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Original Research

The effect of a custom Area Elastic Surface with different stiffness on hopping performance and safety with an emphasis on familiarity to the surface

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ABSTRACT

There is no doubt that sporting surfaces are extremely important for every activity. However, there is not sufficient scientific report regarding the effect of the area elastic surface floor with common range stiffness on vertical hopping safety and performance. The aim of this study was to examine the effect of custom area elastic surface with different stiffness on the hopping performance and safety with emphasis on familiarity to the surfaces. Fifteen young and healthy experienced male were volunteered in this study. Kinematic and kinetic data recorded during hopping on four surfaces (300-500 kN/m) using the Motion Analysis System and AMTI force plate. In the data analysis process, leg and joint stiffness, maximum vertical ground reaction force, mechanical energy and power and angular position of joints calculated. The results of this study show that surface stiffness does not effect on the leg and joint stiffness, but after familiarity to the surface, there was a significant increase in 400 kN/m surface positive mechanical energy and power of ankle joint and a significant decrease in negative mechanical energy and power of knee joint ($P<0.05$). In conclusion, it seems the change in surface stiffness after familiarity to the surface causes an improvement of hopping performance without any change in leg and joint spring stiffness. It can be proposed that deformation following impact also does not enough to significantly reduce the vertical ground reaction force.

Keywords: Stiffness, Custom surface, Hopping.

Introduction

Stiffness of the playing surface is suggested as an important parameter in the sport performance and injury prevention. Researchers have indicated that running track's stiffness could influence the speed enhancement [1] and economy of running [2]. From the performance point of view, it was indicated that sprung surface increased the drop and vertical jump heights by increasing the energy transmitted and recovered from the surface [3, 4]. Regarding the safety, it was shown that tracks with intermediate compliance (i.e., two to four times of the leg stiffness) could attenuate the early peak of the Ground Reaction Force (GRF), which can reach up to five times of the body weight in running on a hard surface [1]. Nigg et al [5] showed that construction strategies of sprung surfaces can affect maximum deformation of surface and might reduce the maximum force acting on the athlete's body during a vertical jump. Moreover, the surface with the minimum deformation was classified as the least comfortable and surface which showed the maximum value of deformation was assessed as the most comfortable [5].

Interaction between surface stiffness and leg mechanics during vertical hopping has shown in the previous studies [6-8]. It is proposed that hopping in place is an ideal model for assessing the interaction between the surface and leg stiffness, since it follows the same basic mechanics as the forward running [6], and yet has a simpler kinematics [7]. Given the relatively high frequency and spring-like characteristics of repetitive vertical hopping, the lower limbs remain more rigid and this reduces the number of joints involved and also the number of biomechanical variables compared with other jump techniques [8]. However, the effect of surface stiffness and familiarity to that following practice on the vertical hopping performance and safety is not well understood.

It has been suggested that surface stiffness about two to four times of the leg stiffness could be better in order to optimize running safety and performance [1], however, standard stiffness proposed for the Area-Elastic gymnasium floor is about 400 kN/m [9]. So the effect of this standard range of stiffness on the leg mechanics is still unclear. In a study by the Stafilidis and Arampatzis [10], it was shown that track stiffness more than four times of leg stiffness during sprinting (about 37 kN/m for leg stiffness Vs. 550, 2200 & 5500 kN/m for surface stiffness) could not affect leg mechanics and subsequently the performance. Therefore, more research on lower surface stiffness is needed.

In addition to surface stiffness, individual action, could affect the interaction between human and playing surface. It was claimed that total mechanical work and joint power depends on the behavior of the energy storing system (i.e., sprung surface) and the energy producing system (i.e., the subject) [3]. In this regard, the effect of practice on an improvement of jumping task on the sprung surfaces has been proposed [4]. Therefore, it can be proposed that the level of familiarity to the surface is an influencing factor on the effect of interaction between human and the surface. However, the number of studies in this area is limited [3, 4, 13].

Hence, the aim of this study was to a) examine the effect of new area elastic surface with different stiffness on the vertical hopping performance and b) examine the effect of familiarity of surfaces with different stiffness values on the hopping performance. It was hypothesized that changes in the surface stiffness in a range of 300-36000 kN/m might affect hopping performance and individual safety.

