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Original Article

# Effects of jumping exercise on maximum ground reaction force and bone in 8- to 12-year-old boys and girls: a 9-month randomized controlled trial

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## Abstract

**Objectives:** To assess adaptations of the lower leg muscle-bone unit in 8- to 12-year-old children following a randomized controlled jumping exercise intervention for 9 months. **Methods:** Twelve boys and 10 girls (INT) performed a supervised jumping protocol during the first 10 min of their regularly scheduled physical education class twice a week, while 11 boys and 12 girls (CON) completed the regular curriculum. We assessed maximum voluntary ground reaction force during multiple one-legged hopping ($F_{\mathrm{m1LH}}$), and tibial bone strength/geometry by peripheral quantitative computed tomography (pQCT) at the 4-, 14-, 38- and 66%-site pre, intermediate, and post intervention. **Results:** Whether increases in $F_{\mathrm{m1LH}}$ (+2.1% points, $P$= 0.752), nor changes in bone strength/geometry (+1 to +3% points, $0.169<P<0.861$), were significantly different for INT relative to CON. The relationship between $F_{\mathrm{m1LH}}$ and volumetric bone mineral content at the 14%-site ($vBMC_{14\%}$) was very strong for both groups, pre and post intervention ($0.51\leq R^2\leq 0.88$). However, changes in $F_{\mathrm{m1LH}}$ and $vBMC_{14\%}$ were not correlated. **Conclusions:** In children, growth and exercise did not increase maximum muscle force and bone strength in proportion to each other, meaning that the adaptive processes were not tightly coupled or follow different time courses.

**Keywords:** Maximum Voluntary Muscle Force, Multiple One-Legged Hopping (m1LH), Bone Strength, peripheral Quantitative Computed Tomography (pQCT), Children

## Introduction

In order to prevent fractures, bone development should aim at making bones as strong as necessary, not as heavy as possible[1]. By only increasing a bone's mass, the additional weight would increase energy expenditure and decrease running speed[1,2]. Consequently, a bone changes its geometry, rather than the amount of material, to withstand stresses[2,3]. As proposed by the Mechanostat theory[4], the increase in bone strength as a function of structural adaptation is driven by the experienced bone strains, and the highest bone strains are induced by muscle force[2,5]. It is therefore understandable that differences in muscle force could explain varying adaptations in bone strength[6,7].

To quantify the relationship between bone strength/geometry and muscle force, it is crucial on the one hand to quantify maximum voluntary muscle force, instead of surrogates thereof. Hopping on the forefoot of one leg with a stiff knee (m1LH) has been proposed as a maneuver to estimate maximum voluntary muscle force of the lower leg[8-10]. On the other hand, peripheral quantitative computed tomography (pQCT) rather than dual-energy X-ray absorptiometry (DXA) should be used to characterize bone strength and geometry, as it provides authentic three-dimensional measures which allow discrimination between trabecular and cortical components of the bone[11,12].

Following this line of reasoning, we recently showed in a

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cross-sectional study[10] that there exists a very strong relationship ($R^2$=0.84) between bone mineral content at the 14%-site of the tibia ($vBMC_{14\%}$) as a pQCT surrogate for bone strength, and maximum voluntary forefoot ground reaction force during m1LH ($F_{\mathrm{m1LH}}$) in healthy individuals, irrespective of age, gender and training status. We also showed that estimation of maximum voluntary force by the pQCT-derived cross-sectional area of the calf muscle results in a weaker correlation. Altogether, our previous findings indicate that $F_{\mathrm{m1LH}}$ and $vBMC_{14\%}$ might be well suited to generally quantify the relationship between muscle force and bone strength.

Based on the effect of muscle force upon bone, exercise can help to build stronger bones, most powerfully during childhood[13-16]. To maximize the osteogenic potential of exercise, activities should be high in magnitude, and impose dynamic and abnormal strains of varying distribution on the skeleton[17]. These exercise principles have been successfully incorporated into the design of previous school-based intervention studies using pQCT[18-20]. However, it also became evident from the same studies that the response of tibial bone to such exercise during growth depends on the maturity status, sex, and in particular the measured site. For instance, prior to puberty, jumping, hopping and skipping activities (20 min/day for 12 months) lead to increases in both periosteal and endosteal circumferences measured at the 20%-site of the tibia[19]. In pre-pubertal boys, activities including skipping, dancing, playground circuits and simple resistance exercise with exercise bands (15 min/day) plus countermovement jumps or side to side jumps (9 min/day) for 16 months are effective for increasing bone strength at the distal tibia (8%-site), whereas the same exercises are ineffective for increasing bone strength at the distal tibia or tibial midshaft (50%-site) in pre- or early-pubertal girls or early-pubertal boys[20]. Furthermore, in pre- and postmenarcheal girls, 50 min of step-aerobic (2x/week for 9 months) has no effect on the cortical bone of the tibial midshaft[18].

Unfortunately, there has been inconsistency with respect to the analyzed tibial site, and there exists no consensus on which sites should be used as regions of interest. Serial pQCT scans showed that the human tibia has a complex internal structure, and that its architectural design, and thus structural strength, varies profoundly along its length[21]. Thus, we analyzed bone mass and geometry at the 4-, 14-, 38-, and 66%-site.

Since the Mechanostat theory predicts that the increasing muscle force during development provides the stimulus for the increase in bone strength, there should be a link between the magnitude of improvements in muscle force (due to jumping exercise and/or simple growth) and the improvements in bone strength. To the best of our knowledge, the change in maximum voluntary muscle force in relation to the change in bone strength during growth has not been investigated in a longitudinal design up to date. Therefore, the main goal of this randomized, controlled 9-month school-based intervention study in children (age range 8 to 12 years) was: (1) to investigate gains in $F_{\mathrm{m1LH}}$, (2) to assess bone structural changes at the 4-, 14-, 38-, and 66%-site of the tibia, (3) to compare the relationship between $F_{\mathrm{m1LH}}$ and $vBMC_{14\%}$ pre and post intervention, and (4) to evaluate the relationship between the changes in $F_{\mathrm{m1LH}}$ ($\Delta F_{\mathrm{m1LH}}$) and the changes in $vBMC_{14\%}$ ($\Delta vBMC_{14\%}$).

First, we hypothesized that the increase in $F_{\mathrm{m1LH}}$ and tibial structural changes from pre to post intervention would be higher for the jumping exercise-based intervention group (INT) as compared to the control group (CON). Based on the fact that the coefficient of determination for the linear relationship between $F_{\mathrm{m1LH}}$ and $vBMC$ is highest ($R^2$=0.84) for the 14%-site relative to the 4-, 38-, and 66%-site[10], we expected that an increase in $F_{\mathrm{m1LH}}$ (due to growth/exercise) would mostly influence $vBMC_{14\%}$ (as a surrogate of bone strength). Second, we hypothesized that $\Delta F_{\mathrm{m1LH}}$ and $\Delta vBMC_{14\%}$ would be strongly correlated in both INT and CON.

## Methods

### *Participants and study design*

For this randomized, controlled school-based intervention trial, we contacted 170, 8- to 12-year-old boys and girls (grade 4 to 6) from three rural elementary schools in the canton of Lucerne, and informed their parents accordingly. Sixty children received parental consent to participate. In two of the three schools (Hergiswil b. Willisau and Sempach), all teachers from grades 4 to 6 were willing to collaborate, while in the third school (Menznau) only one teacher (grade 6) was interested to participate. To ensure an equal number of children in the intervention (INT) and control groups (CON), we randomly assigned the school of Sempach (14 girls, 16 boys) to CON, and the school of Menznau (6 girls, 3 boys), together with the school of Hergiswil b. Willisau (12 girls, 9 boys) to INT.

