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Original Article

Mechanography in childhood: references for force and power in counter movement jumps and chair rising tests

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Abstract

Objective: We sought to procure age- and gender- related reference data and study the characteristics of body weight related peak force (p*Frel*), body mass related peak power (p*Prel*) for counter movement jumps (single two-legged jumps, s2LJ) and chair rising tests (CRT) in children. **Methods:** We examined 868 healthy participants (436 female) aged 3 to 19 years. Weight-related results of the s2LJ and CRT Mechanography parameters were reported. **Results:** p*Prel* during s2LJ ($pPrel_{s2LJ}$) increased linearly with age for males age 5 to 19 and female age 5 to 11 at a rate of 4.6 W/kg per year. $pPrel_{s2LJ}$ for females age 12 to 19 increased only by 2.5 W/kg. CRT time per repetition was 1.065 s, independent of age and gender. p*Prel* per body mass during the rise phase ($pPrel_{CRT}$) showed similar but smaller age and gender relations as peak power during s2LJ. p*Frel* was 2.5 g (multiples of earth's gravity) for s2LJ and 1.5 g for CRT. **Conclusion:** This data from normal children from a healthy Caucasian population provide reference values for tests that reflect everyday motor function.

Keywords: Jumping Mechanography, Muscle Power, Force, Child Age, Efficiency, Reference Values, Chair Rising Test, Counter Movement Jump

Background

The measurements of force over time and their derivates power and force efficiency of the standardized movements performed on a Mechanography system (ground reaction force platform, GRFP with post processing of data) have been shown by Runge[1], Rittweger[2], Fricke[3] and Veilleux[4] to be robust indicators of motor function that are relevant for daily life. The concept of Mechanography is to quantify movement patterns close to those performed during every day life. The published reproducibility data (Rittweger et al. 2004[2], Veilleux et al. 2010[4], Buehring et al. 2011[5,6]) showing high reproducibility compared to sport specific differences (Michaelis et al. 2008[7]) or effects of disuse (Gast et al. 2012[8], Rittweger et al. 2007[9]) or acute Training effects (Cochrane et al. 2008[10]) suggest that the influence of repetition of the measurements on the analysis result can be considered small compared to the effects of training or therapy as suggested by Rittweger at al. 2007[9]. Therefore these tests are being increasingly used in medical contexts (e.g. to study the effects of ageing by Runge[1], Tsubaki[11,12]) and hormonal or other treatment (Fricke et al. (2008)[13] and Ward[14,15]).

To date there is only one study by Fricke et al. (2008)[16] reporting normative reference values for children for few outcome parameters of one of the mechanographic tests, the Single Two Legged Jump (s2LJ).

Especially in the pediatric context Jumping Mechanography can be considered a novel method with recently increasing numbers of publication. Especially for scientific use and basic understanding easy comparison of the published groups is essential. This is of special importance if effects of intervention or training are documented where the initial physical status of the reported group can be considered to have a significant impact on the outcome results. Therefore common reference data is essential. For this reference data we choses to adapt the approach reported by Runge et al.[1] to children and adolescents. Runge selected an "optimal aging" group assuming the lack of physical activity would result in drastic loss in function while extensive sport would lead to higher wear of the system and at the same time would bias the results.

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

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The original concept of Jumping Mechanography is to provide an objective, reproducible but easy and fast to apply quantification of various aspects of human locomotion. We therefore choose to use age, gender and body mass only to characterize the groups during growth. While peak growth rate or bone age in comparison to age might help to minimize the variability per sub-groups, the need of additional longitudinal data or the use of ionizing radiation would compromise the original concept and its potential clinical use.

In addition the present study was prompted by our need for normative data for healthy younger children than the study by Fricke et al.[16] offered. Furthermore, there was a need for normative data for the other tests that have since been used like the Chair Rising Test (CRT). While for most of them reproducibility data is available (Rittweger[2], Veilleux[4]) reference data in children is still missing.

Abbreviation	Test Type
s2LJ	**single two legged jump** non restricted counter movement jump (CMJ) for maximum height
m1LH	**multiple one legged hopping** repeated on legged hopping on the fore foot with stiff knee
CRT	**chair rising test** 5 consecutive chair rises and sit downs as fast as possible with no break in between but to full extent and to complete sitting

Table 1. Nomenclature of test types.

Methods

Participants

A total of 868 participants (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 a 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 willing and able 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=RcCvcy0zAlM).

The study protocol was presented to the school and at each parent evening. No child was examined without written 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. We did not split the groups by ethnic, genetic or socio-economic factors (the reasons for this are given in the discussion section).

The study was approved by the Ethics Committee of Tübingen University.

Questionnaire

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 front of a computer or TV, and whether the child has any injuries or handicaps relevant to bodily performance.

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, allowing stationary forces as well as the variation of forces over time (ground reaction forces) to be investigated2. 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.

Principle of measurement: The applied force to the jumping platform is registered by four sensors on each of the two plates (one plate per leg) of the platform. Each force sensor can detect a maximum of 1500 N. The force applied to each sensor is sampled 800 times per second. Therefore, kinetic parameters can be calculated when the body weight of the jumping individual is known (Rittweger[2]). The software for the detection, storage and calculation of data (Leonardo Mechanography v4.2) was also supplied by Novotec Medical GmbH.

Single two legs jump (s2LJ): The individuals stood on the platform and each foot was placed on one plate. The jump was performed as a counter-movement jump with freely moving arms, and the children and adolescents were instructed to jump as high as possible with the head and chest (non restricted counter movement jump for maximum height). Before the first jump, the system automatically acquires the weight (static ground reaction force while standing still) of the individual to calculate body mass (body mass= body weight/acceleration of gravity). The children and adolescents performed three jumps and the test of the three recordings resulting in the highest jumping height (the movement pattern best complying with the given instruction) was selected for further calculations. The maximum force of the ascending part of the jump was used for further calculations and was defined by Fricke et al.[3] as peak jumping force (*PJF*) and is will be referred to as pF_{s2LJ}. The peak of the calculated power (force * velocity) has been called peak jumping power (*PJP*)[3] and will be referred to as pP_{s2LJ}. For inter individual comparison, especially during growth, a normalization of power [W] to body mass [kg] and force [N] to body weight [N]) is useful (this concept will be explained in detail later on). pP_{s2LJ} divided by body mass is defined as relative peak power ($pPrel_{s2LJ}$, [W/kg], and pF_{s2LJ} divided by body weight as $pFrel_{s2LJ}$ (multiples of body weight which is equivalent to multiples of earth's gravity [g]).

