Differences in Rate of Force Development, Muscle Morphology and Maximum Strength between Weightlifters and Track and Field Throwers

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Abstract: The purpose of this study was to investigate the differences between weightlifters and track and field throwers in terms of the rate of force development (RFD), lean mass, muscle architecture and one-repetition maximum (1-RM) muscle strength. Sixteen elite male athletes (eight weightlifters and eight track and field throwers) participated in the study. Measurements were performed one week after the annual national championships and included anthropometry, body composition analysis (dual X-ray absorptiometry), vastus lateralis (VL) muscle architecture (ultrasonography), countermovement jump (CMJ), leg press isometric RFD and 1-RM strength in snatch and back squat. RFD was similar between groups \( p > 0.05 \), although RFD relative to lean mass was higher for weightlifters \( p < 0.05 \). Throwers had a higher trunk lean mass compared to weightlifters \( p = 0.007 \). Weightlifters had a longer VL fascicle length compared to throwers \( p = 0.037 \). Performances in CMJ height, CMJ power relative to body mass and 1-RM strength were higher for the weightlifters \( p < 0.05 \). Lean body mass index was correlated with back squat \( r = 0.667 \) and snatch \( r = 0.498 \). VL fascicle length was significantly correlated with snatch \( r = 0.631 \) and back squat \( r = 0.718 \). These results suggest that weightlifters may produce greater power outputs and 1-RM strength than track and field throwers, which may be associated with longer VL fascicle length.

Keywords: lean body mass; power; fascicle length; 1-RM strength; athletic performance

1. Introduction

Olympic weightlifting and track and field throwing events are two of the most power-demanding athletic activities [1]. Power athletes, such as weightlifters and track and field throwers, dedicate a large part of their preparation to resistance training programs to enhance competitive lifting and throwing performance, respectively [2–4]. Weightlifting includes the snatch and the clean and jerk, two multijoint movements that require high-power production and the ability of the athletes to produce a large amount of force rapidly [5]. Track and field throwing events include the shot put, the javelin, the hammer and the discus throw. Performance in these events depends, to a considerable extend, on fast force application on the throwing implement [6,7]. For these reasons, weightlifters and throwers share several similarities in their training programs. Both groups of athletes mainly use resistance exercises, such as the snatch, the back squat and the clean and jerk, performed explosively, as well as sprints and plyometric exercises, and they frequently evaluate their maximum strength (1-RM) [2,3]. However, weightlifters use higher resistance loads during their year-round training (>85% of 1-RM) compared to throwers, who use both light (≤30% of 1-RM) and heavy resistance loads (≥80% of 1-RM) [8]. Moreover, throwers aim to overcome a constant external load (the implement’s mass) with maximum
velocity compared to weightlifters, who aim to lift the heaviest possible load during snatch and clean and jerk. These similarities and differences between weightlifting and track and field throwing events may dictate different training-induced adaptations with respect to factors such as the rate of force development (RFD), the amount of lean mass and muscle architecture characteristics.

Regarding RFD, it is thought to be a key factor influencing successful performance in power sports [6,9]. RFD can be assessed by the force–time curve during both dynamic and isometric muscle actions and evaluates the force that can be applied in short time periods ranging from 0 to 250 ms [9–12]. It has been proposed that RFD is subject to numerous biological and non-biological factors that are dependent on time, training type and training background [9,12]. For example, early RFD (<100 ms from the onset of muscle contraction) seems to be primarily determined by neural activation [9] and, at least in well-trained power athletes, by the percentage area of muscle occupied (%CSA) of type IIx muscle fibres [12]. In contrast, lean mass, fibre-type composition, muscle architecture and maximum strength seem to be associated with late RFD (>100 ms from the onset of muscle contraction) [6,9,12]. Power athletes have higher RFDs compared to strength-trained, endurance-trained or sedentary participants, mostly due to longitudinal power training, resulting in type IIX maintenance, lean mass and strength increase [12–14]. Track and field throwers have a high percentage of type II muscle fibres [15], and they maintain a high percentage of type IIX muscle fibres, even after the heavy winter preparation phase [14]. On the contrary, weightlifters have a high percentage of type IIA muscle fibres and fibre area [16,17]. Nevertheless, weightlifters and throwers have similar RFD acceleration times during the second pull of the barbell (150–200 ms) [18,19] and the final thrust of the throwing implement (150–240 ms) [20,21], respectively. However a comparison of RFDs is lacking between these groups of highly trained power athletes.