As explained in detail further below, INT performed a 10-min supervised jumping exercise protocol during the initial phase of the regularly scheduled physical education classes, while CON started physical education classes in accordance to the official curriculum by playing tag and/or related activities thereof. Both groups completed regular physical education in accordance to the official curriculum. Physical education classes took place two times a week for 45 (session 1) and 90 min (session 2). All children in the INT school classes completed the jumping program, irrespective of whether they participated in the study or not. As inclusion criteria, children had to be healthy (asymptomatic) and able to perform maximal jumping maneuvers. They were excluded from the study if they presented with diagnosed musculoskeletal condition or were taking any medication for treating bone/cartilage. Pre (September 2010), intermediate (February 2011) and post (June 2011) intervention measurements at the three schools were performed within a time period of 2 weeks each.

The intervention period lasted 36 weeks, *i.e.* 18 weeks of intervention from pre to intermediate and 18 weeks of intervention from intermediate to post. The three measurement points in time (pre, intermediate and post) were used to correctly implement the linear mixed model (as described further below), while the pre and post intervention measurements were used to analyze changes during the 9-month jumping period. The children and at least one parent were fully informed about the purpose and risks associated with the study before providing written, informed consent. This study conformed to the Declaration of Helsinki and was approved by the ETH Zurich Ethics Committee.

### *Height, body mass and pubertal status*

Children's standing height and body mass were measured while wearing normal indoor clothing without shoes using a wall-mounted double meter stick (PCI®, Zurich, Switzerland) and an electronic scale (Soehnle, Nassau, Germany), respectively. At each measurement point in time, maturity was assessed by self-report on breast development (girls) and pubic hair stage (boys), in accordance to the simple explanations and line drawings of Tanner stages, which have been validated and described as reasonably accurate[22]. Menstrual history for girls was determined by questionnaire, and included age at menarche, and cycle length.

### *Physical activity and calcium and vitamin D intakes*

We used the first question of the Physical Activity Questionnaire for Older Children (PAQ-C) to assess leisure-time physical activity retrospectively via a checklist of common sports[23]. The questionnaire measured the total time (hours/week) spent on common physical activities and was assessed intermediate (referring to the first 18 weeks of intervention, to cover the first half of the school year) and post intervention (referring to the second 18 weeks of intervention, to cover the second half of the school year). To determine the mechanical component of physical activity, we estimated the peak ground reaction force (GRF) acting on the forefoot of habitual physical activities[24]. On the basis of GRFs, we classified all the various types of physical activities into four categories: physical activities with GRF greater than four times body weight (score 4), GRF values between 2 and 4 times body weight (score 3), GRF values between 1 and 2 times body weight (score 2), and GRF values <1 times body weight (score 1). Subsequently, we calculated a physical activity score, which corresponded to the sum of the time spent on the particular activity level multiplied by the estimated mechanical component. Calcium and vitamin D intakes were assessed prior to each measurement point in time by a 4 days food record (including one weekend day), for which daily calcium and vitamin D intakes (in milligrams and micrograms, respectively) were calculated by means of the Swiss nutrition database *(https://www.swissfir.ethz.ch)*. None of our children regularly took supplements or any vitamins besides the dietary intake.

### *Exercise intervention*

Our exercise intervention was designed in accordance with the one of Weeks *et al.*[25]. In their study, jumpers (22 boys and 30 girls, mean age: 13.8 and 13.7 years, respectively) performed 10 min jumping activity twice a week for 8 month, and experienced significantly higher improvements relative to controls (24 boys and 23 girls, mean age: 13.8 and 13.7 years, respectively) for bone mass at the femoral neck, trochanter, whole body, and calcaneus, as well as lean tissue mass measured by DXA. Therefore, we provided progressive, high-impact, 10-min jumping exercises during the initial phase (*i.e.* in place of the usual warm up) of regularly scheduled physical education classes two times a week over the whole school year (holidays excluded). As noticed previously[25], implementing the intervention into regularly scheduled physical activity classes makes it simple and feasible, meaning that no additional staffing, equipment, nor time effort was necessary. In total, 72 training sessions were conducted. Each training session consisted of a circuit of five jumping and sprinting exercises, such as multiple two- and one-legged hopping, drop jumps, side to side jumps, jumping jacks, jumps and landings from a podium, jumps over barriers and short multidirectional sprints. After the 10-min jumping exercise, the regular physical education class continued normally (*i.e.* according to the official curriculum for physical education). Training sessions were pooled into six 6-week training periods, each made up of the same 30 exercises. Within one training period (*i.e.* within the 30 exercises), exercise intensity (estimated by GRFs) increased weekly, meaning that children started with performing single/multiple two legged jumping variations, and towards the end of a training period, more one-legged hopping exercises were performed. Based on the results of standardized jumping maneuvers in children, we know that during single and multiple two-legged jumps peak GRF for both legs corresponds to ~2.4 and ~5.4 times body weight, respectively (*i.e.* 1.2 and 2.7 times body weight per leg, respectively)[9]. Maximum GRF was observed during multiple one-legged hopping (~3.5 times body weight)[9,10]. Exercise frequency (as determined by the number of jumps and sprints within one training session) increased progressively every 6 weeks (*i.e.* between training periods). During the first training period, one training session included ~60 jumps. This number of jumps increased up to ~150 jumps per session until the end of the study. Prior to the study, we instructed the physical education teachers in detail on how to perform the various jumping activities, and we periodically (at least once per month) ascertained on-site that the program was implemented correctly and consistently. Teachers were provided posters depicting the various exercise forms and corresponding information.

### *Mechanography*

Dynamic muscle function was assessed by means of Leonardo Mechanograph® force plate (Novotec Medical, Pforzheim, Germany), as described in detail previously[9,10]. The force plate has eight sensors, with each sensor recording force at a sampling frequency of 800 Hz. For the detection, storage, and calculation of data we used the manufacturer's software (Leonardo Mechanography GRFP version 4.2, Novotec, Pforzheim, Germany). The children's body mass was assessed during quiet stance immediately before each trial. Following a single-tone pitch, children performed the test maneuver as described below. After each trial, children remained still for at least 2 s. The termination of the test was indicated by a double-tone pitch.

| Variables | Definition | Unit | Percent of tibia length |
|---|---|---|---|
| *vBMC* | Bone mineral content | [g·cm$^{-1}$] | 4, 14, 38, 66 |
| *vBMD.tb* | Trabecular bone mineral density | [mg·cm$^{-3}$] | 4 |
| *vBMD.ct* | Cortical bone mineral density | [mg·cm$^{-3}$] | 14, 38, 66 |
| *vBMD.tot* | Total bone mineral density | [mg·cm$^{-3}$] | 4 |
| *Ar.bone.tb* | Trabecular bone area | [mm$^2$] | 4 |
| *Ar.bone.ct* | Cortical bone area | [mm$^2$] | 14, 38, 66 |
| *Ar.bone.tot* | Total bone area | [mm$^2$] | 4, 14, 38, 66 |
| *Peri* | Periosteal circumference | [mm] | 14, 38, 66 |
| *Endo* | Endosteal circumference | [mm] | 14, 38, 66 |
| *SSIpol* | Strength Strain Index | [mm$^3$] | 14, 38, 66 |

