DOI: https://doi.org/10.30795/jfootankle.2024.v18.1809

Original Article

Kinetics assessment of foot injury risk during vertical jump from varying heights in barefoot condition

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Abstract

Objective: Understand how certain kinetic variables change during vertical jumping from different heights in barefoot condition.

Methods: Twenty healthy, physically fit male and female adults were selected for the experiment. Mean age, height, and weight of male participants were 20.08 ± 1.230 years, 174 ± 1.071 cm, and 70.57 ± 3.002 kg; for female participants, mean age, height, and weight were 19.14 ± 1.027 years, 155 ± 0.048 cm, and 52.56 ± 5.461 kg, respectively. Experiments started with barefoot forefoot jumping from two different heights, 33 cm and 49 cm. Initial contact force (N), initial contact time (s), max force (N), max force time (s), stabilization force (N), time from max force to max force before stabilization (s), and time from max force to stabilization force (s) during jumps were measured using a Kistler portable force plate and studied in the MARS Quarter performance analysis software.

Results: Barefoot jumping data showed a scattered pattern for all selected parameters. Maximum force reached 3960.05 ± 2125.255 N at 33 cm and 4844.25 ± 2259.230 N at 49 cm. In a previous study, the average peak force measured was 4640 N. A 50% chance of fracture was linked to an impact of 3562 N, which is very close to the figure found in this study. Stabilization force reached 584.40 ± 106.308 N at 33 cm and 583.35 ± 99.881 N at 49 cm, with a correspondence of 0.56 ± 0.149 s and 0.66 ± 0.258 s, respectively. Minimum force achieved before stabilization was 341.0 N at 33 cm and 320.70 N at 49 cm. Regression analysis of these parameters showed a low R-squared value and a random fit plot.

Conclusion: According to our findings, jumping barefoot from a 49 cm height produces a higher impact on the forefoot than a 33 cm jump, except for initial contact and stabilization force. Before stabilization, the time from max force to max force before stabilization significantly affects stability during take-off, potentially preventing injury by allowing for a smoother transition between the eccentric (braking) and concentric (propulsion) phases. This data can help improve sports and kids' footwear to lower the risk of foot injuries.

Level of evidence IV; Economic and decision analyses – developing an economic or decision model.

Keywords: Foot Injuries; Disease prevention; Genes, jumping.

Introduction

The act of jumping, a fundamental human movement, has been studied extensively in various contexts. From leaping over obstacles to executing high-intensity athletic maneuvers, understanding the biomechanics of jumps is crucial for optimizing performance and minimizing injury risks[1-2]. Footwear greatly affects the jumping mechanics, but barefoot jumping provides a unique perspective on how the human body interacts with the ground. Interest in barefoot activities has grown due to insights into injury risks when not wearing footwear[3-4]. Some past literature suggests that going barefoot enhances interaction with the environment, improving balance and movement efficiency, but it also exposes individuals to specific risks, particularly during jumps, as landing from different heights is influenced by surface properties and the body biomechanics[5].

Jumping in sports and movement activities can lead to lower-limb musculoskeletal injuries in the hip, knee, and ankle. Factors contributing to these injuries include forces, body position at landing, movement execution, and landing

The study performed at the Centre of Excellence, Footwear Design and Development Institute (FDDI), Noida, India.

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Conflicts of interest: None. **Source of funding:** The study was financially supported by Footwear Design & Development Institute (FDDI), Ministry of Commerce, Government of India. **Date received:** July 12, 2024. **Date accepted:** October 19, 2024. **Online:** December 20, 2024.

How to cite this article: Kumar SD, Singh K, Chauhan BR, Maity A, Kumar M, Juneja H, et al. Kinetics assessment of foot injury risk during vertical jump from varying heights in barefoot condition. J Foot Ankle. 2024;18(3):342-9.

surface. Recent studies aim to identify specific performance factors leading to these stresses[6]. It is reported that the jumping and landing biomechanics are closely related to the risk of acute injury due to prolonged exposure to high ground reaction forces (GRFs). Landing biomechanics is related to muscle control, muscle fatigue, flexibility, and musculoskeletal stiffness, but these multiple factors collectively represent the individual's landing technique, which has been considered one of the most important factors related to injury potential. The technique employed directly affects the capacity of joints to absorb the energy associated with the large-magnitude GRFs experienced upon ground contact[7].

