Knee extensor strength differences in obese and healthy-weight 10-13 year olds.

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Abstract

The purpose of this study was to investigate if obese children have reduced knee extensor (KE) strength and to explore the relationship between adiposity and KE strength. An observational case-control study was conducted in three Australian states, recruiting obese [n=107 (51 female, 56 male)] and healthy-weight [n=132 (56 female, 76 male)] 10–13 year old children. Body mass index, body composition (dual energy X-ray absorptiometry), isokinetic/isometric peak KE torques (dynamometry) and physical activity (accelerometry) were assessed. Results revealed that compared with their healthy-weight peers, obese children had higher absolute KE torques (P≤0.005), equivocal KE torques when allometrically normalized for fat-free mass (FFM) (P≥0.448) but lower relative KE torques when allometrically normalized for body mass (P≤0.008). Adjustments for maternal education, income and accelerometry had little impact on group differences, except for isometric KE torques relative to body mass which were no longer significantly lower in obese children (P≥0.013, not significant after controlling for multiple comparisons). Percent body fat was inversely related to KE torques relative to body mass (r= -0.22 to -0.35, P≤0.002), irrespective of maternal education, income or accelerometry. In conclusion, while obese children have higher absolute KE strength and FFM, they have less functional KE strength (relative to mass) available for weight-bearing activities than healthy-weight children. The finding that FFM-normalized KE torques did not differ suggests that the intrinsic contractile properties of the KE muscles are unaffected by obesity. Future research is needed to see if deficits in KE strength relative to mass translate into functional limitations in weight-bearing activities.

Keywords: Body Mass Index, child, isokinetic dynamometry, quadriceps femoris
Introduction

Childhood overweight and obesity continues to be the key health concern of developed nations worldwide (Ebbeling et al. 2002). While the medical consequences of obesity are well known, physical impacts in childhood are receiving increasing attention. Studies consistently report that children with obesity have a reduced capacity to undertake weight-bearing locomotor tasks (Tsiros et al. 2011a; Tsiros et al. in press) and impaired fundamental movement skills (Okely et al. 2004); importantly, the latter has been associated with participation in organized physical activity (Okely et al. 2001) which has important implications for obesity management and long-term health.

Muscle tissue is responsible for generating the forces required for movement. Reduced muscle strength, particularly in the lower limb, may contribute to movement problems in obese children. The knee extensors may be of particular importance, being responsible for the generation of torque required to perform many tasks of daily living, including locomotion, functional tasks (such as getting up from a chair and climbing stairs) as well as sporting activities (Maffiuletti et al. 2008). The importance of the knee extensors (KE) for performing many daily activities is supported by adult literature which has shown that lower isometric KE strength in obese women is associated with physical disability (Rolland et al. 2007). Due to the importance of KE strength for the performance of many daily activities a number of pediatric studies have also focused on KE strength in children with obesity (Tsiros et al. 2011a) although only three (Blimkie et al. 1989; Blimkie et al. 1990; Maffiuletti et al. 2008) have used isokinetic dynamometry to assess both isometric and isokinetic strength – the gold standard method of strength assessment. Two studies were conducted by the same group examining obese and healthy-weight 9-18 year old boys (Blimkie et al. 1989; Blimkie
et al. 1990), while the third study examined severely obese versus healthy-weight 13-17 year olds. Findings from these studies suggest that obese children have similar or higher absolute KE strength than their non-obese peers (Blimkie et al. 1989; Blimkie et al. 1990; Maffiuletti et al. 2008); presumably due to a ‘training-effect’ induced by obesity-related excess mass. In contrast, studies by Blimkie and colleagues (1989; 1990) suggest that relative strength expressed per unit of body mass may be lower in obese children, which is more likely to reflect the functional KE strength available for weight-bearing activities. When corrected for fat free mass (FFM), obese/non-obese KE strength appears similar which suggests that the contractile quality of KE muscle tissue is unaffected by obesity (Blimkie et al. 1989; Blimkie et al. 1990; Maffiuletti et al. 2008). Blimkie et al. (1989) further confirmed this premise, finding no differences between obese and healthy-weight participants in electrically evoked (as opposed to voluntary) KE torques.

