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Effects of shoe and landing heights on impact force and shock attenuation during landing activities

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국문초록

뛰어 내리기 동작 시 신발과 뛰어 내리는 높이가 지면반력과 충격감소에 미치는 효과

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본 연구의 목적은 뛰어 내리기 동작 시 신발과 뛰어 내리는 높이가 지면반력과 충격감소에 미치는 영향을 연구하였다. 10명의 건강한 피험자가 신발 또는 맨발로 네 가지 다른 높이에서 (30, 45, 60 &75 cm) 다섯 번의 뛰어 내리기를 시도하였다. 수직지면반력(VGRF), 영상분석, 경골과 앞이마의 가속도가 함께 측정 되었다. 첫 번째 정점의 수직지면반력 (VGRF1)은 75cm의 높이에서 맨발보다는 신발을 신은 상황에서 더 큰 값을 보여 주었다. 두 번째 정점의 수직지면반력 (VGRF2)은 신발을 신은 것 보다는 맨발의 조건에 더 큰 값을 보여 주었다. 앞 이마의 가속도 (AccHead)는 높이와 지면에 거의 변화를 보이지 않았다. 첫 번째 정점의 경골 가속도 (AccHead)는 높이와 지면에 거의 변화를 보이지 않았다. 첫 번째 정점의 경골 가속도 (AccTibia1)는 맨발의 조건보다 신발을 신은 조건에서 더 크게 나타났다. 반면에 두 번째 정점의 경골 가속도 (AccTibia2)는 특히 60 그리고 75cm 조건에서 신

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발을 신었을 때 보다 맨발일 때 더 큰 값을 보여 주었다. 충격감소지수 (AtteIndex)는 모든 높이에서 맨발의 조건이 신발을 신은 조건 보다 통계적으로 유의하게 높게 나타났다. 결론적으로 뛰어 내리기 동작 시 신발이 지면반력을 최소화 시키고 충격을 감소시키는데 부가적인 완충물로 제공 되었음을 뒷받침 해준다.

KEY WORDS : SHOE, BAREFOOT, LANDING HEIGHT, GRE, ACCELERATION, SHOCK ATTENUATION

I. Introduction

Jumping and landing are integral parts of many sport activities such as basketball, volleyball, and gymnastics. During landing, the human body experiences tremendous impact forces. Studies in biomechanics frequently focus on mechanisms and prevention of lower extremity injuries by investigating vertical ground reaction force (VGRF). Dufek, J.S., and Bates, B.T (1990) examined effects of heights, distances, and techniques on impact forces during landing. Increases in landing stiffness and landing heights were associated with increases of peak VGRF. These results were in agreement with Mizrahi, J., and Susak, Z (1982) who also found that greater VGRF was associated with greater landing heights.

Cavanagh, P.R., Williams, K.R., and Clarke, T.E. (1981) examined VGRF during walking barefoot and in shoes. During barefoot walking, the first peak of VGRF (F1) was significantly greater and the time to F1 was shorter than the three footwear conditions. These results confirmed that differences of VGRF existed between the barefoot and shoe conditions. Wit, B.D., De Clercq, D., and Aerts, P. (2000) found significantly greater peak VGRF, loading rate, and shorter time to F1 in the barefoot running than in the shoe running. The barefoot running also demonstrated greater plantarflexion and knee flexion than the shoe running. These results confirmed that differences in VGRF related variable existed between the barefoot and shoe conditions.

Another aspect of biomechanical studies in dynamic activities is related to impact shock attenuation of the human body. Only few studies have addressed shock attenuation during landing activities, especially using information obtained from accelerometers. In the study conducted by Gross, T.S., and Nelson, R.C. (1995), shock attenuation at the ankle was examined using two uniaxial accelerometers during barefoot landing from a vertical jump. No significant difference was found for peak calcaneal and tibial acceleration across the three surfaces (a midsole foam, a tartan rubber, and a cast aluminum). There was no significant difference between the peak calcaneal and tibial accelerations across all landing techniques (toe and toe-heel landing). The toe landing technique attenuated more peak VGRF and therefore was consisted as a preferable landing technique for injury prevention. Few studies addressed effects of footwear on impact and shock attenuation during more vigorous sport activities such as landing. Therefore, the purpose of this study was to investigate effects of shoe and landing heights on impact force and shock attenuation during landing activities. By investigate the shock attenuation at the tibia and head using accelerometers and VGRF while changing surfaces and heights, one could determine mechanisms of shock attenuation throughout the body.

