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The Effect of Repetitive Drop Jumps among Different Heights on Bilateral Asymmetry of Countermovement Jumps

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Abstract: Background: The study explored the influence of repeated drop jumps (DJs) from different drop heights on the lower extremity bilateral asymmetry and muscle activation of countermovement jumps (CMJs). Methods: Eighteen male athletes performed 200 drop jumps (DJs200) from three drop jump height (DJH30, 40 and 50 cm). The CMJs were performed before the first DJ and after the 50th, 100th, 150th and 200th DJs, recording them as pre-CMJ, CMJs50, CMJs100, CMJs150 and CMJs200. One-way repeated measures ANOVA was used to compare differences among the three drop heights at pre-CMJ, CMJs50, CMJs100, CMJs150 and CMJs200, respectively. Results: The peak ground reaction forces (PGRF) of CMJs100, CMJs150 and CMJs200 at DJH50 were greater than at DJH30 and DJH40 (all $p < 0.05$). The muscle activation during CMJs50 at DJH50 was greater than at DJH30 and DJH40 (all $p < 0.05$). The muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 was smaller than at DJH40 and DJH30 (all $p < 0.05$). The PGRF had no significant difference among the three different drop heights during CMJs50 ($p > 0.05$). Conclusions: The DJs50 at DJH50 had no effect on the bilateral asymmetry and increased muscle activation of CMJs. The excessive DJs100 at DJH50 increased bilateral asymmetry and decreased CMJ muscle activation during CMJs.

Keywords: peak ground reaction force; muscle activation; musculoskeletal injury

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1. Introduction

The countermovement jump (CMJ) is a dynamic plyometric training method for multi-joint movement of the lower extremities, which rapidly develops strength through higher eccentric force to increase the concentric force development of the stretching-shortening cycle (SSC) mechanism [1]. The drop jump (DJ) is widely used to increase muscle strength and improve the SSC ability as an effective plyometric training method [2]. Previous research found that repeated CMJ training and 40 drop jumps training at 40 cm, 60 cm and 80 cm height can increase the CMJ height of athletes after 48 h [3]. Repeated DJ training of 150 drop jumps and 50 drop jumps at 52 cm drop height increased the athletes CMJ height after 48 h [4]. However, repeated DJ training may cause fatigue and joint instability, reducing stretch reflexes, and thereby reducing the SSC ability of CMJs [5,6]. Therefore, reasonable DJ training can be used to increase the muscle strength of the lower extremities and enhance the SSC ability to affect CMJ performance. In addition, the CMJ is an effective method to evaluate the muscle strength and bilateral asymmetry of the lower extremities [7]. The jump height should be different based on each participant's neuromuscular function in order to better activate the muscles during the DJ; a jump height of 75% or below of the maximum vertical jump height can optimize the SSC performance of DJs to maintain a high level power output and prevent lower extremity injury [8]. Previous studies found that different drop height platforms will cause changes in the lower extremity neuromechanical properties during landing, thereby, possibly affecting the bilateral asymmetry of the CMJ [9,10]. A drop height of 20 cm will result in a shorter contact time, the bilateral differences in vertical forces and temporal components will occur [11]. A drop height of 60 cm would cause lower extremity bilateral asymmetry of force and knee joint instability, which increases the risk of lower extremity injuries [12]. An improper drop height may lead to excessive bilateral asymmetry of the peak ground reaction force (PGRF) when DJ training, resulting in lower extremity injury [13]. Thus, appropriate drop heights during DJ training can reduce the extremity bilateral asymmetry, and may reduce the risk of musculoskeletal injury and affect CMJ performance.

The CMJ is a reliable method to measure the bilateral asymmetry of lower extremities related to jump performance [14]. Bilateral asymmetry has been studied by comparing one lower extremity with another [15]. The abnormal neuromuscular control caused by lower extremity bilateral asymmetry is one of the main factors of knee anterior cruciate ligament (ACL) injury [16]. Bilateral asymmetry in the lower extremities may indicate decreased jump performance and power output [7]. Furthermore, the PGRF is usually evaluated for the bilateral asymmetry of CMJ, athletes exposed to greater PGRF facing increased lower extremity risk of injury [17]. Therefore, reducing the bilateral asymmetry of the lower extremities in CMJ exercise is essential to reduce the risk of injury. In addition, excessive DJ training increases muscle fatigue and could lead to lower extremity injuries [18]. However, DJ training intensity is too small to achieve a training effect and cannot effectively improve sports performance. Therefore, appropriate DJ training volumes can prevent excessive fatigue, reducing the bilateral asymmetry and the risk of injuries to the lower extremities during CMJ performance.

The dynamic simulations of CMJ were performed with a model of the human musculoskeletal system to investigate the effects of muscle strength on vertical jump height [19]. The lower extremity neuromusculoskeletal models were developed using computer simulation, which examines the effect of lower extremity muscle strength bilateral asymmetry on CMJ performance [20]. A musculoskeletal model of the CMJ was established and it was found that increasing tibialis anterior muscle activation could increase muscle strength and mechanical efficiency during the CMJ eccentric phase [3]. Increased gastrocnemius and quadriceps femoris muscle activation can improve the jump height and mechanical efficiency of the CMJ concentric phase [2,21]. Increasing the activity of gastrocnemius and soleus muscles during the CMJ eccentric phase can enhance elastic energy storage, and releasing elastic potential energy during the CMJ concentric phase can increase muscle activity [22]. In addition, previous studies on EMG showed that the concentric and eccentric phases of the CMJ rely on the SSC mechanism produced by elastic tissue [23]. The EMG value of the CMJ in the concentric phase is significantly correlated with pre-stretching enhancement. Improved tendon elasticity and muscle activation levels lead to greater CMJ performance [24]. After repeated DJ and CMJ training, a significant increase in the EMG activities for the vastus medialis and rectus femoris [25]. Therefore, lower extremity muscle activity is influenced by the characteristics of different CMJ phases. In addition, DJ training at an appropriate drop height can increase the activation and performance of gastrocnemius, soleus and tibialis anterior muscles [26]. However, DJ training at improper heights (such as too high a drop height) can cause muscle damage, reduce activation of the calf muscles and increase the risk of potential knee injuries [12,27]. Therefore, it is an important issue to explore the influence of different drop jump heights on CMJ lower extremity muscle activation through muscle simulation in DJ training.

