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Article

Lower limb movement analysis of different skipping rope modes based on Opensim: A middle-aged demograrphic study

Congjiang Wang

Civil Aviation Flight University of China, Guanghan 618307, China; wangcongjiang521@163.com

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Abstract: Introduction: Skipping rope is a popular exercise with various techniques. Understanding lower limb movement variance is crucial for optimizing performance and preventing injuries. **Aim:** To comprehensively analyze lower limb movement during different skipping rope modes using OpenSim, investigating biomechanical factors at the knee, ankle, and hip joints. The objective is to forcast the possible injuries and determines perception for optimizing the methods of exercise and analysis procedures. **Method:** The study analyze and evaluate the motions of lower limb in various rope skipping methods like boxer skip, single leg jumps, double-under and crossover jumps to comprehensively analyze the effects of biomechanical. In this research, we employed 56 participants and utilized the kinetic and kinematic data of motion capture model to obtain the data. Statistical analysis was performed to calculate the gathered data. Results: joint moment, joint flexion angle, muscle forces, and maximum joint flexion were thoroughly analyzed by OpenSim. In this research, important variations were examined in biomechanics in lower limb throughput various rope skipping methods. The double-under jumps determined the maximum hip and ankle forces of muscles comparison with other techniques and single leg jumps provided highest angles of knee bending. Boxer skip demonstrated the different types of joints motion and determining load variance mechanisms. Conclusion: The research emphasizes the significance by considering biomechanics in lower limb while demonstrating diverse rope skipping methods.

Keywords: injury risks; biomechanical analysis; statistical analysis; motion capture system; muscle forces

1. Introduction

Hip, ankle and knee joints motion in the sagittal plane, ankle joint motions in the frontal and sagittal planes and knee joint movements in sagittal hip joints in the frontal plane are the distinctive joint methods in the lower limbs (LL) [1]. The trauma or long-term and malignancies, disease are the basis of LL issues. It remains common and complex region of reconstructive treatment. Little flaws can provide issue of the thin soft tissue, non-expandable in the LL [2]. Motor dysfunction such as spasticity, ataxia, incoordination and sensory hypersensitivity couldimpact the functioning of both the upper and lower limbs in people with multiple sclerosis (pwMS) [3]. Skipping rope (SR) is a highly traditional sport with roots tracing back through centuries of cultural practices and physical activity. All it needs is a suitable-length rope. As long as the ground level and there is no breeze, SR is not strictly necessary for the location. Since SR requires synchronization between the upper and lower limbs, it is very relevant to the total body's coordination. SR is a workout that improves body coordination. SR is chosen for the fundamental training of sports like boxing, which demands body synchronization [4]. SR is a term used for aerobic training regimens which is becoming more popular. Combining acrobatic aspects and dancing exercises with one or two SR, SR is a kind of long-distance jumping rope that can be done alone, in relationships, or in groups [5]. SR is a cheap, easy, and healthy activity that is popular among people of all ages. SR improves the cardiovascular system, bone health, balance, strength, coordination, endurance, and agility of the human body [6]. During SR, stretch-shortening cycle (SSC) contractions are induced in the foot and thigh regions which can enhance the LL's ability to perform SSC movements, while core muscle groups controlled by the hips could better preserve body control and stability [7]. The rope skipping, an alternate type of exercise that can be performed within little time and increasingly popular has become more and more in the consequence of the COVID-19 pandemic. Rope skipping has been found in numerous investigations to improve bone health, balance, and strength of muscles, coordination, endurance, agility, and cardiopulmonary function in individuals [8]. The alignment of various Total Knee Arthroplasty alignment ideas with the inhabitant alignment of patients without osteoarthritis was evaluated in [9]. It also introduced a categorization scheme for LL alignment based on phenotypes. In two recent publications, the Tibia and Femur of 308 individuals' non-osteoarthritic knees were phenotypes. Combining all previously introduced traits, the study presents practical knee phenotypes. Therefore, a systematic investigation of the coronal alignment is made possible by the functional knee characteristics, which allow an assessment of all variables to one another. Forty-three of the 125 potential practical knees, ankle and hip characteristics:35 males, 26 and 18 mutual were identified. For Total Knee Arthroplasty (TKA) alignment, a more customized strategy was required. The effects at different intensities (maximum, medium, and minimal efforts), study [10] examined knee, hip and ankle joint loading during jumping, jogging, walking, and hopping activities. A total of 37 fit, active individuals were enlisted by their height, massand age. Each participant's motion capture data was recorded throughout six distinct exercises: running, walking, unilateral hopping, countermovement jumping, squat jumping, and bilateral hopping. The participants chose the intensity of each activity. For every OpenSim user, a lower body musculoskeletal model was created. Study highlights the prospective of hopping and running for bone production compared to jumping only, emphasizing the site-specific influence of activities on LL joint loadings. To assess the functional performance of jump tests and the strength of the knee, study [11] examined land control following anterrior cruciate ligaments reconstruction (ACLR) with respect to active knee strength and entire body group techniques when doing side hops that simulate sports. Joint moments and angles were measured during identical bounce back side-hop landing by 32 people with an ACLR and 32 matched asymptomatic controls using a capture system of 8-camera motion and two force plates that are coordinated.

