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Original Article

Precision Errors and Monitoring Time Interval in Pediatric Muscle Imaging and Neuromuscular Performance Assessment

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Abstract

Objectives: To determine precision errors and monitoring time intervals in imaged muscle properties and neuromuscular performance, and to explore growth-related factors associated with precision errors in children. **Methods**: We included 35 children (mean age 10.5yrs) in the precision study cohort and 40 children (10.7yrs) in the follow-up study cohort. We assessed forearm and lower leg muscle properties (area, density) with peripheral quantitative computed tomography. We measured neuromuscular performance via maximal pushup, grip force, countermovement and standing long jump force, power, and impulse along with long jump length. We calculated precision errors (root-mean-squared coefficient of variation) from the precision cohort and monitoring time intervals using annual changes from the follow-up cohort. We explored associations between precision errors (coefficient of variation) and maturity, time interval (between repeated measures), and anthropometric changes using Spearman's rank correlation (p<0.05). **Results**: Muscle measures exhibited precision errors of 1.3-14%. Monitoring time intervals were 1-2.6yrs, except muscle density (>43yrs). We identified only one association between precision errors and maturity (maximal pushup force: *rho*=-0.349; p=0.046). **Conclusions**: Imaging muscle properties and neuromuscular performance measures had precision errors of 1-14% and appeared suitable for follow-up on ~2yr scales (except muscle density). Maximal pushup force appeared more repeatable in mature children.

Keywords: Growth, Muscle, Pediatrics, Peripheral Quantitative Computed Tomography

Introduction

During physiologic activities, muscle forces balance external loads placed upon the body. Due to short-moment arms, muscle contraction can offer some of the highest loads applied to the bone, which helps stimulate bone adaptation[1,2]. Thus, physical activities may help to optimize bone development, particularly in children with chronic diseases influencing musculoskeletal health and development[3–6]. Less attention though has been directed toward the study of muscle properties (e.g., area, density, strength) in children. In particular, there is little information regarding measurement error and appropriate time between follow-up measures to capture growth-related change.

One method to measure muscle cross-sectional area in children is via imaging technologies like peripheral quantitative computed tomography (pQCT). Here muscle area is regarded as a surrogate of muscle strength (i.e., load-carrying capacity) and is strongly associated with cortical bone size and bone strength[2]. Muscle density, which can also be measured by pQCT, is an index indicating fatness of the muscle (lower density amounts to more fat content) and is associated with bone strength in girls[7]. Neuromuscular performance (i.e., muscle function) measures offer additional, functional information to monitor musculoskeletal development in children[8]. Force-related outcomes measured from neuromuscular assessment, such as grip force and countermovement jump power, are also used as an indicator of underlining bone strength due to the strong association

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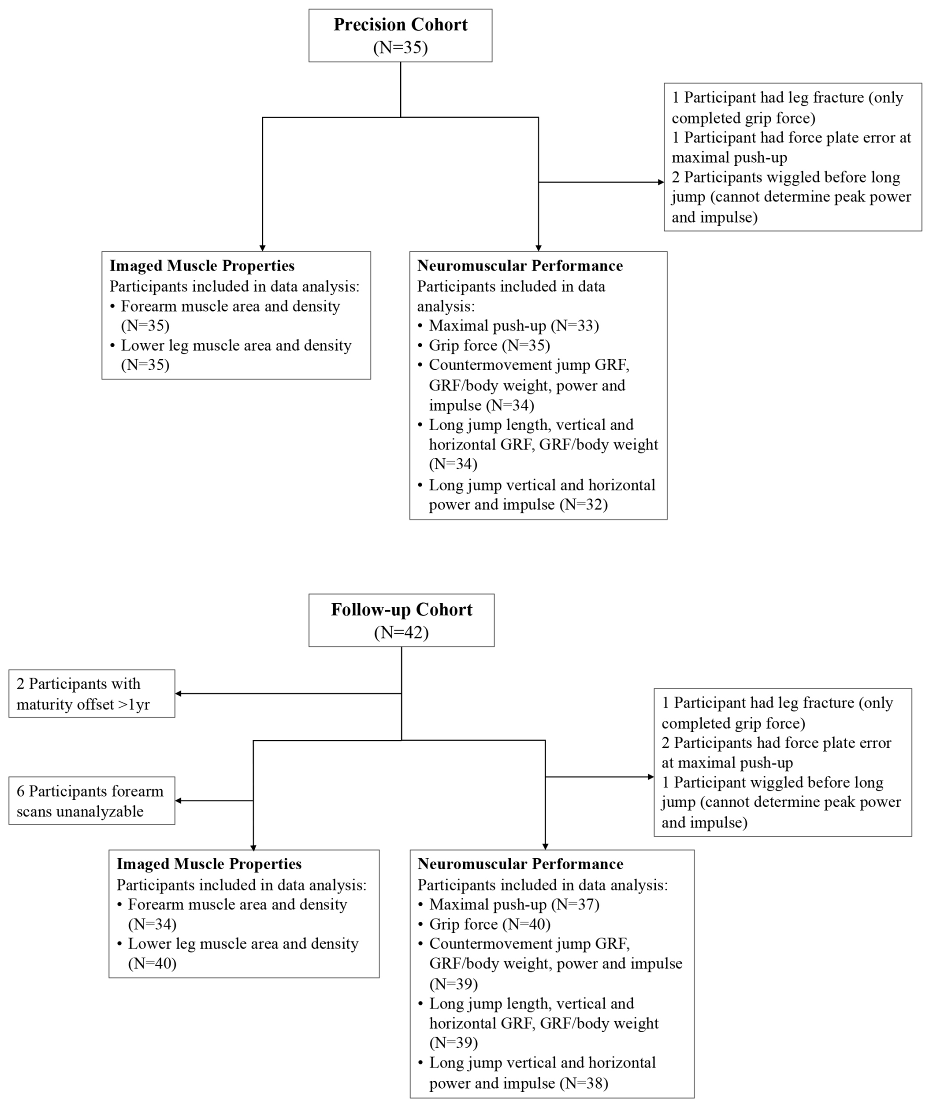

