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Lower extremity joint loading during Bounce rope skip in comparison to run and walk

Rajani Mullerpatan *, Triveni Shetty , Yuvraj Singh , Bela Agarwal

MGM School of Physiotherapy, MGM Institute of Health Sciences, Navi Mumbai, India

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ABSTRACT

Background: Bounce rope-skip holds immense scope as an aerobic exercise in space and time constrained urban setting with additional constraints placed by pandemic situations such as Covid 19, wherein adherence to commonly performed weight-bearing, aerobic activities like walking and running is a challenge. Limited knowledge informing biomechanical demands and misconceptions about knee joint loading, confines safe application of bounce rope-skip in health promotion. Thus, present study aimed to explore kinematics and lower-extremity joint loading during rope-skipping compared to walking and running.

Methods: Following ethical approval, 3D motion analysis of bounce rope-skip, walk and run was captured from 22 healthy female participants aged 18–25yr using 12-camera Vicon system and 2AMTI force plates. Three trials for bounce rope-skip were recorded with five skip-jumps on force-plates at a cadence of 105 skips/min. Mid-skip, mid-gait and mid-run data were averaged to compute kinetic and kinematic variables for hip, knee and ankle during loading/initial contact, take-off/push-off and flight/mid-swing phases of rope-skip, walk and run.

Result: Average time of one rope-skip cycle was 1.2sec; mean foot contact time was 0.55sec and flight time was 0.65sec. In one bounce rope-skip cycle, hip motion ranged between 13.4°-35.3°flexion; knee between 13.6 °-67.9° flexion and ankle between 34.5°dorsiflexion to-13.4°plantarflexion. Vertical ground reaction force (vGRF) during rope-skip (landing-phase) was lower compared to run; however, it was higher than walk ($p < 0.001$). In coronal plane, peak hip and knee adductor moment during rope-skip were lower compared to run and higher than walk ($p < 0.001$).

Conclusion: Bounce rope-skip generated low lower extremity joint loading compared to run; supporting its prescription as a hip and knee joint-protective aerobic weight-bearing exercise for health promotion in young adults.

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1. Introduction

Bounce rope-skip is a simple, high-intensity aerobic activity practiced across most parts of the world; among children, adolescents and youth. Although it is a common leisure activity; it is a less common competitive sport. It involves repeated jumping, bouncing or skipping across a length of rope. The three phases of rope-skip i.e. take-off, flight and landing demand co-ordination between various body segments combining angular momentum and vertical displacement of body (Trecroci et al., 2015). Take −off is a preparatory phase in which both feet leave contact with ground. Flight is an airborne phase, where the rope passes underneath the feet. Landing is the loading phase, where both feet re-establish contact with ground (Lee, 2010). Bounce rope-skip is known to improve speed, agility, balance, strength, power, dynamic balance and cardio respiratory endurance (Ozer et al., 2011; Solis, 1988) and is used extensively as a warm-up exercise prior to several sports.

Walking and running are other commonly practiced aerobic activities which achieve similar health benefits and improve athletic performance. Walking is most conventional and widely practiced low intensity, aerobic, weight bearing activity performed by all age groups for various health benefits. On other hand, running is a high-intensity aerobic weight bearing activity, gaining increasing popularity in last few decades. Alternate training sessions of either running or high intensity walking are known to improve aerobic

* Corresponding author. MGM School of Physiotherapy, Plot Number 1&2, Sector1, Kamothe, Navi Mumbai, Maharashtra, India.
E-mail address: rajani.kanade@gmail.com (R. Mullerpatan).

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capacity and muscular endurance (Fiuza-Luces et al., 2018). Additionally, these weight bearing activities generate moderate repeated tensile forces on lower extremity encouraging bone remodeling (Hong et al., 2018). An appropriate dose of running confers enormous health benefits such as-weight reduction and reduction of risk of non-communicable diseases (Williams et al., 2013).

However, people in cities face several challenges to practice run regularly, such as access to open spaces; safe running tracks and lack of time. Provision of parks and jogging tracks in space-constrained cities places huge financial cost implications on the local government in low to middle income countries. Additional constraints laid by current Covid 19 pandemic situation demand exploration of alternate aerobic exercises like skipping. WHO recommends minimum 150 min of moderate intensity physical activity per week or 75 min of vigorous intensity aerobic physical activity for young adults to improve cardio respiratory and muscular fitness, bone health, reduce the risk of NCDs and depression (WHO ref). Hence, there is an urgent need to identify alternate aerobic activities to achieve health benefits while extenuating extrinsic barriers.