Suspension Training's (SET) impact on patients' knee kinematics, postural control, and neuromuscular function following ACLR surgery was examined [12]. A control group and a SET group were randomly assigned to forty individuals. The participants in the SET group underwent a 6-week SET program. For six weeks, the participants in the control group followed a conventional training regimen. Assessed pre- and post-training included relative translation of the damaged knee, a static and dynamic posture stability test, and isokinetic muscular strength of the hamstrings and quadriceps. Both groups saw a substantial increase in the relative peak torque of their hamstrings and quadriceps, with the SET group represented a greater percentage than the control group [13]. After ACLR, 49 athletes were divided into three groups: early, medium, and late. These groups were compared with a group of athletes who did not have any symptoms (control; $n = 18$). By applying functional data analysis techniques, the damaged and noninjured legs of the ACLR groups and the control group's legs were compared, along with the sagittal plane angles of the ankle, knee and hip, moments, angular velocities, and powers. On both damaged and uninjured legs, all three ACLR groups had higher knee flexion angles and moments than the control group. The issues of establishing, outlining and examining the efficacy of the complicated physical rehabilitation program among patients after arthroscopic surgery for ACLR were covered in [14]. The primary group of patients (21), underwent rehabilitation following ACL replacement, in accordance with the suggested regimen. The standard course of physical therapy was administered to 31 individuals. The fact that all patients in the control group had moderate or high levels of asymmetry in their lower limb load distribution, as revealed by stabilographic study findings conducted during the functional rehabilitation phase, indicates that the patients had persisted in overexerting their intact LL. During a stepdown and cross-over task involving a 45° shift in direction, muscle activity and knee joint mechanics varied between people early after renovation and undamaged controls were investigated [15]. They employed functional t-tests to compare time-normalized curves of transverse and sagittal-plane muscle activity and knee mechanics throughout the cross-over period between groups utilizing motion capture, force plates, and surface electromyography. The injured participants showed longer cross-over phases and smaller cross-over angles for theuninjured and damaged sides, as well asalower internal rotation moment, alarger knee flexion moment and angle, and more anticipatory foot rotation of the changing direction leg when compared to the control. Article [16] created a LL exoskeleton to improve the muscle strength of hemiplegic patients and assist the afflicted side regains its usual gait after a lengthy period of training. The patients were given assistance with rehabilitative walking training using a wire rope-driven exoskeleton that combines a stiff bracket and flexible driven methods. Based on the findings, strephenopodia and hip excessive abduction-related hemiplegic gait were avoided. Examining the association between arm swing kinematics and lower limb muscle EMG activity during vertical jumping was the objective of the investigation [17]. They cannot validate the initial hypothesis with the outcomes of the EMG comparison, whereas jumps are performed with arm swing, they can observe larger vertical GRF during the adverse acceleration of the arm's swing that indicates greater strain on the lower limb.

The objective of the study comprehensively analyses the lower limb movement during different skipping rope modes using OpenSim, investigating biomechanical factors at the knee, ankle, and hip joints to identify potential injury risks and provide insights for optimizing exercise techniques and rehabilitation programs.

1.1. Research gaps

Research on the examination of lower limb movement

during skipping rope primarily concentrates on middle-aged people. The study gap limits the capacity to related the biomechanical modifications and injury risks specific to older persons, which is important for developing personalized exercises and injury prevention techniques. The information can be displayed through the establishment of a research gap, that can be used the common method for communicating the description of all.

1.2. Research questionnaire

(1) What is the impact of different rope skipping techniques on the change in knee joint angle during landing?
(2) How does torque applied by the ankle joint vary under different techniques during a jump?

