Plyometric exercises are used primarily to increase the maximal power output [1, 2] and jumping ability [3]. They are characterized by a specific muscle action sequence: a rapid muscle lengthening movement, i.e. eccentric phase, is followed by an immediate explosive muscle contraction, which has greater strength and power than a contraction without the eccentric phase [4]. The greater force produced by the muscle during plyometric training is related to the storage of elastic energy during muscle stretch (eccentric contraction) and its rapid release during the shortening movement (concentric contraction). This process is often referred to as the stretch-shortening cycle (SSC) [5].

Different authors point to the possibility of simultaneous development of maximal muscle power output and jumping ability through plyometric training [6, 7]. On the other hand, some authors prove these two abilities cannot be shaped identically [8, 9]. To increase the maximal power output the movement should be performed rapidly, while in regular jumping training the movement performance does not have to be that fast, i.e. exercise performance time is an individual parameter. In some studies subjects achieved the maximum jump height with the widest range of counter movement, and their performance time was often longer than that when they generated the maximal power output [10]. Thus it can be assumed that the performance of exercise can significantly determine the plyometric training effects.

Plyometric training programs account for training loads (drop box height), number of rebounds, and length of intervals between sets of exercises, but they often lack precise instructions about the way the exercises should be performed, i.e. speed and range of movement, position of individual body parts during push-off, etc. The precise performance instructions are crucial in plyometric training since incorrect performance of such exercises may not only fail to bring the expected results but also lead to injuries.

The aim of the study was to assess the effects of plyometric exercises performed with the minimum ground contact time on the maximal power output of the legs and jumping ability. The following research hypothesis was formulated: plyometric training with
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Minimum ground contact time improves the maximal power output but does not affect jumping ability.

**Material and methods**

The subjects were 44 non-training second-year full time university students of physical education. The sample was randomly divided into two groups; plyometric (experimental) and control (Tab. 1). The subjects were informed about the research aims and procedure and a pilot study was carried out. The study was approved by the Research Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw.

**Plyometric training program**

The experimental group performed plyometric exercises on Mondays and Thursdays for six weeks. Each plyometric training session commenced with a 5-min run of low intensity, followed by five minutes of stretching exercises (Tab. 2). During each session the subjects were instructed to perform jumps as quickly as possible with the minimum ground contact time. After each rebound the legs were to be straightened in the hip, knee and ankle joints. The feet during jumps were set slightly outwards and the jumps were performed on a synthetic surface. During the exercises no subject complained of muscle or joint pains. The control group did not take part in the exercise program but, like the plyometric group, in regular classes of gymnastics, swimming and football.

**Measurements**

**Vertical jumps**

The measurement station consisted of a force platform (Kistler, Switzerland) with the sampling frequency of 1000 Hz, amplifier, analog-to-digital converter and the BioWare 3.24 software package. Two types of vertical jumps were measured: counter movement jump (CMJ) and depth jump (DJ) with the drop box height of 0.31 m [11]. The subjects were to achieve the maximum height in CMJs and in DIs after a rebound. The arms swung first backwards and then high upwards. The knee flexion angle was not specified. Each subject performed three CMJ and DJ attempts. The best results out of three (the highest results of center of mass displacement) were analyzed. Before each set of exercises the subjects were shown a presentation of correct performance of the jumps. The following parameters were calculated:

- \( P_z \) – maximal power output (concentric phase)

\[
P_z(t) = F_z(t) \cdot v_z(t)
\]

where: \( F_z \) – vertical force, \( v_z \) – velocity;

**Table 1. Parameters of study groups before the commencement of plyometric training**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plyometric group ((n = 22))</th>
<th>Control group ((n = 22))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>20.3 ± 0.5</td>
<td>20.6 ± 0.5</td>
</tr>
<tr>
<td>Body height (m)</td>
<td>1.81 ± 0.06</td>
<td>1.80 ± 0.06</td>
</tr>
<tr>
<td>Body mass (kg)*</td>
<td>73.2 ± 6.9</td>
<td>73.9 ± 6.7</td>
</tr>
</tbody>
</table>

* body mass did not change significantly after plyometric training \((p > 0.05)\)

