Knee Extensor Muscle Strength and Vertical Jumping Performance Characteristics in Pre- and Post-pubertal Boys

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Knee extensor muscle strength and vertical jumping performance characteristics were compared between 14 pre-pubertal (11-year-old) and post-pubertal (16-year-old) boys. Post-pubertal boys had greater (p < .05) absolute values of maximal isometric force (MF) and rate of force development (RFD), absolute and body mass-related values of isokinetic peak torque of the knee extensor muscles at angular velocities of 60, 180, and 240° · s⁻¹, as well as jumping height in squat, counter-movement, and drop jumps, than pre-pubertal boys. This study indicated an inability to use the positive effect of stretch-shortening cycle to vertical jumping performance in pre- and post-pubertal boys.

Introduction

Maximal and explosive muscle strength (power) are important characteristics of neuromuscular performance, which changes throughout the years of growth, particularly during puberty. Numerous studies in this field have focused on measuring the maximal isometric or isokinetic strength, which gives information about the maximal voluntary force-generating capacity of the muscle groups, and vertical jumping performance, which provides information about the explosive force production (power output) of the leg extensor muscles by measuring jumping height. The significant increase in maximal isometric strength (4, 15, 26) or isokinetic peak torque at different angular velocities (9, 14, 26), as well as vertical jumping height (11, 15) during puberty is well documented. However, a smaller number of studies have assessed associations between maximal strength of the leg extensor muscles and vertical jumping performance throughout puberty. Only a few studies have reported the rate of voluntary isometric force development of the knee or leg extensor muscles in pre- and post-pubertal children (11, 15).

The increase in maximal strength of the muscles during puberty is often associated with increase in muscle mass (18) or cross-sectional area (17). Some investigations demonstrated a significant increase in muscle strength in relation to...
body mass between 8-year-old and 13–14-year-old children (9, 26). However, the studies that have used anthropometric measures (8) or ultrasonic techniques (16) have reported that isometric strength expressed per unit of cross-sectional area of the muscles would appear to remain unchanged throughout puberty. Thus, the differences in maximal isometric and isokinetic muscle strength in relation to body mass in pre- and post-puberty need further recordings.

The knee extensor muscles play an important role in many movement activities. These muscles have a great importance in the function and stability of the knee joint as well as prevention of the knee injuries.

The purpose of this study was to compare the isometric and isokinetic strength of the knee extensor muscles and vertical jumping performance in pre- and post-pubertal boys. More specifically, we were interested in examining maximal isometric force and rate of force development as well as isokinetic peak torque of the knee extensor muscles and jumping height in squat, counter movement, and drop jumps in 11-year-old and 16-year-old boys. A squat jump consists of a concentric muscle action of the leg extensor muscles, while counter-movement jump, drop jump (i.e., jumping down from a height), and performing a maximal vertical jump upon landing, consists of an eccentric-concentric muscle action (stretch-shortening cycle). It has been shown to have a potentating effect of stretch-shortening cycle to vertical jumping performance in young adult subjects (2, 6); however, the age-related differences of this potentating effect are poorly understood.

Material and Methods

Subjects

Twenty-eight boys, aged from 11 to 16 years, participated in this study. The subjects were distributed into two groups: pre-pubertal (11-year-old, \( n = 14 \)) and post-pubertal (16-year-old, \( n = 14 \)) boys (Table 1). Pubertal stages were determined according to the criteria of Tanner (27). All 11-year-old boys were in Tanner stage 1 and were classified prepubertal as to pubic hair and genitalia. Informed parental consent was obtained prior to the children’s participation in the experiment. All 16-year-old boys were in Tanner 5 stage and were classified as post-pubertal. Their written informed consent was obtained. The study carried the approval of the University Ethics Committee.

