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Original Research

Determination of the optimal drop height for male with different exercise level in drop jump by unilateral lower limb

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Abstract

Background: Drop jump (DJ) is a kind of plyometric training. There is little research on the effect of drop height (DH) on unilateral DJ. This study explored the optimal DH of DJ by unilateral lower limb, aiming to provide a reference for males with different exercise levels to avoid the imbalance between bilateral lower limbs and for coaches to develop accurate and effective unilateral DJ training programs. **Methods**: 18 college athletes and 13 physically active students were recruited to participate in this study and then asked to take three tests, namely "single-leg DJ at low height (L- SLDJ)", "single-leg DJ at medium height (M-SLDJ)", and "single-leg DJ at high height (H-SLDJ)". Motion Capture System and Force Plate were used to synchronously collect motion parameters. **Results**: At M-SLDJ, both dominant and non-dominant legs performed significantly better than those at the other two types of DH in terms of leg stiffness and power for males with different exercise levels. At H-SLDJ, for males with different exercise levels, dominant leg had significantly better performance in leg stiffness, power etc. than non-dominant leg. **Conclusions**: The M-SLDJ designed in this study can be used by college athletes or students majoring in physical education for unilateral lower limb DJ training to maximize the performance of dominant or non-dominant leg. Due to the significant difference between two legs in the case of H-SLDJ, the eccentric contraction ability and stability of the non-dominant leg should be enhanced during the training to avoid bilateral imbalance.

Keywords: male; drop jump; unilateral lower limb; optimal drop height

1. Introduction

PT (Plyometric training), which refers to a training form in which the muscle firstly stretches for eccentric contraction and then shortens for concentric contraction, has been verified to be effective in developing explosive force of muscles and is now also known as the stretch-shortening cycle (SSC) [1]. When muscles shorten, PT will facilitate the rapid output of elastic potential energy accumulated in the muscles during pre-stretching. As has been demonstrated in many previous studies, the physiological mechanism of PT is quite close to the actual form of athletic performance in athletes [2]. After PT, positive change in the trainer's absolute force, explosive power and reactive force can be determined by a number of training parameters, such as contact time, flight time, and rate of force development (RFD) [3].

PT can be performed by drop jump (DJ), squat jump [4], counter-movement jump, pike jump, standing long jump, hops, and bounds, etc. DJ is an exercise in which the trainer drops from a high platform without any initial velocity while bending his or her hips and knees for buffering as soon as his or her feet touch the ground, and then immediately jumps as high as possible. In recent decades, DJ has been applied in many physical training programs to develop strength and conditioning performance and prevent injuries [5]. Previous studies have investigated the effect of DH height and jump spacing combination on jumping performance. The results indicated that when the drop spacing was 1.40 m and DH was 0.30 m, or when the drop spacing was 0.90 m and DH was 0.45 m, the optimal stimulus intensity was produced, a large number of muscle fibers were accumulated, and muscle group was available for the SSC to the greatest extent to achieve the optimal jumping performance [6]. Besides, other studies have discussed the application of DJ in different sports events, demonstrating that the application of DJ could effectively improve basketball players' short-distance sprint speed [7], starting acceleration ability, vertical jump ability [8] and sensitivity [7], improve volleyball players' single-foot and double-feet spike heights, block height and continuous vertical jump ability [5]. Moreover, other studies have compared DJ by bilateral lower limbs from different DHs. A trial in which the participants were asked to perform DJ from heights of 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, and 80 cm respectively revealed that the performance of lower limbs was enhanced with the increase in height [9] and that when the height exceeded 60 cm, the biomechanical efficiency began to reduce and the risk of injury might be enlarged [10]. However, it should also be pointed out that in this study the researchers noted that the pre-activation extents of soleus and the lateral head of the gastrocnemius when the height was 80 cm were significantly higher than those when the height was 20 cm and 40 cm [11]. To sum up, it seems that DH affects the exercise performance of DJ within a certain range. However, there is no unified optimal DH for DJ at present.

At the same time, while the positive effects of DJ by bilateral lower limbs on physical performance have been verified, its kinetic mechanism still differs from the actual practice in many sports events. Nevertheless, the DJ by unilateral lower limb is more common and more in line with the actual practice such as overarm layup in basketball, the take-off action of long jump in track and field, and single-leg support action in hurdling. The existing researches on unilateral DJ mainly concentrate on the evaluation of ACL injury risk [12], the stabilizing abilities of hips, knees and ankle joints [13] and single-leg complex exercise [14]. There is little research on the optimal DH of DJ by unilateral lower limb. Although there have been some researches on the DH of unilateral DJ [15], they still focus on the taking-off and landing of bilateral lower limbs. The investigation of the optimal DH of unilateral DJ can help us better understand the difference between dominant and non-dominant legs during unilateral DJ and thus avoid the imbalance between the two legs as well as the increased difference in muscle strength or stabilizing ability between the bilateral that might result in injuries on knees and ankle joints in addition to reducing exercise performance [16]. Moreover, the determination of the optimal DH is of great significance to develop effective exercise scheme against the bilateral difference and eventually result in imbalanced development in exercise performances of bilateral lower limbs.

Above all, DJ are of important influence on the exercise performance of lower limbs. Meanwhile, unilateral DJ is more in line with the actual practice. However, there is lack of in-depth research on the optimal DH of DJ by unilateral lower limb. Without determining the optimal DH of unilateral DJ, it would be impossible to improve the rapid expansion and contraction ability of athlete's lower limbs; on the contrary, jumping from a high platform with one leg landing is likely to result in knee and ankle injuries due to instability.