Landing maneuvers are a fundamental task in high-risk sports activities such as volleyball, handball, and basketball[8]. The landing technique and the height may affect the GRF and lower limb kinematics[9]. Thus, poor landing mechanics with inadequate movement at the hip, knee, and ankle joints will not only reduce shock absorption but also increase the risk of lower limb injury[10-11]. During a walk, the vertical ground reaction force (v-GRF) is approximately 1.2 times the body weight. This value increases to 2.5 times the body weight while running and to 4 times the body weight while jumping. Therefore, repetitive jumping can lead to a microtrauma of muscles and, eventually, to sprains. The combination of height and jumping seems particularly important from a kinetic and kinematic perspective, reinforcing the idea that these factors, combined, are likely to increase the risk of ankle injury due to poor landing[12-13].

The purpose of this intense research is to bridge the gap in understanding barefoot jumps by focusing on kinetic responses across varying elevations. This study investigates initial contact force (N), max force (N), min force before stabilization (N), stabilization force (N), and time from max force to stabilization force (s) during descent. By dissecting these kinetic variables, our goal is to identify critical factors that contribute to injury risks and inform evidence-based strategies for injury prevention. Thu, this study aims to shed light on injury prevention strategies and improve performance based on the kinetic responses of barefoot jumping from different heights. Such barefoot data should set the standard value to be considered while developing and identifying the best footwear. To reduce the injury risk, this response delves into the design, integration, and development of footwear for various activities, including sports and children's footwear.

The hypothesis of this study's findings have practical implications for athletes, fitness enthusiasts, and kids engaging in barefoot activities. By elucidating kinetic responses during jumps, these results can tailor jump-specific exercises to optimize performance and reduce injury risks. Insights from barefoot jumps can set a mirror for the development of footwear that mimics natural biomechanics while providing the necessary protection. Whether hiking, parkour, or recreational sports, understanding the risks associated with different elevations empowers individuals to make informed choices.

Methods

The experimental protocol was screened and approved by the Ethics Committee (Ref. No. HMC/ IEC/ FDDI/ 01, dated 18th April 2024) in compliance with the Helsinki Protocol (1964-2013).

Selection of subject trials

This cross-sectional study aimed to collect barefoot jumping kinetic responses considering different heights. For this, 20 (n = 20; male: 13, female: 7) healthy, physically fit male and female adults who had no foot deformities or musculoskeletal abnormalities in the lower limbs and no history of musculoskeletal disorders or fractures on the lower extremity and vestibular system were selected for the final experiment. Mean age, height, and weight of male participants were 20.08 ± 1.230 years, 174 ± 1.071 cm, and 70.57 ± 3.002 kg, while for female participants mean age, height, and weight were 19.14 ± 1.027 years, 155 ± 0.048 cm, and 52.56 ± 5.461 kg, respectively. Experiments started with barefoot forefoot jumping from two different heights, 33 cm and 49 cm.

At least three trials of each subject and for each height condition were required, totaling 120 trials (20 x 3 x 2 = 120 trials). During data processing, the mean of all three trials of each condition was calculated as the final value. Five trials were excluded due to diversity, leaving us with 115 trials for the final experiment.

Before the study beginning, participants received all the necessary information and were informed about the study protocol; they also completed an informed consent form. Subjects had the freedom to withdraw their participation at any point during the experiment.

Experimental design of the study

Participants were previously informed about the procedures and their written consent was obtained. To get them accustomed to the study protocol, participants were asked to jump barefoot from two different heights, 33 cm and 49 cm. Before the study beginning, subjects were asked to comfortably jump from the selected heights and touch the force plates with their toe region. Then, they repeated this process three times for each condition, from the 33 cm height and from the 49 cm height. There was a 30-minute rest period between each trial of a selected height. Each experiment lasted five seconds, and data was collected and processed using the Kistler Quattro Jump (Model 9290DD, Kistler Instrumente AG, Switzerland) equipment and MARS Quarter (Type 2822A, Kistler Instrumente AG, Switzerland) performance analysis software.

Instrumentation

Quattro Jump comprises a portable Kistler force plate and the comprehensive Kistler MARS performance analysis software. The force plate measures the vertical force applied to assess a large variety of performance parameters. Quattro Jump objectively measures force, power, and jump height.