**Table 1.** Definitions of the peripheral quantitative computed tomography (pQCT) variables.

| | INT (n=22) | CON (n=23) | |
|---|---|---|---|
| | Mean±SD | Mean±SD | *P*-Value |
| Age pre intervention [years] | 10.5±1.2 | 10.8±1.1 | 0.516 |
| Height pre intervention [m] | 1.40±0.12 | 1.43±0.07 | 0.372 |
| Height post intervention [m] | 1.45±0.12 | 1.48±0.06 | 0.319 |
| Body mass pre intervention [kg] | 34.6±7.7 | 34.0±5.7 | 0.765 |
| Body mass post intervention [kg] | 37.7±9.0 | 37.0±6.6 | 0.754 |
| Physical activity [h·w$^{-1}$] | 11.7±9.4 | 13.0±7.9 | 0.592 |
| Calcium intake [mg·d$^{-1}$] | 612±160 | 712±196 | 0.067 |
| Vitamin-D$_3$ intake [μg·d$^{-1}$] | 1.3±0.6 | 1.4±0.6 | 0.545 |
| Tanner stages pre intervention (1/2/3/4/5) | 16/4/2/0/0 | 14/6/3/0/0 | 0.450 |
| Tanner stages post intervention (1/2/3/4/5) | 12/4/5/1/0 | 7/11/3/2/0 | 0.497 |

*INT, intervention children; CON, control children.*

**Table 2.** Children's characteristics pre and post intervention, and mean physical activity score, as well as mean calcium and vitamin D intake during the 9-month intervention period.

### *Multiple one-legged hopping (m1LH)*

Multiple one-legged hopping (m1LH) aims to achieve maximum voluntary forefoot ground reaction force during landing ($F_{\mathrm{m1LH}}$). Children started from an upright standing position with feet positioned hip-wide. To start the maneuver, they lifted the dominant sided foot off the force plate and started to jump repeatedly (approximately fifteen jumps comparable to hopping during rope skipping) on the forefoot of their nondominant leg with a stiff knee. During the first few jumps, children were instructed to jump as fast as possible whereas the subsequent jumps (about ten) were accomplished as forceful as possible. Importantly, they were advised never to touch the ground with their heels during the jumping maneuver. Any jumps with heel contact were excluded from the analysis. Heel contact was controlled visually during the jumping maneuver and/or detected by the manufacturer's software. The m1LH was performed with freely moving arms. The best trial was the one with the highest $F_{\mathrm{m1LH}}$ during the maneuver. Maximum ground reaction force per body weight ($F\mathrm{rel}_{\mathrm{m1LH}}$) and $F_{\mathrm{m1LH}}$ were considered the main outcome variables for m1LH[9].

### *Peripheral quantitative computed tomography (pQCT)*

An XCT 3000 Scanner (Stratec, Pforzheim, Germany) was used for pQCT as described in detail previously[10]. Section images were obtained from the nondominant calf scout view of the tibio-talar joint. Scans were obtained at 4- (epiphysis), 14-, 38-, and 66-% (diaphysis) of tibia length. We measured the length of the tibia based on anatomical landmarks (from knee joint line to medial malleolus) using a ruler. For all measurements, the angle between the foot and the tibia was adjusted to 120°. The measured variables are shown in Table 1. Additionally, at 14, 38, and 66% of the tibia length, the polar strength strain index (*SSIpol*) was calculated as the integral of the product of the section modulus and the modulus of elasticity to provide an estimate of torsional bone strength. Section modulus was calculated as $(a \times d^2)/d_{\max}$, where $a$ is the cross-sectional area of a voxel, $d$ is the distance of the voxel from the center of gravity, and $d_{\max}$ is the maximum distance (mm) of one voxel to the center of gravity. The ratio of *vBMD.ct* and normal physiological density (ND=1200 mg/cm$^3$) provides an estimate of the modulus of elasticity[20].

### *Statistical analysis*

For all statistical analyses we used SPSS 17.0 software for Mac OS X (SPSS, Chicago, IL, USA). Normality of data was ascertained by Q-Q plots. Mean and standard deviation (SD) are given as descriptive statistics. Student's unpaired $t$ tests were used to determine pre vs. post differences between INT and CON. Percent changes between pre and post values were calculated. Student's paired $t$ tests were used to compare percent change from pre to intermediate intervention with percent change from intermediate to post intervention within the groups. We used a linear mixed model to evaluate the effect of the intervention between INT and CON. Measurement point in time (pre, intermediate, and post intervention) was defined as a random effect, and group (INT or CON) was the fixed effect. Based on known biological and biomechanical relationships[19,20,26,27], the following covariates were chosen: age, tanner stage, body mass, height, calcium intake, vitamin D intake and activity. Statistical significance was set at $P<0.05$.

## Results

### *Children's characteristics*

Forty-five out of 60 children were included in the analyses. One boy (INT) broke his leg while skiing, one girl (INT) missed the post-measurement because of illness, four girls (INT: 2, CON: 2) were excluded because they were postmenarcheal, and 4 girls (INT) and 5 boys (CON) were excluded from

| | INT (n=22) | | | CON (n=23) | | | |
|---|---|---|---|---|---|---|---|
| | Pre intervention | Post intervention | | Pre intervention | Post intervention | | |
| | Mean±SD | Mean±SD | %-change | Mean±SD | Mean±SD | %-change | *P*-Value |
| $F_{\mathrm{m1LH}}$ [N] | 1050±264 | 1189±312 | 13.4 | 1121±219 | 1246±251 | 11.3 | 0.752 |
| $F\mathrm{rel}_{\mathrm{m1LH}}$ | 3.08±0.35 | 3.22±0.42 | 4.9 | 3.35±0.29[aa] | 3.43±0.37 | 2.4 | 0.478 |

*P-Values are shown for the differences in change over time between groups, evaluated by the linear mixed model. INT, intervention children; CON, control children;* $F_{\mathrm{m1LH}}$*, maximum voluntary ground reaction force;* $F\mathrm{rel}_{\mathrm{m1LH}}$*, maximum voluntary ground reaction force per body weight.* [aa]*P<0.01, relative to INT pre intervention.*