Figure 1. Flowchart demonstrating participant and measurement data inclusion in the analysis for precision study cohort and follow-up study cohort.

between muscle force and bone strength[2,9]. Compared to traditional muscle strength tests (e.g., one-repetition maximum test), neuromuscular performance tests, such as a countermovement jump, not only reflect maximal muscle force but also motor performance and body coordination[10].

To date, a few studies have reported repeatability or agreement related to neuromuscular performance measures in children (coefficient of variation (CV%) 4-14%, interclass correlation coefficient (ICC) 0.84-0.98)[8,11–13]. However, the repeatability of imaging measures of muscle area and density in children is unknown. In addition, evidence of factors (such as maturity, measurement interval, and somatic growth) influencing precision errors in pediatric populations is scarce[14]. There is also limited knowledge regarding what change constitutes a "true" change, such that the measured change in muscle area or density or neuromuscular performance is greater than the error inherent to the measurement technique. In addition, there is a lack of information regarding the time period between repeated measurements to capture true change. Here precision errors can be used to quantify the repeatability of a measuring technique by estimating the amount of error for a specific population[15]. From precision errors, we can calculate the least significant change (LSC), the minimum change between consecutive measurements to be significantly different with 95% confidence[16], which can also be used in combination with measures of annual change to estimate the monitoring time interval (MTI) between follow-up measures required to