In addition, most of the test objects in previous studies were athletes, and it was rarely found that DJ was carried out for national college athletes or students. Only a few studies have proved that DJ has an effect on the athletic ability of students [10]. However, both national college athletes and students were selected as the research objects in this study. However, considering that the unilateral DJ requires high centrifugation of lower limbs and that females have problems such as genu valgus and muscle insufficiency [17], it is difficult for females to accurately express DJ and they are prone to injury. To avoid interference with experimental results, female participants were not included in this study. The research shows that normal subjects experience increased efficiency in working with lower limb muscle groups at the end of the DJ [18], which further indicates that DJ also has a significant effect on the enhancement of the sports performance of healthy people. In conclusion, DJ has application potential. Therefore, this study explored the DH of unilateral DJ to avoid the bilateral imbalance of lower limbs and provide a reference for making unilateral DJ exercise plans for daily exercise or physical activities.

2. Materials and methods

2.1 Participants

In this research, test participants had certain exercise basis and were able to perform unilateral DJ at different heights according to requirements, so as to avoid sports injury to unilateral lower limbs caused by increased height. For this reason, 31 males were selected, including 18 national college athletes (years: 20.56 $\pm$ 1.15, height: 188.78 $\pm$ 8.38, weight: 83.53 $\pm$ 10.43, BMI: 23.38 $\pm$ 1.91) and 13 students (years: 23.77 $\pm$ 1.01, height: 179.15 $\pm$ 8.19, weight: 72.42 $\pm$ 10.66, BMI: 22.47 $\pm$ 1.97) majoring in physical education. The selection criteria of participants were: (a) at least 20 years old; (b) had experience of sports training or maintained normal physical activity for at least 3–4 times per week; (d) without any medical conditions that hindered participation in the study. All participants were received clear guide and explanations to ensure their familiarity with the task. Each participant received and signed the informed consent prior to the trial. The protocol was approved by the ethics committee of Research Academy of Grand Health Ningbo University (RAGH2021023602001; August 2021).

2.2 Research design

Determination of DH. Due to the difference in height, weight, and vertical jumping ability among participants, the fixed heights mentioned in existing researches were used as the DHs in this test so as to ensure the accuracy of the test result. Ishikawa *et al.* [19] treated 50% CMJ (Counter-Movement Jump) as the medium DH of DJ by bilateral lower limbs, 50% CMJ plus 10 cm as the high DH and 50% CMJ minus 10 cm as the low DH. On this basis, taking into account the differences between unilateral and bilateral vertical jumping ability and lower limb stability, the DH of unilateral DJ in this study was finally determined as follows [2]. Before the test, the participants were asked to do CMJ exercise to obtain their optimal CMJ heights of lower limbs on dominant and non-dominant legs. Then, "L-SLDJ, single-leg DJ at low height" ("M-SLDJ" minus 5 cm), "M-SLDJ, single-leg DJ at medium height" (50% of the optimal unilateral CMJ height), and "H-SLDJ, single-leg DJ at high height" ("M-SLDJ" plus 5 cm) were used as three DHs of the participant in DJ (Table 1).

Test steps. Before the test, the participants were asked to stand still on a DJ frame, with arms akimbo; after receiving the instruction, they moved test leg forward and dropped it down freely, followed by "landing, contacting, jumping up into the air, and re-landing" in succession to complete all the movements of DJ. The participants were asked to do such tests this at an interval of 30 s for 3 times at each height

Table 1. CMJ and drop heights of dominant and non-dominant legs.

Participants	Lower limb	CMJ	L-SLDJ	M-SLDJ	H-SLDJ
Collegiate athletes	Dominant	41.03 $\pm$ 5.73a*	15.48 $\pm$ 2.94b*	20.48 $\pm$ 2.94c*	25.48 $\pm$ 2.94d*
	Non-dominant	39.21 $\pm$ 4.71a*	14.76 $\pm$ 2.38b*	19.59 $\pm$ 2.32c*	24.59 $\pm$ 2.32d*
Physical education students	Dominant	33.88 $\pm$ 2.79a	11.96 $\pm$ 1.37b	16.96 $\pm$ 1.37c	21.96 $\pm$ 1.37d
	Non-dominant	33.68 $\pm$ 3.39a	11.78 $\pm$ 1.78b	16.81 $\pm$ 1.77c	21.81 $\pm$ 1.77d

Note: "a" indicated that there was a significant difference in CMJ between different drop heights, $p < 0.05$; "b" indicated that there was a significant difference in L-SLDJ between different drop heights, $p < 0.05$; "c" indicated that there was a significant difference in M-SLDJ between different drop heights, $p < 0.05$; "d" indicated that there was a significant difference in H-SLDJ between different drop heights, $p < 0.05$; "*" indicates that college athletes were significantly different from physical education students, $p < 0.05$.

and then do the test at another height after a 1-minute rest to ensure that their physical condition was fully recovered. As a result, there was no significant difference between dominant and non-dominant legs at the same DH; the same side of lower limb showed significant difference between different drop heights ($p < 0.05$); college athletes were significantly superior to physical education students at the same drop height ($p < 0.05$) (Table 1).

2.3 Measurements and parameters

The kinematic data of participants SLDJ (single-leg drop jump) were recorded and digitized with Motion Capture System at 200 Hz (Vicon MX-Giganet, Englewood, NJ, USA). The CAST Marker ball sticking scheme was adopted to paste 16 reflective Marker balls to the positions of lower limb bone markers such as pelvis, knee, ankle and foot of the participants respectively. For SLDJ, only the best record of three trials was selected for analysis. For quantitative analysis of the data in SLDJ, the movement was divided into three phases: eccentric phase ($t_0 - t_1$), concentric phase ($t_1 - t_2$) and flighting phases ($t_2 - t_3$). Leg stiffness = $\frac{vGRF_i}{\Delta L}$ [20], where $vGRF_i$ is the vertical ground reaction force at the transition from eccentric to concentric actions (t_1); ΔL is the leg displacement from the beginning of the movement (t_0) to the lowest position of the COM (t_1). t_0 is the time of contacting with the force platform; t_1 the time at the lowest position of the COM (the body center of mass); t_2 the time at take-off and t_3 the time of secondary contacting with the force platform.