Repeated DJ training at improper drop heights will increase muscle fatigue and lower extremity bilateral asymmetry, causing muscle injury and affecting CMJ performance. Therefore, the purpose of this study was to explore the influence of repeated DJ training at different drop heights on the lower extremity bilateral asymmetry and muscle activation of CMJs in male athletes. This study hypothesized that the improper drop height of repeated DJ training would increase the lower extremity bilateral asymmetry as well as decrease the muscle activation of CMJs. The appropriate drop height of repeated DJ training would increase the muscle activation of CMJs.

2. Materials and Methods

2.1. Subjects

Eighteen male Division III athletes (age: 20.66 ± 1.37 years old; height: 1.75 ± 0.05 m; weight: 79.79 ± 12.30 kg) were used as subjects from Jilin Sport University. All subjects had received no special DJ or CMJ training. All subjects had suffered no lower extremity injuries within 6 months and did not undergo any lower extremity training 48 h before the test. This study was approved by the Chinese Clinical Trial Registration Center (JLSU-IRB2020005), and subjects were fully informed about the benefits of the research and all risks and gave their informed consent according to the Declaration of Helsinki.

2.2. Procedures

All experimental data collection was carried out in the sports biomechanics laboratory. Before the formal experiment, the subjects were required to practice with 5 DJs and CMJs to ensure their movements were able to define the criteria. They wore the same experimental running shoes and had a regular, specific warm-up comprising dynamic stretching, basic muscular activation and 5 min of running drills at a speed of 8 km/h on a treadmill. After warming up, the subjects completed a set of CMJs (3 in each set) followed by a set of DJs (50 in each set). All subjects needed to complete 5 sets of CMJs (15 total) and 4 sets of DJs (200 total). A 10 s interval was maintained between each DJ. A 1 min interval was maintained between each CMJ. During the CMJ, subjects stood on the two force plates respectively and maintained a stable upright posture. They swung arms and squatted quickly, jumped upward as quickly as possible with maximum effort, then landed on the two force plates, respectively. During the DJ, participants were asked to hold both hands on their waist, jump off from the platform and touch down on both feet simultaneously. After squatting, they jumped upward with maximum effort and as quickly as possible, then landed on the two force plates, respectively [28]. The experiment was divided into 3 different drop heights (DJH)30 cm, DJH40 cm, DJH50 cm, with 7 days intervals in between each different drop height. After warming up, subjects completed 3 CMJs in each set, which was recorded as pre-CMJ. After performing 50 DJs, subjects completed a set of CMJs which was recorded as CMJs50. Subsequently, CMJs were recorded as CMJs100, CMJs150 and CMJs200.

2.3. Data Collection

A 3D motion analysis camera system (BTS DX400, BTS Bioengineering, Milano, Italy) was used to collect kinematic data at a 200 Hz sampling rate. Two 40 cm × 60 cm force plates were installed on the ground (BTS P6000, BTS Bioengineering, Italy) to collect dynamics data at 400 Hz. CMJ analysis was performed with 3D motion analysis camera system synchronized with kinetics data. Nineteen reflective markers (diameter 19 mm) were taped to the lower extremities. The modified Helen Hayes model was used to identify the 7-segment rigid link model of the lower extremity [29]. All raw ground reaction force (GRF) data were filtered by a Bartle worth low-pass digital filter with a cut-off frequency of 50 Hz [29]. The PGRF was normalized to body weight (BW). The raw data were smoothed using a generalized cross-validated quantic spline procedure.

2.4. Data Analysis

Each joint segment (hip, knee, ankle, foot) is defined as a kinematic model. The center of the ankle joint is the midpoint of the lateral and medial malleolus. The center of the knee joint is calculated from the lateral and medial midpoints of the femoral epicondyle. The center of the hip joint is calculated based on the back reflection marks attached to the anterior superior iliac spine [30].

In this study, the average values of 3 CMJs for each set in each subject were calculated and used for statistical analysis. The CMJ was divided into the phases as illustrated in Figure 1. The starting point (t1) of the CMJ is defined as the point at which the force-time curve falls below a 2.5% body weight threshold [31]. The time points of maximum knee flexion (t2) and peak ground reaction force (t3) were defined as the instant of maximum knee flexion angle and maximum GRF after t1, respectively; the take-off (t4) of the CMJ was identified when the GRF of the dominant leg became less than 10 N. The time interval of PGRF after ground contact was from t1 to t3, the squat (eccentric) phase was from t1 to t2, the push-off (concentric) phase was from t2 to t4 and the landing phase was from t1 to t4. The changed symmetry index (SI) was used to calculate asymmetries in this study. Absolute difference of PGRF between two legs were used to calculate bilateral symmetry [32]. The dominant leg is on the side of the participants they usually shoot the ball from [33]. The PGRF was normalized to body weight (BW) [34]. All muscle simulation data were processed with a CusToM toolbox for calibrating linear and optimized models, developed in MATLAB enabling musculoskeletal analyses based on inverse dynamics approaches [35]. The 10 lower extremity muscles were selected for discussion including the right and left tibialis anterior (TA); soleus (SOL); quadriceps femoris (QF); gastrocnemius (GA); biceps femoris (BF).