Table 1  The Physical Characteristics of the Subject Groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Age groups</th>
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<tbody>
<tr>
<td></td>
<td>Pre-pubertal boys ( (n = 14) )</td>
</tr>
<tr>
<td>Age (years)</td>
<td>11.4 ± 0.1</td>
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<tr>
<td>Height (cm)</td>
<td>152.8 ± 2.9</td>
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<tr>
<td>Body mass (kg)</td>
<td>40.3 ± 2.8</td>
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<tr>
<td>Body mass index (kg · m(^{-2}))</td>
<td>17.3 ± 0.5</td>
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</table>

Note. Variables are expressed as \( M ± SE \). All characteristics were significantly different \( (p < .05) \) among groups.
Twenty-four to 48 hours before data collection, the subjects were given instructions and the strength testing procedures, and vertical jump tests were demonstrated. This was followed by a practice session to familiarize the subjects with the procedures. The subject’s dominant leg was determined based on a kicking preference.

Prior to testing, each subject underwent a 10-min warming-up period. Post-pubertal boys performed 5-min submaximal ergometer cycling followed by stretch exercises of knee extensor and plantarflexor muscles. Pre-pubertal boys performed running and stretching exercises.

**Isometric Dynamometry**

During the measurement of maximal isometric force (MF) and rate of force development (RFD) of the knee extensor muscles, the subjects were seated in a specially designed dynamometric chair, with the knee and hip angles equal to 90° and 110°, respectively. The body position of the subjects was secured by three Velcro belts placed over the chest, hip, and thigh. The isometric force of the knee extensor muscles was recorded by standard strain-gauge transducer mounted inside a metal frame that was placed around the distal part of the ankle of the dominant leg above the malleoli using a Velcro belt. The electrical signals from the strain-gauge transducer were digitized online (sampling frequency, 1 kHz) using a personal computer. The digitized signals were stored on a hard disk for further analysis. During the testing, the subject was instructed to react to the light signal (ignition of the signal lamp, placed 1.5 m from the subject) as quickly and forcefully as possible by extending the leg against a cuff fixed to a strain gauge system, maintaining the maximal effort as long as the signal was on (2 s). Three attempts were carried out, and the best result was used for further analysis. A rest period of 1 min was allowed between the attempts. The force-time curve and light signal were analyzed by personal computer. Isometric MF and RFD as the force in relation to time period of 0.2 s from the onset of the force production were calculated.

**Isokinetic Dynamometry**

Isokinetic concentric peak torque (PT) of the knee extensor muscles was measured using a Cybex II dynamometer and manual (Lumex, Ronkonkoma, NY). After calibration of the dynamometer, subjects were seated in the adjustable chair with support for the back and hips, and were stabilized via straps at the chest and thigh. The axis of rotation of the knee joint was aligned with axis of the dynamometer lever arm. The force pad was placed 3–4 cm superior to the medial malleolus, with the foot in plantigrade position. The knee of the dominant leg was positioned at 90° of flexion. Range of motion during testing was set using the goniometer through an arc from 90° of knee angle to full extension. Subjects were instructed to hold their arms across the chest to further isolate knee joint extension movements. During the testing, the subjects were asked to produce knee extension as forcefully and quickly as possible through a complete range of motion. Verbal encouragement was given during every trial. Three attempts were carried out at angular velocities of 60, 180, and 240° · s⁻¹, and the one with the highest PT value was used for further analysis. The trial proceeded from the slow to the high angular velocity. A rest period of 1 min was allowed before and between the attempts. All torque measurements were gravity corrected.
Vertical Jump Tests

The vertical jumping tests were performed on force platform (PD-3A, VISTI, Russia) with the dimensions of 0.75 X 0.75 m and natural frequency of 150 Hz. Three types of maximal vertical jumps were performed: squat jumps, counter-movement jumps, and drop jumps. Squat jump (SJ) started from a static semi-squatting position with a knee angle of 90° of the knee flexion, followed by subsequent action, during which the leg and hip extensor muscles contracted concentrically. Counter-movement jump (CMJ) started from upright standing position immediately after a fast preparatory counter-movement that stretched the leg extensor muscles (eccentric contraction). This was followed by an explosive maximal extension in the opposite direction (concentric contraction). The starting position during drop jump (DJ) was similar to that of the CMJ, but the subject stood on a box of a dropping height of 40 cm. The subject dropped from the box and rebounded after a short contact with the ground for maximal height. The leg muscle work during the ground contact constituted the stretch-shortening cycle. The subjects were instructed to jump with their hands on the hips to eliminate the influence of the arm swing impulse. The movement amplitude of the knee joint during each jump was measured with electrogoniometer (ELGON) attached to the lateral side of the subject’s right knee. Prior to the testing, the subjects performed several preliminary trials. The flight time was used to calculate the jumping height by the height of rise of the center of gravity of the body above the ground (2). Each jump was repeated three times, and the best result was used for further analysis. A rest period of 1 min was allowed between the jumps.

