한국산학기술학회논문지
Vol. 12, No. 3 pp. 1078-1084, 2011

Development of Measurement Device for Bending Stiffness of Footwear

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신발의 굽힘강성 측정 장비의 개발

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Abstract In design of sport footwear, bending stiffness of its toe part is an important factor though it can be hardly measured. This paper introduces a device for measuring the bending stiffness. The device is simply designed with aluminum frames, one AC motor, two load-cells, one encoder and control hardwares. The mechanism measuring the bending moment of a shoe is described. Then, it was used to observe how the midsole material and design of a sports shoe affect on its bending stiffness. For the experiments, various specimens prepared, where each midsole of the specimens is different in terms of material, thickness and hardness. With those specimens, experiments were performed by using the device and then the bending stiffness was computed by applying the least square curve fitting after the bending moment data were measured. The specimen with Poly-urethane(PU) midsole has the higher bending stiffness than the one with Phylon(PH) midsole, and the midsole thickness affects more on the bending stiffness than the midsole hardness. Based on those results, it can be concluded that the measurement device can provide consistent bending stiffness data to sports footwear and the bending stiffness of a footwear measured by the developed device can be used as a major parameter in the footwear design.

요 약 스포츠화의 설계에서 신발 앞축 부분의 굽힘강성은 매우 중요한 설계인자이지만, 측정하기가 어렵다. 본 논문은 이러한 굽힘강성을 측정하는 장비를 소개한다. 장비는 알루미늄 프레임 구조와 AC 모터, 2개의 로드셀, 엔코더와 제어용 하드웨어로 구성되어있으며, 신발의 굽힘 모멘트를 측정하는 메카니즘을 소개하였다. 유용성을 입증하기 위하여, 신발의 소재와 디자인이 굽힘강성에 미치는 영향을 관찰하는데 사용되어 졌다. 실험을 위하여 신발 중창소재의 경도와 두께를 달리하여 완성신발 시편을 제작하였다. 이들 시편으로 굽힘실험을 수행하고, 최소자승법을 사용하여 굽힘강성을 구하였다. 실험결과 PU 중창으로 만든 신발이 PH 중창으로 만든 신발보다 굽힘강성이 높았으며, 중창의 두께가 중창의 경도보다 굽힘강성에 미치는 영향이 크다는 것을 알아낼 수 있었다. 따라서, 이러한 실험결과를 바탕으로, 본 측정장비는 유용한 실험결과를 도출할 수 있었으며, 이 장비를 통하여 측정된 신발의 굽힘강성은 신발 설계의 유용한 설계인자로 활용될 수 있다고 사료된다.

Key Words : Bending stiffness, Bending moment, Footwear, Midsole, Load cell, Hardness

NOMENCLATURE

M_1 = bending moment at the heel part of a footwear
M_2 = bending moment at the toe part of a footwear
s_1 and s_2 = distance from the center of rotational axis
$h(s_1)$ = distributed force at the heel part of a sport shoe
$t(s_2)$ = distributed force at the toe part of a sport shoe
F_1 = load applied to the first load cell
F_2 = load applied to the second load cell

1. Introduction

Since footwears are important in sports activities of human beings, they have been constantly developed and improved for better performance. In design process for better footwear, many important factors need to be considered. One of the sensitive design factors is bending stiffness(or flexibility) at the forepart of a footwear. A

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Received October 10, 2010 Revised February 19, 2011 Accepted March 10, 2011

moment required to bend the forepart of a shoe against its heel in human walk or run can be defined as the bending moment. On the other hand, a bending stiffness is described as the incremental rate of the bending moment per a unit angle increment. Since it bends 800~1200 times during one kilometer walk, a footwear with soft bending stiffness may save energy and provide comfort in long distance walking or running[1,2]. For a hiking in mountain areas, the bottom part of a footwear may need to be stiff in bending to protect foot from injury. Though many researchers had been aware of its importance, shoe industry has only relied on feeling, or personal judgement upon the stiffness which is highly subject-dependent. Since the feeling cannot be an proper criteria in design as well as in quality control process, we might need to quantize the bending stiffness characteristic of a footwear by using a measurement device. It can be affected by shape of a shoe as well as its materials used in outsole, midsole, insole and upper part[3,4]. This paper hence presents a device developed for measuring this bending moment and stiffness and shows results and analyses from various experiments.

