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Original Article

Associations between jumping ability and isokinetic strength of the trunk and lower limb extensors: analysis of countermovement jump and rebound drop jump trials

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Abstract:
This study aimed to establish a correlation between jumping ability and the isokinetic strength of the trunk and lower limb extensors in female university athletes and to provide recommendations for improving jumping ability. Participants were 26 female university students from the track and field and volleyball teams. They performed a countermovement jump (CMJ) and a 30-cm rebound drop jump (RDJ). The following parameters were measured using high-speed video motion analysis: contact time, jump height, RDJ-index, joint angles, and joint angular velocities of the knee and ankle joints during the CMJ and RDJ. Additionally, the peak torques of the trunk and lower limb extensors and the percentage of total torque of three lower limb joints were measured using an isokinetic dynamometer. Based on the mean RDJ-index, the participants were classified into two groups: those with an RDJ-index of 0.80 m/s or higher (HG; n=12) and those with a lower RDJ-index of less than 0.80 m/s (LG; n=14). Our study yielded the following findings. The HG exhibited significantly greater heights in CMJ and RDJ, along with a higher RDJ-index and a notably shorter contact time compared with the LG. In the RDJ, the HG demonstrated significantly higher maximum knee flexion and ankle dorsiflexion angles compared with the LG. The HG tended to display significantly higher peak ankle plantar flexion and peak hip extension torques compared with the LG. Maximum knee flexion and ankle dorsiflexion angles exhibited significant negative correlations with RDJ contact time and positive correlations with RDJ-index. Significant positive correlations were observed between RDJ jump height and peak trunk extension torque as well as between RDJ-index and peak hip extension torque. These findings suggest that the low RDJ-index group can improve jumping performance by utilizing ankle plantar flexor muscle strength to achieve the jump with less contact time and by enhancing the isokinetic muscle strength of the trunk and hip extensors in order to stabilize the upper body and contribute to the acquisition of jump height.
Key Words*:* **Plyometrics, RDJ-index, Stretch-Shortening Cycle, Track and Field, Volleyball**

Introduction

The countermovement jump (CMJ) is a low-intensity exercise that involves a stretch-shortening cycle (SSC) and has a relatively long contact time (Zushi et al., 1993). CMJ jump height is widely utilized in physical fitness tests as a simple method for evaluating lower limb power (Kaneko et al., 1982). Meanwhile, the rebound drop jump (RDJ), which involves a platform, is classified as a ballistic SSC exercise that requires the exertion of explosive power in a short period of time (Zushi et al., 1993). The RDJ-index, calculated by dividing the jump height attained during RDJ by the ground contact time required, is widely used as an index to evaluate muscle strength and power exertion in the lower limbs, from children to top athletes (Shide and Shinkaiya, 1996; Yoshida et al., 2018). A higher RDJ-index indicates better jumping ability in terms of obtaining a high jump height in a short ground contact time (Zushi and Takamatsu, 1995a; Zushi et al., 2017).

Some investigations into the lower limb joints' functions in achieving greater jump heights and reducing ground contact times in CMJ and RDJ have focused primarily on the momentum generated by each body part as well as the joint torques and mechanical work calculated using the inverse dynamics approach (Ae et al., 1994; Zushi et al., 19998; Aoyama et al., 2000; Kigoshi et al., 2004). Aoyama et al. (2000) found that the ankle joint contributed the most to the acquisition of vertical velocity in the RDJ test from a 40-cm platform height among ten male jumpers. Ae et al. (1994) noted that the ankle plantar flexor and knee extensor were responsible for cushioning during landing in CMJ and RDJ with a low platform height (0.25–0.40 m), whereas the hip extensor became more engaged as the platform height increased (0.60–1.00 m). Kigoshi et al. (2004) also highlighted the importance of the hip extensor in RDJ, emphasizing that by tilting the upper body slightly forward with the pelvis, the output of the biceps femoris muscle, which generates hip extension power, could be effectively elicited. Furthermore, Zushi et al. (1998) indicated that the hip joint has a large muscle, primarily the gluteus maximus, which can generate the most significant power through concentric contraction among the three

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lower limb joints, and that it can be utilized for postural control due to its large mass ratio and inertial properties. In addition, the ankle joint, which has a high proportion of tendons and is located at the end of the body, stores power from the hip and knee joints in muscles and tendons through eccentric contraction, which behaves like a spring, and thus controls the trunk posture, which has a large mass ratio and moment of inertia. In contrast, Zushi and Takamatsu (1996) asserted that bending the knee joint angle before ground contact based on temporal and spatial prediction was crucial for the knee joint to shorten the contact time with the ground, allowing a large knee joint extension force to be applied immediately after ground contact.