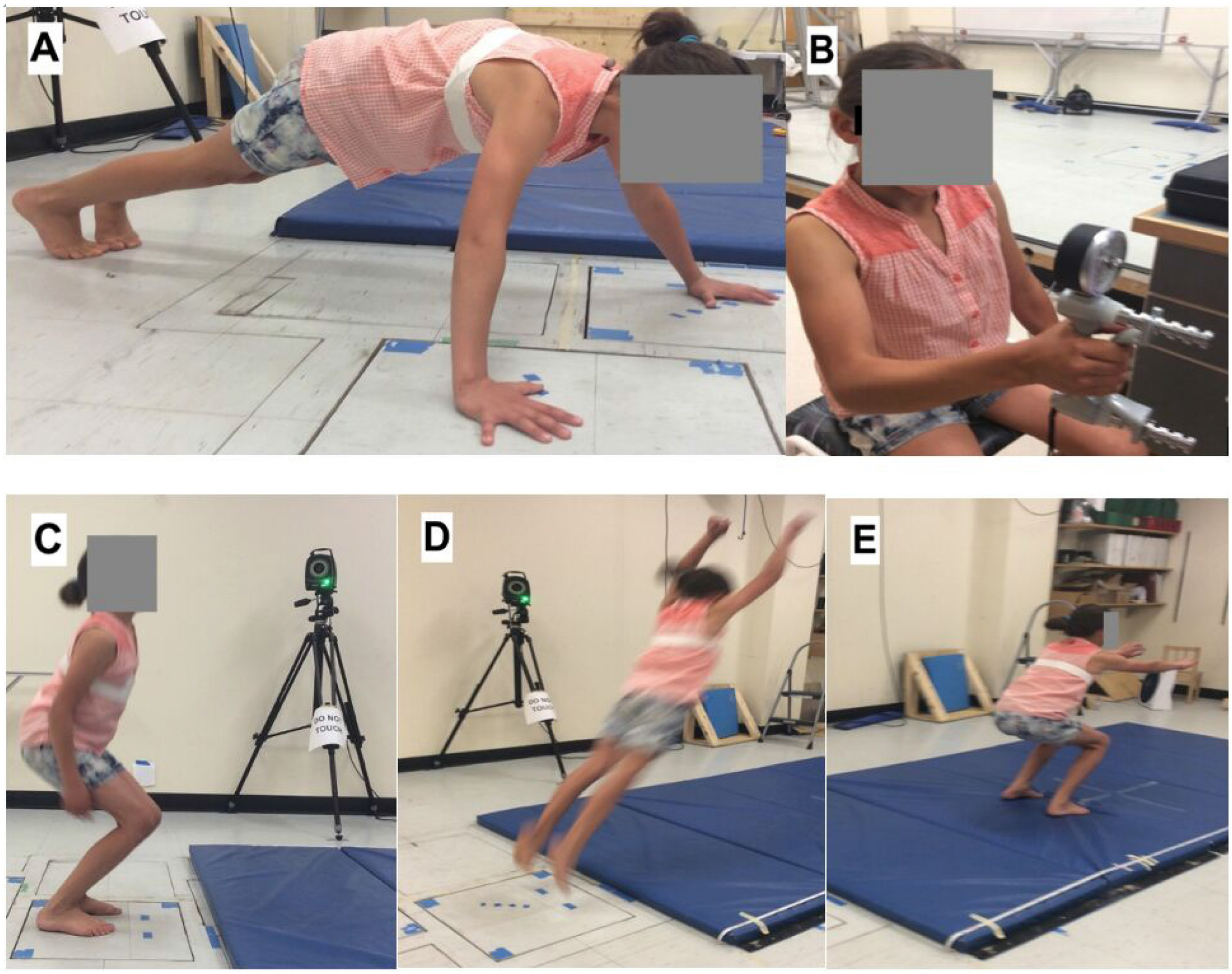

Figure 2. A participant demonstrating neuromuscular performance movements: (A) maximal pushup; (B) grip force; (C) countermovement jump; (D,E) standing long jump. Participant has given permission to publish photos.

capture true change[16,17]. MTI is important for optimal muscle measure selection and efficient longitudinal research study and intervention design.

In this study, our primary objective was to characterize precision errors and MTI for pQCT-acquired muscle properties (area and density) and neuromuscular performance measures in children. Our secondary objective was to explore factors related to the precision errors of muscle measures in children.

Materials and Methods

Participants

We recruited 35 participants (22 females, 8-14yrs) for the precision study[18] and 42 participants (21 females, 8-14yrs) for the 1-year follow-up study[19]. Fourteen participants (11 females) participated in both precision and follow-up studies. We excluded 2 follow-up cohort participants who did not meet the inclusion criteria based on maturity offset <1yr post age at peak height velocity[19,20]. All participants were recruited from local public schools and communities aged 8 to 14 years. The included participants were without disease and did not take medication influencing musculoskeletal growth. We required at least one day apart for two lab visits in the precision study, with an average interval of 28 days (SD 18 days, range from 1-75 days). The average interval between the baseline and follow-up testing was 1.2 yrs (SD 0.2yrs). Participant inclusion is described in Figure 1. We measured height, sitting height, body mass, maturity offset, and length of the ulna in the dominant forearm (preferred writing hand) and tibia in the dominant leg (preferred leg to kick a ball)[18,19]. In the precision cohort, we measured anthropometry at the first visit and used the same anthropometry data for the second visit. In the precision cohort, we obtained anthropometry at both visits from the first seven participants. In the follow-up cohort, we measured anthropometry at both baseline and follow-up visits from all participants.

Peripheral Quantitative Computed Tomography (pQCT)

We scanned the participant's dominant forearm and lower leg using pQCT (XCT 2000, Stratec Medizintechnik GmbH, Pforzheim, Germany)[18]. We obtained images for muscle area and density at the forearm (65% of ulna length from the reference line) and lower leg (66% of tibia length from the reference line). We used density thresholds to separate muscle structure (40-280mg/cm^3) from bone (>280mg/cm^3) and subcutaneous tissue (<40mg/cm^3)[18], and obtained muscle area (MuA, mm^2) and density (MuD, mg/mm^3) at the forearm and lower leg with manufacturer-provided software. Protocols for pQCT data acquisition, analysis and inclusion of all scans are described in detail elsewhere[18].

