Olympic Weightlifting Training Causes Different Knee Muscle–Coactivation Adaptations Compared with Traditional Weight Training

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Abstract
Arabatzi, F and Kellis, E. Olympic weightlifting training causes different knee muscle–coactivation adaptations compared with traditional weight training. J Strength Cond Res 26(8): 2192–2201, 2012—The purpose of this study was to compare the effects of an Olympic weightlifting (OL) and traditional weight (TW) training program on muscle coactivation around the knee joint during vertical jump tests. Twenty-six men were assigned randomly to three groups: the OL (n = 9), the TW (n = 9), and Control (C) groups (n = 8). The experimental groups trained 3 d wk−1 for 8 weeks. Electromyographic (EMG) activity from the rectus femoris and biceps femoris, sagittal kinematics, vertical stiffness, maximum height, and power were collected during the squat jump, countermovement jump (CMJ), and drop jump (DJ), before and after training. Knee muscle coactivation index (CI) was calculated for different phases of each jump by dividing the antagonist EMG activity by the agonist. Analysis of variance showed that the CI recorded during the preactivation and eccentric phases of all the jumps increased in both training groups. The OL group showed a higher stiffness and jump height adaptation than the TW group did (p < 0.05). Further, the OL showed a decrease or maintenance of the CI recorded during the propulsion phase of the CMJ and DJs, before and after training. Knee muscle coactivation index (CI) was calculated for different phases of each jump by dividing the antagonist EMG activity by the agonist. Analysis of variance showed that the CI recorded during the preactivation and eccentric phases of all the jumps increased in both training groups. The OL group showed a higher stiffness and jump height adaptation than the TW group did (p < 0.05). Further, the OL showed a decrease or maintenance of the CI recorded during the propulsion phase of the CMJ and DJs, which is in contrast to the increase in the CI observed after TW training (p < 0.05). The results indicated that the altered muscle activation patterns about the knee, coupled with changes of leg stiffness, differ between the 2 programs. The OL program improves jump performance via a constant CI, whereas the TW training caused an increased CI, probably to enhance joint stability.

Key Words muscle activation patterns, stiffness, jumping performance

Introduction
Power performance is affected by the interaction between agonist, antagonist, and synergetic muscles involved in joint movements. Although the agonist muscles are able to apply a great force in a short period of time, there must be a complementary and simultaneous relaxation of the antagonists (25). This appears to be achieved by a neural strategy of enhanced reciprocal inhibition of the antagonist musculature (26). However, the role of agonist and antagonist muscle interplay in power movements remains unclear. The faster lifting speeds involved in power training may make it difficult, as compared with traditional strength training, to efficiently control unwarranted cocontraction between agonist and antagonist muscle groups, potentially reducing power (6). Examination of muscle coactivation adaptations after different training programs may assist in determining optimal strategies for improvement in jump performance.

Muscle coactivation is necessary to balance joint forces and to increase muscle and joint stiffness (20). It has been suggested that higher stiffness levels of lower-limb muscles during stretch-shortening cycle (SSC) exercises improve performance in terms of the greater amount of stored and reused elastic energy. Further, the coactivity of agonist and antagonist muscles increases in the preactivation and the braking phases of the jump (35). This coordinated response would create a rebound phenomenon in which the active tension developed in the preactivation and breaking phases could be released passively in the toe-off phase. Further, during the toe phase, there is a decline in the activation of the knee extensors while the hamstrings maintain consistent activation in the same phase. This is critical for creating the take-off velocity and to transfer the stored elastic energy in the proper direction with unopposed antagonist activity from the hip flexors (33). However, it is unclear whether these changes in leg and joint stiffness are caused by changes in activation and the mechanical properties of the muscle-tendon complex itself. Further, it is unclear whether the type of mechanical...
and neural adaptations may depend on the type of the exercise program applied.

