Biomechanical Comparison in Different Jumping Tasks Between Untrained Boys and Men

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This study examines the biomechanical differences during different vertical jump tasks in 12 prepubescent and 12 adult males. The sagittal knee kinematics, vertical ground reaction force (vGRF) and electromyographic (EMG) activity of 5 lower extremity muscles were recorded. Compared with boys, men presented higher peak vGRF during the propulsive phase in all examined jumps, but lower values during the braking phase, even when related to body mass. Normalized EMG agonist activity in all phases was higher in men ($p < .05$), while antagonist coactivation was enhanced in boys ($p < .05$). The knee joint was on average 9 degrees more flexed at touchdown in men during drop jump tasks, but boys exhibited 12 degrees and 17 degrees higher knee flexion at the deepest point when performing drop jump from 20 and 40 cm, respectively. In conclusion, the performance deficit observed in boys in all jump types is a reflection of their immature technique, which could be partly attributed to the less efficient stiffness regulation and activation of their neuromuscular system.

Jumping is a motor task that involves a sequence of complex, multijoint movements. Some typical evaluation tests for jumping are the squat jump (SJ), the counter movement jump (CMJ), and the drop jump (DJ). Maximizing jumping performance requires optimal interlimb coordination of the trunk and lower limbs. This actually designates the efficient energy transfer across the involved joints (33). Moreover, jumping performance is enhanced by the stretch shortening cycle (SSC), a mechanism which involves an eccentric contraction (braking phase) before the concentric one (propulsive phase). Comparison between SJ, CMJ, and DJ gives an insight into the contribution of SSC during vertical jumping. Regarding the gain in jump height due to SSC (prestretch augmentation) adults present in CMJ better jumping performance compared with SJ (6,43). It has been shown that the positive work during SSC is increased with higher prestretch intensity, which is achieved
by increasing the dropping height when performing DJ (1). Therefore, in untrained adults, jumping performance increases up to an optimal dropping height of 30–40 cm (6,42) and then a plateau appears. Further increase in dropping height results in a reduction on jump height and this is attributed mainly to a neuronal inhibition to protect the muscle-tendon unit from injury (42,43).

Among other complex motor tasks, jumping is also influenced during the developmental period. There are several investigations regarding the performance in SJ, CMJ and DJ during different maturation stages (7,24,41), which revealed that boys increase continuously their performance in jump height, whereas girls reach a plateau after puberty. Comparisons of different jump types in children, in accordance with the findings in adults, showed that performance in CMJ is greater than in SJ (17,21,41), but this gain decreases from prepuberty to puberty (41). In fact, a recent study in children revealed no gain in CMJ relative to SJ (32), indicating the importance for further research on this issue.

Regarding the DJ, the prestretch augmentation from various drop heights has been minimally investigated in children. Only one study reported that pubertal female basketball players have no gain in jumping when dropping from 15 to 45 cm, nonetheless, these results were not compared with their performance in SJ (13). On this issue, a recent study suggested that the superiority of men in 20 cm DJ compared with boys could be attributed to a more optimal stiffness regulation of the muscle-tendon unit (29). However, drop height is a crucial factor in determining the jump outcome (25) and the examination of only one drop height in recently published studies examining DJ in the developmental ages (29,31) is an important limitation. This argument is strengthened by the fact that the muscle-tendon compliance is a crucial factor for SSC movements, especially in DJ from different heights (43). In view of the fact that children have a more compliant muscle-tendon unit than adults (35), it could be argued that children might adopt a different biomechanical behavior during jumping.

To our knowledge there are no studies examining the overall differences between untrained children and adults in SJ, CMJ and DJ from different heights. The current study was designed to examine these jump types and highlight the possible differences in gain between CMJ and SJ or between different drop heights, by recording 3D kinematics, ground reaction forces and electromyographic (EMG) data in untrained boys and men. This will help us to better understand the underlying causes for the performance deficit which appears in prepubescents compared with adults. Furthermore, the knowledge about how children adapt to different jump types will enhance our ability to improve children’s power output in sports, to identify any compensatory mechanisms that children might develop due to their differences in muscle-tendon unit compliance, and to recognize what is feasible to improve with training and what is not. Part of the presented data has been already published (29).