According to studies published so far $pFrel_{s2LJ}$ hardly

Name	Unit	Explanation
single two legged jump (s2LJ)		
$pPrel_{s2LJ}$	W/kg	relative peak power during the lift off phase of the s2LJ:peak total system power output in relation to body mass
pP_{s2LJ}	W	peak power during the lift off phase of the s2LJ (also referred to as PJP by Fricke et al.[3])
$pFrel_{s2LJ}$	g	relative peak force during the lift off phase of the s2LJ:peak ground reaction force in relation to body weight
pF_{s2LJ}	N	peak force during the lift off phase of the s2LJ(also referred to as PJF by Fricke et al.[3])
dpF_{s2LJ}	%	side difference of peak force as % of the higher value
EFI	%	$pPrel_{s2LJ}$ normalized to age and genderunit: % of mean value of gender matched age group
EFI_{SDS}	SD	SDS* values for $pPrel_{s2LJ}$ normalized to age and gender
pV_{s2LJ}	m/s	peak vertical velocity before lift-off
multiple one legged hopping (m1LH)		
$pKwb_{m1LJ}$	*N/cm*	peak whole body stiffness in center 0,04s around position of peak maximum expressed as kN/cm
$pKwbrel_{m1LJ}$	*g/cm*	relative peak whole body stiffness in center 0,04s around position of peak maximum expressed as multiples of body weight per cm
$Fmvrel_{m1LH}$	g	relative maximum voluntary force during m1LH:peak ground reaction force in relation to body weight (*g*)
chair rising test (CRT)		
$mpPrel_{CRT}$	W/kg	mean relative peak power during the rising phase each repetition of the CRT:peak total system power output in relation to body mass
$mpFrel_{CRT}$	g	mean relative peak force during the rising phase each repetition of the CRT:peak ground reaction force in relation to body weight
$mTPR_{CRT}$	s	mean time per repetition of the CRT:mean time per repetition over repetition 2, 3 and 4 of the CRT
used prefixes		
p	peak	
m	mean	
d	Side difference	

**SDS stands for standard deviation score: for a measurement in a particular child it can be calculated as the measured value minus mean reference value for the respective gender and age divided by the standard deviation of the reference values for that particular gender and age.*

Table 2. Nomenclature of main outcome parameters.

changes with age or fitness and is approximately equal to 2.5 times body weight (2.5 g). $pPrel_{s2LJ}$ is strongly dependent on age and on the individual physical status as reported by Runge[1], Michaelis[7], and Tsubaki[11]. pP_{s2LJ} has been shown to have a good reproducibility (CV=5.5% in elderly and 3.4% in children[4]) and test-retest correlation coefficient (r^2=0.98 [17] and 0.99 [2] in elderly and 0.96 in children[17]).

The two study assistants performing this part of the examinations gave the following instructions to the children "*Jump as high as you can with both legs – try to reach the ceiling with your head*". The assistants assessed whether the child performed a typical counter movement jump including a counter movement or whether the jumps were just quick and short. If needed, further instructions were given to help the children jump as high as they could, like "jump as high as you can, not quick and short – try to jump higher again". Some children landed in a crouched position or on stiff heels, in which case the examination was repeated.

Chair rising test: A specially made, height-adaptable bench was placed on the Leonardo Mechanograph and adjusted in height so that children could sit on it with knees bent 90°. Children held their arms crossed over the torso in front of them, and then they stood up and sat down 5 times as quickly as possible. Instruction: *"hold your arms like this* (the examiner crossed own arms over own torso) *and stand up and sit down as quickly as possible five times in a row"*. To improve reproducibility only the middle three repetitions were used for analysis. Used outcome parameters were mean time per repetition ($mTPR_{CRT}$), mean peak force during the lifting phases in relation to body weight ($mpFrel_{CRT}$), mean peak power during the lifting phases in relation to body mass ($mpPrel_{CRT}$). Special care was taken in the analysis not to use peak forces caused by hitting the chair during landing but only peak muscular forces during the rising phase of the chair rise. A corresponding algorithm is built into the analysis software Leonardo Mechanography v4.2. In addition all measurement curves were manually inspected and measurements where the detected peak force coincided with landing on the chair where corrected manually.

Used nomenclature

Tables 1 and 2 show an overview of the nomenclature for test types and main outcome parameters used within this. In

	Male			Female		
Age (y)	**n**	**Mass (kg)**	**Height (m)**	**n**	**Mass (kg)**	**Height (m)**
3	7	16.8 (1.5)	1.12 (0.10)	4	16.9 (1.8)	1.10 (0.09)
4	13	18.0 (2.4)	1.10 (0.07)	14	17.0 (2.1)	1.13 (0.08)
5	9	19.6 (1.4)	1.13 (0.10)	21	19.5 (2.3)	1.09 (0.08)
6	33	23.8 (4.1)	1.22 (0.13)	24	22.6 (4.3)	1.21 (0.09)
7	38	26.3 (3.7)	1.28 (0.06)	53	25.5 (3.7)	1.28 (0.09)
8	36	27.9 (3.7)	1.33 (0.08)	47	29.0 (4.9)	1.34 (0.07)
9	44	31.8 (4.8)	1.36 (0.08)	40	31.6 (6.1)	1.37 (0.06)
10	27	36.3 (11.5)	1.44 (0.09)	28	34.8 (6.2)	1.43 (0.10)
11	27	38.6 (7.1)	1.52 (0.10)	31	40.3 (6.4)	1.51 (0.12)
12	19	46.5 (10.9)	1.56 (0.09)	20	44.3 (6.2)	1.56 (0.07)
13	28	51.2 (9.5)	1.65 (0.11)	25	48.0 (11.5)	1.60 (0.08)
14	27	57.0 (8.1)	1.63 (0.09)	23	54.3 (7.9)	1.65 (0.13)
15	27	61.2 (10.7)	1.70 (0.09)	16	57.0 (6.7)	1.71 (0.08)
16	30	69.4 (12.4)	1.73 (0.09)	28	58.0 (8.3)	1.71 (0.08)
17	27	73.1 11.0)	1.77 (0.10)	26	62.8 (10.1)	1.71 (0.09)
18	24	72.2 (9.0)	1.71 (0.12)	22	60.1 (8.5)	1.75 (0.11)
19	17	72.5 (6.6)	1.75 (0.10)	14	63.9 (8.6)	1.70 (0.10)

Table 3. Auxology of participants: mean and (SD).

	$pPrel_{s2LJ}$	$pFrel_{s2LJ}$	$pPrel_{CRT}$	$pFrel_{CRT}$	**Body Mass**
ICC 2 days	0.98	0.88	0.75	0.99	0.9998
ICC 7 days	0.95	0.85	0.77	0.99	0.9998
CV 1st day	2.38%	4.37%	n/a*	n/a*	0.12%
CV mean 7 days	3.40%	5.43%	n/a*	n/a*	0.17%

CV 1st Day: mean of individual CV (over 3 measurements) on 1st measurement day.
CV mean 7 days: mean of individual CV per day over 3 measurement days and a period of 7 days.
**CRT was only measured once per measurement day, therefore there is no CV data available.*

Table 4. ICC for 2 measurements over 2 days follow up and for 3 measurements over 7 days follow up.

the opinion of the authors the separation of outcome parameters according to test type is essential for interpretation since the parameters (like peak force) are strongly dependant on the test type. To prevent confusion we added the respective test type in subscript to each parameter.

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 participant's center of mass.

Reference data generation

For the generation of reference data we decided to implement several simplifications which intend to eliminate outliers of individual age groups. The rationale for this approach is that if a mean value or a standard deviation of one age group varies significantly to the adjacent values the reasons for this might be a prominent milestone in growth as well parasitic effects having an impact on the outcome parameters for the individual subgroup like motivation to perform the test, selection of the sub group, habitual differences like sport activities. However, the developmental state within one age group will vary significantly, therefore the effect on the outcome parameters must be spread over several age groups. Therefore we intended to eliminate such outliers which results in continuous reference curves. The Data is presented as means and standard deviation (SD) per age group to allow standard score (SDS) calculation.