2. Methods

2.1. Data collection

The study included 56 participants in healthy conditions (45 male and 11 female). The study consists of two criteria such as inclusion criteria and exclusion criteria.

- Inclusion Criteria
  The study's participants were:
  (1) in good health and did not have any injuries
  (2) Had engaged in jumping rope activities
- Exclusion Criteria
  To avoid bias in the study, participants were excluded if they:
  (1) currently had lower muscle discomfort or injury that may have an impact on the results
  (2) Had a particular ailment or had surgery within the last six months.

Prior to the study, every participant received written information on the goals and procedures of the research and they were obliged to read and sign the consent form. Subsequently, **Table 1** presents the revised demographic features of the individuals.

Table 1. Participants' demographic characteristics.

Samples (*N* = 56)		
Characteristics		**Mean ± SD**
Age (year)		45.30 ± 4.49
Height (cm)		168.64 ± 8.42
Weight (kg)		81.45 ± 15.46
Gender	Male	45
	Female	11
BMI (kg/m^2)		26.50 ± 6.20

2.2. Procedure for experiments

The anatomical bone landmarks on both sides of the participant's body were characterized by the placement of twenty-eight 13-mm infrared reflecting markers on each individual. Anterior Posterior Superior Iliac Spine (PSIS), Greater Trochanter, Anterior Superior Iliac Spine (ASIS) and for the hip joint, Lateral and Medial Malleolus, Calcaneus (Heel Bone) and Talus for the Ankle joint. Lateral and Medial

Femoral Epicondyles and Lateral and Medial Tibial Plateaus for the knee joint. To make sure the participant's movement was fully captured, the markers were positioned on both sides of significant bone landmarks. To record the trajectories of markers throughout the six distinct jumping rope techniques, the motion capture system OpenSim, equipped with sixteen infrared cameras at high speed, was utilized. Two fully integrated three-dimensional force platforms were synchronized for capturing the dynamic ground-reaction force (GRF) data using a motion capture system. **Figure 1** illustrates the types of joints located in LL which was used in the study.

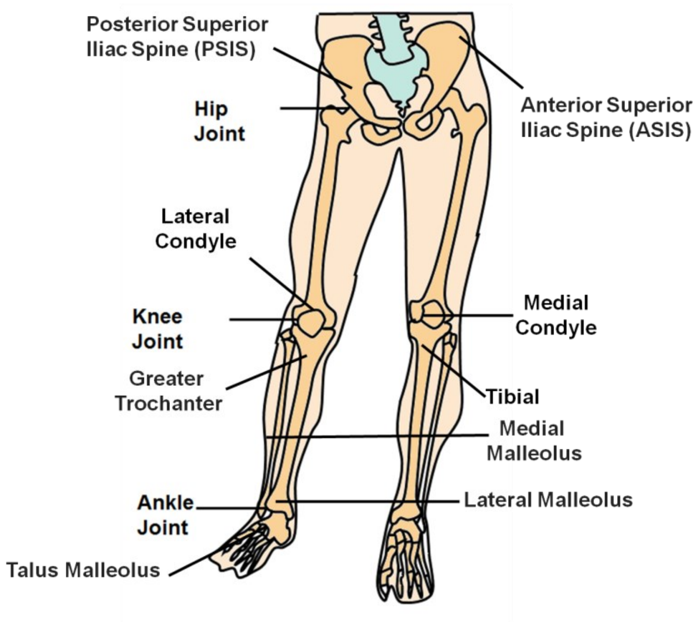

Figure 1. Types of joints located in LL.

Jumping rope techniques

Prior to the experiment, all participants received thorough instructions on the performance assessment, and they were randomly assigned to execute six distinct jumping rope techniques represented in **Figure 2**. The Six techniques are Basic Bounce (BB) having 17 numbers of participants, 10 participants in Double under (DU) technique, the Cross-Over Jump (COJ) techniques are performed by 8 participants, 5 participants were followed a Side Swing (SS) approach, 9 participants were observed in Boxer Step (BS) method and the Single Leg Jump (SLJ) technique was performed by 7 participants.