Lean body mass is also a positive contributing factor in strength power sports. Training-induced increases in lean mass are significantly correlated with increases in RFD in track and field throwers [6]. Moreover, lean mass is closely correlated with RFD, 1-RM strength and power in throwers [2,7,22]. Lean mass is significantly correlated with weightlifting performance in young [23], elite male [24] and well-trained female weightlifters [25]. In such powerful sports like weightlifting and track and field throwing, it would be interesting to investigate how long-term power training may affect lean mass adaptations and how these training-induced adaptations with respect to lean mass may have an effect on RFD and power performance among highly power-trained athletes.

Long-term power training programs may induce significant alterations in muscle architectural characteristics, namely muscle thickness, fascicle angle and fascicle length [26]. Muscle thickness and fascicle angle have been associated with muscle hypertrophy and increased force production [27], whereas increases in fascicle length have been associated with fibre-shortening velocity, resulting in improved sprint, power and RFD performance [6,28,29]. A previous study of young throwers showed that vastus lateralis (VL) muscle thickness and fascicle length were significantly correlated with 1-RM strength in back squat and hang power clean and with RFD [6], whereas studies of male and female weightlifters showed trivial to very large positive correlations between 1-RM strength in snatch and clean and jerk with VL muscle architecture characteristics [24,25]. Although weightlifters and throwers share several training similarities, training-induced adaptations to muscle architecture may differ considerably between these highly power-trained athletes, potentially due to the nature and design of their year-round training regimens.

The purpose of the present study was to investigate the differences in RFD, lean mass, muscle architecture and 1-RM strength between elite weightlifters and elite track and field throwers. We hypothesized that longitudinal training may induce differing adaptations in lean mass and muscle architecture between weightlifters and throwers, resulting in differential strength power and RFD performances.
2. Material and Methods

2.1. Participants

Eight elite weightlifters (age: 25.1 ± 5.3 years; body mass: 91.9 ± 11.4 kg; body height: 1.78 ± 0.06 m; snatch: 149.0 ± 13.7 kg; clean and jerk: 182.7 ± 20.1 kg) and eight elite track and field throwers (age: 24.6 ± 4.8 years; body mass: 98.4 ± 5.3 kg; body height: 1.83 ± 0.06 m; 4 hammer throwers (maximum throwing distance: 67.1 ± 8.9 m), 2 discus throwers (maximum throwing distance: 51.6 ± 1.7 m), 1 shot putter (maximum throwing distance: 16.40 m) and 1 javelin thrower (maximum throwing distance: 73.82 m)) participated in the study. All athletes were members of the national team and regularly participated in national and international competitions, whereas 1 weightlifter and 1 thrower participated in the 2016 Rio de Janeiro Olympic Games. In addition, athletes pass approximately 2 to 3 doping controls during each year. None of them was ever found positive for illegal substances. Athletes were informed about the experimental procedures and signed a written informed consent form. Before entering the study, athletes fulfilled the following criteria: (a) trained on a regular basis (≥10 training sessions per week), (b) participated in the national championship during the year when the current study was conducted, (c) absence of any orthopaedic or neuromuscular issues and (d) absence of any drug or illegal substances. All procedures were in accordance with the 1975 Declaration of Helsinki as revised in 2000 and were approved by the Institutional Ethics Committee of the School of Physical Education and Sport Science of the National and Kapodistrian University of Athens.

2.2. Experimental Procedure

The aim of the current study was to investigate whether longitudinal training may affect training-induced adaptations in highly power-trained athletes. Elite athletes from Olympic weightlifting and track and field athletic throwing events were recruited to participate in the study. Details regarding the longitudinal training programs of weightlifters and throwers can be found on previous studies [2,24]. All measurements were performed 1 week following the national championships, for which athletes were considered to be in their best physical fitness. The duration of the experimental procedure was 3 days. During the first day, athletes visited the laboratory for measurement of anthropometric characteristics, body composition analysis and VL muscle architecture evaluation. On the second day, athletes performed CMJs on a force platform and an RFD test on an isometric leg press seat. On the third day, athletes performed a 1-RM strength test on snatch and back squat at the training facilities of the national team. Results were compared between the two groups of athletes.