Force platform (Kistler, Winterthur, Switzerland) was used to record the Kinetic parameters of participants performing the SLDJ at the sampling frequency of 1000 Hz. The kinetic parameters are as follows: Buffer Time, Take-off time, $vGRF_{max}$ (concentric phase), Jumping Height and Power. Jumping Height = $\frac{g*Ft^2}{8}$. Power [21] = $\frac{g^2*Ft*Tt}{4*Ct}$. g is the acceleration due to gravity where Ft is the flighting time, Ct is the contacting time and $Tt = Ft + Ct$.

The energy changes of lower limb muscles during SLDJ can also be described by the following equations [20]: eccentric phase, Energy stored = $\int_{t_0}^{t_1} F_R(t) \cdot V_C\,(t)\,dt$, where $F_R(t)$ is the vGRF time curve measured by the force platform ($t_0 - t_1$); $V_C\,(t)$= $\frac{1}{m}\int_{t_0}^{t_1}[F_R\,(t) - mg]dt$, where m is the body mass. Concentric phase: The energy returning from the muscles is equal to that stored with the time interval from t_1 to t_2. Active work done = Energy returned − Energy stored.

2.4 Statistical analysis

In this research, SPSS 26.0 (IBM Corp., Chicago, IL, USA) was used to make statistical analysis on the test data. And 2 (exercise level: athletes and physical education students) × 2 (lower limbs: dominant side, non-dominant side) × 3 (drop height: low height, medium height, high height) repeated measurement-based variance analysis method was used to evaluate the participants' changes in buffer time, leg stiffness, jumping height and other indicators in the process of drop jump by unilateral lower limb at different drop heights. The significant main effects and interactions in the experiment were statistically analyzed, pairwise comparison method modified by Bonferroni was used for subsequent analysis, and Greenhouse-Geisser method was used to correct the statistics that did not satisfy the sphericity test condition, taking 0.05 as the standard value of p. An η_p^2 (partial eta square) value for the ANOVAs was used as an indicator of effect size.

3. Results

3.1 Drop jump test by unilateral lower limb in eccentric phase

In terms of buffer time (Tables 2,3), different exercise level showed significant main effect (F = 8.762, p = 0.003, η_p^2 = 0.03); different limb presented significant main effect (F = 5.497, p = 0.002, η_p^2 = 0.02); and different drop height displayed significant main effect (F = 33.184, p < 0.001, η_p^2 = 0.162). However, no significant interaction was found (p > 0.05). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at H-SLDJ underwent significantly longer buffer time than that at L-SLDJ (p = 0.008) and M-SLDJ (p = 0.013); the non-dominant side tested at L-SLDJ showed significantly shorter buffer time than that at

Table 2. Data during the SLDJ testing for male dominant leg with different exercise level.

Phase	Item	Collegiate athletes			Physical education students		
		L-SLDJ	M-SLDJ	H-SLDJ	L-SLDJ	M-SLDJ	H-SLDJ
	Buffer time (s)	0.19 ± 0.04	0.20 ± 0.06	0.26 ± 0.08#*	0.19 ± 0.07	0.24 ± 0.06	0.28 ± 0.07#*
Eccentric	Leg stiffness (BW/m)	12.33 ± 4.94	28.32 ± 19.35#†	20.71 ± 12.66#*†	9.38 ± 2.09	17.66 ± 6.18#	12.02 ± 2.11
	Energy stored (J)	480.44 ± 122.29	522.56 ± 152.37	572.15 ± 124.01	471.21 ± 219.1	480.53 ± 137.79	519.94 ± 221.46
	Take-off time (s)	0.27 ± 0.04	0.21 ± 0.06#	0.22 ± 0.06#	0.26 ± 0.07	0.22 ± 0.04#	0.23 ± 0.04#
Concentric	vGRF (BW)	2.1 ± 0.28	2.7 ± 0.66#†	2.5 ± 0.66#†	1.93 ± 0.21	2.35 ± 0.17#	2.1 ± 0.18*
	Energy returned (J)	788.81 ± 115.35†	862.56 ± 182.24†	814.49 ± 97.57†	623.73 ± 239.07	698.86 ± 157.21	622.93 ± 225.26
	Jumping Height (cm)	21.74 ± 5.79†	24.13 ± 5.79#†	21.49 ± 5.31*	17.02 ± 1.7	20.61 ± 1.61#	19.86 ± 1.6#
Performance	Power (W/kg)	18.37 ± 4.2†	24.04 ± 6.31#†	20.93 ± 6.03*†	14.29 ± 1.16	19.01 ± 1.9#	17.33 ± 0.95#
	Active work done (J)	308.38 ± 138.56†	340.01 ± 218.74†	242.34 ± 146.49†	152.52 ± 281.17	218.32 ± 190.23	102.99 ± 265.46

Note: # or *, H-SLDJ are significantly different from L-SLDJ and M-SLDJ respectively; †, Collegiate Athletes has significant difference compared with Physical education students, $p < 0.05$.

Table 3. Data during the SLDJ testing for male non-dominant leg with different exercise level.