Traditional exercises, such as squats, have been determined to be excellent exercises for improving lower-body strength, but they show a low correlation with vertical jump (VJ) performance (12,18). Resistance training improves the muscle's ability to generate force, but this increase may not be effectively transferred to velocities that simulate the speed of jump performance (14). Toumi et al (31) reported that weight training alone did not induce any change in countermovement jump (CMJ) performance, although increases in maximal strength and squat jump (SJ) were observed. Similarly, it has been demonstrated that training-induced strength improvements are associated with increases in jump performance (1,33). However, maximal gains can be achieved if training exercises that simulate jump movement are used (1,33). This lack of transfer from an enhanced posttraining maximum strength to better jump performance may also be linked with different adaptations in muscle activation between antagonist muscle groups.

In contrast to traditional weight (TW) training, low-speed power lifts, such as Olympic lifts, are ballistic resistance exercises that involve moving an external load at high velocities, resulting in the acceleration of the segments through the entire movement. Olympic lifts may produce high gains in power, offering great potential for improvement in VJ performance (18,27). It seems likely that weightlifting training results in improved motor unit recruitment and inhibition of protective antagonist muscle action, especially given the short time frame (12). Nevertheless, the precise effects of such a training scheme on muscle coactivation during a joint during sport-specific multitasking tasks, such as jumps (CMJ, DJs), are not clear.

It is generally accepted that training-related increases in muscle capacity are associated with a reduction in antagonist coactivation (15,29). However, this adaptation may depend on the type of training program and the type of performance used to examine the effectiveness of training. For example, SJ performance may be affected by different mechanisms compared with CMJ and DJ performances. Further, DJ performance and biomechanical characteristics depend on drop height (7), whereas coactivation differs between different phases of the same type of jump. Further research is needed to obtain a knowledge about the relative involvement and functional significance of neural factors with specific types of training and examine the relative importance of these mechanisms in VJ performance. Neuromuscular adaptations are believed to enhance jump performance (13), but these need to be identified and compared between different training stimuli. The purpose of this study was to compare the changes in muscle coactivation during maximum jumps between an Olympic weightlifting program with those observed after a traditional weightlifting program. We hypothesized that an improvement in jump performance after traditional resistance training would be because of higher muscle strength but an increased muscle cocontraction, whereas Olympic lifting training would improve performance through neural adaptations, that is, a decrease in the cocontraction index (CI) and an associated change in leg stiffness. Further, we expected that differences in adaptations between the 2 training programs depend on the type of jump tested.

**Methods**

**Experimental Approach to the Problem**

The study was designed to compare the electromyographic (EMG) activity and training adaptations in jump performance between 2 training programs. To investigate this, we matched healthy students of physical education and subsequently randomly divided them into 2 training groups: (a) an Olympic weightlifting (OL) group and (b) a traditional weight group (TW). This design enabled us to examine whether OL or TW training augmented jump performance and changed the muscle interplay. The independent variables were time (pretraining, posttraining) and training group (OL, TW, C). The dependent variables were EMG activity (average EMG, coactivation), vertical stiffness, VJ height, mechanical power, and kinematics.

**Subjects**

This study involved a total of 26 male students of physical education in Greece (age = 20.3 ± 2 years, height = 184.8 ± 8.3 cm, mass = 85.2 ± 6.8 kg, maximum strength: 1RM/body mass = 2.11 for the OL group and 1.98 for the WT group) all free from any musculoskeletal or neurological disease or impairment. The participants began the study by performing the squat, CMJ, and maximal half-squat (1RM). Based on these results, they were allocated randomly into 1 of 3 groups and did not differ significantly (p > 0.05) in any of the dependent variables. All the subjects were physically highly active and experienced in performing various jumps through participation in various sport activities through their regular academic program. All the subjects had at least 1 year of experience in resistance training, but they did not systematically perform strength drills and weightlifting exercises. The local University Ethics Committee approved the study. All the subjects were informed of any risk and signed a university-approved human subject’s informed consent form before their participation.

**Study Design**

This study involved 3 groups (Table 1). The first group performed OL exercises, and the second group performed TW drills. The last group served as the control (C) group. The subjects reported to the University Neuromechanics Laboratory. All the groups were tested before and after an 8-week training period (February to March). The training groups attended 24 sessions (3 sessions per week) in total. Before the testing period, the subjects of the OL and TW
groups underwent 6 familiarization sessions (3 training sessions for familiarization with the movement technique and 3 familiarization sessions with the experimental protocol). The participants in the control group performed the laboratory familiarization only. The subjects were given 2–3 days to recover between familiarization before pretesting procedures and initiation of the training period. A similar length of recovery was given between the final training session and posttesting procedures.