2.3. Anthropometric Characteristics and Dual Energy X-ray Absorptiometry Measurement

Anthropometric measurements and body composition analysis were performed during the first day. Athletes were instructed to fast for approximately 10 h and refrain from any strenuous exercise for 24 h prior to measurements [24]. Body mass was evaluated on a portable body scale (Tanita BC-545n, Southampton, UK), and body height was measured with a portable stadiometer (Seca 213, height measure, Surrey, UK). After the evaluation of anthropometric characteristics, body composition was assessed via dual X-ray absorptiometry (DXA; model DPX-L; LUNAR Radiation Corp, Madison, WI, USA). The LUNAR radiation body composition program was used for all images to determine bone mineral density (BMD), percentage body fat, total lean mass, leg lean mass, arm lean mass and trunk lean mass. Lean mass index (LMI) was also calculated and was defined as lean mass divided by the square of body height (kg·m⁻²). The intraclass correlation (ICC) coefficients for body mass and body height were 0.99 (95% confident intervals (CIs): lower = 0.998; upper = 0.999) and 0.99 (95% CIs: lower = 0.998; upper = 0.999), respectively. The ICC for body composition analysis for bone mineral density was 0.99 (95% CIs: lower = 0.973; upper = 0.999); that for body fat was 0.975 (95% CIs: lower = 0.785; upper = 0.995); and those for total, legs, arms and trunk lean mass were 0.99 (95% CIs: lower = 0.966; upper = 0.999),
0.99 (95% CIs: lower = 0.986; upper = 0.999), 0.99 (95% CIs: lower = 0.931; upper = 0.999) and 0.96 (95% CIs: lower = 0.789; upper = 0.992), respectively.

2.4. Vastus Lateralis Muscle Architecture

Following the DXA measurement, athletes remained supine for evaluation of VL muscle architecture with ultrasonography. Specifically, B-mode ultrasound images (product model Z5; Shenzhen Mindray Bio-Medical Electronics Co, Ltd., Shenzhen, China) were taken with a 10-MHz linear-array probe (38 mm width) with extended field of view as previously described [30,31]. Three images were taken at 50% of the distance from the central palpable point of the greater trochanter to the lateral condyle of the femur, and the mean of the 3 images was used for statistical analysis. Images from VL were analysed via image analysis software (Motic Images Plus, version 2.0; Hong Kong, China) for muscle thickness, fascicle angle and fascicle length. The ICCs for VL muscle thickness, fascicle angle and fascicle length were 0.97 (95% CIs: lower = 0.856; upper = 0.987), 0.88 (95% CIs: lower = 0.609; upper = 0.965) and 0.84 (95% CIs: lower = 0.470; upper = 0.955), respectively.

2.5. Countermovement Jump and Rate of Force Development

During the second day, athletes visited the laboratory for CMJs and isometric leg press RFD. Measurements were performed during morning hours, and athletes were instructed to be well-fed and to avoid any training 24 h before measurement. After a 10 min warmup on a treadmill at approximately 7–9 km·h⁻¹ and some full body dynamic stretching, athletes performed 4 CMJs with submaximal intensity, with 1 min rest between jumps. Then, athletes performed 5 maximum CMJs, with 2 min rest between attempts. All CMJs were performed on a force platform (WP800; A/D sampling frequency, 1 kHz; Applied Measurements Ltd. Co, Reading, UK) with arms akimbo. Athletes were instructed to jump as high as possible, and after each jump, they were informed of their jump height, which served as an incentive to jump even higher. All CMJs recorded from the force platform were analysed (Sensor Interface PCD-320A; Kyowa Electronic Instruments, Tokyo, Japan) to calculate the maximum vertical jump height, power output and power relative to body mass during the push-off phase [32]. The best jumping height performance was used for statistical analysis. The ICCs for CMJ height, force, power and power relative to body mass were as follows: 0.97, (95% CIs: lower = 0.850; upper = 0.993), 0.97 (95% CIs: lower = 0.849; upper = 0.994), 0.99 (95% CIs: lower = 0.991; upper = 0.998) and 0.99 (95% CI, lower = 0.992; upper = 0.999), respectively.