Meanwhile, several studies have explored the association between isometric or isokinetic knee and ankle joint movements and jump height in CMJ and RDJ by utilizing an isokinetic dynamometer, a versatile exercise device for analyzing muscle function (Destaso et al., 1997; Tanaka et al., 2006; Miyachi and Kawamura, 2022). Destaso et al. (1997) investigated the relationship between RDJ jump height and the muscular force exerted by the knee extensors and ankle plantar flexors during concentric and eccentric contractions set at an angular velocity of 120 deg/s. They found a significant positive correlation between RDJ jump height and peak knee joint extension torque. Tanaka et al. (2006) examined the effects of a 2-month training program on CMJ jump height in 21 female university students, 7 in each of three groups: the ankle plantar dorsiflexion training group, the knee joint extension-flexion training group, and the non-training group. The results showed a significant positive correlation between CMJ jump height and peak ankle plantar flexion torque ($r = 0.528$, $p < 0.05$), with CMJ jump height increasing significantly only in the ankle plantar dorsiflexion training group. Furthermore, Miyachi and Kawamura (2022) conducted a single leg drop jump landing test with 63 adult male participants to evaluate the center of pressure trajectory length and shock buffer coefficient immediately after landing in RDJ on one leg from a 20-cm platform height and investigated the relationship between the muscle force exerted by the knee joint extensors under isometric and concentric contraction at seven different angular velocities (0, 60, 90, 120, 180, 240, and 300 deg/s). The results showed that the higher the peak value of the knee joint extension torque at medium speeds (90–120 deg/s) or higher, the better the impact-cushioning ability of the knee joint.

The aforementioned studies highlight the significance of augmenting the muscle strength of the knee extensors and ankle plantar flexors in achieving the desired jump heights for both CMJ and RDJ while concurrently reducing the ground contact time. However, the relationship between the strength of the trunk and hip extensors and jump performance parameters such as ground contact time, jump height, and RDJ-index remains largely unexplored. Given that the trunk and hip joints possess the most extensive muscle groups in the body and play a crucial role in power generation, their potential contribution to enhancing jumping ability might be underrated when compared with the knee and ankle joints.

The majority of the abovementioned studies focused on male athletes or high-level competitors, leaving a dearth of recommendations for enhancing the jumping ability of female athletes or those with inferior jumping skills. Hence, the objective of this study was to distinguish the differences in trunk and lower limb extensor muscle strength between female university students specializing in sprinting and jumping events in track and field (Iwatake et al., 2002; Zushi et al., 2017) and in volleyball (Katsumata et al., 2014) who need enhanced jumping ability. Moreover, it is essential to examine the connection between jumping indices such as ground contact time, jump height, and RDJ-index and the muscular force generated by each muscle group. By elucidating these factors, it should be possible to identify which muscle groups to prioritize during weight and plyometric training for athletes with poor jumping ability. Accordingly, this study aimed to establish a correlation between jumping ability and the isokinetic strength of the trunk and lower limb extensors in female university athletes who specialize in sprinting and jumping events in track and field and volleyball, where enhanced jumping ability is necessary, and to provide recommendations for improving jumping ability.

Materials & methods

Participants

Participants were 26 female university students (mean height: 160.19±5.34 cm, mean weight: 53.46±3.89 kg, mean age: 20.58±0.99 years) specializing in sprinting and jumping events in track and field athletics or volleyball. Written informed consent was obtained from all participants after the study protocol, including the purpose, methods, and potential risks, was explained both orally and in writing. This study was approved by the Ethics Committee of the Faculty of * University (approval number: 2021-11).

The 26 participants were divided into two groups based on their jumping ability (RDJ-index): a higher group (HG) with superior jumping ability (n=12), and a lower group (LG) with inferior jumping ability (n=14). The differences between the means of the two groups were compared and analyzed. Prior to the study, the necessary sample size was estimated using G*Power (Version 3.1.9.2, Universität Kiel, Germany), with an effect size of 1.00 based on the study by Kinomura et al. (2021), who classified participants into higher and lower groups based on their jumping ability. The significance level was set at 0.05, and the power at 0.80 in a one-tailed test based on this effect size. The sample size of 14 participants in each group was deemed appropriate. Although some participants withdrew from the study, data from 12 participants in the HG and 14 participants in the LG were collected, with a power of 79.51%, indicating an adequate sample size for the study.

Data collection and processing

Jumping ability measurement

Jumping ability was assessed in a biomechanics laboratory at * University. To measure jumping ability, the participants performed both CMJ and RDJ from a 30-cm platform (a jointed soft plyobox X type, manufactured by FitElite). The 30-cm platform was chosen due to its reported safety and suitability for evaluating SSC exercises (Zushi et al., 1993). During the jumps, the participants were instructed to jump as high as possible on the vertical-jump measurement scale (Yardstick, Swift Performance) without any restrictions on arm swing or lower limb recoil movements, and to perform the RDJ with as short a ground contact time as possible. Additionally, the participants were instructed to jump in such a way that they could place one leg at a time in a 40 × 40 cm jumping zone, and to ground and release at the same position and posture to the extent possible (Fig. 1). A trial was considered a failure if the participant judged the jump to be unsuccessful or if they landed at a substantial distance from the toe-off position. The participant performed the trials until they successfully completed two trials, and the trial with the highest jump height measured by the vertical-jump measurement scale was chosen for motion analysis. Prior to the start of the measurement, the participants were given about 30 min to warm up and practice two trials each. They were also given sufficient rest between trials. All measurements were performed in one day.

