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ORIGINAL

Analysis of Kinematics and Kinetics According to Skill Level and Sex in Double-under Jump Rope Technique

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Objective: The purpose of this study was to perform a kinematic and kinetic analysis of double-under jump rope technique according to skill level and sex.

Method: Participants comprised a skilled group of 16 (9 males, 7 females), and an unskilled group of 16 with 6 months or less of experience (9 males, 7 females). Five consecutive double-under successes were regarded as 1 trial, and all participants were asked to complete 3 successful trials. The data for these 3 trials were averaged and analyzed after collecting the stable third jump in each trial. The variables used in the analysis included phase duration, total duration, flight time, vertical toe height, stance width, vertical center of mass displacement, and right lower limb ankle, knee, and hip joint angles in the sagittal plane during all events.

Results: The skilled group had a shorter phase and total duration and a shorter flight time than the unskilled group. The vertical center of mass displacement and ankle dorsiflexion angle were significantly smaller in the skilled group. The male group had a shorter phase duration than the female group. The vertical toe height was greater, the stance width was smaller, and the ankle and hip flexion angles were smaller in the male group.

Conclusion: Variables that can be used to distinguish between skill levels are phase and total duration, flight time, vertical center of mass displacement, and ankle dorsiflexion angle. Differences between sexes in double-under jump rope technique may be related to lower limb flexion angle control.

Keywords: Double-under, Jump rope, Biomechanics, Stance width, Motion capture, Plyometric training

INTRODUCTION

Jump rope is a sport in which players jump over a rope while swinging the rope with their upper body and hands to pass it under their feet and over their heads (Miyaguchi, Demura & Omoya, 2015), and is one of the most effective aerobic exercises for cardiorespiratory health (Jones, Squires & Rodahl, 1962). Neuromuscular coordination is essential for accurate timing and maintenance of rhythm, which are critical for effective jump rope performance, and good neuromuscular coordination improves dynamic stability while performing jump rope (Ozer, Duzgun, Baltaci, Garacan & Colakoglu, 2011). Furthermore, jump rope effectively enhances muscle strength, endurance, balance, explosive power, speed, cardiopulmonary endurance, and flexibility, and is therefore used as a warm-up exercise and training program in various sports (Hawkins & Kennedy, 1980; Orhan, 2013; Solis & Thompson, 1988; Trampas & Kitisios, 2006). Jump rope is an essential component of professional training programs designed to enhance athletic performance by elite junior athletes, and several studies have reported beneficial effects on physical fitness, growth, and development in these athletes (Baker, Côté & Abernethy, 2003; Miyaguchi, Sugiura & Demura, 2014).

Elite athletes often use plyometric training programs with box jumps or hurdle jumps to improve explosive power and jump performance (Komi, 1984). However, these training programs inflict a heavy load on elite junior athletes who are still undergoing physical development, and increase their risk of injury (Komori, Zushi, Konishi & Komori, 2012). For this reason, it is important to develop alternative training programs that offer effective training with a relatively low risk of injury. Jump rope is one such alternative. Jump rope has the properties of plyometric exercise, as the sport involves repeated contractions and extensions of the quadriceps femoris, gastrocnemius, and soleus muscles, thereby improving explosive power and jumping ability (Komi, 1984; Norman & Komi, 1979; Miyaguchi et al., 2014, 2015). Accordingly, jump rope is utilized in training programs for a variety of other sports, such as volleyball, basketball, soccer, gymnastics, rhythmic gymnastics, boxing, wrestling, tennis, and martial arts (Ozer et al., 2011; Trecroci, Cavaggioni, Caccia & Alberti, 2015).

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In addition to its use in training programs, jump rope is becoming a competitive sport. The first World Jump Rope Championship was held in in 1997, and about 1,200 athletes from 21 countries competed in the 2014 World Championship (International Rope Skipping Federation, 2016), while about 1,500 athletes competed in the 2015 Korean National Jump Rope Competition (Korea Rope Skipping Association, 2016). Among various jump rope skills, double under is a technique in which the jumper passes the rope twice per jump. It is one of the major events in jump rope competitions, in which athletes compete based on the number of double unders performed in 30 seconds (Korea Rope Skipping Association, 2016; Miyaguchi et al., 2014). Double-under technique is performed in competition in kindergarten, elementary, middle, and high school, and adult levels (Korea Rope Skipping Association, 2016).