Results

For baseline characteristics of the participants see Table 3. Out of 868 children and adolescents (432 male, 436 female) two male participants with a body mass above 100 kg were excluded since they showed a decreased peak force of -2 to -

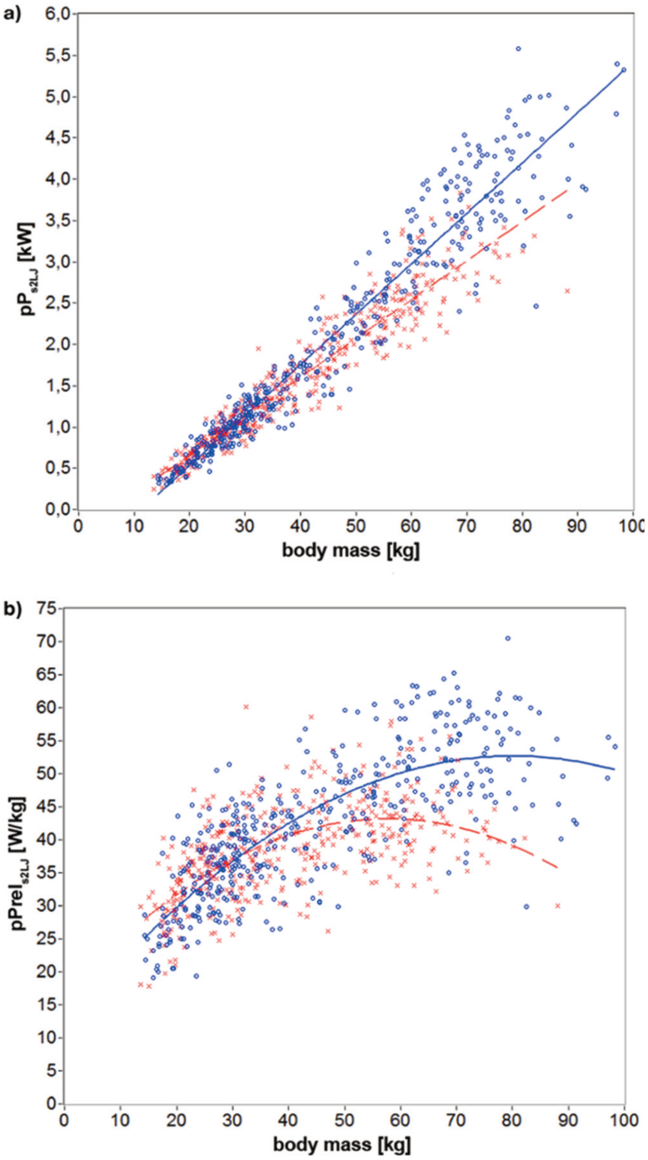

Figure 1. Peak power output (pP_{s2LJ}) during the jumping phase of counter movement jump for maximum height shown in relation to body mass. a) Peak power (kW); solid lines show linear interpolations: male (blue) $R^2 = 0.93$ ($pP_{s2LJ,male}/kW = -0.69+0.061$*age), female (red) $R^2 = 0.91$ ($pP_{s2LJ,female}/kW = -0.28+0.047$*age). b) Peak power relative to body mass (W/kg); lines show 2nd order polynomial interpolation ($pPrel_{s2LJ,male}/W/kg = 11.92 + 1.02$ *age-0.0063 *age^2, $pPrel_{s2LJ,female}$/W/kg = 16.76+0,91*age-0.0079*age^2).

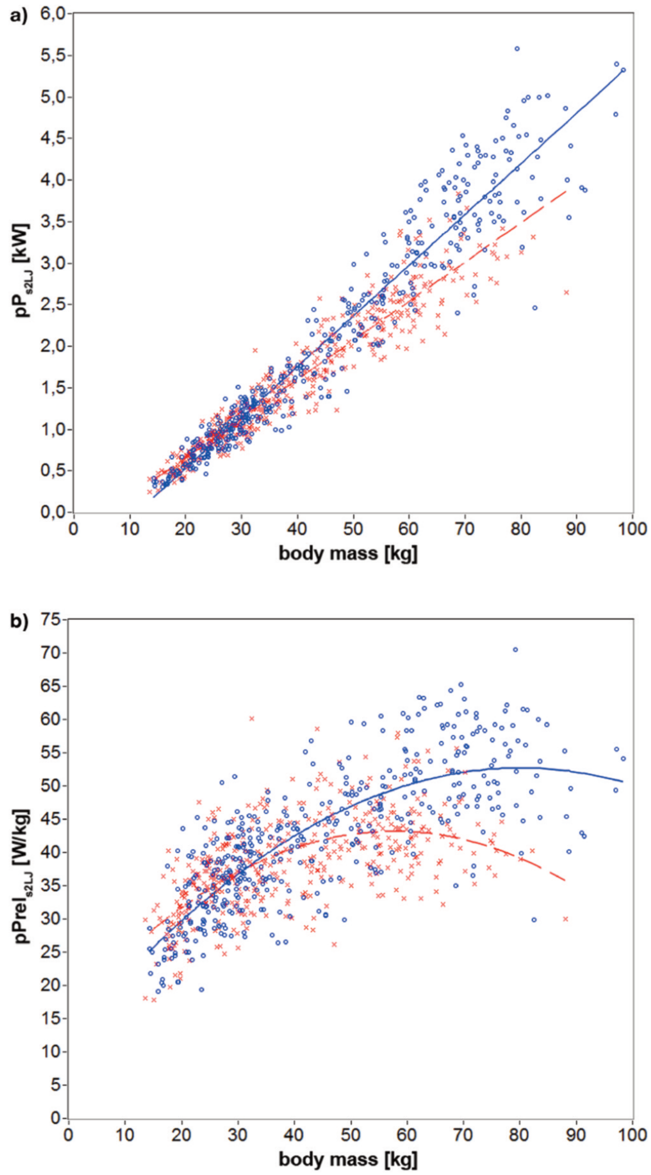

Figure 2. Peak power output during the jumping phase in relation to age. a) Peak power (pP_{s2LJ}) in kW the upper lines are mean values per age group: The lower lines are the corresponding standard deviations. b) Peak power relative to body mass ($pPrel_{s2LJ}$) in W/kg. The upper lines are mean values per age group. The lower lines are the corresponding standard deviations of $pPrel_{s2LJ}$ per age group in W/kg. Male: blue, solid lines; female: red, broken lines.

4 standard deviation relative to this group. Two female participants where excluded because of a peak jumping power below -3.2 and -4.2 standard deviations.

