한국산학기술학회논문지
Vol. 10, No. 12, pp. 3833-3838, 2009

Study on Measuring Mechanical Properties of Sport Shoes Using an Industrial Robot

Jong-Nyun Lee[1*]
[1]**Division of Information System Engineering, Dongseo University**

산업용 로봇을 이용한 스포츠화의 운동역학특성 측정에 관한 연구

이종년[1*]
[1]동서대학교 정보시스템공학부

Abstract This paper introduces a measurement system for mechanical properties of sport shoes using an industrial robot. The robot system used in this paper is a commercial Puma type robot system(FARA AT2 made by SAMSUNG Electronics) with 6 joints and the end-effector is modified to produce a human walking motion. After analyzing human walking with a high speed video camera, each joint angle of the robot system is extracted to be used in the robot system. By using this system, ground impact forces were measured during stepping motion with 3 different shoe specimens made of 3 different hardness outsoles, respectively. As other mechanical properties, both bending moments to bend the toe part of the same specimen shoes and pronation quantities during walking motion were measured as well. In the impact test with the same depth of deformation under the ground level, the effect of the outsole hardness was clearly appeared such that the harder outsole produces the higher ground reaction force. The bending test and the pronation test also show proportional increments in the bending stiffness and the moment Mx according to the outsole hardness. Throughout such experiments, the robot system has produced consistent results so that the system could be used in obtaining valuable informations for a shoe designing process.

요 약 본 논문은 산업용 로봇을 이용하여 운동화의 특성을 측정하는 측정장비를 소개한다. 여기서 사용된 로봇은 6관절의 퓨마타입 로봇(삼성전자의 FARA AT2 모델)을 인간의 보행 동작을 구현할 수 있도록 보완하였다. 보행 동작은 고속카메라로 분석한 후, 로봇 관절각들을 추출하여 동작구현에 사용한다. 3가지 종류의 경도 아웃솔(신발 겉창)로 만들어진 신발 시편을 준비하고, 이 로봇 시스템을 이용하여 걸음동작을 구현하여 신발에 따른 지면 충격력을 측정한다. 걸음동작에서 발생하는 발 앞축 부분을 굽히기 위해 요구되는 굽힘 모멘트의 측정과 걸음동작에서 발생하는 요동현상의 측정에 사용한다. 동일한 압축변형을 유지하도록 시스템을 설정하고, 신발을 측정한 결과 아웃솔의 경도에 따라 지면반력의 크기는 선형적으로 증가하는 추세가 관찰되었다. 또한 굽힘 모멘트와 요동현상 역시 아웃솔의 경도에 따라 선형적으로 증가하는 추세가 관찰되었다. 상기의 몇 가지 실험을 통하여, 본 로봇 시스템은 일관성 있는 실험결과를 제공하였으며, 따라서 산업용 로봇을 이용하여 신발의 유용한 특성 정보 도출이 가능하며, 추후 신발설계의 활용에 대한 가능성을 보여준다.

Key Words : Mechanical property, robot system, sport shoe, outsole hardness, impact force, ground reaction force(GRF), bending moment, pronation

1. Introduction

There have been many studies for finding ways to make a better shoe. F. C. Anderson[1] and A. Gefen[2]

*Corresponding Author : Jong-Nyun Lee(jnlee8282@hanmail.net)
Received July 09, 2009 Revised (1st November 02, 2009, 2nd December 09, 2009) Accepted December 16, 2009

presented studies about the posture and kinetics of human walking. There are many commercial measurement devices that can measure variety of mechanical properties of shoes. NOVEL and SATRA are the well-known companies producing measurement devices for shoes' mechanical properties. Some mechanical properties measured by those devices however frequently failed to give consistent results due to inconsistent human motion[3].

This paper concerns about measuring mechanical properties of sport shoes by using a commercial robot system and suggests a new approach to evaluate performance of sport shoes. In the shoe industry, it is required to develop a better shoe for customers. A better shoe can be determined based on the softness of the heel part that supports customer's weight and reduces impact on walking. The other factors can be the bending stiffness of forefoot and its stability in roll motion (so called pronation)[4]. When those factors of a shoe are measured by using a human foot, reliable test results can be hardly expected due to lack of repeatability in human walking behavior. Hence, experimental results from human walking cannot be used to compare the performances of two or more different shoes. In order to resolve such difficulty, a human walking simulator is considered and developed here as the multi-purpose test device.