There are several methodological issues that bias previous research in this field. Firstly, studies have only used simple ratio standards to scale KE strength for body size (i.e. strength divided by mass or FFM) to enable obese/healthy-weight comparisons. The problem with this approach is that the underlying assumption of a linear relationship between strength and body size does not always hold true (Wren and Engsberg 2007; Nevill and Holder 1995), and this method may in fact overcorrect for body size producing biased results. Therefore, allometric scaling has been recommended (Jaric 2002; Wren and Engsberg 2007; Nevill and Holder 1995), which involves dividing strength by the body size/mass measure raised to the power of a specific scaling exponent (Wren and Engsberg 2007; Nevill and Holder 1995). Secondly, physical activity levels are also likely to impact KE strength, therefore confounding any relationship between obesity and lower limb strength. While Maffiuletti et al. (2008)
described their sample as not engaging in very vigorous activity, this was not quantified (or statistically controlled for) and appeared to be dependent on self-report evaluations which are known to be subject to recall bias (Baranowski 1988). Generalizability of previous work is also limited by small sample sizes (N ≤ 24) restricted to males only. Definitions of weight status have also varied between studies, overlooking International Obesity Task Force (IOTF) criteria (Cole et al. 2000) and no studies have used more accurate assessments of body composition such as dual energy X-ray absorptiometry (DXA).

The current study aimed to examine if children with obesity have reduced KE strength compared with their healthy-weight peers and to explore the relationship between adiposity and KE strength. Limitations with previous research were addressed, meaning this is the first investigation in children using the gold-standard method of isokinetic dynamometry that also allometrically normalizes KE strength, controls for objectively-assessed physical activity levels and characterizes body composition using IOTF criteria and DXA. It is also the largest study in this field, and the first that is generalizable to females.

**METHODS**

Using an observational case-control design, 10-13 year old children who were either obese or healthy-weight according to IOTF criteria (Cole et al. 2000; Cole et al. 2007) were recruited from three Australian states (Queensland, Victoria and South Australia) via media releases, flyers, paid newsprint advertisements, school newsletters and a hospital as previously described (Tsiros et al. in press). Overweight (Cole et al. 2000) and underweight (Cole et al. 2007) children or those who had been engaged in obesity treatment in the prior three months were excluded. Children with conditions that could interfere with their
performance of the tests were also excluded (i.e. an intellectual/neurological condition or an acute injury necessitating medical treatment in the prior six months). Multiple Human Research Ethics Committees provided ethical approval for this study (University of South Australia, RMIT University, Flinders Medical Centre and Queensland University of Technology). Written informed consent (from parents/legal guardians) and verbal assent (from children) was obtained prior to their participation.

**Anthropometry and body composition**

Children attended a single physical assessment appointment (with their parent) at their local research facility. The International Society for the Advancement of Kinanthropometry protocol was used for all anthropometric measures (Norton and Olds 1996). Body mass was measured to the nearest 0.1 kg with participants clothed in a hospital gown and underwear using digital scales (Tanita BWB 600 or TANITA ultimate scale 2000 scales, Tanita Corporation, Tokyo, Japan). Height was measured to the nearest 0.1 cm with participants barefoot using a wall-mounted stadiometer (Heightronics, QuickMedical, Issaquah, USA, or SECA 22, Hamburg, Germany). Body Mass Index (BMI: kg/m²) was calculated and participants were categorized as obese or healthy-weight according to IOTF criteria (Cole et al. 2000).

Estimations of percent body/tissue fat (%) and non-bone fat-free lean tissue mass (FFM, kg) were obtained from whole body DXA scans (Lunar Prodigy, General Electric, Madison, USA. Standard software: ENCORE 2003, version 7.52, General Electric Medical Systems). A standard positioning protocol was used (as per manufacturer recommendations), with participants wearing only a hospital gown and underwear.
Physical activity

Uniaxial accelerometers (Actigraph®, MTI Health Services, Fort Walton Beach, Florida, USA, version 2.2 model 7164) were selected to assess physical activity given their excellent inter-instrument reliability (ICC 0.87) (Trost et al. 1998) and acceptable validity (r=0.50–0.74) (Janz 1994; Puyau et al. 2002). Children wore the Actigraph® consecutively for eight days (plus overnight) on their right hip, only removing it when in the water. Data were collected during the school term (excluding school holidays) using one-minute sampling epochs. Eligible data comprised of at least four weekdays and Saturday and Sunday with at least 10 eligible hours (more than 3000 counts per hour) of daily wearing-time. As children were awake for varying hours per day, eligible data were reduced to average counts per hour per day. Average counts per hour for weekdays and weekend days were then calculated separately and a weighted average taken to reflect overall activity for the week (termed weekly average counts per hour). Weekdays and weekend days were evenly weighted, thereby reflecting the usual annual pattern [children spend about one day in two over the year in school (4 terms x 10 weeks x 5 days=200 days, less around 10 days of public holidays/pupil-free days, and about 10 days of illness =180 days a year)].

