Knee extension strength in obese and nonobese male adolescents

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Abstract: The aim of the present study was to compare "absolute" and "relative" knee extension strength between obese and nonobese adolescents. Ten nonobese and 12 severely obese adolescent boys of similar chronological age, maturity status, and height were compared. Total body and regional soft tissue composition were determined using dual-energy X-ray absorptiometry (DXA). Knee extensors maximum voluntary contraction (MVC) torque was measured using an isometric dynamometer at a knee angle of 60° (0° is full extension). Absolute MVC torque was significantly higher in obese adolescents than in controls. However, although MVC torque expressed per unit of body mass was found to be significantly lower in obese adolescent boys, no significant difference in MVC torque was found between groups when normalized to fat-free mass. Conversely, when correcting for thigh lean mass and estimated thigh muscle mass, MVC torque was significantly higher in the obese group (17.9% and 22.2%, respectively; $P < 0.05$). To conclude, our sample of obese adolescent boys had higher absolute and relative knee extension strength than our nonobese controls. However, further studies are required to ascertain whether or not relative strength, measured with more accurate in vivo methods such as magnetic resonance imaging, is higher in obese adolescents than in nonobese controls.

Key words: adolescence, knee extensors, maximal strength, muscle mass, obesity.

Résumé : Le but de la présente étude a été de comparer la force « absolue » et « relative » des extenseurs du genou entre des adolescents obèses et non-obèses. Nous avons comparés 10 adolescents non-obèses et 12 adolescents sévèrement obèses d'âge chronologique, de statut pubertaire et de taille similaires. La composition corporelle totale et régionale du corps a été déterminée à partir de l'absorptiométrie biphotonique à rayons-X (DEXA). La force de contraction volontaire maximale (FMV) des extenseurs du genou a été mesurée en utilisant un dynamomètre isométrique à un angle articulaire de 60° (0° = extension complète). FMV a été significativement plus élevée chez les adolescents obèses comparés au groupe contrôle. Néanmoins, alors que FMV rapportée à la masse corporelle a été significativement plus faible chez les adolescents obèses, aucune différence significative de FMV normalisée à la masse maigre totale n'a été observée entre les deux groupes d'adolescents. En revanche, lorsque FMV a été rapportée à la masse maigre ou à la masse musculaire estimée de la cuisse, les adolescents obèses ont présenté des valeurs significativement supérieures à celles des adolescents normo-pondérés (17,9 % and 22,2 %, respectivement; $P < 0,05$). Pour conclure, notre groupe d'adolescents obèses a produit une FMV absolue et relative des extenseurs du genou plus élevée que les adolescents normo-pondérés. Des études supplémentaires sont néanmoins nécessaires pour savoir si la FMV relative estimée à partir de méthodes de mesures in vivo plus précises (c.-à-d., imagerie par résonance magnétique) est plus élevée chez les adolescents obèses.

Mots-clés : adolescence, extenseurs du genou, force maximale, masse musculaire, obésité.

Introduction

Although the cardiovascular and metabolic consequences of obesity have been studied extensively, less attention has been paid to investigating the impact of obesity on functional muscle abilities (Tsiros et al. 2011). It is becoming increasingly apparent from the adult literature that obesity is associated with reduced physical function; however, paediatric literature in this area is extremely limited (Tsiros et al. 2011). In particular, the function of the knee extensor muscles, which are highly involved in ambulatory and functional activities, has received little attention in the paediatric population. The high body mass carried by severely obese children could act as a chronic training stimulus generating favourable adaptations of the knee extensor muscles. Alternatively, the extra load associated with severe obesity could also restrain children's spontaneous physical activity (Nantel et al. 2011; Trost et al. 2001) and hence alter the function of

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the knee extensors. As a result, it remains unclear whether the functional characteristics of the knee extensors are positively or negatively affected by overweight in children.