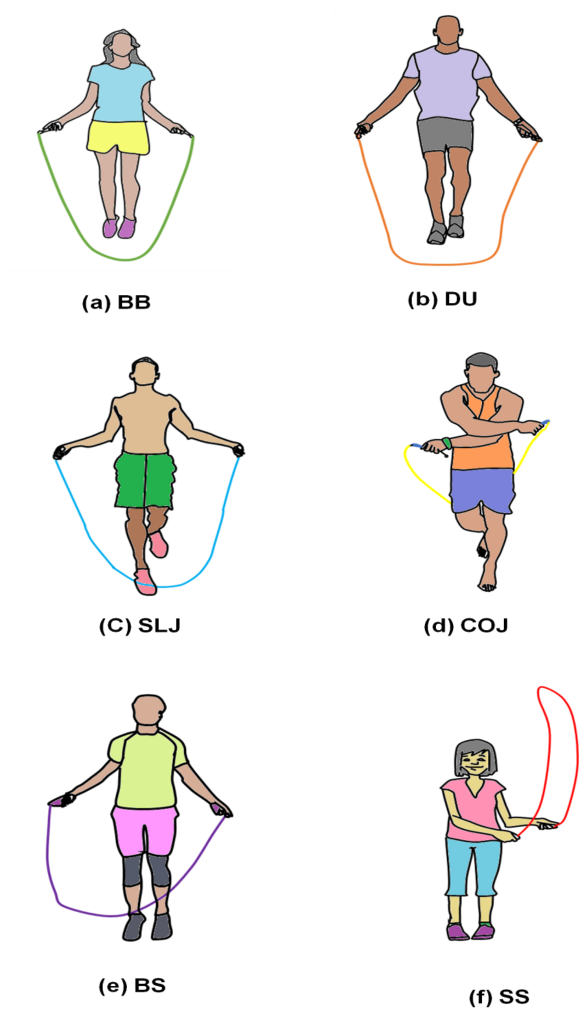

Figure 2. Jumping rope techniques.

a) Basic Bounce (BB): Make a basic up-and-down jump while maintaining a steady rhythm and mild bounce. Jump with both feet together. This technique has resilient impact on foot by repetitive jumping and landing. To lower the possibilities of the impacts in the muscles, dynamic warm-up and stretching activities is needed to target the shins, calves, and Achilles tendon.

b) Double under (DU): To make a jump higher and the rope rotate more quickly, swing the rope twice beneath feet. The stress fractures of the lower leg bones and strain in ankle muscle is the injury of performing DU approach. To avoid injuries caused by DU method, organize personally for adequate time to heal between exercises.

c) Single Leg Jump (SLJ): Execute the fundamental bounce while switching legs or concentrating on one leg for a certain amount of time. To the greater strain on a single limb, the SLJ method has a significant risk of injury such as knee pains, fractures of stress in the foot and lower leg. To reduce falls and injuries, strengthen the balance with single-leg standing and stability soccer exercises.

d) Cross -Over Jump (COJ): Make the rope form an "X" shape as you jump, cross your arms in front of your body, and then uncross for the next jump. The complex motions could potentially result in hip flexor strains and ankle sprains is the risk in COJ technique. Regular stretching are able to avoid strains by maintaining your hip, knee, and ankle flexibility.

e) Boxer Step (BS): Lightly jump rope and shift your weight from one foot to the other, imitatinga boxer's footwork. Shin splints and patellar tendinitis are two repeated stress issues that can result from this technique. To slowly improve muscularity and stamina, start with low-impact BS modifications.

f) Side Swing (SS): Often used as a transitional motion, swing the rope to the side of your body without jumping. With each swing, alternate sides. The side-to-side motions of the SS technique can cause lateral ankle injuries and iliotibial ligament syndrome. Reduce unanticipated lateral stresses on the joints by emphasizing on smooth and steady side swings.

Participants were told to jump with their knees slightly bent, making sure their heels did not touch the ground as they landed. Before the experiment began, every participant was instructed to warm up for five minutes in the self-selected activity and work on jumping rope until they were comfortable with the procedure and motions of the test. Every method was tested for 20 seconds while the participant was barefoot and the metronome tempo was set to 140 bpm and each technique was then used for five minutes of rest. Any leap that a competitor made without tripping or losing their balance qualified as a full jump for each jumping rope style. **Table 2** displays the factors used in this investigation.

Table 2. Features of kinematics and kinetics data.

Types of Data	Features
	Knee flexion (degree)
	Knee moment (%BWm)
Kinematics	Ankle Flexion(degree)
	Ankle Torque(%BWm)
	Hip-Flexion Angle (degree)
	Hip Torque(%BWm)
Kinetics	Knee joint GRF (%BW)
	Muscle forces (%BW)
	Ankle joint GRF (%BW)
	Ankle forces (%BW)
	Hip joint GRF (%BW)
	Hip Joint forces (%BW)

Note: BW-Body Weight; BWm-Body Weight·Hegiht (meter).