Despite rapid advances in the sport, studies on jump rope are largely limited to physiological aspects (Baker, 1968; Baker, Côté & Abernethy, 2003; Jette, Mongeon & Routhier, 1979; Miyaguchi et al., 2014; Quirk & Sinning, 1981; Town, Sol & Sinning, 1980) and training methods and effects (Buyze et al., 1986; Hatfield et al., 1985; Hawkins & Kennedy, 1980; Myles, Dick & Jantti, 1981; Orhan, 2013; Solis & Thompson, 1988; Trampas & Kitisios, 2006). A few researchers have analyzed the properties of jump rope movement. Gowitzke and Brown (1989) analyzed the kinetic variables of alternating foot exercise in skilled and unskilled groups and reported that novice jumpers have a larger wrist joint rotation radius, greater knee and hip flexion, and greater center of mass variability while performing alternating foot exercise, compared to skilled jumpers. Pittenger, McCaw and Thomas (2002) found that the peak vertical ground reaction force (GRF) during the 1-foot jump is greater than that during the 2-feet jump. Kim and Kim (2015) investigated the kinetic differences between a 2-feet jump and a 2-feet double jump (double under) among male jump rope coaches and reported that the 2-feet double jump is associated with greater center of mass displacement, lower limb joint range of motion, and vertical GRF compared to the 2-feet jump.

Studies that analyzed the properties of basic jump rope movements focused on kinetic and kinematic aspects, and few studies examined skills and movements related to jump rope performance. Furthermore, double-under performance rapidly improves as middle school athletes move on to high school; this is a period in which the gap between male and female athletic skill levels and features increases (Kim & Oh, 2010, Korea Rope Skipping Association, 2016). Nevertheless, research data are lacking on differences in jump rope performance in relation to skills and sex in high school athletes. In this context, a study investigating differences in double-under performance in relation to sex and skill level in high school students would be relevant.

Thus, this study investigated kinetic and kinematic differences in double-under performance in relation to skill level and sex in high school students. The data collected can be used to improve double-under performance and coaching strategies. The authors hypothesized that the kinetic and kinematic features of double-under technique would vary according to jump rope skill level and sex.

METHODS

1. Participants

Male and female high school students with no orthopedic condition within the prior 6 months were enrolled in this study. The participants were divided into a skilled group (n=16, 9 males 7 females), comprising skilled jumpers who have won at least one national jump rope competition, and an unskilled group (n=16, 9 males 7 females), comprising students with a jump rope career of fewer than 6 months. Double under is a difficult skill to master, and previous studies have noted that at least 6 months of jump rope practice is needed to perform the technique. Therefore, the unskilled group comprised students with less than 6 months of jump rope experience who were nonetheless capable of performing 5 consecutive double-under jumps. This study was approved by the university Institutional Review Board, and informed consent was obtained from all participants and guardians prior to the experiment. During the study period, the participants were instructed to refrain from exercise programs and vigorous physical activities other than activities of daily living. The physical characteristics of the participants are shown in Table 1.

2. Procedure

An infrared camera (MX-T10, Vicon, UK) and ground force plate (AMTI OR6-7, Watertown, MA, US) were used for the experiment. Identical jump ropes and training shoes were used to ensure consistency of analysis. The experiment was conducted over 2 days. On the first day, consent forms were collected, physical characteristics were measured, environmental adaptation training, and double-under practice. On the second day, the participants performed adequate warm-up stretching,

Table 1. Physical characteristics

		Age (y)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Career (y)
Skilled (n=16)	Male (n=9)	17.6±0.9	170.6±6.9	65.6±6.8	22.5±1.6	3.7±1.0
	Female (n=7)	17.5±0.6	160.1±4.7	54.7±10.9	21.3±4.0	4.3±0.6
Unskilled (n=16)	Male (n=9)	17.6±0.7	170.8±5.6	61.6±7.9	21.1±4.0	0.5±0.1*
	Female (n=7)	17.4±0.5	158.5±5.3	50.8±3.3	20.2±1.5	0.6±0.1*

BMI: Body mass index, independent sample *t*-test comparing skilled and unskilled groups, *p<.05

2-feet jumps, and double-under technique to prevent injuries and enable completion of the main double-under event. Nine cameras for motion analysis and 1 force platform were installed in an area with adequate field of view. With reference to left posterior direction from the participant, the left and right directions were set as the X axis, the anterior and posterior directions as the Y axis, and the vertical direction as the Z axis (Figure 1).