**Table 2. Plyometric training program**

<table>
<thead>
<tr>
<th>Week</th>
<th>Plyometric training program (number of sets × number of rebounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2</td>
<td>Standing vertical hops 2 × 10</td>
</tr>
<tr>
<td></td>
<td>Single foot hops 4 × 8</td>
</tr>
<tr>
<td></td>
<td>Multiple two-foot hurdle jumps (hurdle height 0.55 m) 6 × 6</td>
</tr>
<tr>
<td></td>
<td>Counter movement jumps 3 × 5</td>
</tr>
<tr>
<td></td>
<td>Depth jumps (drop box height 0.20 m) 3 × 6</td>
</tr>
<tr>
<td>3–4</td>
<td>Lateral two-foot jumps 2 × 10</td>
</tr>
<tr>
<td></td>
<td>Two-foot jumps 4 × 8</td>
</tr>
<tr>
<td></td>
<td>Counter movement jumps 3 × 5</td>
</tr>
<tr>
<td></td>
<td>Multiple two-foot hurdle jumps (hurdle height 0.65 m) 6 × 6</td>
</tr>
<tr>
<td></td>
<td>Depth jumps (drop box height 0.30 m) 3 × 6</td>
</tr>
<tr>
<td>5–6</td>
<td>Two-foot jumps forward and backward: 2 × 10</td>
</tr>
<tr>
<td></td>
<td>Single foot jumps 2 × 8 on each foot</td>
</tr>
<tr>
<td></td>
<td>Counter movement jumps 3 × 5</td>
</tr>
<tr>
<td></td>
<td>Multiple two-foot hurdle jumps (hurdle height 0.76 m) 6 × 6</td>
</tr>
<tr>
<td></td>
<td>Depth jumps (drop box height 0.40 m) 3 × 6</td>
</tr>
</tbody>
</table>
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• $t_o$ – rebound time:
calculated for CMJs and DJs as the time between the moment of the lowest position of the body center of mass and the zero ground reaction force;
• $H_{max}$ – maximal jump height:

$$H_{max} = \frac{v_o^2}{2g}$$

where: $g$ – gravitational acceleration (9.81 m/s$^2$), $v_o$ – rebound velocity.

The momentary velocity ($v$) of the center of mass was calculated by way of integration of momentary acceleration ($a$), i.e. force ($F$) exerted on the platform minus body weight (BW) divided by body mass (BM) [13, 14]. The knee flexion angle was determined by video motion analysis. Three markers were placed on the right-hand side of the subject’s body at the greater trochanter, lateral condyle of the tibia, and lateral malleolus of the fibula [15]. The knee flexion angle was calculated as the difference between the angle at the moment of contact of the foot with the ground ($\alpha_{max}$) and the lowest flexion value ($\alpha_{min}$) [16]. The jumps were recorded with a digital vision camera (Basler piA640-210gc, Germany) with the sampling frequency of 100 Hz. The two-dimensional video motion analysis was carried out using the System APAS XP software package (USA). The footage was flat calibrated.

**Five-hop test**
The five-hop test was carried out at a track and field jumping facility. Before the test the subject stood on a take off line on the runway 10–11 meters before the sandpit. The aim of the test was to jump the maximum distance possible. Each subject performed five consecutive jumps: a two-foot push off, four consecutive single alternate leg jumps and two-foot landing in the sandpit. The best result (longest distance) out of three attempts was taken into consideration. The jump length was measured with a tape measure from the take off line to the nearest mark made in the sand by the jumper.

Each test was preceded with a warm up. The measurements were taken twice: three days before the plyometric training program and three days after its completion.

The parameters were expressed as means and standard deviations (± SD). The normal distribution was assessed with the Shapiro-Wilk test. The statistical significance of differences was determined with a two-way analysis of variance (ANOVA): 2 (plyometric group, control group) × 2 (test: before and after). At $p < 0.05$ Tukey’s test was used. The correlations between the measured parameters as well as the reliability of the tests were estimated with the Pearson correlation coefficient. All statistical calculations were made with the use of the Statistica v. 5.1 PL software package.

Table 3. Mean values (± SD) of maximal power output, center of mass elevation, rebound time and knee flexion angle in CMJ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plyometric group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Maximal power output (W/kg)</td>
<td>37.2 ± 7.3</td>
<td>43.8 ± 7.7*</td>
</tr>
<tr>
<td>Center of mass elevation (m)</td>
<td>0.41 ± 0.08</td>
<td>0.42 ± 0.07</td>
</tr>
<tr>
<td>Rebound time (ms)</td>
<td>314 ± 32</td>
<td>307 ± 28</td>
</tr>
<tr>
<td>Knee flexion angle (degrees)</td>
<td>96 ± 8</td>
<td>95 ± 8</td>
</tr>
</tbody>
</table>

*p ≤ 0.001 for differences between measurements before and after the plyometric training program

Table 4. Mean values (± SD) of maximal power output, center of mass elevation, rebound time and knee flexion angle in DJ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plyometric group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Maximal power output (W/kg)</td>
<td>52.2 ± 11.6</td>
<td>59.0 ± 10.6**</td>
</tr>
<tr>
<td>Center of mass elevation (m)</td>
<td>0.40 ± 0.07</td>
<td>0.42 ± 0.06</td>
</tr>
<tr>
<td>Rebound time (ms)</td>
<td>283 ± 31</td>
<td>228 ± 25*</td>
</tr>
<tr>
<td>Knee flexion angle (degrees)</td>
<td>92 ± 8</td>
<td>86 ± 7*</td>
</tr>
</tbody>
</table>

*p ≤ 0.01, **p ≤ 0.001 for differences between measurements before and after the plyometric training program
Results

The reliability of the tests was determined with the test-retest method – the subjects performed two CMJs and two DJs at a five-minute interval. The test’s reliability was determined with the coefficient of correlation: $r = 0.98$ (CMJ) and $r = 0.96$ (DJ) for the center of mass elevation; $r = 0.92$ (five-hop test); and $r = 0.96$ (CMJ) and $r = 0.93$ (DJ) for the maximal power output. The obtained values corresponded to data in literature [11, 17, 18].