**Table 3.** Variables of multiple one-legged hopping (m1LH).

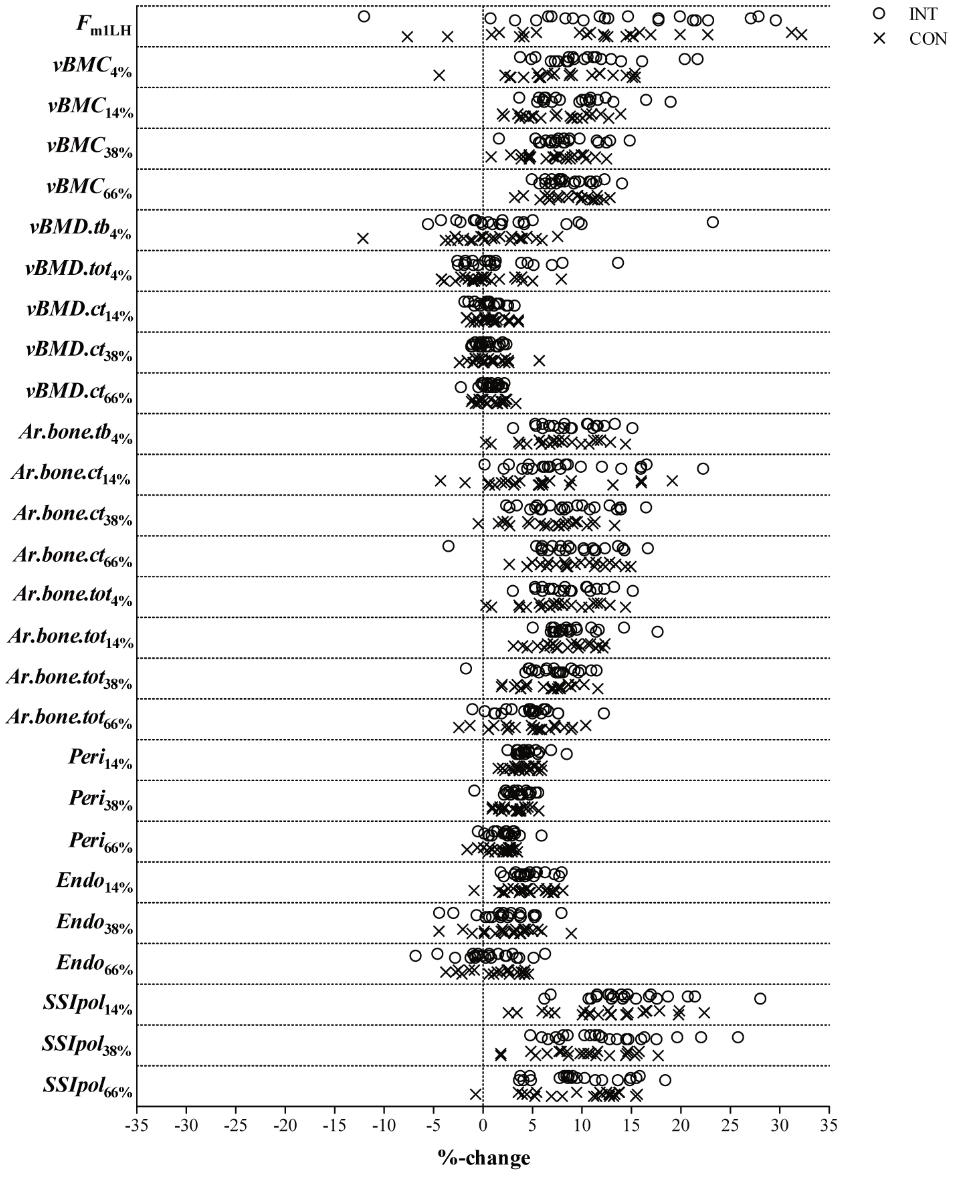

**Figure 1.** Individual percent changes of the respective pre value (%-change) of maximum voluntary ground reaction force ($F_{\mathrm{m1LH}}$), and of the peripheral quantitative computed tomography (pQCT) variables for intervention (INT) and control (CON) children. *vBMC*, bone mineral content; *vBMD.tb*, trabecular bone mineral density; *vBMD.ct*, cortical bone mineral density; *vBMD.tot*, total bone mineral density; *Ar.bone.tb*, trabecular bone area; *Ar.bone.ct*, cortical bone area; *Ar.bone.tot*, total bone area; *Peri*, periosteal circumference; *Endo*, endosteal circumference; *SSIpol*, Strength Strain Index.

| | INT (n=22) | | | CON (n=23) | | | |
|---|---|---|---|---|---|---|---|
| | Pre intervention | Post intervention | | Pre intervention | Post intervention | | |
| | Mean±SD | Mean±SD | %-change | Mean±SD | Mean±SD | %-change | *P*-Value |
| $vBMC_{4\%}$ [g·cm$^{-1}$] | 2.05±0.45 | 2.26±0.52 | 10.4 | 2.19±0.37 | 2.35±0.35 | 8.1 | 0.169 |
| $vBMD.tb_{4\%}$ [mg·cm$^{-3}$] | 205.68±25.57 | 210.41±24.27 | 2.6 | 210.32±25.16 | 211.35±23.32 | 0.7 | 0.231 |
| $vBMD.tot_{4\%}$ [mg·cm$^{-3}$] | 277.33±28.89 | 281.15±28.52 | 1.5 | 275.76±25.78 | 276.76±24.01 | 0.5 | 0.358 |
| $Ar.bone.tb_{4\%}$ [mm$^{2}$] | 330.15±57.90 | 359.03±61.69 | 8.9 | 357.24±56.83 | 382.98±52.18 | 7.6 | 0.312 |
| $Ar.bone.tot_{4\%}$ [mm$^{2}$] | 734.07±128.55 | 798.10±137.15 | 8.8 | 794.13±126.25 | 851.35±115.98 | 7.6 | 0.327 |
| $vBMC_{14\%}$ [g·cm$^{-1}$] | 1.53±0.35 | 1.66±0.36 | 9.2 | 1.56±0.20 | 1.68±0.24 | 7.5 | 0.250 |
| $vBMD.ct_{14\%}$ [mg·cm$^{-3}$] | 978.39±23.97 | 984.40±23.97 | 0.6 | 964.78±24.70 | 972.43±28.16 | 0.8 | 0.634 |
| $Ar.bone.ct_{14\%}$ [mm$^{2}$] | 111.68±27.48 | 120.58±27.78 | 8.5 | 110.92±14.69 | 117.41±17.83 | 5.7 | 0.200 |
| $Ar.bone.tot_{14\%}$ [mm$^{2}$] | 327.57±64.04 | 356.6±66.71 | 9.0 | 353.48±51.90 | 382.02±52.85 | 8.2 | 0.833 |
| $Peri_{14\%}$ [mm] | 63.89±5.99 | 66.69±5.99 | 4.4 | 66.48±4.80 | 69.13±4.73 | 4.0 | 0.499 |
| $Endo_{14\%}$ [mm] | 51.83±5.31 | 54.20±5.41 | 4.6 | 54.99±5.04$^{a}$ | 57.47±4.88$^{b}$ | 4.6 | 0.757 |
| $SSIpol_{14\%}$ [mm$^{3}$] | 781.82±248.63 | 892.35±270.53 | 14.7 | 827.60±161.14 | 933.32±190.72 | 12.6 | 0.723 |
| $vBMC_{38\%}$ [g·cm$^{-1}$] | 2.10±0.43 | 2.27±0.48 | 8.2 | 2.19±0.30 | 2.35±0.35 | 7.2 | 0.515 |
| $vBMD.ct_{38\%}$ [mg·cm$^{-3}$] | 1041.94±29.04 | 1045.44±28.93 | 0.3 | 1032.58±26.22 | 1038.60±27.80 | 0.6 | 0.492 |
| $Ar.bone.ct_{38\%}$ [mm$^{2}$] | 179.18±37.37 | 194.32±41.09 | 8.5 | 188.86±26.37 | 202.05±30.72 | 6.9 | 0.314 |
| $Ar.bone.tot_{38\%}$ [mm$^{2}$] | 278.57±56.89 | 297.59±57.45 | 7.1 | 286.37±38.35 | 304.75±43.72 | 6.3 | 0.836 |
| $Peri_{38\%}$ [mm] | 58.88±5.89 | 60.89±5.78 | 3.5 | 59.86±4.01 | 61.73±4.42 | 3.1 | 0.626 |
| $Endo_{38\%}$ [mm] | 35.07±4.45 | 35.80±4.09 | 2.3 | 34.86±3.32 | 35.77±3.35 | 2.7 | 0.459 |
| $SSIpol_{38\%}$ [mm$^{3}$] | 819.54±239.80 | 921.72±269.10 | 12.6 | 859.78±174.23 | 950.26±205.84 | 10.4 | 0.394 |
| $vBMC_{66\%}$ [g·cm$^{-1}$] | 2.34±0.49 | 2.55±0.53 | 8.6 | 2.38±0.35 | 2.58±0.41 | 8.6 | 0.645 |
| $vBMD.ct_{66\%}$ [mg·cm$^{-3}$] | 1018.85±22.48 | 1027.21±24.82 | 0.8 | 1006.00±20.42 | 1013.78±23.63 | 0.8 | 0.861 |
| $Ar.bone.ct_{66\%}$ [mm$^{2}$] | 186.16±37.95 | 203.27±42.92 | 9.1 | 192.35±30.18 | 210.09±34.40 | 9.2 | 0.703 |
| $Ar.bone.tot_{66\%}$ [mm$^{2}$] | 422.56±98.46 | 441.48±102.22 | 3.5 | 426.30±53.77 | 446.86±61.95 | 4.7 | 0.205 |
| $Peri_{66\%}$ [mm] | 72.40±8.24 | 74.01±8.40 | 2.2 | 73.01±4.73 | 74.74±5.27 | 1.9 | 0.655 |
| $Endo_{66\%}$ [mm] | 54.00±7.43 | 54.22±7.32 | 0.4 | 54.02±4.19 | 54.32±4.78 | 1.7 | 0.818 |
| $SSIpol_{66\%}$ [mm$^{3}$] | 1290.15±421.74 | 1419.45±481.47 | 9.9 | 1282.57±251.26 | 1417.32±303.63 | 10.0 | 0.731 |