Bounce rope-skip can emerge as one such potential aerobic exercise which requires negligible resources to provide minimum recommended level of physical activity. Although several studies report physiological benefits of bounce rope-skip, there is paucity of literature informing biomechanics of bounce rope-skipping. Kinematics of rope jumping during bounce skip, jump skip, alternate leg skip and bell skip are reported (Chow et al., 2014). It is known that vertical ground reaction force (GRF) is low during alternate leg skip (Chow et al., 2014). However, GRF is highest during bounce rope skip and demonstrates a linear relationship with take-off velocity and jump height (Chow et al., 2014). However, paucity of literature on biomechanics of bounce rope-skipping compared to other aerobic and weight bearing activities like walking and running, motivated present study to explore lower extremity joint loading during bounce rope-skipping compared to running and walking. The authors hypothesized that lower extremity joint loading between bounce rope skip, running and walking will be different. Understanding magnitude of ground reaction force during bounce rope skip in comparison to run and walk will inform therapists to promote it as an aerobic exercise option for health promotion and as a sport among young adults. Therefore, the objectives of present study were to describe kinematics of bounce-rope skip, run and walk and explore and compare lower extremity joint loading during bounce rope skip with run and walk.

2. Methodology

The current study was an exploratory cross-sectional study approved by the Institutional Ethics Committee. Twenty-two healthy female University students aged 18–25 years accustomed with bounce rope-skipping were recruited by convenient sampling method. Informed consent was sought as per Declaration of Helsinki guidelines. Volunteers with history of musculoskeletal disorders and traumatic injuries in past six months or presenting with cardio-pulmonary and developmental disorders were excluded. All participants performed all three activities i.e. bounce rope-skip, run and walk on the same day in a supervised environment with 10 min rest pause in between each activity. Total testing time lasted for 1 h including the preparation time.

Demographic information included age (years), body height (cm), body mass (kg) and body mass index (BMI) (kg/m^2). Level of habitual physical activity was recorded using International Physical Activity Questionnaire–Short Version (IPAQ). None of the participants practiced rope-skipping as a sport or leisure activity.

Kinematics was captured with a 12-camera 3D motion capture system using 39 retro-reflective markers placed over bony landmarks (Vicon, Oxford Metrics plc, UK) and kinetics was studied with 2 force plates (AMTI, USA). Data were captured at a frequency of 100 Hz for walk trials and 250 Hz for run and bounce rope-skip. Participants were instructed to perform bounce rope-skipping with one foot striking each force-plate. The preferred base of support for skipping ranged from 17 to 26 cm. Three trials of bounce rope-skip were recorded with minimum five jumps on each force-plate. Two practice trials were performed prior to recording. Average speed of rope jump was 0.22 m/s and the cadence ranged between 100 and 110 jumps per minute. A rest period of 10 min between activities was introduced to avoid fatigue.

Three walk trials were captured. Participants were instructed to walk across a 10 m walkway at self-selected speed to record one walk trial. Average velocity of walking was 1.19 ± 0.17 m/s and average cadence was 118 steps/min. Mid-gait data were used for analysis.

Run was captured across a 25 m runway, at self-selected speed. Arrangement of the force plate allowed single foot strike during a single run trial. A total of six run trials were captured to obtain 3 left foot strikes and 3 right foot strikes. All participants demonstrated a rear-foot strike run pattern. Participants ran at an average speed of 2.79 m/s (0.54) and average cadence of 181 steps/min.

All three activities were performed in a random order amongst 22 participants, to preclude the bias of cross over effect. The three activities were tested in 6 sequence combinations using cross-over design. Each participant was asked to draw a chit on arrival before preparing for motion analysis. The sequence combination on the chit would be the testing sequence for the three activity. The chits were prepared such that each sequence was repeated at least on 3 participants. Data were processed in Nexus 2.5 software. Lower extremity joint kinematics were described by angular displacement (^{0}) of joint segments and center of mass (CoM) excursion during the 3 activities. Lower extremity joint kinetics were described by external net joint moments at hip, knee and ankle. Net joint power described the type of work (eccentric/concentric) indicating absorption or generation of muscle force. Lower extremity joint loading was measured with ground reaction force normalized for body weight and lower extremity external net joint moments during all three activities.

Butterworth filter was used to filter trajectories and analogue data of skip; with a cut-off frequency of 10 Hz. Standard filter settings were used to process walk and run trials (Farland et al., 2015).