The functional capacity of a skeletal muscle can be assessed from its ability to produce force. "Absolute" strength, which is the amount of force that a person can exert, is of great importance for daily activities. "Relative" strength, which is the maximum force that an individual can exert in relation to his or her body size, is particularly useful to compare individuals of different body dimensions and to gain insight into muscle quality and neural drive (Bouchant et al. 2011; Tonson et al. 2008). Whether absolute knee extension (KE) strength differs between obese and nonobese children or adolescents still remains a matter of debate. Although some authors found similar absolute torque during isometric (i.e., static contraction) and isokinetic (i.e., contraction at a constant angular velocity) maximal voluntary contractions (MVC) in obese and nonobese preadolescent and adolescent boys (Blimkie et al. 1989, 1990), others have reported higher isometric and isokinetic absolute torque values in severely obese adolescent boys compared with controls (Maffiuletti et al. 2008). Similarly, controversial results were found on the relationship between KE strength and body mass index (BMI) in obese youth (Almuzaini 2007; Grund et al. 2000). For instance, Almuzaini (2007) established a significant positive relationship between absolute strength and BMI in Saudi children and adolescents, whereas Grund et al. (2000) reported no significant relationship between both variables in German 5- to 11-year-old children. Part of these controversies could be related to the definition of obesity, which varied between studies. Some used the sum of skinfold thickness measurements or the percentage of body fat assessed from measurements of skinfold thickness (Blimkie et al. 1989, 1990), whereas others employed BMI (Almuzaini 2007; Grund et al. 2000; Maffiuletti et al. 2008). However, none of them applied the International Obesity Task Force (IOTF) criteria (Cole et al. 2000), which are highly recommended in international comparisons of prevalence of overweight and obesity (Tsiros et al. 2011). The wide variety of definitions of child obesity could confound some comparisons because children and adolescents could be differently classified (overweight vs. obese vs. severely obese). It should be pointed out, however, that those who are "severely obese" are likely to be classified as obese by all methods.

The effects of obesity on relative strength of children and adolescents are also a matter of debate. Many authors have used ratio standards whereby KE strength is divided by some measures of body dimensions (e.g., body mass (BM) or fat-free mass (FFM)) (Blimkie et al. 1989, 1990; Lazzer et al. 2009; Maffiuletti et al. 2008). These studies demonstrated a lower KE strength – BM ratio and a similar KE strength – FFM ratio in obese adolescents compared with normal weight controls (Blimkie et al. 1990; Lazzer et al. 2009; Maffiuletti et al. 2008). However, the use of such ratio standards may be incorrect because muscle strength is not directly proportional to FFM or BM values (Nevill and Holder 1995; Wren and Engsberg 2007). Indeed, muscle strength is directly related to muscle mass rather than to unit BM or FFM (O'Brien et al. 2009; Tonson et al. 2008). It is also worth noting that, in most studies, FFM was determined by anthropometry and electrical bioimpedance, which are not fully accurate in obese youth (Eisenmann et al. 2004; Lazzer et al. 2003; Reilly et al. 2010). Indeed, these techniques generally overestimate FFM in obese adolescents (Lazzer et al. 2003) and cannot be used to compare relative muscle strength between obese and nonobese young people. Dual-energy X-ray absorptiometry (DXA) would be more appropriate to measure total body and regional soft tissue composition as this technique was found to be highly precise and reproducible in nonobese and obese young people (Figueroa-Colon et al. 1998; Bridge et al. 2011; Tsang et al. 2009). However, to the best of our knowledge, no study has used DXA measures of body dimensions to evaluate relative KE strength in obese and nonobese adolescents.

Therefore, the aim of the present study was to compare absolute and relative KE strength between obese and nonobese male adolescents of 12–15 years by considering the above-cited methodological biases and hence ascertain whether KE maximal strength production capacity is specifically dependent on obesity in youths.