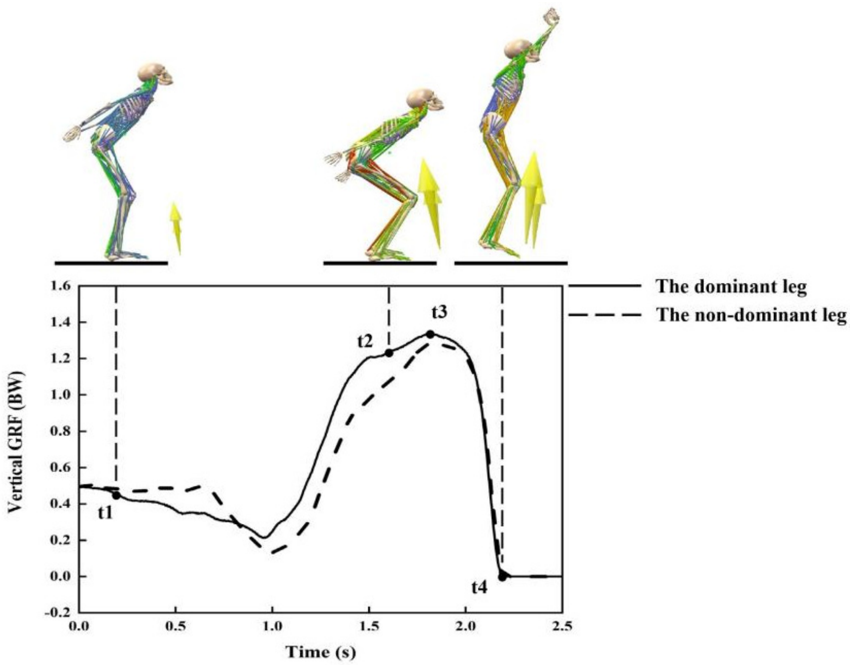

Figure 1. The countermovement jump force-time curves of dominant and non-dominant legs. The t1 is defined as the starting point of the CMJ dominant leg. The t2 and t3 are defined as the instant of maximum knee flexion angle and maximum GRF in the dominant le. The t4 was identified as the instant of take-off in the dominant leg.

2.5. Statistical Analysis

All data are expressed as mean $\pm$ standard deviation. We calculated the coefficient of variability (CV) via the formula: (SD (three CMJs)/average (three CMJs) $\times$ 100%) to measure absolute reliability [14]. CV values of $\leq$ 15% can be considered acceptable [36]. The exact parameter that represented bilateral asymmetry is PGRF. CV values of PGRF among pre-CMJ, CMJs50, CMJs100, CMJs150 and CMJs200 was in Tables S1–S5. The normality of the data was examined by the Kolmogorov–Smirnov Test. One-way repeated measures ANOVA was used in MATLAB (R2019A; MathWorks, Inc., Natick, MA, USA) software to compare differences among three different drop heights (DJH30, DJH40 and DJH50) at pre-CMJ, CMJs50, CMJs100, CMJs150 and CMJs200, respectively. The least significant difference (LSD) was used for post-hoc analysis. The level of significance was set at $p < 0.05$. The effect size (ES) was calculated using generalized η^2 [37].

3. Results

The PGRF bilateral asymmetry of CMJs100, CMJs150 and CMJs200 at DJH50 was greater than at DJH30 and DJH40. The PGRF bilateral asymmetry had no significant difference among the three different drop heights during CMJs50. Muscle simulation results showed that the muscle activation during CMJs50 at DJH50 was greater than that at DJH30 and DJH40. The muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 was smaller than those at DJH40 and DJH30.

The experimental results show (Figure 2, Tables S6–S8) the PGRF of CMJs. A significant difference was observed among the three jump heights of CMJs100, CMJs150 and CMJs200 ($p < 0.05$). The post hoc comparison showed that the PGRF of CMJs100, CMJs150 and CMJs200 at DJH50 was greater than at DJH40 and DJH30 (all $p < 0.001$; ES = 0.50–1.50). There was no significant difference between pre-CMJ and CMJs50 among the three jump heights (all $p > 0.05$).

