

# Effects of Resistance Training on Isometric Force and Muscle Thickness in Prepubertal and Pubertal Boys: A Randomized Controlled Trial

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## Abstract

Komm, YN, Held, S, Gavanda, S, Comfort, P, Faigenbaum, AD, Geisler, S, and Augste, C. Effects of resistance training on isometric force and muscle thickness in prepubertal and pubertal boys: a randomized controlled trial. *J Strength Cond Res* XX(X): 000–000, 2026—While increases in strength in youth are largely attributed to neural adaptations, evidence regarding hypertrophic adaptations in prepubertal youth remains inconsistent. This study compared the effects of resistance training on hypertrophy and strength between prepubertal and pubertal adolescents. Sixty-eight male subjects were classified as prepubertal ( $11.58 \pm 1.04$  years) or pubertal ( $14.28 \pm 0.88$  years) using maturity offset estimates and randomized into 4 groups: prepubertal resistance training ( $n = 19$ ), prepubertal active control ( $n = 20$ ), pubertal resistance training ( $n = 14$ ), and pubertal active control ( $n = 15$ ). The 9-week intervention consisted of 2 weekly sessions of lower-body resistance training, while the active control groups continued their regular soccer training. Strength was assessed using the isometric mid-thigh pull, and hypertrophy was assessed using muscle thickness. Data were analyzed using linear mixed-effects models. Statistical significance was set at  $p < 0.05$ . No significant Time  $\times$  Intervention interactions were observed for rectus femoris and vastus intermedius ( $p = 0.295$ ), and for vastus lateralis ( $p = 0.711$ ). A significant Time  $\times$  Intervention interaction ( $p = 0.042$ ) was found for peak force, indicating superior strength improvements in the training groups. No significant Time  $\times$  Maturity  $\times$  Intervention interactions were detected for absolute strength ( $p = 0.289$ ), relative strength ( $p = 0.656$ ), rectus femoris and vastus intermedius thickness ( $p = 0.451$ ), or vastus lateralis thickness ( $p = 0.731$ ), although these analyses had limited statistical power. These findings indicate that the resistance training protocol in this study increased isometric mid-thigh pull force in prepubertal and pubertal adolescent boys.

**Key Words:** youth, pediatric athletes, hypertrophy, maturity, resistance training adaptations, isometric mid-thigh pull

## Introduction

Resistance training represents a safe and effective training modality for children and adolescents, with the potential to sustainably improve psychological, social, health-related, and performance-related outcomes (8,22,23). In general, when appropriately prescribed and progressively applied, resistance training can lead to substantial increases in muscular strength and muscle size (14,49). From a long-term health perspective, enhanced strength capacities may contribute to the development of a *strength reserve*, which can act as an effective buffer against neuromuscular decline in later stages of life (21,23). From a performance perspective, maximal strength serves as a foundational quality underpinning numerous sport motor abilities including power, rate of force development, jumping, sprinting, change of direction, and injury risk reduction (4,11,32,38,39,58). Although the task-specific nature of athletic performance may limit direct transfer, higher levels of strength are consistently associated with enhanced performance outcomes (4,11,33,58). This is likely due

to the fact that force relative to the mass being accelerated determines acceleration. Greater muscle mass further supports these benefits by increasing the physiological cross-sectional area of skeletal muscle, thereby contributing to force-producing capacity, while also serving as an important strategy for the prevention of sarcopenia and dynapenia (26,43).

While the effectiveness of resistance training for improving strength and muscle mass is well established in adults (14,49), the relative contributions of neural and morphological adaptations in children and adolescents remain less well understood. Puberty represents a critical developmental period characterized by marked hormonal changes, including increases in circulating testosterone concentrations, which are associated with substantial gains in muscle mass and lean body tissue (47). However, accumulating evidence indicates that the role of systemic anabolic hormones in mediating training-induced adaptations may be more limited than traditionally assumed (61). Transient elevations in anabolic hormones appear to contribute only minimally to the hypertrophic response to resistance training (61). This perspective is further supported by findings demonstrating comparable relative increases in muscle hypertrophy in men and women despite substantial differences in basal testosterone concentrations (51). Taken together, these observations suggest that

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metabolic and hormonal factors may play an important role in nontraining-related muscle growth during puberty, whereas their contribution as a driver of exercise-induced hypertrophy appears comparatively modest.

Consistent with this perspective, evidence indicates that puberty does not appear to be a decisive factor in the development of maximal strength, as substantial strength increases have been reported in children largely independent of hormonal status (5). Before puberty, improvements in strength are therefore assumed to be predominantly mediated by neural adaptations, including enhanced motor unit recruitment, synchronization, firing frequency, and intermuscular coordination (39). By contrast, training-induced morphological adaptations, such as increases in muscle cross-sectional area, are thought to become more pronounced with the onset of puberty and the accompanying hormonal changes (25,28,39,42,48). Traditional perspectives have therefore assumed that meaningful training-induced morphological adaptations are unlikely to occur before puberty. In contrast, contemporary mechanistic evidence indicates that mechanical tension represents the primary stimulus for muscle hypertrophy, whereas hormonal and metabolic fluctuations play only a minor role in mediating training-induced adaptations (61,62). Nevertheless, this remains an area of ongoing debate. Metabolic stress and training-induced muscle damage continue to be discussed as potential contributors to hypertrophic adaptation (3). It has been proposed that the accumulation of metabolites may stimulate the release of anabolic hormones such as testosterone, human growth hormone, and insulin-like growth factor 1, thereby potentially contributing to training-induced hypertrophy (3).

To date, few controlled studies have directly compared training-induced hypertrophy and strength adaptations between prepubertal and pubertal youth under standardized conditions. Given this discrepancy between longstanding assumptions and emerging mechanistic evidence, it remains unclear whether the capacity for muscle hypertrophy and strength development truly differs between prepubertal and pubertal individuals. More specifically, it remains unclear whether a resistance training program leads to differential relative adaptations in maximal isometric strength and muscle thickness in biologically distinct male youth athletes. Therefore, the aim of this study was to examine whether training-induced adaptations in maximal muscular isometric strength and muscle morphology differ between prepubertal and pubertal subjects following a structured resistance training intervention. Based on current mechanistic evidence (61,62), it was hypothesized that both groups would exhibit comparable relative improvements in maximal isometric strength and muscle thickness and that biological maturation would not moderate the training response. Furthermore, it was hypothesized that both training groups would demonstrate greater improvements in maximal isometric strength and muscle thickness than their respective control groups.

## Methods

### Experimental Approach to the Problem

This study employed a 2 (maturity: prepubertal vs pubertal)  $\times$  2 (group: resistance training vs control) randomized controlled design with repeated measures. The intervention was designed as a 9-week intervention trial consisting of two 4-week mesocycles separated by a 1-week deload period. This study was conducted among healthy, physically active male youth soccer players. These

athletes were characterized by a high intrinsic motivation for sport participation and possessed sufficient coordinative and physical prerequisites for resistance training. In this study, maturation status served as the independent variable, while muscle thickness and isometric mid-thigh pull force represented the dependent variables. Although the subjects had no prior experience with systematic resistance training, they were regularly exposed to training stimuli for the lower-limb musculature through their habitual soccer practice.

Before group allocation, maturation status was determined based on peak height velocity (PHV) (45). Based on this assessment, subjects were classified as either prepubertal or pubertal. Following maturation stratification, subjects within each maturity category were randomly assigned to either the resistance training group or the control group using a computer-generated randomization procedure implemented with Research Randomizer (60). This randomization approach resulted in 4 groups: a prepubertal resistance training group (PREPUB RT), a prepubertal control group (PREPUB CON), a pubertal resistance training group (PUB RT), and a pubertal control group (PUB CON). Thus, this study comprised a 4-group design with separate resistance training and control conditions within each maturity category. Bonferroni-adjusted baseline comparisons did not indicate significant differences between RT and CON within either maturity group for any outcome measure prior to the intervention (all  $p \geq 0.218$ ). Furthermore, according to Cohen's convention (9), the observed baseline differences were trivial to small (all  $|\text{d}| \leq 0.47$ ). This study design allows for differentiation between training-induced adaptations and maturation-related development. Testing was carried out prestudy and poststudy. Outcomes included muscle thickness of the m. rectus femoris, m. vastus intermedius, and m. vastus lateralis assessed via ultrasound imaging, as well as peak force and relative peak force assessed using the isometric mid-thigh pull (IMTP).