Item	Collegiate athletes			Physical education students		
	Non-dominant			Non-dominant		
	L-SLDJ	M-SLDJ	H-SLDJ	L-SLDJ	M-SLDJ	H-SLDJ
Eccentric phase						
Buffer time (s)	0.17 ± 0.05†	0.25 ± 0.07#	0.27 ± 0.07#	0.22 ± 0.06	0.27 ± 0.07#	0.3 ± 0.10#
Leg stiffness (BW/m)	15.67 ± 7.79†	25.26 ± 14.65#†	13.79 ± 6.67*†	8.87 ± 2.64	16.47 ± 15.03#	7.07 ± 1.55*
Energy stored (J)	472.32 ± 130.17	507.93 ± 136.92	595.17 ± 99.98	447.35 ± 194.95	459.98 ± 135.43	485.41 ± 123.9
Concentric phase						
Take-off time (s)	0.24 ± 0.06†	0.21 ± 0.06	0.24 ± 0.05†	0.28 ± 0.05	0.22 ± 0.03#	0.33 ± 0.04#*
vGRF (BW)	2.25 ± 0.25†	2.71 ± 0.57#†	2.22 ± 0.31*†	1.86 ± 0.22	2.26 ± 0.15#	1.81 ± 0.17*
Energy returned (J)	752.63 ± 170.46†	829.92 ± 133.4†	795.48 ± 178.31†	548.7 ± 188	608.71 ± 208.88	588.87 ± 154.66
Performance						
Jumping Height (cm)	19.72 ± 3.83†	23.35 ± 4.48#†	20.56 ± 3.65*†	17.54 ± 1.2	21.01 ± 2.17#	18.32 ± 0.72*
Power (W/kg)	17.9 ± 3.2†	23.01 ± 4.64#†	18.33 ± 3.35*†	14.52 ± 1.4	18.47 ± 1.98#	14.53 ± 0.79*
Active work done (J)	280.31 ± 176.28†	321.99 ± 177.1†	200.32 ± 104.8	101.36 ± 283.62	185.63 ± 288.4	103.47 ± 158.32

Note: # or *, H-SLDJ are significantly different from L-SLDJ and M-SLDJ respectively; †, Collegiate Athletes has significant difference compared with Physical education students, $p < 0.05$.

M-SLDJ (p = 0.002) and H-SLDJ ($p < 0.001$). For physical education students, the dominant side tested at H-SLDJ went through significantly longer buffer time than that at L-SLDJ ($p < 0.001$) and M-SLDJ (p = 0.034); the non-dominant side tested at L-SLDJ experienced significantly shorter buffer time than that at M-SLDJ (p = 0.006) and H-SLDJ ($p < 0.001$). Between the two test groups, the non-dominant side of collegiate athletes tested at L-SLDJ (p = 0.049) underwent significantly shorter buffer time than that of physical education students. For collegiate athletes tested at M-SLDJ (p = 0.001) and physical education students tested at M-SLDJ (p = 0.038), the dominant side experienced significantly shorter buffer time than the non-dominant side.

In terms of leg stiffness (Tables 2,3), different exercise level showed significant main effect (F = 43.009, $p <$ 0.001 η_p^2 = 0.111); different drop height displayed significant main effect (F = 34.923, $p < 0.001$, η_p^2 = 0.169); and different limb and drop height presented significant interaction (F = 3.186, p = 0.043, η_p^2 = 0.02). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at M-SLDJ showed significantly better leg stiffness than that at L-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.028), H-SLDJ displayed significantly better leg stiffness than that at L-SLDJ (p = 0.042). The non-dominant side tested at M-SLDJ displayed significantly better leg stiffness than that at L-SLDJ (p = 0.008) and H-SLDJ ($p < 0.001$). For physical education students, the dominant side tested at M-SLDJ showed significantly better leg stiffness than that at L-SLDJ (p = 0.004); the non-dominant side tested at M-SLDJ presented significantly higher leg stiffness than that at L-SLDJ (p = 0.006) and H-SLDJ ($p < 0.001$). Between the two test groups, the dominant side of collegiate athletes tested at M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.003) presented significantly better leg stiffness than that of physical education students; the non-dominant side of collegiate athletes tested at L-SLDJ (p = 0.029), M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.01) presented significantly better leg stiffness than that of physical education students. For collegiate athletes and physical education students tested at H-SLDJ, the dominant side showed significantly better leg stiffness than the non-dominant side (Fig. 1).

In terms of energy stored (Tables 2,3), different exercise level showed significant main effect (F = 7.060, p = 0.008, η_p^2 = 0.02); different drop height displayed significant main effect (F = 5.726, p = 0.004, η_p^2 = 0.03). However, no significant interaction was found ($p > 0.05$). The following is a further analysis of the simple effects. Physical education students tested at H-SLDJ, the dominant side displayed significantly higher energy stored than the non-dominant side (Fig. 2).

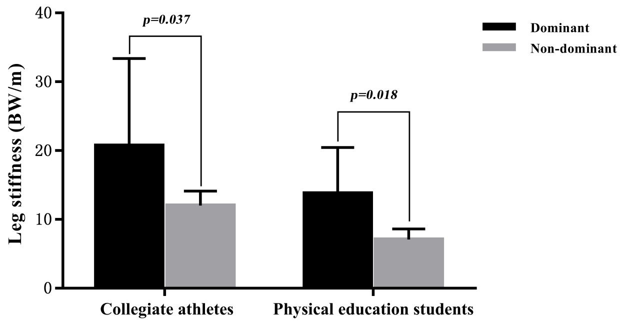

Fig. 1. Comparison of lower limb stiffness of dominant and non-dominant leg at H-SLDJ.

