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Movement Coordination during Forward and Backward Rope Jumping: A Relative Phase Study

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Abstract— **Rope jumping is a popular training method in athletic programs, fitness, and physical education. Forward and backward rope jumping has been used for evaluating athlete's performance. Both of these two jumps require coordination in the upper and lower limbs. However, no study has focused on movement coordination during forward and backward rope jumping. Relative phase (RP) analysis was widely known as an innovative method for evaluating human movement coordination. Thus we aimed to investigate the movement coordination during forward and backward rope jumping by using RP analysis. 78 elementary and junior high school students participated in this study. 30 seconds rope jumping was recorded for both forward and backward by using iPhone video. Pose estimation software was used for jump motion tacking. Movement coordination was analyzed through RP analysis, absolute maximum value, mean absolute RP, and deviation phase were calculated for evaluating movement coordination, the trend of in or out-of-phase, as well as movement stability. As a result, 3994 forward and 3961 backward jumps were analyzed. There was a significant difference in movement coordination between forward and backward rope jumping. Compared to forward, backward jumps showed worse movement coordination, a trend to be out-of-phase, and less stability. It was the first time that movement coordination during rope jumping was studied. We considered that further research on coordination during rope jumping can provide new insight into athlete performance management, fitness guidance, and physical education.**

I. INTRODUCTION

Rope Jumping, a consecutive jump using a rope, has been widely used in sports training, fitness, and physical education [1]. Since 2008, rope jumping has been recognized as an effective approach for improving children's physical performance by the Ministry of Education, Culture, Sports, Science and Technology of Japan [2], [3].

Athletes choose different types of rope jumping, including the single under with timed speed, double or triple unders, and freestyle for different training. Forward and backward single under rope jumping is most often used for evaluating athlete's cardiorespiratory healthy, speed, agility, and quickness [4], [5], [6].

Previous rope jumping studies focused on the joint angle using motion capture system [7], ground reaction force (GRF) using a force plate [8], and plantar pressure with insole force sensors [9]. Goto et al. proposed a new index of real-time feedback during forward and backward rope jumping by only using an inertial measurement unit [10].

However, no study has studied the movement coordination during forward and backward rope jumping. Relative phase (RP) analysis has been known as a higher-order measurement when describing coordination in a dynamic system such as sit-to-stand [11], gait [12], and also showed wide acceptance even for human-robot-interaction study [13]. Moreover, because movement-related kinematics information is normalized in this analysis, RP can provide a universal method for investigating movement coordination. As a consequence, RP analysis is considered as an appropriate method for investigating rope jumping coordination.

In this study, we aimed to investigate the coordinated movement during forward and backward rope jumping using RP analysis. Given that there is different motor control between forward and backward jumps, for both forward and backward, rope jumping involves continuous hopping, the jumping power is mainly produced by the knee and ankle, while the lower limbs are relatively rigid [14]. Thus, we hypothesized that the movement coordination between forward and backward rope jumping would be different.

This paper consists of five sections. Section II shows the details about subjects and method. Section III presents the results. Discussion and future work are in Section IV. Finally, the conclusion of this paper is presented in Section V.

II. SUBJECTS AND EXPERIMENT

A. Subjects

Total 78 elementary (4th and 5th grades) and junior high school (1st to 3rd grades) students (Male: 41, Female: 37, Height: 155.8 $\pm$ 9.3 cm, Body Mass Index: 18.8 $\pm$ 1.9 kg/m^2) participated in the experiment. All students were selected by the sports talent identification program in MIYAZAKI prefecture, Japan

The rope jumping experiment was conducted on November 14th, 2020. Because all subjects were under 18 years old, before the experiment, all parental consent and all subjects' assent prior to their participation were acquired. This study was approved by the Ethics Committee on Ritsumeikan University (Kinugasa-2018-52).

B. Experiment

Fig. 1 shows the concept of rope jumping motion capture and data selection. Before the experiment, we ask all subjects to practice forward as well as backward rope jumping for 10 s to ensure the optimal rope length. Then every subject

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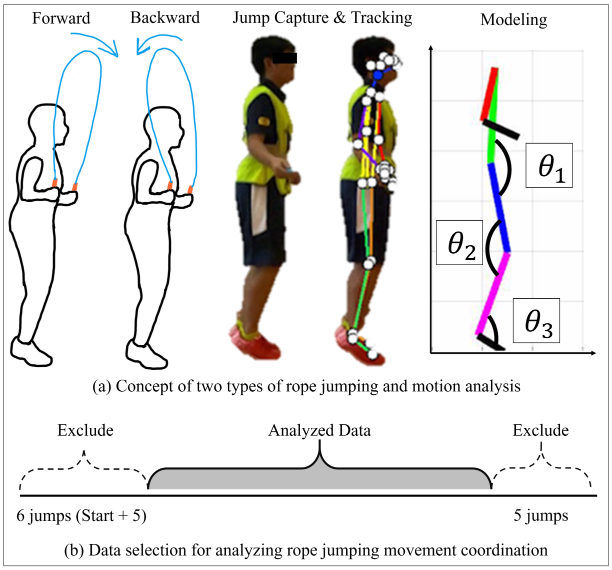

Fig. 1. Rope jumping experiment and data selection.

performs the rope jumping for 30 s both at forward and backward conditions.