### Training Protocol

A standardized warm-up including jogging, stretching exercises, and several weightlifting repetitions was provided for all the experimental groups before the beginning of each training session. All the subjects completed the same resistance training volume. A challenge was the attempt to design 2 different protocols that were comparable in terms of time and effort. For this reason, in each training session, volumes were expressed as the total amount of work in kilograms multiplied by the total number of repetitions and sets per exercise for the training session. Furthermore, the time of each specific exercise was calculated by multiplying with repetitions per training sessions. The subjects repeated these movements without a pause. The subjects performed 4–6 repetitions per set of each exercise and 4–6 sets with a between-set rest interval of 3 minutes. The average total time for each exercise was approximately 20 seconds for the OL program and 18 seconds for the TW program. Consequently, based on the total amount of work estimations, the 2 training protocols were quite comparable.

**Olympic Weightlifting Program.** The OL training protocol was designed to increase maximal muscle strength and mechanical power. The 8-week training regimes included a total of 24 training sessions. The training program consisted of 5 Olympic-style weightlifting exercises: snatch from a squat position, high-pull, power clean, half-squat, and clean and jerk and training followed a progression essentially to the applied protocols (33) (Table 2). During the first 2 weeks, the subjects performed 4 sets of 4 repetitions of each exercise. The initial load corresponded to 75% of 1RM, and a 3-minute rest was provided between sets. For weeks 3 and 4, the volume of training significantly increased to 4 sets of 6 reps at 80% of 1RM. For the last 4 weeks, 4 sets of 4 reps at 80–90% of 1RM were performed. All the exercises were performed in a controlled manner with emphasis on the eccentric-to-concentric transition, which was performed as quickly as possible during the lifting procedure. Initial resistance was determined from each subject’s 1RM strength.

One-repetition maximum was evaluated every 4 weeks to adjust the training load. The loading levels were continually adjusted to the intended relative levels throughout the training period (4–6RM).

**Traditional Weight Program.** The TW training was a high-intensity (80% of 1RM) protocol that aimed to increase maximal muscle strength and rate of force development without inducing hypertrophy in lower-extremity muscle groups. The training program consisted of 5 weight exercises: knee extension, knee flexion, push, pull of biceps femoris (BF), and half-squat. During the first 2 weeks, the subjects performed 4 sets of 4 repetitions of each exercise. The initial load corresponded to 75% of the 1RM, and a 3-minute rest was provided between the sets. For weeks 3 and 4, the volume of training significantly increased to 4 sets of 6 reps at 80% of 1RM. For the last 4 weeks, 4 sets of 4 reps at 80–90% of 1RM were performed. All the exercises were performed over the range of motion, at a self-selected pace using cyclic concentric and eccentric muscle contractions and with emphasis quickly from the beginning of the lifting movement. Initial resistance was determined from each subject’s 1RM strength, which was made every 4 weeks to adjust the training load.

**Control Group.** The control group performed its standard sport activities through their academic program, and no additional weight exercises over the 8-week period were performed.