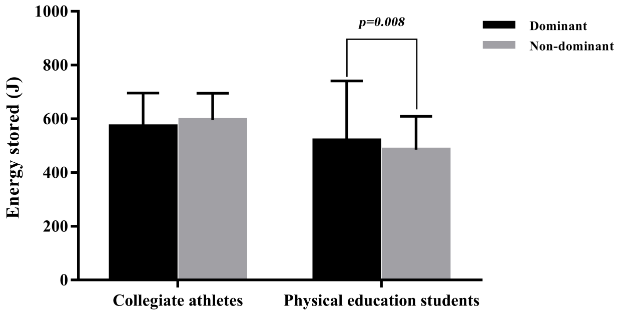

Fig. 2. Comparison of lower limb energy stored of dominant and non-dominant leg at H-SLDJ.

3.2 Drop jump test by unilateral lower limb in concentric phase

In terms of take-off time (Tables 2,3), different exercise level showed significant main effect (F = 21.593, $p <$ 0.001, η_p^2 = 0.06); different limb presented significant main effect (F = 13.474, $p < 0.001$, η_p^2 = 0.04); and different drop height displayed significant main effect (F = 31.218, $p < 0.001$, η_p^2 = 0.154); different exercise level and limb presented significant interaction (F = 11.719, $p < 0.001$, η_p^2 = 0.033); different exercise level and drop height displayed significant interaction (F = 5.069, p = 0.007, η_p^2 = 0.03); different limb and drop height presented significant interaction (F = 12.079, $p < 0.001$, η_p^2 = 0.066); and different exercise level, limb and drop height showed significant interaction (F = 4.656, p = 0.001, η_p^2 = 0.026). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at L-SLDJ underwent significantly longer take-off time than that at M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.033). For physical education students, the dominant side tested at L-SLDJ went through significantly longer take-off time than that at M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.03); the non-dominant side tested at M-SLDJ experienced significantly shorter take-off time than that at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$), L-SLDJ showed significantly shorter take-off time than that at H-SLDJ ($p <$ 0.001). Between the two test groups, the non-dominant side of collegiate athletes tested at L-SLDJ (p = 0.021) and H-SLDJ ($p < 0.001$) underwent significantly shorter take-off time than that of physical education students. For physical education students tested at H-SLDJ, the dominant side experienced significantly shorter take-off time than the non-dominant side (Fig. 3).

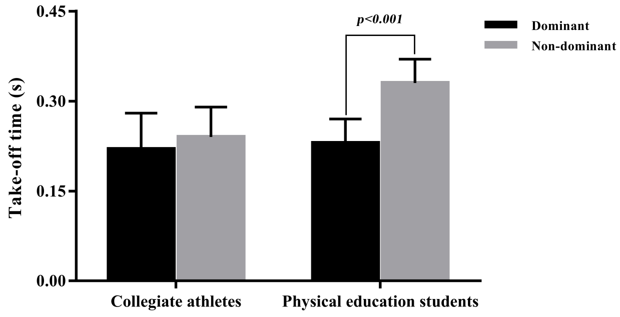

Fig. 3. Comparison of lower limb take-off time of dominant and non-dominant leg at H-SLDJ.

In terms of vGRF (Tables 2,3), different exercise level showed significant main effect (F = 83.280, $p < 0.001$, η_p^2 = 0.195); different limb presented significant main effect (F = 5.933, p = 0.015, η_p^2 = 0.017); and different drop height displayed significant main effect (F = 54.877, $p < 0.001$, η_p^2 = 0.242); and different limb and drop height presented significant interaction (F = 5.841, p = 0.003, η_p^2 = 0.033). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at L-SLDJ showed significantly lower vGRF than that at M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.003), the non-dominant side tested at M-SLDJ presented significantly higher vGRF than that at L-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.033). For physical education students, the dominant side tested at M-SLDJ displayed significantly higher vGRF than that at L-SLDJ $p < 0.001$) and H-SLDJ (p = 0.09); the non-dominant side tested at M-SLDJ presented significantly higher vGRF than that at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$). Between the two test groups, the dominant side of collegiate athletes tested at M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) displayed significantly higher vGRF than that of physical education students, the non-dominant side of collegiate athletes tested at L-SLDJ ($p < 0.001$), M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) displayed significantly higher vGRF than that of physical education students. For collegiate athletes and physical education students tested at H-SLDJ, the dominant side showed significantly higher vGRF than the non-dominant side (Fig. 4).

In terms of energy returned (Tables 2,3), different exercise level showed significant main effect (F = 86.658, $p < 0.001$, η_p^2 = 0.201); different limb displayed significant main effect (F = 5.380, p = 0.021, η_p^2 = 0.015); different drop height presented significant main effect (F = 4.295, p = 0.014, η_p^2 = 0.024). However, no significant interaction was found ($p > 0.05$). The following is a further analysis of the simple effects. Between the two test groups, the dominant side of collegiate athletes tested at L-SLDJ (p = 0.003) and M-SLDJ ($p < 0.001$) showed significantly higher energy returned than that of physical education students, the non-dominant side of collegiate athletes tested at L-SLDJ ($p < 0.001$), M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) displayed significantly higher energy returned than that of physical education students. For physical education students tested at M-SLDJ (p = 0.033), the dominant side had significantly higher energy returned than the non-dominant side.