These force platforms are based on piezoelectric sensors. The MARS Quarter performance analysis software was used to collect and process data. Data was collected for each full jump in each experiment at a sampling rate of 25 Hz. The laboratory environment was maintained at an optimal temperature and humidity of 25 °C–27 °C and 50%–55%, respectively, at the Footwear Design and Development Institute (FDDI), in India.

Studied parameters

Initial contact force (N), initial contact time (s), max force (N), max force time (s), stabilization force (N), time from max force to max force before stabilization (s), and time from max force to stabilization force (s) during the barefoot forefoot jump from two different heights were obtained by using the MARS Quater performance analysis software.

Ethical clearance

Our study followed the principles outlined by the Declaration of Helsinki Protocol, 1964, and as per approved ethical clearance No HMC/ IEC/ FDDI/ 01, dated 18.04.2024.

Statistical analysis

Data were summarized into mean ± standard deviation (SD) values. Shapiro-Wilk normality test showed that parameters were not normally distributed. Thus, the Mann-Whitney *U* test was performed to compare the means of both heights' kinetic parameters. The significance level was defined as 0.05. Statistical software package SPSS-26 was used to analyze data.

Results

A scatterplot compared the initial contact force (N) with initial contact time (s); max force (N) with max force time (s); and stabilization force (N) with time from max force to max force before stabilization (s). Additionally, it included a radar chart of the stabilization force, a probability plot of time from max force to stabilization, and a line plot of time from max force to max force before stabilization. These data demonstrate the balance and stability dynamics of barefoot jumping.

The initial contact force (N) vs. initial contact time (s) scatterplot illustrates the relationship between the force applied during initial contact (e.g., stepping on a jump force plate) and the time it takes for that force to be applied. Points on the scatterplot form an upward-sloping pattern, indicating that a higher initial force tend to occur earlier in the movement.

The ability to stabilize (e.g. maintaining balance after a sudden force) is associated with the time it takes to regain stability after experiencing maximum force. To maintain balance and stability after jumping, there should be a negative correlation. The stabilization force radar chart displays different aspects of stabilization force, such as lateral and anterior-posterior stability. The shape of the radar chart gives an overall picture of stabilization force across these dimensions. The probability plot is used to assess the distribution of a variable – in this case, the time it takes from maximum force to stabilization. It helps determine if data follows a specific distribution. Deviations from a straight line indicate departures from the assumed distribution. The line plot shows how the time from maximum force to reaching another specific stabilization point changes over time. A sloping line indicates the rate of change, while a flat line suggests a constant time interval.

Figures 1 to 6 and Table 1 demonstrate the barefoot jumping dynamics and stability in two jumping heights, 33 cm and 49 cm. This data on dynamics represent the future design dimension achieving better balance and stability.

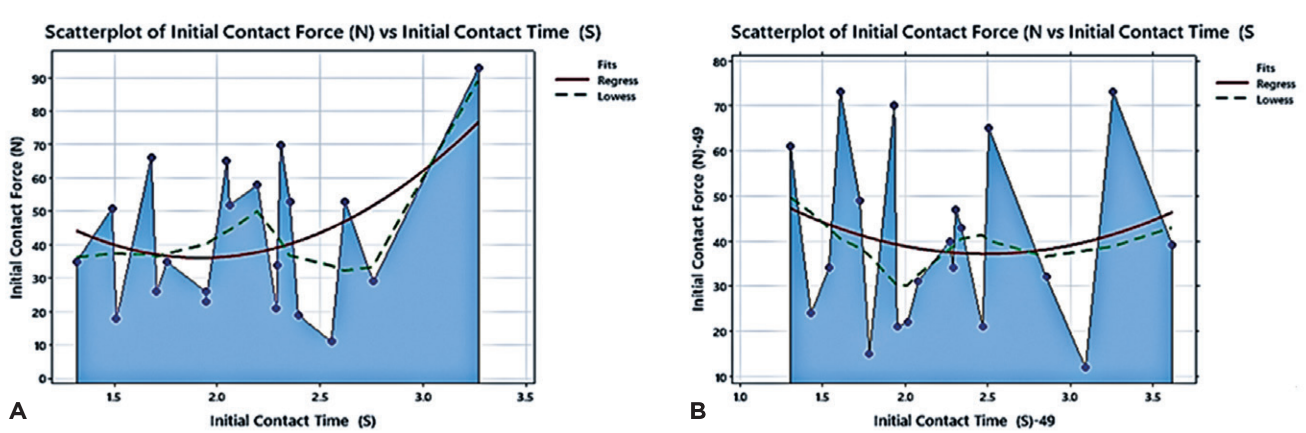

Figure 1. Scatterplot of initial contact force vs. initial contact time with Regress and LOWESS fit models for a 33 cm jump height (A) and a 49 cm jump height (B).