Methods

Participants

Twenty-four male volunteers (12 prepubescents, 12 adults) participated in this study. Prepubescent boys were 9–11 years old (age 9.8 ± 0.6 years, body mass 37.0 ± 4.7 kg, body height 1.41 ± 0.06 m) and men were 19–27 years old (age 25.5 ± 2.7 years, body mass 73.6 ± 8.9 kg, body height 1.77 ± 0.05 m). The classification of children as prepubertal was assessed by a physician according to the
criteria established by Tanner (40). All participants were untrained and did not participate systematically in any sports training program during the past 2 years. They were free of any neurological deficit that could influence the lower extremity performance and they had no history of back or lower limb injury. Before testing, all adult participants and the parents of the prepubescent boys read and signed a written informed consent statement. This study met the ethical standards suggested by Aristotle University of Thessaloniki, Greece.

**Instrumentation**

Kinematic data were captured using a six-camera 3D motion analysis system (VICON 612, Oxford Metrics Ltd, Oxfordshire, UK), with sampling frequency set at 100 Hz. For the kinematics, 16 reflective spherical markers (14 mm diameter) were placed at anatomical bony landmarks of the lower body according to the Helen Hayes model (11). Ground reaction forces were recorded with a ground mounted, 40 × 60 cm force plate (Bertec Type 4060, Bertec Corporation, Columbus, USA), and the EMG activity was recorded with a BTS Telemg EMG device (Milano, Italy), using bipolar surface Ag/AgCl electrodes (contact surface 0.8 cm, interelectrode distance 2 cm) with preamplifier (1,000×). All devices were triggered by the motion analysis system. Analog signals were sampled at 1 kHz.

**Procedures**

After collecting the anthropometric data the participants were warmed-up (15 min walking/running on treadmill, hopping/jumping and stretching exercises) and the reflective markers for the kinematics and the electrodes for the EMG were attached. For the EMG the vastus lateralis (VL), the long head of the biceps femoris (BF), the gastrocnemius medialis (GM), the soleus (SOL) and the tibialis anterior (TA) muscles were measured for the dominant limb only, as determined by the preference to kick a ball. The ground electrode was placed over the bony surface of the contra lateral wrist. Skin was shaved and cleaned with an alcohol solution and skin impedance was below 2 kW.

The jumping test included three maximal efforts at each jumping condition, in random order, with 2 min rest interval in between. Participants were instructed to jump as high as possible, with their hands placed on their hips. Prior testing a familiarization session for practicing all jump types was assessed. For the SJ test, the participants were positioned on the force plate with their knees flexed slowly at 90°, as measured with a manual goniometer. They maintained this position for approximately 2 s before jumping. For the CMJ, participants stood erect, and counter-moved before jumping until knee flexion reached approximately 90°. The DJ test included DJs from a 20 and 40 cm high box (DJ20 and DJ40, respectively). The participants stood on the box and projected slowly one foot forward while the other left the box without pushing upwards or forward. Both feet landed on the force plate which was placed approximately 8 cm in front of the box. During the test no verbal motivation or any kind of feedback about their performance was provided.

**Data Analysis**

Data were processed offline using Matlab scripts of (Matlab 6.1, The MathWorks Inc.). Jump height was estimated taking into account the impulse which was recorded from the vertical ground reaction force (vGRF)–time curve. Only the
best trial in jump height was further analyzed. The peak vGRF was normalized to the body weight. Time to peak vGRF during the braking phase was measured and the SSC performance gain was calculated as follows (17):

$$SSC\ performance = \frac{\text{Height}_{CMJ} - \text{Height}_{SJ}}{\text{Height}_{SJ}} \times 100$$