The control groups functioned as active control groups, continuing their regular soccer training, while the training groups performed the resistance training program during the intervention period. The resistance training program was performed twice weekly over the entire study period.

Subjects were instructed not to alter their habitual dietary intake or sleep behavior to minimize potential confounding variables. All testing sessions were conducted between late morning and early afternoon.

### Subjects

This study was designed to involve physically active children and adolescents with a basic level of intrinsic motivation, an understanding of training processes, and sufficient movement experience to serve as a foundation for progressive resistance training. Therefore, male sub-elite youth soccer players 11–16 years of age were recruited from the youth development program of a German Bundesliga club. A priori sample size estimations were conducted using G\*Power (24) to approximate the planned mixed-model analysis of differential pre-to-post changes in muscle thickness between groups. Based on an expected medium effect size (Cohen's  $f = 0.25$ ),  $\alpha \leq 0.05$  and a desired statistical power of  $\geq 0.90$ , a minimum total sample size of 64 subjects was required. Although a statistical power of 80% is commonly applied as a conventional minimum threshold, according to Giner-Sorolla et al. (27), a higher statistical power of 90% was selected in this study to further strengthen the

robustness of the study design. As a certain dropout rate was anticipated, 73 subjects were recruited. Subjects were eligible for inclusion if they met the following criteria: (a) younger than 18 years, (b) free from medical conditions or disorders, and (c) regular participation in organized sport with no prior resistance training experience. However, although the subjects had little to no prior resistance training experience, they were sub-elite youth soccer players regularly exposed to high-intensity neuromuscular stimuli such as sprinting, jumping, and change-of-direction actions. Therefore, they cannot be considered completely untrained from a neuromuscular perspective. The soccer-related training exposure within the study setting was standardized as far as possible. All subjects attended the training facility twice per week throughout the intervention period. During these sessions, the resistance training groups completed the structured resistance training protocol, while the control groups simultaneously participated in their regular soccer training. This parallel structure ensured similar session frequency and duration between the training and control groups during the intervention. Beyond the supervised sessions, all subjects continued their regular club training of approximately 2–3 sessions per week. As all subjects were recruited from the same competitive level, systematic differences in external training load between groups were considered unlikely.

Subjects were instructed not to engage in any additional resistance training for the duration of this study. Based on their maturation status assessed at the pretest, subjects were first classified as prepubertal or pubertal. Subsequently, subjects within each maturity category were randomly assigned to either a training group, which completed the 9-week resistance training intervention, or a control group, which served as an active control group and continued their regular soccer training.

A minimum adherence threshold of 80% ( $\geq 13$  of 16 prescribed training sessions) was required for inclusion in the final analyses. Accordingly, 68 subjects were retained (Figure 1). Subject dropout was due to non-study-related injuries ( $n = 3$ ), relocation ( $n = 1$ ), and personal reasons ( $n = 1$ ). All subjects and their parents or legal guardians were fully informed about the testing procedures and the training intervention. Parents or legal guardians provided written parental permission, and subjects provided verbal and written assent before participation. The study protocol was approved by the ethics committee of the first author's university (AZ: Komm-22-09-2025). All 68 subjects were included in statistical analyses considering muscle thickness. However, for isometric mid-thigh pull peak force and relative peak force analyses, 8 subjects were excluded because they were unable to achieve at least 2 valid isometric mid-thigh pull trials. Invalid trials were due to countermovement prior to force onset, failure to maintain a stable pulling position, or force-time curves showing a clear peak force at the end of the pull. Despite repeated verbal feedback, these predefined technical criteria were not met. Exclusion was therefore necessary to ensure the validity and reliability of the force measurements. For demographic and anthropometric characteristics of the subjects, see sections "Anthropometry," "Age and Maturity offset," and Table 1.

## Procedures

The intervention targeted the lower-body musculature because of its relevance to soccer performance. As soccer players are regularly exposed to lower-limb loading, the applied stimulus was

additional but not entirely unfamiliar, reducing the influence of pronounced initial adaptations typically observed in untrained individuals. Machine-based, single-joint exercises were selected as they are easy to learn, allow for progressive overload, and enhance standardization across subjects, although typical youth resistance training programs commonly emphasize multijoint exercises.

The resistance training program included both quadriceps and antagonistic hamstring exercises to ensure balanced development of the knee extensor and flexor musculature. Hamstring training consisted of the seated leg curl and a hamstring-dominant back extension variation. For the quadriceps, the protocol consisted of bilateral leg extensions performed on 2 different leg extension machines. Moreover, owing to its single-joint nature, the exercise ensures that knee extension is produced exclusively by the muscle (m.) quadriceps femoris, without assistance from additional muscle groups. Previous research has demonstrated that the leg extension exercise is effective for inducing strength and hypertrophy, especially of the m. rectus femoris (35). Two different leg extension machines were used because differences in resistance profiles and hip joint angles were expected to provide a more comprehensive hypertrophic stimulus of the quadriceps musculature (37) and to enhance strength adaptations, given the joint angle-specific nature of force production (52). In general, the resistance training emphasized individualized load progression and technique-focused supervision, supplemented by age-appropriate challenges and games to promote engagement and fun.

The training intervention lasted 9 weeks and was structured into two 4-week mesocycles, separated by a 1-week deload period. Subjects trained twice per week. All sets were performed to volitional fatigue (13)—defined as the inability to complete an additional repetition while maintaining correct exercise technique—as intensity of effort is considered a key driver of strength and morphological adaptations, and thus essential for ensuring a comparable training stimulus across prepubertal and pubertal subjects. Nevertheless, emphasis was placed on movement quality, and sets were terminated immediately upon technical failure. Furthermore, the use of machine-based exercises allowed for safe execution, while continuous supervision allowed for precise monitoring of exercise technique throughout. Training volume progressed from 4 to 6 sets per exercise during the first mesocycle and from 5 to 7 sets per exercise during the second mesocycle (Table 2). This progression was applied uniformly across all subjects to ensure a volume-equated training program. In contrast, progression of the external load was individualized, given that the magnitude of external load and the repetition range appear to play a limited role in stimulating muscle hypertrophy (50). Training volume and training frequency were aligned with the recommendations of the most recent meta-regression on strength and hypertrophy training in adults (49). Although this progression exceeds typical recommendations for youth resistance training, several considerations justified this approach. Muscle thickness was a primary outcome of interest, and training volume is considered a key mediator of hypertrophic adaptations (12,49). Therefore, higher volume was deemed necessary to provide a sufficient stimulus within the given study duration and twice-weekly training frequency. Moreover, although subjects had little to no prior resistance training experience, their background as sub-elite youth soccer players may be considered indicative of a greater physical capacity to tolerate higher training volumes. Ultimately, given that the active control group was regularly exposed to lower-limb loading through regular soccer