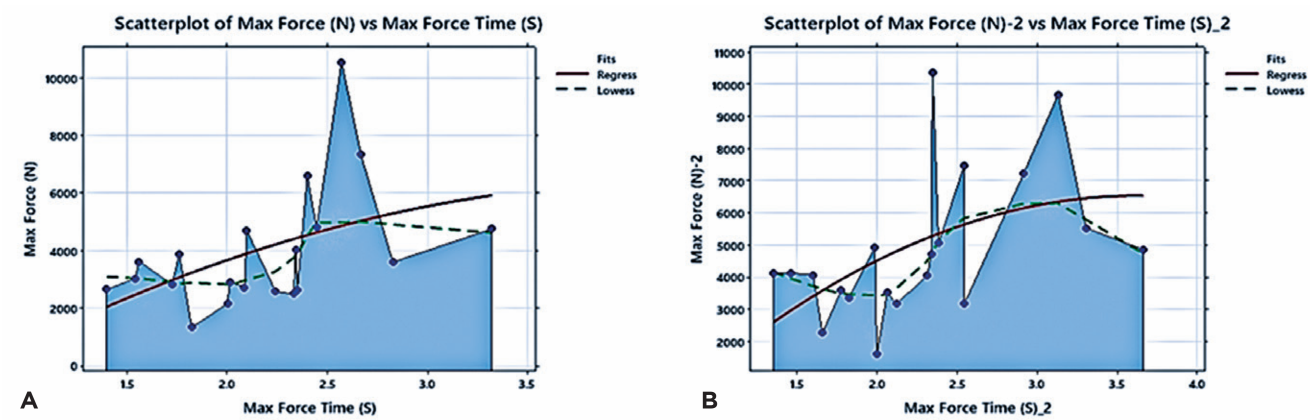

Figure 2. Scatterplot of max force vs. max force time with Regress and LOWESS fit models for a 33 cm jump height (A) and a 49 cm jump height (B).

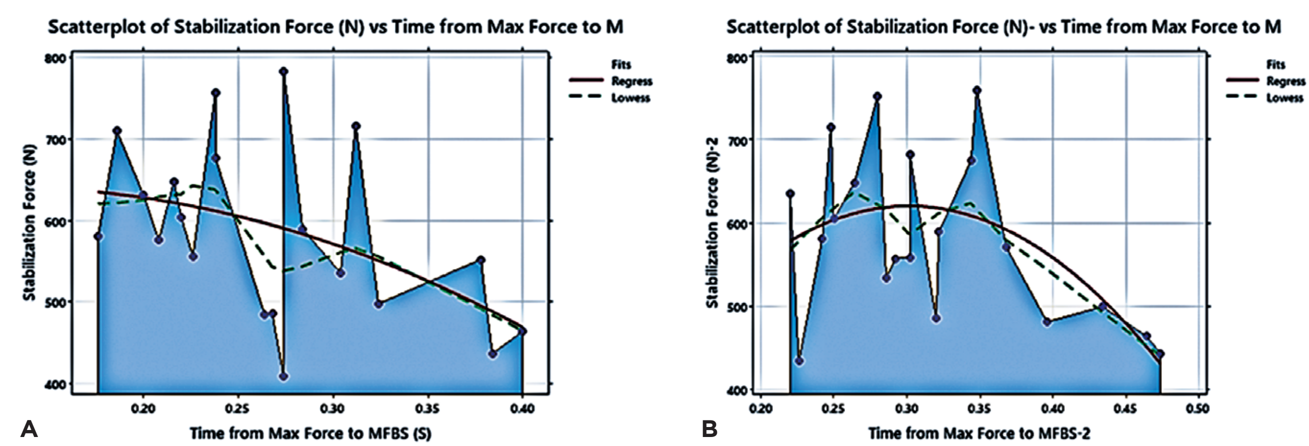

Figure 3. Scatterplot of stabilization force vs. time from max force to max force before stabilization (MFBS) with Regress and LOWESS fit models for a 33 cm jump height (A) and a 49 cm jump height (B).