Neuromuscular Performance Assessment

Neuromuscular performance tests for the upper limb included a push-up and grip test. At the lower limb, the tests included a countermovement jump and a long jump. Before testing, one researcher provided detailed instructions and a demonstration of proper techniques before each neuromuscular performance test. Participants replicated each movement after the demonstration. Each test was performed three times. For the push-up test, participants started from a full plank with elbows fully extended and hands placed on two force platforms (AMTI, OR6-7) (Figure 2A). Then, participants would lower their whole bodies by bending their elbows followed by raising body straightly up as fast as they could. Our analysis included the highest vertical ground reaction force (GRF) from the dominant limb (regarded as the maximal push-off force). For the grip test, participants were required to hold a JAMAR 200 dynamometer (Sammon Preston Inc., Bolingbrook, IL) while bending their elbows at 90 degrees with their arms slightly apart from their bodies (Figure 2B). They were then instructed to squeeze the dynamometer as hard as they could. We obtained grip force from both hands with alternating hands between trials and used the highest maximal force of the dominant hand (regarded as the maximal grip force) in our analysis. For the countermovement jump, we instructed participants to stand upright and still on one force platform and try to jump as high as possible with a countermovement before the jump (Figure 2C). Arm movement and knee angles were not specifically restricted during the test. The maximal take-off vertical GRF, power, and impulse from the trial with the highest impulse were included in our analysis. For the long jump, participants started by standing upright and still on one force platform and feet behind a marked start-line on the force platform. Participants were required to jump forward as far as they could (Figure 2D, 2E). The jump length was measured from the start line to the back of the participant's heel. Arm swing was allowed during this test to help in jumping. The maximal vertical and horizontal take-off GRF, power, impulse, and jump length from the trial with the longest jump were used in our analysis.

Data Analysis

We assessed precision errors using the root-mean-square coefficient of variance ($CV\%_{RMS}$) with the following formulae[15,18].

$$CV\%_j = \left(\frac{SD_j}{\bar{x}_j}\right) \times 100\%$$

$$CV\%_{RMS} = \sqrt{\frac{\sum_{j=1}^{m} CV\%_j^2}{m}}$$

where j represents an individual participant, m is the total number of participants and $\bar{x}$ is the mean of the repeated measurements acquired.

To assess MTI, we first characterized change for each follow-up study participant as annualized change by dividing the change between baseline and follow-up measure by the time interval, expressed in years. We then calculated the annual percentage change by dividing annualized change by the baseline measure. We reported annualized follow-up measures comparison between baseline and annualized follow-up measures (paired t-test, $p<0.05$) to aid interpretation of findings[19]. Next we defined MTIs as the ratio of the least significant change (LSC) to median annual percentage change, representing the time necessary for half of the children to demonstrate age-related changes exceeding the instrument and operator's measurement error[16,17]. We assessed LSC via the equation LSC = 2.77 x $CV\%_{RMS}$, where 2.77 pertains to the selected level of statistical confidence (two-tailed 95% confidence)[16,17].

We explored associations between precision errors (CV%) of all muscle measures with maturity offset and time interval (between the 1st and 2nd visits) in all 35 precision study participants using Spearman's rank correlation (*rho*, $p<0.05$). Accordingly, we also explored correlations between precision errors and anthropometric changes (identified by paired t-tests) in seven precision study participants (with anthropometric measures at both visits).

Results

Muscle area at the forearm and lower leg had precision errors of 3.1% and 3.3%, respectively, while muscle density had precision errors of 2.8% and 1.3%, respectively (Table 1). The precision errors of neuromuscular performance force tests ranged from 5.1% – 14.0% (Table 1). Regarding MTI, muscle area exhibited an interval time of 1.0 – 1.2 years, and muscle density exhibited an interval of >43 years (Table 1). For neuromuscular performance measures, MTIs between 0.9 – 2.6 years were required (Table 1). All outcomes, apart from muscle density, changed between baseline and annualized follow-up measures in the follow-up study ($p<0.05$).