Statistical Analysis

Data are means and standard errors of mean. One-way analysis of variance (ANOVA) following by Tukey post hoc comparisons were used to test for differences between age groups and for each vertical jumping exercises. A level of $p < .05$ was selected to indicate statistical significance.

Results

Post-pubertal boys had higher ($p < .05$) height, body mass, and body mass index than pre-pubertal boys (Table 1). Isometric MF and RFD of the knee extensor muscles were greater ($p < .001$) in post-pubertal boys compared with pre-pubertal boys (Figure 1). However, no significant differences ($p > .05$) were observed in isometric MF and RFD of the knee extensor muscles in relation to body mass between the groups. As shown in Figure 2, post-pubertal boys had greater ($p < .05$) absolute and body mass-related isokinetic PT of the knee extensor muscles at angular velocities of 60, 180, and 240°·s⁻¹ compared with prepubertal boys. Jumping height in SJ, CMJ, and DJ was higher ($p < .05$) in post-pubertal boys than pre-pubertal boys (Figure 3). No significant differences in jumping height between SJ, CMJ, and DJ were observed, either in pre-pubertal or post-pubertal boys.
Figure 1 — Mean (±SE) maximal isometric force (MF) of the knee extensor muscles and MF force relative to body mass (A), rate of isometric force development (RFD) of the knee extensor muscles, and RFD relative to body mass (B) in pre- and post-pubertal boys. ***p < .001.

Discussion

This study indicated markedly greater isometric MF (36.6%) and isokinetic PT of the knee extensor muscles at low, medium, and high angular velocity (54.5%, 52.4%, and 54%, respectively) in post-pubertal boys compared with pre-pubertal boys. The increase in absolute values of maximal voluntary isometric and isokinetic strength characteristics of the knee extensor muscles in boys over puberty is consistent with earlier findings (1, 21, 23). This is mainly due to increase in muscle size and body dimension as well as neural maturation. There is a rapid increase of muscle strength in male children of approximately 13 years of age, corresponding to increase in muscle mass (18), cross-sectional area of muscles (17), and attainment of sexual maturity (4). The increase in secretion of testosterone at puberty...
Figure 2 — Mean (±SE) absolute and body mass-related values of isokinetic peak torque of the knee extensor muscles at angular velocities of 60° s⁻¹ (PT₆₀) (A), 180° s⁻¹ (PT₁₈₀) (B), and 240° s⁻¹ (PT₂₄₀) (C) in pre- and post-pubertal boys. **p < .01; ***p < .001.
has been associated with increase in skeletal muscle mass (20). It is possible that neural maturation has contributed to the age effect for maximal isometric and isokinetic force. It has been suggested that the expression of muscle strength is dependent on myelination of the motor nerves, which is not completed until sexual maturity (7). The maximal voluntary force-generation capacity of the muscles is highly dependent upon the degree of motor unit activation (recruitment and change of the firing rate of the muscle fibers), which is influenced by the development of the central nervous system. Blimkie (4) has found that 16-year-old boys could voluntarily activate a greater percentage of their available motor units during a maximal voluntary contraction than 11-year-old boys.