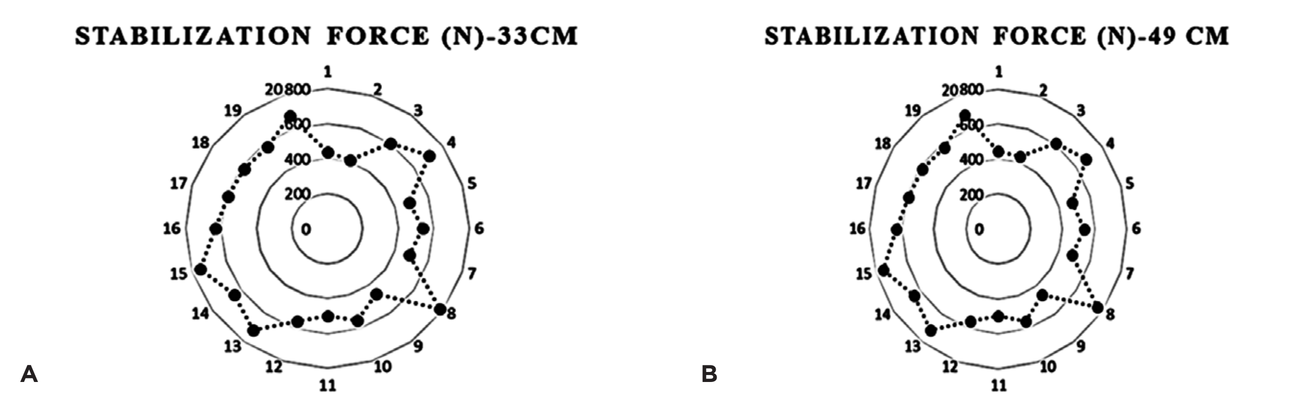

Figure 4. Radar chart of stabilization force in two jump heights, 33 cm (A) and 49 cm (B).

Discussion

Many human activities involve jumping and consequent landing, most commonly in dynamic activities like sports. These activities are usually associated with lower-limb musculoskeletal injuries, specifically in joints such as the hip, knee, and ankle. Toe fractures, ligament injuries, and ankle sprains are the most common injuries that happen without contact during the practice of dynamic activities. It is reported that

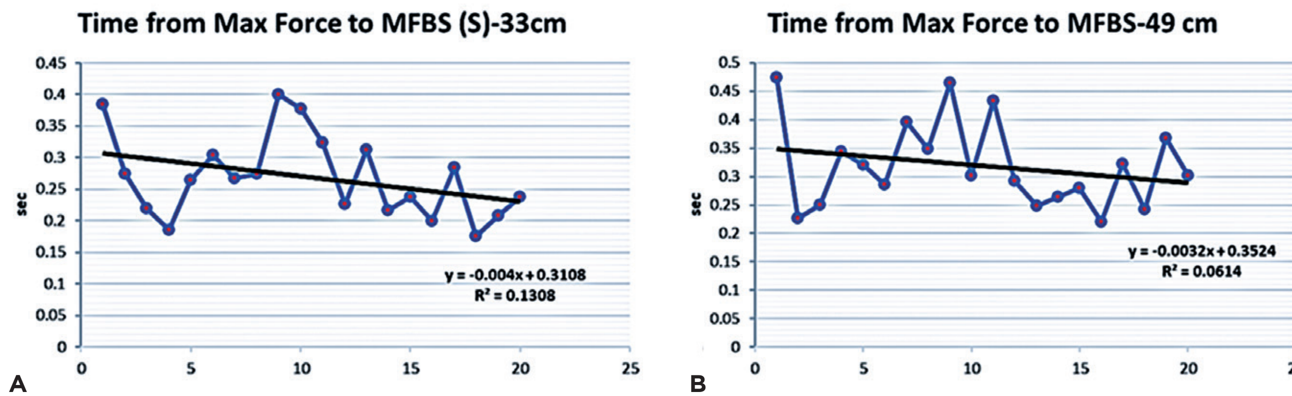

Figure 5. Line chart of time from max force to max force before stabilization (MFBS) in two jump heights, 33 cm (A) and 49 cm (B).