### Instrumentation

**Ground Reaction Forces.** All VJs were performed on a Kistler piezoelectric force platform (type 9281C, Kistler Instruments, Winterthur, Switzerland). The force platform was interfaced through Kistler amplifying units (type 233A) to an Ariel
<table>
<thead>
<tr>
<th>Test</th>
<th>Group</th>
<th>Pre Mean (± SD)</th>
<th>Post Mean (± SD)</th>
<th>Pre Mean (± SD)</th>
<th>Post Mean (± SD)</th>
<th>Pre Mean (± SD)</th>
<th>Post Mean (± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ</td>
<td>Olympic weightlifting</td>
<td>28.1 ± 5.7</td>
<td>33.8 ± 5.5†</td>
<td>28.81 ± 284</td>
<td>29.803 ± 2.99</td>
<td>29.5 ± 4.5</td>
<td>31.1 ± 4.6</td>
</tr>
<tr>
<td>CMJ</td>
<td>Traditional weight</td>
<td>1,319 ± 43.3</td>
<td>1,335.8 ± 523.4</td>
<td>1,604.6 ± 213.5</td>
<td>1,639.8 ± 304.5</td>
<td>1,306.6 ± 474.7</td>
<td>1,294.6 ± 221</td>
</tr>
<tr>
<td>DJ20</td>
<td>Control</td>
<td>-514.8 ± 141.1</td>
<td>-807.6 ± 270.8†</td>
<td>-356.66 ± 107.1</td>
<td>-461.1 ± 157.8</td>
<td>-469 ± 160.3</td>
<td>-571.5 ± 189</td>
</tr>
<tr>
<td>DJ40</td>
<td>Olympic weightlifting</td>
<td>34.6 ± 7.5</td>
<td>39.8 ± 6.8†</td>
<td>31.25 ± 1.97</td>
<td>33.38 ± 3.01</td>
<td>33.3 ± 5.2</td>
<td>35.2 ± 5.8</td>
</tr>
<tr>
<td>DJ60</td>
<td>Traditional weight</td>
<td>-2,745.7 ± 897</td>
<td>-2,654.25 ± 449</td>
<td>-2,301.0 ± 514</td>
<td>-2,269.5 ± 545</td>
<td>-2,826.1 ± 819</td>
<td>-2,870 ± 609</td>
</tr>
<tr>
<td>DJ60</td>
<td>Control</td>
<td>3,342.1 ± 605.6</td>
<td>3,645.2 ± 816.4</td>
<td>2,412.83 ± 433</td>
<td>2,708.16 ± 431</td>
<td>3,119.3 ± 758</td>
<td>3,220 ± 640.1</td>
</tr>
</tbody>
</table>

*Pre = before; post = after; SJ = squat jump; CMJ = countermovement jump; DJ20 = drop jump from 20 cm; DJ40 = drop jump from 40 cm; DJ60 = drop jump from 60 cm.
†Significant difference from pre to post (p < 0.05).
Electromyography. Bipolar surface electrodes (Motion Control, Iomed Inc., voltage range: ±4 to ±12V) analog amplifier (sampling frequency 1,000 Hz, common-mode rejection ratio 100 dB at 50/60Hz, bandwidth 8,500-Hz gain 400) were used to record the EMG activity of the rectus femoris (RF) and BF muscles. Electrode locations were prepared by shaving the skin of each site and cleaning it with alcohol wipes. Electrode placement was carefully measured and marked with permanent nonremovable ink to exactly ensure that the same position was used before and after training.

Kinematics. For motion analysis, 2 video cameras (Panasonic AG188 Tokyo, Japan, frame rate 60 Hz with a high-speed shutter) and a video recorder (Panasonic S500) were used. The cameras were placed at a 90° angle at a focal distance of 8 m. Skin markers were placed at 5 body locations on the body: trunk (midaxillary line at umbilicus height), hip (superior part or greater trochanter), knee (lateral epicondyle), ankle (lateral malleolus), and foot (head of fifth metatarsal). The video image of a calibration frame was recorded before each measurement, and 8 calibration points were digitized to determine the 3 dimensional position of any point in space. The coordinates for these markers were digitized using the Ariel Performance Analysis System (Ariel dynamics Co, San Diego, CA, USA). For synchronization of the force and video data, the computer triggered a stroboscopic light, which was visible on the camera’s field of view.

Vertical Stiffness (KVert)
Vertical stiffness (KVert) was calculated by dividing the change in force (ΔF) by the change in displacement of
center mass ($\Delta L$) during the eccentric phase in the jump (35). The negative phase was defined between the initiation of the movement (the instant at which vertical force began to decrease continually) and the deepest excursion of the knee joint:

$$\Delta F/\Delta L,$$

where $\Delta F$ is the range of the vertical component of the ground reaction force and $\Delta L$ is the range of the center of mass displacement.

Mean and $SD$ were calculated from individual measurements for the 3 groups. An analysis of variance (ANOVA) with repeated measures was used to examine the effects of training (PRE-POST) between the 3 groups (OL, TW, C) on each dependent variable. Post hoc Tukey tests were applied for comparisons between individual means, when required. The level of significance was set at $p \leq 0.05$.