The present study indicated a significantly higher (34%) rate of voluntary isometric force development of the knee extensor muscles in post-pubertal boys compared with pre-pubertal boys. The RFD in isometric and dynamic contractions is related to the contractile speed. The maximum shortening speed determined from the force-velocity curve is closely related to the shortening speed of sarcomeres, which correlates with myosin-ATPase activity (3). The activity of this enzyme in infants and pre-pubertal children is lower than in adults (10). The number of sarcomeres increases, and as a necessary consequence, muscle length increases with growth. Thus the contractile speed of the whole muscle in post-pubertal boys seems to be faster compared to that in pre-pubertal boys. Moreover, contractile speed is highly dependent upon motor unit activation: recruitment and change of the firing rate of slow and fast twitch motor units in voluntary contraction. These two mechanisms are influenced by factors as the development of the nervous system and the differentiation of muscle fiber types. Hence, the effects of the above mentioned factors gradually increase with growth (12).
The changes in maximal voluntary muscle force per unit of body mass during puberty is controversial. Several authors have observed a significantly higher isokinetic PT of the knee extensor muscles in relation to body mass in post-pubertal children compared with pre-pubertal children (9, 26). However, others (13, 25) have reported age-related increase in isokinetic PT of the knee extensor muscles that could not be accounted for by changes in body mass. However, our data clearly indicated that the increase in voluntary isokinetic strength over puberty was closely related to increase in body mass, but maximal voluntary isometric force and rate of force development expressed per unit of body mass would appear to remain unchanged through puberty. It is possible that these differences were attributable to differing motor unit activation pattern between isometric and dynamic muscle contractions.

The vertical jumps can be used as a model to study explosive force-generating capacity of the lower extremities. In the present study, the vertical jumps were performed without (SJ) and with preliminary counter-movement (CMJ and DJ). CMJ and DJ are exercises characterized by so-called stretch-shortening cycle, in which the action of the muscles during the eccentric phase influences the subsequent concentric phase (2, 6). The results of the present study indicated that jumping height in SJ, CMJ, and DJ was 16%, 15%, and 16.8% lower in pre-pubertal boys compared with post-pubertal boys, respectively. In general, this is in agreement with previous findings (11, 15). The differences between pre- and post-pubertal boys regarding their vertical jumping performance are conditioned by the following factors. The vertical jumping height depends on the physiological processes that take place in the muscular and nervous systems. One finding of this study was a significantly higher dynamic force generating capacity of the knee extensor muscles in post-pubertal boys compared with pre-pubertal boys. It is well known that dynamic force of the knee extensor muscles is one important factor limiting performance in jumping exercises. Another important factor is intramuscular co-ordination and co-activation of activity of the agonist-antagonist muscles involved in performing the jump (22). Thus, the greater vertical jumping performance in post-pubertal boys compared with pre-pubertal boys can be partly explained by an increase in the capacity for rapid neural activation of the extensor muscles of lower extremities.

A significantly greater height in jumping exercises with preliminary counter-movement (CMJ or DJ) compared with SJ in adult subjects (2, 24) has been reported. Several mechanisms have been proposed to explain the positive effect of a counter-movement on performance in the subsequent concentric action: (a) It allows for storage of elastic energy that can subsequently be re-utilized (2, 6); (b) it triggers spinal stretch reflexes as well as longer-latency responses (19) that help to increase muscle stimulation during the concentric phase; and (c) it allows for greater joint movements at the start of push-off and more work production (5). The results of the present study indicated no significant differences between SJ, CMJ, and DJ from dropping height of 40 cm either in pre-pubertal or post-pubertal boys, and therefore, that they cannot use the positive effect of a stretch-shortening cycle to vertical jumping performance in counter-movement and drop jumps. However, the question, how does stretch load (drop height) influence the vertical jumping performance in pre- and post-pubertal children, needs further detailed examination.

In summary, this study has shown that in boys the post-puberty compared with pre-puberty is characterized by: (a) increased absolute values of maximal voluntary isometric force and rate of force development as well as absolute and
body mass-related values of isokinetic peak torque of the knee extensor muscles and vertical jumping height, and (b) unchanged maximal voluntary isometric force and rate of force development of the knee extensor muscles in relation to body mass. The results demonstrated an inability to use the positive effect of the stretch-shortening cycle to vertical jumping performance in counter-movement and drop jumps in pre- and post-pubertal boys.

References


