

Original Article

Mechanography in childhood: references for grip force, multiple one-leg hopping force and whole body stiffness

I. Lang¹, P. Busche¹, N. Rakhimi¹, R. Rawer², D.D. Martin¹¹University Children's Hospital Tübingen, Germany; ²Novotec Medical GmbH, Pforzheim, Germany

Abstract

Objective: We sought to study and procure reference values for weight-related maximum isometric grip force (*MIGF*), maximum voluntary force in relation to body weight (*Fmvrel*) and peak whole body stiffness (*pKwb*) in multiple one-legged hopping (m1LH) in childhood. **Methods:** We examined 868 children and adolescents (436 female) aged 3 to 19 yrs. Weight related results are reported as multiples of earth's gravity (*g*). **Results:** *MIGF* and *Fmv_{m1LH}* are highly linearly correlated with body weight. After adjustment for weight, mean *Fmvrel_{m1LH}* increases from the age of 3 to 6 yrs, then remains at 3.33 *g* (SD 0.31 *g*) between 6 and 19 yrs, independent of age and gender. The difference between legs decreases from 10% at 3 yrs to a constant 5.5% after the age of 7 yrs. Weight-adjusted *MIGF* also increases steeply from 3 to 6 yrs, then shows a further linear, less steep increase – in males through to age 19 yrs while females show a near-standstill after the age of 12 yrs. *pKwb_{m1LH}* increases from the age of 7 yrs. **Conclusion:** This data from normal children from a healthy Caucasian population provide a reference for tests of motor function.

Keywords: Jumping Mechanography, Maximum Voluntary Force, Child Age, Reference Values, Multiple One Legged Hopping

Background

Muscle force as measured during standardized movements performed on dynamometer and on a Mechanography system (ground reaction force platform, GRFP with post processing of data) have been shown by to be robust indicators of motor function that are relevant for daily life¹⁻⁴. The influence of measurement repetition can be considered small compared to the effects of training or therapy. The multiple one legged hopping (m1LH) is being used in relation of muscle function and bone parameters^{5,6}. Anliker⁶ et al. showed a good correlation between peak ground reaction forces during multiple one legged hopping (m1LH) and bone parameters assessed by pQCT measurements. These results underline the need for nor-

mative data for this test. The present paper presents such data, as well as maximum isometric grip force (*MIGF*) and whole body stiffness (*kWB*).

Methods

Subjects

A total of 868 children and adolescents (432 male, 436 female) aged 3 to 19 years were studied. The children all attended the Tübingen Waldorf School (www.waldorfschule-tuebingen.de), a private school that is financed by subsidies from the state as well as from a system of contributions from the parents according to their financial abilities – with the philosophy that no child should be prevented from access to Waldorf Education for financial reasons. The school is in an affluent middle-class area of the university town of Tübingen. The school offers the whole spectrum required for children to complete the German 13-year school program and go straight into whatever the pupil is able and willing to aspire to in terms of further education. There is no particular emphasis on sports: about two ¾-hour sessions of sports lessons plus two ¾-hour sessions of Eurythmy per week (Eurythmy is an expressive movement art taught in Waldorf Schools; see for example <http://www.youtube.com/watch?v=RcCvcy0zAIM>).

The study protocol was presented to the school and at each parent evening. No child was examined without written

Rainer Rawer is an engineer at Novotec Medical GmbH, Pforzheim, Germany. The other authors have nothing to disclose.

Corresponding author: PD Dr. David D. Martin, Pediatric Endocrinology and Diabetology, University Children's Hospital, Hoppe-Seyler Strasse 1, D-72076 Tübingen, Germany
E-mail: david.martin@med.uni-tuebingen.de

Edited by: F. Rauch

Accepted 10 April 2013

parental consent and consent from the child. Further exclusion criteria were acute and chronic diseases, syndromatic abnormalities and inability to perform any of the tests. As justified in the discussion, we did not split the groups by ethnic, genetic or socio-economic factors.

The study was approved by the ethics committee of Tübingen University. The written consent was handed in with a questionnaire which the parents had to answer with questions as to the kind and amount of sport their child does per week, the hours spent in from of a computer or TV, and whether the child has any injuries or handicaps relevant to bodily performance. According to these estimates of the parents the median time spent in front of a media screen was 3 hours for boys (mean 5.7; SD 6.7; 80% CI 0-15 hrs; non-normal distribution) and 2 hours for girls (mean 3.5; SD 3.9; 80% CI 0-10 hrs; near-normal distribution). The median time engaged in sporting activities, like soccer, cycling, dancing etc., was 4 hours for boys (mean 3.6; SD 1.0; 80% CI 2-5 hrs; non-normal distribution) and 3 hours for girls (mean 3.4; SD 1.0; 80% CI 2-5 hrs; normal distribution).

Examinations

Height, weight, armspan, leg length, head circumference, waist circumference, hip circumference, lower arm circumference, thigh circumference, calf circumference, fat folds (scapula, iliacal, calv, upper arm), were measured in each subject, in addition to the mechanography and dynamometer tests.

Mechanography

Jumping mechanography was assessed with the Leonardo Mechanograph® GRFP (Novotec Medical GmbH, Pforzheim, Germany). This device measures forces applied to the plate over time (ground reaction forces), allowing stationary forces as well as the variation of forces over time to be investigated¹. The platform is divided into two sections for simultaneous measurement of the right and left lower limb separately in order to assess side dynamic differences. The sample rate of the system is set to 800 Hz (800 measurements per second for each force sensor). The software for the detection, storage and calculation of data (Leonardo Mechanography v4.2) was also supplied by Novotec Medical GmbH.

Multiple one Legged Hopping (mILH or stiff forefoot hopping): The individuals stood on the platform and each foot was placed on one plate. The children were instructed to repeatedly hop on one leg, first in a relaxed manner and then quicker and quicker and finally as fast and as high as possible. “Hop on your toes with a straight leg as if you were rope-skipping, many times, first relaxed hops, then quicker and quicker... and now stay quick and try to hop higher, higher, quicker, quicker, higher, higher... good!”