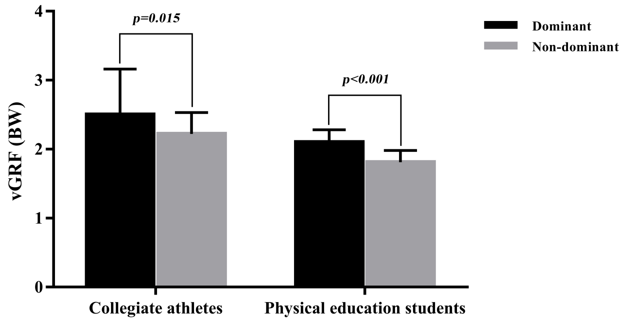

Fig. 4. Comparison of lower limb vGRF of dominant and non-dominant leg at H-SLDJ.

3.3 Exercise performance of drop jump test by unilateral lower limb

In terms of jumping height (Tables 2,3), different exercise level showed significant main effect (F = 56.017, $p < 0.001$, η_p^2 = 0.140); and different drop height displayed significant main effect (F = 28.812, $p < 0.001$, η_p^2 = 0.143). However, no significant interaction was found ($p > 0.05$). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at M-SLDJ showed significantly higher jumping height than that at L-SLDJ (p = 0.037) and H-SLDJ (p = 0.018), the non-dominant side tested at M-SLDJ displayed significantly higher jumping height than that at L-SLDJ (p = 0.002) and H-SLDJ (p = 0.015). For physical education students, the dominant side tested at L-SLDJ presented significantly lower jumping height than that at M-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.002); the non-dominant side tested at M-SLDJ showed significantly higher jumping height than that at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$). Between the two test groups, the dominant side of collegiate athletes tested at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) presented significantly higher jumping height than that of physical education students, the non-dominant side of collegiate athletes tested at L-SLDJ (p = 0.032) and M-SLDJ (p = 0.005) displayed significantly higher jumping height than that of physical education students. For physical education students tested at H-SLDJ, the dominant side showed significantly higher jumping height than the non-dominant side (Fig. 5).

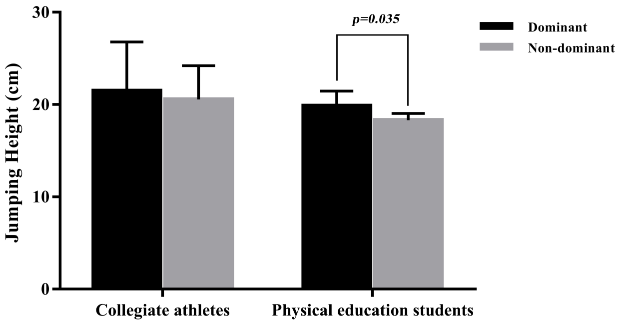

Fig. 5. Comparison of lower limb jumping height of dominant and non-dominant leg at H-SLDJ.

In terms of power (Table 2 and Table 3), different exercise level showed significant main effect (F = 122.543, $p < 0.001$, η_p^2 = 0.263); different limb presented significant main effect (F = 10.694, $p < 0.001$, η_p^2 = 0.03); different drop height displayed significant main effect (F = 65.184, $p < 0.001$, η_p^2 = 0.275); and different limb and drop height presented significant interaction (F = 4.202, p = 0.016, η_p^2 = 0.024). The following is a further analysis of the simple effects. Within specific test group, for collegiate athletes, the dominant side tested at M-SLDJ showed significantly higher power than that at L-SLDJ ($p < 0.001$) and H-SLDJ (p = 0.003), the non-dominant side tested at M-SLDJ presented significantly higher power than that at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$). For physical education students, the dominant side tested at L-SLDJ displayed significantly lower power than that at M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$); the non-dominant side tested at M-SLDJ showed significantly higher power than that at L-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$). Between the two test groups, the dominant side of collegiate athletes tested at L-SLDJ ($p < 0.001$), M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) displayed significantly higher power than that of physical education students, the non-dominant side of collegiate athletes tested at L-SLDJ ($p < 0.001$), M-SLDJ ($p < 0.001$) and H-SLDJ ($p < 0.001$) displayed significantly higher power than that of physical education students. For collegiate athletes and physical education students tested at H-SLDJ, the dominant side presented significantly higher power than the non-dominant side (Fig. 6).

In terms of active work done (Tables 2,3), different exercise level showed significant main effect (F = 30.456, $p < 0.001$, η_p^2 = 0.081); different drop height displayed significant main effect (F = 6.579, p = 0.002, η_p^2 = 0.037). The following is a further analysis of the simple effects. Between the two test groups, the dominant side of collegiate athletes tested at L-SLDJ (p = 0.021), M-SLDJ (p = 0.022) and H-SLDJ (p = 0.031) displayed significantly more active work than that of physical education students, the non-dominant

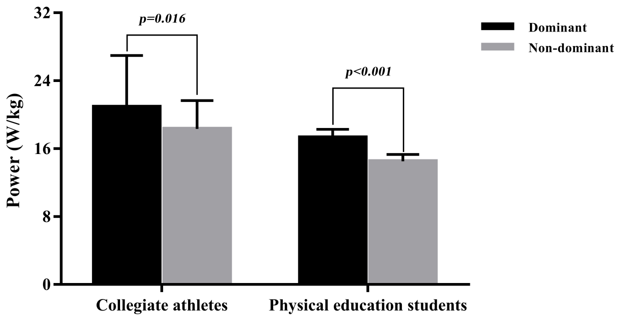

Fig. 6. Comparison of lower limb power of dominant and non-dominant leg at H-SLDJ.

side of collegiate athletes tested at L-SLDJ (p = 0.009) and M-SLDJ (p = 0.015) displayed significantly more active work than that of physical education students.