The motion capture system uses biomechanical plates and sensors to detect muscle forces, joint force, and ground response forces. It enables for a comprehensive examination of the moments and forces involved in the motion by including to the kinetic and kinematic data.

2.3. Data processing

After the data was gathered, by utilizing a Savitzky-Golay filter, the experiment's kinematics and kinetics data were processed with 20 Hz for the force signal and the frequency limits in 6 Hz of the motion capturing system in the OpenSim program. The data from each trial, spanning 10 seconds was examined on the subject's dominant leg.

For use in the biomechanical data analysis, the experiment's knee kinematics and kinetics data were exported and saved in the osim (Model File) file format.

2.4. Biomechanical data analysis

Using 76 muscles, 12 bone segments and 23 degrees of freedom, the OpenSim 4.3 general musculoskeletal template model Gait2354 was simplified for this investigation. In the six distinct jumping rope styles, the study's primary focus was on the risk factors for knee, ankle and hip joint features. The following are the muscle forces determined in this study: Tibialis Anterio, Iliopsoas, and Quadriceps Femoris. The anthropometry was produced by scaling the musculoskeletal model, and OpenSim was used to compute the inverse kinematics (IK). Additionally, the six distinct jumping rope techniques were simulated in reverse using the joint reaction analysis tool, static optimization, and OpenSim.

2.5. Statistical analysis

Using SPSS 28.0, the biomechanical characteristics of the LL from six distinct jumping rope styles were examined. Prior to analysis, each data set was checked for equal variance and normality. Mann-Whitney U test was used to compare the median and mean values of particular features between two distinct skipping rope modes, such as joint angles and muscle activations. If there are statistically significant variations in the LLmovement patterns among the modes, this test can identify for each analysis, the significant difference threshold of P-value was set to $p < 0.05$ and non-significant difference of P-value was set to $p > 0.05$. Before analysis, all the information was examined for equal variance and normality. The average variation in each jumping rope method of IC and MKF was compared using the paired samples t-test and the mean variation among various skipping rope approaches in the IC-MKF phase was compared using the analysis of variance (one-way ANOVA). The significance threshold for differences was established for analyses, and the Tukey test of averages was applied to perform the comparison.

3. Result

The Mann-Whitney U revealed a significant mean difference between IC and MKF in every jumping rope technique. As seen in **Table 3**, these findings demonstrated that variations in MKF had substantial impacts on the Knee features (knee joint GRF, knee flexion angle, muscle forces and knee flexion moment) when compared with IC ($p < 0.05$). Comparing the knee biomechanics of Double-Under (DU) and Boxer Skip (BB) skipping rope methods is represented in **Table 3**.

Table 3. Knee statistics (mean ± SD) between the MKF and ICof two distinct jumping rope methods.

Jumping Rope Techniques	Features	Maximum knee flexion (MKF)	Initial contact (IC)	P Value	Significance
BB	Knee flexion (degree)	30.59 ± 3.55	21.27 ± 3.57	<0.0001	Significant
	Knee extension moment (%BWm)	2.16 ± 0.54	1.01 ± 0.46	<0.0001	Significant
	Knee joint GRF (%BW)				
	Vertical	−145.81 ± 34.50	−128.68 ± 31.75	<0.0001	Significant

Table 3. (*Continued*).

Jumping Rope Techniques	Features	Maximum knee flexion (MKF)	Initial contact (IC)	P Value	Significance
	Knee joint GRF (%BW)				
	Anteroposterior	21.43 ± 19.73	17.12 ± 14.24	0.2079	Not Significant
	Mediolateral	3.85 ± 9.25	4.56 ± 8.79	0.6456	Not Significant
	Muscle forces (%BW)				
	Quadriceps	524.50 ± 92.29	412.08 ± 54.15	<0.0001	Significant
	Hamstring	53.34 ± 37.17	47.15 ± 37.16	0.3723	Not Significant
	Knee flexion (degree)	35.78 ± 8.52	21.42 ± 9.45	<0.0001	Significant
DU	Knee flexion (degree)	30.69 ± 3.57	21.37 ± 3.67	0.021	Significant
	Knee extension moment (%BWm)	2.17 ± 0.55	1.50 ± 0.60	0.042	Significant
	Knee joint GRF (%BW)				
	Vertical	115.57 ± 20.78	100.13 ± 21.73	0.003	Significant
	Anteroposterior	10.52 ± 3.47	13.49 ± 4.38	0.071	Not Significant
	Mediolateral	7.17 ± 13.56	7.18 ± 11.83	0.982	Not Significant
	Muscle forces (%BW)				
	Quadriceps	386.84 ± 74.09	211.44 ± 41.61	0.001	Significant
	Hamstring	51.84 ± 39.08	48.05 ± 42.01	0.221	Not Significant