Fifteen minutes after the CMJs, athletes performed the isometric leg press RFD. Athletes were seated on the leg press and placed their feet on a force platform (WP800, A/D sampling frequency 1 kHz; Applied Measurements Ltd., Co), which was mounted vertically on the laboratory wall. Knee angle was set at 120°, and hip angle was set at 110° [33]. Warmup included 2 attempts with progressive application of force and 2 more attempts as fast as possible but only for 1 s duration. Then athletes performed 4 maximum attempts with 3 s duration. Athletes were instructed to apply their force as fast as possible, and a real-time monitor showed the application of their force. Data from the force platform were recorded (Sensor Interface PCD-320A; Kyowa Electronic Instruments, Tokyo, Japan) and analysed for calculation of specific time windows of 0–30, 0–50, 0–80, 0–100, 0–150, 0–200 and 0–250 milliseconds [33]. The best performance according to overall RFD was used for statistical analysis. The ICCs for RFD time windows were as follows: RFD 30 milliseconds = 0.92 (95% CIs: lower = 0.374; upper = 0.989), RFD 50 milliseconds = 0.96 (95% CIs: lower = 0.385; upper = 0.994), RFD 80 milliseconds = 0.818 (95% CIs: lower = 0.818; upper = 0.995), RFD 100 milliseconds = 0.98 (95% CIs: lower = 0.890; upper = 0.996), RFD 150 milliseconds = 0.98 (95% CIs: lower = 0.940; upper = 0.998), RFD 200 milliseconds = 0.98 (95% CIs: lower = 0.871; upper = 0.996) and RFD 250 milliseconds = 0.97 (95% CIs: lower = 0.778; upper = 0.995).
2.6. 1-RM Strength

During the third day, athletes visited the training facilities of the national team for evaluation of 1-RM strength in snatch and back squat. After a self-selected warmup, dynamic stretching and individual barbell exercises, athletes started with 1-RM measurement with a snatch, and 15 min later, a back squat was performed. Snatch was performed with full technique, whereas back squat was performed with full range of motion. Each athlete individually increased their loads and repetitions until reaching 90% of 1-RM. Then, 5 maximum attempts were allowed to achieve the maximum strength. All lifts were performed on a weightlifting platform using an Olympic barbell. During 1-RM measurement, a certified strength and conditioner researcher was present to evaluate the technique and provide feedback to the athletes to lift a heavier load. The ICCs for the snatch and the back squat exercises were 0.96 (95% CIs: lower: 0.810; upper: 0.990) and 0.99 (95% CIs: upper: 0.990; lower: 0.964), respectively.

2.7. Statistical Analysis

All data are presented as mean and standard deviations (SDs). For the comparison between weightlifters and track and field throwers, a student’s t-Test for independent samples was used. Cohen’s d effect size was also calculated. The r-Pearson correlation coefficient was used to explore the relationships between variables for all athletes (n = 16). The reliability of all measurements was assessed using a two-way random-effect intraclass correlation coefficient (ICC) with 95% confident intervals (CI). Statistical analyses were performed with SPSS Statistics Ver. 20 (IBM Corporation, USA). \( p \leq 0.05 \) was used as a 2-tailed level of significance.

3. Results

All athletes completed the measurements without injuries. Table 1 presents the results of anthropometric characteristics, body composition, CMJ performance and VL muscle architecture characteristics. Weightlifters had 3.7% lower body height compared to throwers. In addition, throwers had 20.9% greater trunk lean mass compared to weightlifters, but weightlifters had 21.2% higher CMJ height and produced 8.2% more power relative to body mass. Interestingly, weightlifters had a significant 13.8% higher VL fascicle length and 17.1% higher VL fascicle length relative to body height compared to throwers.