Physical activity and media exposure

Physical activity and media exposure was reported by a simple questionnaire where parents had to categorize their children. It is obvious that questionnaires trying to address such a range of developmental stages can only give rough estimations of physical activity. Nevertheless we include the results to provide some indication of the physical activity of this cohort. According to these estimates the median time spent in front of a media screen was 3 hours per week for boys (mean 5.7; SD 6.7; 80% CI 0-15 hrs/wk) and 2 hours for girls (mean 3.5; SD 3.9; 80% CI 0-10 hrs/wk); the median time engaged in sporting activities, like soccer, cycling, dancing etc., was 4 hours for

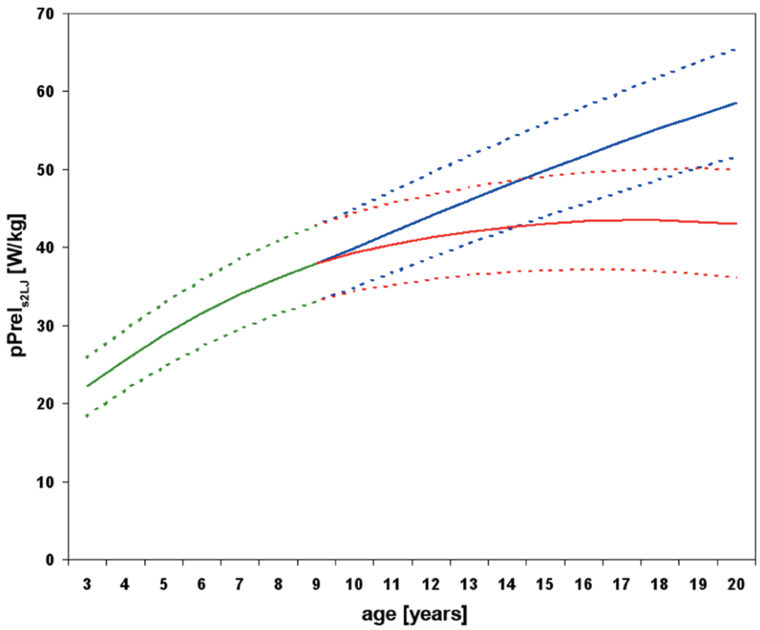

Figure 3. Relative peak power output ($pPrel_{s2LJ}$): Reference curves. The solid line represents the mean and the dotted lines +/- 1 SD. Both genders: green; male: blue; female: red.

boys (mean 3.6; SD 1.0; 80% CI 2-5 hrs/wk) and 3 hours for girls (mean 3.4; SD 1.0; 80% CI 2-5 hrs/wk).

Reproducibility of main outcome parameters

In a subgroup of participants a small reproducibility study was carried out in 4 males and 6 females age 8 to 17. Repetition measurements were done at 1, 2 and 7 days after the baseline measurement. Table 4 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. For s2LJ the peak relative power was found to be more reproducible ($pPrel_{s2LJ}$ ICC_{2day}=0.98, CV=2,38%) than the peak force ($pFrel_{s2LJ}$: ICC_{2day}=0.88, CV=4.37%). For CRT this relation was changed to $pPrel_{CRT}$: ICC_{2day}=0.75 and $pFrel_{CRT}$: ICC_{2day}=0.99.

s2LJ: Relative peak power output ($pPrel_{s2LJ}$)

The peak power and relative (to body mass) peak power are shown in Figure 1 in relation to body mass. (See discussion regarding the necessity to normalize for body mass in the peak power section.) The peak power and relative (to body mass) peak power in relation to age are shown in Figure 2.

When analyzing the peak power output relative to body mass as a function of age, it becomes obvious that below age 10 there is no difference between the genders to be observed. In this age group and for males also up to age 19 an almost linear relation between relative peak power ($pPrel_{s2LJ}$) and body mass can be observed with a slight decrease for age groups 3 and 4.

Defining the reference values

The standard deviations (Figure 2b) show no gender differences and can therefore be expressed using a linear regression: $pPrel_{s2LJ}$=3.15 + 0.19 * age.

For mean values we separated between age up to and above 9 years. This age separation was selected to allow a <u>continuously differentiable</u> (no steps in the curve nor in its derivation) at the intersection of the different interpolation sections. The separation accommodates for the different dynamic and gender dimorphism after the age of 9 years shown by the data.

For age up to 9 years we used a 2nd order polynomial regression independent of gender:

$pPrel_{s2LJ,<9y} = 9.78 + 4.63 * age - 0.167 * age^2$

For males above 9 years we used the 2nd order polynomial regression:

$pPrel_{s2LJ,male,>=9} = 15.57 + 2.71 * age - 0.028 * age^2$

For females above 9 years we used the 2nd order polynomial regression:

$pPrel_{s2LJ,female,>=9} = 21 + 2.58 * age - 0.074 * age^2$

Figure 3 shows the resulting reference curve per age group including +/-1 Standard Deviation.

s2LJ: Esslinger fitness index (EFI)

The EFI compares the $pPrel_{s2LJ}$ of an individual measurement to the average of an age and gender matched reference group (Tsubaki et al. 2009[11]). The solid lines in Figure 3 represent an EFI of 100% for the corresponding age and gender group (see discussion).

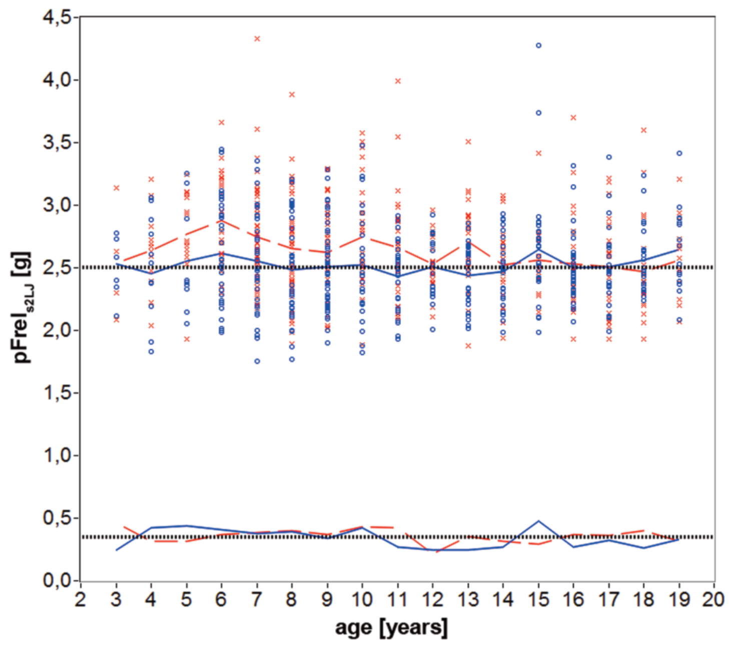

Figure 4. Connected mean values per age group for total peak force during the lift-off phase of the s2LJ (*pFrel*$_{s2LJ}$). Male: blue, solid lines; female: red, broken lines. Upper lines: connected mean values per age group; lower lines: respective standard deviations. Black dotted lines: grand mean of all values as simplified reference value *(pFrel*$_{s2LJ}$ *= 2.5 g (SD=0.34 g))*.

