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ORIGINAL

Effects of Skill Level and Feet Width on Kinematic and Kinetic Variables during Jump Rope Single Under

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Objective: The purpose of this study was to analyze the effects of skill level and width between feet on kinematic and kinetic variables during jump rope single under with both feet.

Method: Fifteen subjects in the skilled group (age: 10.85±0.40 yrs, height: 142.13±5.41 cm, weight: 36.97±6.65 kg) and 15 subjects in the unskilled group (age: 10.85±0.40 yrs, height: 143.31±5.54 cm, weight: 40.81±10.39 kg) participated in this study.

Results: Participants in the skilled group minimized the anteroposterior displacement of their center of mass by modifying the width between their feet and decreased the range of motion (ROM) of their trunk in the sagittal plane. The preferred width during the jump rope decreased by 5.61~6.11 cm (32~37%) in comparison to width during static standing. The induced width was increased by 16.44~16.67 cm (82~85%), regardless of skill level. The kinematic variables of the left and right legs of members of the unskilled group were significantly different from those of members in the skilled group regarding the ROM of the hip, knee, and ankle joint. Otherwise, the members of the skilled group were consistent in terms of the kinematic variables of the right and left legs.

Conclusion: The preferred width between feet during the jump rope was found to be beneficial for maintaining dynamic stability. The unskilled group exhibited asymmetry in left and right motion within the ranges of motion of the ankle, knee, and hip joints, regardless of the width. Therefore, long-term accurate jump rope motions will contribute to an improvement in the left and right imbalances of the entire body.

Keywords: Jump, Kinematics, Kinetic, Feet width, Balance, Landing

INTRODUCTION

Rope jumping has long been practiced as a means of promoting health and fitness (Miyaguchi, Sugiura, & Demura, 2014) since it can easily be learned without special training and can be done almost anytime and anywhere (Miyaguchi, Demura, & Omoya, 2015; Orhan, 2013). A jump rope requires use of the upper limbs and hands to rotate the rope below the foot and above the head, while simultaneously performing a continuous jump of the two lower limbs (Gowitzke & Beown, 1989; Miyaguchi et al., 2015). In this way, it is a typical aerobic exercise that improves respiratory circulation (Chen & Lin, 2012; Gowitzke & Beown, 1989; Hatfield, Vaccaro, & Benedict, 1985; Jung, Lee, Hwang, & Song, 2009; Miyaguchi et al., 2015). Jump rope exercise has been reported to improve cardiorespiratory endurance, strength, muscle endurance, power, agility, bone health, coordination of neuromuscular techniques, and postural control (Arnett & Lutz, 2002; Hawkins & Kennedy, 1980; Miyaguchi et al., 2014; Miyaguchi et al., 2015; Ozer, Duzgun, Baltaci, & Colakoglu, 2011; Solis, 1988; Weeks, Young, & Beck, 2008; Wielligh, 2011).

In Korea, there are approximately 1,100 jump rope clubs, and it is also one of the most popular programs in addition to soccer, badminton, and basketball. Furthermore, it has evolved into popular after-school sports programs and Saturday sports programs for elementary, middle, and high school students (Korea Rope Skipping Association, 2016; Ministry of Culture, Sport and Tourism, 2015). Canada has more than one million students in more than 4,000 schools participating in the jump rope campaign (Jump Rope for Heart, 2014), and it has been reported in the United States that there are approximately 3 million players participating in the jump rope competition (American Heart Association, 2014). In this way, jump rope is being developed not only as a competitive sport, but also as a type of exercise for improving the physical fitness and health of students in Korea and overseas.

The jump rope exercise program is a training program used in school physical education and other elite sports events. It is additionally used as a form of physical strength training for elementary school students. It has been used as a training method to maximize the effects of major stretch shortening cycles in many sports, such as volleyball, basketball, soccer, gymnastics, rhythmic gymnastics, boxing, wrestling, tennis, and martial arts (Duzgun, Baltaci, Colakoglu, Tunay, & Ozer, 2010; Orhan, 2013; Ozer, et al., 2011; Trecroci, Cavaggioni, Caccia, & Alberti, 2015; Wielligh, 2011). A jump rope motion is a form of stretch shortening cycle mechanism in which the quadriceps and calf muscles contract and stretch repeatedly, which helps to generate a greater force of agility (Komi, 1984; Miyaguchi et al., 2015; Norman & Komi, 1979). Furthermore, jump rope exercise programs help improve the fitness and physiological conditioning of young athletes who train regularly in a certain sport (Baker, Côté, & Abernethy, 2003).