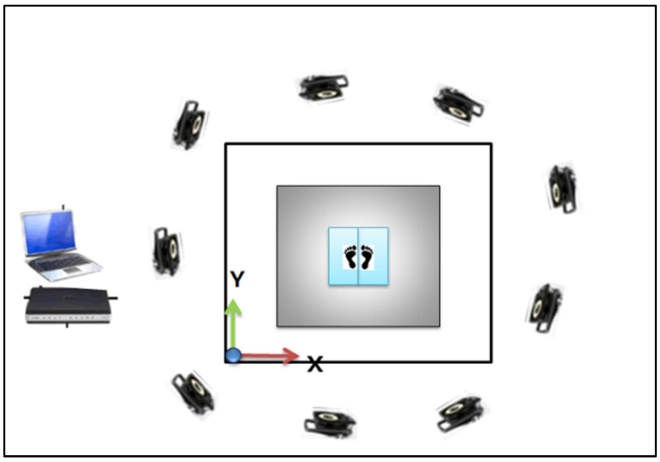

Figure 1. Experimental setup

All participants wore T-shirts and shorts made of spandex material and wore designated training shoes. Heights and weights were measured with a body composition analyzer (GL-150KT, G-TECH, Korea), and the measurements were used to calculate BMI. Shoulder width, elbow width, wrist width, hand thickness, leg length, knee width, and ankle width were measured with a tape measure and caliper to develop body models. Body models were created using the Vicon Plug-in Gait full-body model, with 39 round spherical reflective markers placed on the participant and 1 reflective tape at the mid-point of the jump rope (length: 2.7 m, mass: 120 g) (Figure 2). All reflective markers were placed firmly using double-sided tape and athletic tape to prevent displacement during jumping.

3. Data processing

Image and GRF data for double-under motion were collected with Nexus software (Vicon, UK), at a sampling frequency of 200 Hz for image data and 1,000 Hz for GRF data. The collected data were filtered using a Butterworth low-pass filter with a cut-off frequency of 10 Hz (Decker et al., 2003; Pappas, Sheikhzadeh, Hagins & Nordin, 2007). Five consecutive double-under jumps were regarded as 1 successful trial, and the participants were asked to perform 3 successful trials. The data from the stable third jump in each trial were collected, and the average of the 3 trials was computed for analysis.

Double-under motion was analyzed by dividing the motion into 5 events (E1, E2, E3, E4, E5) and 4 phases (P1, P2, P3, P4). E1 was defined as the point at which the feet contact the ground (when vertical GRF

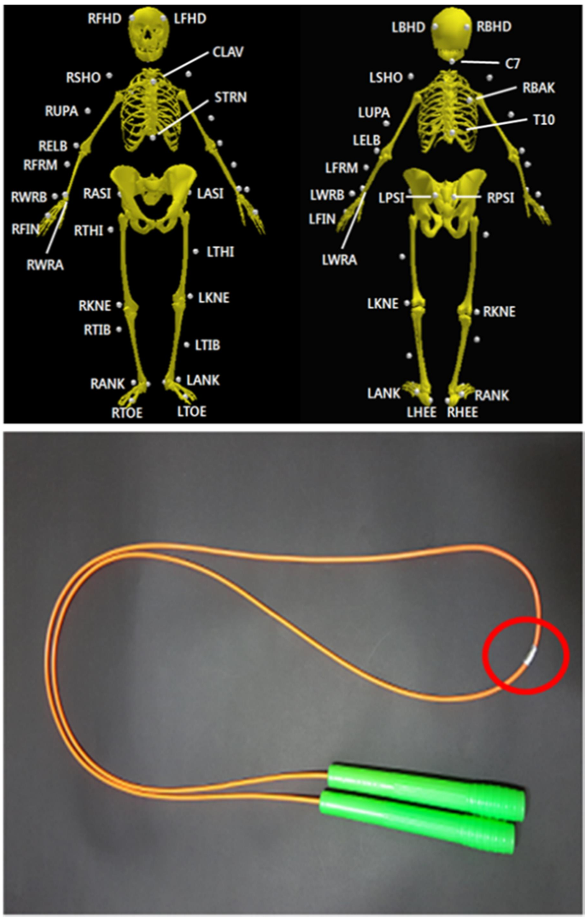

Figure 2. Marker set. Top: Plug-in Gait full-body model; Bottom: jump rope with attached reflective tape