During first contact, DU had a larger knee extension moment (%BWm) of 1.50 ± 0.60 than BB (1.01 ± 0.46), but BB showed lower maximum knee flexion (30.59° ± 3.55°) than DU (35.78° ± 8.52°). Further evidence of unique loading patterns and possible injury risks came from the large disparities in knee joint ground reaction forces (GRF) across all planes and muscle forces that both approaches demonstrated. As shown in **Table 4**, these findings demonstrated that variations in MKF had substantial impacts on the Ankle features (Ankle Flexion, AnkleTorque, Ankle Joint GRF, and Ankle Forces) when compared with IC ($p < 0.05$).

Table 4. Ankle statistics (mean ± SD) between the MKF and IC of two distinct jumping rope methods.

Techniques	Features	MKF	IC	*P* Value	Significance
SLJ	Ankle Flexion (degree)	30.59 ± 3.65	22.37 ± 3.67	0.013	Significant
	Ankle Torque (%BWm)	2.06 ± 0.64	1.11 ± 0.56	0.027	Significant
	Ankle Joint GRF (%BW)				
	Dorsiflexion	–165.91 ± 37.60	–118.78 ± 30.65	0.002	Significant
	Plantarflexion	20.53 ± 18.93	18.02 ± 15.34	0.081	Not Significant
	Muscle Forces (%BW)				
	Tibialis Anterior	530.50 ± 93.59	404.18 ± 55.05	0.001	Significant
	Peroneous Longue and Bevis	54.47 ± 38.07	49.25 ± 35.06	0.351	Not Significant

Table 4. (*Continued*).

Techniques	Features	MKF	IC	*P* Value	Significance
COJ	Ankle Flexion (degree)	37.98 ± 8.62	26.62 ± 9.65	0.008	Significant
	Ankle Torque (%BWm)	1.90 ± 0.60	1.60 ± 0.70	0.056	Not Significant
	Ankle Joint GRF (%BW)				
	Dorsiflexion	–125.67 ± 21.88	–110.23 ± 20.93	0.005	Significant
	Plantarflexion	11.62 ± 3.37	14.59 ± 4.28	0.101	Not Significant
	Muscle Forces (%BW)				
	Tibialis Anterior	396.94 ± 78.09	209.64 ± 42.71	0.001	Significant
	Peroneous Longue and Bevis	53.94 ± 40.18	49.15 ± 43.11	0.621	Not Significant

Participants in crossover jumps (COJ) (37.98° ± 8.62) showed higher maximal knee flexion (MKF) (30.59° ± 3.65) than in single-leg jumps (SLJ), indicating variations in knee biomechanics. In contrast to COJ (26.62° ± 9.65), initial contact (IC) during SLJ (22.37° ± 3.67) happened at a lesser angle, suggesting possible differences in landing mechanics. There were notable variations in ankle flexion, torque, and muscular forces between the two methods, indicating different patterns of LLloading. The Hip Biomechanics of Single Skip (SS) and Boxer Skip (BS) Techniques for Rope Jumping are compared in **Table 5**. These findings demonstrated that variations in MKF had substantial impacts on the Hip features (Hip-Flexion Angle, Hip Torque, Hip joint GRF, and HipJoint forces) when compared with IC ($p < 0.05$).

Table 5. Hip statistics (mean ± SD) between the MKF and IC of two distinct jumping rope methods.