2.1. Statistical tests

Data were analyzed statistically using SPSS version 24(SPSS IBM, New York, USA). Normality of distribution was ascertained using Shapiro- Wilk test; measures of central tendency and dispersion were calculated and reported as means and standard deviation. The three activities i.e. walk, run and bounce rope-skip were symmetrical in weight-bearing. Hip, knee and ankle joint kinematics in sagittal plane were compared on right and left side for skipping, running and walking to investigate difference between sides using Student *t*-test. Comparison among groups was performed using One-way ANOVA with level of significance at $p \leq 0.05$. Post-hoc analysis was performed using Bonferroni test with level of significance adjusted at $p \leq 0.01$ Bonferroni adjustment was performed during post hoc analysis to reduce Type I error (Sedgwick, 2012). Linear contrast was performed to examine a linear trend among three activities.

3. Results

Sagittal plane joint angles and net joint moments of 22 female adults (mean age 21.1 year; body height 160 cm; body mass 53.3 kg; BMI 20.6 (3.5) kg/m^2) are presented in Table 1. Average score of 698.4 (260.0) MET min/week was recorded on IPAQ scale; indicating moderate level of habitual physical activity among all participants. All three activities i.e. walk, run and bounce rope-skip were symmetrical in weight-bearing. Joint kinematics did not demonstrate significant difference in hip flexion/extension, knee flexion and ankle dorsiflexion/plantarflexion during the instances of loading/initial contact and take-off/push-off between right and left side ($p > 0.05$).

Hence, variables measured on only on one side i.e. right lower extremity were considered for comparison of all three weight bearing activities. In the present study, bounce rope-skip is described in three phases viz – take-off, flight and landing phase. Average time duration required to complete one rope-skip cycle was 1.2 s at a cadence of 105 skips/min. During each bounce rope-skip cycle, mean foot contact time was 0.55sec and flight time was 0.65sec. The mean foot contact time was 0.60 s and flight time was 0.85 s during run at speed of 2.8 m/s and 1.42sec as contact time and 0.91 s as flight time during walk at a speed of 1.19 m/s.

Fig. 1 illustrates the three phases of skip namely take-off, flight and landing phase. During take-off phase, hip flexion of 13.4°, knee flexion of 13.6 ° and ankle plantarflexion of −14.8 ^{0}was observed. During flight phase, 35.3^{0}of hip flexion, 67.9° of knee flexion and 6.8^{0}of ankle dorsiflexion was observed; whereas 33.9 ^{0}of hip flexion, 49.2° of knee flexion and 34.5 ° of ankle dorsiflexion was observed during landing phase (Refer Table 1).

In one skip cycle, minimum hip flexion was observed during landing i.e.13.5^{o}and maximum during flight phase i.e.35.3°, resulting in a total motion of 21.9°. Knee flexion ranged between a minimum of 13.6^{0}during landing phase to a maximum of 67.9° during flight phase; resulting in total motion of 54.4°. Ankle motion ranged between 13.4° of plantarflexion during take-off and 34.5^{o}of dorsi-flexion during landing, resulting in total motion of 46.1° (Refer Table 1).

Average vertical displacement of center of mass (CoM) during one bounce rope-skip cycle was 22 cm; 2.9 cm during run and 2.4 cm during walk ($p < 0.001$). The mean descent velocity during bounce rope skip (1.46 m/s) was significantly greater compared to walk (0.11 m/s) and run (0.38 m/s) ($p < 0.001$). The descent time during bounce rope skip was 0.36s. Bounce –rope skip demonstrated highest peak net joint external moment during landing/loading phase. In sagittal plane, the highest net joint moment was observed at ankle joint followed by knee and hip. In frontal plane, the largest peak net joint moment was at knee and hip joint (Refer Table 2).

Peak hip adductor moment during bounce rope-skip was lower by 43% compared to run ($p < 0.001$). Peak knee adductor moment was 32% lower during bounce rope-skip compared to run ($p < 0.001$) and 54% higher than walk ($p < 0.001$). Ankle dorsiflexor moment was significantly different among the three aerobic activities. Walking generated 43% lower ankle moments compared to running and skipping ($p < 0.001$).

On further analysis, although sagittal plane joint loads demonstrated a linear rise in hip and knee flexor moments from walk, to bounce rope-skip to run, between group analysis demonstrated no significant difference in hip and knee flexor moments during bounce rope-skip and run.