*P-Values are shown for the differences in change over time between groups, evaluated by the linear mixed model. INT, intervention children; CON, control children; vBMC, bone mineral content; vBMD.tb, trabecular bone mineral density; vBMD.ct, cortical bone mineral density; vBMD.tot, total bone mineral density; Ar.bone.tb, trabecular bone area; Ar.bone.ct, cortical bone area; Ar.bone.tot, total bone area; Peri, periosteal circumference; Endo, endosteal circumference; SSIpol, Strength Strain Index.* $^{a}P<0.05$*, relative to INT pre intervention;* $^{b}P<0.05$*, relative to INT post intervention.*

**Table 4.** Peripheral quantitative computed tomography (pQCT) variables.

analysis because of motion artifacts during the pQCT measurements. Median compliance with regularly physical education classes was 100% (interquartile range [IQR]: 97-100%) for INT and 99% (IQR: 96-100%) for CON. Pre intervention, there were no differences ($P>0.05$) in age, height, body mass, physical activity, calcium and vitamin D intake, and Tanner stages between INT and CON (Table 2). Regarding maturity, pre intervention, 73% of CON and 61% of INT were Tanner stage 1, 18% of CON and 26% of INT were Tanner stage 2, and 9% of CON and 13% of INT were Tanner stage 3 (Table 2).

### Jumping mechanography

The *P*-values in Table 3 refer to the differences in change over time between groups, as evaluated by the linear mixed model. Pre intervention, CON had higher values for $Frel_{\mathrm{m1LH}}$ ($P=0.007$) relative to INT (Table 3). Following the current 9-month supervised jumping exercise program, the gains for INT relative to CON in $F_{\mathrm{m1LH}}$ (+2.1% points) and $Frel_{\mathrm{m1LH}}$ (+2.5% points) were statistically not significant (Table 3). Individual percent changes of the respective pre value in $F_{\mathrm{m1LH}}$ for both groups ranged from a 12% decrease to an >30% increase (Figure 1).

### pQCT-values

The *P*-values in Table 4 refer to the differences in change over time between groups, as evaluated by the linear mixed model. Regarding all pQCT-derived variables, there were no significantly different adaptations in bone strength and geometry between the two groups from pre to post intervention ($0.169<P<0.861$, Table 4). However, compared with CON, the increase in INT was higher in $vBMC_{4\%}$ (+2.3% points), $vBMC_{14\%}$ (+1.7% points) and $vBMC_{38\%}$ (+1% points), while both INT and CON increased $vBMC_{66\%}$ by the same percentage (Table 4). In addition, we observed slightly higher gains in INT relative to CON in $vBMD.tb_{4\%}$ and $vBMD.tot_{4\%}$ (+1.9% and

+1% points, respectively, Table 4). By contrast, the change during the 9-month study period in $vBMD.ct_{14\%}$, $vBMD.ct_{38\%}$, and $vBMD.ct_{66\%}$ did not differ between INT compared with CON (-0.2%, -0.3% and 0% points, respectively). CON had significantly higher $Endo_{14\%}$ pre ($P$=0.047) and post intervention ($P$=0.039) relative to INT (Table 4). The increase in *Peri* at 14-, 38-, and 66% of tibia length was similar in INT compared with CON (+0.4%, +0.4% and +0.3% points, respectively). Moreover, no difference in the increase of *Endo* existed between INT and CON at the 14%-site, while at the 38- and 66%-site the changes for *Endo* were slightly lower for INT relative to CON (-0.4% and -1.3% points, respectively). Furthermore, INT compared with CON showed higher gains in *Ar.bone.ct* (+2.8% points), *Ar.bone.tot* (+0.8% points) and *SSIpol* (+2.1% points) at the 14%-site, and in *Ar.bone.ct* (+1.6% points), *Ar.bone.tot* (+0.8% points) and *SSIpol* (+2.2% points) at the 38%-site, while there were no differences in the increase in *Ar.bone.ct* and *SSIpol* at the 66%-site between INT and CON. Individual percent changes from pre to post intervention clearly illustrated that the inter-individual variation was highest for *SSIpol* and *Ar.bone.ct*, and very small for *vBMD.ct* (Figure 1).

Regarding *vBMC* in CON, percent changes from pre to intermediate intervention were significantly lower compared to percent changes from intermediate to post intervention at the 4-, 14-, and 38%-site of tibia length ($P$=0.016, $P$=0.025, and $P$=0.001, respectively), and by trend at the 66%-site ($P$=0.055). By contrast, *vBMC* percent changes in INT from pre to intermediate intervention were significantly lower compared to percent changes from intermediate to post intervention only for the 38% ($P$=0.007) and 66%-site ($P$=0.048), while for the 4- and 14%-site, *vBMC* increased equally from pre to intermediate and from intermediate to post intervention ($P$=0.086 and $P$=0.070, respectively).

### *Relationship between $F_{\mathrm{m1LH}}$ and $vBMC_{14\%}$*

Linear regression comprised $vBMC_{14\%}$ as dependent variable and $F_{\mathrm{m1LH}}$ as predictor (Figure 2). Pre intervention, $F_{\mathrm{m1LH}}$ predicted $vBMC_{14\%}$ by 84% in INT ($P$<0.001, Figure 2A) and by 63% in CON ($P$<0.001, Figure 2B). After the 9-month intervention period, the relationship between $vBMC_{14\%}$ and $F_{\mathrm{m1LH}}$ became stronger in INT ($R^2$=0.875, $P$<0.001, Figure 2A), while in CON predictive power of $F_{\mathrm{m1LH}}$ decreased ($R^2$=0.507, $P$<0.001, Figure 2B). Within groups, neither intercepts, nor slopes of the regression lines were statistically different between pre and post intervention (INT: $P$=0.434 and $P$=0.594, respectively; CON: $P$=0.743 and $P$=0.500, respectively). By contrast, the slopes of the regression lines in INT compared to CON were significantly different in both pre and post intervention ($P$=0.010 and $P$=0.019, respectively).