exceeds 10 N), and E2 was defined as the point at which the vertical GRF reaches peak. E3 was defined as the point at which the feet left the force plate (when vertical GRF is less than 10 N), and E4 was defined as the point at which the center of body mass reached a vertical peak. E5 was defined as equal to E1. Phases were defined as the intervals between corresponding events (Figure 3).

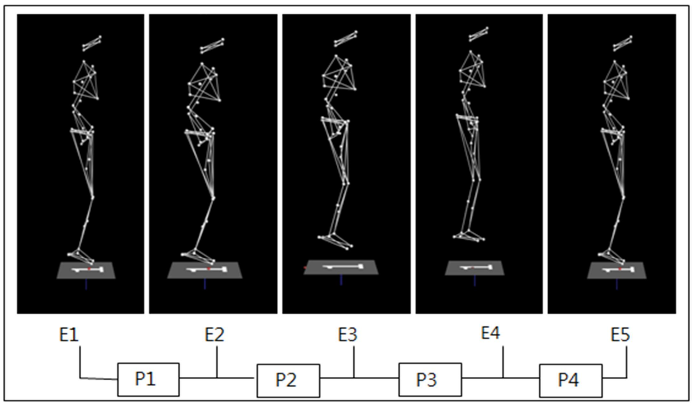

Figure 3. Events and phases

Table 2. Phase and total duration (Unit: s)

		Male	Female	*t*	*F*
P1	Skilled	0.10±0.01	0.11±0.01	1.809	6.539* (G)
	Unskilled	0.11±0.01	0.12±0.01	1.841	5.466* (S)
	t	1.349	2.104		0.153 (G×S)
P2	Skilled	0.10±0.00	0.11±0.01	4.059*	21.002* (G)
	Unskilled	0.11±0.01	0.12±0.01	2.696*	4.093 (S)
	t	1.828	1.100		0.063 (G×S)
P3	Skilled	0.13±0.02	0.13±0.02	0.885	0.690 (G)
	Unskilled	0.15±0.01	0.15±0.01	0.233	13.211* (S)
	t	2.207*	3.053*		0.285 (G×S)
P4	Skilled	0.16±0.02	0.15±0.02	0.664	1.098 (G)
	Unskilled	0.18±0.02	0.17±0.01	0.813	7.946* (S)
	t	1.978	2.266*		0.023 (G×S)
Total duration	Skilled	0.50±0.04	0.51±0.04	0.328	0.540/ (G)
	Unskilled	0.55±0.03	0.56±0.02	0.828	15.783* (S)
	t	2.812*	2.841*		0.036 (G×S)

All data are shown as means and standard deviations. *t*: independent *t*-test comparing skilled and unskilled and male and female groups; P1: phase 1, P2: phase 2, P3: phase 3, P4: phase 4, G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p<.05$

The kinematic variables for analysis were phase duration, total duration, flight time, vertical toe height, stance width, vertical displacement of the center of mass, and right hip, knee, and ankle angles in the sagittal plane for each event. The kinetic variables for analysis were peak vertical ground reaction force (VGRF) and load at P1 (peak VGRF/time from ground contact to peak VGRF).

4. Statistical analysis

The means and standard variations for each variable were calculated using SPSS software (version 21.0; SPSS. Inc., Chicago, IL, USA), and normality of each variable was tested with the Shapiro-Wilk test. Main effects and the interaction effect of skill and sex were assessed using repeated-measures 2-way analysis of variance. An independent sample *t*-test was performed as post hoc analysis for skill and sex. Statistical significance (α) was set at .05.

RESULTS

1. Phase duration, total duration

There was a significant main effect of sex on P2 duration ($p<.000$). Post hoc testing showed that the male group had a shorter P2 than the female group in both the skilled ($p=.001$) and unskilled ($p=.017$) groups. There was a main effect of skill on P3 ($p=.001$). Post hoc testing showed that the skilled group had a shorter P3 than the unskilled group in both male ($p=.042$) and female ($p=.010$) groups. There was a significant main effect of skill on P4 duration ($p=.009$). Post hoc testing showed that the skilled group had a shorter P4 than the unskilled group in the female group ($p=.043$).