Power was absorbed at landing and generated during take-off phase of bounce rope-skipping at an average speed of 0.22 m/s. During landing/initial contact, highest power absorption was observed at ankle joint during rope-skip; at knee joint during run and at hip joint during walk. During take-off/push-off, power generation was greatest at ankle in all three activities. During run, power absorption was 45% greater in hip and 50% lower in ankle at initial contact ($p < 0.001$) compared to landing during bounce rope skip. Conversely, power generation was greater only in hip at push off during run compared to take-off during bounce rope skip ($p < 0.001$).

Comparison of power output between walk and skip revealed, 91% higher power absorption at ankle at landing during skip compared to initial contact of walk ($p < 0.001$). Power generation was greater at knee and ankle at take-off phase of skip compared to push off during walk ($p < 0.001$) (Refer Table 3).

4. Discussion

Present study analyzed biomechanical demands of bounce rope-skip in comparison to commonly practiced aerobic weight-bearing activities like run and walk to inform joint angles and joint loading.

One bounce rope-skip cycle consisted of 45% loading phase (equivalent to stance phase of walk/run) and 55% flight phase (equivalent to swing phase of walk/run); which is exactly opposite to walking; which consists of 62% stance phase and 38% swing phase. However, the loading phase of bounce rope-skip was marginally longer than stance phase of run, which was 41% in the current study and was reported as 30% in earlier studies (Hreljac et al., 2004). Thus, it was evident that, loading phase of bounce rope-skip was shorter than walk; but similar to run i.e. the duration of lower limb contact was similar in skip and run.

In the sagittal plane, motion was greatest at knee joint followed by hip and ankle joint during one cycle of bounce rope skip. Knee joint demonstrated 13.6° flexion at loading compared to 10.9° flexion during run. Higher knee flexion and ankle dorsiflexion angles simulate the stretch shortening cycle at ankle due to intense eccentric (stretch) and concentric (shortening) contraction of calf muscles (Farland et al., 2015) which could be a speculated reason for lower hip adductor (43%) and knee adductor moment (32%) compared to run.

Contact time, descent velocity and power output are other major determinants of net joint loading. Although contact period of skip and run is similar, descent velocity during bounce rope-skip was 63% higher than run and 89% higher than walk. Higher descent

Table 1
Sagittal plane joint angle at hip, knee and ankle joints during bounce rope-skip, run and walk among 22 young healthy adults.

	Bounce Rope-Skip (n = 22)			Run (n = 22)			Walk (n = 22)		
	Sagittal plane Joint angles (^{0})								
	Max Mean (SD)	Min Mean (SD)	Total ROM	Max Mean (SD)	Min Mean (SD)	Total ROM	Max Mean (SD)	Min Mean (SD)	Total ROM
Hip	35.3 (12.4)	13.4 (5.8)	22.1	42.1 (6.7)	−14.2 (3.4)	56.3	31.5 (3.4)	−8.0 (3.9)	39.5
Knee	67.9 (34.4)	13.6 (10.7)	54.3	84.2 (13.6)	10.9 (4.3)	74.7	56.0 (6.1)	−2.9 (2.6)	58.9
Ankle	34.5 (7.06)	−13.4 (6.4)	47.9	−26.3 (7.3)	33.3 (5.2)	59.6	−12.4 (10.1)	25.7 (5.8)	40.1

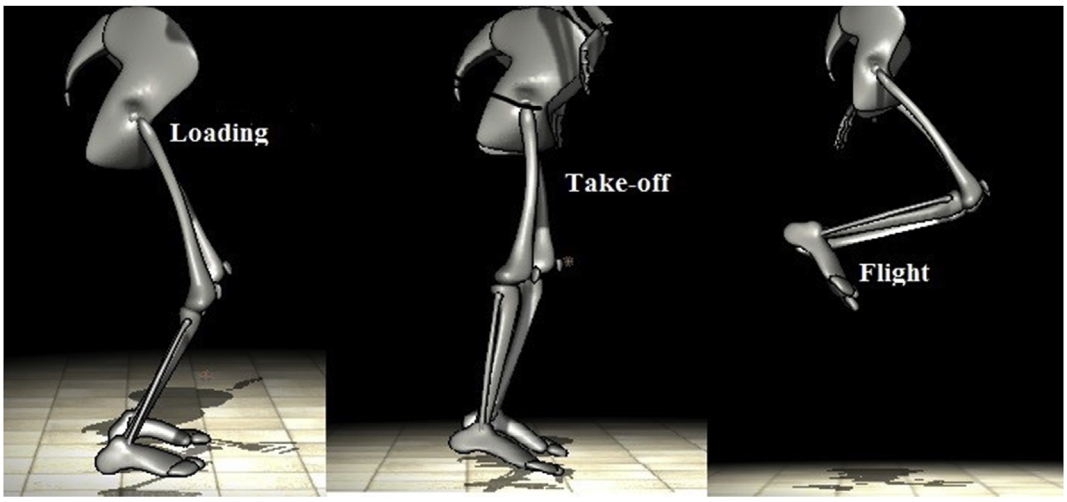


Fig. 1. a Phases of skipping.

