Comparison of the Loading Rate and Lower Limb Angles on Drop-landing between a Normal Foot and Flatfoot

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Abstract. [Purpose] The purpose of this study was to analyze lower limb angles and the loading rate during the drop-landing motion of a normal foot and flatfoot and ultimately to offer basic data for flatfoot exercise therapy. [Subjects] For this study, 18 adults from Cheonan with no musculoskeletal lesions were collected as a sample. The sample was divided into normal foot (n=9) and flatfoot (n=9) groups. Each group performed a drop-landing motion on a force plate with markers attached to the anterior superior iliac spine, the greater trochanter of the hip, the lateral epicondyle of the knee, the lateral malleolus, and the fifth metatarsal head. The motion was measured in 3D. The data for the angle of the hip joint, knee joint, and ankle joint during the drop-landing motion and the loading rate and maximum vertical reaction force at the force plate were measured. [Results] There were significant differences in the maximum vertical reaction force and loading rate during the drop-landing motion between the normal foot and flatfoot. There was a significant difference in the right ankle joint in terms of the variation in the lower limb angles. [Conclusion] It was difficult for the flatfoot to disperse the loading rate during the drop-landing motion, and it showed an increase in the lower limb bending angle. It was considered that proper pose control for the absorption of loads and strengthening of the lower limb were definitely needed for a flatfoot.

Key words: Flatfoot, Loading rate, Lower limb angles

INTRODUCTION

The foot plays an important role in walking, as it disperses shock absorption and weight to provide the momentum and direction required for movement and to maintain balance and weight shift1). The structure of the foot is composed of three arches (medial longitudinal arch, lateral longitudinal arch, and transverse arch) that absorb shock, disperse weight, and reduce fatigue2). The foot can be classified into high arch, normal arch, and flatfoot according to the shape of the medial longitudinal arch, which is the arch that presents the highest elasticity, is more flexible than the lateral longitudinal arch, and carries out the most important role in shock absorption3). As a clinical deformation that touches the surface more closely than the normal arch, the flatfoot is composed of a shape in which the medial longitudinal arch is sunk or nonexistent compared with the normal arch4). The drop of the navicular bone triggers tension in the muscle and muscle fascia and arouses adduction of the hip joint, and lumbar lordosis. This in turn slants the pelvis to one side, which causes scoliosis or increases the risk of backache due to an abnormal lumbar condition and deformation of the lumbosacral posture5). Flatfoot can be caused by congenital or genetic factors or acquired factors, such as uncomfortable shoes, posture, gait, and walking on asphalt or concrete. Other factors include paralysis, foot pronation, accidents, and obesity6). Flatfoot occurs in 5% of the total population on average7) and is characterized by decreased ability to absorb shock, excessive movement of the foot, reduced controlling force, and excessive pronation exercise. In comparison to the normal foot, which exerts nearly 1.5 times the weight pressure6), the flatfoot receives greater shock, which increases fatigue and causes damage such as pain, degenerative arthritis, and stress fractures8). Also, it has been reported that the flatfoot has a higher damage frequency than the normal foot9).

As a motion commonly observed in basketball, soccer, and volleyball, drop-landing is the motion of falling to the ground after a free fall or leaping from a fixed height. During vertical drop-landing after a jump, the maximum vertical reaction force reaches 3.5–7.1 times the person’s weight10). McNitt-Gray11) reported that the maximum vertical reaction force reached 3 times the person’s weight during drop-landing from a height of 50 cm. Generally, the maximum vertical reaction force during drop-landing is proportional to the height and speed of the drop-landing. McNitt-Gray11) also reported that the maximum vertical reaction force was larger when the height of the drop-landing was higher. According to Stürmer et al.12), obese people possessed a larger maximum vertical reaction force than people with a normal weight.
Therefore, as a high maximum vertical reaction force during the drop-landing motion delivers an impact force to the physical body, the changes in maximum vertical reaction force are deeply related with the risk of damaging the musculoskeletal joints\(^\text{(15)}\). An incorrect drop-landing motion can trigger excessive stress on the musculoskeletal system of the human body as it fails to appropriately absorb the shock generated when the foot touches the surface\(^\text{(16)}\). Among the lower limb joints, the knee joints receive the greatest load during drop-landing\(^\text{(17)}\). Self and Paine\(^\text{(18)}\) reported that significant shock was sent to the physical body when the flexion movement of the knees was limited during drop-landing. Also, it was clarified that greater impact force was presented in the physical body during hindfoot drop-landing when compared with forefoot drop-landing\(^\text{(11)}\). Kovacs et al.\(^\text{(19)}\) reported that when drop-landing was performed from a height of 40 cm, a smaller angular impulse was placed on the knee and hip joints and a larger angular impulse was placed on the ankle joint in forefoot drop-landing when compared with hindfoot drop-landing. Zhang et al.\(^\text{(20)}\) reported that the degree of knee joint flexion was effective in reducing the ground reaction force and that women presented a larger vertical reaction force than men in drop-landing that increased the angle of knee flexion\(^\text{(21)}\).

