樹脂フォーム/ゴム積層材料の摩擦挙動の解明と耐滑スポーツシューズへの応用に関する研究

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学 位 論 文 題 目	樹脂フォーム/ゴム積層材料の摩擦挙動の解明と 耐滑スポーツシューズへの応用に関する研究
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論文内容要約

Chapter 1 describes the background and purpose of this thesis. Sports shoes play important roles to prevent injuries and enhance performances in various scenes. Material and structure of the shoes' component parts are designed to fill required functions, e.g., cushioning, stability, flexibility, fitting, lightness, air permeability, durability and grip. Within these various functions, grip property is of crucial importance regardless of the usage conditions because low grip increases the risk of fall and injuries caused by induced slips and decreases performance.

In general, resin foam and rubber materials are mainly used in shoe sole as mid-sole and outer-sole, respectively. A force, which is generated from foot during running, transmits through mid-sole from outer-sole to the ground. Therefore, not only outer-sole but also mid-sole will affect contact and frictional behaviors of the shoe sole. However, previous studies tended to focus on mainly frictional behaviors of rubber itself and there are no studies on friction between shoe sole component, including mid-sole and outer-sole, and floor surface.

Grip condition between shoe sole and floor surface is generally figured out with horizontal ground reaction force (GRF) component and traction coefficient, which is calculated by horizontal GRF component divided by normal GRF component. However, it is difficult to investigate positions where high grip property is required in the design process of the shoe, because GRFs measured with conventional force plates in these studies are corresponding to the resultant forces in the whole contact area between shoe and ground surface. Namely, it is necessary to clarify the distribution of the value and direction of horizontal GRF component or traction coefficient in the contact area to design optimal tread pattern, which provides high slip resistance.

The purposes of this thesis were: 1) to clarify contact and frictional behavior between sole components and flat surface under both dry and water-lubricated conditions; 2) to develop a shoe sole having an excellent grip property and slip resistance based on GRF vector distributions during stance phase of running.

In chapter 2, a simplified system to measure contact area and contact pressure distribution of rubber–glass interface was developed by using a total reflection method. In order to visualize the contact state by the total reflection method, high luminance LEDs (light-emitting diodes) were set at double side of glass plate and the contact image was recorded by using a high speed camera. The Laplacian filter was applied to the detection of an edge between contact and non-contact areas. The threshold value of the luminance could be determined based on the Laplacian filtered image. It was clarified that the contact area determined using the threshold luminance value had close agree with the contact area calculated based on Hertzian elastic contact theory under the elastic region. Furthermore, a contact pressure distribution up to 1.0MPa was estimated based on the relationship between the distribution of luminance values in the contact area and the Hertzian contact pressure distribution as shown in Fig. 1.

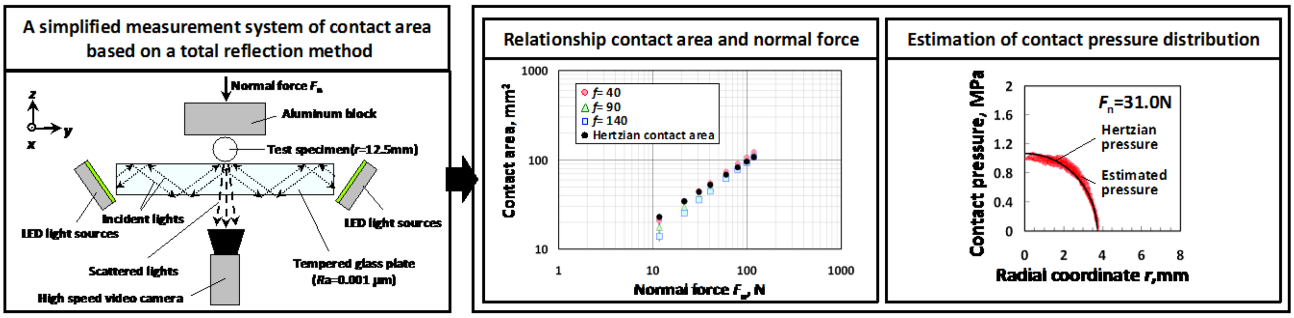

Fig. 1 Calculated contact area and estimated contact pressure distribution by using a total reflection method