Table 2
Net joint external moments at hip, knee and ankle joints during bounce rope-skip, run and walk among 22 young adults.

Kinetics (Joint moments)							
Variables Nm/kg	Run Mean (SD)	Skip Mean (SD)	Walk Mean (SD)	p-value ANOVA	Linear contrast p- value	Skip v/s Run p value Post-hoc using Bonferroni test	Skip v/s Walk p value Post-hoc using Bonferroni
HAM	2.2 (0.25)	1.12 (0.17)	1.06 (0.06)	<0.001*	<0.001*	<0.001**	0.6
KAM	2.06 (0.19)	1.42 (0.17)	0.66 (0.16)	<0.001*	<0.001*	<0.001**	<0.001**
HFM	1.41 (1.36)	1.06 (0.38)	0.71 (0.32)	<0.05*	<0.05*	0.5	0.5
KFM	1.75 (0.59)	1.52 (0.46)	0.36 (0.22)	<0.001*	<0.001*	0.2	<0.001**
ADM	2.64 (0.19)	2.26 (0.38)	1.24 (0.09)	<0.001*	<0.001*	<0.001**	<0.001**
vGRF (N/kg)	218.35 (17.4)	189.20 (22.31)	115.20 (6.8)	<0.001*	<0.001*	<0.001**	<0.001**

ANOVA: * level of significance $p \leq 0.05$.
Post-hoc analysis: **level of significance $p \leq 0.01$.
Abbreviations: HAM: Hip Adductor Moment, KAM: Knee Adductor Moment, ADM: Ankle Dorsiflexor Moment, HFM: Hip flexor moment, KFM: Knee flexor moment, vGRF: Vertical Ground Reaction Force.

Table 3a
Power absorption at hip, knee and ankle joints during bounce rope-skip, run and walk among 22 young adults.

Power output (Absorption)							
	Landing/loading phase (power absorption)			ANOVA p value	Linear contrast p value	Post-hoc using Bonferroni test p value	
	Run Mean (SD)	Bounce rope-skip Mean (SD)	Walk Mean (SD)			Bounce rope-skip vs run	Bounce rope-skip vs walk
Hip	−2.3 (1.22)	−1.3 (1.04)	−0.87 (0.95)	<0.001*	<0.001*	<0.001*	<0.001*
Knee	−6.22 (4.2)	−3.9 (3.1)	−0.72 (0.59)	<0.001*	<0.001*	0.52	<0.001*
Ankle	−3.8 (2.1)	−7.07 (3.8)	−0.58 (0.49)	<0.001*	<0.001*	<0.001*	<0.001*

ANOVA: * level of significance $p \leq 0.05$.
Post-hoc analysis: * level of significance $p \leq 0.01$.

Table 3b
Power generation at hip, knee and ankle joints during bounce rope-skip, run and walk among 22 young adults.

	Power output (Generation)						
	Take off/Push off (power generation)			ANOVA p-value	Linear contrast p value	Post-hoc using Bonferroni test p value	
	Run Mean (SD)	Bounce rope-skip Mean (SD)	Walk Mean (SD)			Bounce rope-skip vs run	Bounce rope-skip vs walk
Hip	2.1 (0.89)	1.3 (1.55)	1.15 (0.77)	<0.001*	<0.001*	<0.001*	0.4
Knee	3.5 (2.49)	5.2 (2.57)	0.48 (0.29)	<0.001*	<0.001*	0.14	<0.001*
Ankle	9.3 (5.0)	11.8 (6.4)	3.05 (1.69)	<0.001*	<0.001*	0.26	<0.001*

ANOVA: * level of significance $p \leq 0.05$.
Post-hoc analysis: * level of significance $p \leq 0.01$.

velocity during bounce rope-skip is speculated to provide greater kinetic energy for take-off of subsequent rope-skip cycle as reported earlier (Chow et al., 2014). It is argued that greater kinetic energy is directly associated with power generation during bounce rope-skip; which is illustrated by 47% higher power generation at ankle and knee compared to run.