Material and Methods

Participants

Fifteen experienced athlete male with the mean age of 24.8 ± 4.26 years, height of 175.2 ± 8.5 cm, and body mass of 70.9 ± 8.2 kg volunteered for this study. None of the participants had a history of neuromuscular or musculoskeletal impairments.

Surface design

The surface used in this study comprised two layers of wood and chipboard (50 × 50 cm). For the top layer, we used wood Parquet tile (50 × 50 cm) that often utilized in the indoor area elastic surface with a thickness of 5 mm. The top layer was adhered to the bottom surface with glue, which was a chipboard plate with 20 mm thickness. Depend on the surface stiffness, 4 to 6 metal springs were attached to the corners of the chipboard surface with screw connections to simulate area elastic surface used on gymnasium indoor surfaces (Figure 1).

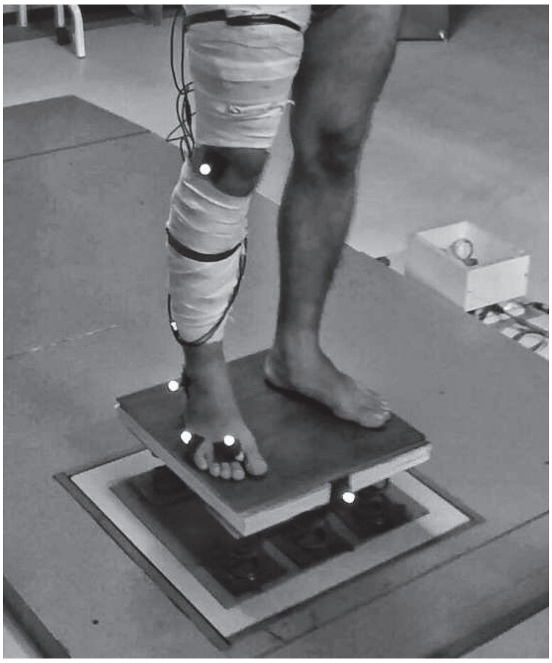

Figure 1. Surface and subject arrangement used in study on a force plate.

Table 1. Physical dimensions and material type of springs.

Spring characteristics	50 kN/m	100 kN/m
Spring wire diameter (mm)	7	8
Inner diameter of spring (mm)	41	39
Free length of spring (mm)	100	100
Spring's coil number	6	6
Distance between coils (mm)	19.75	19
Material type	Steel 17-7 A313	Steel 17-7 A313

Test protocol

Kinematic data were recorded using 6 cameras (Motion Analysis Corporation, Inc., USA). The GRF were measured by AMTI force plate (Advanced Mechanical Technology, Inc. USA). Five retro-reflective markers were attached to the subjects in the following locations: the fifth metatarsophalangeal joint, the lateral malleolus, lateral femur epicondyle, the greater trochanter, and acromion scapulae. Subjects were asked to synchronize their hopping frequency to a digital metronome that was set at 2.2 Hz. Trials were accepted if the hopping frequency was within 2% of the designated frequency. After a practice period of 5 minutes at the given frequency, subjects performed fifteen hops on the each surface with five minutes of rest after each performance. Fifteen consecutive hops considered as one trial and subjects instructed to perform three true trials. Kinematic and kinetic data on the frequencies of 250 and 1000 Hz were collected during each trial, respectively. After measuring trials, subjects became familiar with each of three sprung surface. For this purpose, subjects first received enough information about the spring surface, its stiffness and how it could possibly affect their performance. Then each subject tried to practice on the each surface at the frequency of 2.2 Hz. Practice consisted of approximately 2000 hops on surface until subject could understand spring properties of the surface and felt the effect of surface deformation and the possible effect of that on their hopping performance. After familiarity with the surface, again three true trials were measured for each subject. Three-dimensional positions of the reflective markers were digitized by Cortex software (version 2.5, Motion Analysis Corporation). Kinematic and kinetic data, then low-pass filtered by a fourth-order zero-lag Butterworth filter with a cut-off frequency of 8 and 50 Hz [11]. Five consecutive hops including hops number six to ten were selected for the analysis [12].