We used iPhone 12 (iPhone®, Apple, United States) with 60 fps video for rope jumping capture. Pose estimation software (VisionPose®, NEXT-SYSTEM, Japan) was utilized for motion tracking, which can automatically detect total 30 points on the human body [15]. In this study, we used the following points for human modeling: shoulder, elbow, wrist, hip, knee, ankle, and foot. Then trunk was defined as from shoulder to hip, thigh was from hip to knee, crus was from knee to ankle, foot was from ankle to foot. θ_1 was defined as the angle between trunk and thigh, θ_2 was the angle between thigh and crus, and θ_3 was between crus and foot, as shown at Fig. 1 (a). This angular information was used for analyzing movement coordination.

Fig. 1 (b) shows the data selection in this study. The first six times jumps (start and the next five times) and the last five times jumps were excluded from the data analysis, referenced to [16], because different movement patterns were required to initiate and stop the motion than to maintain it.

C. Movement Coordination Analysis

Movement coordination during rope jumping is analyzed using relative phase (RP) analysis referenced to our previous study [17].

Fig. 2 shows an example of RP for one subject during forward rope jumping. In this sample, a total of 53 jumps were analyzed.

First step in the RP analysis is to normalize angular displacement θ and velocity ω. Fig. 2 (a) shows the measured θ and differentiated data ω, respectively. Normalized $\theta_{Normalized}$ and $\omega_{Normalized}$, shown at Fig. 2 (b), can be calculated using the following equations:

$$\theta_{Normalized} = \frac{2 \times (\theta_i - \theta_{imin})}{\theta_{imax} - \theta_{imin}} - 1 \quad (1)$$

$$\omega_{Normalized} = \frac{\omega_i}{|\omega_i|_{max}} \quad (2)$$

where i is a data point in the cycle.

Fig. 2 (c) shows the phase portrait constructed by plotting $\theta_{Normalized}$ against $\omega_{Normalized}$. The phase angle Φ is obtained by calculating the four-quadrant arctangent angle relative to the right horizontal at each instant in the cycle :

$$\Phi = tan^{-1}(\frac{\omega_{Normalized}}{\theta_{Normalized}}) \quad (3)$$

The times series data of Φ was plotted at Fig. 2 (d)

Finally, movement coordination (i.e., trunk, thigh and crus: Φ_1) is then calculated using following equation and plotted at Fig. 2 (e):

$$\Phi_1 = \Phi_{Thigh-Crus} - \Phi_{Trunk-Thigh} \quad (4)$$

The maximum and minimum point in the RP curve indicates the coordination during rope jumping. Thus we calculate the larger absolute value between maximum or minimum (Abs Max) to compare the forward and backward rope jumping. Two additional feature of coordination evaluation: mean absolute RP (MARP) and deviation phase (DP) can be calculated as follows:

$$MARP = \sum_{i=1}^{N} \frac{|\Phi|}{N} \quad (5)$$

$$DP = \frac{\sum_{i=1}^{N} |SD|}{N} \quad (6)$$

where N is the number of points in the RP curve. MARP quantifies whether the interacting segments display an in-phase or out-of-phase pattern during rope jumping, the smaller (larger) the MARP is, the more (less) in-phase is the relationship of the segments. DP provides a measure of the stability of the organization of the neuromuscular system and is calculated by averaging the standard deviation (SD) of the ensemble RP curve points: The smaller (larger) the DP, the more (less) stable is the rope jumping.

D. Statistic Analysis

Data management and movement coordination analysis were performed using MATLAB (MATLAB R2021a, The Math Works, United States). Statistic analysis was performed using the JASP version 0.14.1.0 statistic software (Department of Psychological Methods University of Amsterdam, Amsterdam, The Netherlands). The normality of data was tested using the Shapiro-Wilk test, and showed significant departure from normality (all $p < 0.05$). As a consequence, movement coordination between forward and backward rope jumping was analyzed using Wilcoxon signed-rank test. Effect size of Rank-Biserial Correlation r_B was calculated (effect size of $r_B < 0.1$ indicates a trivial effect, $r_B = 0.1$ indicates a small effect, $r_B = 0.3$ indicates a medium effect, and $r_B = 0.5$ indicates a large effect). The level of significance was $p < 0.05$.