Attention was paid to whether the children were really hopping on their toes and that the knees were kept stretched during the whole jump. The main outcome parameter of this test is the maximum voluntary force in relation to body weight, F_{mvrel_mILH} (also referred to as maximum voluntary forefoot ground reaction force⁶). A further parameter is *Whole body*

stiffness (Kwb_{mILH}): Farley et al. introduced and described in detail the term whole body stiffness, or leg stiffness in animals⁷⁻⁹ as well as in humans⁷⁻⁹. This group also showed the importance of this parameter for hopping and running mechanics and frequencies⁷⁻⁹. Whole body stiffness is calculated for each point in time as the ground reaction force divided by the displacement of the center of gravity (unit: N/cm) during the contact phase of each hopping interval. For this calculation the height was set to 0 at the first point of contact for each repetition. Farley et al. choose to calculate the stiffness during contact time for the period where the ground reaction force is higher than the body weight. The typical force curve of the presented data showed higher stiffness data at the point of time of peak ground reaction force. In order to minimize the variability of the dataset we choose as main outcome parameter the peak whole body stiffness ($pKwb_{mILH}$) calculated as the mean stiffness in the center 0.04s around the peak force. Farley et al. reported whole body stiffness expressed in multiples of body weight per displacement (g/cm) which we also report as relative peak whole body stiffness ($pKwb_{rel_mILH}$).

Assessment of Grip Force: Maximal isometric grip force (*MIGF*) of the nondominant hand was determined with a standard adjustable-handle Jamar dynamometer (Preston, Jackson, MI, U.S.A.). The handle was adjusted (setting 1 to 5) so that the line of the subject's proximal interphalangeal joints rested exactly on top of the adjustable handle. The children and adolescents were seated with their shoulder adducted and neutrally rotated. The dynamometer was held freely, without support. The elbow was flexed at 90°, and care was taken that it did not touch the trunk. The forearm was in a neutral position, and the wrist was held at between 0° and 30° dorsiflexion and between 0° and 15° ulnar deviation. The children and adolescents were told to put maximal force on the dynamometer. The maximal values of three trials were each noted. The scale of the dynamometer indicates the result in kilograms. *MIGF* (unit: N) was calculated by multiplying the dynamometer reading by a factor of 9.81. Instruction: “Can you see that when you press these two parts together the needle rises in the display? Now try to press them together as strongly as you can, stronger, stronger... good!”

Normalization to body weight or body mass

For power we used a normalization to body mass. The resulting unit is W/kg.

For force we used a normalization to body weight (force of an object acting e.g. on the ground due to earth's gravity). As a unit for multiples of body weight we used the equivalent of earth's acceleration (gravity) *g*. One *g* being equal to one times body weight acting on the subject's center of mass.

Results

Auxology and MIFG

Tables 1 and 2 shows the characteristics of participants per age group, simultaneously offering reference values for weight, height, leg length, head circumference, lower arm circumference, calf circumference, thigh circumference (circum-

Age	n	Mass (kg)	Height (m)	Leg Length (m)	Head circ. (cm)	Calf circ. (cm)	Thigh circ. (cm)	Skin folds (cm)	MIGF (kg)
3	7	16.8 (1.5)	1.12 (0.10)	n/a	50.7 (0.7)	22.0 (0.8)	28.5 (2.4)	11.7 (1.9)	5.9 (1.3)
4	13	18.0 (2.4)	1.10 (0.07)	n/a	51.1 (1.8)	22.0 (1.2)	27.9 (3.1)	9.3 (4.8)	7.6 (1.8)
5	9	19.6 (1.4)	1.13 (0.10)	n/a	51.4 (1.1)	22.6 (1.1)	29.2 (1.6)	9.3 (1.5)	8.9 (2.8)
6	33	23.8 (4.1)	1.22 (0.13)	0.73 (0.05)	52.7 (2.1)	24.0 (2.5)	31.5 (3.5)	11.0 (3.0)	11.6 (2.4)
7	38	26.3 (3.7)	1.28 (0.06)	0.77 (0.06)	52.8 (1.7)	24.7 (2.1)	31.7 (4.2)	11.2 (4.5)	13.5 (2.8)
8	36	27.9 (3.7)	1.33 (0.08)	0.81 (0.06)	53.1 (1.6)	25.9 (1.9)	34.2 (3.9)	11.7 (3.6)	15.2 (2.8)
9	44	31.8 (4.8)	1.36 (0.08)	0.85 (0.05)	53.6 (1.3)	26.8 (2.5)	35.4 (4.3)	12.9 (3.4)	17.5 (2.9)
10	27	36.3 (11.5)	1.44 (0.09)	0.87 (0.06)	53.9 (1.6)	27.7 (3.4)	34.8 (6.1)	13.5 (6.3)	19.7 (3.6)
11	27	38.6 (7.1)	1.52 (0.10)	0.93 (0.05)	54.1 (1.2)	28.8 (2.9)	36.8 (5.2)	12.9 (4.2)	21.7 (3.7)
12	19	46.5 (10.9)	1.56 (0.09)	0.96 (0.06)	55.1 (1.9)	30.6 (3.9)	38.1 (4.6)	15.8 (5.8)	26.5 (3.8)
13	28	51.2 (9.5)	1.65 (0.11)	1.02 (0.05)	54.8 (1.7)	31.7 (3.4)	39.9 (4.4)	15.1 (3.9)	31.7 (5.4)
14	27	57.0 (8.1)	1.63 (0.09)	1.04 (0.05)	55.7 (1.5)	33.8 (2.1)	43.1 (4.4)	12.7 (3.6)	34.3 (7.6)
15	27	61.2 (10.7)	1.70 (0.09)	1.07 (0.05)	56.0 (1.5)	34.7 (2.3)	44.4 (4.8)	14.8 (4.9)	39.4 (8.2)
16	30	69.4 (12.4)	1.73 (0.09)	1.11 (0.05)	56.8 (2.1)	35.4 (3.4)	44.6 (6.2)	11.3 (4.4)	46.5 (8.7)
17	27	73.1 (11.0)	1.77 (0.10)	1.08 (0.05)	56.3 (2.0)	36.6 (2.9)	47.7 (4.6)	14.5 (4.9)	46.9 (6.8)
18	24	72.2 (9.0)	1.71 (0.12)	1.08 (0.05)	56.9 (1.3)	35.5 (2.3)	47.8 (4.7)	12.1 (5.1)	50.6 (8.1)
19	17	72.5 (6.6)	1.75 (0.10)	1.10 (0.04)	57.1 (1.1)	35.3 (3.2)	46.8 (5.2)	10.7 (3.7)	51.7 (7.3)

Table 1. Auxology and *MIGF* of males: mean and (SD).