Demographics/background information

Parents completed a background/demographic questionnaire to capture data on socioeconomic status (SES; average annual household income and maternal education), child medical conditions and any prescribed medications. Children also self-assessed their level of pubertal development with parental guidance using the Tanner scales (Tanner 1962; Brooks-Gunn et al. 1987).
Knee extensor muscle function

Isokinetic and isometric peak KE torques were assessed using an isokinetic dynamometer (Biodex System 4 or Biodex System 3, Biodex Medical Systems inc., New York, USA) on both limbs. The Biodex has excellent test re-test reliability in obese and healthy-weight children (ICC of 0.96) (Tsiros et al. 2011c), and excellent mechanical reliability/validity (ICC of 0.99 - 1.00) (Drouin et al. 2004). Testing protocols were as per our earlier pilot studies (Tsiros et al. 2011c; Tsiros et al. 2011b). In short, testing was done in the order of dominant followed by non-dominant limb (preferred limb ascertained by observing participants kicking a ball three times), and participants were provided with standardized verbal instructions, familiarization repetitions (three submaximal and one maximal), real-time visual on-screen feedback and vigorous verbal encouragement during testing (Wiggin et al. 2006). The dynamometer axis of rotation was aligned both at rest and during a KE contraction to minimize obesity-related malalignments arising from soft tissue compression. Peak isometric KE torque was tested first at 90 degrees of knee flexion, using three five-second contractions interspersed with 45s rest periods. Peak isokinetic KE torque was then assessed using ten consecutive contractions through a 95° range of motion at a velocity of 60°/s. This testing velocity was based on prior evidence that suggests children generate the greatest torque at this velocity compared with faster concentric velocities (Wiggin et al. 2006). Data were exported at a rate of 1000Hz to an external data acquisition device (Powerlab 16/30, BioAmp and LabChart version 6 software, AD Instruments Pty Ltd, Colorado Springs, USA) and were corrected for limb mass [measured using the Biodex Advantage software (Biodex Medical Systems Inc.) with the limb position 30° below horizontal]. Peak torques were normalized for body mass and FFM using allometric modeling exponents (‘b’) determined from a
subsample (n=77 obese, n=78 healthy-weight) employing the log linear regression model outlined by Nevill and Holder (1995) and the following equation:

\[ \text{Torque}_{\text{normalized}} = \frac{\text{Torque}_{\text{measured}}}{(\text{Body mass OR FFM})^b} \]

The specific exponents used in the current study are identified as superscripts in Tables 1 and 2. It was deemed appropriate to calculate specific exponents (i.e. ‘b’) suitable for use with this population (from pilot study/sub-sample data), as factors such as age, sex and physical activity level affect strength, mass and FFM meaning that different populations require different methods for adjusting strength for body size. Hence previously published exponents by Jaric and colleagues (2002) in physically active men (N=16, aged 22-47 years) are not suitable for use, and there is ongoing disagreement regarding the most appropriate exponents suitable for use with children (Wren and Engsberg 2007; Duchê et al. 2002).

Furthermore, the pilot study (N=155) revealed that the correction of isometric and isokinetic torques using the derived allometric exponents were successful in rendering torques independent of body size (both mass and FFM) and were therefore valid (tested using linear regression analyses between allometrically normalized torques and the body size variables of interest, \( r \leq 0.06, P \geq 0.48 \)).

**Statistical analysis**

Statistical analyses were performed using SPSS version 17 for WINDOWS [International Business Machines Corporation (IBM), New York, USA]. Expectation maximization algorithms were used to impute data that were missing completely at random [\( P=0.61, \) Little’s missing completely at random test (Little 1988)]. Obese/healthy-weight group differences were ascertained using the Student’s independent-samples t-test (unadjusted) and were then adjusted for potential confounding variables that were significantly different between groups (accelerometry, maternal education and household income) using
ANCOVA. Relationships between KE strength outcomes and percent body fat were explored using scatter plots and linear regression analyses (unadjusted and adjusted for accelerometry, maternal education and household income). An alpha level of $P \leq 0.05$ was set to explore unadjusted differences in demographic variables and a post hoc sequential Bonferroni procedure (Rice 1989) was used for multiple comparisons between KE strength outcomes (resultant alpha levels of $P \leq 0.008$ and $P \leq 0.006$ for obese/healthy-weight comparisons and linear regressions respectively). Data from males and females were pooled for analyses, as we did not expect gender to modify the relationship between obesity and KE strength given the age and sexual immaturity of this sample. This was confirmed by a post hoc sensitivity analysis revealing comparable $r$ values for males and females when examining relationships between percent fat and KE torque outcomes.