### Results

**Cocontraction index**

The EMG results are presented in Figure 1. There was a significant Group $\times$ Training interaction effect on CI in SJ ($p < 0.05$). Post hoc analysis showed that CI decreased after both programs in the preactivation phase, but it was unchanged for the TW group during the concentric phase ($p > 0.05$). For CMJ, the ANOVA indicated a significant Group $\times$ Training interaction effect on CI ($p < 0.05$). Post hoc analysis showed that CI increased for the 2 groups in the preactivation and eccentric phases, but it increased in the concentric phase only after TW training. Similarly, for the DJ20cm, post hoc analysis showed that the CI increased only for the TW group, but it was unchanged after the OL training ($p < 0.05$). The CI during the preactivation and concentric phases of the DJ60cm
decreased significantly after TW training, but it increased during the eccentric phase ($p < 0.05$).

**Stiffness**
The results for the stiffness are presented in Figure 2. There was a significant Group $\times$ Training interaction effect on stiffness in the SJ for the OL group ($p < 0.05$). In the CMJ, the ANOVA indicated a significant Group $\times$ Training interaction effect on stiffness ($p < 0.05$). Post Hoc analysis showed that both groups increased joint stiffness after training ($p < 0.05$). For DJ20cm and DJ60cm, post hoc analysis showed that only the OL group increased leg stiffness ($p < 0.05$).

**Vertical Jump Height and Power**
The results for the VJ height and mean power for each testing condition are presented in Table 2. The ANOVA indicated a significant Group $\times$ Training interaction effect on

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### Table 3. Training-associated changes in angle displacement of the knee and hip as assessed through SJ, CMJ, and in the DJ20, DJ40, and DJ60.$^\dagger$†

<table>
<thead>
<tr>
<th>Test</th>
<th>Olympic weightlifting</th>
<th>Traditional weight</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>SJ</td>
<td>143.3±4.6</td>
<td>149.6±6.1$^\dagger$§</td>
<td>144.58±10.4</td>
</tr>
<tr>
<td>Knee</td>
<td>147.2±7.1</td>
<td>150.5±11.4</td>
<td>148.5±8.5</td>
</tr>
<tr>
<td>Hip</td>
<td>146.22±5.8</td>
<td>149.3±7.6</td>
<td>145.27±21.8</td>
</tr>
<tr>
<td>CMJ</td>
<td>135.93±15.9</td>
<td>145.7±19.7$^\dagger$§</td>
<td>144.42±13.4</td>
</tr>
<tr>
<td>Knee</td>
<td>140.45±11.9</td>
<td>132.5±26.2$^\dagger$§</td>
<td>140.3±13.3</td>
</tr>
<tr>
<td>Hip</td>
<td>160.9±11.4</td>
<td>153.9±14.0$^\dagger$§</td>
<td>147.45±9.53</td>
</tr>
<tr>
<td>DJ20</td>
<td>146.2±12.3</td>
<td>142.76±10.6</td>
<td>139.03±7.8</td>
</tr>
<tr>
<td>Knee</td>
<td>157.63±9.0</td>
<td>156.28±9.32</td>
<td>153.4±5.6</td>
</tr>
<tr>
<td>Hip</td>
<td>146.6±8.1</td>
<td>149.16±9.6</td>
<td>139.02±5.0</td>
</tr>
<tr>
<td>DJ60</td>
<td>159.5±8.37</td>
<td>156.44±11.4</td>
<td>154.36±12.4</td>
</tr>
</tbody>
</table>

*Pre = before; post = after; SJ = squat jump; CMJ = countermovement jump; DJ20 = drop jump from 20 cm; DJ40 = drop jump from 40 cm; DJ60 = drop jump from 60 cm; C = control group; OL = Olympic weightlifting training; TW = traditional weight training.
†Mean (±SD) group values for each experimental condition in the pretraining and posttraining.
§Significant differences from pre to post ($p < 0.05$).
$^\dagger$Significant differences between groups ($p < 0.05$).
SJ and CMJ height (*p < 0.05*). Post hoc analysis showed that only the OL group improved the SJ and CMJ height (*p < 0.05*), whereas the SJ power did not increase for all the groups (*p > 0.05*). For CMJ, the ANOVA indicated a significant Group × Training interaction effect on CMJ power (*p < 0.05*). Post hoc analysis showed that the OL group improved CMJ, eccentric and concentric power but not the other groups. The OL group showed a significant increase in the DJ height from 20 and 40 cm after training (*p < 0.05*), but both training groups showed a significant improvement in the DJ height from 60 cm (*p < 0.05*). Eccentric power in DJ from 60 cm and concentric power in DJ from 40 and 60 cm improved significantly (*p < 0.05*) only in the OL group.