Table 1. Results of anthropometric characteristics, body composition, CMJ variables and VL muscle architecture for weightlifters and throwers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weightlifters</th>
<th>Throwers</th>
<th>( p )</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass (kg)</td>
<td>91.9 ± 11.4</td>
<td>98.4 ± 5.3</td>
<td>0.164</td>
<td>0.734</td>
</tr>
<tr>
<td>Body height (m)</td>
<td>1.78 ± 0.06</td>
<td>1.83 ± 0.06 *</td>
<td>0.039</td>
<td>1.136</td>
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<tr>
<td>Fat (%)</td>
<td>16.9 ± 2.9</td>
<td>18.3 ± 4.4</td>
<td>0.483</td>
<td>0.360</td>
</tr>
<tr>
<td>BMD (gr·cm(^{-2}))</td>
<td>1.475 ± 0.09</td>
<td>1.441 ± 0.04</td>
<td>0.342</td>
<td>0.495</td>
</tr>
<tr>
<td>LMI (kg·m(^{-2}))</td>
<td>23.1 ± 1.9</td>
<td>23.1 ± 1.2</td>
<td>0.988</td>
<td>0.006</td>
</tr>
<tr>
<td>Total lean mass (kg)</td>
<td>72.2 ± 8.2</td>
<td>77.5 ± 4.7</td>
<td>0.132</td>
<td>0.799</td>
</tr>
<tr>
<td>Legs lean mass (kg)</td>
<td>26.4 ± 2.8</td>
<td>25.3 ± 3.7</td>
<td>0.497</td>
<td>0.348</td>
</tr>
<tr>
<td>Trunk Lean Mass (kg)</td>
<td>32.2 ± 4.9</td>
<td>38.9 ± 3.4 *</td>
<td>0.007</td>
<td>1.588</td>
</tr>
<tr>
<td>Arms lean mass (kg)</td>
<td>9.1 ± 1.1</td>
<td>8.3 ± 1.0</td>
<td>0.164</td>
<td>0.736</td>
</tr>
<tr>
<td>Trunk and arms lean mass (kg)</td>
<td>41.3 ± 5.9</td>
<td>47.2 ± 3.1 *</td>
<td>0.025</td>
<td>1.252</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weightlifters</th>
<th>Throwers</th>
<th>p</th>
<th>Cohen’s d</th>
</tr>
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<tbody>
<tr>
<td>Countermovement Jump Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ height (cm)</td>
<td>49.3 ± 6.1</td>
<td>38.9 ± 5.7*</td>
<td>0.003</td>
<td>1.770</td>
</tr>
<tr>
<td>CMJ power (W)</td>
<td>4897.2 ± 625.9</td>
<td>4821.4 ± 434.9</td>
<td>0.783</td>
<td>0.140</td>
</tr>
<tr>
<td>CMJ relative to body mass (W·kg(^{-1}))</td>
<td>53.3 ± 3.1</td>
<td>48.9 ± 3.1*</td>
<td>0.013</td>
<td>1.415</td>
</tr>
<tr>
<td>Vastus Lateralis Muscle Architecture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VL muscle thickness (cm)</td>
<td>2.96 ± 0.16</td>
<td>2.86 ± 0.35</td>
<td>0.495</td>
<td>0.356</td>
</tr>
<tr>
<td>VL fascicle angle ((^\circ))</td>
<td>20.6 ± 3.6</td>
<td>22.7 ± 4.4</td>
<td>0.314</td>
<td>0.522</td>
</tr>
<tr>
<td>VL fascicle length (cm)</td>
<td>9.31 ± 1.45</td>
<td>8.02 ± 0.86*</td>
<td>0.035</td>
<td>1.084</td>
</tr>
<tr>
<td>VL fascicle length relative to body height (cm·m(^{-1}))</td>
<td>5.28 ± 0.88</td>
<td>4.38 ± 0.52*</td>
<td>0.018</td>
<td>1.249</td>
</tr>
</tbody>
</table>

* p = significant difference between weightlifters and throwers. BMD = bone mineral density, LMI = lean mass index, CMJ = countermovement jump, VL = vastus lateralis.