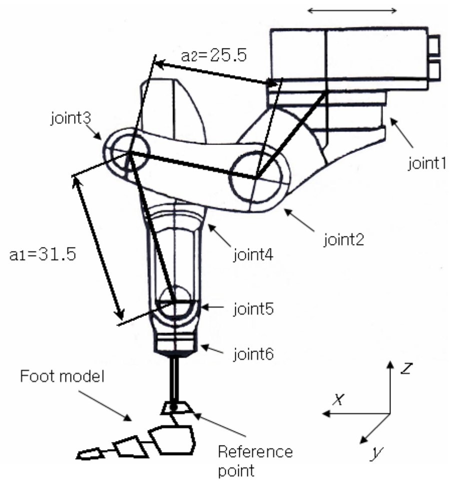
The goal of this research is to measure reliable mechanical properties such as cushioning, flexibility, stability, and traction of sport shoes by using a robot system. Although this study only covers three mechanical properties for checking the performance of shoes, it can be further extended to measuring other mechanical properties.

2. System Configuration

The measurement device utilized a FARA AT2 robot with 6 joints made by SAMSUNG Electronics and added a passive foot model as an end-effecter. The important specifications of the robot are listed in Table 1. Its overall arm length when it is stretched is 720mm and its payload is 7kg. The total degrees of freedom of the robot is 6. The robot was then modified such that the base is hanged on a linear trailer underneath the ceiling of a main frame to perform the translational movement of the human hip in walking as shown in Fig. 1.

[Table 1] Specification of The Robot System

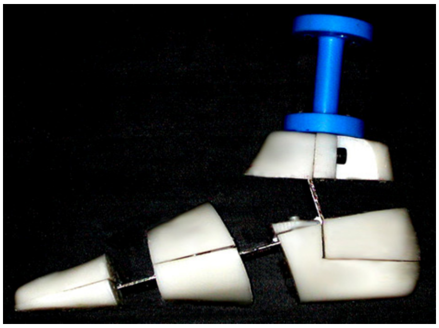
ROBOT TYPE	FARA AT2(Samsung)
Degrees of Freedom	6
Pay load	3kg
Repeat Precision	±0.04mm
Length of arm	720mm
Motor Type	AC servo motor
Position detect type	Absolute encoder
Controller type	SRCP Series



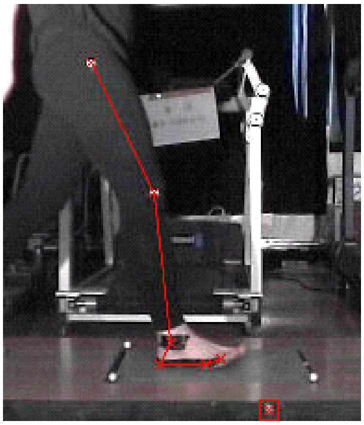
[Fig.1] System Configuration

In the motion of a foot, a lot of small joints and muscles are involved so that it is hard to duplicate the motion by using a mechanical system with several actuators. Hence, we developed a passive type of the foot model with 3 carbon steel plates shown in the Fig. 2. Its structure and stiffness were determined by various trials until reaching a satisfying result similar to a human walking. After we mounted a specimen shoe on the foot model, various experiments had been performed. Here we prepared 3 different specimen shoes for the experiments, where each specimen shoe had different hardness of outsole. On the ground, we placed a force platform made by Advanced Mechanical Technology Inc.(AMTI) on the floor, which is a leading manufacturer of force and motion measurement devices, and its measurement data were transmitted to a PC. Inside the force platform, there are various sensors mounted to measure the ground reaction forces(GRF) that are composed of 6 components F_x, F_y, F_z, M_x, M_y, and M_z corresponding to 6 DOF in a 3-D space. Then we wanted to measure some mechanical properties of a sport shoe from the overall measurement system which includes the robot, the foot model and the force platform.

In order to generate a motion of the foot model similar to a human walk, we first tried to capture a human working motion after posting 6 white reflective markers on one leg and 3 on the floor as shown in Fig. 3. After capturing a walking motion by 250 frames per second, we extracted the point geometric trajectories as shown in Fig. 4 by using the commercial digitizing program APAS. Then the joint angles of the robot system at each time step, 5msec, were calculated from the inverse kinematics in robotics[5]. According to each joint angle, the robot can generate a proper motion of the foot model.