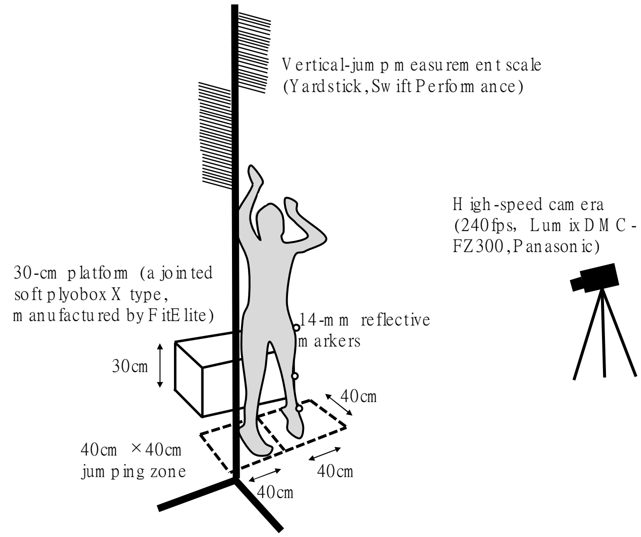

Fig. 1 Experimental setup

The participant trials were recorded at a frame rate of 240 fps using a high-speed camera (Lumix DMC-FZ300, Panasonic) positioned on the participant's side. The participant wore a motion-capture suit (OptiTracks) and indoor shoes, and 14-mm reflective markers with an X-base (OptiTracks) were attached to their toes, ankle, knee, and hip joints. The video images of the test were loaded into a video analysis system (Frame-DIAS V, Q'sfix, Corp.) and digitized at 240 fps, using each reflective marker and the calibration marks placed at the four corners as landmarks. The obtained two-dimensional body coordinate values on the sagittal plane were smoothed using a fourth-order Butterworth low-pass digital filter, and the optimal cutoff frequency (16.8-24.0 Hz) was determined using the method described by Wells and Winter (1980).

Calculation items

Jump index

The measurement of ground contact time and flight time was achieved by examining the frames of ground contact or ground release at a rate of 240 fps (equivalent to 0.004 s per frame) using video playback software (Quick Time Player ver. 7.7.9, Apple Inc.) on a personal computer. The first half of ground contact was determined as the duration from ground contact to maximum knee flexion, while the second half was determined as the duration from maximum knee flexion to toe-off. Furthermore, the jump height and RDJ-index were calculated using the following equations.

$$\textit{Jump height (m)} = 1/8 * 9.81 * \textit{flight time} \quad (1)$$

$$\textit{RDJ-index (m/s)} = \textit{Jump height / contact time} \quad (2)$$

Joint angle and joint angular velocity

The knee joint flexion-extension angle was measured as the angle formed between the line segment extending from the knee joint to the hip joint and the line segment extending from the knee joint to the ankle joint. Similarly, the ankle plantar dorsiflexion angle was determined as the angle formed between the line segment extending from the ankle joint to the knee joint and the line segment extending from the ankle joint to the toes. These angles were defined such that the knee joint angle was 180 deg when fully extended and the ankle joint angle was 180 deg when fully plantar flexed. The joint angular velocities were calculated by numerically differentiating the joint angles. Positive angular velocities were assigned to extension and plantar flexion, while negative angular velocities were assigned to flexion and dorsiflexion. The maximum flexion angle of the knee joint, maximum dorsiflexion angle of the ankle joint, maximum extension angular velocity of the knee joint, and maximum plantar flexion angular velocity of the ankle joint were then determined from the time series data of the joint angles and joint angular velocities.

Muscle strength measurement of the extensors of the trunk and lower extremities

Muscle strength was measured using an isokinetic dynamometer, a device designed for analyzing muscle function (Cybex NORM, CSMi). The focus of this study was four specific joint axes: the trunk flexion–extension axis, hip flexion–extension axis, knee flexion–extension axis, and ankle plantar dorsiflexion axis. Measurements were limited to the right leg only, and all trials consisted of concentric contractions at an angular velocity of 60 deg/s, with one practice repetition followed by three full repetitions. Peak values of extension, flexion, or plantar and dorsal flexion torque were obtained from the measurement data, and peak values were normalized by dividing them by the participant's body weight (peak value per body weight). Only extension or plantar flexion torque was considered in this study. The total torque of the hip, knee, and ankle joints was defined as the sum of the peak values of the hip extension torque, knee extension torque, and ankle plantar flexion torque. The percentage contribution of each joint to the total torque of the three lower limb joints was calculated. The measurement methods used to obtain joint torques exerted by the muscles around each joint axis using the isokinetic dynamometer are described in detail below (Fig. 2).

(1) Muscles groups involved in trunk flexion–extension:

To measure trunk flexion–extension muscle strength, the participant was positioned in a standing posture with 15 deg of knee flexion. The center of rotation axis of the trunk (fifth lumbar vertebra) was aligned with the dynamometer's axis of rotation. The upright posture was set to 0 deg, and the range of motion was set to 10 deg in the extension direction and 90 deg in the flexion direction.

(2) Muscle groups involved in hip flexion–extension:

To measure hip flexor–extensor muscle strength, the participant was placed in a supine posture on a seat with the hip joint center aligned with the dynamometer's axis of rotation. The pelvis was secured with a special belt, and the thigh was secured with a special pad. The posture where the line segment from the hip joint center to the knee joint center pointed vertically upward was set to 90 deg. The range of motion was set to 80 deg in the extension direction and 20 deg in the flexion direction (with the maximum extension position set to 0 deg and the range from 10 to 110 deg in the flexion direction).

(3) Muscle groups involved in knee joint flexion–extension:

To measure knee joint flexion–extension muscle strength, the participant's upper body and right thigh were secured with a special belt, and the right lower leg was secured with a special pad. The maximum extension position was set to 0 deg, and the range of motion was set from there to 100 deg in the flexion direction.