Ⅱ. Methods

1. Subjects

Ten healthy and physically active male subjects (age: 20.4±2.9 years, body mass: 77.0±9.5 kg, heights: 182.9 ±5.6 cm) were volunteered to participate in the study.

2. Instrumentation

A video camera (AG-188U, Panasonic) was used to obtain kinematic data from the right sagittal view of the subjects during the test. The camera (60 Hz) was set parallel to the floor and the shutter speed was set at 1/1000 sec. Reflective markers were placed on the right side of the body (acromioclavicular joint, the greater trochanter, the tibial epicondyle, the lateral malleolus, the heel, and the head of the fifth metatarsal). In the shoe conditions, the last two markers were affixed to the corresponding sites on the lateral side of the shoe. These markers were used to obtain right sagittal kinematics of the subjects during the landing activities. The recorded video images were digitized to obtain coordinates of these markers using APAS biomechanics system (Ariel Dynamics Inc.). A force platform (OR6-7, AMTI) was used to measure ground reaction forces (GRF) and moments during the test. Two miniature accelerometers (A353B17, Piezotronics, Inc.) were used to measure accelerations at the forehead and distal tibia of the subjects. The accelerometer has a range of 500 g and a resolution of 0.005 g. Two accelerometers were securely fastened to the tolerance of the subject, on the forehead and the anteromedial surface of distal tibia of the subject with adhesive tape and Velcro straps. Signals from the force platform and accelerometers were also sampled at a frequency of 1200 Hz using the APAS and amplified before being stored in the APAS computer through the A/D converter. The force platform, the accelerometers, and the sagittal view video were simultaneously recorded during the experiment. The synchronization between the kinematic and analog signals (the force platform and the accelerometers) was achieved by using a customized trigger device with a light emitting diode (LED). Subjects wore lab shoes provided by the Biomechanics/Sports Medicine Lab. The midsole and outsole of the shoe consisted of lightstrike EVA and minimal carbon rubber.

3. Experimental Protocol

The subject began the test session with a warm-up by riding a stationary bike for five minutes. Subjects were asked to only their right feet onto the middle of the force platform during landings. Forty trials of step-off landing were performed by the subjects in eight conditions. Eight conditions (30 cm with shoe, 45 cm with shoe, 60 cm with shoe, 75 cm with shoe, 30 cm without shoe, 45 cm without shoe, 60 cm without shoe, and 75 cm without shoe) were randomized.

4. Data Processing

Images collected from the video camera were used to obtain kinematic variables. The video images were first captured and then digitized using the APAS biomechanical system. The raw coordinates of the reflective markers were smoothed using a fourth-order and zero-lag Butterworth digital filter (Winter D.A., 1990). The cutoff frequency was individually chosen for the each x and y coordinate of the reflective markers using an optimized algorithm (Jackson K.M., 1979). A Shannon algorithm was used to reconstruct the video signal from 60 Hz to 240 Hz (Hamill, J., Caldwell, G.E., and Derrick, T.R., 1997).

The shock attenuation index (AtteIndex) was calculated as:

$$AtteIndex = (1 - \frac{AccHead}{AccTibia2}) \times 100$$

Voloshin, A., Wosk, J., and Brull, M. (1981)

Where AccHead is the peak head acceleration and AccTibia2 is the peak tibia acceleration.

Data collected from the force platform and the accelerometers were analyzed in two steps. Analog data file stored on the APAS file was decoded using customized Visual Basic program to obtain ASCII time-history of GRF and acceleration data. Second, using Visual Basic program, the decoded data files were imported to compute and obtain GRF and acceleration variables.

5. Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for each kinematic and kinetic variable. A two-way (surface × height, 2×4) analysis of variance (ANOVA) was employed for selected variables with using a statistical package SAS (SAS Institute, Inc., Cary, NC, USA). Post-hoc comparisons were performed using simple main effects in SAS (Schabenberger O., 1998). A confidence level of $p < .05$ was used to determine statistical significance.

Ⅲ. Results

The purpose of this study was to investigate the shock and impact attenuation during landing activities from different height on different surfaces. The results of the kinematic and kinetic data were obtained for eight different conditions.