For performing consistent experiments, a special jig which can hold the shoe at a constant position is designed. From the bending test, the data signal from the two load cells can be collected to the micro-controller and sent to the main PC through the RS232 serial communication[5,6]. After the PC collecting the data, the bending moment of the specimen with respect to the bending angle will be displayed as a graph in the PC monitor by using Microsoft Visual Basic.

In order to observe tendency of bending stiffness of various shoes by using this device, we prepared total 8 kinds of specimen shoes based on hardness, thickness, and material. The materials and design of the shoes are same except the midsole part only. The midsole material used here are PH(Phyron) and PU(Poly-Urethane) forms[3]. For checking thickness effect, three types of midsoles were prepared as 8, 10 and 12(mm) in fore part thickness as shown in Fig. 1. And for checking hardness effect, two types of shoes were prepared with different midsole hardness, 55 and 60, measured by the Shore B hardness as specified in Table 1. After the various specimens prepared, the bending stiffness test had been performed and the test results and their analyses were presented here.

(a) (b)

[Fig. 1] Side view(a) and cross section(b) of the footwear specimen

[Table 1] Specimen Shoes

Specimen	Midsole Material	Thickness Fore-part(mm)	Hardness (Shore)
PU_1	Poly Urethane	8	55
PU_2		10	55
PU_3		10	60
PU_4		12	55
PH_1	Phylon	8	55
PH_2		10	55
PH_3		10	60
PH_4		12	55

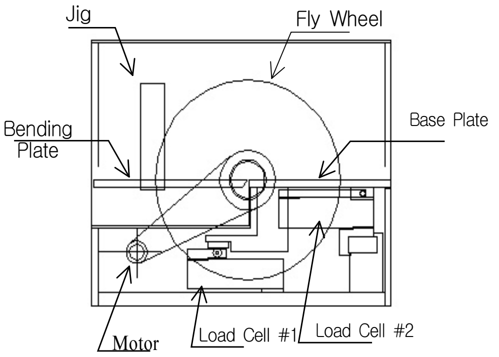
2. System Descriptions

2.1 System Mechanism

Bending moment of a footwear is a moment required in bending its toe part and then bending stiffness of a footwear is an incremental rate of the bending moment with respect to a unit bending angle. Hence, in mechanical point of view, we can simply consider a shoe as a torsional spring. Hence, a test device as shown in Fig. 2 is designed to measure the bending moment of a specimen shoe under a given bending speed, which corresponds to walking speeds .

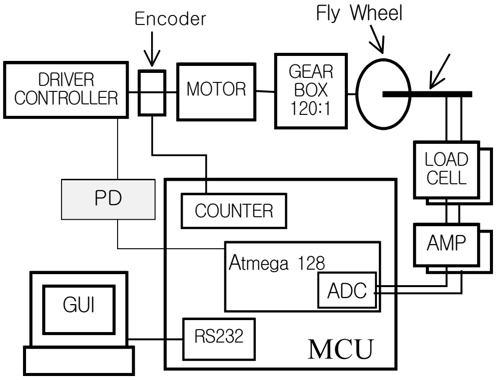
The developed system is mainly composed of a mechanical unit, an actuator unit, a sensing unit and a MCU(Main Control Unit) as shown in Fig. 3. The major components of the actuator unit are an AC motor and its driver which generate the bending motion of the specimen shoe and are controlled by one micro-controller ATmega 128 in the MCU. The sensing part is composed of one encoder and two load cells with their signal transducers. The encoder is installed at the motor axis to measure the rotational angle and its speed of the bending motion of the heel part of the specimen shoe. A power train is used in the mechanical unit to amplify and to transmit a bending torque from the AC motor to the fly wheel to generate a proper rotational bend speed to a specimen shoe. The fly wheel which has a large inertia moment is connected to the bending plate with a pin joint. The bending plate is designed to hold and to rotate the heel part of the specimen shoe with a special jig. The toe part of the shoe is rested at the base plate.

When we consider to measure a pure bending moment required to rotate the heel part of the shoe, we can recognized difficulty in the measurement because the motor rotates not only the shoe but also many other parts, such as the bending plate, the flywheel, and other power train parts as shown in Fig. 2 Thereby, we figured out an indirect way to measure the moment. It is clear that a moment due to distributed forces at the heel part of the shoe is developed to a pure bending moment along a rotational axis. By the Newton's 3rd law, this pure moment is equal to the moment due to the reaction force distributed at the toe part. Now, we want to measure the moment generated by the distributed force at the toe part. We placed two load cells underneath of the base plate to measure the bending moment as shown in Fig. 2.

