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Research Article / Araştırma Makalesi

Comparison of the biomechanical parameters during drop jump on compliant and noncompliant surfaces: A new methodological approach

Esnek ve sert zeminlerde yapılan düşerek sıçrama sırasındaki biyomekanik parametrelerin karşılaştırılması: Yeni bir metodolojik yaklaşım

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ABSTRACT

Objective: Bilateral plyometric training of the lower extremities has been shown to provide improvement in vertical force production. However, designing a proper plyometric training program and choosing the appropriate surface is critical, otherwise the risk of injury and lower extremity joint pathologies increases. The aim of this study was to compare biomechanical parameters between mini-trampoline and noncompliant surface during drop jumping.

Materials and Methods: Thirty-four male adults participated in the study. Active markers were placed on the left knee, ankle and hip joints of the participants. Also, a force sensing resistor was placed under the participants' left shoes. During drop jumping, the knee joint angles were recorded by the camera while a *data* set of reaction forces and loading rates were collected using a force sensing resistor. Data were compared with paired samples T-test. The level of significance was set at $p \leq 0.05$.

Results: The mean values of maximum reaction forces and loading rates were greater on the noncompliant surface ($p < 0.001$). Mean knee joint angles for frame at which the knee angle is minimum and the frames one before and one after the frame at which the minimum value is obtained were similar between surfaces, however, were found to be smaller on noncompliant surface for the remaining eight frames ($p < 0.05$).

Conclusion: This study indicates that the range of bending values in the knee joint is greater on noncompliant surface compared to mini-trampoline during drop jump. Since the mini-trampoline resulted in lower reaction forces and loading rates, it can be used as an exercise equipment to minimize the injury risk of plyometric training.

Keywords: *Plyometric training, reaction force, motion analysis, knee joint angle, drop jump, motion analysis*

ÖZ

Amaç: Bilateral alt ekstremite pliyometrik egzersizlerin dikey kuvvet üretim gelişiminde etkili olduğu görülmektedir. Ancak avantajlarının yanı sıra yanlış planlanan ve yanlış zeminlerde uygulanan pliyometrik egzersizler yaralanma riskini ve alt ekstremite eklem patolojisi riskini artırabilmektedir. Bu araştırmanın amacı mini trambolinde ve düz zeminde yapılan derinlik sıçramalarının biyomekanik parametrelerinin karşılaştırılmasıdır.

Gereç ve Yöntemler: Çalışmaya 34 yetişkin erkek katıldı. Katılımcıların sol diz, ayak bilek ve kalça eklemlerine aktif işaret noktaları yerleştirildi. Ayrıca, katılımcıların sol ayakkabılarının altına kuvvet sensörü yerleştirildi. Sıçramalar kamera ile kayıt altına alınırken bu sıçramaların kuvvet sensör verileri de kaydedildi. Kameradan elde edilen verilerin analiziyle diz eklem açıları hesaplandı. Kuvvet sensöründen elde edilen verilerin analiziyle ise tepkime kuvvetleri ve yüklenme hızları elde edildi. Elde edilen veriler bağımlı gruplarda T testi ile karşılaştırıldı. Çalışmanın anlamlılık düzeyi $p \leq 0.05$ olarak belirlendi.

Bulgular: Maksimum tepkime kuvveti ve yüklenme hızı ortalamaları düz zeminde daha yüksek bulundu ($p<0.001$). Diz eklem açısının minimum olduğu "frame" ile bundan bir önceki ve bir sonraki "frame" sırasında diz eklem açı ortalamalarının iki zemin için benzer olduğu gözlemlendi. Ancak geri kalan sekiz "frame"deki diz eklem açı ortalamaları düz zeminde daha küçük bulundu ($p<0.05$).

Sonuç: Bu çalışma derinlik sıçraması sırasında diz ekleminin düz zeminde mini tramboline göre daha çok büküldüğünü ortaya koymuştur. Mini trambolinde yapılan derinlik sıçraması sırasındaki tepkime kuvveti ve yüklenme hızı daha düşük olduğundan, mini trambolin pliyometrik antrenmanlar sırasında riski azaltan bir ekipman olarak kullanılabilir.