Age	n	Mass (kg)	Height (m)	Leg Length (m)	Head circ. (cm)	Calf circ. (cm)	Thigh circ. (cm)	Skin folds (cm)	MIGF (kg)
3	4	16.9 (1.8)	1.10 (0.09)	n/a	50.5 (0.6)	22.1 (0.6)	29.1 (3.0)	12.2 (0.8)	5.5 (1.0)
4	14	17.0 (2.1)	1.13 (0.08)	n/a	50.0 (1.9)	22.0 (1.6)	28.9 (2.5)	10.9 (4.5)	7.5 (1.8)
5	21	19.5 (2.3)	1.09 (0.08)	n/a	50.5 (1.2)	23.2 (1.2)	31.5 (2.8)	10.3 (3.2)	8.1 (1.6)
6	24	22.6 (4.3)	1.21 (0.09)	0.70 (0.04)	50.9 (1.7)	23.9 (2.3)	31.8 (4.5)	11.8 (3.3)	10.1 (2.1)
7	53	25.5 (3.7)	1.28 (0.09)	0.77 (0.05)	52.1 (1.3)	24.6 (2.0)	32.4 (4.0)	11.6 (3.7)	12.2 (2.5)
8	47	29.0 (4.9)	1.34 (0.07)	0.82 (0.04)	52.9 (1.2)	26.0 (2.6)	34.5 (4.7)	12.7 (3.0)	14.1 (2.7)
9	40	31.6 (6.1)	1.37 (0.06)	0.85 (0.06)	52.8 (1.4)	27.1 (2.3)	37.0 (4.1)	13.6 (4.3)	15.7 (3.0)
10	28	34.8 (6.2)	1.43 (0.10)	0.90 (0.06)	53.1 (1.4)	27.6 (2.6)	36.5 (4.1)	14.2 (4.8)	18.4 (2.1)
11	31	40.3 (6.4)	1.51 (0.12)	0.94 (0.05)	53.5 (1.4)	29.3 (2.6)	40.2 (3.9)	14.6 (6.1)	21.5 (4.0)
12	20	44.3 (6.2)	1.56 (0.07)	0.97 (0.04)	54.0 (1.3)	30.1 (2.7)	39.9 (3.9)	14.7 (4.3)	24.5 (4.3)
13	25	48.0 (11.5)	1.60 (0.08)	0.99 (0.07)	53.9 (2.0)	30.7 (3.6)	42.4 (5.5)	14.5 (5.4)	26.3 (6.0)
14	23	54.3 (7.9)	1.65 (0.13)	1.02 (0.07)	54.7 (1.5)	33.5 (2.4)	46.5 (3.3)	18.7 (4.9)	30.1 (5.6)
15	16	57.0 (6.7)	1.71 (0.08)	1.02 (0.05)	54.2 (1.2)	34.1 (2.0)	47.5 (3.3)	17.1 (4.2)	32.0 (4.4)
16	28	58.0 (8.3)	1.71 (0.08)	1.04 (0.06)	54.4 (1.2)	33.9 (2.2)	46.1 (3.6)	13.9 (6.7)	31.6 (4.7)
17	26	62.8 (10.1)	1.71 (0.09)	1.03 (0.06)	54.9 (1.5)	36.0 (3.1)	50.5 (4.9)	19.5 (7.2)	34.1 (5.3)
18	22	60.1 (8.5)	1.75 (0.11)	1.01 (0.06)	54.8 (1.6)	35.4 (2.6)	50.2 (3.7)	20.8 (6.5)	33.9 (5.7)
19	14	63.9 (8.6)	1.70 (0.10)	1.03 (0.05)	55.3 (1.3)	34.8 (3.6)	48.3 (5.4)	16.2 (4.3)	35.4 (5.8)

Table 2. Auxology and *MIGF* of females: mean and (SD).

ferences were all measured at the largest part of each child's member) and *MIGF* for middle-European children.

Maximum isometric grip force (*MIFG*)

Figure 1 shows the maximum isometric grip force (*MIGF*) in relation to body mass. About 85% of the variation of *MIGF* can be explained by body mass. Males show a linear increase of *MIGF* per body mass with age of: $MIGF/g = 0.38 + 0.017 \cdot \text{age}$.

Females show a stabilization of *MIGF* per body weight from age 12 on with a second order polynomial regression of: $MIGF/g = 0.28 + 0.036 \cdot \text{age} - 0.0011 \cdot \text{age}^2$.

The standard deviation (SD) of *MIGF* was found to be independent of age and gender at a mean value of 0.11 g.