Furthermore, the reactive strength of the lower limbs (jumping performance/total contact time in cm/ms) during DJ tasks was estimated (8). EMG signals were filtered with a Butterworth filter (10–500 Hz band-pass, zero lag, second order), followed by full-wave rectification and low-pass filtering at 50 Hz. Depending on the jump type the mean EMG was calculated for the preactivation (DJ), the braking phase (CMJ and DJ), and the propulsion phase (SJ, CMJ, and DJ). The preactivation onset was set when the processed EMG signal exceeded 2 standard deviations (SD) of the EMG amplitude during standing and ended at touch-down. The braking phase was determined from the instant of movement initiation (CMJ) or touchdown (DJ) to the instant of the maximum knee flexion. The propulsion phase started from the maximum knee flexion until the take-off. The EMG signals were normalized to the maximum EMG value during each jump trial (10,29). The maximum knee flexion angles were calculated whereas for the DJ tests, knee flexion angles were calculated 100, 50 ms before touchdown and during touchdown. Finally, peak angular velocity of the knee joint during the braking and propulsion phase was evaluated.

**Statistics**

Statistics were performed with SPSS/PC 16.0 (SPSS Inc.). Mean and SD was assessed for all dependent variables. Two-way analysis of variance (ANOVA) was applied to examine the group main effect (2 levels: boys vs. men), the task main effect (4 levels: SJ vs. CMJ vs. DJ20 vs. DJ40) and their interaction. The significance level was set to 0.05 with Bonferroni correction.

**Results**

ANOVA revealed that jumping height performance was significantly higher in men ($F = 653.5, p < .001$) and varied across different jump types ($F = 12.8, p < .001$). Furthermore, the interaction between the age groups and jump types was significant ($F = 13.0, p < .001$). More particularly, boys presented their highest performance in CMJ compared with all other jumping tasks, whereas the best performance in men was observed in DJ40 ($p < .05$).

**Squat Jump**

Normalized vertical ground reaction forces and knee angular velocities during the propulsion phase were significantly higher in adults ($p < .001$). As shown in Table 1, prepubescent boys presented longer propulsive phase compared with men ($p < .01$). Regarding the EMG (Figure 1), boys had lower VL, SOL, MG and TA activation but only MG and SOL reached the level of significance ($p < .05$). In contrast, men had lower coactivation BF/VL ratio although without statistical significance (Figure 2). Furthermore, men reached their peak vGRF value significantly earlier than boys ($p < .001$).
<table>
<thead>
<tr>
<th>Variable</th>
<th>Boys§</th>
<th>CMJ</th>
<th>DJ20</th>
<th>DJ40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vertical ground reaction force during braking phase (times body weight)</td>
<td></td>
<td>1.9 ± 0.3*</td>
<td>4.5 ± 1**</td>
<td>5.8 ± 1.4**</td>
</tr>
<tr>
<td>Time to Peak vertical ground reaction force during braking phase (ms)</td>
<td></td>
<td>87.2 ± 14**</td>
<td>54.2 ± 17***</td>
<td>42.9 ± 6.5***</td>
</tr>
<tr>
<td>Peak vertical ground reaction force during propulsive phase (times body weight)</td>
<td>1.7 ± 0.2***</td>
<td>2.0 ± 0.3***</td>
<td>2.5 ± 0.6***</td>
<td>2.1 ± 0.4***</td>
</tr>
<tr>
<td>Time to Peak vertical ground reaction force during propulsive phase (ms)</td>
<td></td>
<td>109.5 ± 22.2</td>
<td>117.5 ± 25.5</td>
<td>114.8 ± 36.9</td>
</tr>
<tr>
<td>Jump height (cm)</td>
<td>15.2 ± 1.1***</td>
<td>20.9 ± 1.7***</td>
<td>15.8 ± 1.9***</td>
<td>15.2 ± 1.8***</td>
</tr>
<tr>
<td>Contact time (ms)</td>
<td></td>
<td>466 ± 50*</td>
<td>186 ± 35**</td>
<td>219 ± 50**</td>
</tr>
<tr>
<td>Braking phase</td>
<td></td>
<td>420 ± 36</td>
<td>148 ± 17</td>
<td>152 ± 36</td>
</tr>
<tr>
<td>Propulsive phase</td>
<td>395 ± 50**</td>
<td>244 ± 21**</td>
<td>244 ± 60***</td>
<td>272 ± 26***</td>
</tr>
<tr>
<td>Total</td>
<td>395 ± 50**</td>
<td>710 ± 45***</td>
<td>430 ± 76***</td>
<td>491 ± 62***</td>
</tr>
<tr>
<td>Knee angular velocity (deg·sec⁻¹)</td>
<td></td>
<td>312 ± 37</td>
<td>588 ± 95***</td>
<td>669 ± 77***</td>
</tr>
<tr>
<td>Braking phase</td>
<td></td>
<td>299 ± 38</td>
<td>446 ± 70</td>
<td>503 ± 69</td>
</tr>
<tr>
<td>Propulsive phase</td>
<td>568 ± 30***</td>
<td>694 ± 38**</td>
<td>618 ± 79**</td>
<td>593 ± 53***</td>
</tr>
<tr>
<td>Total</td>
<td>734 ± 63</td>
<td>769 ± 80</td>
<td>786 ± 30</td>
<td>806 ± 41</td>
</tr>
</tbody>
</table>