(4) Muscle groups involved in ankle plantar–dorsiflexion:

To measure muscle strength in ankle plantar flexor and dorsiflexor, the participant was placed in a supine posture on a seat with the ankle joint center aligned with the dynamometer's axis of rotation. The pelvis was secured with a special belt, the thigh with a special pad, and the foot with a special attachment. The position where the toe pointed vertically upward was set to 0 deg, and the motion range was set to 50 deg in the plantar flexion direction and 20 deg in the dorsiflexion direction from 0 deg.

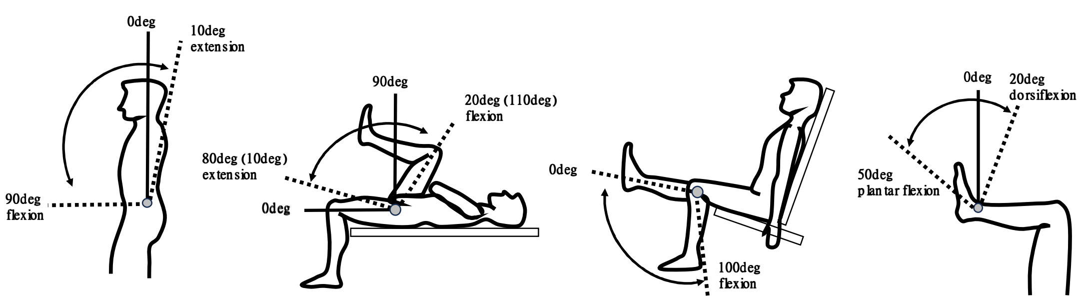

Fig. 2 Strength measurement using the isokinetic dynamometer

Statistical processing

Levene's test of equal variances was employed to confirm the assumption of equal variances for each calculated item, followed by an unpaired *t*-test to compare the means of the 12 HG participants with superior jumping ability and the 14 LG participants with inferior jumping ability. Cohen's d was calculated as the difference between the means obtained and the unbiased variance of each sample to evaluate the effect size (Demura, 2007). Pearson's product-moment correlation coefficient was used to examine the correlation between each calculated item. The statistical analyses were performed using SPSS ver. 28.0 (IBM) and Excel 2019 ver. 2312 (Microsoft). The significance level was set at 5%, and a p-value of $0.05 \leq 0.10$ was also considered to indicate a significant trend. The effect size of Cohen's d was interpreted as follows: $0.50 < d$ = small, $0.50 \leq d < 0.80$ = medium, and $0.80 \leq d$ = large (Cohen, 1992).

Results

Table 1 shows the participants' height, weight, age, and jump index results. The mean RDJ-index was used to classify the participants into two groups: the HG, consisting of the 12 participants with an RDJ-index greater than 0.80 m/s, and the LG, consisting of the 14 participants with an RDJ-index less than 0.80 m/s. Mean differences between the two groups were compared and analyzed. The results indicate that there were no significant differences in height and weight between the two groups. However, the HG exhibited a significantly greater CMJ jump height compared with the LG. Additionally, for first half, second half, and total ground contact time, the HG demonstrated significantly shorter ground contact time compared with the LG. Furthermore, both the RDJ height and RDJ-index were significantly greater for the HG than for the LG.

Table 1 Body height, body weight and jump index

				RDJ				
Group	Participant	Body height (m)	Body weight (kg)	Contact time (s) 1st-half	2nd-half	Total	Jump height (m)	RDJ-index (m/s)
HG	No.1	162	53	0.18	0.18	0.36	0.34	0.95
	No.2	161	56	0.11	0.12	0.23	0.35	1.55
	No.3	161	52	0.14	0.16	0.30	0.31	1.04
	No.4	158	48	0.12	0.18	0.29	0.29	0.98
	No.5	156	52	0.09	0.15	0.25	0.31	1.27
	No.6	164	59	0.14	0.15	0.29	0.30	1.03
	No.7	167	60	0.10	0.11	0.21	0.37	1.75
	No.8	150	53	0.15	0.17	0.32	0.28	0.88
	No.9	158	48	0.10	0.17	0.28	0.25	0.90
	No.10	161	57	0.14	0.18	0.33	0.34	1.04
	No.11	159	49	0.21	0.24	0.45	0.38	0.85
	No.12	160	50	0.23	0.22	0.44	0.37	0.83
LG	No.13	173	54	0.22	0.22	0.44	0.23	0.53
	No.14	153	49	0.21	0.23	0.44	0.28	0.64
	No.15	159	53	0.20	0.21	0.41	0.26	0.64
	No.16	159	60	0.23	0.20	0.43	0.30	0.69
	No.17	160	49	0.21	0.30	0.52	0.32	0.61
	No.18	160	52	0.27	0.26	0.53	0.32	0.61
	No.19	150	47	0.23	0.26	0.48	0.24	0.49
	No.20	152	52	0.21	0.23	0.44	0.29	0.66
	No.21	161	57	0.26	0.28	0.53	0.33	0.62
	No.22	164	58	0.25	0.31	0.55	0.28	0.51
	No.23	167	53	0.30	0.24	0.54	0.25	0.47
	No.24	159	57	0.22	0.44	0.66	0.21	0.32
	No.25	164	55	0.23	0.28	0.51	0.22	0.44
	No.26	167	57	0.25	0.28	0.53	0.25	0.47
Mean±S.D.	HG (n=12)	159.75±4.22	53.08±4.12	0.14±0.04	0.17±0.04	0.31±0.08	0.32±0.04	1.09±0.29
	LG (n=14)	160.57±6.27	53.79±3.81	0.23±0.03	0.27±0.06	0.50±0.07	0.27±0.04	0.55±0.11
	All (n=26)	160.19±5.34	53.46±3.89	0.19±0.06	0.22±0.07	0.41±0.12	0.30±0.05	0.80±0.34
t-test	*p-value*	n.s.	n.s.	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Cohen's d	<0.01	0.99	2.57	1.95	2.68	1.35	2.39