Methods

Population

Ten nonobese male adolescents (12–14 years) and 12 severely obese male adolescents (12–15 years) were included in the present study. None of the boys had any orthopaedic condition that precluded involvement in the study. All obese participants were recruited in a children's medical centre (Clermont-Ferrand, France). The nonobese participants were recruited from a sporting association. They were classified as obese and nonobese according to the IOTF criteria (Cole et al. 2000). Both groups were formed so that chronological age, biological age, and height were not significantly different (Table 1). At first, both groups were formed according to chronological age and height, and only afterward we checked whether or not biological age differed between obese and nonobese adolescents. As shown in Table 1, no significant difference in biological age was observed between both groups. The nonobese adolescents were physically active: they practiced physical education at school for 3 $h \cdot week^{-1}$ and soccer in a sporting association for 4 $h \cdot week^{-1}$. Obese adolescents were tested before being engaged in a physical reconditioning program for about 3 $h \cdot week^{-1}$ at the medical centre. Before this period, they practiced physical education at school for 3 $h \cdot week^{-1}$, as did their nonobese counterparts. Written informed consent was obtained from the parents of each participant. The protocol was approved by the local Ethics Committee.

Experimental protocol

All subjects were tested on two occasions separated by at least 1 week. The first session was dedicated to gathering subjects' anthropometric characteristics and the second was devoted to measuring isometric MVC torque of the dominant knee extensors.

Session 1

During the first session, BM was measured to the nearest 0.1 kg using a calibrated electronic scale (Seca, model 873 Omega, France). Height was determined to the nearest 0.01 m using a standing stadiometre (Seca, model 720, Ham-

Table 1. Subjects' anthropometrical characteristics.

	Obese (n = 12)	P value	Controls (n = 10)
Age (years)	14.2±1.4	NS	14.4±0.7
APHV (years)	13.6±0.7	NS	13.8±0.9
Years to (from) APHV	0.63±1.16	NS	0.64±1.19
Height (m)	1.66±0.08	NS	1.65±0.12
BM (kg)	94.4±16.0	<0.001	53.3±10.4
BMI (kg·m^{-2})	34.1±5.4	<0.001	19.4±1.7
Body fat (%)	40.6±6.8	<0.001	14.9±3.7
FFM (kg)	53.3±8.5	<0.05	43.9±8.5
LM_{thigh} (kg)	5.6±1.3	NS	5.3±1.3
MM_{thigh} (kg)	3.9±0.8	NS	3.7±0.9

Note: APHV, age at peak height velocity; BM, body mass; BMI, body mass index; FFM, fat-free mass; LM, lean mass; MM, muscle mass; NS, nonsignificant.

burg, Germany). Height and BM were measured without shoes and clothing. BMI was calculated using the standard formula (mass (kg) divided by height squared (m^2)). Body fat (BF), FFM, and thigh lean mass (LM_{thigh}) were determined using DXA (HOLOGIC, QDR-4500, Hologic Inc., Bedford, Massachusetts, USA). The DXA measurements were performed in supine position and required about 240 s per subject. The ankles were extended and the feet were rotated medially to place the hip joint in a neutral position. A phantom was scanned daily to calibrate the body composition results. LM_{thigh} was measured according to the method described by Skalsky et al. (2009); the thigh region was delineated by an upper border formed by an oblique line passing through the femoral neck and a horizontal line passing through the knee (Fig. 1). LM_{thigh} is composed primarily of muscle but also includes noncontractile constituents such as skin, connective tissue, and the lean portion of adipose tissue. As the noncontractile constituents do not account for force production, the normalization of force to LM_{thigh} could not be really specific to KE strength. The best normalization procedure could be the normalization to thigh muscle mass (MM_{thigh}) because MM_{thigh} is directly related to force production. Therefore, MM_{thigh} was assessed from a DXA-based mathematical model validated in typically developing children (Modlesky et al. 2010):

$$[1] \quad MM_{thigh} = (LM_{thigh} \cdot 0.648) + (\text{age} \cdot 27.5) - 114.2$$

This DXA-based mathematical model was found to provide highly valid estimates of the thigh muscle mass from magnetic resonance imaging. However, as this model does not account for the intramuscular adipose tissue and intramyocellular lipid content within the thigh, it is likely that thigh muscle mass is overestimated, especially in obese adolescents.

Pubertal timing was estimated according to the biological age of maturity of each individual as described by Mirwald et al. (2002). The age of peak linear growth (age at peak height velocity (APHV)) is an indicator of somatic maturity representing the time of maximum growth in stature during adolescence. Biological age of maturity (years) was calculated by subtracting the chronological age at the time of the measurement from the APHV. Thus, a maturity age of –1.0 indicates that the subject was measured 1 year before this peak velocity; a maturity of 0 indicates that the subject was measured at the time of this peak velocity; and a maturity age of +1.0 indicates that the participant was measured 1 year after this peak velocity.