Although various studies and approaches have been conducted to investigate drop-landing motion, as a majority of these studies have researched the characteristics of normal people and floor properties, there is an absolute shortage of studies conducted on the loading rate, maximum vertical reaction force, and lower limb angles during the drop-landing of flatfeet. Thus, this study classified subjects into a normal foot group and flatfoot group to investigate the shock absorption ability and risk of musculoskeletal system damage during drop-landing, a motion that commonly occurs in daily life. This study also conducted a comparative analysis on the loading rate, maximum vertical reaction force, and lower limb angles to present basic data for flatfoot exercise therapy.

**SUBJECTS AND METHODS**

This study selected 9 subjects with normal feet and 9 subjects with flat feet after conducting a foot-type test on students attending N University in Cheonan, South Korea. The subjects voluntarily agreed to experiment participation after receiving an explanation of the experiment process. This study excluded subjects who had not lower limb musculoskeletal diseases within the past 6 months or any experience of receiving surgical procedures for a lower limb injury or lesion. The general characteristics of the research subjects are as presented in Table 1. The Ethics Committee of Namseoul University in Korea also approved the study.

First, the 18 subjects who participated in this experiment lightly tapped their right foot on the printing foot stamp, rested their entire weight on a white piece of paper, and then lifted their foot\(^\text{(22)}\). The analysis method using the printing foot stamp is described in Fig. 1.

A 3D motion analyzer (Smart-E Apsun inc., Italy) was used to measure the maximum vertical reaction force and lower limb angles during drop-landing in relation to the changes in the foot arch height of the subject. To measure the ground reaction force generated during drop landing, 1 ground reaction force measuring device (Smart-E force plate, 600×900, BTS, Italy), 6 infrared cameras, 2 VCRs, a data processing device, and a PC were used. The image data was collected at 200 Hz whereas the ground reaction force data was collected at 2000 Hz\(^\text{(23)}\). Calibration was performed to correct for the error generated in the camera before inspection, and 20 mm markers perceived by the infrared camera were attached by a representative researcher to the anterior superior iliac spine, the greater trochanter of the hip, the lateral epicondyle of the knee, the lateral malleolus, the calcaneus, the far right outside point of the 5th metatarsal head, the far right outside point of the calcaneus, and the center of gravity of the 2nd toe, respectively. Line A, connection of the left point of the heel bone head with the left point of the heel bone; line B, connection of the right point of the fifth heel bone head and the right point of the heel bone; line H, connection of the centroid point of the forefinger with the contact point of lines A and B. Note that if the foot arch existed on line HB, the foot was classified as a normal foot, and if the foot arch existed on line HA, the foot was classified as a flatfoot.

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<tr>
<th>Table 1. Subject characteristics</th>
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<td>Height (cm)</td>
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<td>Gender (male/female)</td>
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Values are expressed as means±standard deviation. BMI : Body mass index.
and the fifth metatarsal head. The researcher connected the markers attached to each joint to measure 3D movement and measured the maximum vertical reaction force when the hip joint, knee joint, and ankle joint touched force platform during drop-landing. The angle of the hip joints was derived by connecting the anterior superior iliac spine, greater trochanter of the femur, and lateral epicondyle of the femur. The angle of knee joint was derived by connecting the greater trochanter of the femur, lateral epicondyle of the femur, and lateral malleolus of the fibula. The angle of the ankle joint was derived by connecting the lateral epicondyle of the femur, lateral malleolus of the fibula, and head of the fifth of metatarsal bone.

This study measured the flexion angle of all joints and the angle of the joints during occurrence of the maximum vertical reaction force.