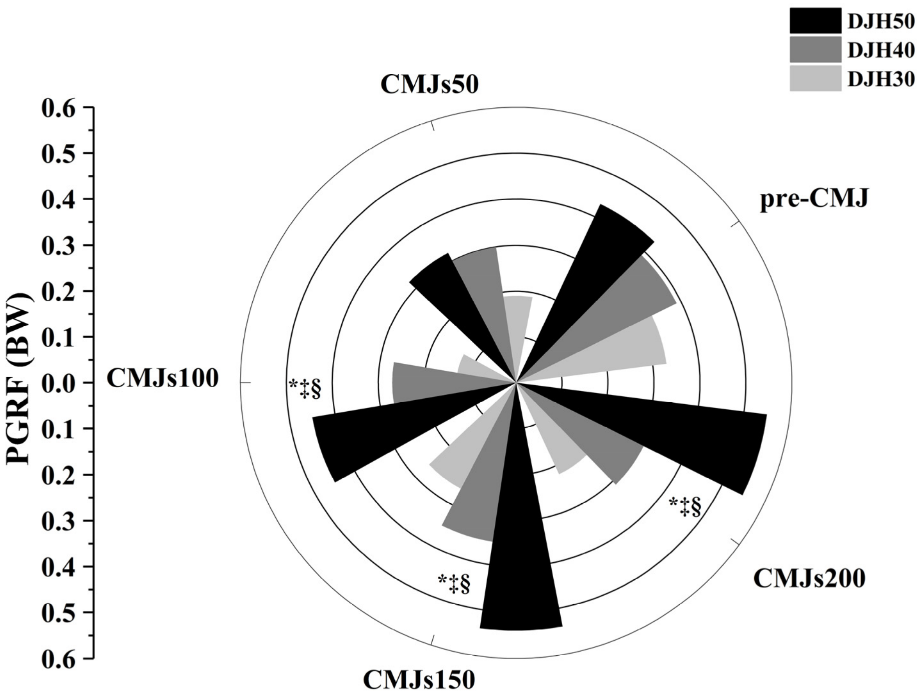

Figure 2. The side-to-side asymmetry during countermovement jumps among three heights at pre-CMJ, CMJs50, CMJs100, CMJs150, CMJs200. CMJ = countermovement jump; PGRF = peak ground reaction force. DJH30 = drop jump from 30 cm drop height; DJH40 = Drop jump from 40 cm drop height; DJH50 = drop jump from 50 cm drop height. * Indicates a significant difference among three drop heights; ‡ indicates a significant difference from DJH30 and DJH50; § indicates a significant difference from DJH40 and DJH50 ($p < 0.05$).

The experimental results show (Figure 3, Table S9) the muscle activation in the CMJ squat phase. A significant difference was observed in CMJs50, CMJs100, CMJs150 and CMJs200 among the three jump heights (all $p < 0.05$). The post hoc comparison showed that the right and left TA, SOL, QF, GAS and BF muscle activation during CMJs50 at DJH50 was greater than at DJH40 and DJH30 (all $p < 0.002$; ES = 0.08–1.69). The post hoc comparison showed that the right and left of TA, SOL, QF, GA and BF muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 was smaller than at DJH40 and DJH30 (all $p < 0.04$; ES = 0.02–1.70). There was no significant difference in pre-CMJ among the three jump heights ($p > 0.05$).

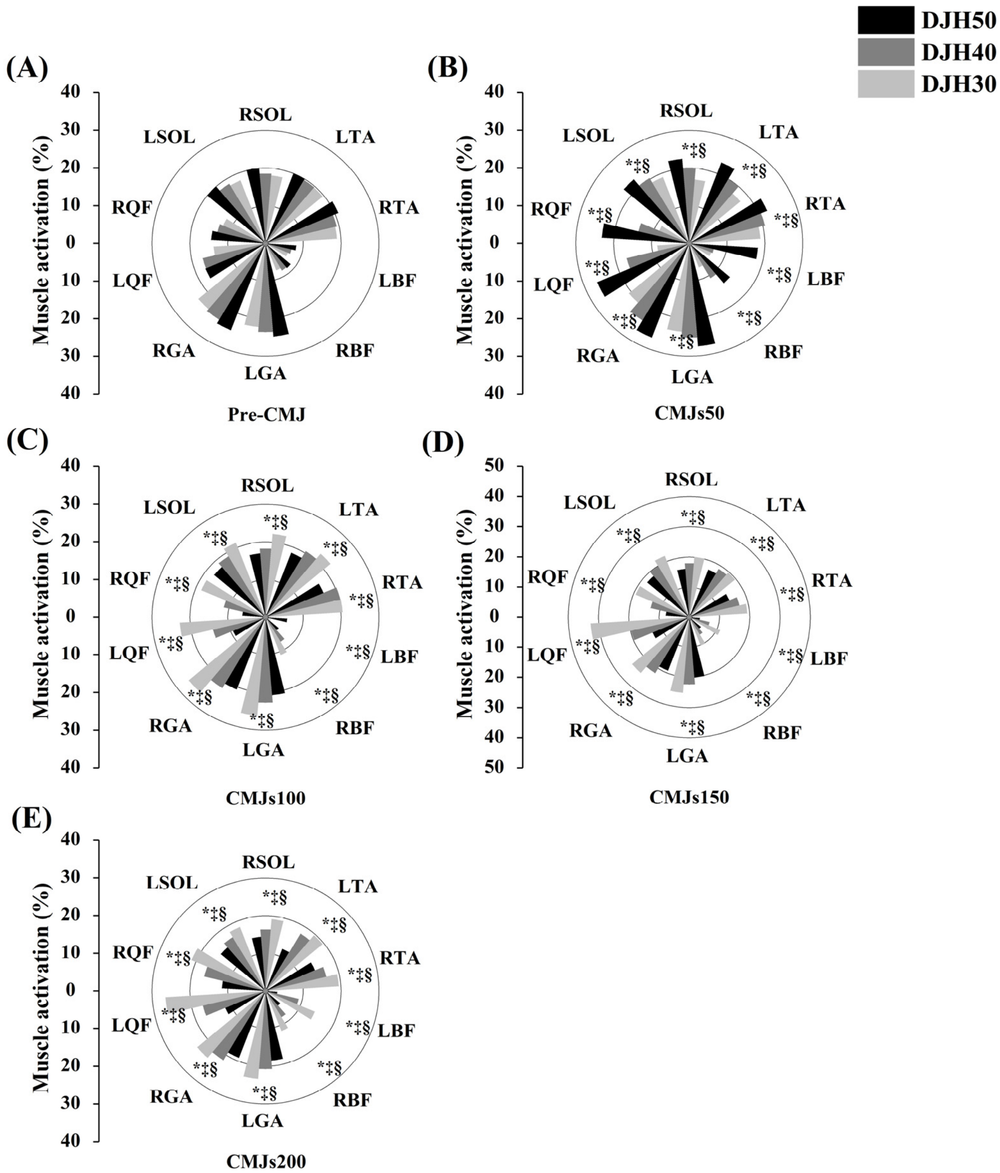

Figure 3. Muscle simulation activation during countermovement jump squat phase (**A**–**E**), CMJ = countermovement jump; DJH30 = drop jump from 30 cm drop height; DJH40 = drop jump from 40 cm drop height; DJH50 = drop jump from 50 cm drop height. RTA = right tibial anterior; LTA = left tibial anterior; RSOL = right soleus; LSOL = left soleus; RQF = right quadratus femoris; LQF = left quadratus femoris; RGA = right gastrocnemius; LGA = left gastrocnemius; RBF = right biceps femoris; LBF = left biceps femoris. * Indicates a significant difference among three drop heights; ‡ indicates a significant difference from DJH30 and DJH50; § indicates a significant difference from DJH40 and DJH50 ($p < 0.05$).

