strength in children. Finally, detailed equations are provided to give a more precise prediction regarding a specific patient when height and weight are known. ■

Footnotes: ^aJamar[®] dynamometer, Lafayette Instrument Company, Lafayette, USA.

Ethics: The study was conducted in accordance with the regulations of the METC Institutional Review Board of the University Medical Center Groningen. Children were included in the study after permission of parents had been given. However, it was also ensured that each child knew the examination was not mandatory, and children were not included if they did not want to participate.

Support: None.

Competing interests: There are no competing interests.

Acknowledgements: The authors thank all the children, their parents, and the schools for their contribution to this study as well as the students who aided the researchers with measurements. The authors also thank PU Dijkstra, A Shepherd, RE Stewart, and WFA Klijn for their assistance.

Correspondence: JJW Ploegmakers, Department of Orthopaedics, University of Groningen, University Medical Center Groningen, The Netherlands. Email: j.j.w.ploegmakers@umcg.nl

References

- Ager CL, Olivett BL, Johnson CL (1984) Grasp and pinch strength in children 5 to 12 years old. *American Journal of Occupational Therapy* 38: 107–113.
- Balogun JA, Akomolafe CT, Amusa LO (1985) Grip strength: effects of testing posture and elbow position. *Archives of Physical Medicine and Rehabilitation* 66: 69–74.
- Bear-Lehman J, Kafko M, Mah L, Mosquera L, Reilly B (2002) An exploratory look at hand strength and hand size among preschoolers. *Journal of Hand Therapy* 15: 340–346.
- Bechtol CO (1954) Grip test: the use of a dynamometer with adjustable handle spacings. *Journal of Bone and Joint Surgery America* 36: 820–832.
- Boadella JM, Kuijjer PP, Sluiter JK, Frings-Dresen MH (2005) Effect of self-selected handgrip position on maximal handgrip strength. *Archives of Physical Medicine and Rehabilitation* 86: 328–331.
- Butterfield SA, Lehnhard RA, Loois EM, Coladarci T, Saucier D (2009) Grip strength performances by 5- to 19-year olds *Perceptual and Motor Skills* 109: 362–370.
- Coldham F, Lewis J, Lee H (2006) The reliability of one vs. three grip trials in symptomatic and asymptomatic subjects. *Journal of Hand Therapy* 19: 318–327.

- Crosby CA, Wehbé MA (1994) Hand strength: normative values. *The Journal of Hand Surgery* 19: 665–670.
- De Smet L, Vercammen A (2001) Grip strength in children. *Journal of Pediatric Orthopaedics B* 10: 352–354.
- Fess E (1992) Grip strength. In: Clinical assessment recommendations (2 edn). Chicago: American Society of Hand Therapists, pp 41–45.
- Firrell JC, Crain GM (1996) Which setting of the dynamometer provides maximal grip strength? *The Journal of Hand Surgery* 21: 397–401.
- Fredriks AM, Van Buuren S, Burgmeijer RJF, Meulmeester JF, Beuker RJ, Brugman E, et al (2000) Continuing positive secular growth change in the Netherlands 1955–1997. *Pediatric Research* 47: 316–323.
- Frenken F (2007) Vertraging in lengtegroei en gewichtstoename. CBS, *Bevolkingstrends, 4e kwartaal 2007* [Deceleration in height growth and weight gain. *Statistics Netherlands, Population Trends, 4th quarter 2007*] 92–98.
- Häger-Ross C, Rösblad B (2002) Norms for grip strength in children aged 4–16 years. *Acta Pædiatrica* 91: 617–625.
- Haidar SG, Kumar D, Bassi RS, Deshmukh SC (2004) Average versus maximum grip strength: which is more consistent? *The Journal of Hand Surgery: Journal of the British Society for Surgery of the Hand* 29: 82–84.
- Hamilton A, Balnave R, Adams R (1994) Grip strength testing reliability. *Journal of Hand Therapy* 7: 167–170.
- Innes E (1999) Handgrip strength testing: A review of the literature. *Australian Occupational Therapy Journal* 46: 120–140.
- Lindstrom-Hazel D, Kratt A, Bix L (2009) Interrater reliability of students using hand and pinch dynamometers. *American Journal of Occupational Therapy* 63: 193–197.
- MacDermid JC, Kramer JF, Woodbury MG, McFarlane RM, Roth JH (1994) Interrater reliability of pinch and grip strength measurements in patients with cumulative trauma disorders. *Journal of Hand Therapy* 7: 10–14.
- Mathiowetz V, Weber K, Volland G, Kashman N (1984) Reliability and validity of grip and pinch strength evaluations. *Journal of Hand Surgery (American Volume)* 9: 222–226.
- Mathiowetz V, Wiemer DM, Federman SM (1986) Grip and pinch strength: norms for 6- to 19-year-olds. *American Journal of Occupational Therapy* 40: 705–711.
- Molenaar HM, Selles RW, Zuidam JM, Willemsen SP, Stam HJ, Hovius SE (2010) Growth diagrams for grip strength in children. *Clinical Orthopaedics and Related Research* 468: 217–223.
- Newman DG, Pearn J, Barnes A, Young CM, Kehoe M, Newman J (1984) Norms for hand grip strength. *Archives of Disease in Childhood* 59: 453–459.
- Portney LG, Watkins MP (1993) Foundations of clinical research: applications to practice. Norwalk: Pearson/Prentice Hall.
- Rauch F, Neu CM, Wassmer G, Beck B, Rieger-Wettengl G, Rietschel E, et al (2002) Muscle analysis by measurement of maximal isometric grip force: new reference data and clinical applications in pediatrics. *Pediatric Research* 51: 505–510.
- Roberts HC, Denison HJ, Martin HJ, Patel HP, Syddall H, Cooper C, et al (2011) A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach. *Age and Ageing* 40: 423–429.
- Ruiz-Ruiz J, Mesa JLM, Gutiérrez A, Castillo MJ (2002) Hand size influences optimal grip span in women but not in men. *The Journal of Hand Surgery* 27: 897–901.
- TNO/LUMC (1998) Groei-onderzoek 1997, Bohn Stafleu Van Loghum 9000025389. [Dutch Organization for Applied Scientific Research / Leiden University Medical Center, growth study 1997, Bohn Stafleu Van Loghum 9000025389]
- Van den Beld WA, Van der Sanden GAC, Sengers RCA, Verbeek ALM, Gabreëls FJM (2006) Validity and reproducibility of the Jamar dynamometer in children aged 4–11 years. *Disability and Rehabilitation* 28: 1303–1309.