In chapter 3, frictional behavior of resin foam/rubber laminated material under dry condition was investigated using a specially developed dead-weight type tribometer. Ethylene vinyl acetate copolymer (EVA) foam/styrene butadiene rubber (SBR) laminated materials were prepared as upper specimen slid against glass plate with surface roughness of 0.001μm. Parallel length and perpendicular width of the specimens to the sliding direction were set 25 mm. Total thickness of the specimens was 10.0 mm and EVA foam thickness ratios t_f/t to the total thickness were varied from 0.2 to 0.8. Contact area and strain distribution on the side surface of the specimen were measured by the total reflection method developed in chapter 2 and image correlation method, respectively. In the experiment, influences of EVA foam thickness and normal force on the contact area, static and dynamic friction coefficients were investigated under dry condition.

It was found that contact area, static and dynamic friction coefficients had positive correlation to EVA foam thickness ratio. On the other hand, static and dynamic friction coefficients had negative correlation to normal force within 11.7 to 118.5 N. These results indicated that static and dynamic friction coefficients had negative correlation with mean contact pressure at onset of sliding and during steady sliding phase, respectively. Furthermore, in order to investigate the shape effect of the specimen on the static and dynamic friction coefficient, horizontal stiffness K_h and normalized parameter R_s, which is the ratio of the deflection caused by shear force to that caused by bending moment, defined based on Timoshenko beam theory were introduced. Width and length of specimens were varied under the same bottom area and thickness. It was found that static and dynamic friction coefficients increased with an increase of both the horizontal stiffness K_h and normalized parameter R_s. On the basis of these results, an increase of EVA foam thickness ratio t_f/t horizontal stiffness K_h, and normalized parameter R_s of EVA foam/SBR laminated sole component would be a design criterion for a high grip shoes on dry smooth surface (Fig. 2).

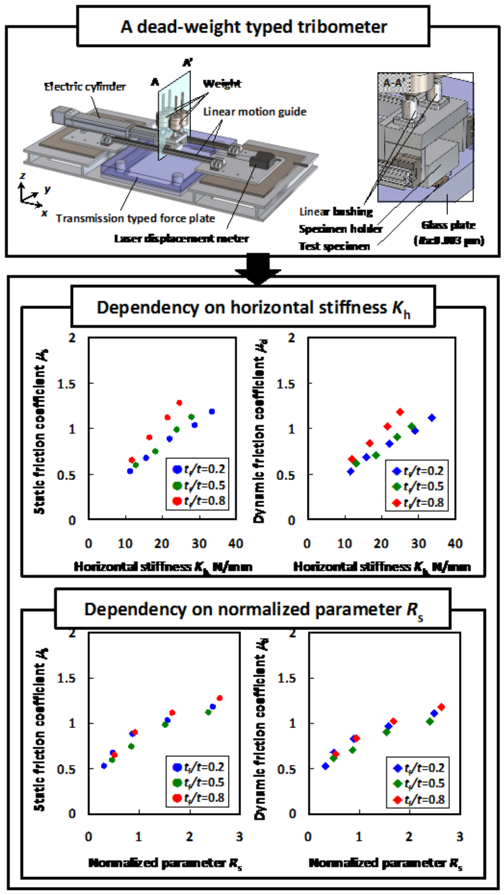

Fig. 2 Influence of horizontal stiffness and normalized parameter on static and dynamic friction coefficient under non-lubricant

In chapter 4, static and dynamic friction coefficients of EVA foam/SBR laminated material with different EVA foam thickness ratios were measured under water-lubricated condition. Then, effect of resin foam thickness ratio and normal force on the contact area, static and dynamic friction coefficients were also investigated. It was found that static friction coefficient was very small because of small area of contact between specimen and glass surface. Dynamic friction coefficient gradually increased during sliding phase due to water drainage from the contact interface between specimen and glass surface, resulting in an increase of specimen/glass contact area. Then, dynamic friction coefficient got constant value after the contact area got constant. Static and dynamic friction coefficients had negative correlation to normal force. With an increase of EVA foam thickness ratio, static and dynamic friction coefficients decreased at normal force within 40.1 to 99.5N due to reduced contact area. It was confirmed that static and dynamic friction coefficients under water-lubricated condition also had negative correlation with mean contact pressure at onset of sliding and during steady sliding phase, respectively. Furthermore, the effect of specimens' shapes on static, dynamic friction coefficients and an ability of water drainage were investigated. Water drainage ability was evaluated by an increase rate of dynamic friction coefficients from 0.1 to 0.5 s. It was found that static friction coefficient was not related to deformation mode of the specimen, i.e. horizontal stiffness or the normalized parameter R_s. Dynamic friction coefficients increased with an increase of both horizontal stiffness K_h and normalized parameter Rs. On the other hand, the increase rate of dynamic friction coefficient was decreased with a decrease of both horizontal stiffness K_h and normalized parameter R_s because water drainage was promoted. Hence, the reduced horizontal stiffness K_h and normalized parameter R_s of the EVA foam/SBR laminated material are needed for high slip resistance sole design on wet surface (Fig. 3).