1. Vertical Ground Reaction Force

Vertical GRF variables included the first (F1, forefoot contact) and the second (F2, heel contact) maximum VGRF, the time to F1 (T1) and F2 (T2), and the loading rate of F1 (LrateF1) and F2 (LrateF2). F1 loading rate was computed as a ratio of F1 and T1. F2 loading rate was computed as ratio of (F2-Fmin)/(T2-Tmin).

Significant omnibus F was found for F1 (F = 26.15, $p<0.05$), F2 (F = 4.01, $p<0.05$), LrateF1 (F = 3.95, $p<0.05$), and Imp100ms (F = 4.55, $p<0.05$). Significant main height and surface effects were found for F1, F2, and LrateF1. No significant omnibus was found for T1, T2, and LrateF2. Increased landing heights in the shoe and the barefoot landing were showed to cause significantly greater magnitude of F1. The height of 75 cm with shoes produced significantly greater F1 than the same height with barefoot (Figure 1). F2 at 75 cm with shoes and barefoot produced significantly greater forces than F2 at 30 cm with shoes and barefoot.

LrateF1 at 75 cm in the shoe conditions revealed significantly greater loading rate than that at 30 cm. LrateF1 at 30 cm in the barefoot conditions was significantly smaller than that at 45, 60, and 75cm (Table 1).

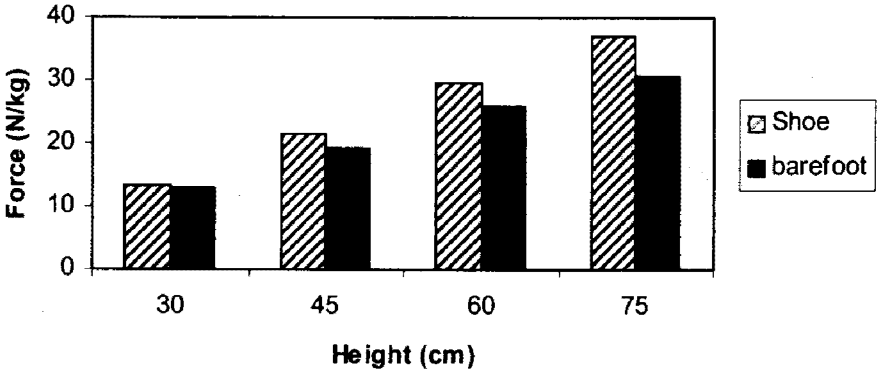

Figure 1. Mean F1 values at different heights
* denotes sig. differences.

2. Acceleration

Acceleration variables included maximum head acceleration (AccHead), the time to AccHead (TaccHead), the first (AccTibia1) and second (AccTibia2) maximum tibia accelerations, the time to AccTibia1 (TaccTibia1) andAccTibia2 (TaccTibia2), and shock attenuation index (AtteIndex).

Table 1. Means and standard deviations of vertical ground reaction force variables

Surface	Height (cm)	F1	F2	LrateF1	LrateF2
Shoe	30	13.424	54.273	1953.058	1831.765
		(5.039)	(10.071)	(1086.067)	(952.811)
	45	21.460 ^{a}	59.279	2922.792	1965.419
		(3.432)	(13.118)	(1039.659)	(915.225)
	60	29.558 ^{b,d}	65.403	3592.578	2168.216
		(4.774)	(10.030)	(814.218)	(781.164)
	75	36.863 ^{c,e,f}	75.902 ^{c}	4546.078 ^{c}	2771.090
		(7.415)	(17.894)	(1030.121)	(1184.135)
Barefoot	30	13.104	65.202	2623.742	1692.260
		(3.590)	(18.683)	(1667.453)	(811.473)
	45	19.415 ^{a}	76.169	4370.646 ^{a}	2126.449
		(4.476)	(21.535)	(2605.665)	(937.333)
	60	25.992 ^{b,d}	80.965	5095.213 ^{b}	2305.932
		(5.848)	(27.035)	(3215.794)	(1162.897)
	75	30.897 ^{c,e,f,*}	91.241 ^{c}	5338.847 ^{c}	2857.155
		(6.236)	(27.029)	(2564.041)	(1262.236)

Note:
Force was normalized to subject's body weight. Force unit is in N/kg and time unit is in s. Loading rate unit is in N/kg/s. Standard deviation values are in parenthesis.

a denotes significant difference between heights 30 and 45 cm. b denotes significant difference between heights 30 and 60 cm.

c denotes significant difference between heights 30 and 75 cm. d denotes significant difference between heights 45 and 60 cm.

e denotes significant difference between heights 45 and 75 cm. f denotes significant difference between heights 60 and 75 cm.