[Fig. 2] Foot model

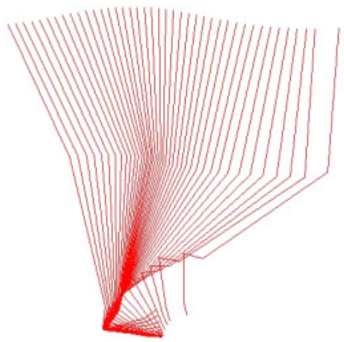


[Fig. 3] Motion capturing process

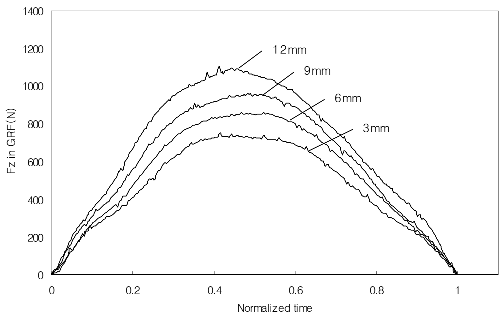
3. Experiments

3.1 Motion test of the system

We mounted a test shoe on the foot model and programed the robot system to behave like a moderate stepping motion. So the foot model gradually hit the ground, and pressed the ground by a commended deformation, then was gradually released from the ground. To test stiffness of the foot model in walking, we performed 4 experiments with different stepping deformations, 3, 6, 9 and 12mm below the ground level. The results are shown in Fig. 5, where increments of the maximums of F_z in GRF are nearly proportional to the deformation depth below the ground level. The x-axis shows the normalized time from the initial contact time to the releasing time. From the results, we conclude the foot model is deformed nearly proportional to the ground reaction force generated from a walking motion so that we can apply this system to other simulations following.



[Fig. 4] Sequential view of the leg motion

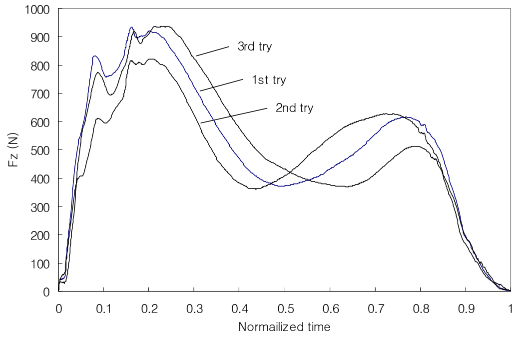


[Fig. 5] The responses of Fz in GRF corresponding to the stepping deformations

3.2 Impact Test of Assembled Shoes

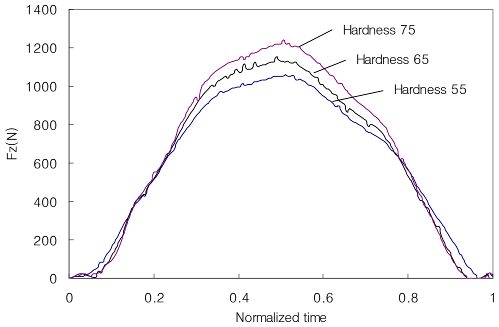
It is well known that the maximum impact force of the rear foot is generally high about 1.5 to 3 times of human weight during heel strike of walking period. Such serious and repetitive impact force may cause damage in the knee joint as well as the brain[4]. This impact depends on not only walking but also shoe design. The shoe design here means material and thickness of midsole and outsole. The hardness of midsole and outsole of a shoe is then considered to be closely related to the impact force on the ground so that it could be a major property to be examined for shoe designers to reduce the peak of the rear foot impact. Here we tried to use this device to measure the rear foot impact force of a shoe after it is assembled from parts in a factory.

Then, we had prepared three different shoes of which the outsoles are made of Shore hardness rubber 55, 65 and 75, respectively. At first, we let one adult(70kg weight) wear those specimen shoes and walk along a straight path several times as shown in Fig. 3. On the floor of the path we placed one force plate to measure the GRF. In Fig. 6, we can see the inconsistent results lacking repeatability from 3 trials, where the hardness of the shoe was 65. It is obvious because a human cannot perform a same walking pattern every time and is willing to quickly adapt on the change of walking condition.



[Fig. 6] Fz trends from several tries of a human walking

Then we mounted those same shoes on the foot model of the device instead of a human to check whether the device could produce reliable results on the walking motion. If so, we could use the measurement device to measure the dynamic response of a shoe in walking. We performed walking motion from the device after three different shoes mounted on the foot model and measured the response of F_z in GRF. After collecting data from the experiments, we showed one set of results in case of the shoe with Shore hardness 55 of outsole in Fig. 7, where the trend seems very consistent in every try. After taking the three different result sets corresponding to the shoes with Shore hardness 55, 65 and 75 of outsoles, we combined and plotted them in the Fig. 8, where the trends seem proportional. Hence we could utilize the data taken from the developed device as a reference to measure the hardness of assembled shoes. We could expand various walking conditions, such as walking speed, walking style and ground condition, etc.