**Kinematics**

The results for knee and hip angles are presented in Table 3. There was a significant Group × Training interaction effect on the knee and hip angle in SJ (*p < 0.05*). Post hoc analysis showed an increased knee angle after OL training (*p < 0.05*) and a decreased hip angle after TW training (*p < 0.05*). For CMJ, the ANOVA indicated a significant Group × Training interaction effect on hip angle (*p < 0.05*). Post hoc analysis showed that the OL group increased the hip joint angle after training (*p < 0.05*). For DJ20 cm, the ANOVA indicated a significant Group × Training interaction effect on knee and hip angle (*p < 0.05*). Post hoc analysis showed a decreased knee and hip angle after OL training and an increased Hip angle after TW training (*p < 0.05*). There was no significant Group × Training interaction effect on the knee and hip angle in DJ40 cm (*p > 0.05*). For the DJ60 cm, the ANOVA indicated a significant Group × Training interaction effect on the hip angle (*p < 0.05*). Post hoc analysis showed that the TW group showed a lower hip joint angle after training (*p < 0.05*).

**DISCUSSION**

The results of this study showed that the OL group showed better improvements in jump height than the TW group did. Further, OL training resulted in a reduction or maintenance of CI and an increase in leg stiffness during the push-off phase of all jumps, whereas TW training increased in CI and leg stiffness. This partly confirms our initial hypothesis indicating that TW exercises may be appropriate for enhancing joint stability, whereas OL exercises are better for improving power performance through better coordination of antagonistic muscle groups. Because the mechanisms that contribute to performance differ among the 3 types of jumps tested, training adaptations must be examined separately for each jump.

During the SJ, the CI in the preactivation phase decreased for both training groups (Figure 1), mainly because of a higher agonist EMG, which is frequently observed after training (30,31). However, changes in CI during the main SI movement differed between the 2 groups. For the TW group, the vertical stiffness and CI were unchanged (Figures 1 and 2) as both RF and BF EMG increased. This increase might explain the absence of significant SJ height improvements (Table 2) as any benefits from a higher quadriceps activity are probably counteracted by a higher BF activation, thus leading to a more extended hip joint (Table 3) (31,32). It could be suggested that strength improvements in both knee extendors and flexors after TW training were equally transferred to SJ movement. In contrast to the TW group, the OL group showed a decline of CI (Figure 1). This might indicate an increase in the net joint knee extension torque at propulsion, because of a reduction in antagonist (BF) cocontraction (17). This, in association, with the increase in vertical stiffness may contribute to a greater gain in the SJ jump height and power, which is in agreement with the findings of previous studies on ballistic resistance training adaptations (2,21,28,35).

In CMJ, there was an increase in the CI during the reactivation and breaking phases after both training programs (Figure 1). However, an increase of CI during the propulsion CMJ phase was found for the TW group but not for the OL group (Figure 1). A higher CI and stiffness during the transition phase, seen after TW training, may not be sufficient for the transfer of elastic energy from the eccentric-to-concentric phase (8,33,35). For this reason, traditional resistance exercises are thought to be beneficial for enhancing joint stability and the functional capacity of the activated muscles (19) but not jump performance. In contrast, the OL group improved CMJ height by means of a lower CI and an altered hip joint angle (Tables 2 and 3). Particularly, the combination of a higher BF EMG activity and hip flexion angle (Table 3) during the stretch phase can explain the increase in vertical stiffness (Figure 2). In turn, a higher stiffness facilitates the release of greater amounts of stored elastic energy during the propulsion phase (3,10,24), with a relatively unopposed antagonist activity from the hip flexors (35).