Although there were strong positive correlations between $F_{\mathrm{m1LH}}$ and $vBMC_{14\%}$ both pre and post intervention, the absolute change in $F_{\mathrm{m1LH}}$ ($\Delta F_{\mathrm{m1LH}}$) was not related to the absolute change in $vBMC_{14\%}$ ($\Delta vBMC_{14\%}$) neither in INT nor CON (Figure 2C). By contrast, the absolute change in height ($\Delta$*Height*) and body mass ($\Delta$*Body mass*) correlated significantly with $\Delta vBMC_{14\%}$ in CON ($R^2$=0.242, $P$=0.017 and $R^2$=0.482, $P$<0.001, respectively), but not in INT ($R^2$=0.158, $P$=0.067 and $R^2$=0.114, $P$=0.124, respectively).

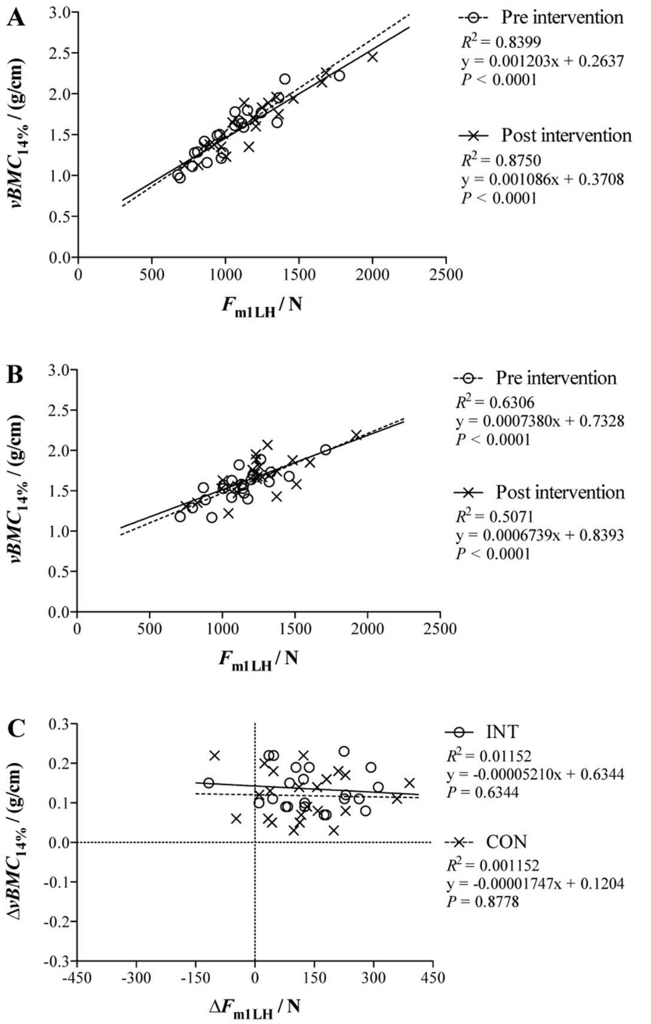

**Figure 2.** Relationship between bone mineral content at the 14%-site ($vBMC_{14\%}$) and maximum voluntary ground reaction force ($F_{\mathrm{m1LH}}$) pre and post intervention in 22 intervention children (**A**) and 23 control children (**B**), as well as the relationship between absolute changes in $vBMC_{14\%}$ ($\Delta vBMC_{14\%}$) and absolute changes in $F_{\mathrm{m1LH}}$ ($\Delta F_{\mathrm{m1LH}}$) from pre to post intervention (**C**).

## Discussion

This was the first study to assess the relationship between muscle and bone in 8- to 12-year-old boys and girls undergoing a 9-month supervised jumping exercise intervention, using a longitudinal design with multiple one-legged hopping as a measure for maximum voluntary muscle force ($F_{\mathrm{m1LH}}$) and $vBMC_{14\%}$ representing tibial bone strength. Whether the increase in $F_{\mathrm{m1LH}}$ nor changes in all pQCT-derived variables over the 9 months intervention period were significantly different between the intervention group (INT) and the control group (CON). In addition, this study showed that the relationship between $F_{m1LH}$ and $vBMC_{14\%}$ pre (INT: $R^2$=0.84, CON: $R^2$=0.63) and post intervention (INT: $R^2$=0.88, CON: $R^2$=0.51) was very strong. Critically, absolute changes in $F_{m1LH}$ ($\Delta F_{m1LH}$) were not related to absolute changes in $vBMC_{14\%}$ ($\Delta vBMC_{14\%}$), meaning that during childhood momentary occasions of simple growth might override training-induced increases in $F_{m1LH}$.

### *Relationship between $F_{m1LH}$ and $vBMC_{14\%}$*

Regarding the relationship between $F_{m1LH}$ and $vBMC_{14\%}$, the slopes and intercepts pre compared to post intervention were not significantly different in both INT and CON. According to the Mechanostat theory, bone reacts to challenges to its stability, and adaptations of bone strength and geometry can only follow but not precede the challenge[2]. By contrast, body mass, bone length and muscle force keep increasing during growth[28]. Thus, we expected the slopes in both INT and CON to decrease. However, our data did not show a decrease in the slopes from pre to post intervention, indicating that adaptations of bone strength and geometry in our study did not lag behind the momentary need. As a consequence, there is a strong and robust relationship between $F_{m1LH}$ and $vBMC_{14\%}$ at any time (*i.e.* in ‘static’ view).

By contrast, the slopes of the regression lines in INT compared to CON were significantly different in both pre and post intervention ($P$=0.010 and $P$=0.019, respectively). Therefore, CON exhibited less bone mass per unit $F_{m1LH}$, indicating that their bone strength was less adapted to the corresponding maximum voluntary muscle force. Moreover, the coefficient of determination ($R^2$) was much higher in INT compared to CON both pre ($R^2$=0.84 vs. $R^2$=0.63) and post intervention ($R^2$=0.88 vs. $R^2$=0.51). We think that the differences in $R^2$ between the two groups were due to the small standard deviation of $F_{m1LH}$ in CON (pre intervention: ±218.8 N, post intervention: ±250.7 N) compared to INT (pre intervention: ±264 N, post intervention: ±311.9 N), and therefore, values along the x-axis were less distributed. The resulting homogenous distribution of $F_{m1LH}$ in CON coincided with the findings that the standard deviations of height and body mass were also diminished.