Reproducibility of main outcome parameters

In a subgroup of participants a small reproducibility study was carried out in 4 males and 6 females aged 8 to 17. Repe-

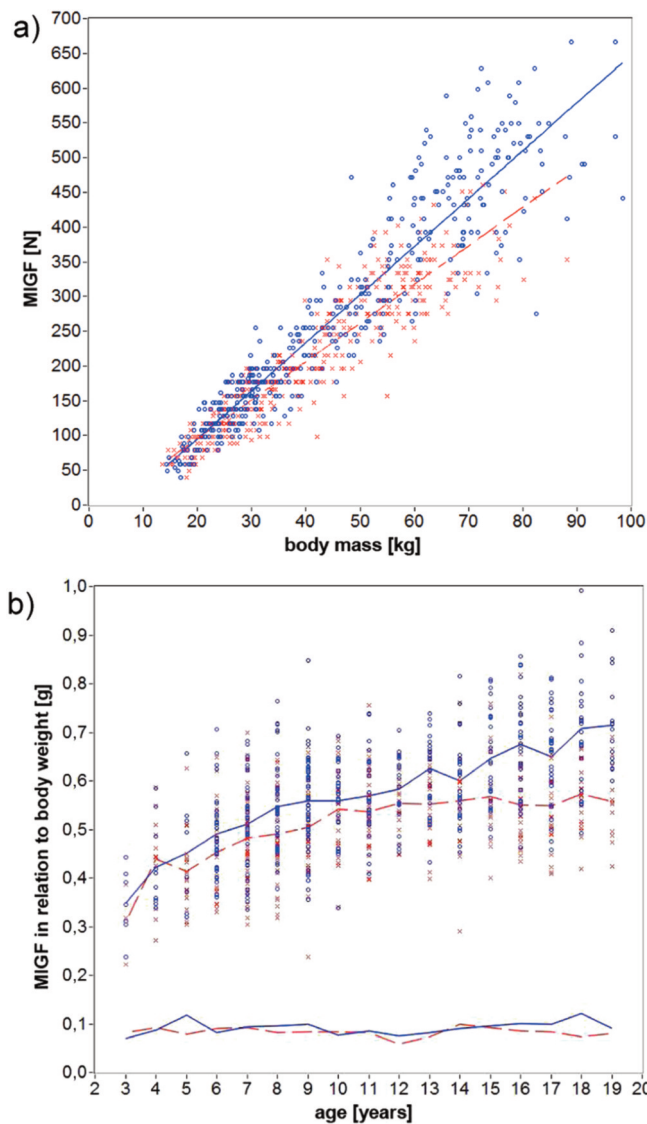


Figure 1. Maximum grip force (MIGF). **a)** MIGF vs. body mass. Male (blue circles) $R^2=0.88$ female (red crosses) $R^2=0.86$. The lines show the linear regressions ($MIGF_{male}/N=-4.34+0.70*age$, $MIGF_{female}/N=-1.55+0.57*age$). **b)** MIGF in relation to weight (g). The upper lines (males: solid lines, females: broken lines) connect mean values per age group; the lower lines connect the respective SD.

tition measurements were done at 1, 2 and 7 days after the baseline measurement. Table 3 shows the Interclass Correlation (ICC) values for reproducibility of the typical outcome parameters reported within this study using only day 1 and day 2 follow up or using day 1, 2 and day 7 follow up.

m1LH: Relative maximum voluntary force in multiple one-legged hopping ($F_{mvrel_{m1LH}}$)

The relation between maximum ground reaction force in stiff forefoot hopping without heel contact (maximum volun-

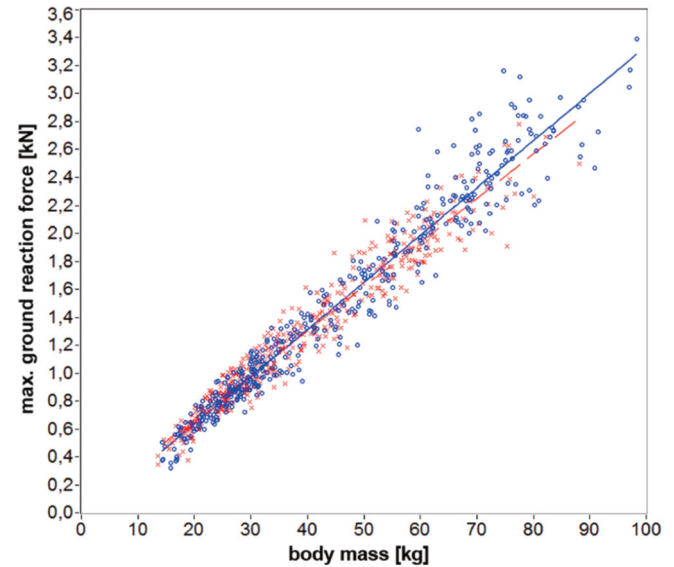


Figure 2. Maximum ground reaction force in stiff forefoot hopping ($F_{mv_{m1LH}}$, in kN) in relation to body mass (kg) for males (blue circles) and females (red crosses) and their respective linear fits (male: blue, solid lines; female: red, broken lines, $F_{mv_{m1LH}male}/kN=0.041+0.034*age$, $F_{mv_{m1LH}female}/kN=0.037+0.032*age$).

	$F_{mvrel_{m1LH}}$	Body Mass
ICC 2 days	0.88	0.9998
ICC 7 days	0.90	0.9998
CV 1 st day	L: 2.66% R: 4.24%	0.15%
CV mean 7 days	L: 3.55% R: 3.56%	0.19%

CV 1st Day: mean of individual CV (over 2 measurements per Leg) on 1st measurement day

CV mean 7 days: mean of individual CV per day over 3 measurement days and a period of 7 days.

Table 3. ICC for 2 measurements over 2 days follow up and for 3 measurements over 7 days follow up and CV for 1st day and for 6 measurements on 3 days over a period of 7 days.

tary force, $F_{mvrel_{m1LH}}$) and body weight shows a linear correlation (males: $R^2=0.950$, females: $R^2=0.944$). Since both linear regression curves show almost identical parameters (Figure 2) we did not separate for gender in the following analysis. The coefficient of determination of the linear regression for both genders together is $R^2=0.948$. The equation of the linear interpolation independent of gender is: $F_{mvrel_{m1LH}}=0.014+0.033 g$.

As discussed later, children below 6 years of age seem to show deficits in coordination resulting in lower peak force. When only including children age 6 and older the linear interpolation is: $F_{mvrel_{m1LH}}=0.0328 g$.