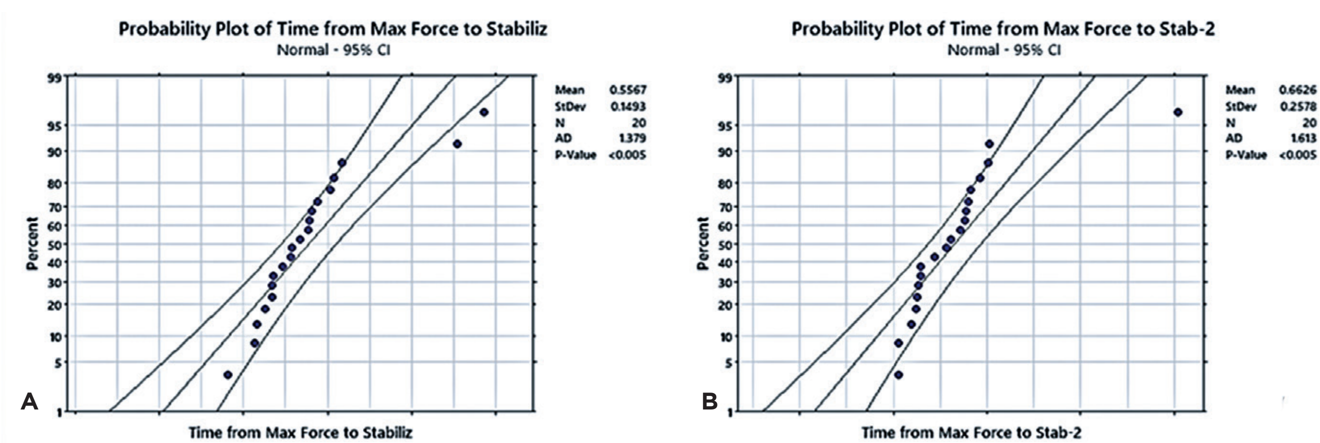

Figure 6. Probability plot of time from max force to stabilization in two jump heights, 33 cm (A) and 49 cm (B). Confidence interval: 95%.

Table 1. Barefoot kinetic dynamics

Parameters	Barefoot (N = 20) Height: 33 cm (n = 20) Mean ±SD	Barefoot (N = 20) Height: 49 cm (n = 20) Mean ±SD	Mann-Whitney U Test	Asymptotic Significance level
Initial contact force (N)	41.90 ± **21.618**	40.30 ± **19.480**	195	0.89 (p > 0.05)
Initial contact time (s)	2.12 ± **0.480**	2.22 ± **0.622**	208.5	0.81 (p > 0.05)
Max force (N)	3960.05 ± **2125.255**	4844.25 ± **2259.230**	268	0.06 (p > 0.05)
Max force time (s)	2.18 ± **0.477**	2.27 ± **0.622**	207	0.85 (p > 0.05)
Stabilization force (N)	584.40 ± **106.308**	583.35 ± **99.881**	201	0.97 (p > 0.05)
Time from max force to max force before stabilization (s)	0.27 ± **0.066**	0.32 ± **0.076**	279.5	**0.03 (p < 0.05)**
Time from max force to stabilization force (s)	0.56 ± **0.149**	0.66 ± **0.258**	264.5	0.08 (p > 0.05)

the jumping and landing biomechanics are closely related to the risk of acute injury due to prolonged exposure to high GRFs. Of course, landing biomechanics are related to muscle control, muscle fatigue, flexibility, and musculoskeletal stiffness, but these multiple factors collectively represent an individual's landing technique, which has been considered one of the most important factors related to injury potential. The technique employed directly affects the capacity of joints to absorb the energy associated with the large-magnitude GRFs experienced upon ground contact. Even though the joint kinematics is a significant factor in generally defining a good or poor landing technique, other variables affected by the overall technique and perhaps more directly associated with landing-related injuries are the moments occurring about the involved joints[7]**.** According to Roberts et al.[14], fractures sustained at forces ranging from 7854 N to 12206 N (mean: 9751 N) affected the calcaneus, tibia, and fibula bones[14]. Another study, by Begeman[15], reported intra-articular distal tibia fractures. In specimens with no injury, forces ranged from 3430 N to 7550 N (mean: 6157 N), and in specimens with fractures, forces ranged from 6110 N to 8690 N (mean: 7848 N)[15]. Yoganandan et al.[16] used data from these two abovementioned studies to derive a probability distribution based on Weibull analysis. According to the authors, a force of 6.8 kN represented a risk of injury of 50%[16]. One of the most common injuries experienced by individuals involved in physical activity is lateral ankle sprain and, after an acute ankle sprain, 32%–47% of patients report functional ankle instability[17].