The experimental results show (Figure 4, Table S10) the muscle activation in the CMJ push-off phase. A significant difference was observed between the three jump heights in CMJs50, CMJs100, CMJs150 and CMJs200 (all $p < 0.05$). The right and left TA, SOL, QF and GAS muscle activation during CMJs50 at DJH50 was greater than at DJH40 and DJH30 (all $p < 0.008$; ES = 0.3–1.2). The post hoc comparison showed that the right and left TA, SOL, QF and GA muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 was smaller than at DJH40 and DJH30 (all $p < 0.007$; ES = 0.2–1.3). The post hoc comparison showed that the right and left BF during CMJs50 at DJH50 was smaller than at DJH40 and DJH30 ($p < 0.01$; ES = 0.2–0.9). The post hoc comparison showed that the right and left BF in CMJs100, CMJs150 and CMJs200 at DJH50 was greater than at DJH40 and DJH30

($p < 0.001$; ES = 0.3–1.2). There was no significant difference in pre-CMJ between the three jump heights ($p > 0.05$).

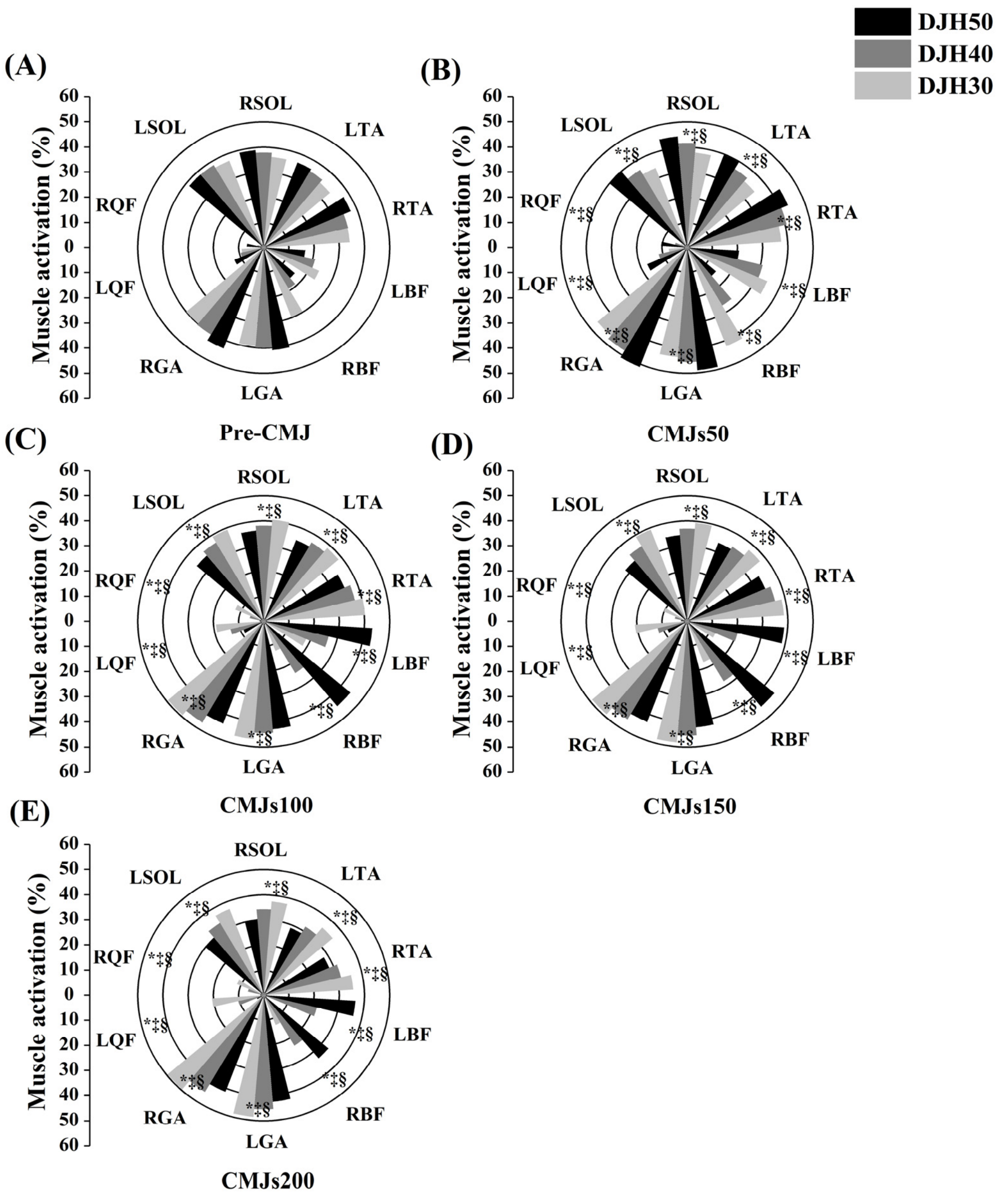

Figure 4. Muscle simulation activation during countermovement jump push-off phase (**A**–**E**). CMJ = countermovement jump; DJH30 = drop jump from 30 cm drop height; DJH40 = drop jump from 40 cm drop height; DJH50 = drop jump from 50 cm drop height. RTA = right tibial anterior; LTA = left tibial anterior; RSOL = right soleus; LSOL = left soleus; RQF = right quadratus femoris; LQF = left quadratus femoris; RGA = right gastrocnemius; LGA = left gastrocnemius; RBF = right biceps femoris; LBF = left biceps femoris. * Indicates a significant difference among three drop heights; ‡ indicates a significant difference from DJH30 and DJH50; § indicates a significant difference from DJH40 and DJH50 ($p < 0.05$).