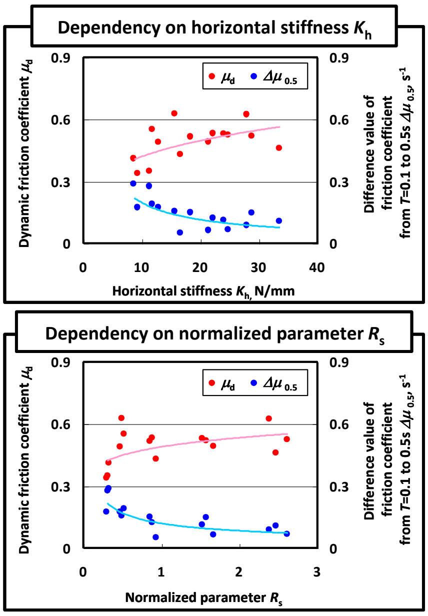

Fig.3 Influence of horizontal stiffness and normalized parameter on static and dynamic friction coefficient under lubricant condition.

In chapter 5, a shoe mounted miniature triaxial force sensors was developed to construct a new technique for the measurement of GRF distributions in the contact area during running. Six sensor and 13 dummy block devices were mounted to a commercial marathon shoe. By using the shoe, distributions of lateral, longitudinal and normal GRF components at 19 local positions were measured by changing sensor arrangements at running speed of 4.15 m/s.

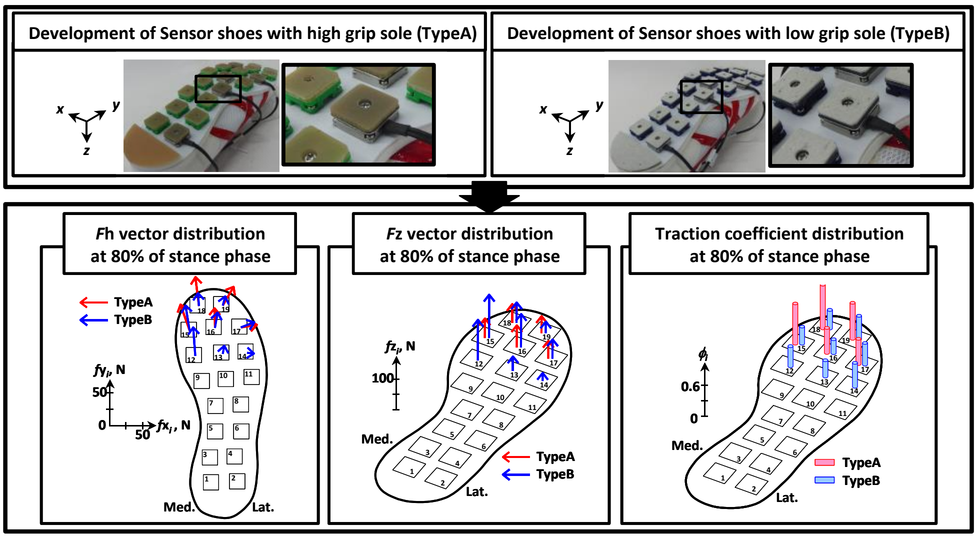

Fig.4 Ground reaction force vector distributions obtained from a developed sensor shoes.