Anahtar Sözcükler: *Pliyometrik antrenman, tepkime kuvveti, hareket analizi, diz eklem açısı, derinlik sıçraması*

INTRODUCTION

Today, basketball is one of the most popular sports. Basketball is a versatile team sport and requires increased anaerobic capacity of players for successful performance (1, 2). The possession of the ball, the ability of quick movements, and ability to generate explosive power required for defense and score is crucial. In addition to the capacity to gene–

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rate explosive power, vertical jumping is one of the main movements required for basketball, and vertical jump performance is highly related to the playing time of basketball players in a game (1, 3). Plyometric training, such as hopping, jumping, skipping, depth jump, drop jump is known to be effective at improving vertical jump (2, 4).

During a complex movement including plyometric exercises, eccentric and concentric muscle contractions occur. This process is defined as stretch-shortening cycle. Stretch-shortening cycle consists of three phases. The first phase refers to eccentric phase that the muscle performs an eccentric contraction. During the next phase, that is called amortization phase, the transition from the eccentric phase to concentric phase occurs. The third phase includes concentric muscle contraction (5).

Various studies have examined the knee kinematics and variation in knee angle during plyometric exercises (4, 6). It has been concluded that greater degrees of knee flexion lead higher energy absorption and lower loading rates on noncompliant surfaces (7), and plyometric exercises performed on a mini-trampoline reduces knee flexion (4). Furthermore, it has been reported that jumping trainings on a mini-trampoline increases vertical jump performance (8).

Besides the benefits, plyometric exercises can cause injuries due to its dynamic nature along with the other reasons including poor performance or technique, low pre-training leg strength, dynamic valgus, reduced active shock absorption. (9-11). Since the musculoskeletal system may fail to distribute high ground reaction forces and loading rates (rate of forces affecting the body) produced during plyometric exercises, the risk of injury and lower extremity joint pathologies may increase (7, 12-14). For instance, ground reaction force can increase 3 to 4 times of the body mass during the landing phase of depth jump (4). Moreover, the loading rate is one of the factors that increase the risk of injury, which is calculated by dividing the maximum reaction force by the time to maximum reaction force (7). Thus, it is thought that during a drop jump, prolonging this duration by using a mini-trampoline may reduce the reaction force.

The effects of plyometric exercises conducted on different surfaces on performance improvement have been investigated in various studies (2, 8). Crowther et al. (4) have examined variations in the range of movements for ankle, knee, hip, and trunk between mini-trampoline and noncompliant surface during drop jump and counter movement jump exercises. The authors have emphasized the need for further studies to determine reaction forces during plyometric exercises on the mini-trampoline. To the best of our knowledge, no study has been carried out to measure the reaction forces during plyometric exercises performed on the mini trampoline. The present study compared the reaction forces during drop jumps on a mini trampoline and a noncompliant surface (ground) with a new approach in which a sensor is placed under the shoe.

The use of mini-trampoline during plyometric exercise may reduce the reaction force exposed by the body compared to landing on a flat surface, as the elastic surface of the mini-trampoline absorbs some of the energy (4). Similarly, the loading rate may decrease due to the prolonged duration between at the time of initial foot contact on the surface and at the time of maximum reaction force (7). These differences in the loading rate and reaction force during plyometric exercise can prevent or reduce injury risks that may occur because of the dynamic characteristic of plyometric exercises.

In plyometric exercise models such as drop jump, the greater the size of the tension obtained in the eccentric phase, the better the performance. Elastic elements (tendons, stress potential of connective tissues covering the muscle) increase the tension in the eccentric phase (5, 15, 16). Due to having elastic elements with weak tensile potential, athletes who only use muscular strength to handle the entire workload may have an increased risk of injury. It is thought that using mini-trampoline during a drop jump may reduce the workload of the elastic elements, therefore the risk of injury may also reduce. Accordingly, mini-trampoline can be an important auxiliary equipment in plyometric training for this type of athletes.