There was a significant main effect of skill on total duration ($p<.000$). Post hoc testing showed that the skilled group had a shorter total duration than the unskilled group in both male ($p=.013$) and female ($p=.015$) groups (Table 2).

2. Flight time

There was a significant main effect of skill on flight time ($p<.000$). Post hoc testing showed that the skilled group had a shorter flight time than the unskilled group in both male ($p=.015$) and female ($p=.003$) groups (Table 3).

Table 3. Flight time (Unit: s)

	Male	Female	*t*	*F*
Skilled	0.10±0.01	0.11±0.01	1.809	6.539* (G)
Unskilled	0.11±0.01	0.12±0.01	1.841	5.466* (S)
t	1.349	2.104		0.153 (G×S)

All data are shown as means and standard deviations. *t*: independent *t*-test comparing skilled and unskilled and male and female groups; G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p<.05$

Table 4. Vertical toe height (Unit: cm)

		Male	Female	*t*	*F*
Left toe	Skilled	21.04±4.05	16.38±4.19	2.253*	8.803* (G)
	Unskilled	25.07±5.37	20.33±3.80	1.975	6.339* (S)
	t	1.797	1.848		0.001 (G×S)
Right toe	Skilled	21.84±4.43	16.88±4.20	2.275*	12.227* (G)
	Unskilled	26.30±4.76	20.21±4.21	2.663*	6.085* (S)
	t	2.055	1.486		0.124 (G×S)

All data are shown as means and standard deviations. *t*: Independent *t*-test comparing skilled and unskilled and male and female groups; G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p<.05$

Table 5. Stance width (Unit: cm)

		Male	Female	*t*	*F*
	Skilled	5.19±2.30	7.79±4.02	1.635	0.063 (G)
E2	Unskilled	6.79±3.08	4.71±2.06	1.529	0.500 (S)
	t	1.246	1.802		5.002* (G×S)
	Skilled	3.98±1.75	5.89±1.20	2.472*	4.693* (G)
E4	Unskilled	3.99±1.14	5.01±3.09	0.916	0.409 (S)
	t	0.025	0.704		0.442 (G×S)

All data are shown as means and standard deviations. *t*: independent *t*-test comparing skilled and unskilled and male and female groups; G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p<.05$

3. Vertical toe height

Main effects of sex ($p=.006$) and skill ($p=.018$) on vertical left toe height were observed. Post hoc testing showed that male students had significantly greater vertical left toe height compared with female students in the skilled ($p=.041$) group. Significant main effects of sex ($p=.002$) and skill ($p=.020$) on vertical right toe height were observed. Post hoc testing showed that male students had significantly greater vertical right toe height compared with female students in both the skilled ($p=.039$) and unskilled ($p=.019$) groups (Table 4).

4. Stance width

There was a significant main effect of sex on stance width at E4 ($p=.039$). Post hoc testing showed that male students had a significantly narrower stance width than female students in the skilled group ($p=.027$) (Table 5).

5. Vertical center of mass displacement

There was a significant main effect of skill on vertical center of mass displacement ($p<.000$). Post hoc testing showed that the skilled group had significantly smaller vertical center of mass displacement compared with the unskilled group in both male ($p=.012$) and female ($p=.018$) students (Table 6).

Table 6. Vertical center of mass displacement (Unit: cm)

	Male	Female	*t*	*F*
Skilled	23.36±3.80	23.02±4.52	0.164	0.000 (G)
Unskilled	28.20±3.45	28.50±2.73	0.194	15.520* (S)
t	2.825*	2.748*		0.062 (G×S)

All data are shown as means and standard deviations. *t*: Independent *t*-test comparing skilled and unskilled and male and female groups; G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p<.05$

6. Lower limb joint angles in the sagittal plane

There was a significant main effect of sex on the hip angle at E1 ($p=.011$). Post hoc testing showed that male students had a significantly smaller hip flexion angle at E1 compared with female students in the skilled group ($p=.022$). There was a significant main effect of sex on the hip angle at E2 ($p<.000$). Post hoc testing showed that male students had a significantly smaller hip angle at E2 compared with female students in both the skilled ($p<.000$) and unskilled ($p=.015$)