Table 2 shows the results for the maximum angle of knee flexion, maximum angle of ankle dorsiflexion, maximum angular velocity of knee extension, and maximum angular velocity of ankle plantar flexion. The HG exhibited a significantly higher maximum dorsiflexion angle in the ankle joint compared with the LG. Moreover, the maximum dorsiflexion angle in the ankle joint during plantar flexion was significantly greater in the HG than in the LG. There were no significant differences between the groups in the angular velocity of maximum knee extension. However, the angular velocity of maximum ankle plantar flexion was significantly higher in the LG than in the HG.

Table 2 Knee and ankle joint angles and angular velocities during the CMJ and RDJ

		Mean ± S.D.			t-test	
		HG (n=12)	LG (n=14)	All (n=26)	*p-value*	*Cohen's d*
CMJ	Maximum knee flexion angle (deg)	88.45±10.70	88.32±12.46	88.38±11.45	n.s.	0.01
	Maximum ankle dorsiflexion angle (deg)	72.73±5.00	70.91±6.54	71.75±5.84	n.s.	0.31
	Maximum knee extension angular vel. (deg/s)	1085.08±128.77	1017.77±134.26	1048.84±133.57	n.s.	0.51
	Maximum ankle plantar flexion angular vel. (deg/s)	1074.68±137.69	1076.41±193.57	1075.61±166.81	n.s.	0.01
RDJ	Maximum knee flexion angle (deg)	100.75±14.28	87.72±8.68	93.73±13.15	< 0.01	1.12
	Maximum ankle dorsiflexion angle (deg)	82.80±7.68	75.29±4.73	78.75±7.22	< 0.01	1.20
	Maximum knee extension angular vel. (deg/s)	1038.05±143.83	1037.90±150.32	1037.97±144.41	n.s.	< 0.01
	Maximum ankle plantar flexion angular vel. (deg/s)	1078.76±147.18	1225.10±149.22	1157.56±163.23	<0.05	0.99

Table 3 shows the peak values of trunk extension torque, total torque of the three lower extremity joints, hip extension torque, knee extension torque, and ankle plantar flexion torque, as measured by the isokinetic dynamometer, as well as their respective percentages in the total torque of the three lower extremity joints. No significant differences were observed between the two groups in trunk extension torque and total torque of the three lower extremity joints. In both groups, the values for trunk extension torque were higher than those for the total torque of the three lower extremity joints. Peak hip joint extension torque was significantly greater in the HG than in the LG, while knee extension torque did not exhibit any significant differences between the groups. Moreover, ankle plantar flexion torque tended to have significantly higher peak values in the HG compared with the LG.

Regarding the percentage of total torque of the three lower extremity joints, there were no significant differences between the groups in the percentage of total torque of the hip and ankle joints. However, the LG exhibited significantly greater torque at the knee joint compared with the HG.

Table 3 Peak torques of the trunk and lower limb extensors and percentage of total torque of the three lower limb joints

		Mean ± S.D.			t-test	
		HG (n=12)	LG (n=14)	All (n=26)	*p-value*	*Cohen's d*
Peak torque (Nm/kg)	Trunk extension torque	2.64±1.15	2.32±0.85	2.47±0.99	n.s.	0.33
	Total torque of 3 lower limb joints	2.04±0.73	1.72±0.35	1.87±0.57	n.s.	0.54
	Hip extension torque	0.83±0.24	0.66±0.13	0.74±0.20	< 0.05	0.84
	Knee extension torque	0.66±0.34	0.68±0.22	0.67±0.28	n.s.	0.10
	Ankle plantar flexion torque	0.56±0.28	0.38±0.19	0.46±0.25	<0.1	0.76
Percentage of each joint (%)	Hip extension torque	43.38±12.81	39.33±9.46	41.20±11.09	n.s.	0.36
	Knee extension torque	30.05±11.41	39.20±7.78	34.98±10.51	< 0.05	0.95
	Ankle plantar flexion torque	26.58±7.26	21.47±9.06	23.83±8.52	n.s.	0.62

Table 4 shows the correlation coefficients between the jump index and joint angles and the angular velocities in the RDJ. There were significant correlations observed between the CMJ jump height and the RDJ-index for the second half of the ground contact time as well as the total ground contact time. Furthermore, a significant correlation was observed between the jump height and the RDJ-index for the first half of the ground contact time, the second half of the ground contact time, and the total ground contact time. The results also indicated a significant negative correlation of the RDJ ground contact time with the maximum knee flexion angle and maximum ankle dorsiflexion angle. Specifically, the ground contact time tended to be shorter when the maximum knee joint flexion angle was higher in extension and the maximum ankle dorsiflexion angle was higher in plantar flexion. In addition, both the first half of the ground contact time and the total ground contact time showed significant positive correlations with the maximum plantar flexion angular velocity of the ankle joint. The jump height exhibited a significant positive correlation with the maximum angular velocity of knee joint extension. Furthermore, the RDJ-index showed a positive correlation with both the maximum knee joint flexion angle and the maximum ankle dorsiflexion angle.