Overall, there were no consistent associations between

Table 1. Mean (standard deviation, SD) of the participants' characteristics and muscle outcomes in Precision and Follow-up Studies, along with precision error (root-mean-square coefficient of variation, $CV\%_{RMS}$), least significant change (LSC), mean and median annual % changes, and monitoring time intervals (MTI) for muscle outcomes.

	Precision Study				Follow-up Study				
	Visit 1	Visit 2	$CV\%_{RMS}$	LSC (%)	Baseline	Follow-up	Mean Δ (%)	Median Δ (%)	MTI
Age (yrs)	10.5 (1.8)				10.4 (1.6)	11.6 (1.6)			
Maturity Offset (yrs)	-1.7 (1.6)				-2.0 (1.4)	-0.9 (1.5)			
Height (cm)	143.9 (12.7)				142.9 (10.9)	150.6 (12.2)			
Body Mass (kg)	38.0 (11.1)				38.8 (13.8)	43.6 (13.8)			
Ulna Length (mm)	229.1 (23.5)				227.4 (20.3)	240.9 (21.6)			
Tibia Length (mm)	344.4 (34.9)				340.6 (30.9)	360.6 (30.5)			
Muscle Imaging									
Forearm									
Area (cm^2)	20.2 (4.5)	20.6 (4.4)	3.1	8.7	20.3 (5.1)	22.3 (6.1)	10.0	9.0	1.0
Density (g/cm^3)	74.4 (2.0)	74.6 (1.8)	2.8	7.6	75.4 (2.7)	74.9 (2.3)	-0.5	0.2	44
Lower Leg									
Area (cm^2)	38.7 (8.1)	38.9 (8.0)	3.3	9.1	39.3 (11.8)	42.5 (13.8)	7.9	7.7	1.2
Density (g/cm^3)	73.8 (1.4)	74.1 (0.9)	1.3	3.6	74.1 (3.7)	73.6 (3.5)	-0.6	-0.1	43
Maximal Pushup									
Vertical GRF (N)	166.9 (51.8)	171.9 (48.8)	8.6	23.7	159.1 (61.5)	194.1 (69.9)	25.6	19.5	1.2
Maximal Grip Force									
Force (N)	175.5 (57.8)	164.3 (60.5)	13.6	37.8	164.8 (50.8)	196.8 (61.5)	30.2	18.4	2.0
Countermovement Jump									
Vertical GRF (N)	774.6 (241.7)	803.2 (237.5)	8.4	23.3	783.4 (289.7)	891.3 (345.0)	13.3	11.2	2.1
Vertical Power (W)	1588.0 (587.1)	1572.9 (587.4)	12.7	35.1	1661.8 (833.9)	1851.1 (825.8)	17.3	19.4	1.8
Vertical Impulse (Ns)	84.6 (29.2)	84.0 (30.1)	9.7	26.9	88.1 (38.4)	100.8 (44.1)	17.3	18.0	1.5
Long Jump									
Vertical GRF (N)	763.9 (260.9)	767.1 (222.2)	6.4	17.8	752.5 (278.2)	872.3 (324.9)	15.9	14.5	1.2
Horizontal GRF (N)	267.7 (81.4)	264.0 (66.8)	8.5	23.6	251.5 (87.9)	302.4 (102.4)	21.3	19.7	1.2
Vertical Power (W)	925.5 (362.7)	963.0 (337.8)	13.2	36.5	915.4 (393.3)	1128.3 (432.1)	29.1	15.9	2.3
Horizontal Power (W)	480.4 (160.2)	475.8 (123.8)	11.9	32.8	440.7 (175.9)	548.4 (204.7)	26.9	26.7	1.2
Vertical Impulse (Ns)	50.0 (16.8)	52.0 (16.8)	14.0	38.8	51.0 (20.9)	61.5 (23.5)	26.8	15.0	2.6
Horizontal Impulse (Ns)	78.9 (23.0)	79.8 (21.5)	5.1	14.2	85.7 (29.1)	99.5 (33.3)	17.0	15.1	0.9
Length (cm)	133.2 (20.4)	134.4 (21.2)	5.8	15.9	125.9 (19.1)	132.7 (21.4)	5.9	6.4	2.5

precision errors and maturity, time interval or limb length changes in all precision study participants (Supplementary Table 1). Only maturity was correlated with maximal push-up GRF precision error (Spearman's *rho*= -0.349, *p*=0.046) (Supplementary Table 1). Both ulna and tibia lengths increased between the repeated visits in seven precision study participants (Supplementary Table 2), but those changes were not associated with precision errors (Supplementary Table 1).