Data analysis
Leg and joint stiffness

The average stiffness of the leg during the contact phase on the force plate was calculated from the ratio of the maximum VGRF to the displacement of the Center of Mass (COM) [7]. However, for hopping on the sprung surface, displacement of the COM comprised two components, vertical displacement of the subject and surface [7], so actual displacement of the subjects' COM was calculated through the subtracting sum of these two displacements from the surface displacement (calculated from dividing peak VGRF from surface stiffness).
Joint stiffness was calculated by dividing peak joint moment by joint angular displacement [13, 14]. It was assumed that the peak joint moments and maximal joint flexions coincide in the middle of the ground contact phase. In order to ensure correct calculation of stiffness, following criteria, were applied during the data analysis:
a) The relationship between force - displacement/moment- angular displacement has R-square value more than 0.8 [14].
b) The time difference between the occurrences of peak force/moment and the peak displacement/angular displacement was, 10% of the hop period [15].
C) Calculated stiffness in each hop should not be more than Mean+2SD of all five trials of the same subject.

Mechanical energy and Power

The joints mechanical power was estimated by multiplying the joint moment by the joint angular velocity, and joint energy was calculated by integrating of the power-time curve using trapezoidal rule. Joint moments were determined by utilizing rigid-linked segment model, anthropomorphic data [16], and an inverse dynamics analysis [11].

Statistical analysis

One-way repeated measure ANOVA and Bonferroni post-Hoc tests were performed to compare the leg stiffness, joint stiffness and mechanical energy and power among four surfaces. Additionally, Paired-t-test was applied to compare these parameters before and after familiarity to the surfaces. Statistical significance was set at $P \leq 0.05$. SPSS Software (Version 16.0, SPSS Inc.) was used for all statistical analysis.

Results

Leg stiffness

Descriptive statistics for the leg stiffness are presented in Table 2. The results of repeated measure ANOVA showed that there was no significant difference in the leg stiffness between the four surfaces, before and after familiarity to the surface (Before; F= 1.83, sig=0.162. After; F=1.31, sig= 0.29) (Table 2). However, as it presented in Figure 2, the magnitude of the leg stiffness during hopping on the force plate was greater as compared to other surfaces, but leg stiffness on the other surfaces were similar.
Comparison of the leg stiffness before and after familiarity to the surface also showed no significant effect of familiarity ($P \geq 0.05$) (Table 2). However, as it depicted in the Figure 2, there is some increase in the leg stiffness on the 400 kN/m surface after familiarity to this surface.

Joint stiffness

The mean and standard deviation of values for joint stiffness are shown in Table 2. The Results of statistical comparison did not show any significant differences in the ankle and knee joint stiffness between four surfaces, before and after familiarity to the surface (Table 2) (Before; Ankle; F=0.598, sig= 0.62. Knee;

F=2.69, sig= 0.06-After; Ankle; F= 1.8, sig= 0.17. Knee; F=1.97, sig=0.14). Figure 2 shows some decrease in ankle and knee joint stiffness following an increase in surface stiffness, however, like leg stiffness; joint stiffness on the force plate was higher.

Comparison of joint stiffness before and after familiarity to the surface also showed no significant effect of familiarity (P≥0.05) (Table 2). However, as it has shown in Figure 2, there is some increase in ankle joint stiffness and decrease in knee joint stiffness after familiarity to the surfaces.

Table 2. Mean (SD) maximum VGRF, leg stiffness, ankle joint stiffness and knee joint stiffness on 300, 400, 500 kN/m surfaces and force plate before and after familiarity to the surface.

variables	Surface Stiffness values						
	300 kN/m		400 kN/m		500 kN/m		36000 kN/m
	Before	After	Before	After	Before	After	-
Maximum force (N)	26.25 (4.09)	26.27 (4.83)	25.84 (2.83)	27.68 (4.19)	25.58 (4.13)	28.12 (3.32)	29.19 (4.75)
Leg stiffness (kN/m)	18.27 (2.83)	18.95 (2.68)	18.96 (4.09)	18.56 (3.83)	17.94 (3.31)	18.53 (3.23)	19.74 (3.06)
Ankle Joint stiffness (kN.m/rad)	501.26 (146.1)	470.25 (148)	480.84 (121.8)	476.6 (125.1)	448.76 (141.3)	439.8 (13.64)	503.14 (113)
Knee Joint stiffness (kN.m/ rad)	600.1 (252.2)	660.81 (280.5)	515.5 (259.6)	529.05 (283.6)	528.7 (266.6)	540.71 (204.2)	598.48 (141.5)