Table 4 Correlation coefficients between jump index and joint angle or joint angular velocity during the RDJ

			Contact time (s)			Jump height	RDJ RDJ-index	Joint angle (deg)		Joint angular vel. (deg/s)	
			1st-half	2nd-half	Total	(m)	(m/s)	Knee	Ankle	Knee	Ankle
CMJ	Jump height (m)		-0.28	-0.51＊	-0.44＊	0.89＊	0.57＊	—	—	—	—
RDJ	Contact time (s)	1st-half	—	0.71＊	0.91＊	-0.29	-0.83＊	-0.81＊	-0.55＊	0.25	0.40＊
		2nd-half	—	—	0.94＊	-0.49＊	-0.83＊	-0.57＊	-0.40＊	0.08	0.30
		Total	—	—	—	-0.43＊	-0.90＊	-0.73＊	-0.50＊	0.17	0.37†
	Jump height (m)		—	—	—	—	0.66＊	-0.04	0.22	0.60＊	0.14
	RDJ-index (m/s)		—	—	—	—	—	0.67＊	0.61＊	-0.02	-0.19

† p<0.1, ＊p<0.05

Table 5 shows the correlation coefficients between the jump index and muscle strength of the trunk and lower limbs. The percentage of hip joints among the three lower limb joints exhibited a significantly negative correlation with the jump index, whereas the percentage of knee joints showed a significant positive correlation. Moreover, a significant positive correlation was observed between the peak value of trunk extension torque and the RDJ-index, whereas a significant negative correlation was found between the peak value of hip extension torque and the RDJ-index. In addition, a significant positive correlation was detected between the RDJ-index and peak hip extension torque.

Table 5 Correlation coefficients between jump index and isokinetic strength of trunk and lower limb extensors

			Peak torque (Nm/kg)					Percentage of each joint (%)		
			Trunk	Lower limb	Hip	Knee	Ankle	Hip	Knee	Ankle
CMJ	Jump height (m)		0.17	0.06	0.14	-0.12	0.16	0.21	-0.32	0.13
RDJ	Contact time (s)	1st-half	-0.08	-0.07	-0.38†	0.25	-0.14	-0.37†	0.54＊	-0.19
		2nd-half	-0.27	-0.03	-0.36†	0.11	0.09	-0.38†	0.26	0.16
		Total	-0.20	-0.06	-0.40†	0.19	-0.01	-0.40＊	0.42＊	0.00
	Jump height (m)		0.39†	0.29	0.29	0.09	0.31	0.09	-0.22	0.16
	RDJ-index (m/s)		0.34	0.18	0.45＊	-0.08	0.13	0.32	-0.39†	0.07

† $p<0.1$, ＊$p<0.05$

Discussion

1. Validity of the participant classification

Compared with the LG, the HG exhibited significantly higher CMJ jump height and significantly shorter ground contact time as well as higher RDJ jump height, resulting in a significantly higher RDJ-index, as shown in Table 1. These findings are consistent with a previous study by Zushi and Takamatsu (1995a), in which RDJ was performed from a height of 30 cm. In addition, our study revealed a significant positive correlation of CMJ jump height with both RDJ jump height and RDJ-index, as shown in Table 4. Therefore, the HG in our study demonstrated superior jumping ability compared with the LG, in both low-intensity SSC exercises (e.g., CMJ), which require a longer contact time, and ballistic SSC exercises (e.g., RDJ), which require explosive force exertion in a very short period of time.

2. Association between jumping ability and the muscular performance of the trunk and lower limb extensors

First, we investigated the factors that led to the HG being able to perform RDJ in a shorter duration. The HG demonstrated a significantly greater maximum knee joint flexion angle in extension and a significantly greater maximum ankle joint dorsiflexion angle in plantar flexion compared with the LG (Table 2). In addition, the RDJ-index of the HG was observed to be relatively shorter than that of the LG in the first half, second half, and total duration, when the maximum knee joint flexion angle was in extension and the maximum ankle dorsiflexion angle was in plantar flexion (Table 4). As shown in Fig. 3, the HG also exhibited a lower overall lower limb sinkage compared with the LG, which might have contributed to the shorter RDJ duration.