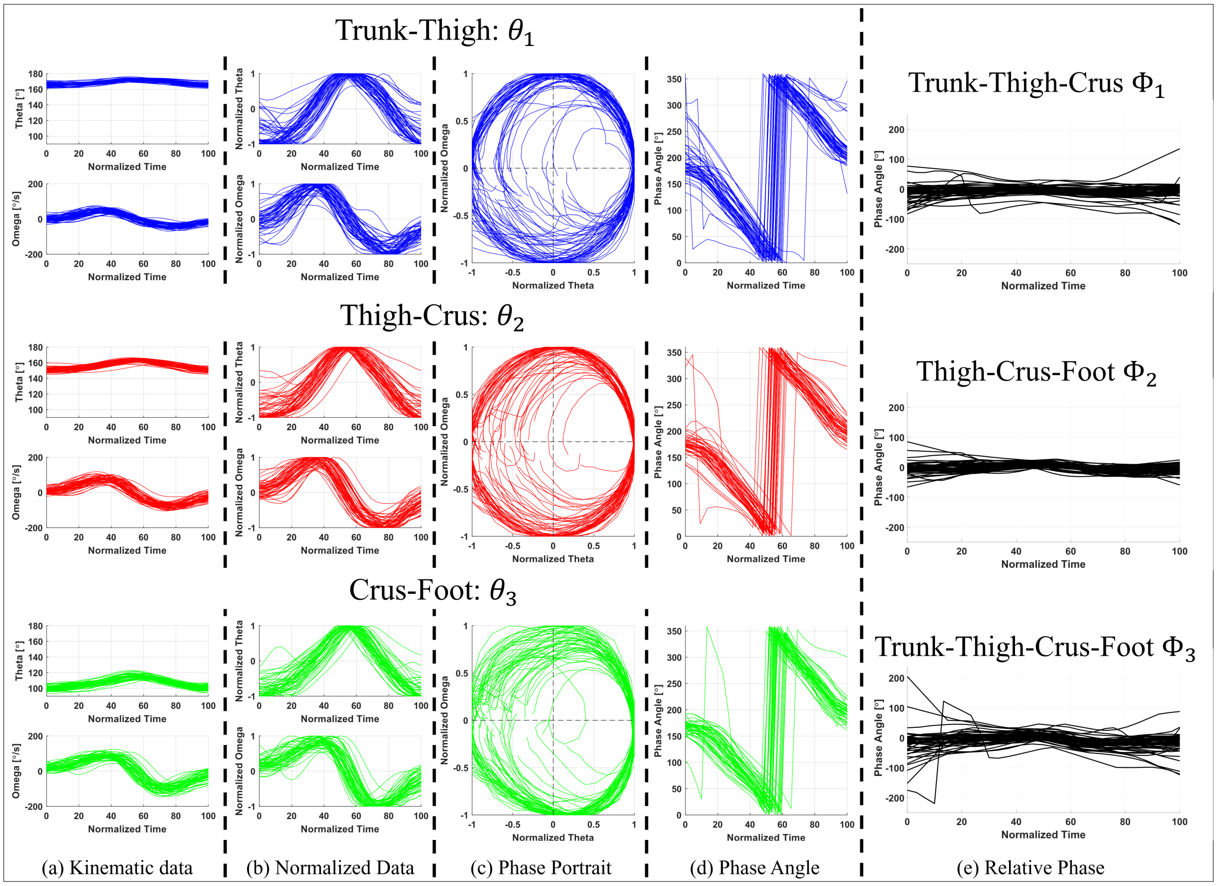

Fig. 2. Example of RP Analysis. Blue lines represent the data of Trunk-Thigh, red lines represent the data of Thigh-Crus, green lines represent the data of Crus-Foot, Black lines represent relative phase curves. Time is normalized to 100%.