The continuous jumping motion during jump rope movement is performed in the form of a rapid recoil jump with almost no flexion of the ankle joint, the knee joint, or the hip joint. This results in rapid movement by minimizing the time required to apply a force to the ground (Butler, Crowell, & Davis, 2003). Such a continuous jumping motion using a jump rope is related to dynamic stability, which is defined as the acceptance sensitivity of the movement system to the agitation caused by the movement variability (i.e., noise in the neuromuscular system; Stergiou, 2004). Kinematically and kinetically, humans are characterized by their ability to maintain joint stability during functional activities, and landing in a jump is the most representative of human physical activity that requires dynamic stability as well as a typical cause of lower limb-related injuries (Wright, Arnold, & Ross, 2016). The jump rope movement, which is inefficient in absorbing shock, results in overuse syndrome due to either inaccurate jumping and landing movements or the consequent impairment of the shock absorptive mechanism as well as inadequate exercise intensity and frequency setting, which can affect the increasing risk of injury of the surrounding connective tissue in the ankle and knee joints (Bennell, Malcolm, Wark, & Brukner, 1996; Grimston & Zernicke, 1993; Karim & Bruker, 1998; Kim & Youm, 2013; McNitt-Gray, 2000; Pittenger, et al., 2002; Tanikawa et al., 2014). Moreover, asymmetry in the lower limbs due to unbalanced movements is a major cause of orthopedic disease in infants and children in terms of growth development. In particular, it has been reported that diseases such as varus, stressful fractures, pain, and osteoarthritis can be caused by asymmetry (Sánchez et al., 2013). Therefore, an analysis of unbalanced jump motion may be useful in detecting lower extremity asymmetry in adults as well as in children (Paterno, Ford, Myer, Heyl, & Hewett, 2007). Furthermore, it would be necessary to analyze the degree of unbalance between the two lower limbs through the jump rope motion. In addition, the jump motion performed in many sports utilizes various feet widths. For example, a stop-jump performed in volleyball is recommended to be of shoulder width, whereas the width of a jump motion performed while coordinating the upper and lower extremities, such as during a basketball jump shot, is recommended to be as narrow as possible. However, there is little quantitative data related to feet width during the jump rope movement.

In a previous study, Kim and Kim (2015) analyzed the difference in jump rope motion between single under and double under jumping movements using both feet among seven adult male jump-rope leader qualification holders and reported that double under jumps utilize a greater range of motion of the lower limbs and produce more vertical ground reaction force. Ghafouri et al. (2014) analyzed the fatigue effect of 12 young girls by using the rating of perceived exertion (RPE) of the jump rope in 3-minute alternating jumps and reported that the factors associated with fatigue were the ankle joint angle and the ankle joint movement distance. Yoshioka et al. (2015) analyzed the movement of hand and wrist joints during double under jumps in 12 jump-rope female athletes, and proposed that the proficiency of the hand and wrist joints cannot determine success in performing the double under technique.

As shown in the previous studies, there has been some progress regarding the jump rope exercise in terms of physiological studies, training methods and effects, and studies on injuries. However, there is a lack of research on the optimal feet width and preferred posture for jump rope exercise related to kinematic and kinetic approaches, injury prevention, and maximal performance. Therefore, the purpose of this study was to investigate the effect of different skill levels and feet widths on kinematic and kinetic variables in jump rope during single under jumps.

METHODS

1. Participants

We enrolled 4th grade elementary school boys and girls who had no difficulties in daily life and had no history of an orthopedic condition within the last 6 months. These subjects were then divided into (i) a skilled group of 15 students (7 males and 8 females) who each had more than 2 years of experience in performing jump rope exercises periodically 5 times a week for 30 minutes a day, and (ii) an unskilled group of 15 students (7 males and 8 females) who each had 6 months

Table 1. Physical characteristics

	Age (yrs)	Height (cm)	Left leg length (cm)	Right leg length (cm)	Weight (kg)	BMI (kg/m^2)	Career (yrs)
Skilled (n=15)	10.85±0.40	142.13±5.41	73.97±3.75	73.70±3.63	36.97±6.65	18.57±2.32	2.44±0.49
Unskilled (n=15)	10.85±0.40	143.31±5.54	73.30±3.93	73.40±3.87	40.81±10.39	19.72±4.27	0.55±0.06*

BMI: Body mass index, Independent sample *t*-test between Skilled and Unskilled, *$p<.05$

or less of experience. Dong-A University Institutional Review Board (IRB) evaluated all subjects prior to the study and all subjects, and their guardians provided written informed consent. During the experiment, subjects restricted their participation in other exercise programs other than daily life. (Table 1) shows the physical characteristics of the participants.

2. Procedure

Nine infrared cameras (MX-T10, Vicon, UK) and one ground reaction force plate (AMTI OR6-7, Watertown, MA, US) were used in this study. Furthermore, the same type of jump rope and sneakers were used by all subjects in this study. Experiments were conducted for 2 days. On the first day, consent forms were obtained, physical characteristics were measured, and environment adaptation training and preliminary exercises were performed. During the initial practice, all subjects were matched for the jump rope speed for consistency of motion, and the speed was set to 135 beats/min using a metronome (Metronome, SMM-88) (Pittenger, McCaw, & Thomas, 2002). Additionally, a sufficient preliminary exercise was conducted to acclimate subjects to a consistent speed for single under type jumps using both feet. On the second day, all subjects stretched and performed jump rope single under type jumps to prevent injury. This was followed by the actual experiment. The experiment was conducted using an apparatus containing nine infrared cameras and one ground reaction force system. In the global coordinate system, the left and right direction of the subject was set as the X-axis, the front and back direction was set as the Y-axis, and the vertical direction was set as the Z-axis, with the position on the left rear surface of the subject as the origin (Figure 1).