Figure 1A presents the force in absolute values during the isometric leg press test. No significant difference was found between groups. However, when force was expressed per total lean mass, weightlifters produced 24.5% more force at 80 ms (p = 0.045, d = 1.102), 24.5% more force at 100 ms (p = 0.031, d = 1.120) and 21.7% more force at 150 ms (p = 0.036, d = 1.159) compared to throwers (Figure 1B). Similarly, Figure 1C presents the RFD in absolute values. No significant difference was observed between weightlifters and throwers. However, when RFD was expressed relative to total lean mass, weightlifters had 24.1% higher RFD at 80 ms (p = 0.045, d = 1.102), 24.6% higher RFD at 100 ms (p = 0.031, d = 1.202) and 21.8% higher RFD at 150 ms (p = 0.036, d = 1.159) (Figure 1D).

Performance in 1-RM strength in snatch and back squat is presented in Figure 2. Weightlifters had 22.8% greater 1-RM strength in snatch (p = 0.001, d = 2.161) and 13.2% greater 1-RM strength in back squat (p = 0.038, d = 1.188) compared to throwers.

Table 2 presents the correlation coefficients between snatch and back squat with LMI and CMJ variables. Lean mass was significantly correlated with CMJ power production (r = 0.781, p = 0.001). Table 3 presents the correlation coefficients between 1-RM strength and isometric leg press RFD. VL muscle thickness was significantly correlated with CMJ height (r = 0.631, p = 0.009) and CMJ power relative to body mass (r = 0.634, p = 0.008). VL fascicle length was significantly correlated with snatch (r = 0.631, p = 0.009) and back squat (r = 0.718, p = 0.001).

<table>
<thead>
<tr>
<th>LMI</th>
<th>CMJ Height</th>
<th>CMJ Power</th>
<th>CMJ Power per BM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snatch</td>
<td>0.498*</td>
<td>0.685 **</td>
<td>0.528 *</td>
</tr>
<tr>
<td>Back Squat</td>
<td>0.667*</td>
<td>0.553 *</td>
<td>0.522 *</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, RFD = rate of force development, LMI = lean mass index, CMJ = countermovement jump.

Table 3. Correlation coefficients between snatch and back squat with isometric leg press rate of force development (n = 16).

<table>
<thead>
<tr>
<th>RFD30 ms</th>
<th>RFD50 ms</th>
<th>RFD80 ms</th>
<th>RFD100 ms</th>
<th>RFD150 ms</th>
<th>RFD200 ms</th>
<th>RFD250 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snatch</td>
<td>0.550*</td>
<td>0.593 *</td>
<td>0.608 *</td>
<td>0.627 **</td>
<td>0.637 **</td>
<td>0.610 *</td>
</tr>
<tr>
<td>Back Squat</td>
<td>0.521 *</td>
<td>0.534 *</td>
<td>0.502 *</td>
<td>0.527 *</td>
<td>0.539 *</td>
<td>0.521 *</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, RFD = Rate of force development.
Arms lean mass (kg) 9.1 ± 1.1 8.3 ± 1.0 0.164 0.736
Trunk and arms lean mass (kg) 41.3 ± 5.9 47.2 ± 3.1 * 0.025 1.252

Countermovement Jump Performance
CMJ height (cm) 49.3 ± 6.1 38.9 ± 5.7 * 0.003 1.770
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VL fascicle angle (°) 20.6 ± 3.6 22.7 ± 4.4 0.314 0.522
VL fascicle length (cm) 9.31 ± 1.45 8.02 ± 0.86 * 0.035 1.084
VL fascicle length relative to body height (cm/\text{m}) 5.28 ± 0.88 4.38 ± 0.52 * 0.018 1.249

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Figure 1. (A) Force production in absolute values during the isometric leg press measurement (±SD). No significant differences were observed between groups. (B) Rate of force development in absolute values (±SD). No significant difference was observed between weightlifters and throwers. (C) Force production relative to total lean mass (±SD). Significant difference at 80, 100 and 150 ms between weightlifters and throwers. (D) Rate of force development relative to total lean mass (±SD). Significant difference at 80, 100 and 150 ms between weightlifters and throwers. * denotes a significant difference between weightlifters and throwers.
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Performance in 1-RM strength in snatch and back squat is presented in Figure 2. Weightlifters had 22.8% greater 1-RM strength in snatch ($p = 0.001$, $d = 2.161$) and 13.2% greater 1-RM strength in back squat ($p = 0.038$, $d = 1.188$) compared to throwers.