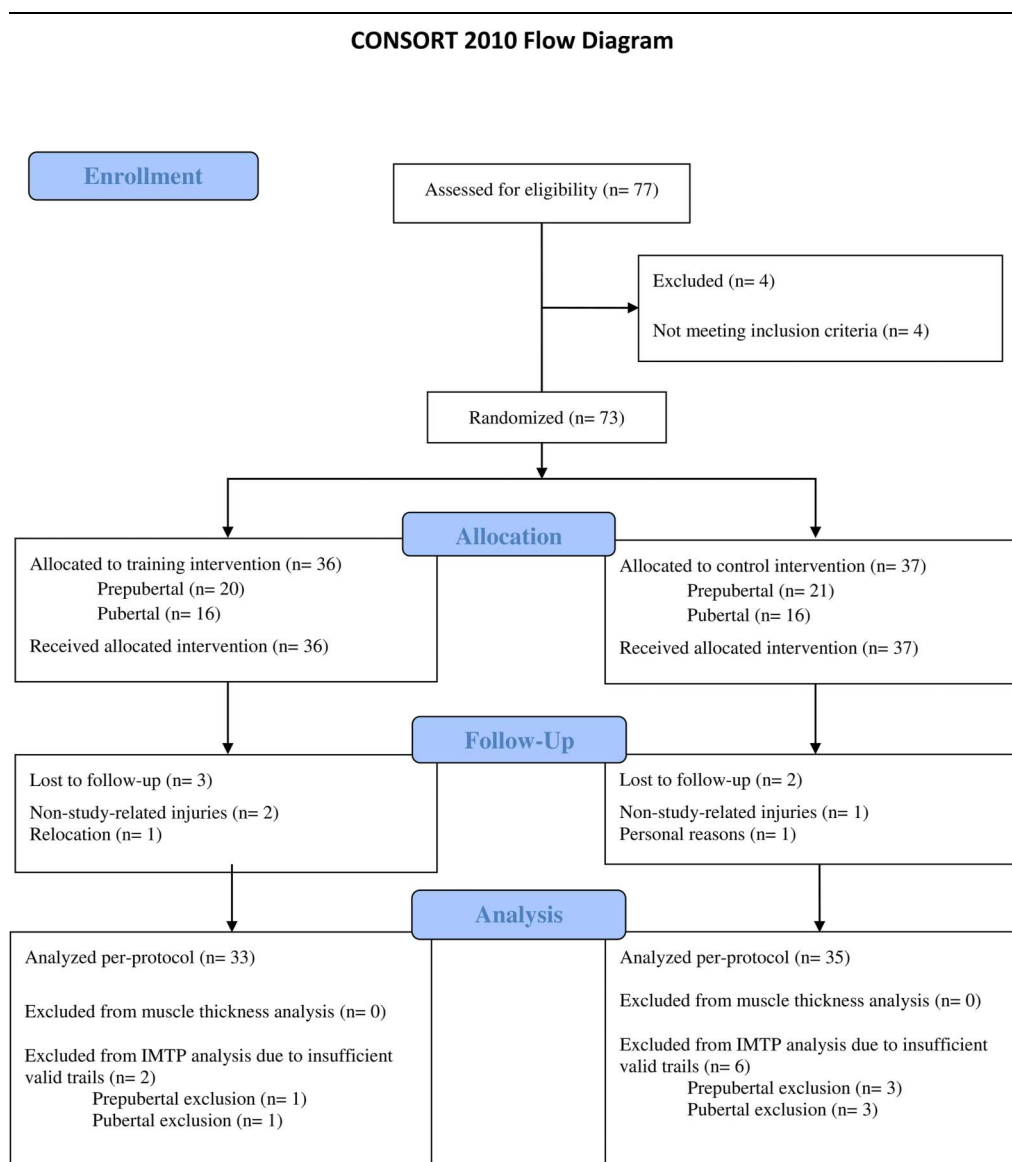


**Figure 1.** CONSORT flow diagram about the enrollment, allocation, follow-up, and analyses of this study.

training, a sufficiently higher training volume was expected to be necessary to elicit muscular and strength adaptations.

Furthermore, training programming was based on a volume progression approach, as progressively increasing training volume in accordance with the dose–response relationship appears more favorable for promoting morphological adaptations than fixed-volume prescriptions (18,19). Movement cadence was

characterized by an approximately 1-second concentric phase and a controlled 2-second eccentric phase, with the concentric phase inevitably slowing as the set progressed toward failure. Furthermore, inter-set rest periods lasted approximately 90 seconds. These parameters were implemented to standardize the training protocol across subjects. Nevertheless, it should be noted that both movement cadence (20) and rest interval duration (55)

**Table 1**  
**Demographic and anthropometric group characteristics for included subjects.\*;†**

|                     | PREPUB RT (n = 19)                          | PREPUB CON (n = 20)                         | PUB RT (n = 14)                          | PUB CON (n = 15)                         |
|---------------------|---------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------------|
| Chronologic age (y) | 11.6 ± 1.1 [10.2–14.2]                      | 11.6 ± 1.0 [10.2–13.5]                      | 14.2 ± 0.6 [13.3–15.7]                   | 14.4 ± 1.1 [12.5–16.0]                   |
| Age PHV (y)         | 13.8 ± 0.6                                  | 13.8 ± 0.6                                  | 14.1 ± 0.7                               | 14.0 ± 0.6                               |
| Distance PHV (y)    | −2.1 ± 0.8 [−3.3; −1.0]<br>IQR [−2.8; −1.5] | −2.3 ± 0.6 [−3.2; −1.2]<br>IQR [−2.9; −1.7] | 1.1 ± 0.8 [−0.9; 2.0]<br>IQR [−0.6; 0.6] | 0.4 ± 1.1 [−0.9; 2.9]<br>IQR [−0.6; 0.9] |
| Height (cm)         | 147.9 ± 5.4                                 | 147.8 ± 6.6                                 | 164.9 ± 8.0                              | 168.1 ± 6.8                              |
| Body mass (kg)      | 38.6 ± 6.6                                  | 38.6 ± 4.2                                  | 51.4 ± 9.4                               | 54.7 ± 8.8                               |

\*PREPUB = prepubertal; PUB = pubertal; RT = resistance training group; CON = control group; PHV = peak height velocity.

†Values are displayed as a mean (SD), range (for chronologic age), and min/max and interquartile range (IQR; Q25/Q75) (for distance PHV).

**Table 2****Resistance training exercises during the intervention period including sets, repetitions, and rest periods.\***

|                        | Week 1         |                | Week 2         |                | Week 3         |                | Week 4         |                |
|------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Agonist training       | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     |
|                        | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           |
|                        | 4              | 4              | 5              | 5              | 5              | 5              | 6              | 6              |
|                        | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           |
|                        | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           |
|                        | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest |
|                        | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           |
| Antagonist training    | Seated lc      | Hypext.        | Seated lc      | Hypext.        | Seated lc      | Hypext.        | Seated lc      | Hypext.        |
|                        | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           |
|                        | 3              | 3              | 3              | 3              | 4              | 4              | 4              | 4              |
|                        | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           |
|                        | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           |
|                        | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest |
|                        | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           |
| <b>Deload (week 5)</b> |                |                |                |                |                |                |                |                |
|                        | Week 6         |                | Week 7         |                | Week 8         |                | Week 9         |                |
| Agonist training       | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     | Leg ext. A     | Leg ext. B     |
|                        | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           |
|                        | 5              | 5              | 5              | 5              | 6              | 6              | 7              | 7              |
|                        | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           |
|                        | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           |
|                        | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest |
|                        | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           |
| Antagonist training    | Seated lc      | Hypext.        | Seated lc      | Hypext.        | Seated lc      | Hypext.        | Seated lc      | Hypext.        |
|                        | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           | Sets           |
|                        | 4              | 4              | 4              | 4              | 5              | 5              | 5              | 5              |
|                        | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           | Reps           |
|                        | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           | 8–12           |
|                        | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest | Inter-set rest |
|                        | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           | 90 s           |

\*Leg ext. A = leg extension Gym80; Leg ext. B = leg extension nautilus; Hypext. = hyperextension; Seated lc = seated leg curl.

appear to play a relatively subordinate role in the context of muscular hypertrophy.

Initial training loads were individually determined through a 10-repetition-maximum (10RM) testing procedure, during which the load was progressively adjusted until subjects could complete 10 repetitions with proper technique, with adequate rest periods between attempts. This load was then used as the starting weight for the intervention. Thereafter, the external load was increased in the subsequent training session whenever subjects successfully completed more than 12 repetitions at a given load.

Before each training session, subjects completed a standardized warm-up. This consisted of a general aerobic component on a cycle ergometer, followed by a specific warm-up with lighter loads performed immediately before each exercise on its respective machine. Each training session, lasting between 25 and 40 minutes, was closely supervised by the research team. Proper exercise technique was ensured through continuous verbal instruction and feedback, as well as manual guidance to standardize range of motion and technique throughout each repetition. Sets were terminated immediately upon the first sign of technical breakdown, ensuring that subjects trained close to volitional fatigue while maintaining movement quality at all times.

**Measurement.** Anthropometry. Anthropometric assessments included the measurement of standing height, sitting height, and body mass (kg). To ensure measurement reliability, 3 trials were performed for each variable. Standing and sitting height were assessed using a Seca Alpha stadiometer (Seca, Hamburg,

Germany) and recorded to the nearest 0.1 cm. Body mass was measured using a calibrated electronic scale (Beurer, Ulm, Germany) and likewise assessed in 3 repeated measurements.

**Age and Maturity Offset.** Chronological age was calculated precisely for each subject by subtracting their date of birth from the date of assessment. To determine maturation status, a peak height velocity prediction equation was applied (45). This equation uses anthropometric measurements, including standing height, seated height, and body mass, together with chronological age, to estimate the age at which each subject will reach, or has reached, their maximum growth rate. For each subject, the number of years from PHV was calculated by subtracting the estimated age at peak height velocity from their actual chronological age (years and months). Based on their years from PHV, subjects were classified as either prepubertal ( $n = 39$ ) when the PHV offset was at least 1.0 years ahead (PHV offset  $\leq -1.0$  years) or pubertal ( $n = 29$ ) when the PHV offset was less than 1.0 years ahead or had already passed (PHV offset  $> -1.0$  years). The distance from their peak height velocity, therefore, represents the value on which the classification into prepubertal and pubertal is based and is a commonly used method in studies of children and adolescents (40,46). The group characteristics are presented in Table 1.