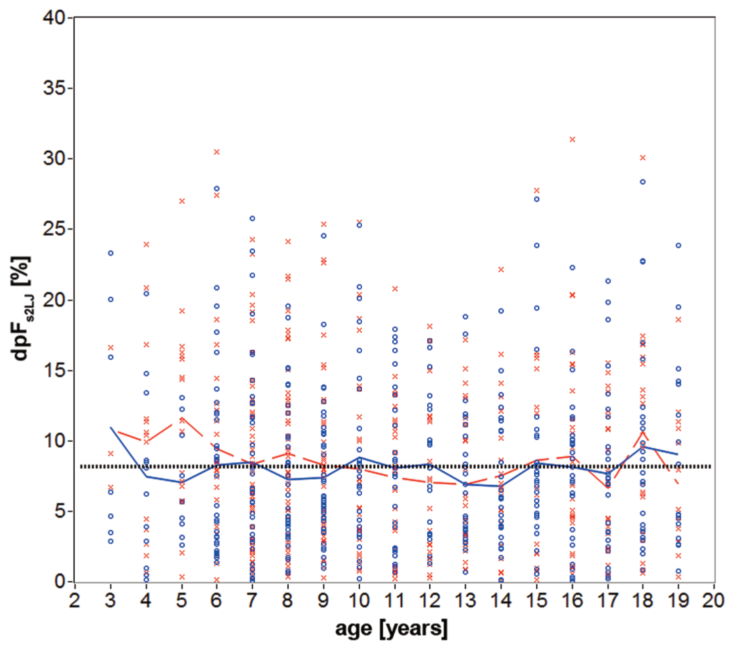

Figure 5. Side differences in relative peak jumping force (*dpFrel*$_{s2LJ}$) in %. Male: blue, solid lines; female: red, broken lines. Upper lines: connected mean values per age group; lower lines: respective standard deviations. Black dotted lines: grand mean of all values as simplified reference value (*dpF*$_{s2lJ}$ = 8.2%).

s2LJ: Relative peak force (pFrel$_{s2LJ}$*)*

Figure 4 shows the peak force (sum of left and right leg) in relation to body weight during the counter movement and the lift-off phase of the s2LJ (non restricted counter movement jump for maximum height). Linear regression of *pF*$_{s2LJ}$ and body mass was found to be independent of gender ($R^2 = 0.89$). In males the relative peak force in relation to body weight is constant at 2.5 g (2.5 times body weight for both feet together

	pF_{s2LJ}	*Body Height*	*Age*	pP_{s2LJ}	$pPrel_{s2LJ}$	pV_{s2LJ}
Regression type	2nd order pol.	2nd order pol.	2nd order pol.	2nd order pol.	linear	2nd order pol.
R^2 males	0.68	0.65	0.8	0.82	0.86	0.97
R^2 females	0.51	0.6	0.68	0.72	0.75	0.94
R^2 both	0.58	0.59	0.68	0.78	0.83	0.96

Table 5. Correlations of jumping height and other parameters.

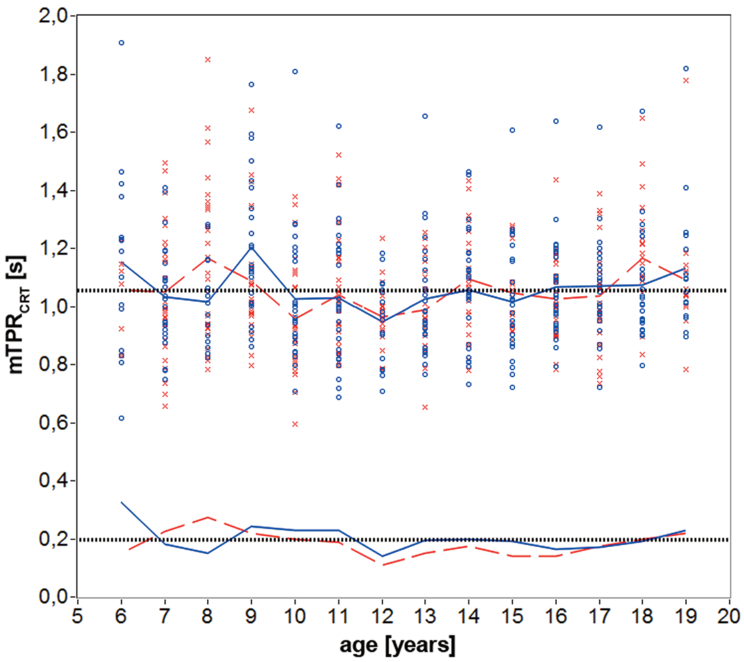

Figure 6. Time per repetition of the CRT ($mTPR_{CRT}$). Male: blue, solid lines; female: red, broken lines. Upper solid lines: connected mean values per age group; lower solid lines: the lower solid lines are the respective standard deviations. Black dotted lines: grand mean of all values as simplified reference value ($mTPR_{CRT}$ = 1.065s, (SD = 0.22s)).

or 1.25 times body weight per leg) with a standard deviation of 0.34 g. In females between 5 and 13 the mean peak force was slightly higher at 2.7 g.

Defining the reference data

For simplification we choose to use a constant value of 2.5 g independent of age and gender.

s2LJ: Side differences of peak force

Since the used GRFP was separated in two plates (one for each foot) side dynamic differences during the complete movement can be analyzed. For the following analysis only counter movement and lift-off phases of each jump were used. Within this section the peak force for both legs was assessed separately. Figure 5 shows the side differences of the relative peak force (dF_{s2LJ}). The side difference is expressed as the percentage of the weaker leg in comparison to the stronger leg (a value of 100% would be equivalent to a counter movement jump using only one leg). The side difference is independent of gender and age with a mean value of 8.2% with the exception of values of up to 13% for females age 3 to 5 and males at age 3 probably caused by psychomotor immaturity.

Jumping height s2LJ

Jumping height was calculated from the 2nd integration of force over time. Table 5 shows correlations coefficients for linear and 2nd order polynomial regression for jumping height and various other parameters separated by genders and both genders together.

Chair rising test (CRT)

CRT: mean time per repetition ($mTPR_{CRT}$)

Figure 6 shows the mean time per repetition ($mTPR_{CRT}$) for repetitions 2 to 4 for the children between age 6 and 19. The

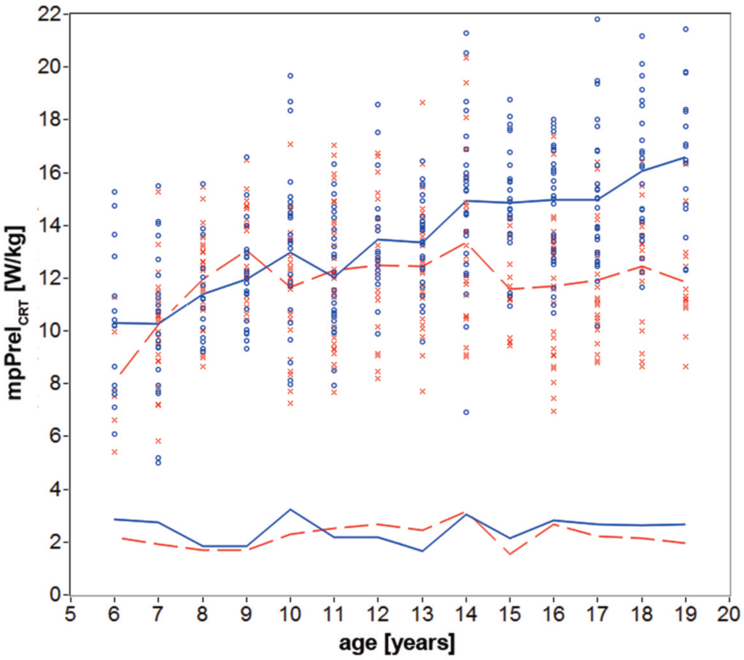

Figure 7. Peak power in the rising phase of the CRT in relation to body mass ($mpPrel_{CRT}$). Male: blue, solid lines; female: red, broken lines. Upper lines: connected mean values per age group; lower lines: respective standard deviations.