A functional model of bone development, which is based on the Mechanostat theory and proposed by Schoenau[29], includes modulators such as hormones, nutrition as well as behavioral and environmental factors. For example, hormones and nutrition can influence the mechanical loads on growing bone by acting on longitudinal bone growth and muscular force. They also might alter the mechanostat set point, or the width of the tolerance zone around the set point, and they could modify many aspects of osteoblast and osteoclast action. However, hormones and nutrition cannot replace the guiding effect of mechanical strain on bone[2]. Interestingly, between the two groups, we found no differences in the pubertal status, physical activity, and vitamin D intake. The only difference was that CON had a higher calcium intake (not significant) at the beginning of the study, but this would rather be an argument if CON would have had a steeper regression line compared to INT. We rather think that the different geographical location of the recruited schools could be a reason for the steeper regression line in INT. Although all three towns were geographically located close to each other, INT schools appeared to be more rural with a larger catchment area. As a consequence, INT frequently rode to school by bicycle and/or walked long distances every day. In addition, INT consisted of numerous children living on a farm. Therefore, we assume that daily activities and associated loads were already higher in INT than CON, the latter living in a more urban area. Unfortunately, such basic differences in lifestyle could not be completely captured by our questionnaire for physical activity because we were asking for time spent in sports rather than daily activities *per se*. However, our findings are in line with previous work showing that lower bone mass values occur among urban compared to rural children[30].

### *Relationship between $\Delta F_{m1LH}$ and $\Delta vBMC_{14\%}$*

Based on the Mechanostat theory, which states that during growth muscular force drives bone development, we hypothesized that a strong correlation should exist between $\Delta F_{m1LH}$ and $\Delta vBMC_{14\%}$. Our results showed that there was no such correlation, neither for INT ($R^2$=0.012, $P$=0.634) nor CON ($R^2$=0.001, $P$=0.878). It is curious that the adaptations did not occur in proportion to each other since this means that children with identical increases in $F_{m1LH}$ adapted their $vBMC_{14\%}$ differently. On the other hand, we observed a significant relationship between $\Delta$*Height* and $\Delta vBMC_{14\%}$ as well as between $\Delta$*Body mass* and $\Delta vBMC_{14\%}$ in CON, and a tendency thereof in INT, meaning that during childhood momentary occasions of simple growth might override training-induced increases in $F_{m1LH}$. The different coefficients of variations (CV) for $F_{m1LH}$ and $vBMC_{14\%}$ might principally also explain why there was a lack of correlation between $\Delta F_{m1LH}$ and $\Delta vBMC_{14\%}$. From the data of Veilleux *et al.*[9] on repeated measurements of $F_{m1LH}$ in children, we thus calculated the test-retest reliability in terms of the “typical error” expressed as a coefficient of variation (CV)[31]. Accordingly, the CV was calculated as $100 \cdot (e^{SEM/100}-1)$, with SEM= standard error of measurement (standard deviation of the difference scores divided by $\sqrt{2}$). As a result, the CV of $F_{m1LH}$ was 5.8 and 5.0% for the right and left leg, respectively, representing the noise of a measurement separate from a systematic error. A threshold for deciding that in an individual a “real” change has occurred appears to be 1.5-2.0 times the CV[31], in the specific case of $F_{m1LH}$ 1.5-2.0 times 5.0-5.8%. Thus, when monitoring single individuals, changes in $F_{m1LH}$ should be ±11.6% for the detection of “real” changes. As previously assessed, the CV for $vBMC_{14\%}$ is 0.5%[10], and we assumed here that this value also holds true for the particular settings of this study (children, age, time period etc.). In this study, we observed real changes in $vBMC_{14\%}$ (>1%) for each child, while $\Delta F_{m1LH}$ was not above 11.6% in all cases. To test whether the lack of correlation could originate from the disparate CVs for $F_{m1LH}$ and $vBMC_{14\%}$, we thus refined our data set to include only children with $\Delta F_{m1LH}$>11.6% (2 times the CV for $F_{m1LH}$ for the left leg), and performed the regression analysis again. However, we found no correlation between $\Delta F_{\mathrm{m1LH}}$ and $\Delta vBMC_{14\%}$ (data not shown). It is thus unlikely that the lack of correlation between $\Delta F_{\mathrm{m1LH}}$ and $\Delta vBMC_{14\%}$ was simply due to methodological issues related to the disparate magnitude of the related CVs.

*Maximum voluntary ground reaction force*

The key task of Jumping Mechanography is to provide a simple, easy, and at the same time highly reliable and reproducible measurement method to objectively quantify key parameters of human movement[9]. We used multiple one-legged hopping (m1LH) to estimate maximum voluntary ground reaction force. Contrary to our hypothesis, INT did not display a significant higher increase in $F_{\mathrm{m1LH}}$ as compared with CON (+2.1% points, $P$=0.752). Nevertheless, because $F\mathrm{rel}_{\mathrm{m1LH}}$ increased in INT by 4.9% and in CON by 2.4%, and body mass increased in both groups equally (INT: +8.7%, CON: +8.7%), we suggest that the slightly higher increase in $F_{\mathrm{m1LH}}$ observed in INT was probably an adaptation to the jumping exercise. In accordance with earlier findings[9,10], $F\mathrm{rel}_{\mathrm{m1LH}}$ (irrespective of age and gender) corresponded to 3-3.5 times body weight in both INT and CON both pre and post intervention. This value is higher than the generated force among all other standardized jumping maneuvers[9].

*Peripheral quantitative computed tomography (pQCT)*

Compared with previous school-based interventions, this study is unique in that we assessed bone strength and geometry at the 4, 14, 38, and 66% of tibia length[21]. Despite of no statistical significance in the improvements between INT and CON for the single variables, the overall results (*i.e.* not each variable *per se*) may be well of relevance, in that the jumping exercise may have had some additional effect (even though the effect was very small). We also would like to point out that only because a $P$-value is >0.05 (non-significant), this does not mean that the null hypothesis (no effect in the population) is true. Thus, all that a non-significant result can tell is that the effect is not big enough to be anything other than a chance finding -it doesn't certainly tell that the effect is zero. As Cohen[32] pointed out, a non-significant result should never be interpreted (despite the fact that it often is) as "no difference between means" or "no relationship between variables". Similarly, Stapleton *et al.*[33] elaborated on the notion that statistical significance makes no reference to the clinical or functional value of an intervention. On the basis of our overall (*i.e.* over all measured variables) data we feel that the equation "non-significant= non-relevant" might be too simplistic. Therefore, and because all pQCT-measures changed in favor of INT, we have discussed some non-significant results which are, however, in line with known biomechanical regularities.

Because the ratio between bone mass and lean body mass in boys and girls increases equally until the age of 12 years[6], and differences between boys and girls in the ratio between bone mass and muscle cross-sectional area as a function of the Tanner stages of puberty become apparent from stage 4 onward[34], we did not analyze bone measures for boys and girls separately. Pre intervention, all our participants were 8 to 12 years old and had Tanner stage 3 or less.

As previously observed by others[21,35], we also found the absolute values for *vBMC* and *SSIpol* (as an indicator of the rigidity in bending and torsion) to be minimal at the 14%-site in both INT and CON both pre and post intervention. As a consequence, it has been suggested that the mechanical competence of this bone site is mainly adapted to uniaxial compression[21]. More proximally (from the 14%-site up to the 66%-site), the absolute values for *vBMC* and *SSIpol* increased, indicating a progressive adaptation of the bone to additional stresses caused by two independent compression axes through the two joint surfaces at the knee. Thus, because the human tibia has a complex internal structure, intervention-induced changes observed in the different bone indicators measured by pQCT were site-specific rather than homogenous throughout the tibia.