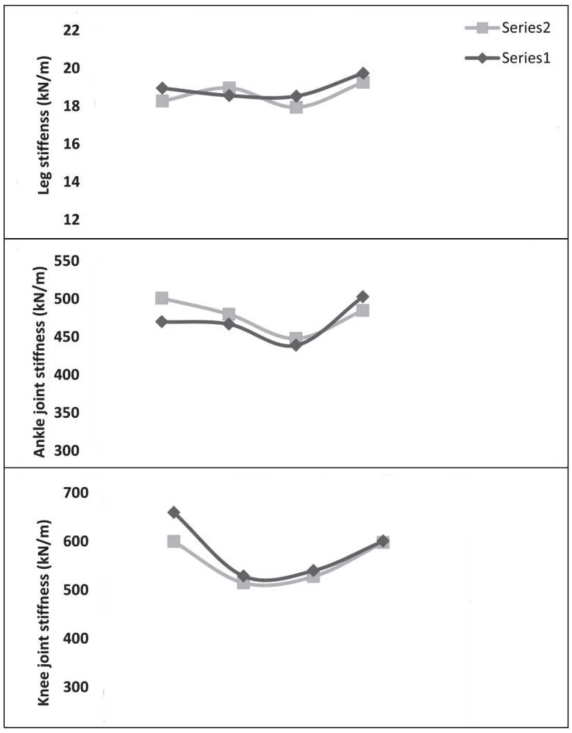

Figure 2. Relationship between leg stiffness (a), ankle joint stiffness (b) and knee joint stiffness (c) on 300 kN/m, 400 kN/m, 500 kN/m surfaces and force plate before (dark line) and after (bright line) familiarity to surfaces.

Mechanical power and energy of the joints

Descriptive statistics for the mechanical energy and peak power of ankle and knee joints are presented in Table 3. Results of Analysis of Variances (ANOVA) didn't show significant difference between peak power of ankle and knee joint on the four surfaces before familiarity to the surface (Ankle; F=2.08, sig=0.108. Knee; F=2.06, sig= 0.14), but there was a significant main effect of surface stiffness on the peak power of ankle and knee joints on the four surfaces after familiarity (Ankle; F=3.08, sig= 0.03. Knee; F=5.4, sig=0.000). Post-Hoc comparison revealed that peak positive power of ankle joint on the 300 kN/m surface was significantly lower than 400 and 500 kN/m surfaces and the force plate (P<0.05). Also it was shown that peak negative power of knee joint on the 300 and 400 kN/m surface was significantly lower than the force plate (P<0.05) (Table 3 and Figure 3).

Comparison of mechanical power of joints before and after familiarity to the surface showed statistically significant differences between peak positive power of ankle joint and peak negative power of knee joint on the 400 kN/m surfaces (Ankle; t=4.4, sig=0.01. Knee; t=2.8, sig=0.04) (Table 3 and Figure 3).

Table 3. Mean (SD) peak power and mechanical energy of ankle and knee joint in positive and negative phase on 300, 400, 500 kN/m surfaces and force plate before and after familiarity to surface.