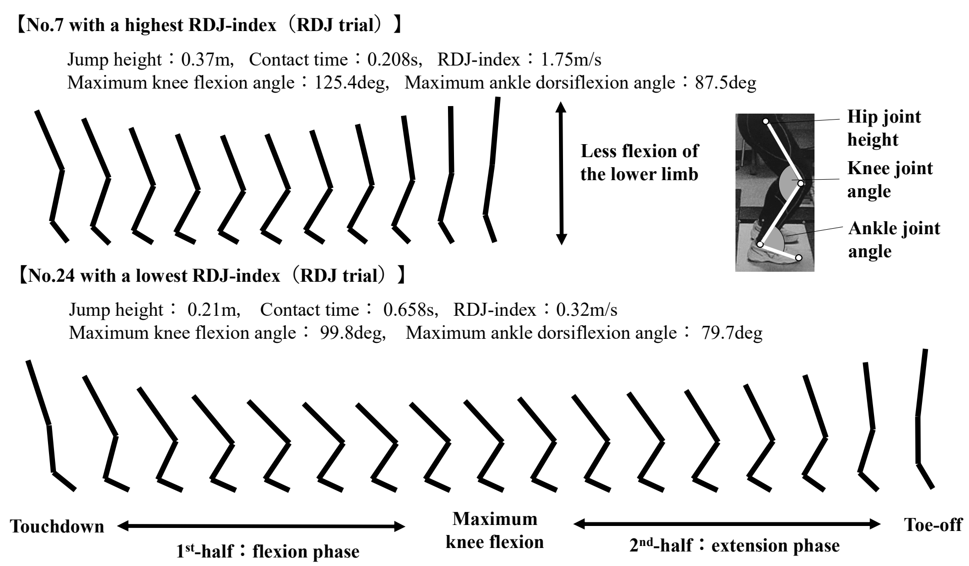

Fig. 3 Comparison of jumping motion in typical participants with the highest and lowest RDJ-index

Nakamata et al. (2014) reported that athletes with a higher hip joint height at the point where the entire lower limb transitions from a sinking motion to an extending motion, specifically at maximum knee joint flexion, tend to achieve higher jump heights in subsequent years. Similarly, Kigoshi et al. (2004) noted that the higher group with superior jumping ability is characterized by minimal angular displacement of the knee joint angle of flexion and lower limb sinking. Additionally, Sakuma et al. (2009) stated that landing with the smallest possible maximum dorsiflexion angle and jumping in a way that the ankle joint switches to plantar flexion before the knee joint enables efficient utilization of the SSC for RDJ. To enhance the RDJ-index, it is necessary to reduce ground contact time or obtain a high jump height. The above-mentioned studies suggest that minimizing sinking of the entire lower limb is advantageous for achieving a higher jump height. Thus, it is proposed that minimizing the sinking of the entire lower limb, as observed in the HG, may have allowed for not only shorter RDJ execution time but also higher jump heights.

Second, we explored the reasons why individuals with higher jumping ability (i.e., HG) exhibit less sinking of their lower limbs. Specifically, we focused on the results obtained from muscle strength measurements. In this study, an isometric dynamometer was used to measure the peak value of ankle plantar flexion torque and the strength of the trunk and three lower limb joints. The results showed that the HG exhibited a tendency towards a significantly higher peak value of ankle plantar flexion torque compared with the LG, with a moderate effect size (Table 3). Meanwhile, the knee joint accounted for a significantly larger percentage of the total torque in the LG than in the HG (Table 3). These findings suggest that the HG has an advantage in generating force through ankle plantar flexion muscles, while the LG has an advantage in generating force through knee extensors. Although no significant correlation was found between ground contact time and peak values of knee joint extension torque or ankle plantar flexion torque, there was a trend observed in which ground contact time increased as the percentage of knee joint torque relative to the total torque of the three lower limb joints increased (Table 5). Zushi and Takamatsu (1995b) reported that the relative mechanical work of the ankle joint was greater than that of the knee joint or hip joint in RDJ. Takamatsu et al. (1989) also reported that in RDJ using relatively shallow knee flexion movements from a 30-cm platform height, the mobilization of the muscle groups involved in the ankle joint was greater than that of the hip and knee joints. However, in RDJ using relatively deep knee flexion movements with increased CMJ and platform height, the mobilization of the muscle groups involved in the hip and knee joints was relatively large. Similarly, Ae et al. (1994) reported that the ankle plantar flexor and knee extensor muscle groups were responsible for cushioning during landing in CMJ and RDJ with a low platform height, while the hip extensor muscle group became more mobilized as the platform height increased.

In this study, RDJ was performed from a 30-cm platform height, which is considered to have a relatively low load. Therefore, it is thought that the mobilization of the ankle plantar flexor muscle group was relatively high in the case of athletes with excellent jumping ability. These findings suggest that HG athletes are superior in demonstrating the muscle strength of the plantar flexors of the ankle joint and can perform the cushioning action after landing under the leadership of the ankle joint, while LG athletes are inferior in demonstrating the muscle strength of the plantar flexors of the ankle joint and may already have performed the cushioning action after landing under the leadership of the knee joint from the 30-cm height. This suggests the possibility that the knee joint is already leading the cushioning motion after landing from the 30-cm height. The present findings indicate the potential for the knee joint to initiate cushioning motion following landing, possibly through increased flexion of the knee joint from a 30-cm height. It is possible that ankle-joint-driven jumping, as observed in the HG, may facilitate more efficient execution of the RDJ with reduced sinking of the lower limb. Previous research by Tanaka et al. (2006) demonstrated that 2 months of ankle plantar dorsiflexion training can improve peak ankle plantar flexion torque and CMJ jump height. Although the study by Tanaka et al. (2006) examined only the association between peak ankle plantar flexion torque and CMJ jump height, the present study suggests that muscle strength of the ankle plantar flexor group and a relative increase in the contribution of the ankle joint to the total torque of the three lower limb joints may result in an ankle-joint-driven jump, similar to the jumping pattern observed in HG. The present findings suggest that an increase in ankle plantar flexor muscle group strength and the relative contribution of the ankle joint to the total torque of the three lower limb joints may lead to a less pronounced sinking of the lower limb during jumping.