Discussion

Our findings suggest that the precision errors range from 1-3% in imaged muscle properties, and 5-14% in neuromuscular performance measures. The imaged muscle area, maximal push-up, and some long jump measures are appropriate to follow up ~1 year, while the grip test and countermovement test measures are appropriate to follow up around ~2 years.

This is the first study using $CV\%_{RMS}$ to assess short-term precision errors of children's imaged muscle properties and neuromuscular performance. In our previous study with adult participants, precision errors ($CV\%_{RMS}$) were comparable (2.1% and 1.4% for forearm muscle area and density and 3.5% and 1.9% for lower leg muscle area and density, respectively)[21]. This was surprising, as we included all scans in the pediatric study whereas in the adult precision study, we rejected scans if cortical shell was irregular due to movement artefacts[21].

For neuromuscular performance, most previous research assessed the average of individual precision errors among repeated measures by the coefficient of variation ($CV\%_{MEAN}$), which may underestimate the true precision error[15], or intraclass correlation coefficient (ICC), which is a measure of the correlation between duplicated tests and does not directly quantify measurement error. Previous studies involving male athletes aged 6-16 reported that the maximal push-up force was only repeatable for older ages (10-15 years) and when taken from a starting position where the knees were grounded ($CV\%_{MEAN}$: 17.5–20.7%)[22]. A later study by the same group suggested a much larger $CV\%_{MEAN}$ (39%)[23]. These precision errors were higher than those found here ($CV\%_{RMS}$: 8.7%), which may be attributed to differences in the applied push-up approach (i.e., toes vs knee push-ups). For grip force, two previous studies reported ICC from 0.47-0.78 in children aged 7-10 years and ICC from 0.70 to 0.96 in children aged 4-6 years and 10-14 years, respectively[11,24]. These findings agreed with somewhat poor precision errors found here for grip force. Molenaar et al. reported a minimal detectable change (MDC) 15–35% for grip force[24], which was close to our LSC finding (LSC: 37.8%) (of note, LSC and MDC are comparable metrics, with the main difference being that MDC uses ICC in its calculation whereas LSC uses $CV\%_{RMS}$). Interestingly, Molenaar et al. suggested that different handgrip dynamometers may have different reliability in children[24], which is an area of future investigation. Regarding jumping-based activities, Meylan et al. and Veilleux & Rauch reported high repeatability for GRF, power, and impulse ($CV\%_{MEAN}$: 4-15%; ICC: 0.84 – 0.98)[8,12]. These results were comparable to our findings ($CV\%_{RMS}$: 8-13%). For the long jump, our findings were comparable (~1.2cm) with the reported inter-session differences in length (0.8–1.1cm)[12,13,25,26].

We did not rigidly control the time interval between the repeated visits in the precision study due to the varied scheduling needs of our participants and their families. Potential growth, particularly in participants with over 2 months between the repeated visits, may have led to an overestimation of precision errors and MTIs. However, observed growth in limb lengths was not associated with precision errors in any muscle outcomes (Supplementary Tables 1 & 2). This is likely due to growth at both distal and proximal growth plates, which likely maintained muscle scanning sites (that were relative to limb lengths) within pQCT slice thickness (~2.5mm)[27]. Future work should address the role of somatic growth in precision errors as exploratory analyses of data from seven participants should be interpret with caution. We also explored the roles of maturity and time interval within all 35 precision study participants and only maturity was negatively correlated with precision error of maximal pushup GRF. This agrees with a previous report of worse maximal push-up GRF precision in younger (6-11yrs) versus older (12-15yrs) boys[22].

Although no previous study characterized MTI in pQCT-measure muscle properties, several studies characterized the pQCT-measured muscle area growth curve[28,29]. Ashby et al. produced a growth curve for muscle area measured at the 50% radius site and reported areal growth of ~1cm^2 at the 50th percentile in both boys and girls between 10-11 years[28]. Although our median annualized change in the forearm area (1.7cm^2) was slightly larger than the ~1cm^2 reference value, we measured the 65% radius site which had the largest circumference and likely the largest muscle cross-sectional area, which may have a larger growth trajectory compared to the 50% radius site[30]. Conversely, we did not observe an increase in muscle density in the follow-up study, despite a previous cross-sectional study in female children suggesting a weak positive association between maturity and thigh and lower leg muscle density (correlation coefficient 0.10–0.14)[7]. Rationale for this discrepancy may be due to samples from different populations, as we had both male and female participants with wider maturity offset ranges.