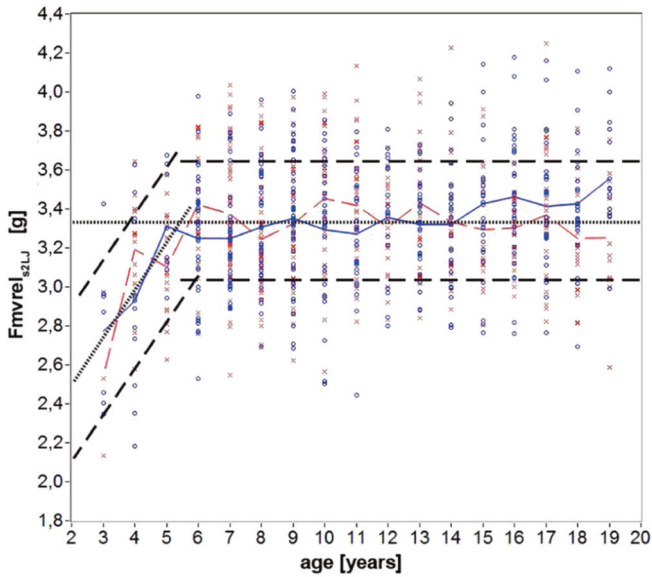


Figure 3. Relative maximum voluntary force ($Fmvrel_{m1LH}$): Maximum ground reaction force in stiff forefoot hopping (m1LH) normalized to body weight vs. age. Red crosses: females, blue circles: males. The lines (male: blue, solid lines; female: red, broken lines) connect the mean values per age group. The dotted line represents the simplified mean values used as reference data (3.33 g) and the dashed lines show ± 1 SD (0.33 g).

This linear relation can be described as a static value of force in relation to mass or body weight (Figure 2). When plotting this relation e.g. as force as multiples of body weight expressed in multiples of earth gravity g (1 g is equivalent to the body weight or 9.81 times the body mass, hence a person of a mass of 100 kg has a body weight of 981 N) over age the constant relation independent of gender and age becomes obvious. The dotted line in Figure 3 marks the mean relative (to body weight) maximum voluntary force ($Fmvrel_{m1LH}$ [g]). The SD stays constant from age 5 onwards at an average value of 0.31 times body weight. For age groups below 5 years it increases to 0.4 times body weight. From the age of 6 years onwards $Fmvrel_{m1LH}$ can be considered as constant and independent of gender at a value of around 3.33 g. A slight increase in males for the age group 15 to 19 was found.

Defining the reference data

For simplification reasons (see discussion) we decided to interpret the reference values of $Fmvrel_{m1LH}$ for the age groups starting from 6 years as being constant at 3.33 g with an age and gender independent constant SD of 0.31 g. For age 3 to 5 we use a linear interpolation independent of gender resulting in the equation $Fmvrel_{m1LH,3-5} = 1.8 + 0.31 \cdot \text{age}$. Since the SD at age 4 is slightly higher in males and slightly lower in females than at age 3 we chose for these two age groups the higher SD of 0.4 g. The resulting mean reference values for peak voluntary force independent from gender are shown in Figure 3 as thick

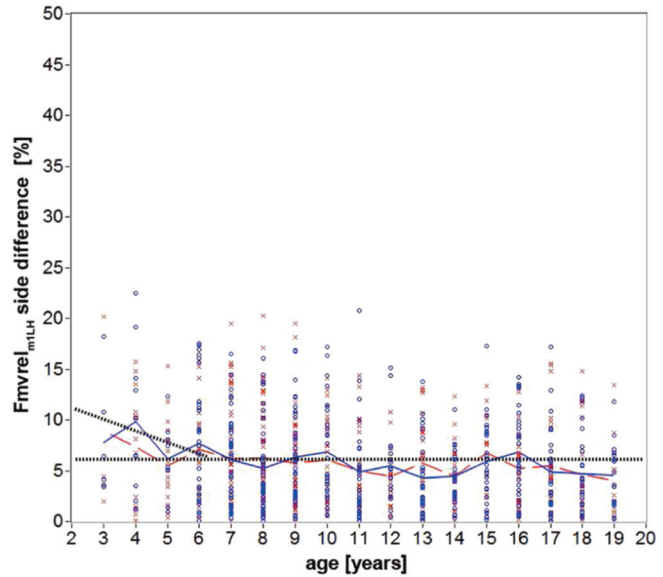


Figure 4. Side differences of maximum voluntary force ($Fmvrel_{m1LH}$): Maximum ground reaction force in stiff forefoot hopping (m1LH) normalized to body weight vs. age. Red crosses: females, blue circles: males. The blue, solid (male) and red, broken (female) lines connect the mean value of each age group. The dotted line represents the simplified mean values used as reference data ($dFmvrel_{m1LH,6+} = 5.6\%$, $dFmvrel_{m1LH,2-6} = 12 - 1.07 \cdot \text{age}$).

dotted line – with thick dashed lines marking ± 1 SD.

Side differences. The dominant as well as the non dominant leg were assessed. Figure 4 shows side differences of the $Fmvrel_{m1LH}$ as percentage of the stronger leg (10% difference is equal to the $Fmvrel_{m1LH}$ being 10% lower in the weaker leg than in the stronger). Again for age groups 6 to 19 the observed side difference is independent of age and gender (Figure 4). Age groups below 6 years showed an increasing side difference.

For simplification and in analogy to $Fmvrel_{m1LH}$ for age groups from 6 to 19 we chose a constant reference value of $dFmvrel_{m1LH,6+} = 5.6\%$ (d being “difference between left and right”).

For age groups below 6 years we chose a linear interpolation of $dFmvrel_{m1LH,2-6} = 12 - 1.07 \cdot \text{age}$.

m1LH: whole body stiffness

Absolute peak whole body stiffness ($pKwb_{m1LH}$, Figure 5a) shows an increase of 65% in females and of 75% in males between age 7 and age 17. The age groups 3 to 5 show slightly decreasing values. From 7 to 14 there are no gender specific differences and a linear increase of 9.19 N/cm per year (stiffness = $30.12 + 9.19 \cdot \text{age}$). Starting with age 15 there seems to be a separation between the genders. While males still increase by additional 12%, females stay more or less constant.