Previous studies have shown biomechanical differences between different surfaces during plyometric activities (4, 6). However, the effects of mini-trampoline on the reaction force, time to maximum reaction force, loading rate and knee angle change during plyometric exercises is not well known. The purpose of this study was to examine the knee angle change, loading rate, reaction force, and time to maximum reaction force during drop jumps both on a mini-trampoline and a flat surface. We hypothesized that during plyometric exercises, loading rate, reaction force and knee flexion are less on the mini-trampoline than on the flat surface.

MATERIALS AND METHODS

Subjects

A priori sample size calculation was performed. The minimum number of participants required for paired T-test with effect size of 0.5 and 0.8 power at the 0.05 significance level was calculated using R statistics software. Accordingly, the minimum number of participants was determined as 34. Thirty-four healthy male basketball players (mean age: 20.09 ± 2.0 years, height: 191.06 ± 9.6 cm, weight: 89.40 ±

13.2 kg, body fat percentage: 13.86 ± 4.2%, sports experience: 10.91 ± 3.0 years) aged between 18 and 29 years and play in professional leagues participated in the study. All the participants were training regularly as a member of a professional basketball team. Those with chronic or acute lower extremity injuries in the last three months and those who made heavy physical exertion 24 hours before each test session were excluded from the study. The current study was approved by the Dokuz Eylül University Noninvasive Research Ethics Board (# 2012/25-34) and performed in accordance with the Helsinki Declaration, revised 2013. Participants signed an informed consent form prior to the study.

Anthropometric measurements

Body mass, height and body fat percentage of the participants were measured without shoes, only with shorts and t-shirts on. Biospace Inbody 720 Bioimpedance analysis device was used to measure body mass and body fat percentage.

Warm-up, familiarization, and drop jump protocols

After the anthropometric measurements, a standard 10-minute warm-up program including five minutes of jogging and five minutes of stretching exercises were performed by the participants prior to drop jumping procedure. Participants performed drop jumping from a 60 cm platform first onto a flat surface and then onto a mini trampoline in the laboratory environment. Participants were asked to stretch their left leg forward standing with their hands on the waist, feet shoulder width apart and knees straight. Participants landed without jumping, and as soon as they touched the surface with both feet contacting the surface, they jumped the highest and landed again (4). The drop jumps performed with a different technique were repeated. Participants familiarized with drop jump twice before the data was recorded during the third jump. Participants were given a 30 second resting time between each jump. The same procedure was applied for the mini-trampoline surface, and participants were asked to land on the center of the mini-trampoline. While the procedure was applied for the mini trampoline, a drop jump was performed on a second step prepared at a height of 60 cm from the trampoline.

Biomechanical measurements

Knee angle measurements

To investigate the knee angle change, motion capture data was used to calculate knee angles (17). The posterior angle between tibia and femur was measured as the knee angle. Infrared modified GoPro Hero 3 camera was used for motion capturing. All the recordings were done from the left side of participants with the same distance and angle. Videos were recorded as 1280 x 720-pixel resolution with 50 frames/second. 850 nm infrared LEDs were used as active markers for motion capture. Markers were placed on the left knee (Epicondylus Lateralis), ankle (Mallelous Lateralis), and hip joints (Trochanter major) of participants by the same experienced researcher.

The camera was modified to be infrared sensitive by removing the filter to eliminate the problems that may occur during the tracking of the markers. Videos were recorded under a fixed light in an isolated room that did not receive sunlight. Videos were analyzed by the researchers with a program developed in Matlab. The camera was placed perpendicular to the jump performance area to minimize the error that can occur from using a single camera. The calibration image was placed into the sagittal plane of the drop jump performance area. A calibration process was applied to correct lens distortion, and then all the images were corrected with the obtained calibration matrix. The calibration library developed by the Vision group at California Institute of Technology was used (18). Then, images were segmented using threshold value, and they were converted to the binary data format. Kanade – Lucas – Tomasi algorithm was used to detect and track of the marker points (19-21). Spatial information belonging to three points marked on the person was transferred to the computer. Knee angle was computed using inverse trigonometric functions.