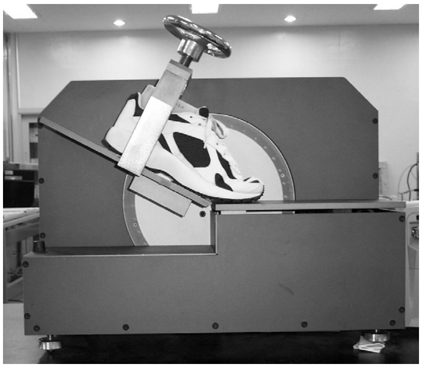


[Fig. 2] CAD drawing of the system

When the system try to bend a speciment shoe, the pure moment to bend the shoe transmitted to the two load cells. Then, analog force data from the two load cells are then amplified and passed to the AD converter channels in the micro-controller ATmega128 and sent to the main PC through RS232 serial communication as shown in Fig 3. After the PC collecting the data, the bending moment of the specimen with respect to the bending angle will be gathered and displayed as a graph in GUI by Microsoft Visual Basic. The prototype of the system is built and shown in Fig. 4.



[Fig. 3] Schematic of the measurement system



[Fig. 4] Measurement device for a shoe bending stiffness.

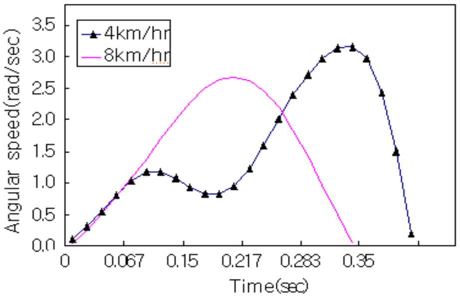
2.2 System Calibration

In order to measure a precise moment applied to bend the shoe, two load cells are placed under the base plate shown in Fig.2, we need to calibrate the load cell and its amplifier. The load cell used in the system is BA-15A model produced by CAS INC., which has maximum range of 15 kgf. From calibration of the load cell, the data listed in Table 2 were obtained. By using the least square regression, the ratio between force and output voltage from the sensor is determined as 2.9 kgf/V with 0.99 of R_{xy}. correlation coefficient.

[Table 2] Force and Voltage measured for calibration

Force(kgf)	Voltage(mV)
1.0	344
2.0	686
3.0	1024
4.0	1364
5.0	1704
10.0	3410

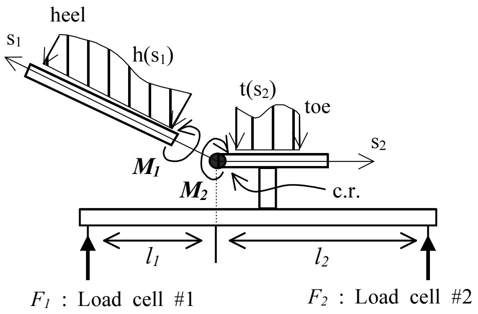
From the analysis of bending motion of a footwear during walking or running, we need to choose a proper angular speed profile of the bending motion of the toe part of foot. In order to obtain the speed profile, we put three bright marks along the side of a shoe, such as toe, heel and a bending axis. After capturing the walking motion by using a high speed camcorder, each angular speed at every time step was extracted by using a motion analysis software(DV-9800, JVC, Japan). From several walking experiments based on various speeds, we have learned that the angular velocity of shoe bending in walking varies depending on walking speeds and the angular speed of bending motion is not an effective factor for determining the bending property of a footwear. Hereby, we select one of the measured data shown in Fig. 5 as the bending speed profile, which will be implied to the specimen shoes. The two speed profiles in Fig. 5 were obtained when a test man is walking with 4 km/hr and 8km/hr speeds along a straight path, where 4km/hr speed is known as the walking speed of an average man. The maximum speed during bending motion for 8 km/hr is 2.8 deg/sec, which is equivalent to 30 rpm rotation of the rotating plate and 270 rpm of the motor(9:1 of the gear ratio). For the bending moment measurement test, we select the whole speed profile of 8 km/hr walking.