The analysis of the differences in muscle force exerted by the trunk and lower limb extensor muscle groups, which was the original focus of this study, revealed that the peak value of hip joint extension torque was significantly greater in the HG than in the LG. Although there were no significant differences, it was also evident that the values of trunk extension torque were greater than the total torque of the three lower extremity joints in both groups, and that the hip joint accounted for a larger percentage of the total torque of the three lower extremity joints (Table 3). Moreover, a significant positive correlation trend was found between RDJ-jump height and peak values of trunk extension torque, and between RDJ-index and peak values of hip extension torque (Table 5). These results, coupled with the fact that the trunk and hip joints are capable of exerting large torque and power due to their possession of the largest muscle groups in the body, suggest that these joints play a pivotal role in the acquisition of CMJ and RDJ jump height. In recent years, several studies have investigated the functions of the trunk and the three lower limb joints in the acquisition of jump height during the jumping motion using the dynamic analysis. For instance, Koike et al. (2006) found that the hip extension torque immediately after ground contact, knee extension torque in the middle of the step-off, and ankle plantar flexion torque during most of the second half of the step-off contributed to the vertical velocity of the body center of gravity (COG) during a single leg jump test with a running aid. Suzuki et al. (2018) discovered that the ankle joints generated most of the vertical body COG velocity, the ankle joints generated most of the forward horizontal body COG velocity, and the knee joints generated most of the backward horizontal body COG velocity during the dynamic analysis of forward, upward, and backward jumping movements, respectively. In addition, Murata et al. (2020) investigated the contribution of each joint torque to the control of whole-body momentum and angular momentum in CMJ and found that ankle and knee joint torques are responsible for the acquisition of whole-body upward momentum, while the hip and trunk virtual joint torques are adjusted to correctly raise the torso in the vertical direction. Although no studies involving the dynamic analysis of RDJ have been conducted so far, similar results have been obtained in various jumping movements, suggesting that the main functions of the trunk and three lower limb joints in CMJ and RDJ are not significantly different. In other words, the trunk and hip extensor muscle groups in CMJ and RDJ are responsible mainly for stabilizing the upper body and correctly transferring the upward momentum acquired by the knee and ankle joints to the vertical plane, indirectly contributing to the acquisition of jump height. The present study newly suggests that superior isokinetic muscle strength of the trunk and hip extensor muscle groups, as in the HG, and resistance training of these muscle groups, as in the LG, may be advantageous for the acquisition of jump height in CMJ and RDJ among athletes with poor jumping ability. Finally, potential areas for future research are outlined. This study focused solely on female university athletes with limited sport-specific characteristics, such as sprinting and jumping events in track and field or volleyball, and measured only CMJ and RDJ at a height of 30 cm as well as muscle force during concentric contraction. Additionally, the study did not explore the association with each muscle group's function during jumping using inverse dynamics methods. Therefore, in the future, it is recommended to examine female athletes from various sports, investigate the association with RDJ using multiple platform heights, investigate the association with muscle force exertion under various angular velocity conditions during both concentric and eccentric. contractions, and explore the contribution of mechanical work and each joint torque to the vertical velocity of the body's COG during the leap. In conclusion, it is essential to investigate the association between mechanical work and the contribution of each joint torque to the vertical velocity of the body's COG during jumping.

Conclusions

This study aimed to establish a correlation between jumping ability and the isokinetic strength of the trunk and lower limb extensors in female university athletes and to provide recommendations for improving jumping ability. The mean value of the RDJ-index from all 26 participants was utilized as a benchmark for classifying them into two categories: the HG (n=12) and the LG (n=14). The results of the present study are outlined below.

1) The HG exhibited significantly greater heights in CMJ and RDJ, along with a higher RDJ-index and a notably shorter contact time compared with the LG, indicating superior jumping ability for both low-intensity and ballistic stretch-shortening cycle exercises.

2) In the RDJ, the HG demonstrated significantly higher maximum knee flexion and ankle dorsiflexion angles compared with the LG, indicating an ankle-joint-driven jumping motion with less sinking of the entire lower limb.

3) The HG tended to display significantly higher peak ankle plantar flexion torque and peak hip extension torques compared with the LG. In contrast, the LG exhibited a significantly greater ratio of knee joint torque to the total torque of the three lower limb joints compared with the HG.

4) Maximum knee flexion and ankle dorsiflexion angles exhibited significant negative correlations with RDJ contact time and positive correlations with RDJ-index.

5) Significant positive correlations were observed between RDJ jump height and peak trunk extension torque, as well as between RDJ-index and peak hip extension torque.

The findings of this study suggest that the enhancement of ankle flexor muscle group strength and the ratio of ankle joint torque to the total torque of the three lower limb joints, as observed in the HG, leads to a shorter ankle-joint-driven jump with reduced sinking of the entire lower limb and a decreased ground contact time. The findings also indicate that having superior isokinetic muscle force exertion of the trunk and hip extensor muscle groups, as in the HG, and performing resistance training on these muscle groups might be advantageous in improving CMJ and RDJ jump height in athletes with poor jumping ability, primarily by enhancing the capacity to stabilize the upper body.

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