To our knowledge, no previous studies exist regarding characterizing MTI in neuromuscular properties in children. Though, grip force reference values from the literature indicate median differences of 8-19% between adjacent age groups[31], which is comparable with median 1-year change results found here (18%). For jump power, countermovement jump reference data suggested a 10-18% median difference between adjacent age groups for age 9-14yrs[32], which is comparable to our study (19%). For long jump length, a previous study reported up to 3-21cm/year increase from 16 months before the age of peak height velocity to one year over[33], which was similar to what we reported in this study (~7cm annual change), though the annual change was close to the precision error.

Study findings can be widely used in pediatric studies monitoring musculoskeletal growth. The precision errors and LSC can help interpret findings in longitudinal and intervention studies. For example, if a statistical test indicated a 5% difference (p<0.05) and the LSC was 7%, the difference may reflect the measurement error rather than a true (biological) difference. MTIs can guide prospective research designs by informing of optimal follow-up timing and selection of neuromuscular measures[17,19]. Our results indicate that, overall, imaged muscle area offers a precise and detectable outcome for monitoring muscle growth in children whereas muscle density, albeit of comparable precision, is less ideal due to minimal annual change. The neuromuscular performance outcomes had around 1-2yrs MTIs making them ideal for annual or biannual follow-ups. Nonetheless, it is important to be cognizant that some neuromuscular performance tests offer a relatively cheap and convenient way to quantify physical growth in children and thus should be considered for future studies on motor skill development[10]. Overall, all neuromuscular performance measures can be followed up on around a two-year scale.

There are some specific factors that may influence our results. As discussed earlier, participants' growth between repeated visits in the precision study may have led to an overestimation of precision errors and MTIs. Although we did not observe associations between precision errors and anthropometric changes, our analyses were likely underpowered and limited to data from seven participants. Second, the learning (or practice) effect on neuromuscular performance may play a role in precision error calculation and annual changes for both the precision and follow-up studies[12]. For example, inexperienced participants may have different jumping techniques over all visits, resulting in different jump take-off angles and different power and impulse measures in horizontal and vertical directions[12]. Here experience may explain high precision errors found with neuromuscular performance tests. Third, we characterized annual %-changes, which assumed a linear development in muscle outcomes. Related to this, we further acknowledge males and females experiencing differences in timing and tempo of maturation[28]. Accordingly, the MTIs reported here offer general estimates for children up to the age of 14. This is supported by relatively similar growth rates for muscle properties and neuromuscular performance measures in both sexes before 12-14 years of age[28,31,34]. Finally, we did not assess participants' physical activity and nutrition, which could have influenced muscle growth and performance between baseline and one-year follow-up measures[35]. However, since the MTI was calculated based on median change, instead of mean annual % change, the influence of large gains or losses by individual participants should be minimized.

In conclusion, precision errors for pQCT-acquired measures of muscle area and density ranged from 1.3% to 3.3%, and precision errors for neuromuscular performance outcomes ranged from 5.1% to 14%. The MTI for muscle area was about 1 year (forearm: 1.0 years; lower leg: 1.2 years). Although precision errors for image-acquired muscle density were low, MTIs were high (>43 years) due to minimal annual change. MTIs for neuromuscular performance measures ranged from 1-2.6 years. There were no consistent associations between precision errors and maturity, time interval or limb length changes; however, one association suggested higher repeatability of maximal pushup ground reaction force with more mature children.

Ethics approval

This study was approved by the University of Saskatchewan Biomedical Research Ethics Board (Bio 13-43).

Consent to participate

All participants have provided their assent, and their parents or legal guardians have given consent for their children to participate in this study.

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Authors' Contributions

SK conceived and designed the study. YZ performed data processing and analysis with the code and guidance from JL. YZ interpreted the results together with SK, and drafted and revised the manuscript based on the feedback from JL, JDJ and SK.

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Supplementary Material

Supplementary Table 1. Correlations (Spearman's *rho*) between maturity offset at the 1st visit of precision study, time interval, and limb length changes between the repeated visits and precision errors (coefficient of variation, CV%).