RESULTS
A total of 529 children were screened, of whom 267 were eligible consenting volunteers. Twenty-eight healthy-weight children were declined as the recruitment quota had already been met, leaving a final dataset of 239, made up of 107 obese (51 female, 56 male) and 132 healthy-weight children (56 female, 76 male). More children were recruited from South Australia (n=155) compared with Victoria (n=53) and Queensland (n=31). The obese and healthy-weight group did not differ by age or height ($P \geq 0.334$) but as expected, there were significant differences in mass, BMI, percent fat and FFM (Table 1, $P<0.001$). Obese children also had significantly lower physical activity (accelerometry, $P<0.001$, Table 1). Pubertal maturation was similar between groups ($P=0.13$) (pre to mid-pubertal), with only 4% having reached pubertal maturation (level 5 Tanner). Maternal education was lower in the obese group (27% being University educated vs 49% in the healthy-weight group, $P=0.005$), as was
average household income (27% earning ≥$100,000 AUS compared with 43% of healthy-weight families, P<0.001).

Dominant limbs were significantly stronger than non-dominant limbs for all strength variables in all volunteers (paired t-tests, P<0.001). Although absolute peak KE torques were significantly higher in obese children vs. healthy-weight peers (P≤0.004, unadjusted), mass-normalized torques were lower in obese children (P≤0.008, unadjusted) (Table 2). Conversely, there were no significant between-group differences in FFM-normalized KE torques (P≥0.339, unadjusted). For the most part, adjustments for maternal education, household income and physical activity had little impact, with the exception of isometric KE torques relative to mass which were non-significant when controlling for: maternal education/household income (dominant limb, P=0.013) and accelerometry/maternal education/household income (both limbs, P≥0.040) (Table 2).

Linear regressions revealed significant inverse relationships between percent fat and peak KE torques normalized for mass that persisted after controlling for maternal education, household income and accelerometry (r= -0.22 to -0.35, P≤0.002, unadjusted and adjusted) (Table 3). In contrast, there were no significant relationships between percent fat and absolute or FFM-adjusted KE torques (r=0.001 to 0.18, P=0.017 to 0.988, unadjusted and adjusted). Further regression analyses were conducted to assist in explaining the aforementioned results. Specifically, accelerometry was positively related to KE torques relative to mass (r=0.19 to 0.23, P≤0.003, unadjusted), but not absolute or FFM-normalized KE torques (P≥0.071, unadjusted).
DISCUSSION

Findings from the current study are consistent with previous dynamometry research (Blimkie et al. 1989; Blimkie et al. 1990; Maffiuletti et al. 2008) investigating effects of obesity on KE strength in children, although such research is scarce. In this study children with obesity, when compared with their healthy-weight peers, experienced approximately 10-15% functional KE strength deficits relative to mass. Such functional deficits are most likely the result of a disparity between contractile tissue and the load imposed by excessive fat. Differences in the quality and contractile properties of the muscle tissue itself are unlikely given the lack of FFM-normalized differences observed between obese and healthy-weight groups. Obese children had higher FFM and correspondingly higher absolute KE torques (14-17% higher compared with healthy-weight children), not dissimilar to the 16% differences previously found in severely obese boys (Maffiuletti et al. 2008). However, this compensatory effect was insufficient to offset functional strength deficits relative to mass.

A novel finding of this study was that peak KE torques normalized for mass consistently reduced as percent fat increased, offering further support that obesity is associated with KE muscle function deficits relative to mass. In contrast, percent fat and absolute KE torques were not significantly related which supports the notion that increased absolute KE torques in obese children may be attributable to their increased FFM, given that percent fat represents adiposity normalized for FFM/bone mass. This lack of relationship between percent fat and absolute KE torques is also consistent with prior research in presumably healthy-weight boys using less accurate adiposity measures (i.e. skin folds) (Almuzaini 2007).
The inclusion of physical activity (i.e. accelerometry) and SES factors as covariates had little impact on observed relationships between adiposity and KE torques and obese/healthy-weight differentials, with the exception of isometric KE torques relative to mass which were non-significant when controlling for physical activity (both limbs) and SES factors (dominant limb). The most likely explanation for these discrepant findings is that physical activity changes the ratio of fat mass to FFM, thereby impacting KE torques relative to mass, most notably when comparing BMI-based obese/healthy-weight comparisons that could be impacted by such changes. Further data from this sample supports this premise whereby overall physical activity (accelerometry) was positively related to KE torques normalized for mass. SES factors could indirectly contribute via the same pathway given that higher maternal education/household income (as observed in the healthy-weight group) has been shown to promote higher moderate to vigorous physical activity levels in children (Gordon-Larsen et al. 2000).