The experimental results show (Figure 5, Table S11) the muscle activation in the CMJ landing phase. A significant difference was observed in CMJs50, CMJs100, CMJs150 and CMJs200 between the three jump heights (all $p < 0.05$). The post hoc comparison showed that the right and left of TA, SOL, QF and GAS muscle activation of CMJs50 at DJH50 was greater than at DJH40 and DJH30 (all $p < 0.003$; ES = 0.3–1.4). The post hoc comparison showed that the right and left TA, SOL, QF and GAS muscle activation of CMJs100, CMJs150 and CMJs200 at DJH50 were smaller than at DJH40 and DJH30 (all $p < 0.005$; ES = 0.3–1.3). The post hoc comparison showed that the right and left BF of CMJs50 at DJH50 was smaller than at DJH40 and DJH30 ($p < 0.005$; ES = 0.3–1.1). The post hoc comparison showed that the right and left BF muscle activation of CMJs100, CMJs150 and CMJs200 at DJH50 was greater than at DJH40 and DJH30 ($p < 0.001$; ES = 0.2–1.3). There was no significant difference in pre-CMJ between the three jump heights ($p > 0.05$).

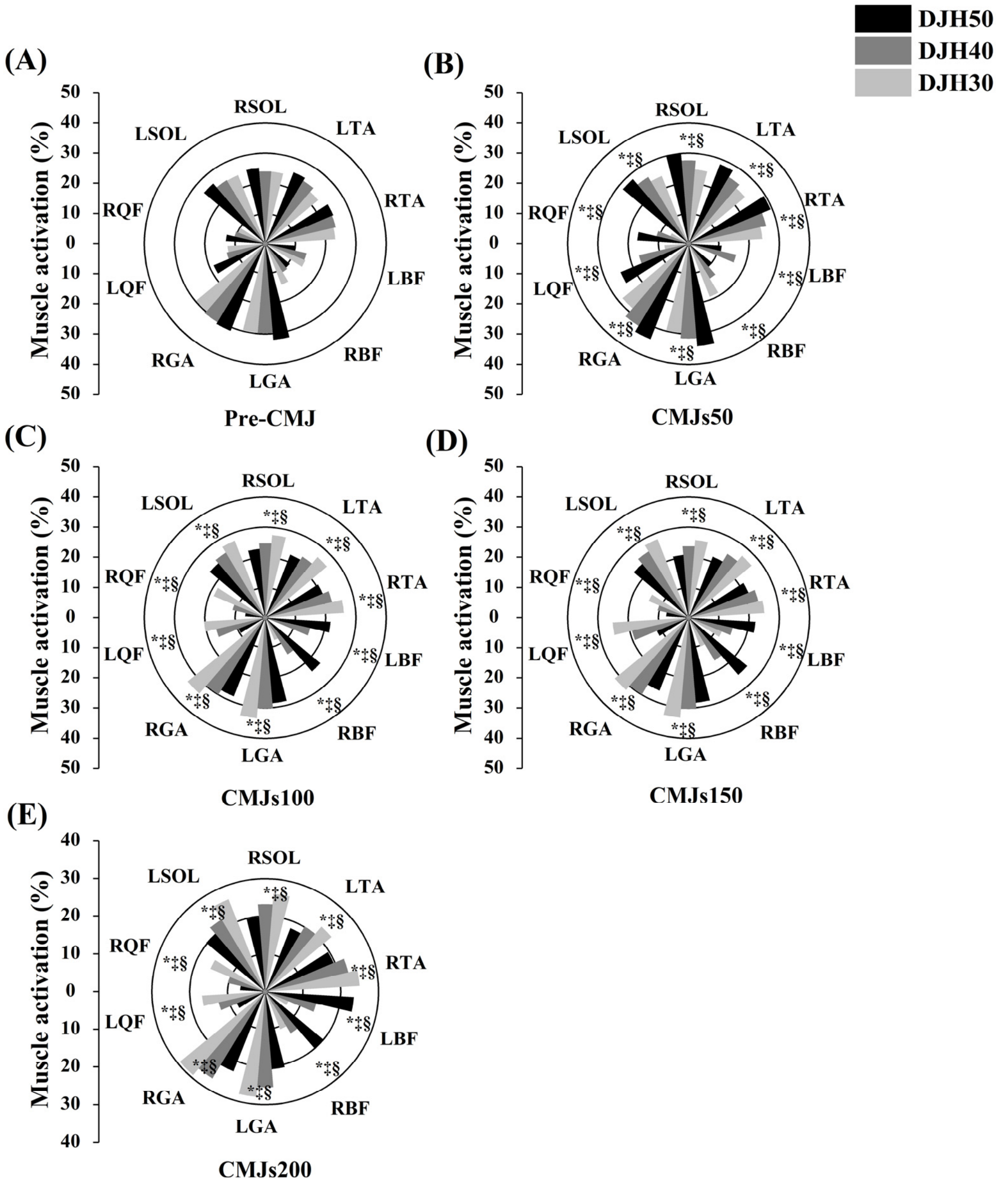

Figure 5. Muscle simulation activation during countermovement jump landing phase(**A**–**E**). CMJ = countermovement jump; DJH30 = drop jump from 30 cm drop height; DJH40 = drop jump from 40 cm drop height; DJH50 = drop jump from 50 cm drop height. RTA = right tibial anterior; LTA = left tibial anterior; RSOL = right soleus; LSOL = left soleus; RQF = right quadratus femoris; LQF = left quadratus femoris; RGA = right gastrocnemius; LGA = left gastrocnemius; RBF = right biceps femoris; LBF = left biceps femoris. * Indicates a significant difference among three drop heights; ‡ indicates a significant difference from DJH30 and DJH50; § indicates a significant difference from DJH40 and DJH50 ($p < 0.05$).