Individual Precision Error (CV%)	Maturity Offset (N=35)		Time Interval (N=35)		Ulna Length Δ (N=7)		Tibia Length Δ (N=7)	
	Spearman's *rho*	*p*-value	Spearman's *rho*	*p*-value	Spearman's *rho*	*p*-value	Spearman's *rho*	*p*-value
Muscle Imaging								
Forearm								
Area (%)	-0.176	0.321	0.229	0.192	0.377	0.461	0.359	0.485
Density (%)	-0.055	0.759	0.210	0.234	-0.029	0.957	0.837	0.038
Lower leg								
Area (%)	-0.116	0.507	0.247	0.153	0.408	0.364	-0.220	0.635
Density (%)	-0.139	0.424	0.047	0.787	0.075	0.873	-0.074	0.875
Maximal Pushup								
Vertical Ground Reaction Force (%)	-0.349	0.046	0.161	0.372	-0.152	0.774	-0.353	0.492
Maximal Grip Force								
Force (%)	-0.044	0.800	0.056	0.748	0.075	0.873	-0.074	0.875
Countermovement Jump								
Vertical Ground Reaction Force (%)	0.092	0.607	-0.089	0.616	-0.630	0.129	0.698	0.081
Vertical Power (%)	-0.118	0.507	-0.167	0.345	-0.593	0.161	0.018	0.969
Vertical Impulse (%)	-0.096	0.589	0.077	0.665	-0.556	0.195	-0.055	0.907
Long Jump								
Vertical Ground Reaction Force (%)	0.210	0.233	0.005	0.979	-0.371	0.413	0.606	0.149
Horizontal Ground Reaction Force (%)	0.051	0.776	-0.214	0.225	0.222	0.632	0.385	0.393
Vertical Power (%)	-0.337	0.060	0.011	0.953	0.577	0.231	0.265	0.612
Horizontal Power (%)	-0.075	0.683	-0.333	0.062	0.577	0.231	0.088	0.868
Vertical Impulse (%)	-0.165	0.367	-0.089	0.629	0.334	0.518	0.177	0.738
Horizontal Impulse (%)	-0.141	0.440	-0.225	0.217	0.395	0.439	0.500	0.312
Length (%)	-0.042	0.811	0.276	0.114	-0.334	0.465	-0.110	0.814

Supplementary Table 2. Mean (standard deviation, SD) of the participants' characteristics and muscle outcomes from the 7 participants who had anthropometry measured at both visits in precision study along with precision error (root-mean-square coefficient of variation, $CV\%_{RMS}$), least significant change (LSC) calculated from the precision study.

	Visit 1	Visit 2	$CV\%_{RMS}$	LSC (%)
Age (yrs)	10.3 (2.3)	10.4 (2.2)		
Maturity Offset (yrs)	-1.4 (2.1)	-1.4 (2.1)		
Height (cm)	142.8 (15.0)	142.6 (14.9)	0.2	0.5
Body Mass (kg)	34.1 (9.0)	35.6 (9.9)	0.8	2.3
Ulna Length (mm)*	222.3 (22.6)	227.3 (23.2)	1.6	4.2
Tibia Length (mm)*	342.9 (35.9)	345.6 (36.9)	0.5	1.5
Muscle Imaging				
Forearm				
Area (cm^2)	18.8 (3.4)	19.2 (2.6)	3.4	9.4
Density (g/cm^3)	75.5 (3.1)	75.0 (2.0)	4.4	12.1
Lower Leg				
Area (cm^2)	35.2 (5.2)	36.0 (6.1)	2.4	6.7
Density (g/cm^3)	74.7 (1.4)	74.7 (0.9)	1.3	3.6
Maximal Pushup				
Vertical GRF (N)	148.4 (36.6)	151.2 (41.7)	7.4	20.6
Maximal Grip Force				
Force (N)	159.7 (44.1)	152.9 (68.6)	14.3	39.5
Countermovement Jump				
Vertical GRF (N)	737.6 (254.2)	864.7 (292.5)	15.3	42.3
Vertical Power (W)	1378.4 (546.1)	1548.7 (500.4)	15.2	42.1
Vertical Impulse (Ns)	73.6 (24.5)	77.1 (22.1)	8.2	22.8
Long Jump				
Vertical GRF (N)	781.2 (298.5)	771.9 (262.1)	9.3	25.8
Horizontal GRF (N)	244.3 (74.0)	255.2 (80.3)	12.2	33.8
Vertical Power (W)	914.2 (468.8)	941.7 (404.2)	13.1	36.3
Horizontal Power (W)	408.9 (147.2)	463.0 (106.6)	13.6	37.8
Vertical Impulse (Ns)	47.0 (21.1)	50.1 (27.1)	15.5	42.8
Horizontal Impulse (Ns)	67.8 (18.8)	74.7 (19.2)	6.0	16.7
Length (cm)	125.4 (16.9)	131.4 (22.3)	8.1	22.5

**Significant difference between Visit 1 and 2 (paired t-test, $p<0.05$).*