**Muscle Thickness.** The dependent variable, hypertrophy, was operationalized as muscle thickness. Muscle thickness was assessed using B-mode ultrasound (Mindray DP-50, Mindray Medical International Ltd., Shenzhen, China) with an 8.5-MHz linear probe (Mindray 75L53 EA, Mindray Medical International Ltd). Ultrasound imaging represents a valid method

for assessing muscle hypertrophy when compared with the gold standard of magnetic resonance imaging (41). All ultrasound measurements were conducted by a single researcher who was trained in musculoskeletal ultrasound imaging and blinded to subjects' group allocation.

For the m. rectus femoris and m. vastus intermedius (assessed as a combined measure), subjects lay supine with the legs fully extended and measurements were taken on the right leg at 50% of the distance between the anterior inferior iliac spine and the proximal border of the patella. The thickness of m. vastus lateralis was assessed with subjects lying on their left side, with measurements obtained at 50% of the distance between the most prominent point of the greater trochanter and the lateral condyle of the tibia. The right side of the body was chosen for all muscle thickness measurements, a standard and widely accepted practice in hypertrophy research (53). Owing to the smaller muscle size in children and adolescents, reliably separating individual muscles using ultrasound is more difficult compared with adults. In addition, distinguishing between rectus femoris and vastus intermedius can be challenging because the fascial structures separating both muscles do not always follow a clear linear course, whereas the femur provides a more reliable anatomical reference point. Therefore, rectus femoris and vastus intermedius were assessed as a combined anterior quadriceps muscle thickness measure to improve measurement reliability. By contrast, vastus lateralis was measured separately to avoid including the vastus intermedius region twice in the analyses. Furthermore, this approach has been used in studies involving children and adolescents (44,63) and in adult studies assessing anterior quadriceps muscle thickness (54).

Muscle thickness of the m. rectus femoris and m. vastus intermedius was defined as the distance from the subcutaneous fat-muscle interface to the femur, whereas m. vastus lateralis thickness was defined as the distance from the subcutaneous fat-muscle interface to the fascial boundary separating the m. vastus lateralis from the m. vastus intermedius. A water-soluble gel was applied, and the ultrasound transducer was positioned perpendicular to the longitudinal axis of the thigh, with care taken to avoid compression of the underlying tissue. Three images were obtained for each muscle, and the mean of the 3 measurements was used for further evaluation. Post-intervention ultrasound assessments were conducted 120 hours after the final training session to further minimize potential confounding effects associated with exercise-induced muscle swelling and edema (1). Previous studies have reported excellent reliability of ultrasound-based muscle thickness measurements in children and adolescents, with minimal measurement error (<1.0 mm) and low coefficients of variation (<5%) (44,59).

**Isometric Mid-Thigh Pull.** The other dependent variable, muscular strength, was operationalized as peak force and relative peak force in the IMTP. The IMTP is a valid and standardized test to assess the isometric strength of the lower-body musculature (10). The evaluation of both relative and absolute IMTP peak force is particularly relevant in youth sports, since biological maturation and body weight need to be considered to more accurately contextualize and interpret outcomes based on absolute measures (11,46). The IMTP is a reliable and safe method for assessing isometric strength in adult and youth populations (6,15–17). It involves an explosive vertical pull on a fixed barbell from a standardized slight squat posture replicating the second pull phase of a clean.

Isometric mid-thigh pull testing was conducted before and after the training intervention using dual force platforms

(ForceDecks, VALD Performance, Brisbane, Queensland, Australia) with a sampling frequency of 500 Hz. Although higher sampling frequencies have sometimes been proposed, 500 Hz has been shown to be sufficient for the accurate assessment of IMTP peak force and relative peak force, with maximal force reliability remaining largely unaffected (6,10). Force data were analyzed using the unfiltered force signal provided by the ForceDecks system. Isometric mid-thigh pull peak force was defined as the maximal gross vertical force recorded during the pull (46). Relative IMTP peak force was calculated by normalizing gross peak force to body mass ( $\text{N} \cdot \text{kg}^{-1}$ ). Prior to both pre- and posttesting, subjects were instructed to refrain from any strenuous physical activity for at least 48 hours to minimize the potential influence of fatigue.

Each testing session began with a 5-minute general warm-up on a cycle ergometer, followed by standardized instructions and familiarization. Subjects then completed a specific warm-up, consisting of IMTP pulls at approximately 50, 75, and 90% of perceived maximal effort. Subsequently, subjects performed 3 maximal trials, each lasting 3–5 seconds, with at least 1–2 minutes of rest between trials. Subjects adopted a self-selected stance on the force plates and were then adjusted to achieve the recommended knee ( $125^{\circ}$ – $145^{\circ}$ ) and hip ( $140^{\circ}$ – $150^{\circ}$ ) joint angles (10), as variations in joint angles could influence force production characteristics (2,10,29). All tests were performed using lifting straps to eliminate grip strength as a potential confounding variable (10). Cueing was standardized across all testing sessions using the instruction: “push your feet into the ground as fast and as hard as possible” (10). Trials were considered valid if they demonstrated a stable weighing phase, no evident countermovement before the onset of force production, and no clear secondary force application toward the end of the pull (10). To ensure acceptable reliability, each subject was required to complete at least 2 valid trials. The IMTP peak force values obtained from these 2 trials had to differ by no more than 250 N (10). If no 2 valid and reliable trials could be obtained within 6 attempts, the subject was excluded from the analysis to avoid fatigue- and learning-related confounding effects. Of the excluded subjects, 4 were classified as prepubertal and 4 as pubertal, with 2 in the training groups and 6 in the control groups (Figure 1). Importantly, the exclusion of the 8 subjects did not meaningfully affect group balance or the overall study design. For subsequent analyses, the trial with the highest IMTP peak force was used (46). In general, peak force outcomes derived from the IMTP have demonstrated good-to-excellent reliability in youth athletes (intraclass correlation coefficients [ICCs] = 0.72–0.99; coefficients of variation [CVs] = 2.0–8.3%) (6).

### Statistical Analyses

Within-session reliability of ultrasound-derived muscle thickness was assessed using a 2-way mixed-effects ICC for absolute agreement, based on the mean of 3 images obtained. Reliability was calculated separately for m. rectus femoris and m. vastus intermedius thickness (combined measure) and m. vastus lateralis thickness at pre- and posttesting. The CV was calculated as the within-subject SD of the 3 images divided by the within-subject mean, expressed as a percentage and averaged across subjects. Furthermore, IMTP peak force reliability was evaluated at pre- and posttesting using a 2-way mixed-effects ICC with absolute agreement. The highest valid trial was retained for analysis (46). Absolute reliability was assessed via the CV, calculated as the

mean within-subject *SD* of the 2 trials divided by the subject mean. Reliability was interpreted using the 95% confidence interval for the ICC estimate, following Koo and Li (36), with thresholds of poor (<0.50), moderate (0.50–0.74), good (0.75–0.90), and excellent (>0.90). All reliability analyses were conducted using SPSS Statistics (Version 30, IBM Corp., Armonk, NY).

For each outcome variable, a separate linear mixed-effects model was fitted with a random intercept for each subject to account for repeated measurements. Fixed effects included time, maturity, intervention, and their interactions (time  $\times$  maturity, time  $\times$  intervention, and time  $\times$  maturity  $\times$  intervention). Baseline values of the respective outcome were included as a covariate to obtain baseline-adjusted estimates. All analyses were conducted in Python 3 using the *pandas*, *numpy*, *scipy*, and *statsmodels* libraries for data handling and model estimation. Model assumptions were evaluated separately for each outcome using residual diagnostics, including visual inspection of residual plots and quantile-quantile plots as well as Shapiro-Wilk tests of model residuals. Log transformation was applied only when residual diagnostics indicated substantial deviations from model assumptions, particularly skewness and heteroscedasticity. This was the case for m. vastus lateralis and m. rectus femoris. For all other outcomes, residual diagnostics did not indicate substantial violations of model assumptions; therefore, analyses were performed on the original scale. The log transformation helps to stabilize variance and to make skewed distributions more symmetric (31). In addition, prespecified post hoc comparisons were performed to describe within-group pre-to-post changes and between-group differences at pre and post (Bonferroni-adjusted *p*-values). For post hoc contrasts, mean differences, Cohen's *d*, and *p*-values were reported. The magnitude of standardized mean differences was interpreted according to Cohen's convention (9): trivial (<0.2), small (0.2–0.49), moderate (0.5–0.79), and large ( $\geq 0.8$ ). Statistical significance was set at  $p < 0.05$ .