$mTPR_{CRT}$ in the age group between 6 and 19 was found to be independent of gender and age (linear interpolation results in constant values of 1.07 s for males and 1.06 s for females). For simplification we chose the mean value of 1.065 s as a constant reference for the age group between 6 and 19 years independent of gender. The standard deviation is almost constant at 0.22 s with a slight increase for age 6 to 11. For simplification purposes we choose a constant value of 0.22 s as standard deviation of the reference group independent of gender and age.

CRT: mean peak power ($mpPrel_{CRT}$)

The mean peak power during the rise phases of the chair rises ($mpPrel_{CRT}$, Figure 7) showed similar age and gender dependencies as the relative peak power in s2LJ ($pPrel_{s2LJ}$). Females and males showed an increase of pPrel during chair rise in the age between 6 and 10 years. A separation of the genders could be observed starting at about age 12. Males showed linear increase of relative peak power $pPrel_{CRT}$ (0.48 W/kg per year; the linear regression formula being $mpPrel_{CRT,}$=9.22+0.48. * *age*). The linear regression of the age groups 10 to 19 for females was constant at $mpPrel_{CRT}$=12.2 W/kg. The standard deviation of $mpPrel_{CRT}$ was found to be independent of age and gender at a mean value of 2.9 W/kg.

CRT: mean peak force in relation to body weight ($mpFrel_{CRT}$)

The mean peak force during the rise phase of the chair rise ($mpFrel_{CRT}$, Figure 8) was found to be almost constant in females with a mean value of 1.48 times body weight (1.48 g). Males showed a slight linear increase mpFrelCRT (0.014 g/year) and a mean value of 1.54 g. Linear regression of peak force vs. body mass showed coefficients of determination of R^2=0.96 for males and R^2=0.95 for females. The standard deviation of $mpFrel_{CRT}$ was found to be independent of gender and age, with a mean value of 0.12 g.

Discussion

In this study we present reference data for various tests of submaximum force, power and force efficiency in children and adolescents 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 spends compared to German average little time in front of TV or computer screens. According to KIGGS[18] about 15% of German children are overweight and 6.3% are obese. In our population only 33 children (3.8%) were overweight and 8 children (1%) were obese. The average media consume of children between 14 and 19 year in Germany is 9.43h per week (ARD longitudinal study). In comparison in our population it is between 2 (female) and 3 (male) hours per week.

Two males and 2 females were excluded due to untypically poor measurements results. The results for all the other children were so homogeneous (SD($pPrel_{s2LJ}$) between 10 and 15 W/kg independent of age and gender, average 2 W/kg increase per year for males age 3 to 19 and females age3 to 11) that we did not see any need for further selection by differences in physical activity as assessed by the questionnaires.

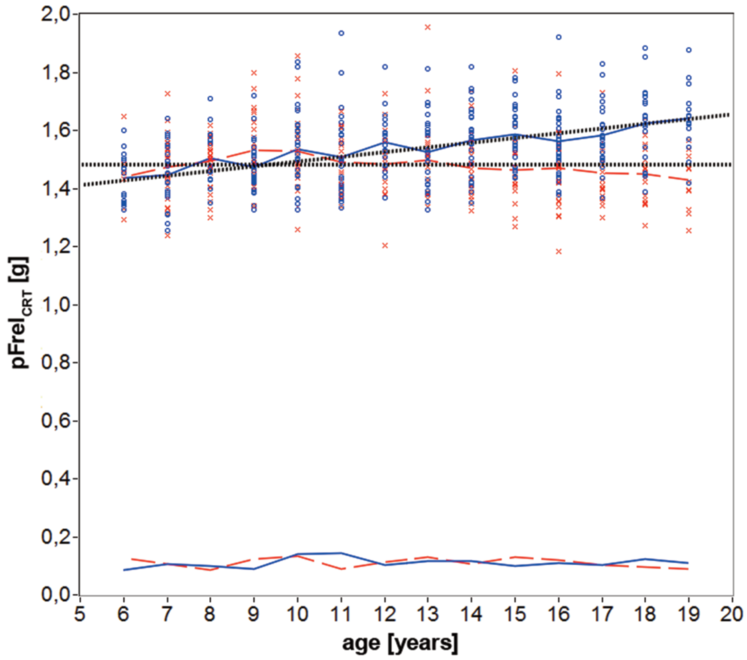

Figure 8. Peak force in the rising phase of the CRT as multiples of body weight *(g)*. Male: blue, solid lines; female: red, broken lines. Upper lines: connected mean values per age group; lower lines: respective standard deviations. Black dotted lines: simplified reference values ($pFrel_{CRT,male}$ /g = 1.36 + 0.014*age, $pFrel_{CRT,female}$ = 1.48 g).

The relevance of these data is exemplified by the fact that they have already been used to produce standard deviation score (SDS) values for the mechanography results for the children in our clinic that are treated with growth hormone (publication in preparation) and that Novotec Medical GmbH has included them in their Leonardo Mechanography software.

Selection

The first publication giving reference data for Mechanographic measurements by Runge et al.[1] was designed not to give average data but optimum data for a population. The intention of this approach was to minimize effects of decreased average values of a population caused by increased sedentary life style. Recent studies[5,13] give support for this approach. As a selection criteria to assess an optimal aging Runge et al.[1] included only participants able to complete certain locomotor tasks typically used in the field of geriatrics (e.g. chair rising test and tandem walk over a certain distance) but excluded very sportive participants at the same time. Identical selection criteria in a Japanese population[11] (age 7 to 82) led to almost identical results. Using no selection criteria for average Greek women[19] (age 20 to 80), however found decreased parameters in $pPrel_{s2LJ}$.

While the selection criteria used by Runge et al.[1] can be considered to be sufficient for older age groups, they seem not to be feasible in growing children. Hence we designed a simple questionnaire aimed to give guidance for a selection comparable to the work by Runge et al.[1]. We are aware of the obvious limitations of such a questionnaire covering the developmental stages between age 3 and age 19. It shows a mean of 3 to 4 hours of sports per week covering organized physical activity in sports clubs as well as non-organized activities.

Since there was no obvious separation between the groups and all assessed Mechanographic parameters showed small variation we chose not to use any of the results of the questionnaire for further selection. However we are aware that selecting this school in a mid-size university-town of Germany is itself a positive selection. This is expressed in the small amount of time the children spent in front of TV or computer screens – in fitting with the school's overall philosophy, which emphasizes creative activities more than sports and encourages parents to limit time in front of screens. We did not divide the groups according to ethnicity. The children in this study all have average to good socioeconomic status, so that a bias through socioeconomic disadvantage can be excluded.

s2LJ: Peak power

An important function of muscle concerning locomotion is muscle power. As discussed elsewhere[4] we chose as a very reproducible movement[2,4] with high power output: the non-restricted counter movement jump for maximum height (also referred as single two leg jump, s2LJ). The main outcome parameter of mechanography for this movement is the peak power output of the body relative to body mass during the jumping phase ($pPrel_{s2LJ}$). The normalization to body mass is needed due to pure physics. A body of double the mass performing an equivalent movement (same time, same jumping height, same peak velocity) needs to generate double the potential energy in order to lift the body to the given height ($E_{pot}=m*g*h$). If this energy is generated during the same time period double the power is needed. This demonstrates the importance of normalization to body mass for inter-individual comparison. This strong linear relation is evident in the cohort of this study: during growth body mass obviously increases substantially (Figure 9), and over 90% of the variation of $pPrel_{s2LJ}$ can be explained by body mass alone. Figure 2 also shows that standard deviation in non-normalized pP_{s2LJ} data substantially increases with age while after normalization to body weight the $pPrel_{s2LJ}$ can be considered constant from age 6 on.