Figure 2. Performance in 1-RM strength in snatch and back squat (±SD). With (*) denoted the significant difference between weightlifters and throwers.

Table 2 presents the correlation coefficients between snatch and back squat with LMI and CMJ variables. Lean mass was significantly correlated with CMJ power production ($r = 0.781$, $p = 0.001$). Table 3 presents the correlation coefficients between 1-RM strength and isometric leg press RFD. VL muscle thickness was significantly correlated with CMJ height ($r = 0.631$, $p = 0.009$) and CMJ power relative to body mass ($r = 0.634$, $p = 0.008$). VL fascicle length was significantly correlated with snatch ($r = 0.631$, $p = 0.009$) and back squat ($r = 0.718$, $p = 0.001$).

Table 2. Correlation coefficients between snatch and back squat with LMI and CMJ ($n = 16$).

<table>
<thead>
<tr>
<th></th>
<th>Snatch</th>
<th>Back Squat</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMI</td>
<td>0.498 *</td>
<td>0.667 *</td>
</tr>
<tr>
<td>CMJ Height</td>
<td>0.685 **</td>
<td>0.553 *</td>
</tr>
<tr>
<td>CMJ Power</td>
<td>0.528 *</td>
<td>0.522 *</td>
</tr>
<tr>
<td>CMJ Power per BM</td>
<td>0.558 *</td>
<td>0.342 *</td>
</tr>
</tbody>
</table>

*p < 0.05, **p < 0.01, RFD = rate of force development,  LMI = lean mass index, CMJ = counter-movement jump.

4. Discussion

The purpose of the current study was to examine whether there were differences between elite weightlifters and track and field throwers in RFD, lean mass, VL muscle architecture and 1-RM strength. The main finding of the study was that RFD was similar for both groups of athletes, although when RFD was expressed relative to lean mass, weightlifters performed better at 80, 100 and 150 ms. In addition, weightlifters had higher 1-RM strength and higher CMJ height and power relative to body mass compared to throwers. Throwers were taller and had higher trunk lean mass. Weightlifters had longer VL fascicle length compared to throwers, which may partially explain the differences in RFD and CMJ with throwers. These results suggest that longitudinal training (specific for each sport) may induce different muscle adaptations between power-trained athletes, which may lead to further enhanced RFD, power and 1-RM strength.

Although many physiological and fitness parameters contribute to performance in power sports, RFD is an important factor for success, especially in weightlifting and track and field throwing events [6,7,24,34]. In the current study, no significant difference was found between weightlifters and throwers when RFD was expressed in absolute values. It can be hypothesized that the high percentage of type II and especially type IIx muscle fibres in throwers [14,22] and the high percentage of type IIa muscle fibres and percentage type II fibre area in weightlifters [16,17] may balance the difference between groups during RFD evaluation. As previously mentioned, the early phase of RFD is primarily determined by neural activation [9] by the percentage area of muscle occupied (%CSA) by type II and especially by type IIx muscle fibres [12], whereas the late phase of RFD is mainly determined by lean mass, fibre-type composition, muscle architecture characteristics and 1-RM strength [6,9,12]. Considering that the athletes who participated in the current study were all active elite athletes and the evaluations were performed immediately following a national competition, neural adaptations may have been already highly developed for both groups [35,36], therefore increasing the external validity of the study. However, when RFD was expressed relative to total lean mass, significant differences were found at 80, 100 and 150 ms. Similarly, a previous study of power-trained athletes showed that when RFD was expressed relative to total lean mass, athletes with lower lean mass produced greater...
early RFD compared to athletes with higher lean mass [37]. Given that no difference was observed between groups for total lean mass, weightlifters may apply their force more rapidly compared to throwers when RFD is expressed relative to lean mass, especially in the early phase of the force–time curve.