Reaction force and loading rate measurements

A force sensing resistor (FSR) was placed under the participant's left shoe to calculate the reaction force and loading rate. Because data acquired with FSR is not on a linear character, a conversion was applied to the data with nonlinear mapping method during system calibration. Tekscan Flexiforce A201 model having 445 N sensing capacity, ± 3% linearity, and ± 2.5% repeatability was used as FSR during the research (22). Reference circuit design provided by the company was used during connecting of FSR to the microcontroller (Atmel ATMega2560), and data was digitized with 10-bit analog-digital converter and 1000 Hz sampling rate.

Firstly, the FSR system was placed in a neoprene band which was prepared by the researchers, ensuring that the system is protected and fixed when placed under the shoe. The assembly was designed to produce five V correspond to the maximum resistance value obtained. This value with 10-bit analog-digital converter was acquired at 1024 resolution (as 5 V/1024 unit). The acquired data was then converted to N value Using the software developed for the analysis of the data in the Matlab environment, force-time curve was drawn and the time from baseline to maximum reaction force measured through this curve. Loading rate was calcula–

ted by dividing the maximum reaction force value by the time to the maximum reaction force (7, 23).

Mini-trampoline flexibility measurements

In case the flexibility of the trampoline would change as the measurements were being carried out, a method was developed by the researchers to test the flexibility of the trampoline. Before the testing procedure, a 41.2 kg object was placed in the center of the trampoline, and the trampoline was observed to stretch for 5 centimeters under this weight. Accordingly, it was planned to continue the testing procedure with a new trampoline in case of a change of up to 10% (0.5 centimeters). A mechanism was designed to measure the flexibility of the trampoline under the abovementioned weight. The study was completed with one trampoline since no change reaching 0.5 centimeters was observed in flexibility measurements which were made once every five participants throughout the tests.

Statistical analyses

The data were analyzed with SPSS 22.0. Data acquired during plyometric jumps which were performed on mini-trampoline and flat surface was analyzed with paired T-test. The mean values of maximum reaction force, mean time to maximum reaction force acquired with FSR and mean loading rates were compared. Finally, last five frames of the eccentric phase, the frame of the amortization phase and first 5 frames of the concentric phase were examined for the knee angle change. The mean of minimum knee angles, and the mean of the knee angles at the frames five before and five after the frame at which the minimum value obtained were compared (total of 11 frames). The level of significance was set at $p \leq 0.05$ for the study.

RESULTS

There were significant differences between the two surfaces in the maximum value of reaction force, time to maximum reaction force and loading rate (Table 1). The mean maximum values of reaction force acquired with FSR was less on mini-trampoline than on flat surface ($p < 0.001$). The mean time to maximum reaction force was longer on the mini-trampoline than on flat surface ($p < 0.001$). The mean loading rates calculated on mini-trampoline was lower than on flat surface ($p < 0.001$).

Table 1. Comparison of FSR related data (means ± SD)

Surface	FSR Max (N)	FSR Time (ms)	Loading Rate (N/ms)
Flat Surface	397.84 ± 62.4	150.50 ± 64.5	3.207 ± 1.6
Mini Trampoline	311.91 ± 73.5	238.94 ± 96.8	1.481 ± 0.6
p	< 0.001	< 0.001	< 0.001

FSR – force sensing resistor; FSR Max – maximum reaction force; FSR Time – time from landing to the maximum reaction force; Loading Rate – calculated by dividing FSR Max to FSR Time.

Use of mini-trampoline led to significant differences in the knee angles (Figure 1). In all the 11 frames, mean knee angles were smaller on flat surface. However, while there was no significant difference for the frame at which the knee angle was minimum, and the frames one before and one after the frame at which the minimum value is obtained, significant differences were detected among the mean of the knee angles for the remaining eight frames ($p < 0.05$).