4. Discussion

The purpose of this study is to explore the influence of repeat DJ training between different drop heights on the bilateral asymmetry and lower extremity muscle activation during CMJs. The study found that the PGRF of CMJ bilateral asymmetry at DJH50 is greater than at DJH30 and DJH40. Muscle simulation results showed that the muscle activation with appropriate repeat DJ training at DJH50 is higher than at DJH30 and DJH40. However, excessive repeat DJ training at DJH50 may increase muscle fatigue and decrease lower extremity muscle activation during CMJs.

The study found that the PGRF bilateral asymmetries during CMJs100, CMJs150 and CMJs200 at DJH50 are greater than at DJH30 and DJH40. Previous studies have found that the PGRF at a drop height of 72 cm was greater than 32 cm and 52 cm [38]. The 14 sets of 10 continuous vertical jumps causes lower extremity muscle fatigue and increases the PGRF bilateral asymmetry [39]. The PGRF bilateral asymmetry may increase following repeated DJ training at higher drop heights. In this study, training above DJs100 at DJH50 can cause muscle fatigue in the lower extremities and increase bilateral PGRF asymmetry during CMJs100, CMJs150 and CMJs200 at DJH50. In addition, the PGRF bilateral asymmetry showed no significant difference among the three different drop heights in CMJs50. Past study has found that there was no difference in bilateral asymmetry at the drop height of 60 cm, the DJ training increased the SSC mechanism and muscle coordination at the drop height of 60 cm [11]. In this study, the DJs50 at DJH50 training may increase the SSC mechanism and muscle coordination, which made no difference to the PGRF bilateral asymmetry in CMJs50 at DJH50. Therefore, excessive repeat DJs100 training at DJH50 could produce lower extremity muscle fatigue and increase the PGRF bilateral asymmetry of CMJs. The DJs50 training at DJH50 may increase the SSC mechanism and muscle coordination but has no effect on the PGRF bilateral asymmetry of CMJs.

The study found that right and left TA, SOL, QF, GA and BF muscle activation during CMJs50 at DJH50 is greater than at DJH40 and DJH30 in the CMJ squat phase. A previous study found that increasing the drop height in the range of 20 cm to 60 cm can enhance the training intensity and increase the activation of QF, TA and GA muscles in the eccentric phase [40]. The drop height of 50 cm increases the muscle load; the activation of the QF muscle at a drop height of 50 cm is greater than 20 cm and 35 cm during the eccentric phase [41]. The drop height of 50 cm may increase the muscle load and muscle activation during the eccentric phase. In this study, the DJs50 training at DJH50 increased the muscle load and muscle activation in CMJs50 at DJH50 during the CMJ squat/eccentric phase. However, in this study, the right and left TA, SOL, QF, GA and BF muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 are smaller than at DJH40 and DJH30 in the CMJ squat phase. A past study found that the DJs200 at a drop height of 60 cm caused muscle damage and reduced the eccentric force of CMJs [42]. The 100 DJs from a drop height of 30 cm cause muscle fatigue and decrease the EMG activity of SOL, QF and GA muscles during the eccentric phase [6]. Therefore, exceeding DJs100 may cause muscle fatigue and decrease muscle activation during the CMJ squat/eccentric phase. In this study, the DJH50 training of excessive repeat DJs100 produces muscle fatigue and decrease muscle activation in CMJs100, CMJs150 and CMJs200 at DJH50 during the CMJ squat phase. Therefore, the DJ50 training at DJH50 increases muscle load and muscle activation in the CMJ squat phase. The excessive repeat DJs100 training at DJH50 increases muscle fatigue and decreases muscle activation during the CMJ squat phase.

Our results showed that right and left TA, SOL, QF and GA muscle activation during CMJs50 at DJH50 is greater than at DJH40 and DJH30 in the CMJ push-off phase. Schuster, R.W. et al. found that the drop height in the range of 20 cm to 60 cm can increase the stretch reflex and SOL muscle activation in the concentric phase [43]. The drop height in the range of 40 cm to 60 cm can increase the reutilization of elastic energy and the EMG activity of GA in the concentric phase [40]. In this study, the DJs50 training at DJH50 increased the reutilization of elastic energy and the stretch reflex, which increased the muscle activation during CMJs50 at DJH50 in the CMJ push-off/concentric phase. However, the right and left TA, SOL, QF and GA muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 are smaller than at DJH30 and DJH40 in the CMJ push-off phase. A past study found that the 200 DJs at the drop height of 60 cm cause muscle damage and decreased jump height and concentric peak power during the CMJ push-off phase [42]. The 100 DJs at the drop height of 30 cm cause muscle fatigue, which reduces the stretching reflex and the EMG activity of SOL, QF and GA muscles during the concentric phase [6]. Therefore, the excessive 100 DJs may produce muscle fatigue and decrease the concentric peak power and stretch reflex, which reduces muscle activation in the CMJ push/concentric phase. In this study, the excessive DJs100 training at DJH50 may cause muscle fatigue and decrease the concentric peak power and the stretching reflex, which reduces muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 in the CMJ push-off phase. Therefore, the DJs50 training at DJH50 can increase the reutilization of elastic energy and the stretch reflex, which increases muscle activation in the CMJ push-off phase. The excessive repeat DJs100 training at DJH50 may cause muscle fatigue and decrease the concentric peak power and the stretching reflex, which decreases muscle activation in the CMJ push-off phase.