## Results

Within-session reliability of the ultrasound-derived muscle thickness measurements was excellent across muscles and time points. For the combined m. rectus femoris and m. vastus intermedius thickness, ICC values were 0.998 at both baseline- and posttesting (95% confidence interval [CI] = 0.997–0.999; CV = 0.86 and 0.91%, respectively). For m. vastus lateralis thickness, ICC values were 0.996 at baseline-testing (95% CI = 0.995–0.998; CV = 1.63%) and 0.995 at posttesting (95% CI = 0.992–0.996; CV = 1.83%). In addition, IMTP peak force demonstrated moderate-to-excellent within-session reliability at both baseline-testing (ICC = 0.962; 95% CI = 0.618–0.988; CV = 3.60%) and posttesting (ICC = 0.967; 95% CI = 0.572–0.991; CV = 3.13%). An overview of baseline and post-test values for muscle thickness of m. rectus femoris, m. vastus intermedius, and m. vastus lateralis, as well as peak force and relative peak force in the IMTP test across all 4 groups, is provided in Table 3 and illustrated in Figures 2–5.

### Muscle Thickness

For the combined muscle thickness of the m. rectus femoris and m. vastus intermedius, a significant main effect of Maturity was found ( $F = 9.72$ ,  $\eta_p^2 = 0.07$ ,  $p = 0.002$ ), demonstrating that

pubertal subjects exhibited greater muscle thickness than pre-pubertal subjects, independent of time and intervention (Table 3). However, the main effect of Time did not reach statistical significance ( $F = 3.89$ ,  $\eta_p^2 = 0.03$ ,  $p = 0.051$ ).

Regarding the interactions, no significant Time  $\times$  Intervention interaction was observed ( $F = 1.10$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.295$ ), indicating that changes over time did not differ between the training and control groups (Figure 2). Similarly, no significant Time  $\times$  Maturity interaction ( $F = 1.46$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.229$ ) was observed.

Finally, the 3-way interaction of Time  $\times$  Maturity  $\times$  Intervention was not significant ( $F = 0.57$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.451$ ), suggesting that the effect of the intervention was not moderated by maturational status. Within-group effect sizes for pre-to-post changes were moderate for the training groups (prepubertal:  $d = 0.75$ ; pubertal:  $d = 0.77$ ), whereas control groups showed small-to-moderate effects (prepubertal:  $d = 0.47$ ; pubertal:  $d = 0.74$ ).

Analysis of the m. vastus lateralis muscle thickness (Figure 3) revealed significant main effects for both Maturity ( $F = 12.77$ ,  $\eta_p^2 = 0.09$ ,  $p = 0.001$ ) and Time ( $F = 7.07$ ,  $\eta_p^2 = 0.05$ ,  $p = 0.009$ ). The former demonstrates greater muscle thickness of the m. vastus lateralis in pubertal compared with prepubertal subjects, while the latter confirms a general increase in m. vastus lateralis thickness across the entire study period and across all subject groups (Table 3).

None of the 2-way interactions reached statistical significance. The Time  $\times$  Intervention interaction ( $F = 0.14$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.711$ ) was nonsignificant, as was the Time  $\times$  Maturity interaction ( $F = 0.23$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.630$ ). Finally, the 3-way Time  $\times$  Maturity  $\times$  Intervention interaction was also nonsignificant ( $F = 0.12$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.731$ ), providing no statistical evidence that the intervention's effect over time was modulated by maturational status.

Within-group effect sizes indicated moderate-to-large effects for the training groups (prepubertal:  $d = 1.00$ ; pubertal:  $d = 0.69$ ) and small-to-moderate effects for the control groups (prepubertal:  $d = 0.67$ ; pubertal:  $d = 0.49$ ).

### Strength and Relative Strength

Analysis of IMTP peak force revealed a highly significant main effect for Maturity ( $F = 41.07$ ,  $\eta_p^2 = 0.27$ ,  $p < 0.001$ ), demonstrating greater peak force in pubertal compared with prepubertal subjects (Table 3). In addition, a significant main effect of Time was found ( $F = 5.51$ ,  $\eta_p^2 = 0.05$ ,  $p = 0.021$ ), reflecting an overall increase in IMTP peak force from pretesting to posttesting.

A significant Time  $\times$  Intervention interaction was observed ( $F = 4.23$ ,  $\eta_p^2 = 0.04$ ,  $p = 0.042$ ), indicating that the change in IMTP peak force over time was more pronounced in the training groups compared with the control groups (Figure 4). Furthermore, the significant Time  $\times$  Maturity interaction showed ( $F = 6.75$ ,  $\eta_p^2 = 0.06$ ,  $p = 0.011$ ) that pubertal subjects exhibited a greater increase in IMTP peak force over the study period than prepubertal subjects (Table 3). However, no significant effect was found for the 3-way Time  $\times$  Maturity  $\times$  Intervention interaction ( $F = 1.14$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.289$ ), suggesting that the efficacy of the intervention over time was not dependent on biological maturation.

Within-group effect sizes for peak force were large and nearly identical across the training groups (prepubertal:  $d = 1.56$ ; pubertal:  $d = 1.52$ ), supporting the hypothesis that training-induced strength adaptations are comparable regardless of biological

**Table 3**  
Mean baseline and posttest values, including SDs and change values (%).\*

| Parameter                                                                               | Baseline PREPUB<br>CON                                    | Post PREPUB<br>CON | Baseline<br>PREPUB RT                                     | Post PREPUB<br>RT | Baseline PUB<br>CON                                       | Post PUB<br>CON | Baseline PUB<br>RT                                        | Post PUB<br>RT |
|-----------------------------------------------------------------------------------------|-----------------------------------------------------------|--------------------|-----------------------------------------------------------|-------------------|-----------------------------------------------------------|-----------------|-----------------------------------------------------------|----------------|
| <i>M. rectus</i> femoris and <i>m. vastus</i> intermedius (cm)                          | 3.6 ± 0.4                                                 | 3.7 ± 0.4          | 3.6 ± 0.4                                                 | 3.8 ± 0.4         | 4.0 ± 0.5                                                 | 4.2 ± 0.6       | 4.0 ± 0.6                                                 | 4.3 ± 0.6      |
| <i>M. rectus</i> femoris and <i>m. vastus</i> intermedius change (%)                    | 2.9 ± 5.6                                                 |                    | 5.0 ± 6.4†                                                |                   | 5.8 ± 7.2†                                                |                 | 5.6 ± 7.3†                                                |                |
| <i>M. rectus</i> femoris and <i>m. vastus</i> intermedius within post hoc (pre vs post) | MD = 0.1 ± 0.2<br><i>d</i> = 0.47<br><i>p</i> = 0.050     |                    | MD = 0.2 ± 0.2<br><i>d</i> = 0.75<br><i>p</i> = 0.004     |                   | MD = 0.2 ± 0.3<br><i>d</i> = 0.74<br><i>p</i> = 0.012     |                 | MD = 0.2 ± 0.3<br><i>d</i> = 0.77<br><i>p</i> = 0.013     |                |
| <i>M. vastus</i> lateralis (cm)                                                         | 1.6 ± 0.3                                                 | 1.7 ± 0.3          | 1.7 ± 0.2                                                 | 1.8 ± 0.2         | 2.0 ± 0.3                                                 | 2.1 ± 0.3       | 1.8 ± 0.4                                                 | 1.9 ± 0.3      |
| <i>M. vastus</i> lateralis change (%)                                                   | 6.1 ± 8.9†                                                |                    | 6.4 ± 6.9†                                                |                   | 5.7 ± 12.3                                                |                 | 6.1 ± 9.3†                                                |                |
| <i>M. vastus</i> lateralis within post hoc (pre vs post)                                | MD = 0.1 ± 0.1<br><i>d</i> = 0.67<br><i>p</i> = 0.007     |                    | MD = 0.1 ± 0.1<br><i>d</i> = 1.00<br><i>p</i> < 0.001     |                   | MD = 0.1 ± 0.2<br><i>d</i> = 0.49<br><i>p</i> = 0.078     |                 | MD = 0.1 ± 0.1<br><i>d</i> = 0.69<br><i>p</i> = 0.022     |                |
| IMTP peak force (N)                                                                     | 1,128 ± 223                                               | 1,234 ± 160        | 1,189 ± 205                                               | 1,377 ± 175       | 1,595 ± 302                                               | 1797 ± 257      | 1,482 ± 280                                               | 1716 ± 298     |
| IMTP peak force (N) change (%)                                                          | 11.3 ± 14.0†                                              |                    | 17.3 ± 13.3†                                              |                   | 14.1 ± 14.0†                                              |                 | 16.7 ± 11.5†                                              |                |
| IMTP peak force (N) within post hoc (pre vs post)                                       | MD = 106.5 ± 149.5<br><i>d</i> = 0.71<br><i>p</i> = 0.010 |                    | MD = 188.7 ± 121.2<br><i>d</i> = 1.56<br><i>p</i> < 0.001 |                   | MD = 202.1 ± 165.9<br><i>d</i> = 1.22<br><i>p</i> = 0.001 |                 | MD = 234.1 ± 154.3<br><i>d</i> = 1.52<br><i>p</i> < 0.001 |                |
| IMTP relative peak force (N·kg <sup>-1</sup> )                                          | 29.6 ± 4.7                                                | 32.0 ± 4.3         | 30.7 ± 5.0                                                | 35.1 ± 5.3        | 28.8 ± 5.0                                                | 31.5 ± 4.3      | 29.0 ± 5.5                                                | 33.1 ± 6.5     |
| IMTP relative peak force (N·kg <sup>-1</sup> ) change (%)                               | 9.1 ± 13.7†                                               |                    | 15.2 ± 13.1†                                              |                   | 10.8 ± 12.0†                                              |                 | 14.3 ± 11.6†                                              |                |
| IMTP relative peak force (N·kg <sup>-1</sup> ) within post hoc (pre vs post)            | MD = 2.4 ± 3.9<br><i>d</i> = 0.61<br><i>p</i> = 0.023     |                    | MD = 4.4 ± 3.5<br><i>d</i> = 1.27<br><i>p</i> < 0.001     |                   | MD = 2.8 ± 2.5<br><i>d</i> = 1.12<br><i>p</i> = 0.003     |                 | MD = 4.0 ± 3.3<br><i>d</i> = 1.20<br><i>p</i> = 0.001     |                |