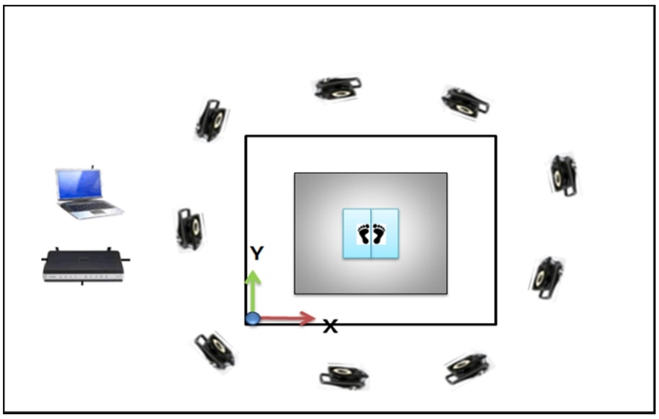

Figure 1. Setting up an experimental apparatus

All subjects wore shirts and shorts of span material during the experiment, and sneakers were also worn for safety. The physical characteristics of the subjects were measured by measuring the height and weight using a body composition analyzer (GL-150KT, G-TECH, Korea) that was capable of measuring height, followed by body mass index calculation. Furthermore, to calculate kinematics data of each joint during a jump rope motion, the subject's shoulder width, elbow width, wrist width, hand thickness, leg length, knee width, and ankle width were measured using a tape measure and a caliper. The body model was constructed by attaching 39 spherical reflective markers that were 14 mm in diameter of the markers using the Plug in Gait Full Body Model of Vicon (Oxford, UK).

3. Data processing

Nexus software (Vicon, UK) was used to collect and analyze 3 dimensional position coordinate data and ground reaction force data during the single under motion using both feet, with the sampling frequency of the 3D data set to 200 Hz and the sampling frequency of the ground reaction force data set to 1,000 Hz. All collected data were filtered using a second-order Butterworth low-pass filter with a cut-off frequency of 6 Hz (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007). The single under motion was divided into the preferred width and the induced width of 10 cm, which was performed 10 times in a row. The 5th, 6th, and 7th data points of the 10 consecutive operations were analyzed since they were the most stable. The minimum range of induced width was specified as 10 cm, which was marked on the ground reaction force plate.

To analyze single under motion, it was divided into five events (E1, E2, E3, E4, E5) and four phases (P1, P2, P3, P4). E1 is the moment when the feet come into contact with the ground (i.e., when the vertical ground reaction force value is 10 N or higher), E2 is the moment when the vertical ground reaction force value reaches a maximum, E3 is the moment when the foot falls from the force plate, E4 is the moment when the body center of gravity reaches a maximum vertical position, and E5 is set to the same point as E1. Each phase was defined between two events. Analyzed variables included elapsed time; displacement of the center of mass; the range of motion of the thorax segment, hip, knee, and ankle joints of the left and right limbs; and the peak vertical ground reaction force and load rate, which are the kinetic variables.

4. Statistical analysis

Statistical analysis was performed using SPSS 23.0 to calculate the mean and standard deviation for each variable, and a normality test for all data was performed using the *Shapiro-Wilk* test. The range of motions of the thorax, hip joint, knee joint, and ankle joint were measured repeatedly using Multivariate analysis of variance (*ANOVA*) to determine the mean differences between proficiency (skilled and unskilled), feet width (preferred and 10 cm width), and lower limbs (left and right). *Two-way ANOVA* with repeated measurements was also used to determine the mean difference between proficiency (skilled and unskilled) and width (preferred width and 10 cm width). A *post hoc* independent sample *t*-test was used to assess proficiency, while a paired sample *t*-test was used to assess width and left and right limb. The statistical significance level (α) of all variables was set at 0.05.

Table 2. Elapsed time (s)

		PW	IW	t^a	F
P1	Skilled	0.14±0.01	0.14±0.02	0.465	0.002 (W)
	Unskilled	0.14±0.02	0.14±0.02	0.579	0.062 (G)
	t^b	0.546	0.062		0.511 (W×G)
P2	Skilled	0.13±0.01	0.14±0.01	0.172	0.048 (W)
	Unskilled	0.14±0.03	0.14±0.02	0.138	0.510 (G)
	t^b	0.614	0.710		0.000 (W×G)
P3	Skilled	0.09±0.02	0.09±0.02	0.093	0.005 (W)
	Unskilled	0.10±0.01	0.10±0.01	0.447	2.076 (G)
	t^b	1.326	1.093		0.060 (W×G)
P4	Skilled	0.10±0.02	0.11±0.02	0.658	0.034 (W)
	Unskilled	0.12±0.02	0.12±0.01	1.037	5.509* (G)
	t^b	2.424*	1.271		1.040

All data are presented as the mean and standard deviation, a: Paired sample *t*-test within PW and IW, b: Independent sample *t*-test between Skilled and Unskilled, P1 is phase 1, P2 is phase 2, P3 is phase 3, P4 is phase 4, PW means preferred width, IW means induced width, W: Main effect between widths, G: Main effect between groups, W×G: Interaction effects, *$p<.05$

RESULTS

1. Elapsed time

As a result of analysis of the elapsed time by phase, P4 showed a significant difference in main effect between groups (F1, 28=5.509, p=.033) and a post hoc analysis showed that the preferred width was shorter in the unskilled group than in the skilled group (t28=2.424, p=.022) (Table 2).