Session 2

During the second session, all subjects were tested on a home-built ergometer dedicated to measuring isometric MVC strength of the dominant knee extensors. This ergometer was built to adjust the force transducer at the level of the lateral malleolus and change the seat depth depending on the length of the thighs. The knee angle and the hip angle were set at 60° (0° is full extension). The knee was fixed at an angle of 60° of flexion as this has been demonstrated to be the angle of maximal isometric force generation for human knee extensor muscles (Thorstensson et al. 1976; Tihanyi et al. 1982). In addition, in a pilot study, Maffiuletti et al. (2008) showed that peak isometric MVC torque was produced at an angle of 60° of flexion in obese and nonobese adolescents. The dominant leg was defined as the preferred kicking leg. Subjects were secured to the chair by a strap slung over their shoulders to avoid any compensatory movement of the trunk. Subjects were also instructed to grip the seat during the voluntary contractions to further stabilize the pelvis. The subjects were first familiarized with the MVC: they repeated trials until they were able to produce consistent results. After this familiarization period and 5 min of passive rest, the subjects were verbally encouraged to perform 3 s MVCs. This procedure was repeated three times with a recovery of at least 3 min between. Isometric MVC strength was determined as the best trial among three reproducible measurements. During each trial, subjects were instructed to contract as strongly as possible. Force output was measured using a calibrated force transducer (model F2712, 0- to 100-daN force range, Meiri Company, Bonneuil, France) connected to an ankle cuff and transmitted to a PC using an analog–digital converter (Phoenix contact type UEGM, Bertrange, France). Visual feedback about force and verbal encouragements during MVCs were provided to the subject by the same experimenter. Isometric MVC torque of knee extensor muscles was calculated as the product of maximal force and moment arm length, the latter being measured from the lateral malleolus to the lateral femoral condyle in resting conditions using a tape meter. Relative torque was calculated by dividing torque by BM, FFM, LM_{thigh}, or MM_{thigh}. These multiple normalization procedures were conducted to compare our results with those previously pub-

Fig. 1. Dual-energy X-ray absorptiometry (DXA) body segmentation used for regional measurement of thigh lean mass. The thigh region was delineated by an upper border formed by an oblique line passing through the femoral neck and a horizontal line passing through the knee.

lished (expression of torque relative to BM and FFM) and to ascertain whether the specificity of the normalization procedure could affect the comparison of relative KE torque between obese and nonobese adolescents.

Statistical analysis

Values are reported as mean ± standard deviation (SD). The data distribution was analyzed using the Kolmogorov–Smirnov test, and the homogeneity of variance was tested using the Bartlett test. With these two conditions being met, unpaired samples *t* tests were used to compare chronological age, APHV, anthropometrical (BM, height, BMI, BF, FFM, LM_{thigh}, MM_{thigh}), and absolute–relative torque outcome measures between obese and nonobese adolescents.

The limit for statistical significance was set at $P < 0.05$. Data were analysed with the Statview Software (StatView SE + Graphics, Abacus Concepts, Inc., Piscataway, New Jersey, USA).

Results

Subjects' anthropometrical characteristics are presented in Table 1. There was no significant difference between groups for chronological age, height, and maturity status. As expected, body fat (%), body mass, BMI, and FFM were significantly higher in obese adolescents. The obese and lean adolescent boys were considered as circum,-pubertal as they reached peak high velocity by age 13.6 ± 0.7 and 13.8 ± 0.9 years, respectively.

Absolute and relative isometric MVC torque values are presented in Table 2. Absolute MVC torque of the dominant knee extensors was significantly higher in obese adolescents compared with controls (24.2%; $P < 0.05$). However, although MVC torque expressed per unit of BM was found to be significantly lower in obese adolescents (24.8%; $P < 0.05$), no significant difference in MVC torque normalized to FFM was found between both groups. Conversely, when correcting for LM_{thigh} and MM_{thigh}, MVC torque values were significantly higher in the obese adolescent group (17.9% and 22.2%, respectively; $P < 0.05$ for both).