The study found that right and left TA, SOL, QF and GA muscle activation during CMJs50 at DJH50 are greater than at DJH40 and DJH30 in the CMJ landing phase. A previous study found that the drop height of 60 cm can increase the joint flexion angle and absorb the impact effect to reduce the risk of injury. The GA, TA and SOL muscle activation at a drop height of 60 cm is larger than 40 cm and 80 cm during the landing phase [44]. The drop height in the range of 40 cm to 60 cm can increase knee flexion and dissipate the magnitude of the impact forces, which increases the QF muscle's activation during the landing phase [12]. Therefore, the drop height in the range of 40 cm to 60 cm may increase joint flexion and shock absorption, increasing the muscle's activation during the landing phase. In addition, past studies have found that DJ training at different drop heights can increase muscle stiffness during landing and reduce the risk of injury by strengthening lower extremity muscles [45]. During the landing phase of jumping, increased muscle coactivation can increase joint stiffness, decrease shear forces and contribute to better joint stability [46,47]. The increased inherent stiffness of the muscles that may result from coactivation helps to increase the ability of the lower extremities to absorb shocks and protect the knee from injury [48]. In this study, DJs50 at DJH50 may enhance the CMJ landing phase muscle activation in the lower extremities and reduce the risk of injury by changing the muscles' mechanical properties and stabilizing with the longer muscles' stretch length [49]. However, the right and left TA, SOL, QF and GA muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 are smaller than at DJH40 and DJH30 in the CMJ landing phase. A past study found that the DJs100 at a drop height of 30 cm produced a protective neuromuscular effect to decrease the risk of muscle fatigue, decreasing the GA, SOL and QF muscle activation in the landing phase [6]. The excessive DJs200 from the drop height of 20 cm causes muscle fatigue and reduces the energy absorption of the knee in the landing phase [50]. Therefore, the excessive repeated DJs100 may increase the neuromuscular protective capacity and muscle fatigue, which decreases the muscle activation in the landing phase. There is a coupling between the reduced performance of SSC and muscle injury. Fatigue induced by exhaustive SSC exercise may lead to changes in muscle architecture and disturbance of the stretch reflex activation, such as destroying the titin and desmin protein structure, causing muscle damage to inhibit muscle machinery [51,52]. In this study, the excessive DJs100 training at DJH50 may increase neuromuscular protection and muscle fatigue, decreasing muscle activation during CMJs100, CMJs150 and CMJs200 at DJH50 in the CMJ landing phase. Therefore, the DJs50 training at DJH50 increases joints' absorbance capacity and muscle activation in the CMJ landing phase. The excessive DJs100 training at DJH50 produced neuromuscular protection and muscle fatigue, which decreased muscle activation in the CMJ landing phase. Therefore, the excessive repeated DJs100 may increase the neuromuscular protective capacity and muscle fatigue, which decreases muscle activation in the landing phase.

In addition, the study found that right and left BF muscle activation during CMJs50 at DJH50 is smaller than at DJH30 and DJH40 in the CMJ push-off and landing phase. The right and left BF muscle activation of CMJs100, CMJs150 and CMJs200 at DJH50 is greater than at DJH30 and DJH40 in the CMJ push-off and landing phase. Previous studies have found that the biphasic coupling was caused by concentric and eccentric contractions during the SSC, decreasing BF muscle activation and increasing QF muscle activation in the DJ landing phase [10,23]. The agonists and antagonists produce a stretch reflex and reciprocal inhibition, reducing BF muscle activation during the CMJ eccentric and concentric phase [23]. Therefore, the QF and BF muscles may produce biphasic coupling and reciprocal inhibition during DJs and CMJs. In this study, the QF and BF muscles' activation produced biphasic coupling and reciprocal inhibition during the CMJ50, CMJs100, CMJs150 and CMJs200 at DJH50 in the CMJ push-off and landing phases.

5. Conclusions

In summary, the excessive DJs100 training at DJH50 increased the PGRF bilateral asymmetry of CMJs. The DJs50 training at DJH50 has no effect on the PGRF bilateral asymmetry of CMJ. In addition, the DJs50 training at DJH50 can increase muscle activation in the squat, push-off and landing phases. The excessive DJs100 training at DJH50 decreased muscle activation in the squat, push-off and landing phases. Therefore, the current study suggested that the DJs50 with DJH50 training increases the CMJ's muscle activation to improve the CMJ's performance, but has no effect on the bilateral asymmetry of CMJs. As a result, if properly planned, the current research could aid the coach in regulating the drop height and volume of the training week.

6. Limitation

There are some limitations of this research. Firstly, the study did not include EMG data. In the future, it should be compared with surface EMG and other potentially related neuromechanical variables. Secondly, the limitation of this study was that during continuous repetitive DJ, participants only rested for 10 s between each DJ; we did not objectively measure such as visual analogue scale, and the fatigue state of subjects could only be observed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sym14020190/s1, Table S1: Side-to-side asymmetry of PGRF among pre-CMJ; Table S2: Side-to-side asymmetry of PGRF among CMJs50; Table S3: Side-to-side asymmetry of PGRF among CMJs100; Table S4: Side-to-side asymmetry of PGRF among CMJs150; Table S5: Side-to-side asymmetry of PGRF among CMJs200; Table S6: The PGRF among countermovement jumps of left foot; Table S7: The PGRF among countermovement jumps of right foot; Table S8: The Side-to-side asymmetry of PGRF among countermovement jumps; Table S9: Muscles simulation activation (%) during countermovement jump squat phase; Table S10: Muscles simulation activation (%) during countermovement jump push-off phase; Table S11: Muscles simulation activation (%) during countermovement jump landing phase.

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Abbreviations

DJ	Drop jump
CMJ	Countermovement jump
SSC	Stretch-shortening cycle
PGRF	Peak ground reaction force
TA	Tibialis anterior
SOL	Soleus
QF	Rectus femoris
BF	Biceps femoris
GA	Gastrocnemius
ES	Effect size
LSD	Least significant difference

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