Table 7. Right hip angle in sagittal plane (Unit: °)

		Male	Female	*t*	*F*
E1	Skilled	15.45±5.58	23.22±6.50	2.572*	7.331* (G)
	Unskilled	15.95±6.42	20.94±8.08	1.380	0.141 (S)
	t	0.178	0.580		0.348 (G×S)
E2	Skilled	15.01±6.04	28.49±4.09	5.054*	23.781* (G)
	Unskilled	16.92±9.16	30.30±10.08	2.777*	0.455 (S)
	t	0.521	0.440		0.000 (G×S)
E3	Skilled	13.50±4.35	16.81±6.21	1.255	1.373 (G)
	Unskilled	11.67±6.11	13.52±8.00	0.525	1.353 (S)
	t	0.731	0.858		0.110 (G×S)
E4	Skilled	17.98±4.59	21.99±10.96	0.999	1.752 (G)
	Unskilled	16.4±9.86	21.78±12.311	0.911	0.044 (S)
	t	0.340	0.033		0.023 (G×S)

All data are shown as means and standard deviations. Positive value is flexion, Negative value is extension, *t*: Independent *t*-test comparing skilled and unskilled and male and female groups; E1: event 1, E2: event 2, E3: event 3, E4: event 4, G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p < .05$

Table 8. Right ankle angle in the sagittal plane (Unit: °)

		Male	Female	*t*	*F*
E1	Skilled	3.89±8.61	1.55±11.75	1.070	0.017 (G)
	Unskilled	1.31±8.30	5.01±10.50	1.349	0.039 (S)
	t	1.304	1.102		2.895 (G×S)
E2	Skilled	16.85±6.60	25.86±5.38	2.929*	11.719* (G)
	Unskilled	24.80±5.19	29.47±4.90	1.831	8.344* (S)
	t	2.838*	1.33		1.174 (G×S)
E3	Skilled	15.22±7.29	12.29±11.25	0.633	1.684 (G)
	Unskilled	13.27±8.58	24.95±11.02	2.388*	2.521 (S)
	t	0.521	2.126		4.703* (G×S)
E4	Skilled	11.02±10.04	10.45±9.81	0.113	3.438 (G)
	Unskilled	14.48±9.04	0.60±17.74	2.221*	0.810 (S)
	t	0.768	1.443		2.958 (G×S)

All data are shown as means and standard deviations. Positive value is flexion, Negative value is extension, *t*: Independent *t*-test comparing skilled and unskilled and male and female groups; E1: event 1, E2: event 2, E3: event 3, E4: event 4, G: Main effect of sex, S: Main effect of group, G×S: Interaction effect, *$p < .05$

groups (Table 7).

There were no significant main effects or interaction effects on knee angles in the sagittal plane.

There was a significant main effect of sex ($p = .002$) and skill ($p = .007$) on ankle angle at E2. Post hoc testing showed that male students had significantly less dorsiflexion compared with female students in the skilled group ($p = .011$), and that the skilled group showed significantly lower dorsiflexion compared with the unskilled male group ($p = .012$). There was a significant sex and skill interaction effect on ankle angle at E3 ($p = .039$). Post hoc testing showed that male students showed significantly smaller dorsiflexion angles at E3 compared with female students in the unskilled group ($p = .032$) (Table 8).

Table 9. Kinetic variables

		Male	Female	*t*	*F*
PVGRF	Skilled	50.30±5.20	48.97±2.85	0.606	0.495 (G)
	Unskilled	50.19±8.33	48.63±4.35	0.450	0.012 (S)
	t	0.174	0.033		0.003 (G×S)
Loading rate	Skilled	485.80±68.41	442.18±42.86	1.471	3.445 (G)
	Unskilled	463.27±111.71	438.82±90.29	1.251	1.143 (S)
	t	0.516	1.550		0.052 (G×S)

All data are shown as means and standard deviations. Positive value is dorsiflexion, Negative value is plantarflexion, *t*: Independent *t*-test comparing skilled and unskilled and male and female groups; VGRF: Vertical ground reaction force, G: Main effect of sex, S: Main effect of group, G×S: Interaction effect

7. Peak vertical ground reaction force and loading rate

There were no significant main effects or interaction effects on peak VGRF and loading rate (Table 9).