\*PREPUB = prepubertal; PUB = pubertal; RT = resistance training group; CON = control group; IMTP = isometric mid-thigh pull.

†Significant pre-to-post change.

maturation. Control groups demonstrated moderate-to-large effects (prepubertal: *d* = 0.71; pubertal: *d* = 1.22). Thus, these results indicate that additional resistance training led to greater

improvements in absolute IMTP peak force than the active control condition, despite the control groups also showing substantial increases.

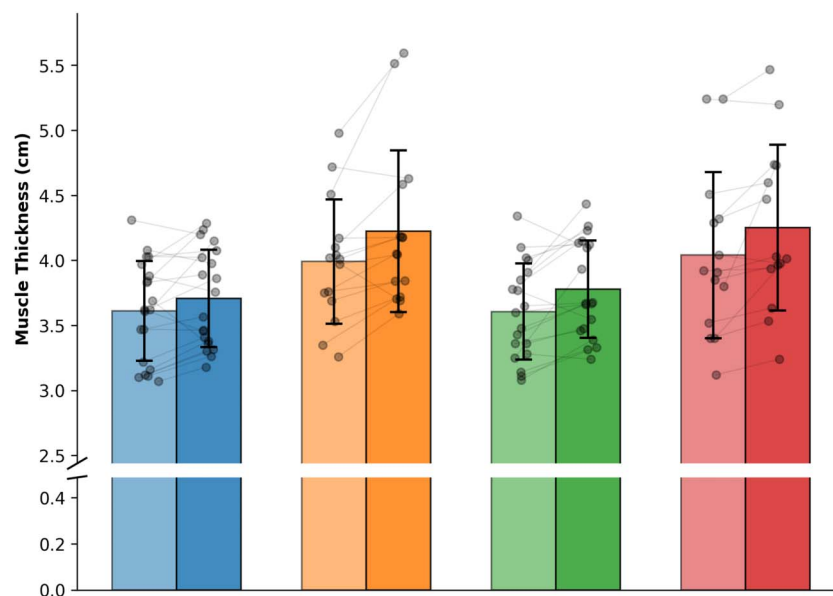


**Figure 2.** Development of the muscle thickness (cm) from pretest to posttest of *m. rectus* femoris and *m. vastus* intermedius: control group prepubertal (blue), training group prepubertal (orange), control group pubertal (green), and training group pubertal (red). No significant time × intervention ( $F = 1.10$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.295$ ), time × maturity ( $F = 1.46$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.229$ ), and time × maturity × intervention ( $F = 0.57$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.451$ ) interaction was observed. The main effect of time ( $F = 3.89$ ,  $\eta_p^2 = 0.03$ ,  $p = 0.051$ ) was not significant, but the main effect of maturity ( $F = 9.72$ ,  $\eta_p^2 = 0.07$ ,  $p = 0.002$ ) reached significance.

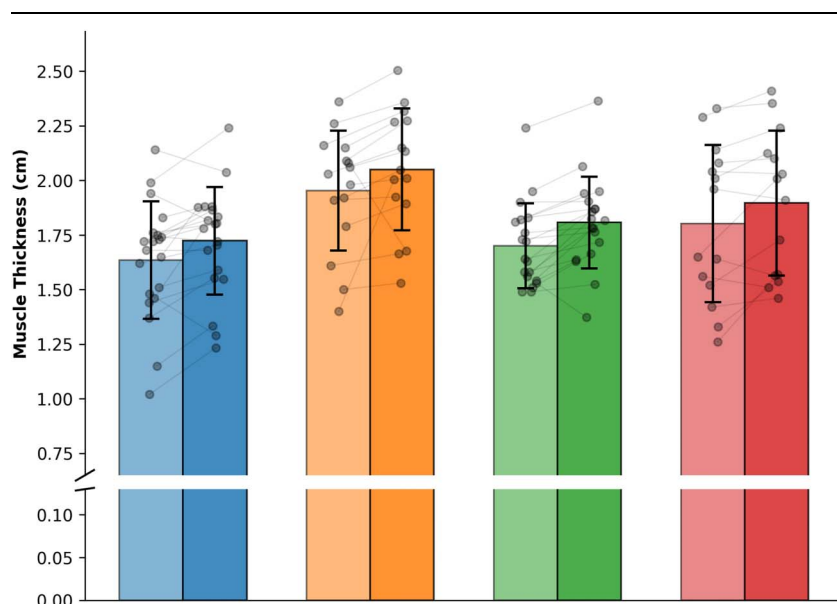


**Figure 3.** Development of the muscle thickness (cm) from pretest to posttest of m. vastus lateralis: control group prepubertal (blue), training group prepubertal (orange), control group pubertal (green), and training group pubertal (red). The main effects of maturity ( $F = 12.77$ ,  $\eta_p^2 = 0.09$ ,  $p = 0.001$ ) and time ( $F = 7.07$ ,  $\eta_p^2 = 0.05$ ,  $p = 0.009$ ) reached significance. However, the time  $\times$  intervention ( $F = 0.14$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.711$ ), time  $\times$  maturity ( $F = 0.23$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.630$ ), and time  $\times$  maturity  $\times$  intervention ( $F = 0.12$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.731$ ) did not reach significance.

With respect to relative IMTP peak force (Figure 5), the only statistically significant finding to emerge was a main effect of Time ( $F = 8.54$ ,  $\eta_p^2 = 0.07$ ,  $p = 0.004$ ), confirming a general pre- to posttest improvement in relative IMTP for the cohort as a whole. However, a corresponding main effect for Maturity was not evident ( $F = 0.05$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.827$ ).

Descriptive statistics indicated a greater improvement in the training group over time. However, the Time  $\times$  Intervention interaction did not reach statistical significance ( $F = 3.16$ ,  $\eta_p^2 = 0.03$ ,  $p = 0.078$ ). Furthermore, the analysis did not yield a significant Time  $\times$  Maturity interaction ( $F = 0.12$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.726$ ).