[Fig. 5] Angular bending speed profiles of a specimen shoe

2.3 Computations of bending moment and stiffness

After a specimen shoe is mounted on the system, it is bended by rotating the bending plate on which the heel part of the shoe is placed and we need to measure a pure moment applied to bend the shoe at each angle. Since the motor needs to rotate not only the heel part of shoe but also the flywheel and the bending plate with a mechanical friction. Then the pure moment for bending the shoe can only be measured by an indirect way. Here the pure moment is measured indirectly from a reaction force distributed along the base plate shown in Fig. 6.



[Fig. 6] Schematic diagram for measuring the pure bending moment

Since an inertia moment shoe and an angular acceleration of the heel part of sport shoes in walking are small, the pure bending moment M_1 to bend the heel part of the shoe is simplified as

$$M_1 = \int s_1 h(s_1) ds_1 \quad (1)$$

where, s_1 is the distance from the center of the rotation axis(c.r.) and $h(s_1)$ is an arbitrary function of distributed force acting on the bending plate. Then at the base plate, an arbitrary distributed reaction force $t(s_2)$ is appeared against the pure bending moment at the heel part, where s_2 is the distance from the center of the rotation axis(c.r.). From the reaction force at the base plate we can also calculate the moment as

$$M_2 = \int s_2 t(s_2) ds_2 \quad (2)$$

If the shoe is bended with constant angular velocity, there is no angular acceleration in the motion so tha we did not consider any inertia part in the Eqs.(1) and (2). It is then sure that the two bending moments M_1 and M_2 are equal from the basic mechanics, the Newton's 3rd law, so that it can be described as

$$M_1 = M_2 \quad (3)$$

then the pure bending moment M1 can be calculated from the forces transmitted to the two load cells, F_1 and F_2 as shown in Fig. 6.

The distributed forces compress two load cells placed under the base plate and we find the bending moment at the rotational axis as

$$M_1 = - l_1 F_1 + l_2 F_2 \quad (4)$$

where M_1 is the bending moment (kgf·cm), and F_1 and F_2 are the forces measured at the load cells 1 and 2, respectively, in Fig. 6. This bending moment measured here is the pure bending moment required to bend the toe part of a sport shoe along the c.r. axis. The c.r. axis is equivalent to the metatarsophalangeal(MP) joint of the forefoot, which permits the bending of the toes relative to the metatarsal bones during walking motion.

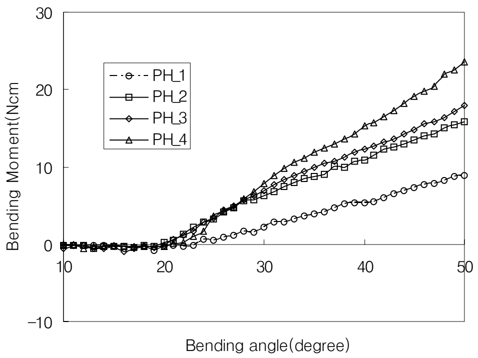
The bending stiffness is then defined as a rate of the bending moment change against the bending angle change. It can be computed by finding a slope of the bending moment curve with respect to the bending angle, which can be simply obtained by MS Excel or other numerical ways using the least square curve fitting. When we try to compare the bending property of footwear, the bending moment is not an appropriate quantity because its value changes every angle of shoe's bending. However, the slope is not significantly varying along the bending angle range. Therefore, the slope which is the bending stiffness of footwear can be the most proper quantity in characterizing how soft and hard of the given footwear in bending motion of walking.

3. Experimental Results

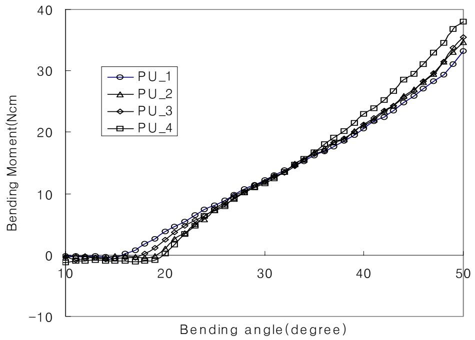
For the purpose of demonstration of the developed device, one set of experiments were performed with eight different specimen shoes as shown in Fig. 1. The eight specimen shoes were made with two different midsole materials and four different thicknesses in midsole as shown in Table 1. The specimen were selected to figure out which design parameter affects bending stiffness more, where the design parameters considered are thickness of shoe's fore part, hardness of its midsole. Additionally, two midsole materials(PU and PH) were used for making specimen. The specimen footwear and its cross section were shown in Fig. 1. The experiments are performed 5 times for each specimen with the prescribed speed profile of bending and the results are shown in Fig. 7 and 8. At the beginning of the bending, we can notice zero bending moment is required to bend the shoe by around 20 degrees. This is due to sports shoe design that the toe part is rounded with a certain amount of angle.