The results explained that behaviors of GRF components at each position were clearly different during stance phase. In order to clarify the influence of grip property, i.e. static friction coefficient of shoe–floor surface, on distributions of GRF vectors and traction coefficient, two typed sensor shoes having different outer sole materials with high/low static friction coefficients were developed. The results showed that traction coefficients for the low grip typed shoe decreased in the whole contact area at the end of stance phase during running as shown in Fig. 4. Relationship between propulsion force components at 19 local positions and stride length explained that production of propulsion force beneath toe area could efficiently acquire sufficient stride length to keep running speed.

In chapter 6, two-prototype (No. 1 and No. 2) of marathon shoes with different outer sole pattern were developed based on the results obtained from the above chapters. The outer sole pattern of No. 1 was designed with large parallel length and small perpendicular width to horizontal GRF direction. On the other hand, small parallel length and large perpendicular width to horizontal GRF direction were applied to the outer-sole pattern of No. 2. Grip property of these two types of shoes and shoes having non-outer sole pattern (No. 3) and commercial marathon shoe (No. 4) were evaluated by four participants running on dry and wet surfaces based on traction coefficient, contact area and sliding velocity. It was found that traction coefficient increased from 50 to 100% of stance phase and it was much higher than that from 0 to 50% of stance phase under both dry and wet conditions. Therefore, high grip and high slip resistance are especially needed in the shoe outer-sole during 2nd half of stance phase. In the case of dry condition, contact area between shoe sole and floor surface for the shoe No. 1, No. 2 and No. 3 was higher than that for the shoe No.4 and mean contact pressure of the shoe No. 4 got 1.2-7.2 times higher than those of the other shoes after 10% of stance phase. Traction coefficient for the shoe No. 1 was significantly higher than commercial marathon shoe (No. 4) at 95% of stance phase. In the case of wet condition, slip occurs during stance phase in all of the test shoes. Traction coefficient of the shoe No. 2 was significantly higher than that of the shoe No. 4 at 90% of stance phase because of better water drainage ability. The maximum sliding velocity for the shoe No. 2 was prone to get lower than that for the shoe No. 4 (Fig. 5).

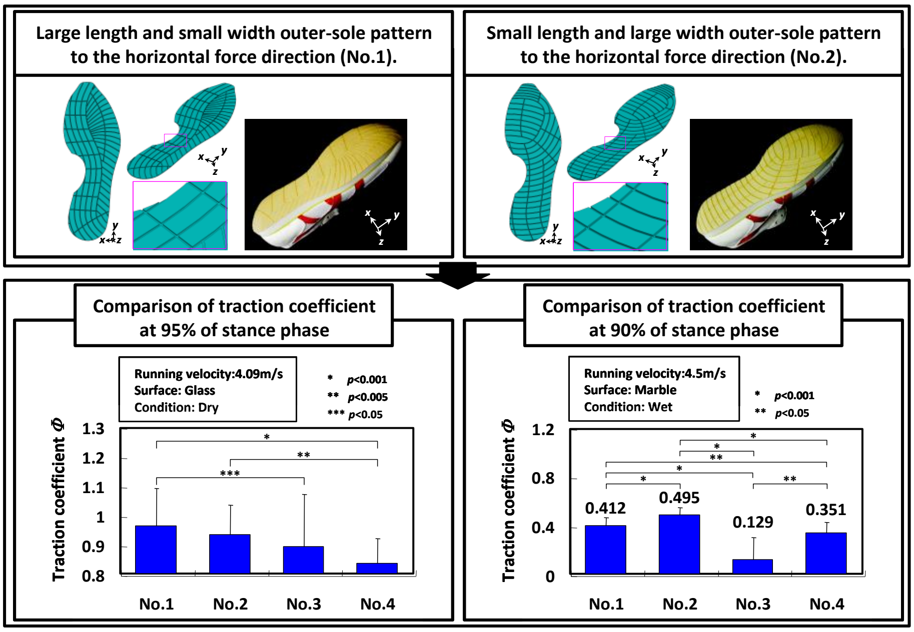

Fig. 5 Evaluation results of traction coefficient under dry and wet conditions with prototypes (No. 1 and No. 2) designed outer-sole pattern based on the results obtained from the above chapters.

As observed above, it is expected that outer-sole pattern developed in this study, in which tread block shape was designed based on horizontal GRF direction, provides high grip performance on dry surface and high slip resistance on wet surface during running.

Chapter 7 describes the conclusions. The matters that have been clarified in this thesis are summarized.