Relative (to body mass) peak whole body stiffness ($pKwbr_{m1LH}$) displays no gender dimorphism in age groups 5 to 19.

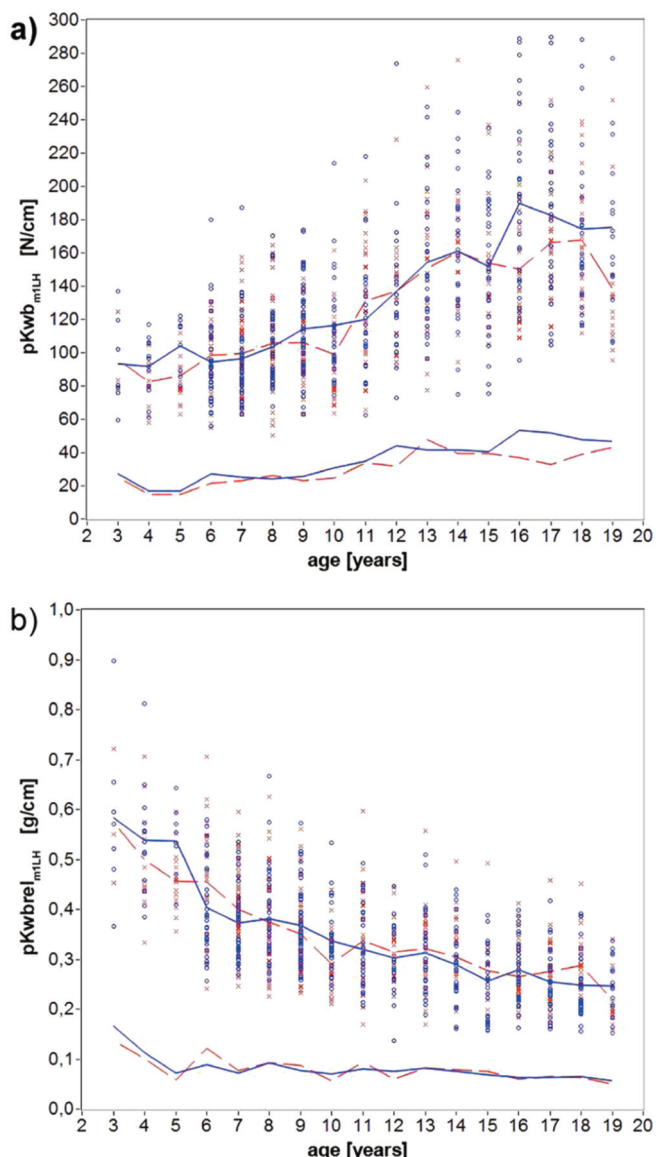


Figure 5. a) whole body stiffness ($pKwb_{mILH}$), b) whole body stiffness in relation to body weight ($pKwbrel_{mILH}$). Red crosses: females, blue circles: males. Top lines: mean peak stiffness per age group, bottom lines: SD per age group (male: blue, solid lines; female: red, broken lines).

The SD decreases with age and is independent of gender.

Based on the existing data we chose to neglect the gender differences in age group 3 to 5 and defined the following reference data set for relative whole body stiffness ($pKwbrel_{mILH}$):
 Age group 3 to 6: $pKwbrel_{mILH}/g/cm = 0.468 - 0.012 \cdot \text{age}$
 Age group 7 to 19: $pKwbrel_{mILH}/g/cm = 0.888 - 0.072 \cdot \text{age}$

Discussion

In this study we present reference data for tests focusing on force in children aged 3 to 19 years. These data are derived from a healthy population of a Waldorf School that is not yet

touched by the obesity epidemic and spend little time in front of media screens. Two males and 2 females were excluded due to untypically poor measurements results. The results for all the other children were so homogeneous that we did not see any need for further selection by differences in physical activity as assessed by the questionnaires.

The relevance of these data is exemplified by the results for research in muscle and bone relation⁹ utilizing the mechanographic measurement approach. This data is included in the reference parameters of the Leonardo Mechanograph and completes the set of reference data we are publishing elsewhere¹⁶ in order to cover all basic mechanographic tests reported so far².

m1LH: Maximum voluntary force ($Fmvrel_{mILH}$)

Peak deformations of bone are major stimulating signals for bone formation or absorption^{10,11}. Peak forces acting on bone are physiologically caused by muscle contractions multiplied by the relation of the effective internal leverage^{2,12}. Therefore to determine whether bone strength and geometry are adapted to the peak forces generated by muscle it is crucial to quantify the maximum muscular force. It is essential to separate between absolute values (measured in N) and relative values (e.g. measured in multiples of body weight or g). Absolute values (Fmv_{mILH} [N]) are used for the comparison of force and structural parameters of bone like cross sectional area or bone mineral content per slice. Relative data ($Fmvrel_{mILH}$ [g]) is used for inter-individual comparison to minimize the effects of inter-individual differences of body mass.

Obviously, different movements like hopping, jumping or running will provoke different peak forces depending on the used motion pattern (e.g. 3.33 g per leg in $Fmvrel_{mILH}$ as reported in this study of compared to 1.25 g per leg in peak force during the single two legged jump ($pFrel_{s2L}$) reported in our previous study¹⁶). To distinguish between a peak force typical for a specific movement pattern and the largest peak force observed among all kinds of movement patterns the latter is called maximum voluntary force (Fmv) or relative maximum voluntary force ($Fmvrel$). Hopping on one leg with a stiff knee (m1LH) has been proposed as a measure for this maximum voluntary force^{2,5,6}. Anliker⁶ et al. showed a correlation between pQCT bone parameters and maximum voluntary force (Fmv_{mILH}) of $R^2=0.841$ in males and $R^2=0.765$ in females aged 8 to 82 yrs. He also showed that estimation of maximum voluntary force by cross section of the calf muscle assessed by pQCT resulted in a lesser correlation ($R^2=0.724$ in males and $R^2=0.597$ in females). These results indicate that Fmv_{mILH} assessed by mechanography is a well-suited quantification of muscle functional parameters as one determinant of the muscle bone unit.