Weightlifters achieved higher CMJ height and power relative to body mass compared to throwers. CMJ may strongly predict competitive performance in weightlifting and throwing events [36,38]. These differences in CMJ and RFD relative to lean mass between weightlifters and throwers may partially be explained by the significant difference in VL fascicle length. We found that weightlifters had approximately 13.8% longer VL fascicle length compared to throwers. Even when VL fascicle length was expressed relative to body height, weightlifters still had approximately 17.1% higher fascicle length compared to throwers, although throwers were significantly taller than weightlifters. Longer fascicle length may produce higher shortening contraction velocities compared to shorter fascicle length and, as a consequence, increased power outputs [39]. Results from a recent study showed that 6 weeks of fast eccentric back squats may increase VL fascicle length, RFD and 1-RM strength in back squat [31]. In weightlifting, athletes perform fast eccentric squats to place their bodies under the barbell during the snatch and clean and jerk, which may lead to a significant increase in VL fascicle length, as previously described [31]. Weightlifters constantly perform these fast eccentric squats with maximum loads during training and sometimes with super-maximum loads during competitions (>100% of 1-RM). These findings should be interpreted with caution, as other neuromuscular factors, such as the percentage of type II muscle fibres, may also differentiate the two groups.

Lean mass is a significant contributor to performance in both weightlifting and throwing events [14,24]. In our study, weightlifters were found to have lower trunk lean mass compared to throwers, although no significant difference was observed with respect total, legs and arms lean mass. Generally, weightlifters focus on increasing lower body lean mass, mainly because lower body mass/strength is essential for an elevated performance. On the contrary, throwers aim to increase whole-body lean mass. Similarly, no significant difference was found for LMI between weightlifters and throwers. Previous studies showed that LMI can predict performance in elite powerlifters [40]. Likewise, in the current study, LMI was significantly correlated with performance in snatch and back squat. Thus, LMI may be a useful index for predicting performance in power sports, such as weightlifting and track and field throwing and to evaluate training-induced adaptations following long-term training programs. Finally, no significant difference was found for VL muscle thickness and fascicle angle. A previous study of power athletes revealed that athletes with higher lean mass had also higher VL muscle thickness and fascicle angle compared to power athletes with lower lean mass [37]. However, this finding was not supported by the current study, as no significant difference was observed for total lean mass between athletes.

As expected, 1-RM strength in snatch and back squat was significantly greater for weightlifters compared to throwers. This result may have resulted from the higher technical level and experience of weightlifters in snatch and back squat. Furthermore, weightlifters use high training loads (>85% of 1-RM) during their year-round training, compared to throwers, who train with both light and heavy resistance loads [8]. An interesting finding is that VL fascicle length was significantly positively correlated with 1-RM strength in snatch and back squat. Snatch is a high-velocity, high-load, full-body exercise whereby athletes apply their force rapidly [41], whereas back squat is a low-velocity, high-load exercise, although athletes apply their force with maximum intentional movement velocity [42]. Hence, power-trained athletes with longer VL fascicle length may perform better in 1-RM snatch and back squat. In addition, RFD was also correlated with 1-RM strength. Although throwers had lower 1-RM strength, recent studies have shown that snatch and back squat may be significant determinants for competitive track and field throwing performance, meaning that as 1-RM strength increases, track and field throwing performance also increases [2,7]. In support of the current results, previous studies of weightlifters and throwers showed significant positive correlations between RFD and 1-RM strength [6,24].
This study is subject to some limitations. No neural analysis or muscle biopsies were evaluated, both of which could have provided improved insight into the nature of the results. Athletes were measured one week after the main national competition; therefore, these differences may not be applicable during other training periods (i.e., specific preparation etc.). Another limitation is the small sample size in each group of athletes, although the elite level of the athletes used in the current study may counterbalance this particular limitation. Differences were found only for male athletes; therefore, more research is needed for female athletes.

5. Concussions

In conclusion, the results of the present study suggest that long-term training induces different muscle adaptations between elite power athletes, which may affect RFD, power and 1-RM strength performance. Longer VL fascicle length may partially explain the differences in RFD, CMJ and 1-RM strength, although other neuromuscular factors may contribute to these differences. Further research is required to draw reliable conclusions regarding the comparison between power-trained athletes in terms of RFD and power performance.

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