After receiving an explanation of the foot position during vertical jumping and drop-landing, all subjects attempted to perform natural drop-landing 5 times prior to the actual experiment. The subjects performed natural vertical jumping 2 times on top of a 40 cm wooden box. Further, the experiment did not include drop-landings in which the subject landed with only one foot or moved his or her foot due to loss of balance after landing.

To analyze the maximum vertical reaction force, loading rate, and lower limb angles during drop-landing in the normal foot group and flatfoot group, the subjects repeated the motion 2 times to allow for statistical processing of the mean value. For the maximum vertical reaction force, this study calculated the maximum value generated during drop-landing, and the results were divided by the BW (body weight) of the subject for standardization. Further, the loading rate was calculated by dividing the maximum vertical reaction force generated during drop-landing by the time it took for the maximum vertical reaction force to be generated after drop-landing. For the lower limbs angle, this study measured the flexion of the hip joints, knee joints, and ankle joints during the maximum vertical reaction force and performed statistical processing to calculate mean values. To investigate the difference in the maximum vertical reaction force and loading rate between the normal foot group and flatfoot group, the independent t-test was implemented. To investigate the difference in the left/right lower limb angles between the normal foot group and flatfoot group, SPSS (ver. 18.0) was used to implement two-way ANOVA. The significance standard was set as α=0.05.

RESULTS

Table 2 presents the maximum vertical reaction force (BW) and loading rate (BW/s) generated during drop-landing in the normal foot group and flatfoot group. The maximum vertical reaction force was 29.70±2.77 in the normal foot group and 35.26±1.91 in the flatfoot group, and the difference between the groups was statistically significant. Further, the loading rate was 129.09±13.93 in the normal foot group and 105.55±11.18 in the flatfoot group, and the difference between the groups was statistically significant.

Table 3 compares the lower limb angles during the maximum vertical reaction force of drop-landing in the normal foot group and flatfoot group. There was no interaction between group and the direction of the normal foot group and flatfoot group in terms of the hip joint, knee joint, and ankle joint. Significant main effects between the groups were found in the ankle joint for both the normal foot group and flatfoot group. The right ankle joint angle was 66.68±4.41 for the normal foot group and 67.20±8.01 for the flatfoot group, and the difference between the groups was statistically significant (p<0.05). However, a statistically significant difference was not shown for the joint angles of other joints.

DISCUSSION

As a motion commonly generated during sports activities or daily life, drop-landing triggers an extremely strong impact force and muscle control when the body touches the ground and increases the vertical ground reaction force according to increase in potential energy.

This study compared the maximum vertical reaction force between a normal foot group and flatfoot group during drop-landing from a 40 cm height and found a statistically significant difference between the two groups (p<0.05). The feet touched the ground through plantar flexion of the ankle during drop landing. The heels touch the ground after the forefoot. Further, as the medial longitudinal arch absorbs shock and disperses physical weight during drop-landing, flatfoot refers to a condition in which this arch is collapsed. Brizuela et al. reported that a higher impact
force is generated when drop-landing is performed with the middle part of the foot when compared with drop-landing performed with the forefoot or hindfoot. Gross and Nelson\(^1\) also stated that the impact force was smaller in forefeet drop-landing than toe-heel drop-landing, which corresponded with another study that presented a larger maximum vertical reaction force in flat feet, which display low shock absorption ability due to loss of the medial longitudinal arch. Among the lower limb joints, the knee joint receives the greatest load during drop-landing\(^17\). Self and Paine\(^18\) reported that shock was intensified when the curvature movement of the knees was limited during drop-landing. Although there was no statistical significance in the comparison of the lower limb angles in the present study, the average flexion angle of knee joints was larger in the flatfoot group than in the normal foot group, which is thought to be due to the fact that the subjects used more knee flexion to absorb shock. However, Chuckpaiwong et al.\(^28\) reported that there was no significant difference in the mean pressure of the entire foot between the normal foot and flatfoot, thus presenting different results compared with the present study. As a high vertical reaction force is transmitted to the body by the impact force resulting from drop-landing motion, different kinematic factors and the maximum vertical reaction force are present according to the landing method.