Variables	Surfaces Stiffness Values						
	300 kN/m		**400 kN/m**		**500 kN/m**		**36000 kN/m**
	Before	After	Before	After	Before	After	-
Peak power of ankle J (-) (W/kg)	12.17 (4.32)	12.33 (7.69)	10.4 (4.95)	10.81 (3.49)	10.97 (4.15)	10.09 (4.67)	14.03 (4.64)
Peak power of ankle J (+) (W/kg)	8.53 (3.24)	8.01 (5.32)	8.51 (4.7)	9.89 (4.11)	9.36 (3.7)	10.78 (3.2)	11.94 (3.41)
Peak power of knee J (-) (W/kg)	4.38 (1.41)	4.19 (2.58)	5.17 (1.38)	4.14 (2.69)	5.57 (2.01)	5.38 (2.13)	5.74 (2.93)
Peak power of knee J (+) (W/kg)	3.26 (2.07)	1.54 (1.41)	3.04 (1.74)	3.2 (1.55)	3.54 (2.48)	3.21 (2.68)	4 (2.36)
Mechanical energy of ankle joint (-) (J/kg)	1.12 (0.18)	1 (0.29)	0.93 (21)	0.97 (0.17)	0.93 (0.16)	0.92 (0.14)	1.09 (0.22)
Mechanical energy of ankle joint (+) (J/kg)	0.88 (0.46)	1.19 (0.28)	0.85 (0.28)	1.09 (0.16)	0.95 (0.23)	0.99 (0.07)	1.11 (0.19)
Mechanical energy of knee joint (-) (J/kg)	0.4 (0.19)	0.42 (0.25)	0.4 (0.13)	0.44 (0.17)	0.44 (0.23)	0.48 (0.17)	0.39 (0.17)
Mechanical energy of knee joint (+) (J/kg)	0.27 (0.09)	0.21 (0.14)	0.28 (0.11)	0.31 (0.13)	0.31 (0.16)	0.33 (0.14)	0.31 (0.13)

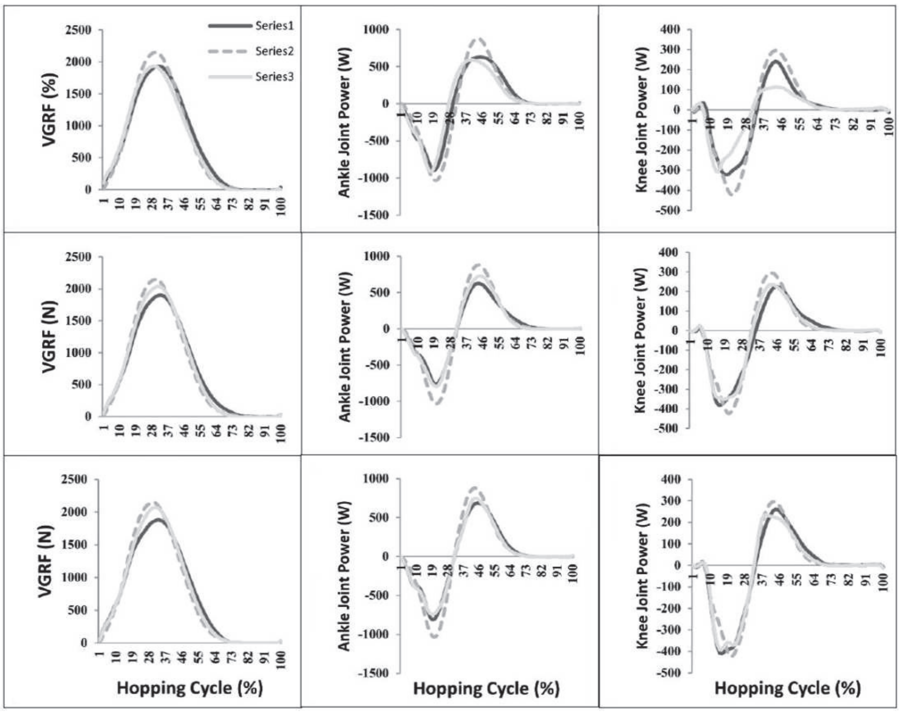

Figure 3. Vertical ground reaction force and mechanical power of ankle and knee joint on 300 kN/m (a), 400 kN/m (b) and 500 kN/m (c) surfaces in comparison to force plate (dotted line) before (dark line) and after (bright line) familiarity to surfaces.