* , ** , ***: significant difference between boys and men (p < 0.05, p < 0.01, and p < 0.001, respectively)

a,b,c: significant difference between SJ and CMJ, SJ and DJ20, and SJ and DJ40, respectively (p < 0.05)
d,e: significant difference between CMJ and DJ20, and CMJ and DJ40, respectively (p < 0.05)
f: significant difference between DJ20 and DJ40 (p < 0.05)
§: significant two-way interaction
Figure 1 — EMG amplitude during preactivation, braking and propulsion phase of all jumping tasks. Asterisks indicate statistical significance ($p < .05$).

Figure 2 — Coactivation ratio level (biceps femoris/vastus lateralis) during the examined phases of all jumping tasks. Asterisks indicate statistical significance ($p < .05$).
Counter-Movement Jump

In comparison with adults, boys had decreased and delayed peak vGRF, and less knee angular velocity during the propulsion phase. The duration of the braking and propulsion phase was significantly longer in boys compared with men ($p < .001$) and this was accompanied by greater maximal knee flexion (Figure 3). Concerning the EMG amplitude in both phases, men presented higher values for the VL, SOL, MG and TA but not for the TA during the propulsive phase. Boys had higher coactivation BF/VL ratio compared with men ($p < .05$) and both groups presented improvement in CMJ relative to the SJ jumping performance (SSC performance gain) but this improvement was higher in boys than in men ($38.3 \pm 13.5\%$ vs. $19.1 \pm 18.3\%, p < .05$).

Drop Jump

During the propulsion phase presented men higher knee angular velocity, with higher and earlier generated vGRF ($p < .05$). On the other hand, during the braking phase prepubescent boys showed greater knee range of motion, longer contact time, with higher and earlier generated vGRF ($p < .05$). Both groups had more extended knees in DJ40 than in DJ20 100 ms before touchdown ($p < .01$) and at touchdown ($p < .05$), whereas 50 ms before touchdown men flexed their knees more than boys in DJ40 ($p < .01$, Figure 3). The maximum knee flexion in CMJ, DJ20 and DJ40 was significantly higher in boys compared with men ($p < .05$). Regarding the EMG, men revealed higher VL, MG, and TA amplitude during preactivation during DJ20 and higher VL and TA for the DJ40 compared with boys. Higher VL EMG in men compared with boys was during all examined phases. Men’s soleus exhibited increased EMG during the propulsion phase in DJ20 and DJ40 compared with boys, and during the braking phase in DJ20. TA had higher activity in men during all phases of DJ40 and higher preactivation in DJ20, whereas the MG showed increase values in men during DJ20 preactivation and DJ40 propulsion. The coactivation ratio of prepubescent boys was higher compared with men in DJ20 and DJ40. The reactive strength of the lower limbs was significantly higher in men for DJ20 ($0.109 \pm 0.020$ vs. $0.038 \pm 0.007$ cm/ms, $p < .05$) and in addition to this during DJ40 a further increment appeared for the men ($0.117 \pm 0.022$ vs. $0.031 \pm 0.004$ cm/ms, $p < .01$).