DISCUSSION

This study analyzed the kinematic and kinetic characteristics of the double-under technique of jump rope according to skill level and sex. With regard to phase duration, total duration, and flight time according to skill level, male and female students in the skilled groups showed significantly shorter durations of P3, defined as the time from takeoff (E3) to the time at which the center of body mass reaches peak vertical height (E4), than the male and female students in the unskilled group. The female students in the skilled group showed significantly shorter P4, defined as the period from the point at which the center of body mass reaches peak vertical height (E4) to the point at which the feet contact the force plate (E5), than the female students in the unskilled group. In addition, the male and female students in the skilled group showed significantly shorter total duration and flight time than the male and female students in the unskilled group.

Because athletes compete in terms of the number of double-under jumps within a 30-second period, the recommended strategy for double under is to increase the number of jumps by shortening total duration and flight time as much as possible (Korea Rope Skipping Association, 2016; Miyaguchi et al., 2014). For this reason, the skilled group in this study is likely to have attempted to increase the number of jumps by shortening phase duration, total duration, and flight time. In other words, the skilled and unskilled groups differ in their double-under strategies, in that the former perform their motions as quickly as possible by maintaining low jumps, while the latter take relatively higher jumps than the former.

With regard to the differences in phase duration, total duration, and flight time according to sex, both skilled and unskilled male students showed significantly shorter P2, defined as the period from the peak VGRF (E2) to the point at which the feet take off from the force plate (E3), than skilled and unskilled female students. As shown here, male students in this study showed significantly shorter P2 (take off) in double under compared with female students, regardless of skill level, indicating that they use strategies for minimizing flight time as much as possible. Conversely, female students performed double unders with relatively longer flight times than males.

Skilled male students showed significantly higher vertical left toe height compared with skilled female students. Both skilled and unskilled male students showed significantly greater vertical right toe height compared with skilled and unskilled female students. The difference in vertical toe height according to sex is attributable to the difference in restriction of ankle flexion and extension at takeoff, which ultimately induces stiffer landing and affects overall jump rope performance (Pittenger et al., 2002). The male students in this study used a strategy that minimized anterior-posterior ankle movement by keeping the soles of the feet parallel to the ground as much as possible. This strategy increases the vertical toe height, which in turn reduces the duration of takeoff (P2).

With regard to skill level-specific vertical center of mass displacement, the skilled male and female students showed significantly smaller displacement compared with the unskilled male and female students. Gowitzke and Brown (1989) reported that novice jumpers show large vertical displacements when performing alternating foot exercise. Maintaining a consistent vertical center of mass contributes to preserving dynamic energy, ultimately increasing the efficiency of jump rope performance (Brancazio, 1984). The skilled group in this study maintained efficiency of jump rope performance by minimizing vertical center of mass displacement. Therefore, vertical center of mass displacement during a double under is believed to be a meaningful indicator of jump rope skill level, and strategies that maintain low jumps by minimizing vertical center of mass displacement are recommended for better performance.

Previous studies reported that the mean distance between the medial malleoli in an upright posture is about 9 cm (Murray, Seireg & Sepic, 1975; Perry & Burnfield, 2010), and the mean stance distance during walking in men and women is 7 cm and 8 cm, respectively (Murray, Drought & Kory, 1964; Murray, Kory & Sepic, 1970; Perry & Burnfield, 2010). These findings suggest that individuals increase the base of support in an upright posture to maintain static stability, while decreasing the base of support when walking to ensure dynamic stability and momentum (Shin, Youm & Son, 2013). In the present study, stance width at E2 (peak VGRF) of double under was 5.2 cm in skilled male students and 7.3 cm in skilled female students. Compared to the stance width in an upright posture found in a prior study (9 cm), these are about 42% and 13% narrower, respectively. Moreover, stance widthat E4 (point at which vertical center of mass reaches maximum) was 4.0 cm in skilled male students and 5.9 cm in skilled female students. Compared to the stance width in an upright posture, these are about 56% and 35% narrower, respectively. Motions such as landing after jumping require dynamic stability, and a lack of dynamic stability may lead to an injury (Wright, Arnold & Ross, 2016). In particular, jump rope is a sport that requires minimization of energy consumption while performing repeated motions. In this context, narrowing stance width during a double under would be beneficial for maintaining consistency of movement and increasing dynamic stability.