When eliminating this physical relation by normalization to body mass a secondary effect can be observed: An almost linear increase of specific muscle function (peak power per body mass, already compensated for muscle mass and therefore indirectly also partly compensated for muscle size assuming that a larger muscle results in a higher mass and the body composition is identical) in males and in girls up to about age 12. Only parts of this effect might be explained by allometry. However, when analyzing the same parameter in adults and elderly, independent of whether they were average fit Caucasian individuals[1], fit Asian individuals[11] or top athletes[7], the $pPrel_{s2LJ}$ dropped between age 35 and age 60 by about half, while in athletes over the same time the body mass increased by less than 10%. Hence there seems to be an additional aging effect of decreasing muscle function. Interestingly an opposite effect can be observed during growth. Further studies are needed to clarify whether or not a common cause for these opposite effects can be identified.

Obviously, the described jumping procedures assesses peak anaerobic power output instead of the commonly assessed aerobic power output using, for example, a bicycle ergometer at a much lower power output. Rising from a chair or climbing stairs needs a peak power of between 1000 W and 1500 W (equivalent to 10 to 20 W/kg) for healthy adults (non published data of authors) or on average 10 to 15 W/kg in the cohort of this study (see CRT data). Comparing an endurance power of typically 100 W to 200 W (equivalent of 0.5 to 2 W/kg) on a bicycle ergometer makes it obvious that the assessment of anaerobic peak power is an essential parameter related to human locomotion and important for every day movements like rising from a chair or stair climbing. Keeping in mind that fast movements and high forces and therefore also high power is needed to avoid falling, it is also obvious that a decrease in peak anaerobic power must be an essential component of fall risk.

Typical peak power during chair rise ($pPrel_{CRT}$) is in the same order as peak power during Wingate tests at about 10 to 20 W/kg as reported before[20], while reported $pPrel_{s2LJ}$ results[1,11,7], as well as for the adult males of this study are in the order of 50 W/kg to 70 W/kg.

When comparing these finding to the increase of muscle mass (e.g. shown in the analysis of Schießl[20] which is based on data of Zanchetta et al.[21], visible by the difference in lean mass between the values per age group) body parameters show similar effects during growth. Approximately before puberty, males and females show almost identical increase in muscle mass and peak power output in relation to body mass. While males more than double their muscle massas well as their relative peak power output (Figure 1b) between age 10 and 19 females only increase their muscle mass by about 45% between age 10 and 16, varying the average value by less ten 10% from age 14 on. At the same time they significantly gain fat mass. These changes of body composition and gender differences over age described by Schießl et al.[20] coincident with the changes in relative peak power and its gender differences with age and therefore might explain part of the effect. Figure 9 shows body mass

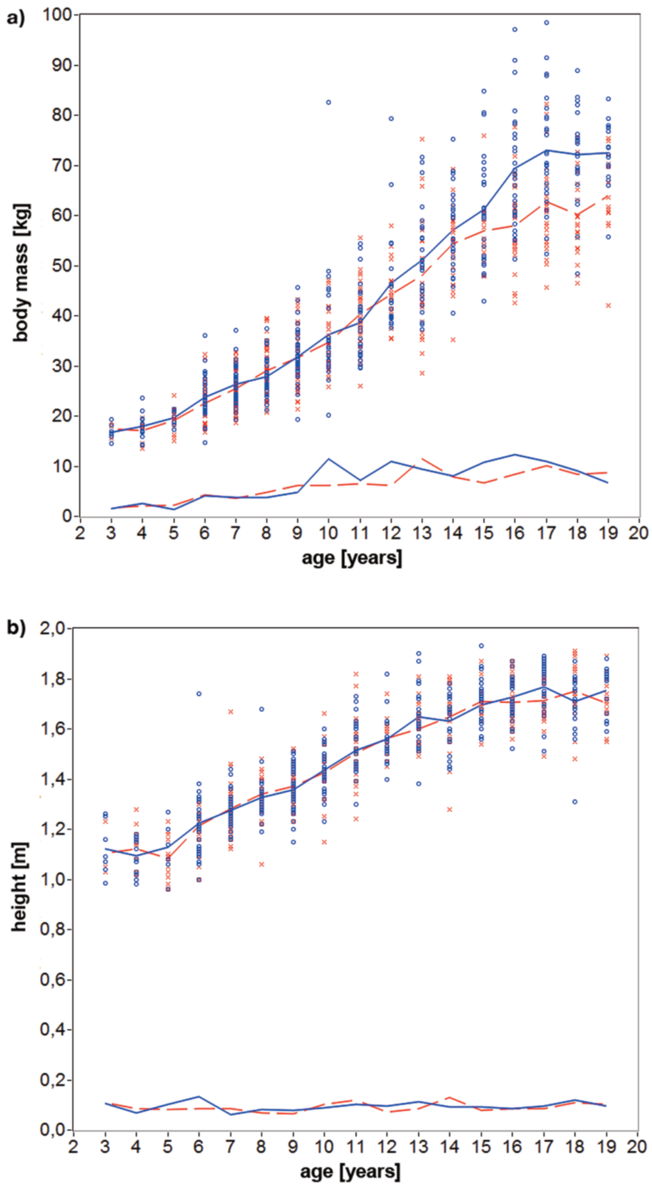

Figure 9. Body mass and height. a) Body mass of participants per age group. b) Height of subjects per age group. Male: blue, solid lines; female: red, broken lines. Upper lines: connected mean values per age group; lower lines: respective standard deviations.

and height per age group and gender. In line with the findings above, no gender difference of height could be observed and up to the age of about 12 no gender difference in body mass could be observed. For age groups above 12 years a separation of body mass was found between the genders. Males show an increase in body mass up to age 17 which is also in line with the findings of Schiessl et al.[20] who showed a constant value of the BMC – lean mass relation in males for age 18 to age 20.

