Shock attenuation properties of sports surfaces with two-dimensional impact test

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Accepted 02 March 2012


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Abstract

To evaluate the properties of the sports surfaces, friction tests and force attenuation tests have been generally adopted to determine the horizontal and vertical characteristics, respectively. Although the diagonal impacts are often observed in human activities, these tests treat only the vertical impact test. Therefore we developed a two-dimensional impact test device for examining the two-dimensional cushioning characteristics of sport surfaces in previous studies. In this study, the various cushioned and non-cushioned impact tests were examined to calculate the FR(Force Reduction) values not only in vertical but also in horizontal impact force. As the results, horizontal shock attenuation characteristic was different from that of the vertical one in terms of initial angles.

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Keywords: Sports surface; two-dimensional impact test; parallelogram linkage; shock attenuation; force reduction

1. Introduction

Sports surfaces, such as artificial lawns and polyurethane tracks and fields, mainly have two important functions: to provide the conditions necessary for athletes to perform well, while the other is to protect athletes from injuries. To evaluate the properties of the sports surfaces, friction tests and force attenuation tests have been generally adopted to determine the horizontal and vertical characteristics, respectively. For example, the tests of I.A.A.F.\cite{1} and DIN\cite{2} treat these characteristics separately. In EN14808\cite{3} adopted by I.A.A.F. as the shock attenuation test only treats the vertical impacts, although the diagonal
impacts are often observed in human activities. In other words, we should consider the horizontal shock attenuation characteristics for sports surfaces. Therefore we developed a two-dimensional impact test device for examining the two-dimensional cushioning characteristics of sport surfaces in previous studies and considered the comparison between the impact friction and the static/dynamic friction test[4,5,6].

In this study, we improved the two-dimensional impact test device to measure the initial angle and drop height precisely with the angle sensor and laser displacement sensor to calculate the \( FR \) (Force Reduction) values not only in the vertical force but also the horizontal force.

2. Two-dimensional impact test

2.1. Two-dimensional impact test device

Figure 1 shows the structure of the two-dimensional impact test device. To produce a simultaneous two-dimensional force against a test specimen, we incorporated a parallelogram linkage in the measuring system. An impact force \( F \) is produced by dropping an impact mass upon the upper edge of the parallelogram linkage represented by dashed line. The parallelogram linkage divides impact force \( F \) into a horizontal force \( f_x \) and a vertical force \( f_y \) through the impact transfer unit (A) when the upper edge of the parallelogram linkage descends along the vertical linear guide way attached to the frame. At the same time, the lower edge slides horizontally along the bottom of the parallelogram without moment, because the upper edge is attached to the frame and restricted in movement to a vertical slide.

![Two-dimensional impact test device](image)

Fig.1. Two-dimensional impact test device. The test device consists of the frame with linear guides, impact mass, the parallelogram linkage, the sensor unit, the angular sensor and the laser displacement sensor. According to the parallelogram linkage, the impact force produced by impact mass onto the upper edge of the linkage is divided into the vertical force \( f_y \) and the horizontal force \( f_x \). The forces applied to the specimen (\( f_y \), \( f_x \)) are obtained by subtracting the inertial force of the sensor unit from each directional force with precise initial angle and drop height.
The initial angle $\theta$ controls the ratio of $f_x/f_y$. Parts B and C are force transducers that measure horizontal force and vertical force, respectively. To calculate the forces applied to a specimen, $f'_x$ and $f'_y$, a multiple of total mass of the sensor unit minus the parallelogram linkage including impact transfer unit, and the relevant directional acceleration, are subtracted from the measured forces $f_x$ and $f_y$. Part D is a two-dimensional accelerometer. Horizontal and vertical velocity and displacement are calculated from acceleration by integration. Initial angle $\theta$ and drop height $H$ are measured by an angular sensor and laser displacement sensor, respectively. Impact mass is 3.8 kg and is kept and released by electromagnet system to produce a complete freefall from a certain height. A test specimen is completely fixed on test device frame.

2.2. Validity of the data from impact test device

In previous study, to confirm the behavior of the sensor unit during the impact phase, we took high-speed video movie (1200 frames per second [fps]) from the side of the sensor unit. From these results, the parallelogram linkage restricted the sensor movement while keeping it horizontally even in the impact phase. Additionally, the force transducers were tested with a two-dimensional force plate (Kistler: Type 9281B) in static and dynamic conditions. In both situations, the force transducers could measure accurately and the initial angle $\theta$ was almost equal to the value of $\tan^{-1}\left[\frac{f_x}{f_y}\right]$.