* denotes significant difference between the shoe and barefoot conditions on the same landing height.

Significant omnibus F was found for AccHead (F = 4.41, $p<0.05$), AccTibia1 (F = 12.03, $p<0.05$), AccTibia2 (F = 8.10, $p<0.05$), and AtteIndex (F = 6.24, $p<0.05$). Significant main effects of height and surface were found for AccHead, AccTibia1, and AccTibia2. Significant main of surface effect was found for AtteIndex.

For the shoe condition, the post-hoc comparison showed that the AccHead at 75 cm was significantly greater than that at 30 and 45 cm (Table 2). The maximum head acceleration at 75 cm in the shoe conditions was significantly greater than that in the barefoot conditions at the same height.

The Increase in landing heights caused increased AccTibia1 values. The AccTibia1 at all heights in the shoe conditions was significantly greater than the barefoot conditions except for between 30 and 45 cm. AccTibia1 with barefoot at 75 cm was significantly greater than that at 30 and 45 cm. The barefoot at 60 cm produced greater AccTibia1 than the barefoot at 30 cm.

The shoe condition at 75 cm produced greater AccTibia1 than the barefoot condition at the same height.

The AccTibia2 at 75 cm in the shoe conditions was significantly greater than that at 30 and 45 cm. For the barefoot condition, the height of 75 cm produced significantly greater AccTibia2 than 30, 45, and 60 cm. AccTibia2 at 60 and 75 cm with barefoot were significantly greater than those with shoes at each same height. The shock attenuation index with barefoot at all heights were significantly greater than those with shoes at each height.

Table 2. Means and standard deviations of head and tibia acceleration variables

Surface	Height (cm)	AccHead	AccTibia1	AccTibia2	AtteIndex
Shoe	30	2.571 (0.763)	7.821 (5.219)	18.251 (8.170)	84.363 (5.829)
	45	3.301 (1.079)	12.073 (4.424)	23.816 (9.582)	85.235 (4.131)
	60	3.631^{b} (0.974)	17.965^{b,d} (6.074)	28.508 (6.705)	87.009 (3.167)
	75	4.463^{c,e} (1.180)	22.840^{c,e,f} (7.631)	38.240^{c,e} (9.410)	88.099 (2.844)
Barefoot	30	2.305 (1.010)	7.473 (2.382)	30.101 (12.868)	90.608* (5.625)
	45	2.687 (1.141)	10.843 (2.991)	37.688 (15.471)	91.730* (4.874)
	60	2.961 (1.108)	14.656^{b} (4.278)	47.494b* (24.881)	92.076* (4.567)
	75	3.220* (0.936)	17.454^{c,e,*} (3.962)	63.943^{c,e,f,*} (27.666)	93.958* (3.010)

Note: Acceleration unit is in g and time unit is in s. Shock attenuation index unit is in %.

IV. Discussion

Two peaks of vertical GRF were observed during the barefoot and shoe landing: the first (F1, forefoot contact) and the second impact forces (F2, heel contact). These two peaks demonstrated different responses to the changes in the height during the shoe and barefoot landing. F1 increased from 13.42 N/kg at 30 cm to 36.86 N/kg in the shoe conditions, and from 13.10 N/kg at 30 cm to 30.90 N/kg at 75 cm in the barefoot conditions (Table 1). The difference of F1 between the shoe and barefoot was significant at the 75 cm. At the other two heights (45 and 60 cm), F1 was greater in the shoe landing than in the barefoot landing even though they were not statistically significant. These results initially counterintuitive. Greater F1 values are expected since impact forces are expected to increase without the footwear protection in the barefoot landing. The occurrence of F1 is associated with the forefoot contact with the ground. These results also suggest that the subjects were sensitive to the change of the surface condition at the forefoot contact, and were able to adapt to such changes through active and necessary neuromuscular intervention.

On the other hand, the second maximum VGRF (F2) demonstrated a different trend across the surface conditions compared with the changes of F1. Even though they were not significant, the F2 values for the barefoot were generally greater than those for the shoe conditions (Table 1). The F2 event occurs at the time of heel contact with the ground after the initial forefoot contact. It was found that VGRF with barefoot was 1.1 times (4.3 BW) greater than that with shoes during netball landings (Steele, J.R. and Milburn, P.D., 1987). This reversal of responses of the shoe and barefoot was not observed in running studies. In the study conducted by Wit, B.D., et al., (2000), the F2 values between shoe and barefoot running were same (2.9 BW) at a speed of 4.5 m/s.