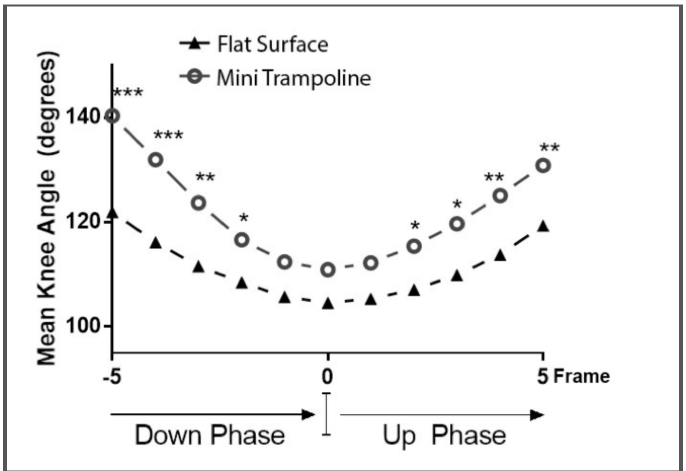

Figure 1. Plots for averages of knee angles on flat surface and mini trampoline.

* Significantly larger than Flat Surface ($p < 0.05$)
** Significantly larger than Flat Surface ($p < 0.01$)
*** Significantly larger than Flat Surface ($p < 0.001$)

DISCUSSION

The purpose of this study was to compare the knee angle change, reaction force, time to maximum reaction force and loading rates during drop jumps on a mini-trampoline and a flat surface. The main finding of this study is that the reaction force and loading rate affecting the body during drop jumps are lower on mini-trampoline than on flat surface. There is a limited number of studies about performing plyometric jumps on compliant surface and its effects (4, 6, 8). Moreover, the differences in biomechanical parameters caused by different surfaces during plyometric jumps and the investigation of surface types to reduce the possible harmful effects of plyometric jumps are still up-to-date research subjects (6).

Number of studies examining knee angles during drop jumps on different types of surfaces is limited. Crowther et al. (4), have found knee angle is larger on a mini-trampoline than flat surface during depth jumps. On the other hand, in a study conducted with 14 physically active and healthy male and female subjects, Prieske et al. (6) have found that during drop jumps the knee angle is smaller on flat floor than on a balance pad. The results of the current study and previous studies are coherent in terms of knee angles (4, 6). Furthermore, Crowther et al. (4) have concluded that smal–

ler knee flexion reduces reaction forces on the body during jumps in line with the current study. It is thought that the elastic surface of the mini-trampoline enables prolonged contact time during drop jump, allowing a decrease in the loading rate as well in the reaction force. Consequently, the reaction force and loading rate that the body has to absorb decreases on mini-trampoline, resulted in a reduced crouch compared to the flat surface.

Ground reaction forces and loading rates during drop jumps performed on flat surface have been measured with force plate in many studies. However, any study conducted to measure the reaction force or the loading rate during drop jumps performed on a mini-trampoline has not been encountered. The different approach of this study, on the other hand, is the use of a force sensor (22, 24, 25) placed under the shoe to examine the effects of plyometric jumps on different surfaces. With this methodological innovation, reaction forces could be measured, and loading rates could be calculated during drop jumps performed on mini-trampoline. By using this method, biomechanical parameters such as reaction forces and loading rates can be measured on uneven and/or unstable surfaces, as well. By this new method, the ground reaction force can be measured outside the laboratory, allowing to examine the reaction force even on surfaces of different shapes and flexibility or when movements are unpredictable (i.e., competitions), and more innovative studies can be planned.

During landing or jump on a flat surface, crouch action helps to prolong the time between the first touch to the ground and the maximum ground reaction force occur (7, 26). As a result of this prolongation, loading rate becomes lower. Furthermore, greater flexion improves ground reaction force absorption (7, 26) and results in a lower maximum ground reaction force. In other words, during a drop jump greater flexion leads lower loading rate and ground reaction force (7, 26). Contrary to these, current study indicates that knee flexion is lower during drop jump on a mini-trampoline and loading rate and reaction force are lower, as well. These finding suggest that the main reason of lower reaction force and loading rate is the elastic surface of the mini-trampoline, not knee flexion.