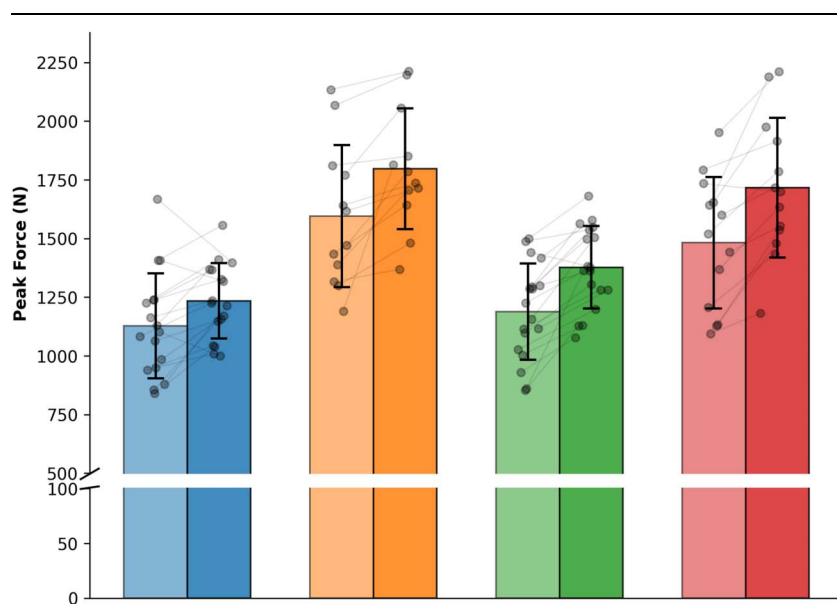


**Figure 4.** Development of absolute peak force (N) in the mid-thigh-pull from pretest to posttest: control group prepubertal (blue), training group prepubertal (orange), control group pubertal (green), and training group pubertal (red). The analysis revealed a significant main effect for maturity ( $F = 41.07$ ,  $\eta_p^2 = 0.27$ ,  $p < 0.001$ ) and for time ( $F = 5.51$ ,  $\eta_p^2 = 0.05$ ,  $p = 0.021$ ). Furthermore, a significant time  $\times$  intervention interaction ( $F = 4.23$ ,  $\eta_p^2 = 0.04$ ,  $p = 0.042$ ) and a significant time  $\times$  maturity interaction ( $F = 6.75$ ,  $\eta_p^2 = 0.06$ ,  $p = 0.011$ ) were observed. The 3-way time  $\times$  maturity  $\times$  intervention interaction ( $F = 1.14$ ,  $\eta_p^2 = 0.01$ ,  $p = 0.289$ ) was not significant.

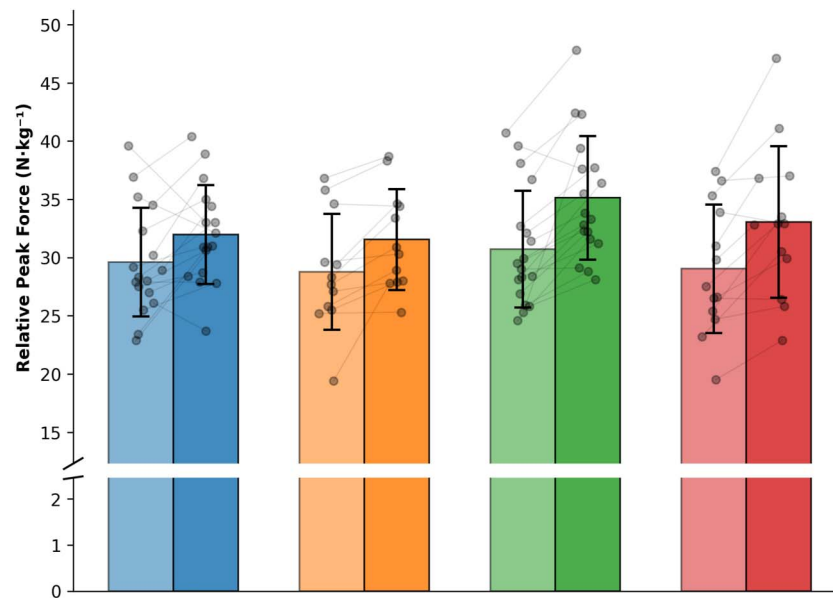


**Figure 5.** Development of relative peak force ( $\text{N}\cdot\text{kg}^{-1}$ ) in the mid-thigh-pull from pretest to posttest: control group prepubertal (blue), training group prepubertal (green), control group pubertal (orange), and training group pubertal (red). The main effect of time ( $F = 8.54$ ,  $\eta_p^2 = 0.07$ ,  $p = 0.004$ ) was significant, but maturity ( $F = 0.05$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.827$ ) did not reach significance. The time  $\times$  intervention interaction ( $F = 3.16$ ,  $\eta_p^2 = 0.03$ ,  $p = 0.078$ ), time  $\times$  maturity interaction ( $F = 0.12$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.726$ ), and time  $\times$  maturity  $\times$  intervention ( $F = 0.20$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.656$ ) did not reach statistical significance.

Finally, no significant 3-way interaction between Time, Maturity, and Intervention was detected ( $F = 0.20$ ,  $\eta_p^2 = 0.00$ ,  $p = 0.656$ ), which suggests that the impact of intervention on IMTP relative peak force over time was not modulated by maturational status.

Within-group effect sizes for relative IMTP peak force were similarly large in both training groups (prepubertal:  $d = 1.27$ ; pubertal:  $d = 1.20$ ), further supporting the absence of a maturation-dependent training effect. The control groups demonstrated moderate-to-large effects (prepubertal:  $d = 0.61$ ; pubertal:  $d = 1.12$ ).

## Discussion

The primary finding of this study is that resistance training improved maximal isometric strength in youth regardless of maturation status, while additional hypertrophic adaptations beyond regular sport participation were not observed. Overall, the additional resistance training led to greater improvements in absolute isometric strength but not to significantly greater increases in muscle thickness compared with the active control condition. Furthermore, no evidence was found that maturity status moderated the training response in any of the outcomes examined.

In this context, it is important to note that growth, maturation, and active sport participation—including soccer training and resistance training—all contributed to significant increases in muscle thickness across groups from pre- to posttesting. Nevertheless, the findings demonstrated that resistance training did not result in significant increases in muscle thickness of the m. rectus femoris, m. vastus intermedius and m. vastus lateralis when compared with an active control group. Furthermore, no evidence was found of significantly greater hypertrophy

attributable specifically to the resistance training intervention beyond that observed in the active control condition. One possible explanation is that early adaptations to resistance training in youth may be predominantly neural (39). Nevertheless, these interpretations should be interpreted with caution, as this study did not include explicit measures of neural adaptations. In addition, growth-related factors and the use of an active control condition may have attenuated detectable between-group differences, potentially contributing to the absence of a significant training effect on muscle hypertrophy. In addition, soccer training itself may provide a substantial lower-limb stimulus, potentially reducing the hypertrophic contrast between the intervention and control conditions. It should be noted that isolating training-induced hypertrophic adaptations in active, growing youth is inherently challenging, as ongoing biological maturation and regular sport participation may independently contribute to changes in muscle size. Consequently, subtle training-specific hypertrophic adaptations may have been masked by concurrent growth-related changes occurring in both the intervention and active control groups, particularly within the relatively short 9-week intervention period. Furthermore, muscle thickness assessed via site-specific ultrasound reflects localized changes and may not fully capture adaptations across the entire muscle. Nevertheless, the high reliability observed indicates that the ultrasound protocol was sufficiently precise to detect meaningful changes in muscle thickness.

The significant main effect of Maturity on both muscle thickness outcomes confirms that pubertal subjects displayed greater muscle size than prepubertal subjects. Given the absence of a significant Time  $\times$  Intervention interaction alongside significant within-group increases in almost all groups, the observed improvements in muscle thickness of the m. rectus femoris, m. vastus intermedius, and m. vastus lateralis appear to reflect

general growth, soccer training, resistance training, or broader developmental processes occurring during the study period. Accordingly, while significant increases in muscle thickness were observed across groups, no evidence was found for significant additional hypertrophic adaptations of these muscles attributable specifically to the resistance training intervention beyond those observed in the active control condition. Thus, the nonsignificant Time  $\times$  Maturity  $\times$  Intervention effect suggests that no statistically significant differences in hypertrophic responses between pubertal and prepubertal subjects were detected in the present sample. This could indicate that hormonal changes associated with puberty may play a greater role in natural, growth-related increases in muscle size rather than in training-induced muscular adaptations. This interpretation would be consistent with current evidence indicating that mechanical tension represents the primary driver of muscle hypertrophy (61). However, it should also be acknowledged that this study may have been underpowered to detect higher-order interaction effects, such as Time  $\times$  Maturity  $\times$  Intervention interactions. Although the subjects had no prior resistance training experience, they were sub-elite youth soccer players and therefore regularly exposed to high loading of the lower-body musculature through sport-specific activities. Thus, they cannot be considered completely untrained, and the absence of hypertrophic adaptations is unlikely to be solely attributable to their resistance training status.