The results didn't show significant differences in negative mechanical energy of ankle and knee joints between the four surfaces before and after familiarity to the surfaces (Ankle; F=2.07, sig= 0.13. Knee; F= 0.86, sig=0.47. After: Ankle; F=2.64, sig= 0.07. Knee; F=0.57, sig=0.64). But statistical comparison showed significant main effect of surface stiffness on the positive mechanical energy of ankle and knee joints before and after familiarity to the surface (Before: Ankle; F=3.37, sig= 0.03. Knee; F=0.5, sig=0.68. After; Ankle; F=2.06, sig= 0.07. Knee; F= 3.81, sig=0.02). Results of Bonferroni Post-Hoc test showed that positive mechanical energy of ankle joint on the 400 kN/m surface was significantly lower than force plate (Figure 4). Also it was shown that positive mechanical energy of knee joint on the 300 kN/m surface was significantly lower than 400 kN/m surface and the force plate ($P<0.05$) (Figure 4).

Comparison of mechanical energy of joints before and after familiarity to the surface showed statistically significant differences between peak positive power of ankle joint on the 400 kN/m surfaces (Ankle; t=4.4, sig=0.01. Knee; t=2.8, sig=0.04) (Table 3, Figure 4).

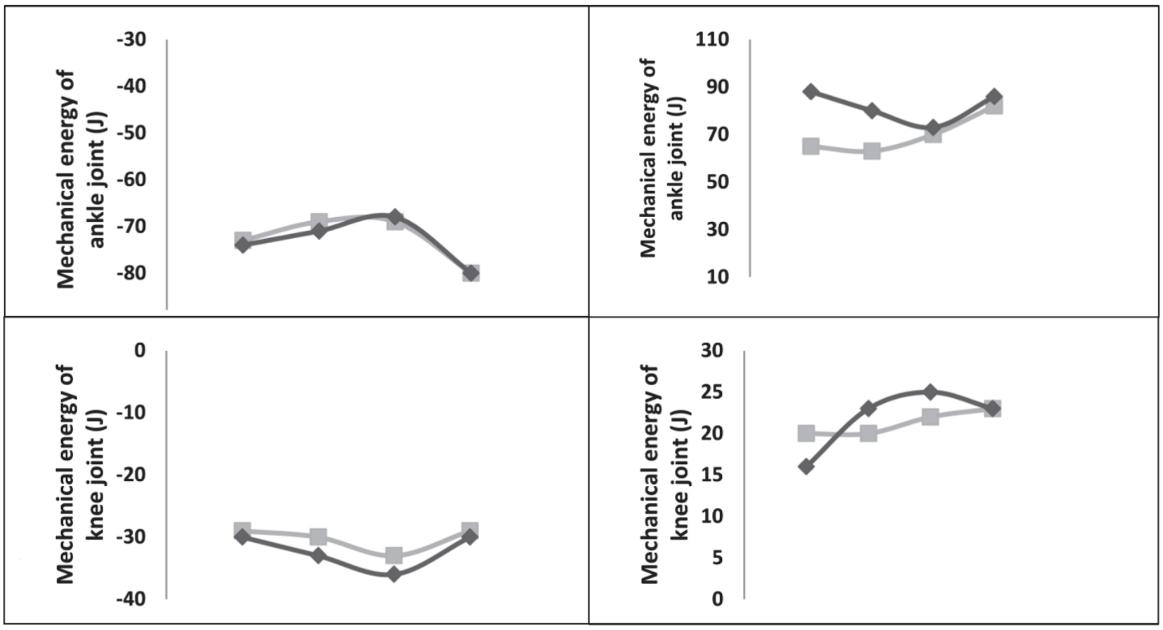

Figure 5. Relationship between mechanical energy of ankle joint in negative (a) and positive (b) phase and knee joint in negative (c) and positive (d) phase on 300 kN/m, 400 kN/m, 500 kN/m surfaces and force plate before (bright line) and after (dark line) familiarity to the surfaces.

Vertical Ground Reaction Force (VGRF)

Although higher value of VGRF belongs to hopping on the force plate and seems that familiarity to surface cause an increase VGRF on spring surfaces, ANOVA showed no significant differences between VGRF on the four surfaces before and after familiarity to the surface (Before; F= 1.74, sig=0.145. After; F= 1.94, sig=0.17) (Table 2).

VGRF comparison before and after familiarity to the surface also showed no significant effect of familiarity (P>0.05) (Table 2). However, as it depicted in the Figure 3, there is some increase in the VRF on the 400 and 500 kN/m surfaces after familiarity.