Prieske et al. (6) have compared maximum ground reaction forces produced by drop jumps performed on a force plate (flat surface) to those by drop jumps performed on a balance pad which was placed on a force plate. Researchers have concluded that the maximum ground reaction force is lower on flat surface, which contradicts the current study. Furthermore, Prieske et al. (6) have interpreted these results as less knee flexion can cause a higher ground reaction force. In the present study, contrary to a higher reaction force, a lower reaction force developed as a result of less knee flexion on a compliant surface. Therefore, the presence of less knee flexion during drop jumps performed on a compliant surface did not increase reaction force.

These different results may be due to the structural and flexibility differences between mini-trampoline and balance pad. The other possible reason is the measurement performed with a force sensor placed under the shoe instead of a force plate. Another cause could be the fact that the measurement device was between the surface (mini-trampoline) and the shoe whereas in Prieske et al.'s (6) study it was between the two surfaces (ground and balance pad). Conducting new studies are necessary to clarify this difference. For instance, modeling of the data acquired from motion capture, vector calculation of the force affecting knee and tibia can be useful to reveal in simulation studies (27-29). Thus, forces on knee and tibia can be calculated and interpreted.

It is known that greater reaction force and loading rate may increase the risk of lower extremity injuries (7, 30). The results of the current study indicate that the reaction force and the loading rate are lower when a drop jump task is performed on a mini-trampoline. In the light of these findings, it can be inferred that the risk of injury during drop jumps can be reduced when performed on mini-trampoline. Because of this risk-lowering feature of mini-trampoline, it can be useful for individuals such as athletes in rehabilitation processes, who have low leg strength or poor technique to perform a drop jump on flat surface, and for new beginners. Moreover, it is also known that using compliant surface such as mini trampoline improves performance including balance, jump height, technique (4, 8).

The limitation of this study is that the data obtained by the FSR may not be suitable for comparison with data of other studies. Since the FSR used (9.53 mm diameter sensing area) covers a very small part of the shoe, it shows only the reaction force that affects the sensing area, not the total reaction force that the body is normally exposed to. The neoprene band, in which the FSR system was placed, also can be considered to reduce the reaction force to some extent due to its absorptive property. Because of these two factors, although the results acquired with FSR can be compared with each other, comparing this data with data of other studies may not be appropriate. Another limitation of this study is that the participants' landing spots on the mini-trampoline might not be exactly the same. This can affect the standardization of the FSR data on the mini trampoline. To eliminate this limitation, the participants were asked to land on the center of the mini-trampoline, and researchers visually observed the drop jumps throughout the study. When it was observed that a participant did not land on the center of the mini-trampoline, that drop jump was repeated. Nevertheless, it is thought that, the results acquired with FSR can be used to compare two surfaces with each other, because the athletes may not land exactly at the center of the mini-trampoline during a plyometric training session in real-life conditions, as well. Lastly, since only a single camera was used, the motion was captured in two dimensions and it was assumed that the motion occurs in a plane.

CONCLUSION

The most important finding of this study is that the loading rate is lower during drop jump performed on mini-trampoline. Hence, the use of mini-trampoline during plyometric exercises can be beneficial for athletes due to lower loading rate and reaction force. Another finding of this study was that the mean of knee angles at eight frames was smaller on flat surface. Compliant surface showed reduced knee flexion and this reduction leads to less reaction force. Finally, this new approach offers a cheaper and easier-to-use method.

Supplement 1. Table of Abbreviations

Abbreviation	Meaning
FSR	Force sensing resistor
FSR Max	Maximum reaction force
FSR Time	Time from landing to the maximum reaction force

Ethics Committee Approval / Etik Komite Onayı

The approval for this study was obtained from Dokuz Eylül University Noninvasive Research Ethics Board, İzmir, Turkey (Decision no: 2012/25-34 Date: 24 July 2014).

Conflict of Interest / Çıkar Çatışması

The authors declared no conflicts of interest with respect to authorship and/or publication of the article.

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Author Contributions / Yazar Katkıları

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