4. Discussion

Drop jump, as a type of classic plyometric training for lower limbs, plays a key role in promoting the rapid explosive ability of the lower limbs and strengthening the "stretch-shortening cycle (SSC)" mechanism. The performance of DJ task could be used as an indicator to measure the SSC intensity of muscle. Therefore, many researchers have carried out researches on DJ from the perspectives of contact time, take-off time [10], ground reaction force [22], etc. Difference from the same type of researches, on the basis of practical exercise, the DJ was conducted by unilateral lower limb at different DH heights in this study, and the suitable DH for DJ by unilateral lower limb was determined by observing the changes in multiple indicators.

The impact of DJ on the take-off explosive force of lower limbs essentially lies in that the DJ at different DH heights would facilitate the rapid activation of the SSC mechanism of lower limb muscle group, instant and efficient eccentric stretch of muscles as well as the accumulation of huge energy for the concentric contraction of lower limbs in the take-off phase [23]. This research found that with the gradual increase in DH, buffer time and energy absorption gradually increased on the dominant and non-dominant sides of the subjects' lower limbs, and that the buffer time in test at H-SLDJ was obviously longer than that at the other two heights, further suggesting that the musculoskeletal system of unilateral lower limb needed more time and effort to cope with the strong impact caused by increased height. However, at M-SLDJ, both of the two test groups showed higher lower-limb stiffness than that at L-SLDJ and H-SLDJ, which implied that the ground reaction force generated in eccentric phase of the test at M-SLDJ did not affect the lower-limb stiffness, compared with that at the other two heights. Stiffness plays an important role in maintaining joint stability and reducing the risk of musculoskeletal injury under high load conditions caused by the moment of fall to the ground [24]. Lower limbs with high stiffness would be advantageous in the storage and release of elastic potential energy [23] , as well as in increasing the tension growth rate in the stretch-shortening phase [25] and power generation intensity [26], and speeding up the transition from eccentric to concentric so that the elastic potential energy stored during the eccentric contraction of the extensor muscle of lower limbs could be fully utilized during the concentric contraction [27]. The reduction of lower-limb stiffness would result in great joint flexion, which might increase the energy absorption of tendon unit at an extended position, further increasing the risk of injury from overuse [28].

Although the stimulation on SSC mechanism might be intensified with the increase in DH, negative influence would inevitably be brought on the exercise performance, especially on the DJ by unilateral lower limb after reaching a certain height [9]. Similar to the results of the same type of researches, the exercise performance of unilateral lower limb did not increase with the increase in DH. During concentric contraction, the increase in DH showed no positive influence on the DJ by the participants' unilateral lower limb. On both dominant and non-dominant sides, the energy absorption in eccentric phase was directly proportional to the increase in DH, while the energy release in concentric phase presented no positive correlation. But at M-SLDJ, the energy release reached the highest, and the take-off time and vGRF were significantly higher than those at the other two DH. With respect to the exercise performance at M-SLDJ, the participants' unilateral lower limbs all performed optimally in jumping height, power and active work, which revealed that at H-SLDJ, the participant's muscles and tendons absorbed the most energy and born the highest mechanical pressure but could not efficiently drive the joints to generate explosive power or active work. The reason was not hard to understand, as at H-SLDJ, the buffer time was the longest and the lower-limb stiffness was the least in eccentric phases, which demonstrated that the ground reaction force was large at such DH so that the lower limb muscle group was stretched by external force, and the lower limb joint bent largely and was stretched for a longer time, thus reducing elastic energy stored in the viscoelastic muscle-tendon complex and stretch reflex efficiency. As a result, the jumping height, power and other exercise indicators were not ideal. As discovered by Ishikawa, when the maximum tensile load was exceeded at a DH, the contractile components of the muscles would be suddenly stretched within 30–50 s after dropping on the ground, which was caused by nerve inhibition and mechanical bridge sliding (or detachment) of the Golgi tendon organ, resulting in reduction in the power generation efficiency [29].

To sum up, when the DH exceeded M-SLDJ, the mechanical power output efficiency of lower limb decreased, followed by the consumption of larger energy by the joints and muscles for deceleration in landing. Thus, M-SLDJ could be treated as the optimal DH for males with different exercise levels in DJ by unilateral lower limb, which was the basically same as the result of the research on the DH of bilateral DJ that DH was within an optimal range and exercise performance were not improved with the increase in DH. As Bobbert reported, the power output of lower limb in the phase of concentric contraction decreased after reaching a certain value. When the participant dropped from a suitable height, the average force and jump height of the concentric phase is maximized, along with an increase in impulse and jump ability [30]. Taube pointed out that the increase in DH within a certain range would enhance the pre-activation level, stretch reflex activities and stiffness of the calf muscle, and promote the accumulation of elastic potential energy in buffer phase [1]. Many indicators were at H-SLDJ lower than those at M-SLDJ. There were mainly two reasons. One was that the second phase of SSC (amortization phase, the transition from eccentric to concentric contractions) took too much time and the concentric contraction failed to occur immediately after the end of eccentric contraction so that the elastic energy stored in the eccentric phase faded away in form of heat, resulting in the reduction of overall power. According to Schenau [31], dropping from a higher height might increase the negative power and elastic energy stored in the tendon tissue during landing, which facilitated the release of more energy in the take-off phase. However, if the muscle strength was limited, the power would disappear in form of heat instead of being stored in the muscle-tendon tissue. The other reason was that when the participant dropped from a different height, lower limb muscles might have different pre-activation modes. Before the participant dropped from a platform at H-SLDJ, the feed-forward control mechanism would activate lower limb muscles as per the experience signal system before landing; after landing, the mechanism could perceive and adjust any deviation while suppressing the excitement of afferent nerve and reminding that the pre-activation and vGRF of lower limb were out of tune when dropping from a height higher than the optimal height and that the length of the muscle-tendon complex needs to be adjusted again during the eccentric phase after landing. Consequently, a decrease in muscle strength was detected at the end of the eccentric phase. Luis's research revealed that when the DH exceeded a certain value, the pre-activation and stretch reflex activities of lower limb muscles were restricted by the damage prevention strategy of spinal nerve muscle control to a certain extent, so that the active contraction ability of the lower limb muscles was affected, finally leading to a decrease in vGRF, power and other indicators in the take-off phase [32]. Therefore, athletes and such college students majoring in physical education are advised to select M-SLDJ as the appropriate DH for unilateral DJ exercise when making daily arrangement for the movements of unilateral DJ so as to accurately optimize the explosive ability of lower limbs.