Techniques	Features	MKF (Maximum Knee Flexion)	IC (Initial Contact)	P Value	Significant Value
BS	Hip-Flexion Angle (degree)	32.69 ± 3.65	24.77 ± 5.47	0.031	Significant
	Hip Torque (%BWm)	2.07 ± 0.54	1.21 ± 0.56	0.045	Significant
	Hip Joint GRF (%BW)				
	Tensile Force	–175.91 ± 37.60	–118.78 ± 30.65	0.001	Significant
	Compression Force	21.53 ± 18.93	18.02 ± 15.34	0.071	Not Significant
	Shear Force	3.96 ± 10.35	4.86 ± 8.99	0.201	Not Significant
	Hip Joint Forces (%BW)				
	Quadriceps	535.40 ± 93.59	404.18 ± 55.05	0.002	Significant
	Hamstring	54.47 ± 38.07	49.25 ± 35.06	0.101	Not Significant
SS	Hip-Flexion Angle (degree)	37.88 ± 8.62	26.72 ± 9.65	0.012	Significant
	Hip Torque (%BWm)	1.80 ± 0.60	1.60 ± 0.70	0.056	Not Significant
	Hip Joint GRF (%BW)				
	Tensile Force	–125.67 ± 21.88	–110.23 ± 20.93	0.005	Significant
	Compression Force	11.62 ± 3.37	14.59 ± 4.28	0.101	Not Significant
	Shear Force	7.07 ± 13.46	7.17 ± 12.83	0.982	Not Significant
	Hip Joint Forces (%BW)				
	Quadriceps	396.94 ± 78.09	209.64 ± 42.71	0.001	Significant
	Hamstring	53.94 ± 40.18	49.15 ± 43.11	0.621	Not Significant

The maximal knee flexion of BS is 32.69°, but that of SS is 37.88°. This difference may indicate that BS experiences less knee stress. Furthermore, compared to SS (1.80% BWm), BS exhibits a greater hip torque (2.07% BWm), indicating a higher level of hip muscle involvement in BS for propulsion or stabilization. Finally, compared to SS (-125.67% BW), BS exhibits a larger tensile force at the hip joint (-175.91% BW), suggesting that BS has greater hip joint loading, which could have an impact on training adaptations or injury risks.

3.1. Activities of muscles in lower limb biomechanical effects

In this analysis, we have employed the lower limb biomechanics with muscle activities. Compared to gait kinetics, the impact of simulated lowered gravity on biomechanics muscle activation was less apparent. When gravity was lowered, the amplitude of activity in specific muscles dropped and in other muscles increased. While impacted by gravity, certain muscles were not affected in amplitude of activity. During the skipping phase, the research observed that lowered gravity considerably decreased the activity of the Tibialis Anterio, Iliopsoas, and Quadriceps Femoris ($p<0.01$). Reduced gravity was shown to significantly enhance activation of the tibialis anterior during falling phase and the biceps femoris during skipping phase ($p=0.05$ and $p<0.01$). **Table 6** shows the statistical results of muscle activities.

Table 6. Statistical outcomes of muscle activities significant levels.

Factors		*p*-value
Skipping phase of EMG	Iliopsoas	0.06
	Quadriceps Femoris	< 0.01*
	Tibialis Anterio	0.78
Strength	Absorption of Knee	< 0.01*
	Ankle generating	< 0.01*
	Hip Generating	< 0.01*
	Knee Generating	< 0.01*
Force	Highest Break	< 0.01*
	More Accelerations	< 0.01*
	Highest Medical-Lateral Possibilities	< 0.01*
	Vertically high	< 0.01*
Motion	Ankle Flextion	< 0.01*
	Knee Flexion	0.89
	Hip Flextion	< 0.01*

3.2. Rope skipping actions and types of injuries

The primary components of impact stresses, joint angle variations, and muscle activation for every skipping rope method, provide an in-depth explanation of the biomechanical requirements at various phases of the movements. The detailed could found in **Table 7**.

Table 7. Various rope skipping actions.

Rope Skipping Techniques	Actions			Types of injuries
	Muscle activation in Take-off stage	Angle changes in Air stage	Landing stage impact force	
BS	Hip flexors, quadriceps and calf	Little alteration in joint angle	Soft landing	Achilles tendon
BB	Quadriceps and gastrocnemius	Flexible knees	Impact force on moderation	Patellar tendinitis
SLJ	Glutes and quadriceps	Alexion dorsi in ankle	Soft landing	ACL tears, meniscus injuries
DU	Hamstrings and quadriceps	Alexion dorsi in ankle	Knee bending	ACL tears
SS	Abductors and adductors	Lateral motion modifications	Control in knee and importance on balance	Ankle sprains
COJ	Activation in hip flexors	Rotational motion	Hip and knee joint	Knee ligament strains