2. Width

As a result of analysis of width, there was a significant difference in the effect of width (F1, 28=205.395, p=.000) (preferred width of the skilled group: 6.11±1.61, induced width of the skilled group: 16.67±5.35, preferred width of unskilled group: 5.61±2.73, induced width of unskilled group: 16.44±4.04). Furthermore, a *post hoc* analysis indicated that the preferred width was significantly smaller than the induced width in the skilled group (t14=7.828, p<.001) as well as in the unskilled group (t14=16.969, p<.001) (Figure 2).

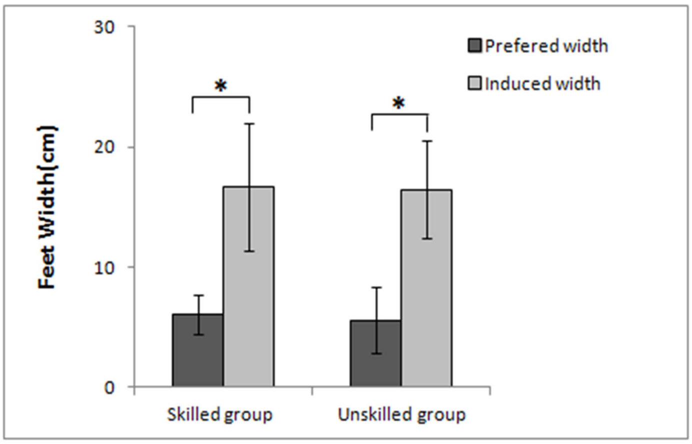

Figure 2. Feet width

3. Displacement of center of mass

We then analyzed the displacement of center of mass. In doing so, we found no significant differences in the main and interaction effects for the meiolateral and vertical displacements. Meanwhile, the main effect between groups (F1, 28=5.481, p=.027) was significant in the anteroposterior displacement (preferred width of the skilled group: 2.07±0.79, induced width of the skilled group: 2.13±1.14, preferred width of the unskilled group: 2.80±0.79, induced width of the unskilled group: 2.64±1.08), and the *post hoc* analysis indicated that the preferred width of the skilled group was significantly smaller than that of the unskilled group (t28=2.497, p=.019) (Figure 3).

4. Range of motion (ROM) of the thorax segment

In analyzing the ROM of the thorax segment, we found that the main effect between groups (F1, 28=5.481, p=.027) was significant in the flexion/extension movement (preferred width of the skilled group: 6.20±1.85, induced width of the skilled group: 6.88±1.95, preferred width of unskilled group: 8.72±3.50, induced width of unskilled group: 9.30±2.65). *Post hoc* analysis revealed that the skilled group exhibited significantly smaller preferred width (t28=2.426, p=.022) and induced

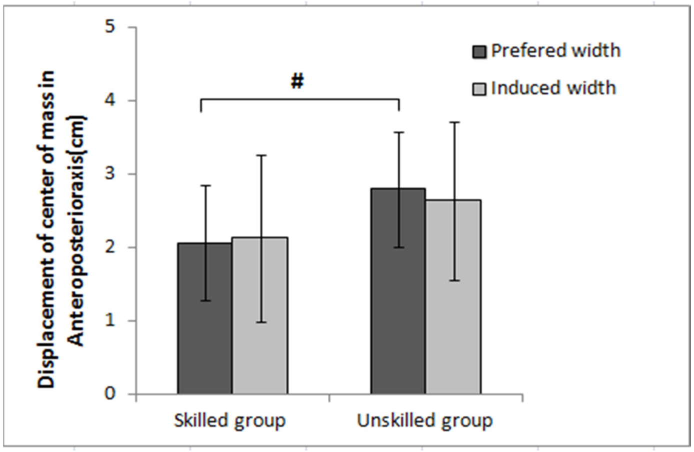

Figure 3. Displacement of the center of mass

width (t28=2.849, p=.008) than did the unskilled group. Furthermore, they found that the preferred width was significantly smaller than the induced width in the skilled group (t14=2.773, p=.015) (Figure 4).