With regard to limb joint angles in the sagittal plane according to skill level, skilled male students showed significantly less ankle dorsiflexion at E2 (peak VGRF) compared with unskilled male students.

Jump rope features a stiff landing, in which the dorsiflexion range of motion of the ankle in the contact phase is controlled to limit ankle, knee, and hip flexion (Pittenger et al., 2002). Increasing the stiffness within an ideal range increases the stability of lower limb joints in the early contact phase, contributes to generating maximum energy at takeoff, and reduces the risk of injury (Butler, Crowell III & Davis, 2003). The skilled group in this study maintained ankle dorsiflexion not only at E2, when the VGRF reaches peak after landing, but also at E3, when the feet take off from the force plate; this increases the ankle joint stiffness, thereby improving the efficiency of double-under technique. Although both feet are used for takeoff and landing in a double under, maintaining ankle dorsiflexion is thought to improve double-under performance, and ankle dorsiflexion angle is deemed a meaningful indicator of jump rope skill level.

With regard to lower limb joint angles in the sagittal plane according to sex, the skilled male students showed significantly smaller hip angles at E1 (ground contact) compared with the skilled female students. At E2, when the GRF reaches peak, the skilled male students showed significantly less ankle dorsiflexion compared with the skilled female students. Furthermore, both the skilled and unskilled male students showed significantly less hip flexion compared with the skilled and unskilled female students. At E3, when the feet take off from the force plate, the unskilled male students showed significantly less ankle flexion compared with the unskilled female students. At E4, when the center of mass reaches peak vertical height, the unskilled male students showed significantly smaller ankle dorsiflexion compared with the unskilled female students. As shown here, compared with female students, male students restricted ankle and hip flexion more while performing a double under. These results suggest that male students use a strategy in which they increase lower limb stiffness by maintaining less lower limb joint flexion during a double under (Butler et al., 2003). Therefore, the sex-specific differences in the lower limb joint flexion angles during a double under are a result of the difference in strategies used to improve performance.

Load rate for landing is increased by high VGRF and reduced lower limb joint range of motion (Quatman, Ford Myer, & Hewett, 2006). Reduced ankle range of motion increases loading rate for landing, thereby heightening the risk of injury (De Ridder et al., 2015). In this study, there were no significant differences in peak VGRF and loading rate for P1 (landing phase); however, the loading rate tended to be higher in the skilled group compared with the unskilled group and in male students compared with female students. The higher loading rate in the skilled and male groups is thought to be the result of a strategy that maintains ankle dorsiflexion to improve double-under performance, but the effect of such high load rate on the risk of injury is unclear.

In summary, the skilled group employed a strategy in which they increased jump rope speed by reducing flight time and jump height as much as possible with dorsiflexed ankles during a double under. Based on these findings, double-under training programs should aim at training athletes to speed up rope rotations while maintaining low and fast jumps for better performance. Furthermore, we found that male students used strategies to minimize ankle and hip flexion by maintaining short flight time, while female students showed higher ankle and hip movement and greater flight time. Such differences in strategies have an impact on the stiffness of lower limb joints, and the appropriate flight time and lower limb joint movement for each sex should be identified to help athletes achieve optimal performance. Future studies should recruit a larger sample and investigate the associations between double-under performance and potential injury using variables such as joint stiffness, joint work, and joint contribution.

CONCLUSION

This study analyzed the kinematic and kinetic characteristics of double-under technique according to skill level and sex. The skilled group displayed significantly shorter phase duration, total duration, and flight time, and less vertical center of mass displacement compared with the unskilled group. Further, the skilled group maintained significantly less ankle dorsiflexion compared with the unskilled group. Skilled male students displayed significantly shorter takeoff, but a significantly greater left and right toe height at takeoff compared with the skilled female students. In addition, male students exhibited significantly smaller ankle, knee, and hip flexion angles during a double under compared with female students. In conclusion, phase duration, total duration, flight time, vertical center of mass displacement, and ankle dorsiflexion angle were found to be meaningful indicators of double-under skill level. Moreover, the control of lower limb joint flexion was found to be an indicator of sex-specific differences in double-under strategy. These findings may contribute to improving double-under performance and coaching strategies.

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