2.3. Two-dimensional force reduction values

In EN14808, the $FR$(Force Reduction) value is defined by comparing the maximum impact forces between the cushioned condition and non-cushioned condition. In this study, we conducted the experiment in various initial angles and drop heights against one of the sports surface certified by I.A.A.F. as the cushioned condition. On the other hand, the various conditions without the sports surface are recorded as the non-cushioned conditions, i.e, the sensor unit is placed on the rigid floor directly without the sports surface. We proposed new two-dimensional force reduction values, $VFR$ and $HFR$ as follows,

$$VFR(\theta, H) = \left(1 - \frac{f_{v_{\text{max}}}(\theta, H)}{F_{v_{\text{max}}}(\theta, H)}\right) \times 100$$

$$HFR(\theta, H) = \left(1 - \frac{f_{h_{\text{max}}}(\theta, H)}{F_{h_{\text{max}}}(\theta, H)}\right) \times 100$$

Where $VFR(\theta, H)$ is the vertical force reduction value at the initial angle $\theta$ and the drop height $H$. The subscript $(\theta, H)$ means a certain initial angle and a drop height of a trial. $F_{v_{\text{max}}}(\theta, H)$, $f_{v_{\text{max}}}(\theta, H)$ are the non-cushioned and cushioned vertical maximum impact force at the initial conditions, respectively. And $HFR(\theta, H)$, $F_{h_{\text{max}}}(\theta, H)$, $f_{h_{\text{max}}}(\theta, H)$ are the horizontal force reduction value, the non-cushioned horizontal maximum impact force and cushioned horizontal maximum impact force, respectively.

2.4. Two-dimensional impact forces

In this study, 67 cushioned trials and 107 non-cushioned trials impact tests were recorded in a certain sports surface. The initial conditions of these trials varies from $3.5^\circ$ to $31.3^\circ$ in initial angle $\theta$ and varies from 15.6 mm to 186.3 mm in drop height. Figure 2(a), (b) show the vertical and horizontal cushioned impact forces in two trials that have the initial angle is $7.5^\circ$ and the drop height is 160.0 mm, 23.5° and 163.2 mm, respectively. It is obvious that the ratio of horizontal force increases with increasing of the initial angle. Figure 3 shows the combination of the initial angle and the drop height of all trials. Circle dots indicate the impact tests with non-cushioned conditions and the square dots indicate the impact tests with cushioned conditions.
Fig. 2. Vertical and horizontal cushioned impact forces in two trials. (a) shows the case of the initial angle is 7.5° and the drop height is 160.0 mm and (b) shows the case of 23.5° and 163.2 mm, respectively.

Fig. 3. The combinations of the initial angle and drop height of all trials.

2.5. Estimating the non-cushioned maximum force for calculating VFR and HFR

To calculate the FR values, VFR and HFR, we have to have the cushioned and non-cushioned maximum impact forces at exactly the same initial angle and drop height in shown in Eq.(1) and (2). Because it is very difficult to set exactly the same experimental conditions, we calculated the equivalent non-cushioned maximum impact force by interpolation from 5 non-cushioned values around the cushioned conditions. Figure 4 shows the calculation of the equivalent non-cushioned force for force reduction value with initial angle $\theta_i$ and drop height $H_i$ from 5 non-cushioned values.

Fig. 4. The non-cushioned maximum force in a certain condition, $\theta_i$ and $H_i$, is estimated from the plane that comes from 5 non-cushioned points by the least-squares method. Although this figure shows the example of vertical non-cushioned force, the horizontal non-cushioned force is also calculated in the same way.
As a first step, five points were selected from non-cushioned points that close to the target condition, $\theta_i$ and $H_i$. And then the plane parameters are calculated by the least-square method from these 5 points. As a final step, the equivalent non-cushioned maximum force, $F_{v_{\text{max}}} (\theta_i, H_i)$ or $F_{h_{\text{max}}} (\theta_i, H_i)$, for given condition is estimated with the plane parameters.

3. Results and Discussions

3.1. The vertical and horizontal maximum forces in various conditions

Figure 5(a) shows the cushioned and non-cushioned vertical maximum forces ranged from 485.3 N to 2569.6 N and from 645.5 N to 3385.1 N, respectively. And Figure 5(b) shows the cushioned and non-cushioned horizontal maximum forces ranged from 144.0 N to 905.0 N and from 80.2 N to 1990.0 N. It was apparent that the non-cushioned horizontal maximum force increases with increasing the initial angle despite that of the vertical one was not so clear. On the other hand, the drop height is strongly related to the maximum forces in both vertical and horizontal direction.

3.2. The two-dimensional FR values

Figure 6(a) shows $VFR$ values with dot and the plane that is estimated by the least-squares method with all data and Figure 6(b) shows the $HFR$ and estimated plane. And the equation of each plane was shown at the bottom of each diagram. It is apparent that the FR values increase with increasing initial angle especially in horizontal direction, despite the FR values were not influenced by the drop height in both direction. It means that the $HFR$ has high sensitivity than that of the $VFR$ in this test specimen and $HFR$ has little interaction with $VFR$. The reason why $HFR$ has high sensitivity is due to the particular structure of this test specimen. This test specimen does not have flat bottom, in other words, only the foot part of the bottom touches to the floor. Therefore, the response against the diagonal force may be influenced by its angle. Although we should discuss other sports surfaces, the difference between $HFR$ and $VFR$ in this test specimen is a kind of new knowledge. Therefore the $HFR$ should be considered more carefully in various sports activities.
4. Conclusions

In this study, we measured the two-dimensional impact forces in various initial angles and drop heights with cushioned and non-cushioned conditions. The results are summarized as follows:

- $VFR$ and $HFR$ values are proposed for two-dimensional shock attenuation characteristics
- $FR$ value is influenced by the initial angles especially in $HFR$

Acknowledgements

We would like to express our thanks to Oku En-tout-cas Co.Ltd. for their valuable contributions to the study. And this study was financially supported in part by the Grant-in-Aid for Scientific Research(c) from the Japan Society for the Promotion of Science (23500759)

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