4. Discussion

In our study, significant differences were observed in LL biomechanics across different skipping rope modes. Double-under jumps demonstrated higher ankle and hip muscle forces compared to other modes, while single leg jumps exhibited increased knee flexion angles. Boxer skip showed distinct patterns in joint moments, suggesting varied loading mechanisms. When compared to Boxer Skip (BB) (1.01 ± 0.46), Double-Under (DU) displayed a larger knee extension moment (%BWm) at initial contact (1.50 ± 0.60), and DU had a higher maximum knee flexion (35.78° ± 8.52) than BB (30.59° ± 3.55). Individuals who participated in crossover jumps (COJ) had a greater maximum knee flexion (37.98° ± 8.62) in comparison to those who performed single-leg jumps (SLJ), suggesting variations in knee biomechanics. In comparison to Single Skip (SS) (37.88°), Boxer Skip (BS) showed a lower maximum knee flexion (32.69°), which may indicate less knee stress in BS. Furthermore, BS showed higher hip torque (2.07% BWm) and hip joint tensile force (-175.91% BW) than SS. The biomechanical elements were experimental during various jumping rope techniques: BB, DU, and two-foot SS. **Table 1** represents the significant variations in MKF and IC between BB and DU strategies, with *p*-values of 0.012 and 0.021 respectively. **Table 2** depicts significant differences in ankle flexion and torque, as well as muscle forces, between the SLJ and COJ strategies, with significant ranges of 0.013 and 0.008 for MKF and IC. **Table 3** shows the disparities in hip flexion angle, torque, joint forces, and muscle forces between BS and SS strategies, with significant values of 0.031 and 0.012 for MKF in BS and SS respectively. The valuable insights into the biomechanical variations among several jumping rope strategies, offering potential implications for training and injury prevention strategies.

The aim of the research is to examine and compare potential biomechanical adverse effects that could occur from various jumping rope activities. ACL [18] reconstructing decreases while the knee flexion angle increases during knee motion, based on a past investigation. Compared to other jumping rope techniques, the lower knee flexion angle in higher maximum knee can boost the risk of knee injury and increase its strain. Knee strains including osteoarthritis and patellofemoral pain syndrome can be caused by increased vGRF [19] or inadequate shock absorption. The ACL and MCL, two internal knee joint ligaments, contribute in stabilizing and resisting the leg against side-to-side stresses and excessive movement while falling after a jump or changing directions quickly. Excessive usage of mGRF [20] can result in inadequate knee stabilizing mechanisms and can cause injuries such as rips to the ACL. Ankle overpronation can occur from the lateral side's high impact lateral mGRF [21]. To raise the leg's anterior shear strength and hit the leg forward as opposed to the the femoral the greater movement required for leaping and falling could result in greater quadriceps muscle forces [22]. The anterior tibial translation, increased pressure on the ACL and resulting injury could occur from inadequate protection. Different approaches can be able to show the knee joint risk factors in this research for multiple causes. The research revealed that in comparison to other jumping rope techniques, SS exhibited a larger knee extension moment, knee joint aGRF, mGRF, and quadriceps muscle forces that can increase the ACL stress and cause an ACL injuries. In the IC and MKF phases, higher maximum knee showed less knee flexion. ACL damage can be more probable to the unique jumping and landing motion.

5. Conclusion

The study concluded the importance of considering LL biomechanics when performing different skipping rope modes. Utilizing OpenSim, we are able to examine the lower limb movement in various skipping rope modes with effectiveness while examining biomechanical aspects at the ankle, hip, and knee joints. We analyze six roping techniques (BB, DU, CLJ, SLJ, BS, SS) related to three specific lower limb movements. The results indicate possible hazards for injuries and offer guidance for improving training methods and recovery plans. Thus, it is advised that SS be used in further research on ACL risk assessment, based on jumping rope techniques. By examining joint motions and force distribution, gait kinetics can be utilized for evaluating skipping in rope. Enhancing technique and effectiveness in skipping processes, it improves by determining biomechanical effectiveness and potential injury issues. Naturally leaping and landing jumping rope techniques, such as BB, have demonstrated a reduced risk of damage than other techniques, which can minimize the risk of ACL and knee joint problems. Therefore, it may be appropriate for normal people to use it in their rehabilitation programs or for workouts. The sample size and the findings' applicability to a range of cultures could pose limitations to the study. Personalized training plans based on unique biomechanical characteristics could be developed in the future to maximize performance and lower the risk of injury during skipping rope activities.

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Conflict of interest: The author declares no conflict of interest.

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