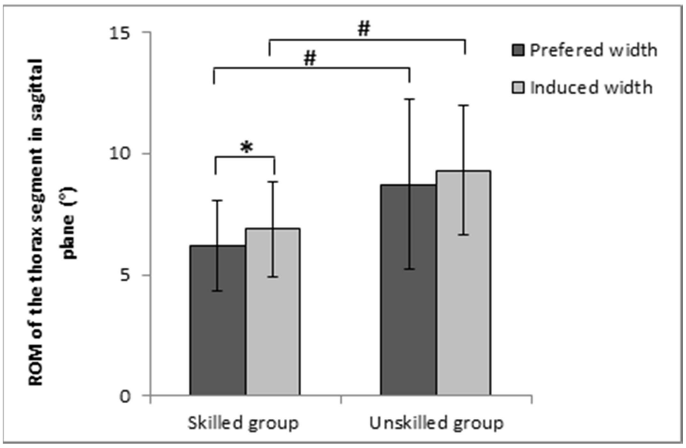

Figure 4. ROM of the thorax segment

5. Range of motion (ROM) of the left and right lower limb joints

1) ROM of hip joints

Upon analyzing the ROM of the hip joint, the range of motion in flexion/extension movement was significant in the main effect between widths (F1, 28=5.643, p=.025) and between the left and right foot (F1, 28=10.924, p=.003) (the preferred width of the skilled group was 12.66±4.96 / R: 12.66±4.96, the induced width of the skilled group was 13.85±5.43 / R: 14.42±5.74, and the preferred width of unskilled group was 15.35±7.64 / R: 17.42±8.94, induced width of unskilled group: L: 16.73±7.36 / R: 18.94±8.67). *Post hoc* analysis results showed a significant difference in the right foot of the preferred width and the right foot of the induced width in the skilled group (t14=2.813, p=.014), and results of the left foot were significantly smaller than those of the right foot in the unskilled group's preferred width (t14=3.102, p=.008) and induced width (t14=2.781, p=.015). The difference in range of motion in adduction/abduction movement was significant in the main effect between preferred widths (F1, 28=5.643, p=.025), between the left and right hip (F1, 28=10.924, p=.003, and between induced widths (F1, 28=11.675, p=.002), respectively (the preferred width of the skilled group: L: 3.97±1.67 / R: 4.29±1.806, the induced width of the skilled group: L: 5.09±1.89 / R: 4.64±1.52, the preferred width of the unskilled group: L: 4.51±1.97 / R: 4.65±1.88, and the induced width of unskilled group: L: 6.44±2.82 / R: 6.31±2.73). *Post hoc* analysis indicated that the left hip of the preferred width was significantly different from the left hip of the induced width (t14=3.439, p=.004) in the unskilled group, and that this measurement was significantly smaller in the skilled group than in the unskilled group for the right foot of the preferred width, the right foot of the induced width (t14=2.381, p=.032), and in the induced width (t14=2.381, p=.032).

The difference in range of motion for rotational movement was significant in the main effect between widths (F1, 28=5.643, p=.025), between the left and right hip (F1, 28=10.924, p=.003), and between the left and the right hip (F1, 28=20.545, p<.001), respectively (the preferred width of the skilled group: L: 17.66±7.26 / R: 13.36±1.79, the induced width of the skilled group: L: 17.83±8.64 / R: 9.77±4.24, the preferred width of unskilled group: L: 16.27±8.44 / R: 6.67±2.38, and the induced width of unskilled group: L: 17.15±8.41 / R: 8.29±3.53). *Post hoc* analysis showed a significant difference in the right hip of the preferred width of the unskilled group and the right hip of the induced width (t14=2.305, p=.037), and the measurement appeared higher in the left hip than in the right hip for the induced width of the skilled group (t14=4.906, p<.001), the preferred width of the unskilled group (t14=4.659, p<.001) and induced width (t14=4.610, p<.001) (Figure 5).

2) ROM of knee joints

An analysis on the ROM of the knee joint indicated that the range of motion in flexion/extension movements was significant in the main effect between the left knee and the right knee (F1, 28=4.580, p=.041) (the preferred width of the skilled group: L: 34.34±6.29 / R: 36.83±5.60, the induced width of the skilled group: L: 34.93±6.71 / R: 36.42±7.00, the preferred width of the unskilled group: L: 36.70±7.69 / R: 36.83±9.13, the induced width of the unskilled group: L: 39.97±6.37 / R: 41.09±8.61). The range of motion in the rotational movement was significant in the main effect between the left and the right knee (F1, 28=14.608, p=.001) (preferred width of the skilled group: L: 19.17±9.39 / R: 16.49±7.16, induced width of the skilled group: L: 18.28±6.55 / R: 14.93±3.76, preferred width of the unskilled group: L: 19.73±4.00 / R: 15.20±3.54, induced width of unskilled group: L: 20.93±3.29 / R: 16.12±3.00). *Post hoc* analysis indicated that the ROM in the left knee was significantly larger than in the right knee in the preferred width of the unskilled group (t14 = 4.007, p=.001) and in the induced width (t14=5.106, p<.001) (Figure 6).