Discussion

Although boys and men demonstrated a significant gain in CMJ relative to the SJ, no gain was observed in boys when executing DJ from two different heights, whereas men showed an additional gain in DJ40 relative to CMJ. This different behavior in jumping performance between the two age groups could be attributed to several parameters that have been assessed in the current study. Specifically the total contact time, and the duration of the braking and propulsive phases were longer in boys. The normalized to body weight vGRF was higher for men during the propulsion phase in all jump types but higher in boys during the braking phase during DJ20 and DJ40. Normalized to maximal value agonist activity during preactivation, braking and propulsive phase was higher in men, and antagonist activity was greater for all jump types in prepubertal boys. Knee flexion before
Figure 3 — Knee joint angle for countermovement jump (CMJ) and drop jump from 20cm (DJ20) and 40cm (DJ40) during different instances of jump. Asterisks indicate statistically significant differences, and vertical lines show standard deviation of the mean.
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and at the instant of touchdown was higher in men, but prepubertal boys flexed their joints more at the deepest point. Maximal knee flexion angular velocity in both DJ20 and DJ40 during the braking phase was higher in boys but during the propulsive phase was higher in men.

Based on our findings, the differences in performance between untrained boys and men might have several explanations. First, it could be attributed to the higher normalized propulsive force that was observed in adults for all jump types. Second, men required less time than boys to achieve this maximal propulsive force and higher values of reaction forces than boys, revealing a higher rate of force and power development. This point is supported by the adults’ higher reactive forces during DJ which is in agreement with previous studies on hopping in children and adults (31).

Regarding muscle activation, boys had lower normalized agonist EMG activity during the propulsive phase in all selected jumping tasks. This point could be partially supported by previous studies which showed that agonist activation during maximal voluntary contraction (19), and hopping activities (31) is lower in boys than men. A possible explanatory mechanism for boys’ lower activation may involve an incomplete maturation of their feed-forward system (39).

The superiority of men in jumping performance compared with prepubertal boys could be also attributed to their lower antagonist activity. This was true in both braking and propulsive phase. Originally, antagonist activity was suggested as a mechanism to increase joint stiffness, to decrease shear forces and to contribute to better joint stability (27). Specifically for children, it seems that coactivation is task dependent. During maximal isometric contractions the level of coactivation showed no differences for the knee (3,36), and elbow flexor/extensor muscles (12), but higher level of coactivation for the plantar flexors (19,23). On the other hand, during more complex movements, such as walking/running (15) or balancing (38), children demonstrate higher values of coactivation. Furthermore, in Barber-Westin et al.’s study (2), adults demonstrated higher coactivation during the landing phase of jumping compared with children, although no age-related differences were observed during the braking phase. However, nonskilled children express higher coactivation values compared with skilled, without having any differences between them in the lower limb stiffness regulation (20). This might indicate that higher coactivation in children during jumping is not necessarily related with stiffness regulation, but with a deficit in coordination, as partially suggested previously (14). This could be supported by the fact that children present higher energy cost during jumping (20). Therefore, the higher coactivation during the braking and propulsive phase observed in boys could be attributed to factors related to coordination or immaturity of the neuromuscular system, which could affect their jumping performance negatively.