Discussion

The aim of this study was to a) examine the effect of surface stiffness on vertical hopping performance and b) examine the effect of familiarity of surfaces with different stiffness values on the hopping performance.

The results of this study showed hopping on the sprung surface in the range of 300-36000 kN/m could not affect the leg mechanics. This result doesn't support those studies whose pointed out to the interaction between surface and leg stiffness during vertical hopping [2, 6-9, 16, 18]. Based on their results, human adjust their leg stiffness when to move on the surface with different stiffness values. It has been suggested that moving on the stiffer surface reduces the leg stiffness and it increases while moving on a more compliant surface, therefore, combination stiffness of two springs in series (leg and surfaces) remain constant and consequently, the center of mass dynamic remain unchanged. It can be assumed that the ranges of stiffness (300-500 kN/m) and the following deformation (4 – 6 mm) used in this study might not be enough to affect the leg and joint stiffness. This is in accordance with the previous study, which didn't find the effect of track stiffness (in the range of 550-5500 kN/m) on the leg mechanics during sprinting [10]. They concluded, because of short track deformation, the athletes didn't show any adjustment in their leg mechanics and the benefit to the sprinters of a higher energy storage and return of the more compliant tracks. However, a range of stiffness used in this study were lower than the study of kerdok et al [2], who showed stiffness of the leg is progressively increased as surface stiffness decreases from 945.7 to 75.4 kN/m. This discrepancy between results may be due to difference in tasks (submaximal running), although it was proposed that basic mechanics and spring-mass model of forward running are same between forward running and vertical hopping [7]. In our study, we tested the hopping task; given the relatively high frequency and spring-like characteristics of repetitive vertical hopping [8] and its simpler kinematics.

We assessed the effect of surface stiffness on the performance based on mechanical energy and power analysis. The results of this study showed surface stiffness could affect the mechanical energy and peak power of ankle and knee joints. After familiarity to the surface, there was an increase in peak ankle power at the positive phase and a decrease in peak power of knee joint on the 400 kN/m surface. This result support a previous study which mentioned total mechanical work and power are dependent on both the behavior of the sprung surface and the behavior of subject [3, 4]. Decrease peak knee power in negative phase could be in accordance to previous finding which found subjects reduce energy absorbed during the negative phase and increase of the energy transmitted to the sprung surface and consequently, increase in vertical jump height [4]. Moreover, the results of this study supported the previous study, which pointed out the effect of energetics of both ankle and knee joints on change in drop jump performance on the sprung surface. Based on this result, we can say, although surface stiffness could not affect hopping biomechanics, however, it seems subjects could use the benefit of sprung surface following familiarity to it.

By investigating in maximum VGRF on the four surfaces, it appears that greater VGRF occurs on the stiffest surface (force plate), and there are no a much differences between other surfaces. Although some increase of VGRF seen on the surface with no deformation (force plate) as compared to compare to other sprung surface (4-6 mm), but these differences were not significant. This finding is in accordance with studies that found no significant differences between GRF on the sprung surfaces [10], but is in conflict with those studies that insisting on the effect of the softer surface on the reduction of maximum VGRF [1, 5]. It was shown intermediate surface compliance could attenuate the early peak in foot force, which can reach 5 times of body weight during running on a hard surface [1]. However, studies regarding the effect of softer shoe midsole on the impact force have shown that this strategy didn't effect on impact force peaks during landing or even it may increase [17, 18]. The results of this study also showed some increase in VGRF after familiarity, but this increase may be due to change in hopping performance and is in accordance with another study that assuming an increase in the rate of ground reaction force generation on hard surface compared with softer tracks [18]. They concluded that a higher rate of ground reaction force generation should increase the maximum running velocity. However, based on results of this study we can’t propose one single value at this range (300-500 kN/m) as the best stiffness for reducing the risk of injury following impact force.

In conclusion, it seems that familiarity to the sprung surface cause improves of hopping performance, without any change in leg and joint spring stiffness. Also, deformation following impact to sprung surface was not enough to significantly reduce the vertical ground reaction force.

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