Since our goal was to report reference data according to age and gender we report relative maximum voluntary force ($Fmvrel_{mILH}$). Due to the small variation of the mean values per age group we decided to interpret the reference values of $Fmvrel_{mILH}$ for the age groups starting from 6 years as to be constant at 3.33 g with an age and gender independent constant SD of 0.31 g . The variation of mean $Fmvrel_{mILH}$ from one age

group to the next in the order of 0.15 g cannot be explained by strictly age dependent systematic growth effects. An even larger number of individuals in a longitudinal, prospective study and an assessment in relation to Tanner stages, bone age and peak growth rate might show whether any of these variations are biologically founded or whether they are merely random effects. However, Tanner staging is intrusive and has poor precision, assessing bone age would require a radiograph and a precise estimation of the time of peak growth rate is only feasible in a retro-perspective. Therefore the simple classification according to age groups seems to be the most promising approach for clinical use of this reference data.

An obvious explanation for the lower $F_{mvrel_{m1LH}}$ at age 3 to 5 (Figure 3) is the steep learning and development curve with regards to coordination of these young children. During the measurements a considerable number of 3 yr-olds seemed to be performing one legged hopping for the first time (a limitation of this study is that the number of 3 and 4 yr-olds is lower than for the other age groups due to the fact that several children were not able to perform the jump and a few also refused to do so). Therefore insufficient coordination or lack of understanding or of the ability to transfer the instructions certainly played a role in some of the youngest children. The steeper increase of $F_{mvrel_{m1LH}}$ and $MIFG$, as well as of peak power in the Single Two Legged Jump ($pPre_{s2LJ}$)¹⁶ and in the chair rising test ($pPre_{CRT}$)¹⁶ in the first 6 to 7 years of life corresponds to – and may actually throw light on – our finding in the largest existing longitudinal radiograph study that metacarpal length, width, cortical thickness and metacarpal index increases more steeply before the age of 6.5 years than thereafter^{13,14}. A longitudinal study would be necessary to examine these and other non-linear phenomena (e.g. dentition changes, the brain attains 99% of its adult mass, there is a small peak in statural growth) around this age of attainment of a preliminary level of psychomotor maturity traditionally associated with school-readiness (the ignorance of which may lead to an increase in the “prevalence” of attention-deficit/hyperactivity disorder (ADHD))¹⁵.

While Schönau¹¹ et al. have published reference data for older children with regards to the s2LJ, our study is the first to present reference values for one legged hopping (m1LH) – over a wide age range of 3 to 19 years. Also, our study is the first to present the results in relation to body weight which can improve inter-individual comparison.

These results are in line with the results for the peak force during the single two Legged counter movement jump (s2LJ) for maximum height ($pF_{rel_{s2LJ}}$), which we reported to be constant and independent of age and gender at a value of 2.5 g (1.25 g per leg) and a SD of 0.34 g¹⁶. This is about 30% of the average results for ($F_{mvrel_{m1LH}}$).

One explanation for this difference in peak force is the different goal of the movement. For a typical counter movement jump (s2LJ) potential energy (proportional to the elevation of the center of mass) has to be created by active muscle contraction (concentric muscle function), while for multiple one legged hopping (m1LH) energy has to be stored efficiently to

allow a maximum number of repetitions with minimum energy expense. Therefore the dominant muscle function for counter movement jump (s2LJ) is active energy generation while for m1LH it needs to be elastic energy storage (eccentric muscle function). The text book force-velocity curve of muscle fibers shows that eccentric (elastic energy storage) movements can create up to 60% higher force than concentric movements which is one of the obvious reasons why $F_{mvrel_{m1LH}}$ needs to be larger than $pF_{rel_{s2LJ}}$.

Since force causes acceleration, and the first integration of acceleration results in velocity and the second in distance or height, acceleration (and therefore force) over time is decisive for movement. If peak force per body weight and therefore peak acceleration is constant for movements like hopping and jumping then this is an indication that the requirements of locomotion are more or less identical for all included children and adolescents. Taking into consideration that gravity on earth can be considered as constant, this assumption seems plausible.

Grip Force Data (MIGF)

While 86% of variation in $MIFG$ could be explained by body weight, $MIFG$ is nevertheless clearly age- and gender-related (Figure 1). Females show a lower $MIFG$ in relation to males and this difference increases from age 12 onwards due to a continuous increase in the males (in accordance with the increase of lean mass in relation to total body mass) while the females show no further increase in relation to body weight. This contrasts with our measurements of peak force of the lower extremities: Peak forces in the same cohort during the Single Two Legged Jump (s2LJ)¹⁶, the Chair Rising Test (CRT)¹⁶ and m1LH (presented here) are almost independent of age and gender but linearly related to body mass (89%, 96%, and 95%, of peak force variation was explained by body mass in s2LJ, CRT and m1LH, respectively). The age and gender related differences of $MIFG$ are in fact more similar to those found for peak power than for peak force in the s2LJ or CRT¹⁶. An obvious explanation for differences between the test types is the assessed muscle function: while mechanography focuses on highly dynamic movement patterns resulting in high power output as well as high ground reaction force, $MIFG$ utilizes an isometric measurement approach. In addition, typical movements of everyday life could be assumed to result in much more uniform requirements for the lower extremities than for the upper extremities. Therefore behavioral differences between the genders might be predominantly visible in the upper extremities. These behavioral differences could explain the slightly lower $MIFG$ in females as well as the further separation in puberty. In this context it is interesting to note that metacarpal cortical thickness – and therefore most probably also hand muscle strength – was higher in the 1st Zurich Longitudinal Study (participants born 1954) than in the 3rd Zurich Longitudinal Study (which examines the offspring of the 1st Zurich Longitudinal Study, born around the 1980s)¹³.