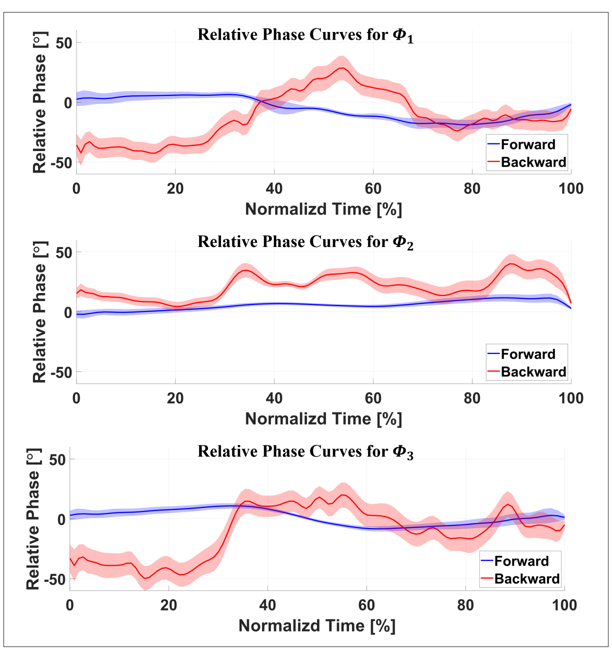

Fig. 3. Results of RP analysis. $N_{Forward}$ = 3994, $N_{Backward}$ = 3961. Graphics are plotted using mean and standard error.

III. RESULTS

Total 3994 forward and 3961 backward successful jumps were recorded and analyzed. Fig. 3 shows the results of RP analysis. Blue lines represent forward jump and red lines represent backward jump. Compared to the forward jumping, RP curves for all backward jumping showed more fluctuation, which indicates that the movement coordination between the two types of rope jumping was different.

Results of movement coordination evaluate features are shown in Table I. The absolute maximum value for backward rope jumping was significantly higher than it for forward rope jumping (all $p < 0.05$). There was a small effect in coordination Φ_1 ($0.1 < r_B < 0.3$) and a large effect in Φ_2 and Φ_3 (all $r_B > 0.5$). MARP in Φ_2 and Φ_3 was significantly different (both $p < 0.001$) between forward and backward rope jumping and there was a large effect (both $r_B > 0.5$). DP, only in Φ_2, showed a significant difference ($p < 0.001$) and a large effect ($r_B > 0.5$).

IV. DISCUSSION

To our best knowledge, it is the first time that the movement coordination during forward and backward rope jumping was studied. After investigating the movement coordination during rope jumping for 78 children, experimental

TABLE I
RESULTS OF ROPE JUMPING COORDINATION

	Index	Forward	Backward	p	r_B
Φ_1	Abs Max [°]	26.63 (44.63)	42.44 (28.01)	<0.05	-0.266
	MARP [°]	11.51 (22.44)	21.96 (16.64)	0.055	-0.250
	DP [°]	9.29 (28.25)	11.19 (17.24)	0.254	0.149
Φ_2	Abs Max [°]	15.71 (22.31)	44.36 (34.70)	<0.001	-0.810
	MARP [°]	7.72 (14.19)	22.02 (19.61)	<0.001	-0.740
	DP [°]	5.71 (9.09)	10.22 (12.65)	<0.001	-0.718
Φ_3	Abs Max [°]	35.39 (42.38)	73.55 (34.17)	<0.001	-0.569
	MARP [°]	18.27 (22.98)	40.38 (24.18)	<0.001	-0.659
	DP [°]	12.28 (26.34)	15.39 (18.16)	0.334	-0.126

$N_{Forward}$ = 3994, $N_{Backward}$ = 3961
Wilcoxon signed-rank test
Data: Median (Standard Deviation)

results verified our hypothesis: there was significant difference between these two types of jumping.

A significantly higher absolute maximum value during backward rope jumping in all Φ indicates worse coordination between different segments compared to forward jumps. Lower limbs including thigh, crus, and foot, were more easily to be out-of-phase and showed worse stability when jumped backward with higher MARP and DP values in Φ_2. The coordination that involved trunk, thigh, crus, and foot Φ_3 during backward rope jumping was worse and easier to be out-of-phase than the forward jumps.

It has to be pointed out that, all students were selected by the sports talent identification program, and some of those are accepting professional training. Thus it was difficult to conclude our findings in the broad representation. Nevertheless, the proposed method for evaluating movement coordination during rope jumping can be used for other subjects and under different types of rope jumping, because RP provides a universal evaluate method.

There were still some limitations in this study. Only 30 second period jumps were required in this study and we did not record the fatigue level. Bruce et al. found that fatigue during rope jumping changed the rotating range of motion at the shoulder [16]. More internal rotation at the shoulder may decrease the rope speed and thus affect the movement coordination during the rope jumping. It is important to dig deeper into this topic, because fatigue-related changes may increase the risk of developing an injury.

V. CONCLUSIONS

In this paper, movement coordination during forward and backward rope jumping was studied using relative phase analysis. As we hypothesized, there was a difference in coordination between forward and backward jumps. Backward jumping is a less coordinated movement, much easier to be out-of-phase, and less stable than the forward rope jumping. New findings in our research are expected useful in sports training, as well as physical education. Future work should focus on investigating movement coordination under different types of rope jumping and revealing the relation between rope jumping coordination and fatigue-related changes.

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