This study defined loading rate as the time it takes for the maximum vertical reaction force to be generated from the moment the foot lands on the ground. The loading rate was 72.23±11.34 for the normal foot group and 93.92±18.34 for the flatfoot group, and the difference between the groups was statistically significant (p<0.05). Although it was difficult to compare the loading rate between a normal foot and flatfoot due to lack of precedent studies, the research results of Cho et al.\(^29\) compared drop-landing in athletes with functional ankle instability–which is a condition similar to flatfoot–with a normal foot group, showed a higher loading rate in athletes with functional ankle instability. It is thought that a disadvantageous mechanism was generated in the shock absorption of the flatfoot group, as the maximum vertical reaction force was delivered to the heels by passing the middle of the foot. Furthermore, as the loading rate reflects the manifestation of strength generated during impact, it is thought that the high loading rate of the flatfoot group was caused by the longer time it takes for the group to generate the maximum vertical reaction force due to decreased shock absorption ability and loss of the arch of the foot.

Drop-landing is a representative type of exercise for evaluating the maximum performance ability of the lower limbs. However, inaccurate motions after jumping prevent the subject from appropriately absorbing the shock generated when the feet touch the ground and thus trigger excessive stress on the musculoskeletal system, which increases the risk of injury\(^19\). Flexion is generated in the lower limb joints (hip joint, knee joint, and ankle joint) to reduce the impact exerted on the physical body during drop-landing. Joint flexion is an important kinematic function of the human body for adjusting the human body mass generated by the lower part of the body and the momentum generated by the acceleration of gravity and alleviating the impact force. Self and Paine\(^18\) reported that shock is intensified if the flexion movement of the knees is limited during drop-landing. Thus, compensation behaviors that can minimize the impact force during drop-landing must be carried out in the lower limb joints to achieve a soft landing. This study compared the lower limb angles of the normal foot group and flatfoot group during drop-landing from a height of 40 cm and found a statistically significant difference only in the right ankle joint. There were differences in both hip joints and knee joints and in the left ankle joint, but the differences were not statistically significant.

There was no statistically significant difference in the lower limb angle of the hip joint between the flatfoot group and normal foot group, but the average angle was high. Wilson et al.\(^30\) reported that the hip strategy can be used instead of the ankle strategy to maintain balance, and Cho et al.\(^29\) presented that the flexion angle of the hip joint was larger in athletes with functional ankle instability than in a normal foot group, which corresponds with the results of this study. It is thought that the flatfoot group used their hip joint to control the instability of the ankle joint caused by the excessive pronation of the ankle during drop-landing.

Zhang et al.\(^20\) reported that as an important structure for shock absorption, lower flexion of the knee joint decreased the ability to absorb shock, which generates cartilage damage. On the other hand, Kernozek et al.\(^31\) stated that increasing the flexion angle of the knee joint during drop-landing can reduce the risk of an acute anterior cruciate ligament rupture injury, reporting that the injury rate was higher for women, as they had a smaller flexion angle during drop-landing. The present study also presented similar results, as the average joint flexion angle was higher in the flatfoot than in the normal foot, although the results were not statistically significant. Further, Decker et al.\(^32\) reported that the angle of the knee increased to absorb the shock generated in the physical body due to vertical reaction force. This is thought to be related to the flatfoot group’s increase in knee joint flexion angle to absorb the shock generated by the maximum vertical reaction force and reduce knee injury.

To absorb the ground reaction force generated by the ground during drop-landing, plantar flexion and dorsiflexion are performed in the ankle joint\(^33\), and ankle joint movements are used more than hip joint movements to absorb shock\(^13\). Further, Tabrizi et al.\(^25\) reported that the rate of ankle injury can increase if the movements of the ankle joints decrease during drop-landing. The results of the present study correspond with these research results in that they present a statistically significant decrease in the right joint angle in the flatfoot group. It is thought that high lower limb angles were present to absorb shock in the knee joint and hip joint in relation to the fact that the flatfoot group did not effectively use movements in each of these joint and had a low shock absorption rate in drop-landing due to decreased ankle joint function.

In conclusion, the maximum vertical reaction force and loading rate were significant due to the reduced shock absorption ability of the flatfoot group during drop-landing. The decrease in the right ankle joint angle was caused by the low shock absorption rate during drop-landing due to
decreased foot function. For this reason, it is thought that a high flexion angle was present in the knee and hip joints for shock absorption. Thus, it is thought that minimization of damage must be achieved by adjusting the flexion angle of the ankle, knee, and hip joints, which are body parts that are significantly influenced by shock absorption. Also, motor analysis must be conducted to analyze kinematics and motor mechanics, and analysis of the muscular activity must be achieved by attaching an EMG.

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