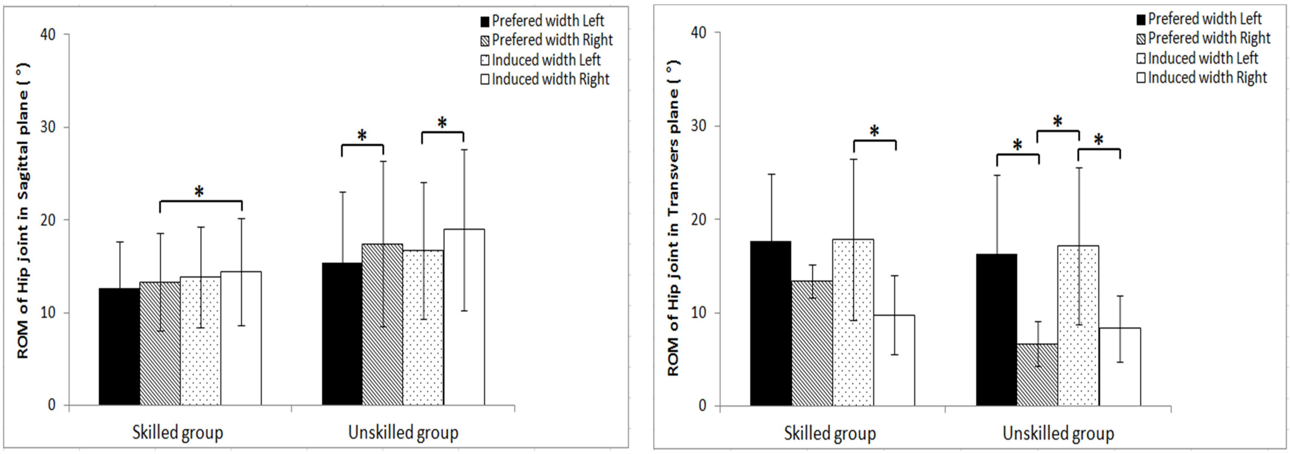

Figure 5. ROM of the hip joint

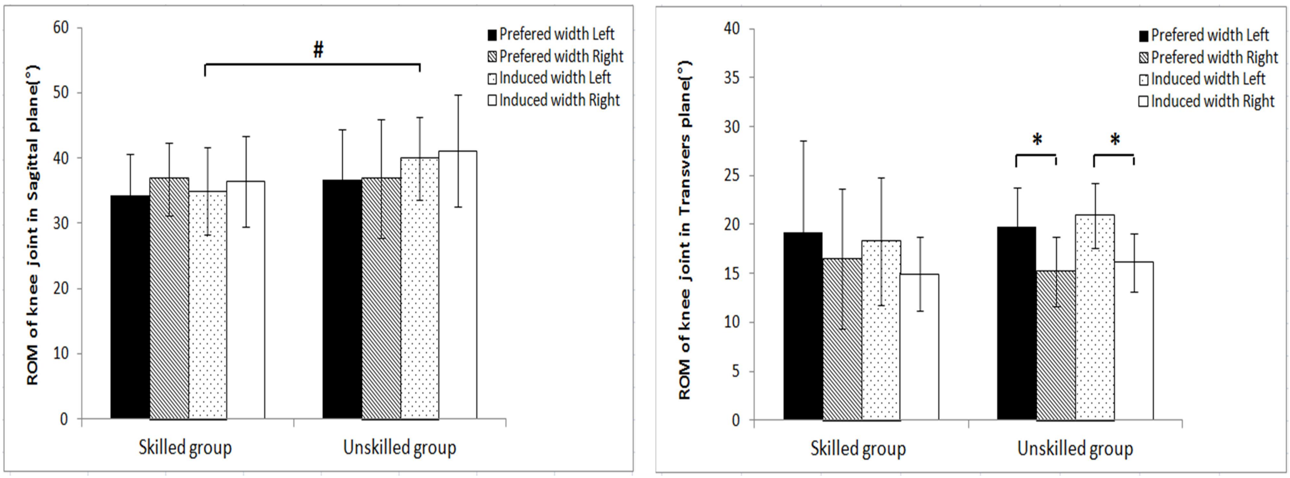

Figure 6. ROM of the knee joint

3) ROM of ankle joints

Ankle joint ROM analysis indicated that the range of motion during adduction/abduction was significantly different in main effect between the left ankle and the right ankle ($F_{1, 28}$=14.608, p=.001) and the main effect between the left ankle and the right ankle ($F_{1, 28}$=6.562, p=.016) (the preferred width of the skilled group: L: 8.62±4.48 / R: 7.11±3.18, the induced width of the skilled group: L: 9.43±0.31 / R: 7.21±0.71, the preferred width of the unskilled group: L: 9.13±4.85 / R: 6.95±2.16, and the induced width of the unskilled group: L: 9.85±4.52 / R: 7.31±2.99). *Post hoc* analysis indicated that ROM of the ankle was significantly greater in the left ankle than in the right ankle at the induced width of the unskilled group (t_{14}=2.337, p=.035). The range of motion in the rotational movement was significantly different in main effect between the left and right ankle ($F_{1, 28}$=9.880, p=.004) (the preferred width of the skilled group: L: 26.61±6.45 / R: 24.23±9.80, the induced width of the skilled group: L: 28.20±8.90 / R: 24.78±8.14, the preferred width of the unskilled group: L: 27.59±6.24 / R: 23.20±5.69, the induced width of unskilled group: L: 30.73±9.91 / R: 24.06±7.62). *Post hoc* analysis indicated that the ROM in the left ankle was significantly larger than in the right ankle for the preferred width (t_{14}=2.614, p=.020) as well as the induced width (t_{14}=2.458, p=.028) in the unskilled group (Figure 7).

6. Kinetic variables

Peak vertical ground reaction force and loading rate of P1 showed no significant difference between main effects and interaction effects (Table 3).