With regard to strength development, the significant Time  $\times$  Intervention interaction demonstrated that the training groups improved to a significantly greater extent than the control groups. This finding is consistent with the notion that neural adaptations may play a prominent role in increases in strength following resistance training in youth (39), although direct assessment of neural mechanisms was beyond the scope of this study.

In contrast, for relative isometric peak force, only a descriptive trend toward greater improvements in the training groups was observed, but the Time  $\times$  Intervention interaction did not reach statistical significance. This discrepancy emphasizes that, particularly in youth populations, both absolute and relative strength measures should be considered and their importance should be interpreted in relation to the specific demands of the respective sport.

The absence of a significant interaction effect for relative peak force is plausible, as children and adolescents undergo continuous growth and maturation that strongly influence body mass and, consequently, relative strength values. Nevertheless, these findings underline the practical importance of developing strength in youth athletes, as increases in body mass associated with normal growth require corresponding increases in force production. Insufficient development of strength relative to body mass may not only impair performance but also increase the risk of injury (7). In this context, the magnitude of isometric strength increases observed with only twice-weekly training is particularly noteworthy, underscoring the efficiency and effectiveness of resistance training as a time-efficient strategy for youth athletic development. Despite the wide 95% CI, the high ICC and low CV values suggest that the measured strength is still very reliable, with values comparable to or exceeding those reported in the meta-analysis by Bruno et al. (6). The wide 95% CI likely reflects the relatively small sample size available for reliability estimation. Although Koo and Li (36) recommend prioritizing CI, the present findings should nonetheless be considered very reliable given the strong ICC and low CV values (6). The distinction between the main effect of Maturity and the

Time  $\times$  Maturity interaction is essential for interpreting the strength outcomes. The significant main effect of Maturity for absolute peak force indicates that pubertal subjects were generally stronger than prepubertal subjects, independent of time and intervention. By contrast, the significant Time  $\times$  Maturity interaction shows that pubertal subjects improved to a greater extent over the study period, regardless of group allocation. One possible explanation is that older children and adolescents possessed a better understanding of the instructions and greater concentration for explicit information, allowing for more purposeful execution and more stable learning curves from pre-testing to posttesting (57).

Maturation status had a significant influence on performance, with pubertal subjects demonstrating greater muscle thickness and absolute peak force. However, no significant Time  $\times$  Maturity  $\times$  Intervention interactions were observed for any of the examined outcomes, suggesting that biological maturation may not have substantially moderated the training response in the present sample. Nevertheless, these findings should be interpreted with caution, as this study may have been underpowered to detect such interaction effects.

Given the limited statistical power of the 3-way interaction, our findings did not provide clear evidence of differences in training responsiveness between prepubertal and pubertal youth. This interpretation was also supported by the observed effect sizes. Taken together, the present results would support the implementation of resistance training across all stages of youth development. The significant main effects of Time for both peak force and relative peak force indicate that all subjects improved their isometric strength across the study period.

The significant increases in strength observed in the training groups indicate that traditional resistance training represents an effective and appropriate training approach for both prepubertal and pubertal athletes. These findings are consistent with previous research by Keiner et al. (33,34) and Skratek et al. (56), who demonstrated that traditional resistance training effectively enhances strength in youth sport and should therefore be given high priority in athletic development programs for elite youth soccer players. The present results not only confirm these findings but also extend them by suggesting that comparable benefits may also apply to sub-elite youth soccer players across different stages of maturation. Accordingly, these findings suggest that well-structured traditional resistance training can effectively improve isometric strength in youth athletes, regardless of maturation status.

The following limitations should be considered when interpreting the findings of this study. First, the control group continued regular sport training and therefore represented an active rather than a passive control condition. This may have reduced the detectable contrast between groups, particularly with regard to muscle hypertrophy and strength adaptations, as the control subjects were also exposed to regular lower-limb loading through their habitual soccer training activities. Nevertheless, this study design substantially enhanced the ecological validity of this study, as the resistance training group's adaptations were observed against a background of habitual athletic activity rather than inactivity.

Second, ongoing biological growth and maturation in the studied cohort may have masked or diluted the detection of training-specific adaptations, particularly for morphological outcomes, as growth-related changes in muscle size cannot be fully separated from training-induced hypertrophy. This challenge is inherently greater in youth populations than in adults,

where muscle development is typically negligible without dedicated training. The relatively short 9-week intervention period may have further limited the ability to detect subtle hypertrophic adaptations.

Third, the use of predominantly machine-based, single-joint exercises may limit the generalizability of these findings to typical strength training programs for children and adolescents, which typically emphasize multijoint exercises and free-weight exercises. Finally, sport-specific performance parameters such as jump height, sprint speed or change of direction were not measured. Consequently, it remains unclear to what extent the observed isometric strength and hypertrophy adaptations translate into improvements in athletic performance, although improvements in strength abilities in the IMTP show generally high correlations with sport-specific performance parameters.

Fourth, muscle hypertrophy was assessed using ultrasound measurements at standardized anatomical locations. Despite efforts to ensure measurement consistency, continuous growth and changes in body dimensions could have affected the sensitivity and accuracy of the muscle thickness measurements. In addition, although ultrasound-based muscle thickness assessments represent an established and practical approach for evaluating hypertrophic adaptations in youth populations, single-site measurements may provide only a limited proxy for overall muscle hypertrophy. Although more comprehensive imaging techniques such as MRI or muscle biopsies may provide more detailed information regarding muscular adaptations, their application in pediatric populations is often limited by practical, financial, and ethical considerations. Moreover, the exclusion of subjects who were unable to produce valid IMTP trials may have introduced a selection bias in strength-related analyses and potentially limited the generalizability of the findings.

Furthermore, although PHV-based estimations are widely established for assessing biological maturation in children and adolescents (40), this method represents an indirect approach to maturity assessment and may therefore be associated with potential estimation errors and classification inaccuracies. In addition, it should be noted that the pubertal group included subjects across a range of maturational stages, reflecting natural variation in hormonal and physiological development within this maturation group.

Moreover, although the present sample size was comparatively large for a pediatric resistance training intervention study, the a priori power analysis was primarily based on detecting pre-to-post changes and was not specifically designed to detect 3-way interaction effects. Therefore, this study may have been underpowered to detect Time  $\times$  Maturity  $\times$  Intervention interactions, and the absence of significant effects should be interpreted with caution.

Finally, although subjects were instructed to refrain from additional resistance training and to maintain their habitual dietary patterns throughout the study period, full compliance with these instructions cannot always be guaranteed. Uncontrolled variations in physical activity or nutrition may therefore have influenced individual responses to the intervention. Minor variations in external soccer training load due to playing position or individual club schedules cannot be entirely excluded.

Despite these limitations, the selected training modality, frequency, and intervention duration are highly relevant from a practical perspective, as off-season training phases in youth sport - during which strength- and hypertrophy-oriented

programs are commonly implemented - typically last between 6 and 10 weeks (30).

### Practical Applications

From a practical perspective, these findings support integrating resistance training into athletic development programs for male semi-elite youth soccer players. A twice-weekly resistance training program was sufficient to produce meaningful improvements in maximal isometric strength, which are directly relevant to sport actions requiring high levels of force production. Although no significant training effect was observed for relative isometric strength, this likely reflects concurrent increases in body mass during growth and maturation. Even the relatively high training volume may have been insufficient to offset growth-related increases in body mass, underscoring the importance of sustained resistance training during biological development. In youth athletes who must repeatedly accelerate, decelerate, and control their own body mass, strength development may need to outpace increases in body mass to meaningfully enhance relative force production. Importantly, the results indicate that semi-professional youth athletes can benefit from resistance training. Overall, machine-based, single-joint resistance training appears to represent a useful strategy for supporting the long-term development of functional strength capacities in young athletes.

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