Muscle coactivation in DJs showed variable responses, depending on training group and dropping height. As far as the TW group is concerned, the results showed that CI, hip flexion angle, and leg stiffness increased during the DJ20 without increases in performance (Figures 1 and 2, Tables 2 and 3) which is in line with previous findings (13,23). Bobbert et al (8) reported that stronger muscles do not necessarily result in greater jumping ability. The increased muscle coactivation in DJ after TW training may assist knee stability especially during the breaking phase, but it may have no effect on the propulsion and the reuse of elastic energy (23). Thus, it appears that the central nervous system counterbalances force production and joint stability to ensure joint integrity (by increasing joint stiffness via elevated antagonist coactivation) in unstable movement conditions, such as DJs (16). Although TW training increased CI in DJ20, the opposite was found for DJ60 (Figure 1). This agrees with the findings of previous studies, and it could be explained by an...
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offset of the positive (increased muscle function) and negative (decreased prestretch augmentation) effects on DJ performance (23,32). Furthermore, the lower CI coupled with a change in the hip flexion angle might signify a higher activity of the back thigh muscles, which has a direct role in landing and in assisting knee stability (13).

According to our initial hypothesis, it was expected that the increase in vertical stiffness during the DJs would be the result of neural adaptations after OL training. However, there were no significant changes in muscle activity (Figure 1). This suggests that DJ performance gains after OL training are because of a change in the mechanical properties of muscle-tendon complex rather than caused by muscle coactivation. It is interesting as to why the OL group showed a lower CI during CMJ and SJ but in the DJ the CI did not change. This could be because of the following factors: first that the faster SSC (DJ) depends more on the mechanical properties of the muscle than the slower SSC jumps (CMJ, SJ) and, second, the greater need for enhanced joint stability prevents any reductions in CI after OL training. The above result is accompanied by kinematic (as interpreted through hip flexion decrease) (Table 3) and vertical stiffness increase in the DJ20 and DJ60 (Figure 2). To our knowledge, there are no reports on the effects of OL training on DJ performance (11).

Nevertheless, our observation agrees with previous findings (3,22,31) and suggests that a higher stiffness level of lower-limb (knee joint stiffness) muscles and an optimum amount of preactivation in the muscles during fast SSCs facilitates greater usage of elastic energy and maximization of mechanical power.

Taking these previous findings into account, it is likely that the difference between the 2 training programs could be because of the differences in work and muscle activation patterns, whereas adaptations may differ depending on the type of jump examined. The results partly confirmed our hypothesis because TW training did not induce SJ performance gains despite the increase in CI and agonist muscle activity. In contrast, the OL group improved in the SJ performance via a reduction in antagonist cocontraction. It appears that the superior performance in CMJ after OL training is achieved by a higher neural input of the agonist muscles and less antagonist muscle coactivation in the propulsion phase. In contrast, the TW training program increased antagonist coactivation and vertical stiffness probably to maintain joint stability without changing jump performance (13). For the DJs, however, performance adaptations included an increase in CI for the TW group, but this was height specific. In contrast, increases in the CMJ and DJ performance increases for the OL group were not related to CI changes but to other mechanical properties of the involved musculature.

In conclusion, the CI increased by TW training without changes in vertical stiffness and jumping performance during jumping. Conversely, CI was unchanged, and leg stiffness increased after weightlifting training. Jump performance improved mainly by weightlifting training. These results suggest that weightlifting training increases the jump height via an increase in leg stiffness and constant CI. Finally, the cocontraction increase in the breaking phase after both training protocols may be seen as an attempt for dynamic restrain and functional knee stability.

Practical Applications

An implication of the present findings is that a proper periodized training program should focus on the specific training stimulus either to avoid possible injury or improve the use of SSC. In a practical sense, coaches might prefer to use hierarchical OL programs when there is a need to improve SSC. Alternatively, when there is a need to improve joint stability, TW programs are more beneficial. Because in most cases both injury avoidance and performance improvements are desirable, we propose that TW training may precede OL training exercises so that participants first achieve a muscle strength increase and joint stability and then perform power-specific exercises to achieve better performance.

References