DISCUSSION

The analysis results of width, the independent variables in this study, showed that the preferred width of the skilled group was 6.11 cm and that the induced width was 16.67 cm. The unskilled group had a preferred width of 5.61 cm and an induced width of 16.44 cm. Therefore,

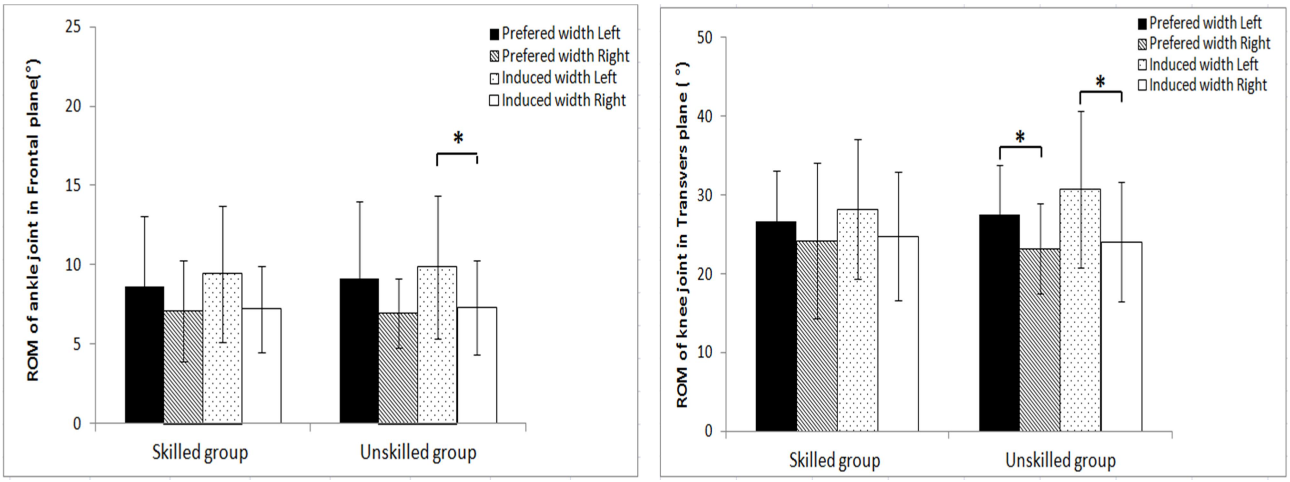

Figure 7. ROM of the ankle joint

Table 3. The kinetic variables

		PW	IW	t^a	F
Peak VGRF (N/kg)	Skilled	35.96±5.80	37.27±4.17	1.307	0.084 (W)
	Unskilled	36.50±6.31	35.57±5.76	1.155	0.090 (G)
	t^b	.248	.928		3.037 (W×G)
Loading rate of P1 (N/kg/s)	Skilled	244.25±66.45	272.87±57.79	1.538	2.020 (W)
	Unskilled	261.22±97.81	263.29±71.90	.190	0.025 (G)
	t^b	.592	.428		1.510 (W×G)

All data are presented as the mean and standard deviation, [a]: Paired sample *t*-test within PW and IW, [b]: Independent sample *t*-test between Skilled and Unskilled, P1: phase 1, PW: preferred width, IW: induced width, W: Main effect between widths, G: Main effect between groups, W×G: Interaction effects, VGRF: Vertical ground reaction force, $*p<.05$

the preferred width and the induced width were significantly different. In general, the mean distance between the medial and lateral sides of the ankle joint in a static standing posture is approximately 9 cm (Murray, Seireg, & Sepic, 1975; Perry & Burnfield, 2010) and the mean distance between the medial and lateral sides of the ankle joint during dynamic walking was reported to be approximately 7 cm for women and approximately 8 cm for men (Murray, Kory, & Sepic, 1970; Perry & Burnfield, 2010). Such characteristics are related to static stability as well as dynamic stability. Indeed, width during dynamic walking is slightly decreased in an effort to secure dynamic stability and propulsion. Furthermore, improving static stability by widening the base of support results in an increase in width during a static standing posture (Shin, Youm, & Son, 2013). In the jump rope of this study, the preferred width was found to decrease by approximately 32~37% and the induced width decreased by 82~85%. Therefore, the width is shown to be a meaningful factor when comparing the kinematic difference in terms of static and dynamic stability in the jump rope motion of this study. Furthermore, the study results show that the optimal jump rope movement can be performed with a recommended width of approximately 6 cm for single under motion.

As a result of the kinematic difference depending on width, the preferred width of the skilled group showed that the ROM of the right hip joint in flexion/extension motion and the ROM of the thorax segment were smaller than the induced width. Furthermore, the preferred width of the unskilled group showed that the ROM of the left hip joint during abduction/adduction movement and the ROM of the right hip joint during rotational movement was smaller than the induced width. Therefore, as the width increases during the jump rope motion, it affects the hip joint and thorax segment more than the ankle joint and knee joint. The jump rope motion of this study is characterized by iterative repetition, and thus it should be able to minimize energy while making such movements. However, the increase in the range of motion of the hip joint and thorax segment of induced width is contrasted with this strategy. During a typical jumping motion, the lower limb joint extensively flexes and extends the ankle, knee, and hip joints in an effort to have sufficient time to apply force to the ground. Meanwhile, in the landing phase, it performs a larger range of motion on the lower limb to absorb the impact generated in the jumping phase (Kim, 2000; Aragon-Vargas & Gross, 1997; Decker et al., 2003; Dowling & Vamos, 1993; Markovic, Dizdar, Jukic, & Cardinale, 2004). However, the jump rope movement is performed by using the recoil almost without flexion of the ankle, knee, and hip joint, and jumping motion during such movement occurs as fast, regularly, and consistently as possible by minimizing the time required to apply force to the ground (Butler et al., 2003). Therefore, the preferred width of the jump rope motion in this study is considered a favorable strategy for maintaining dynamic stability.