It is interesting to note that while peak force in the lower extremities in relation to body weight does not increase after the

age of 6.5 years, peak grip force continues to increase in relation to body weight and reaches about 50% of body weight. One could speculate that humans have the genetic potential to reach a grip force that is close to 100% of body weight but that in a society where hanging on trees is not an important part of life, this potential is not reached. In this connection it is worth mentioning that there is a difference in the force needed between developing a grip and maintaining a grip, thus while most healthy non-obese children can briefly (more or less) maintain the grip needed to hang on one hand from a pole, hardly any child will be able to develop that grip – or recreate it if they even slightly loosen their hand while hanging. Thus, as in most other isometric tests, the hand dynamometer test is not truly isometric because the children have to actively tighten their grip instead of just trying to maintain isometry. In this regard it would be more consistent to speak of “peak grip force” instead of MIGF. But since the matter is rather complex (hanging on a pole is also not strictly speaking an isometric test: there is a loss of isometry until the child can hold the grip no more and falls) we have chosen to stick to the internationally used nomenclature (MIGF) in this paper.

Whole body stiffness ($pKw_{brel_{m1LH}}$)

Whole body stiffness (Kwb) was shown to be a parameter with a strong impact on locomotion^{7,8}. In a spring-mass system the stiffness (k) and the mass (m) define the resonance frequency (f_{res}) as⁹: $f_{res} = (m/k)^{1/2} / (2\pi)$

For walking and running, resonance frequency defines the most efficient locomotion frequency for each individual⁸. When limiting the included movement patterns to movement patterns where the spring-mass system of the body is working in resonance (optimal energy storage, no active acceleration in the lift-off phase no damping or energy dissipation in the landing phase), the ability in adult humans to vary whole body stiffness is in the range of about 0.1 g/cm to 0.4 g/cm (1 g is equivalent to 1 times body weight)^{7,8}. Our data showed only slight gender differences but a strong age dependency. The mean relative whole body stiffness for age groups 16 to 19 was 0.27 g/cm (SD 0.065 g/cm) which is within the region reported before⁷.

Conclusion

As a result of these findings, peak force in relation to body mass of all reported mechanographic tests can be considered to be independent of gender and age. *MIGF*, on the other hand, showed a slight correlation to gender and age reminiscent of that found for mechanographic peak power measurements. Peak whole body stiffness in relation to body weight ($pKw_{brel_{m1LH}}$) is independent of gender but has a relation to age which stabilizes with the end of puberty. We could show that maximum voluntary force in relation to body weight ($rFmv_{m1LH}$) is a very stable and constant parameter which is independent of age and gender for age group 5 and older and offer reference values for parameters that are closely related to bone mineral content⁶ and therefore help assess the role of muscle weakness in bone conditions.

Acknowledgements

Gabriele von Oldershausen is thanked for data Management, Christine Stadelmann, Rob Kiviet, Ina Busche, Hartmut Stadelmann, Charlotte Günther and the teachers, parents and, last but not most important, pupils of the of the Freie Waldorfschule Tübingen are thanked for their support and participation!

References

1. Rittweger J, Schiessl H, Felsenberg D, Runge M. Reproducibility of the jumping mechanography as a test of mechanical power output in physically competent adult and elderly subjects. *J Am Geriatr Soc* 2004;52(1):128-31.
2. Veilleux LN, Rauch F. Reproducibility of Jumping Mechanography in healthy children and adults. *J Musculoskelet Neuronal Interact* 2010;10(4):256-66.
3. 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(6):335-40.
4. Fricke O, Weidler J, Tuttlewski B, Schoenau E. Mechanography - a new device for the assessment of muscle function in pediatrics. *Pediatr Res* 2006;59(1):46-9.
5. Rantalainen T, Heinonen A, Komi PV, Linnamo V. Neuromuscular performance and bone structural characteristics in young healthy men and women. *Eur J Appl Physiol* 2008;102(2):215-22.
6. Anliker E, Rawer R, Boutellier U, Toigo M. Maximum ground reaction force in relation to tibial bone mass in children and adults. *Med Sci Sports Exerc* 2011; 43(11):2102-9.
7. Farley CT, Blickhan R, Saito J, Taylor CR. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J Appl Physiol* 1991;71(6):2127-32.
8. Farley CT, González O. Leg stiffness and stride frequency in human running. *J Biomech* 1996;29(2):181-6.
9. Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *J Biomech* 1999;32(3):267-73.
10. Frost HM, Schöna E. The ‘muscle-bone unit’ in children and adolescents: a 2000 overview. *J Pediatr Endocrinol Metab* 2000;13(6):571-90.
11. Schoenau E, Fricke O. Mechanical influences on bone development in children. *Eur J Endocrinol* 2008;159(Suppl.1): S27-31.
12. Rittweger J. Ten years muscle-bone hypothesis: What have we learned so far? -Almost a Festschrift-. *J Musculoskelet Neuronal Interact* 2008;8(2):174-8.
13. Martin DD, Heckmann C, Jenni OG, Ranke MB, Binder G. Comparison of radiogrammetric metacarpal indices in children and reference data from the First Zürich Longitudinal Study. *Pediatric Radiology*; in Press 2012.
14. Martin DD, Heckmann C, Jenni OG, Ranke MB, Binder G, Thodberg HH. Metacarpal thickness, width and

- medullary diameter in children - reference curves from the First Zurich Longitudinal Study. *Osteoporos Internat* 2011;22(5):1525-36.
15. Morrow RL, Garland EJ, Wright JM, Maclure M, Taylor S, Dormuth CR. Influence of relative age on diagnosis and treatment of attention-deficit/hyperactivity disorder in children. *Canadian Medical Association Journal* 2012; 184(7):755-62.
16. 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(2):213-26.