This study aimed to investigate differences in toe kinetic variables at different drop heights to provide insights into balance and stability dynamics while barefoot forefoot jumping. This information is crucial for future design and development of footwear. Results revealed that barefoot balance dynamics provided a clear picture of balance and stability, which is important for making footwear that effectively absorbs forces during jumping activities before they reach the injury threshold.

During the initial contact phase, the subject's foot makes contact with the ground. The ground exerts a force on the subject (GRF) in response to this contact. The magnitude and direction of this force affects the subsequent phases of the jump. The initial force contributes to the subject's ability to overcome gravity and achieve vertical lift. A stronger initial force helps propel the body frontward, depending on the jump height. The force-time curve shows how the subject accelerates during this phase. The regression analysis of initial contact force vs. time indicated distinct patterns and curved fits, with R-squared values of 18.1% and 20.7% for drop heights of 33 cm and 49 cm, respectively. The study found that the initial contact force significantly affects the subject's stability during the take-off phase. Proper force distribution is essential for balanced movement and to prevent loss of control. Imbalances or asymmetries in force distribution and contact time may lead to suboptimal jumps or increased risk of injury. The illustrated image defines that the force vs. time distribution should ideally fall within the range of 35 N–40 N, reaching this level around 2.20 s into the activity. Understanding the initial contact force vs. time relationship helps individuals enhance their balance dynamics and maintain stability during any jumping activity. The significance of displayed data suggested a mirror idea of force absorption during jumping activities in general, including any sports and kids activities.

The scatterplot of max force vs. max force time also showed a dispersed pattern. Noticeable differences were observed between the regression fit model and the locally weighted scatterplot smoother (LOWESS) fit model. The regression analysis indicated R-squared values of 22.6% (33 cm) and 26.2% (49 cm) for the force vs. time fit model. This highlights the significant difference in force from the point of initial contact to reaching max force, with a large force difference occurring within 5 s–6 s. This could potentially lead to major foot injuries, especially in the metatarsal and phalanges. Excessive force during initial contact may also increase the risk of metatarsal stress fractures.

The muscle force component acting by the attached bone is called stabilization force. This force has a moment arm and is responsible for stabilizing the joint by producing the necessary amount of force. During a jump, the body goes through a sequence of movements known as triple extension, which includes ankle extension, knee extension, and hip extension[18]. Stabilization forces ensure efficient energy transfer from the ground to the body during this extension phase. Proper stabilization allows for maximal force generation, contributing to upward motion. During jumping activities, the stabilization force reduces the risk of injury during take-off and landing. It ensures proper alignment, balance, and control during the explosive phase of the jump. Without adequate stabilization, excessive forces or improper alignment can strain muscles, tendons, and ligaments[19]. This force minimizes energy loss due to unnecessary movement or misalignment. An efficient energy transfer ensures that the force generated during triple extension is effectively used for upward propulsion. Data analyzed in this study showed an 85% increase in force when reaching the maximum force achieved by the stabilization force within 0.56 s–0.66 s. Previous literature suggests that there should not be a significant difference in data between the contact force to max force and max force to stabilization. This difference could lead to acute ankle injuries and fractures. According to the radar chart analysis, the average stabilization force should be between 400 N and 500 N, and the time difference from when the maximum force is reached to when the stabilization force is achieved should be minimal.

Time from max force to stabilization is an important measure during jumping activities. It refers to the time it takes for an individual to regain stability after landing from a jump. It measures how quickly a person regains balance and control after the landing impact. When jumping from a height, the landing impact forces are significant, and a quick stabilization response reduces the risk of injury from excessive forces or misalignment[20]. Efficient stabilization ensures that the energy generated during the jump is effectively used for propulsion.

A faster time from max force to stabilization enables athletes to transition smoothly from landing to take-off, for example, in basketball, volleyball, or gymnastics. In non-athletic situations, rapid stabilization helps prevent falls and lowers the risk of injuries. An article by Kalra et al.[21] highlighted that metatarsal fractures are the most common traumatic foot injury, yet the thresholds for metatarsal fractures remain poorly characterized, affecting performance targets for protective footwear. In their experiment, these researchers studied impact energies, forces, and deformations to understand the risk of metatarsal fractures during workplace impact loading, finding that the most common fracture location was the second metatarsal. Average peak energy, force, and deformation during a fracture were 46.6 J, 4640 N, and 28.9 mm, respectively. By using survival analyses, they found that there was a 50% fracture probability associated with 35.8 J of impact energy and 3562 N of impact force[21].