Regarding the differences in performance between SJ and CMJ, both examined groups jumped higher during CMJ. This gain in CMJ has been previously confirmed in children (17,22,41). The gain during CMJ expressed as percentage of the SJ height was higher in boys than in men. This indicates that for this task boys use more effectively the SSC effect, as supported by previous studies (9,22,41). It is interesting to mention that in a previous study (17) which involved trained basketball players, the gain during CMJ of children was less than in the current study, and this gain was closer to the gain levels of adults. Although one study did not show any gain in jumping performance during CMJ (32), it seems that there is a maturation process in gain, which shows that the gain between SJ and DJ in both
pubertal and prepubertal boys decreases with age (41). This gain has been attributed to the potentiation of the contractile machinery at the beginning of the propulsive phase (4) due to the preceding loading of the muscle tendon unit. This preparatory loading may involve the following mechanisms: storage and reuse of the elastic energy (18), building up of a preparatory active state (4, 5), better interlimb coordination (4) and more optimal force/length relationship (26). Regarding the above mentioned mechanisms, earlier studies in adults (5, 16), argue that the storage and reuse of the elastic energy is not an important mechanism during CMJ, because the stretching velocities during the countermovement are not optimal. However, a recent study showed that adults compared with elderly people, were able to store and reuse more elastic energy and this could partially explain their higher performance in CMJ (30). Concerning children, it is still not clear whether the higher knee angular velocities in the braking phase, observed in the current study, affect storage and utilization of the elastic energy. This issue needs further investigation and cannot solely explain the differences between the two groups. Regarding the differences in force/length relationship between children and adults, during knee extension at various joint angles children’s optimal force output is shown at more flexed joint angles (34). Our results show that boys flexed their knees more than men at the deepest point during CMJ, and this could actually be more advantageous for their torque production, as previously proposed (26).

Concerning DJ, it has been recently reported (29) that children during DJ20, adopt a technique that has similar biomechanical characteristics to the “absorb” jump type, which is typical for low performers in jumping (25). It has been argued that adults use more optimally the stored elastic energy, based on the higher preactivation, agonist activity and stretch-reflex in adults compared with children (29). Our data show that this occurs for DJ20 and DJ40 as well, showing on average 5.3 cm (effect size $d = 1.4$) and 8.0 cm (effect size $d = 2.8$) gain relative to SJ, respectively. Respective effect sizes for boys were <0.4. The longer braking phase duration of children, in conjunction with the higher maximum knee flexion angle, is indicative of lower stiffness. The latter might also result in an inefficient SSC, where nonoptimal recoil of the stored energy into kinetic energy occurs (9, 28). Moreover, during the braking phase, knee angular velocity was significantly higher in boys, and this could have a negative effect by inhibiting the muscles which are responsible for the propulsive phase (42), because possibly they exceeded the optimal level of stretching velocity. The fact that the reactive strength in our study tends to decrease in DJ40 in children and increases in adults, seems to support this statement. It seems therefore that the neuromuscular system of boys is not prepared to accept the load of drop heights from 20 and 40 cm and to use it as positive work.

Another interesting point is that the vGRF (normalized to body weight) which is developed during the braking phase was higher in men during CMJ, but higher in children during DJ20 and DJ40. This could be attributed to the fact that drop height was not adjusted to the height of the participants and therefore boys jumped from a relatively higher drop height. Although it cannot be excluded that such difference could contribute to the increased maximal knee flexion observed in boys compared with adults, such an adjustment ($4.1 \pm 0.6$ cm and $8.1 \pm 1.3$ cm for DJ20 and DJ40, respectively) would have only a minor impact on performance. Therefore, we assume that these findings are related to differences in the technique of jumping, as previously reported (37). That is, children’s knee joint was more extended during precontact and touchdown, which has been previously
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characterized as a prelanding pattern of “poor” preparatory state (25). This could imply that children who adopt this technique might run higher risk for injuries due to increased loading on their joints.

In conclusion, inferiority of boys in jumping performance for all selected jump tasks could be partially attributed to their immature technique exemplified by their lower agonist and higher antagonist activation. It seems that adults develop a technique for more optimal storage/reuse of the elastic energy and more efficient stiffness regulation and therefore muscle output is higher during the propulsive phase. Therefore, from a practical point of view, the efficacy of drop jumps in children as a training tool is questionable, particularly when using drop heights between 20 and 40 cm, since these drop jumps resulted in no benefit to their performance. However, more research is required to clarify why children show no gain in performance during DJ and how this behavior could be modified.

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References