An explanation of the mechanisms of different VGRF responses at the forefoot contact and heel contact in the shoe and barefoot conditions are attempted below. F1 with shoe was slightly greater than that with barefoot whereas F2 with barefoot was slightly greater than that with shoes. Impact forces in landing usually occur within 50 ms that is beyond the human reaction time. Any attempt to reduce impact forces during the impact phase is preprogrammed by the neuromuscular system prior to the touchdown (Lees A, 1981). The preset neuromuscular program intension is rather effective in reducing F1 in the barefoot conditions. The heel contact occurs at a later time than forefoot contact. The neuromuscular intervention may be therefore, less effective reducing F2 at the heel contact than at the forefoot contact. The reaction of kinematic variables could be indicative of muscular responses. In this study, the contact angle and the range of motion of the ankle, knee, and hip joints did not show any significant differences between with and without shoe. It is, therefore, suggested that the shoe provided an additional capacity to attenuate impact forces.

The maximum head acceleration (AccHead) significantly demonstrated minimum amount of changes with changes in heights and surfaces. AccHead ranged from 2.57 g at 30 cm to 4.46 g at 75 cm in the shoe conditions, and from 2.30 g at 30 cm to 3.22 g at 75 cm in the barefoot conditions. Only AccHead with shoes was statistically greater than that with barefoot at 75 cm.

AccHead with shoe displayed statistically significant increases with increased height, however the increases were incredibly small. The AccHead values with barefoot remained relatively constant across heights. This finding is in partial agreement with several previous studies (Hamill, J., Derrick T.R., and Holt K.G., 1995, Shorten, M.R., and Winslow, D.S., 1992, Wosk, J and Voloshin, A., 1981). The maximum head acceleration was shown to be constant during barefoot walking (Wosk J., 1981). During treadmill running, the maximum head acceleration did not change with increased treadmill speed (Hamill J., 1995, Shorten M.R., 1992). The constant AccHead values indicate that a body serves as a low pass filter and shock absorber during landings (Wosk J., 1981).

The second maximum tibia acceleration (AccTibia2) revealed statistical differences across height and surface conditions. AccTibia2 occurs at the time of the heel contact when F2 is observed. The AccTibia2 values increased from 18.25 g at 30 cm to 38.24 g at 75 cm, and from 30.10 g at 30 cm to 63.94 g at 75 cm with shoe and barefoot, respectively. AccTibia2 displayed a different pattern compared with the AccTibia1: the barefoot landing was significantly greater than the shoe landing at 60 and 75 cm. At the same time, kinematic results of lower extremity joints did not show any significant changes at these heights across the surface conditions. The response was similar to that of F2. This indicated that the shoe provided the additional cushioning capacity in the barefoot landing at the higher heights. In one of few studies of shock attenuation in landing, Gross and Nelson (1988) did not show any significant changes in the peak calcaneal and tibial accelerations in barefoot landing from vertical jump among three surface conditions (a midsole foam, a tartan rubber, and a cast aluminum - the top of a force platform). Because the subjects were asked to land from a vertical jump, the input energy and landing heights were not controlled in the study, which could influence the results.

The shock attenuation index (AtteIndex) indicates that how much impact shock is attenuated by the human body. A higher AtteIndex value indicates greater shock attenuation while a smaller AtteIndex indicates lesser shock attenuation. The result demonstrated that the AtteIndex with barefoot was significantly greater than those with shoe at all landing heights (Table 2). The AtteIndex, for example, was 87 and 92 % for the shoe and barefoot at 60 cm, respectively. This result suggested that impact shock in the barefoot condition was more attenuated than in the shoe conditions. It is logical to assume that the shoes can provide additional impact shock. Impact shock may be attenuated through passive structures such as bones and soft tissues (Wosk J., 1981). Impact shock can also be minimized by active muscle contraction. Subjects may change their landing strategies in order to protect their body from injury in the barefoot landings. Even though the kinematic results did not show any significant changes across the surface conditions, they seemed to be more cautious in the barefoot conditions than in the shoe conditions.

Future studies need to explore neuromuscular changes of the human body in impact during landing activities. It is necessary to examine the relationship between muscle activities of lower extremity joints and impact shock attenuation during landing activities.

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