Discussion

The results of the present study clearly show that absolute KE strength is significantly higher in circumpubertal obese adolescents compared with lean controls of similar chronological age, biological age, and height. They also highlight, for the first time, that relative KE strength is significantly higher in obese adolescents, thereby suggesting that KE strength, on its own, is not a factor contributing to the reduced motor performances typically observed in obese adolescents (see the review article by Tsiros et al. (2011)).

One of the main findings in the current study is that the outcome of the KE MVC torque comparison between obese and nonobese is affected by the specificity of the torque normalization procedure: nonobese were stronger when torque was expressed per unit BM. Conversely, no difference between groups was observed for the torque–FFM ratio, whereas the torque – thigh lean mass ratio was 17.9% higher in obese adolescents compared with their nonobese counterparts. The difference increased to 22.2% when normalizing to thigh muscle mass. Given the inability of DXA to quantify intramyocellular lipids content, it is likely that the difference between obese and nonobese adolescents in torque – thigh muscle mass is greater than estimated here. The difference of activity level between the experimental groups cannot account for the greater relative torque in the obese as they were

Table 2. Strength measurements.

	Obese (n = 12)	P value	Controls (n = 10)
MVC torque (N·m)	232.1±65.2	<0.05	176.0±55.1
MVC torque/BM (N·m·kg^{-1})	2.46±0.59	<0.05	3.27±0.78
MVC torque/FFM (N·m·kg^{-1})	4.31±0.70	NS	3.94±0.82
MVC torque/LM$_{thigh}$ (N·m·kg^{-1})	40.2±9.3	<0.05	33.0±5.9
MVC torque/MM$_{thigh}$ (N·m·kg^{-1})	57.3±12.8	<0.05	46.9±8.7

Note: MVC, maximum voluntary contraction; BM, body mass; FFM, fat-free mass; LM, lean mass; MM, muscle mass.

less active than their nonobese counterparts. It could be speculated that the higher absolute and relative KE peak torque in obese adolescents is partly attributable to neural factors as no significant difference in thigh lean mass or estimated thigh muscle mass was observed between obese and nonobese adolescents. These neural factors could include higher agonist muscle activation, lower antagonist muscle co-activation, and (or) an increased contribution of synergistic muscles in the obese group (Bouchant et al. 2011). However, a certain caution should be made with this suggestion as Blimkie et al. (1990) reported, using twitch interpolation technique, lower voluntary activation scores during isometric knee extensor MVC in obese adolescents compared with normal-weight counterparts (85.1% vs. 95.3%, respectively). Also, to our knowledge, no data are available regarding the effects of obesity on antagonist muscle co-activation and synergistic muscle recruitment in adolescents. Interestingly, the results of the present study are comparable with those showing increased absolute muscle strength without significant changes in corresponding muscle size after resistance training in children and adolescents (Granacher et al. 2011; Ramsay et al. 1990). On that basis, we suggest that the extra weight chronically carried by severely obese adolescents could act as a continuous resistance training stimulus for knee extensor muscles, inducing potential neural adaptations. However, further studies are warranted to evidence the underlying mechanisms.

The results of the present study are also in accordance with the results previously obtained in prepubertal children and adolescents for absolute cycling peak power (Aucouturier et al. 2007; Duché et al. 2002) and peak KE isokinetic and isometric torque at shorter muscle length, i.e., 40° of knee flexion (Maffiuletti et al. 2008). Similar to these studies, our results clearly show a lower strength–BM ratio in obese adolescents and a comparable muscle strength – FFM ratio between obese and nonobese adolescents. However, some studies did not report any significant difference in peak absolute muscle torque for knee extensors and elbow flexors between obese and nonobese preadolescent and adolescent boys (Blimkie et al. 1989, 1990). Similarly, Maffiuletti et al. (2008) reported no significant difference in peak isokinetic and isometric KE torque at longer muscle length (80° of knee flexion) between severely obese and nonobese adolescent boys.