The presented data intersects with the data published by Runge et al.[1] when ignoring his proposed linear interpolation for the age groups 20 to 40. It is obvious that decreases in $pPrel_{s2LJ}$ in adults and increases in children and adolescents need to intersect. It is also likely that this intersection results in a plateau over a certain life span. Data by Buehring et al.[5,6] showing constant values for an age group 20 to 40 supports this idea. Based on the presented standard deviation data no differences could be found to the cohort published by Anliker et al.[17] (s2LJ data not published) while a Japanese cohort (Tsubaki et al.[11]) was in average 0.5SD higher (independent of gender). The combination of the study results listed above suggests a further increase of $pPrel_{s2LJ}$ in males from 20 to 25 (about 2% increases per year) and a plateau form 25 to 35. In females a plateau can be observed from about age 15 to age 30. However data in the age group between 20 and 50 is still limited and further data is needed to clarify this suggestion.

s2LJ: Esslinger index (EFI)

EFI as introduced by Runge et al.[1] and Tsubaki et al.[11] is originally calculated (e.g. by Leonardo Mechanograph) by dividing the measured value of peak jumping power per body mass ($pPrel_{s2LJ}$) of a subject by the mean of sex and age matched reference. *EFI* is expressed as a percentage, 100% being the 50th percentile for sex and age. Alternatively, corresponding standard deviation scores (EFI_{SDS}) values can be calculated. The $pPrel_{s2LJ}$ data can be used as a reference for the age groups 3 to 19: the solid lines in Figure 3 represent an EFI of 100% for the respective age and gender group. For age groups between 20 and 50 the number of participants in the original study[1] is limited. Further adult data is needed for future normative data over the whole life span

s2LJ: Peak force

In analogy to the results of the mmultiple one legged hopping (m1LH) reported in Part II[23] (where mean peak relative force per leg was 3.33 g), the relative peak force in relation to body weight can be considered as constant at 2.5 g (*for both legs together or 1.25g per leg respectively*). In females between 5 and 13 the mean peak force was slightly higher at 2.7 g. It is unclear why this parameter shows a slight gender difference while most other parameters when normalized to body weight or body mass do not show gender related differences before puberty. $pFrel_{s2LJ}$ was not lower in the 3 to 5 year-olds, in contrast to maximum voluntary force during multiple one legged hopping (Fmv_{m1LH}), which only reached its plateau of 3.33 g per leg at the age of 6 in both genders[23].

s2LJ: Peak force side differences

Side differences of force during a symmetric movement like s2LJ can be used to quantify effects of one sided traumata or one sided neurological defects as well as the efficiency of corresponding training or therapy concepts. For the interpretation of these results reference values for a healthy population are helpful. The side difference within our study has been found to be at an average 8.2% for all age groups but for females age 3 to 5 and males age 3 where it was up to 13%. For these young age groups the number of participants[18] were lower then for the older age groups which makes the impact of few outliers and parasitic effects on the mean values larger. At the same time it could be argued that coordination in the age group below 5 years of age might be limited therefore resulting in larger side differences. No rational explanation has been found to explain the increase of side differences in the younger age groups.

s2LH: Jumping height

Highest correlation coefficients (Table 5) were found between jumping height and $Vmax_{s2L}$ which is calculated from the 1st integration of force over time. pF_{s2LJ} was found to be least correlated to jumping height which is in line with the results of pF_{s2LJ} of this cohort being constant in relation to body weight and independent of age and gender (Figure 5). While regression curves of pF_{s2LJ}, body height and age show similar gender differences, $Vmax_{s2LJ}$ as well as $pPrel_{s2LJ}$ show no gender differences and at the same time higher coefficients of determination. An explanation for these effects might be that pF_{s2LJ} and body height are obviously correlated to age due to growth, an effect which is also present in the correlation between jumping height and age (Table 5) assuming that older children are taller, heavier and jump higher. pP_{s2LJ} (unit: W) shows higher coefficients of determination but still a strong gender difference while $pPrel_{s2LJ}$ (unit: W/kg) is already compensated for some of these growth effects due to the normalization to body mass. After this normalization gender differences disappear indicating that gender differences in the absolute values (e.g. power measured in W) are mainly caused by the difference in body mass. This again shows the additional information that can be derived when compensating for body mass or body weight for inter-individual comparison.

Chair rising test

The chair rising test (CRT) as described by Guralnik[22] is originated in the field of geriatrics where typically the main outcome parameter is the time needed to perform 5 (or the middle 3) consecutive repetitions used as an estimator for the resulting power output. Mechanography allows the use of this outcome parameter as well as the calculated peak power output during the rising phase of each repetition. The CRT has been suggested to be a test corresponding to the s2LJ for decreased power output (e.g. for less fit individuals[4]).

It has been shown that the time-based outcome parameters showed a so-called ceiling effect for fairly fit individuals. This can be explained by simple physical observations since the maximum possible velocities are limited by gravity: For the downward phase the shortest time and highest velocity would result in the case of a free fall, for the rising phase there is an optimal time and velocity because increasing the upward velocity over a certain threshold would result in jumping and hence increase the time per repetition. This ceiling effect could also be shown in the data of this study with a mean time of 1.056 s and a standard deviation of 0.2 s both results being independent of age and gender (Figure 6).

Due to this ceiling effect time-based outcome parameters are not feasible for differentiation between fit individuals. However the power per body mass data ($pPrel_{CRT}$ in W/kg) of the CRT provided in Figure 7 shows similar age and gender dependencies as the peak power output in the s2LJ ($pPrel_{s2LJ}$, Figure 2b). It shows a separation between genders at about age 12, a constant increase of 0.47 W/kg per year for males age 6 to 19 and a constant value of 12.2 W/kg for females age 10 to 19.

Force data during CRT showed almost constant values. For males a slight linear increase of peak force per body weight of 0.014 times body weight per year was observed resulting in an about 10% increase of force peak force in males between age 6 and 19. Irrespective of these minor gender differences, 96% of the variation in males and 95% of the variation in females can be explained by body mass. It is unclear why peak force per body weight in males shows a linear increase with age while females stay at a constant value and while there is no gender dimorphism for $pFrel_{s2LJ}$ and $Fmvrel_{m1LH}$.

The used peak force with an average gender-independent value of 1.54 times body weight is considerably smaller than the peak force used for s2LJ (2.5 times body weight) and in m1LH (3.33 times body weight per leg resulting in 6.66 times body weight for both legs for comparison to CRT and s2LJ).

Peak power per body mass in CRT results in similar data as in s2LJ but at much lower levels of force and power. This suggests that both tests can be used to assess peak power output but at different intensities (as proposed by Veilleux et al.[4]). While s2LJ is not feasible in some cases of severe impairments CRT still is. A comparison of the mean differences between age groups and the equivalent standard deviation, however, shows a considerable difference between CRT and s2LJ: Peak power output in relation to body mass in CRT for males shows a mean standard deviation of 2.9 W/kg which is equivalent to 4.1 times the annual increase of the mean value or 21% of the overall mean value. The mean standard deviation of the $pPrel_{s2LJ}$ of 5 W/kg in males is equivalent to 1.85 times the annual increase or 12% or the mean value. Hence the s2LJ can be considered to be more selective than the CRT.

Since the s2LJ offers a better separation it should be used whenever possible. For cases of severe impairments the CRT can be used to assess similar functional parameters at lower intensities.

Conclusion

In conclusion, this paper offers normative reference values from a healthy population regarding muscle force, power and efficiency on the Mechanograph. The mechanography tests single two legged jump (s2LJ, non restricted counter movement jump for maximum height) and chair rising test (CRT) were investigated. With regards to force per body weight, males and females hardly differ for the given tests, whereas from the age of 12 males have more power per body mass than females in all analyzed tests. While power per body mass was reported to decrease drastically in adults past the age of 35 it shows a linear increase in males as well as in females between age 3 and age 12. We also proposed Force Efficiency as a new parameter as an expression of the relationship between resulting peak power output and used peak force.

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