At the 4%-site, where trabecular bone predominates, the strongest adaptations in INT relative to CON were found for $vBMC_{4\%}$ (+2.3% points) and $vBMD.tb_{4\%}$ (+1.9% points). These results are in line with previous findings that in prepubertal gymnasts, as compared to controls, differences in bone density rather than geometry were increased at trabecular sites[36]. Moreover, *vBMC* and Bone Strength Index for compression (product of total area and squared *vBMD*) at the 4%-site predicted 75% and 85% of the variance in failure load, respectively[37], and, in a school-based physical activity intervention study, prebubertal intervention boys tended to have a greater change in *vBMD* at the 8%-site than prebubertal control boys[20].

More proximally, the strongest differences in bone adaptations between INT and CON were found for $vBMC_{14\%}$ (+9.2% vs. +7.5%), $Ar.bone.ct_{14\%}$ (+8.5% vs. 5.7%), $SSIpol_{14\%}$ (+14.7% vs. 12.6%), $Ar.bone.ct_{38\%}$ (+8.5% vs. +6.9%) and $SSIpol_{38\%}$ (+12.6% vs. +10.4%). The highest change in *SSIpol* at the 14%-site was paralleled by the highest increase in $Peri_{14\%}$, while moving towards the knee, the gain in periosteal expansion decreased. These findings are consistent with earlier studies, which found that periosteal expansion with skeletal loading is greater at the distal versus proximal sites[38], and, a greater periosteal circumference was found in intervention children compared to controls at the 20%-site[19]. In our study, the percent change of $Endo_{14\%}$ was equal for both INT and CON, while the increase for *Endo* at the 38- and 66%-site was higher for CON. Since INT had slightly higher adaptations in Peri than CON, cortical thickness for INT increased more than for CON at the 14-, 38-, and 66%-site. Nevertheless, neither the change in *Peri* nor the change in *Endo* was significantly different between groups at any measured site. Taken together, at the distal tibia the highest adaptations were found for the amount of bone, and moving more proximally, children predominantly changed the bone's geometry, with both adaptations being more pronounced in INT relative to CON.

The values for *vBMD* at the 14-, 38-, and 66%-site remained constant in both INT and CON. These findings are comparable to the results of a pQCT study investigating side-to-side differences in male tennis players. The additional bone mineral in the dominant arm was mainly used for increasing bone size, not *vBMD*[39]. Moreover, it has been shown that *vBMD* (as a material characteristic) of the distal radius is an age-independent variable which does not change significantly with increasing muscle force in 14 healthy children[3]. The slightly higher increases in bone mass and geometry at the distal part of the tibia in INT relative to CON (even though the differences were not significant) may suggest, that our 9-month jumping exercise has the potential to positively adapt tibial bone mass and geometry.

For CON, we found significant higher increases from intermediate to post intervention (*i.e.* in spring/summer) than from pre to intermediate intervention (*i.e.* in winter) in *vBMC* at the 4-, 14-, and 38%-site, as well as by trend at the 66%-site. By contrast, we did not observe 'seasonal' differences in the adaptation of *vBMC* in INT at the 4- and 14%-site, while the percent changes from pre to intermediate intervention were significantly lower compared to the percent changes from intermediate to post intervention at the 38- and 66%-site. As assumed by others[40,41], seasonal variations in vitamin D metabolites (*e.g.* due to the limited sun exposure in winter) may influence seasonal bone mass/geometry. Therefore, a potential vitamin D deficiency in winter might have affected (*i.e.* limited) bone adaptations in the first half of the study period. However, in this study, we did not find neither direct evidence for seasonal variation in vitamin D intakes nor potential correlations between vitamin D intakes and bone mass/geometry.

### *Exercise intervention*

In comparison with Weeks *et al.*[25], we did not find any significant differences in the adaptation of bone strength and geometry between INT and CON. It seems that the applied jumping exercise did not generate an adequate stimulus to additionally affect bone strength and geometry. Based on the mechanostat theory, intrinsic muscle force leads to bone deformation (*i.e.* bone strain). When these bone strains exceed a certain threshold (~2000 μStrain), bone adapts its bone mass and geometry. Although, *in vivo* strain measurements of specific activities are limited in humans up to date[42], we assumed that the jumping and sprint activities in our study would cause strain magnitudes that are adequate to exceed the bone modeling threshold. However, the mechanostat theory makes no assumption about an optimal strain frequency, and it is not yet possible to describe in detail an exercise program for children and adolescents that will optimize bone strength, because quantitative dose-response studies are lacking[43]. Following this line of reasoning, it remains unclear whether to perform jumping exercise two times a week for 9 months was adequate to beneficially adapt bone strength and geometry in children.

Another reason why INT compared to CON did not benefit from the additionally applied loads could be that CON completed regular physical education in accordance to the official curriculum during the time in which INT performed a progressive, high-impact 10-min jumping exercise, which always took place at the beginning of the regularly scheduled physical education class. In particular, CON usually started physical education classes by playing tag and/or related activities thereof. Many of these activities involved walking or running, which cause lower GRFs than the GRFs achieved during our jumping exercise protocol. In addition, multidirectional activities, such as those implemented in our jumping exercise protocol, produce higher strains and strain rates (measured at the mid-diaphysis of the tibia) than walking and running[44]. However, although INT certainly completed higher impact exercises relative to CON, we cannot preclude an osteogenic effect of the activities performed by CON during the initial phase of their physical education class.

### *Limitations*

We do acknowledge some limitations with the current investigation. (1) Due to the small sample size, it is likely that this study was underpowered[31]. Unfortunately, of 170 children only 60 boys and girls received parental consent to participate. We suggest that most parents were afraid of the (low) radiation exposure of the pQCT measurements, although they were informed about the measurement in detail, or the effort to complete all the questionnaires (in particular the 4 days food record three times per year) was too demanding for them. Thus, due to the limited number of participants, the generalization of our findings is limited. (2) During childhood, the tibia is influenced by longitudinal growth and is rebuilding its structure. As a result, it is not possible to determine the same exact location along the length of the tibia over time. However, after we determined the length of the tibia prior to each measurement, we used a fixed anatomical landmark to locate the same relative region along the tibia length during intermediate and post measurements. (3) To assess physical activity, we calculated a physical activity score as the sum of time spent on the particular activity (collected by questionnaire) multiplied by the estimated mechanical component. This activity score is rather comparative than an exact measure of the loads children were exposed to during their leisure time. (4) Four days food record protocols varied considerably in quality and quantity from child to child. Therefore, we calculated an individual mean value over all three measurement points in time in an attempt to describe the daily calcium and vitamin D intake more properly.

### *Conclusion*

In conclusion, there was no significant difference neither in the increase in $F_{\mathrm{m1LH}}$, nor in the adaptations in bone strength and geometry measured by pQCT at the 4-, 14-, 38-, and 66%-site of tibia length during the 9-month exercise intervention between INT and CON. However, $F_{\mathrm{m1LH}}$ was strongly correlated with $vBMC_{14\%}$ in both INT and CON both pre and post intervention. This leads to the assumption that the concurrent assessment of pQCT-derived bone strength (*i.e.* $vBMC_{14\%}$) and maximum voluntary muscle force during m1LH showed to be well suited to quantify the relationship between muscle and bone (*i.e.* the muscle-bone unit). Nevertheless, unlike proposed by the Mechanostat theory, the change in $F_{\mathrm{m1LH}}$ was not related to the change in $vBMC_{14\%}$ for the 9-month intervention period, which may indicate that growth occasions may simply outweigh any exercise-induced gains.

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