Inconsistent results in comparisons of muscle strength between obese and nonobese adolescents could be related to numerous factors, including the definition and degree of obesity, the potentially confounding effect of puberty, the muscle length investigated, and the different assessments or components of muscle function (i.e., power–strength, isometric–dynamic muscle contractions, etc.). In particular, none of the above-mentioned studies applied the IOTF criteria to classifying subjects as nonobese, overweight, and obese. Specifically, the wide variety of definitions of child obesity used in the studies cited above could confound some comparisons. For example, in the study of Blimkie et al. (1989), some preadolescent boys were classified as obese individuals based on the sum of measurements of skinfold thickness, whereas they would have been considered as nonobese according to the IOTF criteria. The degree of obesity could also confound the comparison of KE strength data, as differences in the level of physical activity and in the intramyocellular lipids content could be expected among obese children with wide-ranging BMI (Ruiz et al. 2006). In the current study, physical activity level was not measured objectively, and DXA was not able to quantify intramuscular lipids. Therefore, the respective influences of overweight, physical activity level, and intramyocellular lipids content on KE strength in obese youth remain to be established. Furthermore, in most studies, obese and nonobese groups were matched mainly for chronological age and standing height (Aucouturier et al. 2007; Duché et al. 2002), and the biological age of maturity was not considered for muscle strength comparisons. However, it is now well accepted that the development of muscle strength during childhood and adolescence is dependent on the maturation level and associated circulating levels of growth hormones acting on muscle size (Hulthén et al. 2001). In the present study, we chose to apply the age of peak linear growth as an indicator of somatic maturity as this method is inexpensive compared with testosterone dosage (Denzer et al. 2007) and hand–wrist radiographs (Akridge et al. 2007) and has less ethical constraints compared with Tanner evaluation stages (Tanner and Whitehouse 1976). Interestingly, our results confirmed those found by Akridge et al. (2007) showing no significant difference in skeletal maturation (determined by Fishman's hand–wrist analysis) between 13- to 16-year-old normal weight and obese adolescents. However, others have found that obesity in children was associated with an earlier onset of puberty (Ribeiro et al. 2006).

Another confounding factor could be the joint angle at which the MVC torque is measured. Specifically, Maffiuletti et al. (2008) showed that KE absolute isometric torque was significantly higher in severely obese adolescents (BMI 34 kg·m^{-2}) compared with lean controls at short but not at long knee extensors length (40° and 80° of knee flexion, respectively). Similarly, Blimkie et al. (1989, 1990) showed no significant difference in absolute voluntary isometric and isokinetic torque of knee extensors between obese and nonobese preadolescent and adolescent boys for any knee angle superior to 80°. In the present study, severely obese adolescent boys exhibited a greater MVC torque than nonobese at a knee angle of 60°. On that basis, it could be suggested that obese adolescents develop greater MVC torques than nonobese adolescent boys at short muscles lengths, i.e., for any knee angle inferior to 60°–70°, and similar MVC torques for any knee angle superior to 80°. According to Maffiuletti et al. (2008), severely obese subjects would present an advantage at short rather than at long knee extensors length because they would probably deliberately limit their range of motion during daily activities involving deep knee flexion due to the excessive stress acting on the articular joint surfaces. This would result in favourable but specific adaptations at short muscle length. However, this is speculation and further research is required before definitive conclusions can be drawn on this issue.

To conclude, the results of the present study indicate that our sample of obese adolescent boys had higher absolute and relative isometric KE strength than our nonobese controls. It could be suggested that the extra weight chronically carried by the obese adolescents induces neural adaptations, as no significant difference in estimated thigh muscle mass was observed between obese and nonobese adolescents. However, further studies are required to elucidate these mechanisms. Additional research is also warranted to ascertain whether or not the results of the current study extend to longer muscle lengths and to muscle groups that are not chronically loaded by extra weight (i.e., elbow flexors, finger muscles, etc.) in severely obese adolescents. Such studies should be conducted on a larger sample of adolescents including both males and females. Furthermore, relative strength should be determined using more accurate in vivo measurement methods of regional muscle and fat mass such as magnetic resonance imaging.

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