While using the preferred width during the jump rope motion, the skilled group used a strategy to reduce the center of mass displacement and decrease the ROM in the segment thorax in the flexion/extension movement as well as the rotational movement when compared to the unskilled group. Meanwhile, while using the induced width, they used a strategy to reduce the ROM of the left knee joint as well as the ROM of the thorax segment during flexion/extension movements and to decrease the ROM of the right hip joint during adduction/abduction movements. This reflects a strategy of reducing the ROM of the left knee joint as well as the ROM of the thorax segment during flexion/extension movement and to decrease the ROM of the right hip joint during the adduction/abduction movement. Also, the skilled group can precisely perform repetition by maintaining the anteroposterior coherence of the entire body by minimizing the ROM of the thorax segment of the preferred width during flexion/extension movement and the anteroposterior displacement of the center of mass. Furthermore, elapsed time analysis showed that the time required for the skilled group in P4 was shorter than the unskilled group in both the preferred and the induced width. This shows that the skilled group performs jumping and landing in which the distance from the highest point of the center of mass to the landing point is small in a short amount of time, which means that the skilled group maintains dynamic stability during jump rope motion with the same tempo, and operates more efficiently than the unskilled group.

Importantly, the human body serves to absorb shock by decreasing the velocity of the bodily center of mass when landing after the jump. The lower extremity muscle group is needed for this purpose (Devita & Skelly, 1992). In particular, the decrease in vertical angular velocity and the horizontal angular velocity of the center of mass during the landing motion is an essential factor for the balance control of the bodily center of mass (Wooten & Hodings, 2000; Kim & Youm 2015). In this study, there was no significant difference in the loading rate of the landing phase and the peak vertical ground reaction force, though in the case of the skilled group, the loading rate at the preferred width was larger than that at the induced width. Therefore, a theoretical basis for minimizing the movement of the thorax segment and preserving posture and energy efficiency during landing is supported by our observations. The landing motion is also divided into forefoot landing and hindfoot landing depending on where the foot touches the ground after the jump (Cortes et al., 2007). A forefoot landing occurs when the toe part of the foot touches the ground first. This mainly occurs during landing after the jump and affects the stiffness of the knee joint. During hindfoot landing, the heel touches the ground first, mainly occurs in landing motion while walking or jogging, and affects the stiffness of the ankle joint (Butler et al., 2003). Therefore, the jump rope motion used in this study maintains the form of forefoot landing that minimizes the height of the center of mass. Furthermore, it may be necessary to further study the stiffness and contribution of the knee joints to clarify the relationship between the ankle and knee joints.

The analysis results for differences between the left and right segments of the body using the preferred width showed that the ROM of the ankle joint during rotational movement in the unskilled group was larger in the left limb than the right limb, the ROM of the knee joint during flexion/extension movement was larger in the left than the right, the ROM of the hip joint during flexion/extension movement was smaller in the left than the right, and the ROM of the hip joint during rotational movement was smaller in the left than in the right. Furthermore, using the induced width in the same group, the ROM of the ankle joint during adduction/abduction and rotational movement was larger in the left than the right. Similarly, the ROM of the knee joint during rotational movement was larger in the left, and the ROM of the hip joint during rotational movement was larger in the left. However, there was no significant difference between the left and right lower extremity joint in the preferred width of the skilled group. As described, the unskilled group has an imbalance of left and right motion in the range of motion of the ankle, knee, and hip joints regardless of the width, which may affect subsequent musculoskeletal injuries. An unbalanced physical posture of children in adolescence produces various side effects throughout the body, such as vertebral deformities. Some studies of the potential mechanisms and interventions used to address this imbalance have been conducted and include the use of yoga, flexibility exercises, ballet, and correction exercises (Choi, 2008; Lim, Kang & Kim, 2004). The results of this study show that the skilled group has a highly aligned left and right limb during jump rope motion. These results suggest that long-term accurate jump rope motion helps to improve lateral unbalance throughout the whole body.

CONCLUSION

In the jump rope movement, the preferred width decreased by approximately 5.61~6.11 cm (32~37%) from the static standing posture regardless of proficiency, while the induced width increased by approximately 16.44~16.67 cm (82~85%). As the width increases during jump rope motion, the hip joint and thorax segment, rather than the ankle joint and knee joint, are affected, which shows that the preferred width during a jump rope motion is a more favorable strategy for maintaining dynamic stability. The skilled group minimized the anteroposterior displacement of the center of mass and the range of motion of the thorax segment in the flexion/extension movement while using the preferred width. Furthermore, the jump rope motion used in this study involves the use of forefoot landing, which minimizes the height of the center of mass. The unskilled group showed an imbalance in the left and right movement in the ROM of the ankle joint, the knee joint, the hip joint, and the thorax segment regardless of the width. Furthermore, long-term accurate jump rope motion may contribute to an improvement in lateral imbalance of the whole body.

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