The plyometric training caused an increase in the relative maximal power output in CMJ (significant interaction between group and time: $F_{1,42} = 5.12$, $p \leq 0.05$) and in DJ (significant interaction between group and time: $F_{1,42} = 10.23$, $p \leq 0.01$) (Tab. 3, 4).

No significant changes in the center of mass elevation were noted in either type of jumps. The changes in the five-hop test results, before and after the completion of the plyometric training were also non-significant: $13.02 \pm 0.68$ and $13.07 \pm 0.61$ m in the plyometric group; and $12.97 \pm 0.93$ and $12.95 \pm 0.84$ m in the control group, respectively.

A significant reduction of the rebound time (significant interaction between group and time: $F_{1,42} = 8.15$, $p \leq 0.01$) was noted in the DJs as well as significantly lower knee flexion angles were noted in the plyometric group (significant interaction between group and time: $F_{1,42} = 10.63$, $p \leq 0.01$).

Discussion

The subjects from the plyometric group significantly improved their maximal power output in the vertical counter movement jump (CMJ) and depth jump (DJ). Their jumping ability in CMJ, DJ and five-hop test remained unaffected. This confirms the hypothesis that performance of plyometric exercises aimed at improvement of the speed of execution can improve the maximal power output of the legs, but not the level of jumping ability.

The different impact of the plyometric training program on the same parameters (rebound time, knee flexion angle) in CMJs and DJs may be related to a different characteristic of both tests. Hennessy and Kilty [19] claim that the CMJ involves a long stretch shortening cycle (SSC), whereas a DJ a short SSC as the ground contact time in the latter is relatively shorter. This is why the same parameters measured in both jumping tests do not reveal strong correlations [20, 21].

The results of the present study point to the need of inclusion of precise instructions about the performance of plyometric exercises as they can significantly affect the direction and size of changes in the development of skills. Insufficient control of the performance of plyometric exercises may lead to unintended consequences [22]. Unfortunately, as shown in a review study by Markovic [3], the instructions in the methodological parts of plyometric training programs which describe the execution technique are often missing or are too vague.

The issue of technique of performing plyometric exercises in the context of improvement of the maximal power output and jumping ability has been rarely discussed in research studies [23]. Among the very few researchers who have dealt with the problem are Walsh et al. [24], who showed that depth jump technique affects the key determinants of maximal power output and jumping ability more significantly than, for example, drop box height.

The results of the present study also indicate those components of plyometric training programs (performance of exercises strictly following precise instructions) which can improve one ability (maximal power output) without affecting another one. It is therefore important to remember that guidelines on improving the maximal power output may differ from guidelines on improvement of jumping ability.

The study also shows that effects of training aimed at the shortening of the time of jump performance are reflected in the reduction of the knee flexion angle and the rebound time. Most likely, the changes noted in these two parameters affected the increase of the maximal power output [25]. Such changes are highly desired in the majority of sports in which the results rely on the speed of a start task execution, e.g. in 100 m sprint races. Although the study failed to reveal any significant changes in the jumping ability level, plyometric exercises can be nevertheless recommended as part of jumping training in volleyball or basketball players. The possibility to reach the same jump height, however, in a shorter time, can bring measurable effects in rebounding or blocking. Thus if a player’s jump height is satisfactory but the entire movement lasts too long the speed of execution of exercises should be emphasized. If the player’s jump height requires improvement the rebound time can be lengthened and the knee flexion angle reduced.

In all likelihood the lack of improvement in jumping ability in the depth jump test was related to the reduc-
tion of time of force release (smaller knee flexion angle, shorter rebound time) and thus a lower force impulse, which determines jumping ability to a large extent [10]. According to Trzaskoma et al. [26] a significant improvement of jumping ability without strength training is rather difficult to achieve. Trzaskoma and Trzaskoma [27] revealed that when strength in the legs was not changed significantly, a significant increase in the maximal power output was noted with a decrease in the level of jumping ability. The effect of plyometric training on strength has not been precisely determined as yet. Some authors observed an increase in strength after plyometric training [28, 29], and some found no changes [30, 31].

The present study shows that performing jumps with the fastest possible rebound and the shortest ground contact time improves the maximal power output with no effects on jumping ability. The question remains whether it is possible to improve jumping ability without improving the maximal power output. The results of the present study confirm this indirectly [31]. However, the precise instructions of training aimed at the improvement of jumping ability are difficult to formulate since – as stated before – the highest jumps were achieved with fairly diverse kinematic parameters [10].

Conclusions

The results obtained show that each plyometric training program should include precise instructions of performance of exercises. Methodological guidelines in plyometric training concerning the improvement of the maximal power output can differ from the guidelines aimed at the improvement of jumping ability.

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References


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