Moreover, human body is asymmetric. If the dominant side is used to do an exercise for a long term, asymmetry would be enlarged, leading to an imbalance. In most sports, athletes need to do multiple high-intensity movements by unilateral lower limbs, such as take-off action in long jump and kicking in football games. Therefore, bilateral asymmetric development is predictable. Researches have shown that the frequent use of unilateral lower limb would aggravate the imbalance of lower limbs, resulting in asymmetric impulse attenuation between bilateral lower limbs [33]. Bishop *et al*. [34] found that when the difference of leaping height on one side was 12.5%, it was correlated with their slow linear velocity and high jump performance. Bilateral asymmetric use of lower limbs for long term might cause cumulative traumas [35]. If this problem was not solved, the exercise performance might be affected and risk of injury would be increased when doing explosive force exercises or directional-change speed exercises [36]. In a unilateral jump test by lower limbs of professional athletes, the bilateral performance difference exceeded 10% and the risk of anterior cruciate ligament (ACL) was four times that of other athletes [37]. The three DHs designed in this research are displayed in Table 1. In terms of DH, the dominant side was higher but not significantly higher than the non-dominant side. The research results also showed that there was no significant difference between the two sides in many indicators of lower limbs such as stiffness, vGRF and power. It demonstrated that plyometric training of lower limbs arranged in this way would obtain training benefit without causing large bilateral difference while avoiding the imbalance between the bilateral exercise performances. Ball's research proved that DH with little difference between lower limbs could make good use of the elastic potential energy stored in SSC and effectively promote the balanced development of the strengths on bilateral lower limbs [15]. As pointed out in the research of Gonzalo-Skok, differentiated asymmetric training on the lower limbs could effectively improve athletes' sprint speed and instant directional-change ability, and played an important role in improving exercise performance and preventing sport injuries caused by imbalance [38].

However, in this research, it was also found that with the increase in DH, most indicators on the non-dominant side were significantly inferior to those on the dominant side when the DH was at H-SLDJ, compared with L-SLDJ and M-SLDJ. Especially for physical education students with low exercise level, there were significant bilateral difference in many indicators, which indicated that two sides of the lower limbs would become obviously asymmetric with the increase in DH and decrease in exercise level. Peng's research showed that as the DH increased, the participants became more asymmetric when contacting the ground [10], with stiffness of the hips, knees, and ankle joints obviously lower than those at other DH, and without advantage in power output of SSC. When the DH was at H-SLDJ, the bilateral different tended to be obvious, which might be because the non-dominant leg had poor neuromuscular control ability and eccentric contraction ability [39] and could not effectively control the hips, knees and ankle joints, leading to a decrease in stability of muscles around the knees and ankle joints [40], rapidly attenuating energy stored in lower limbs and weakening jumping ability. Besides, unlike athletes who design training plans for non-dominant parties, sports major students' daily sports activities are mainly carried out by dominant parties. Hence, in daily training, both athletes and physical education students should attach importance to training the eccentric contraction ability and the stability of joints on the non-dominant side to gradually shorten the bilateral difference and avoid sport injury caused by bilateral imbalance.

5. Conclusions

At M-SLDJ, the DJ performance by unilateral lower limb was superior to that at the other two DH (L-SLDJ and H-SLDJ), which indicated that the medium DH designed in this research helped optimize the unilateral DJ exercise of males with different exercise levels and promote the exercise performance of lower limbs. Furthermore, at H-SLDJ, the stiffness, power and other indicators of the dominant leg was significantly higher than those of the non-dominant leg, revealing the increasingly significant bilateral difference with the increase in DH. Therefore, the participants should formulate targeted unilateral DJ exercise plans against the bilateral difference and strengthen the eccentric contraction ability and stability on the non-dominant side so as to promote the coordinated development of both sides.

6. Limitations

This study had some limitations. We examined only DJ; the findings might not apply to other jumping modes such as squat jumps. Another limitation was that the participants were homogenous as male players and hence the results might not be applicable to females or athletes engaged in other sports. Thus, practitioners are advised to take note of the weaker limb, which might require specific attention during targeted training interventions. Lastly, the present study focused only on peak forces and loading rates during the landing phase of DJ and did not consider the propulsive phase. Future studies could examine the kinetic (e.g., impulse) and kinematic (e.g., joint angles) profiles of different phases of the DJ to enhance the understanding of how temporal asymmetry is related to kinetic asymmetry. In addition, randomization and blindness were not adopted in this study, and all subjects were tested in accordance with the set order, so learning effect cannot be excluded.

Author contributions

These should be presented as follows: DL and RX designed the research study. DL performed the research.

ZZ provided help and advice on. Initials DL wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

All study participants provided informed consent, and the study design was approved by an ethics review board. The protocol was approved by the ethics committee of Research Academy of Grand Health, Ningbo University (RAGH2021023602001; August 2021).

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Conflict of interest

The authors declare no conflict of interest.

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