From the results in Fig. 7 and 8, we can observe that each bending moment profile is different by material and thickness of its midsole. In the material point of view, PH is more flexible in bending than PU. For the same hardness of midsole(PH_1, PH_2 and PH_4 in Fig. 7), it is known that the thickness is certainly an effective factor for the bending moment. For the same thickness of midsole(PH_2 and PH_3 in Fig. 7), we can also notice that the higher hardness causes the higher bending moment. In Fig. 8, we can see higher moment profiles for the shoes with PU midsole materials than those for the shoes with PH midsole materials. Since PU is generally harder than PH, those results seem reasonable. However, the effect of thickness of the shoe's PH midsole is greater than that of its PU midsole. Especially, it seems that its hardness does not affect on the bending moment according to PU_2 and PU_3.

Based on the results of bending moment, we calculate the bending stiffness by using the least square regression as shown in Table 3 and 4. From the experiments, we can also notice that PU has higher bending stiffness than PH does. In the bending moment graphs in Fig. 7 and 8, we can only judge the tendency by looking. However, the bending stiffness values in the Table 3 and 4 clearly show the tendency. Hence the bending stiffness can be used in evaluating bending flexibility of a shoe.



[Fig. 7] Bending moments of specimen shoes with PH midsole



[Fig. 8] Bending moments of specimen shoes with PU midsole

[Table 3] Bending Stiffness of PU Specimens

Specimen	Bending stiffness (kgfcm/deg)
PU_1	0.92
PU_2	1.02
PU_3	1.03
PU_4	1.18

[Table 4] Bending stiffness of PH specimen

Specimen	Bending stiffness (kgfcm/deg)
PH_1	0.32
PH_2	0.51
PH_3	0.57
PH_4	0.80

4. Conclusions

The bending stiffness of the toe part of a shoe was successfully measured by using the newly developed measurement device through performing tests with 8 different specimen shoes. From the quantified bending stiffness of each shoe, we can notice that variations in thickness and hardness of a shoe midsole slightly affect on bending stiffness(25% increase) for the case of PU midsole material. On the other hand, when PH is selected as its midsole material, variations in thickness and hardness of midsole significantly influence on its bending stiffness. Considering application of the measured bending stiffness, we can use that information to not only selecting midsole material for a footwear design process but also one of test criteria for the quality control process in the footwear manufacturing industries.

References

[1] Clarke, T.E., Frederick, E.C., and Cooper, L.B., "Biomechanical measurement of running shoe cushioning properties.", In B.M. Nigg & B.A. Kerr(Eds.), Biomechanical aspects of sport shoe and plating surface, pp25-33, 1983.

[2] Benno M. Nigg, Biomechanics of running shoes, Human Kinetics Publishers, Inc., 1986.

[3] Dong-Bae Kang, Hwa-Young Kim, "Development of the Roughing Path Measurement System for Footwear", Journal of Korean Society of Precision Engineering, 1225-9071, Vol. 20, No. 10, pp120-129, 2003,

[4] B.M. Nigg, Eberle,G., Frey,D., Luethi, S.M., Segesser, B., and Weber, B, "Gait analysis and sport shoe construction.", In E. Asmussen & K. Joergensen(Eds), Biomechanics VI-A, pp303-309, 1978.

[5] R. S. Figliola, Theory and design of mechanical measurement, Wiley, 1999.

[6] Gab-Soon Kim and Se-Hun Rhee, "Design and Strain Analysis of Precision 3-component Load Cell", International Journal of Precision Eng. and Manufacturing, vol. 1 no. 1. pp. 22-32, 2000.

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<Research Interests>
Dynamics and Control, Bio-mechanics, Vehicle Dynamics.