Despite similar contact time and higher descent velocity in bounce rope-skip compared to run, vertical ground reaction force during landing phase of rope-skip was 15% lower than run and 40% higher than walk. It is conjectured that type of foot strike, knee flexion angle and power absorption during landing influenced net joint moments during bounce rope-skip and run.

All participants landed on forefoot during bounce rope-skip. Fore-foot landing provides a relatively larger lever arm between the point of force application and center of axis of ankle joint and increased deceleration distance, resulting in a reduction in magnitude of vertical GRF. On the other hand, runners demonstrated rear-foot strike, deactivating the ankle rocker; and subsequently causing forward pivot of the body over the foot; resulting in increased vGRF (Ozer et al., 2011). However, it will be interesting to compare vGRF generated by bounce rope-skip and run of forefoot-strike runners.

Lower vGRF during bounce rope-skip compared to running could be attributed to greater knee flexion along with ankle dorsiflexion, stimulating the stretch shortening cycle at ankle caused by intense eccentric (stretch) and concentric (shortening) contraction of calf muscles (Farland et al., 2015). The above kinematic pattern along with soft forefoot landing is also speculated to result in higher power absorption observed in current study. Stretch-shortening cycle produced during bounce rope-skip is speculated to generate low muscle activity in concentric phase and activation of short latency stretch reflex which contributes to force generation in the flight phase of bounce rope-skip. Low loads with shorter contact time during landing may provide a protective effect on joints (Farland et al., 2015; Hernandez et al., 2003). It may be reasonable to speculate that people engaged in bounce rope-skip may experience lower rate of musculoskeletal injuries compared to run (Bosco et al., 1983).

The displacement of COM during bounce rope-skip was 7 times greater than run & 11 times greater compared to walk. Greater displacement of center of mass (CoM) during bounce rope-skip suggests higher demands on postural control mechanisms. Additionally, greater power absorption and generation at the ankle are suggestive of activation of ankle strategy to maintain postural control during bounce rope-skip (Trecroci et al., 2015). Additionally, large vertical translation of center of mass to propel the body upward for clearance and landing on the same spot demands kinesthetic awareness, synchronous recruitment of large number of muscles, co-ordination and proprioceptive input. Hence bounce rope-skip holds potential for stimulation of postural control mechanisms to improve balance and co-ordination (Trecroci et al., 2015).

To summarize, the current study demonstrates bounce rope skip as a safe weight bearing aerobic exercise in young adults which is hip and knee protective due to lower hip and knee joint loads compared to run. Other than its common application as an aerobic exercise to enhance fitness, bounce rope-skip can also be safely promoted as a preparatory physical exercise to high-impact aerobics sports demanding balance control and co-ordination such as racket sports and sports demanding landing control such as soccer. However, findings of present study can be applied to design fitness programs for healthy young adults. Future studies are necessary to compare bounce rope-skip, run and walk in people of both genders in varying age groups with known musculoskeletal disorders for wider clinical application.

5. Conclusion

In summary, bounce rope-skip demonstrated greater descent velocity and lower vertical ground reaction force coupled with lower peak hip and knee external adductor moment indicating lesser lower extremity joint loading compared to run. Therefore, bounce rope-skip emerged as a hip and knee joint −protective, aerobic, weight-bearing exercise for health promotion and sport among young adults. Seven times larger vertical translation of center of mass during bounce rope-skip can cause considerable stimulation of postural control mechanisms to improve balance and co-ordination. However, present findings do not permit recommendation of skipping to adults with sub-acute ankle and foot injuries, because maximum power absorption was observed at ankle joint.

Clinical relevance

- Bounce rope-skip emerged as a hip and knee joint −protective aerobic, weight-bearing exercise for health promotion and a sport among young adults due to lesser lower extremity joint loads and vertical ground reaction force compared to run.
- Bounce rope-skip can be safely promoted as a preparatory exercise to sports people engaged in high-impact aerobics sports which demand balance control and co-ordination for e.g. racket sports and sports demanding landing control such as soccer.

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CRediT authorship contribution statement

Rajani Mullerpatan: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Triveni Shetty:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Yuvraj Singh:** Methodology, Investigation, Supervision, Project administration. **Bela Agarwal:** Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing - review & editing, Project administration.

Declaration of competing interest

None.

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