The present study showed asymmetric lines regarding the time from maximum force to just before stabilization force for both jump heights analyzed. The regression analysis indicated R-squared values of 0.1308 and 0.0614, suggesting a risk of injury during landing. The probability plot indicated that the study results were within the 95% confidence interval, but not between mean values. Furthermore, rapid stabilization is crucial after the initial contact within a minimum time[22]. However, the study did not find significant correlations between static/dynamic core stability and jumping height. As a result, individuals with higher core stability should have improved dynamic performance, better balance, and firmer stability.

Limitation

The current study had limitations such as a small sample size and the inclusion of only barefoot forefoot jumping from two different heights in laboratory conditions. In the future, for a better understanding of kinetic responses, a similar study with a larger sample size and with and without different types of footwear should be carried out to help translate the findings hereof to real field conditions.

Conclusion

The present study revealed that barefoot jump from a height of 49 cm exerts more impact on the forefoot, except for the initial contact and stabilization force, as compared to a 33 cm jump regarding the studied parameters. The only factor found to significantly affect the subject's stability during take-off is the time from max force to max force before stabilization (s), which represents the time between reaching maximum force and achieving stable balance after landing. It reflects how quickly subjects transition from generating force during take-off to controlling that force during landing. This efficient energy transfer ensures that the force generated during the jump contributes optimally to upward motion and minimizes energy loss. A rapid transition from max force to stabilization reduces the risk of injury. If an athlete remains in a high-force state for too long (e.g., due to delayed stabilization), they can strain muscles, tendons, and ligaments upon landing. A shorter time to stabilization allows athletes to smoothly transition from the eccentric (braking) phase to the concentric (propulsion) phase, having a lower risk of injury. Quicker stabilization also enables faster recovery for subsequent movements, such as another jump or a change of direction.

The force vs. time plot for initial contact exhibited scattered patterns and poor fit, with low R-squared values of 18.1% and 20.7% for drop heights of 33 cm and 49 cm, respectively. The maximum force recorded at 33 cm was 3960.05 N, and at 49 cm, it was 4844.25 N, which is 68% closer to the values associated with metatarsal fractures (as 3562 N of force has a 50% probability of causing a fracture). Stabilization force during barefoot forefoot jumping was 584.40 N at 33 cm and 583.35 N at 49 cm. The difference between the minimum force and the stabilization force was 71.37% at 33 cm and 82.11% at 49 cm. It was revealed that an efficient and rapid stabilization is necessary to achieve a better balance and firmer stability after jumps from heights. This kinetic data will be beneficial and set standard values for the optimization of material properties in sports and children's footwear to reduce the risk of foot injuries.

Acknowledgment

The authors would like to express their sincere gratitude to all the participants for volunteering in the study. We are indebted to and convey our deepest sense of appreciation to Col. Pankaj Sinha, Managing Director at the Centre of Excellence, Footwear Design and Development Institute, for his administrative support. We would like to express our sincere gratitude to Deepak Sahni, Deputy Manager; Shyam Katiyar, Senior Faculty – Grade 2; Ashok Sahai, Senior Faculty – Grade 1; and Suresh Joshi, from the Centre of Excellence, Footwear Design and Development Institute for their assistance and cooperation in liaising with the participants for the experiment, as well as for their help in completing this study. We are also thankful to the Ministry of Commerce of India for their financial support.

Authors' Contribution: Each author contributed individually and significantly to the development of this article. SDK*(https://orcid.org/0000-0002-0581-9336) was involved in the Statistical analysis and manuscript preparation; KS *(https://orcid.org/0009-0000-8001-9526) was involved in data collection, data processing, and tabulation; BRC *(https://orcid.org/0009-0009-9316-5915) was involved in data collection data processing and tabulation; AM *(https://orcid.org/0009-0007-1320-4108) was involved in data collection data processing tabulation and review of literature; MK*(https://orcid.org/0009-0003-7874-4261), and HJ *(https://orcid.org/0009-0001-1122-1891) Data collection, data processing, and tabulation; MSP *(https://orcid.org/0000-0002-9657-5858) was developing the finalized study protocol and providing step-by-step guidance for data collection, analysis, review, and finalization of the manuscript. All authors read and approved the final manuscript. *ORCID (Open Researcher and Contributor ID) iD.

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