The findings of this study may have important implications for obese children in their daily lives. While it is likely that reduced physical activity levels contribute to poorer knee strength in obese children, (a premise our data supported with a weak correlation between accelerometry counts and KE torques relative to mass), it is also possible that this is a bi-directional relationship setting up a negative cycle - for example, reduced functional KE strength relative to mass may pose yet another barrier to obese children’s capacity for engaging in physical activity. Although speculative, functional lower-limb strength deficits may also contribute to previously reported obesity-related disability in common weight bearing activities like walking, climbing stairs and getting up from a chair (Tsiros et al. 2011a; Tsiros et al. in press). Furthermore, given the key role of the KE extensors in stabilizing the
knee joint and attenuating ground reaction forces during locomotion (Mikesky et al. 2000), it is also possible that such functional KE weakness could lead to increased joint loading and the development of pain/osteoarthritic changes over time, as has been reported in obese elderly women (Slemenda et al. 1997; Slemenda et al. 1998; Mikesky et al. 2000).

This study has a number of notable strengths. Generalizability has been improved by the large sample size inclusive of females and the use of IOTF criteria and DXA-measured percent fat provide a clearer picture of obesity-related strength deficits. To our knowledge, this is the first study to control for the confounding influence of physical activity using an objective tool, thereby avoiding recall bias linked to self-report measures (Baranowski 1988). Perhaps most importantly, the use of allometric scaling (over ratio standards) reduces the risk of bias from KE strength outcomes being overcorrected for body size/mass. However, some limitations are still evident. Specifically, as children were already undertaking 2 hours of assessments, we opted to minimize further participant burden by only testing two isokinetic velocities [$60^\circ$/s and $0^\circ$/s (isometric)]. However, we recognize that many functional tasks (especially sports) would require eccentric and concentric muscle contractions at much higher velocities. Furthermore, the cross-sectional nature of this study precludes conclusions about causation.

**CONCLUSION**

These findings suggest that despite higher FFM and KE muscles with comparable torque-generating capacities per unit of FFM to their healthy-weight peers, KE strength deficits relative to mass were observed in obese children. The additional burden of excess adipose tissue mirrored by such mass-relative strength deficits potentially reflects the true
functional strength that obese children have available to contend with weight-bearing activities in their daily lives. Future investigations are needed to ascertain whether deficits in relative KE strength are related to functional limitations in locomotor tasks and the development of pain in this population, as well as longitudinal and intervention studies to confirm causation of these relationships.

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CONFLICTS OF INTEREST

The authors declare they have no conflict of interest.
1 REFERENCES


LIST OF ABBREVIATIONS

1. BMI – body mass index
2. DXA – dual energy X-ray absorptiometry
3. FFM – fat free mass
4. IOTF – International Obesity Task Force
5. ICC – intra class correlation coefficient
6. KE – knee extensor
7. SES – socioeconomic status

This research was conducted in Australia in accordance with Australian law.
1 **ONLINE RESOURCE 1 CAPTION**

2 **Online resource 1 Relationships between knee extensor torques and body mass.**

3 These figures demonstrate that the applied allometric exponents (‘b’) used to normalize absolute isometric/isokinetic torques were successful in rendering corrected torques independent of body mass [using the equation of Nevill and Holder 1995; Torque\textsubscript{normalized} = Torque\textsubscript{measured} / (Body mass OR FFM)^b]. This is depicted in Panel’s B and D where there is no linear relationship between allometrically-mass normalized knee extensor torque and body mass (isokinetic Panel B r=0.02, P=0.820; isometric Panel D r=0.04, P=0.603). In contrast, strong linear relationships can be observed between absolute knee extensor torques and body mass (isokinetic Panel A r=0.72, P<0.001; isometric Panel C r=0.65, P<0.001).