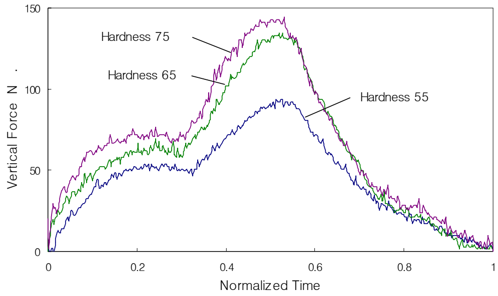


[Fig. 7] F_z trends from stepping tests by using three different hardness specimen shoes.

3.3 Bending Test of Assembled Shoes

For the next study, we concerned the stiffness of assembled shoes. Generally the stiffness of bending is an important factor on sports performance. Its small difference may cause significant difference in runners' fatigue in marathon. Since a shoe is assembled from several parts, such as insole, midsole, outsole, and texon, we may want to know the bending stiffness of the shoe after those parts assembled. Here we want to use the developed device to measure reaction force to bend a shoe after instructing the device to generate a proper motion of forefoot bending.

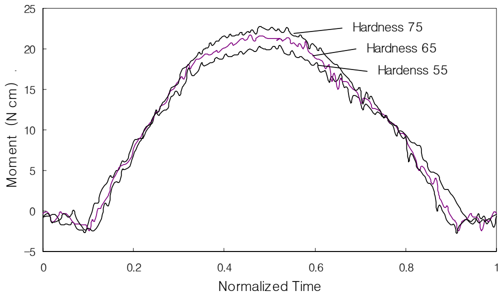
We chose three badminton shoes with different outsole hardness, 55, 65, and 75, like the previous section. Then we mounted those onto the foot model, and performed the prescribed motion and measured the F_z of GRF from the force platform. The trends are shown in Fig. 8. At one third of the total period of motion, abrupt changes can be observed. This can be caused from the foot model and the bending motion. We can also observe the responses increased according to the hardness of outsole of shoes. Hence, the overall trends, we can see reasonable difference among each test so that after some correction of the foot model and the bending motion, the device could be utilized as a proper measurement device to test reaction forces to bend assembled shoes.



[Fig. 8] Bending stiffness trends from toe bending test by using three specimen shoes.

3.4 Pronation Test of Assembled Shoes

Pronation is defined as a roll motion of shoe during walking on the ground and it depends on the shoe material and design. Generally slight pronation of foot could reduce the peak impact of the walking motion. However, excessive pronation occurred in the shoe may cause fatigue on the ankle of the foot and the knee joint. Hence, we tried to measure this pronation occurred in walking and to use the data for reference in a shoe design process. Fig. 9 shows similar trends and gradually increasing peak according to the hardness. The maximum moment M_x is 22.7 Ncm for Shore hardness 75 outsole shoe, 21.5 Ncm for Shore hardness 65 outsole shoe, and 20.0 Ncm for 55, respectively. Since we prepared the same specimen shoes only except the different hardness of their outsoles, the differences in moment M_x are considered only due to the outsole hardness of the shoe. When the outsole is harder, we can easily recognize that the reaction moment M_x of the same pronation of the shoe is bigger. Hence we can consider the developed device is a proper device measuring the pronation property of an assembled shoe. For further usage of this device, a further research may be required to find other criteria of sports activities.



[Fig. 9] Moment M_x trends of three different specimen shoes

4. Conclusions

An industrial robot system was adopted and modified to perform a human walking as a measurement device for an assembled shoe. With this device, we could measure various mechanical properties of a sport shoe by reducing uncertainty and lack of repeatability inherent in the human walking behavior. Possible test items can be performed here are impact test, bending test and pronation test. Each motion for the test was prepared through motion capture and robot kinematics to calculate joints angles of the robot system. After three sets of shoes with different outsole hardness 55, 65, and 75 were prepared, they were tested by using the developed device according to the prescribed motions. From the results, the device was successfully utilized in measuring mechanical properties of an assembled shoe corresponding to midsole materials and its design. In the impact test with the same depth of deformation under the ground level, the effect of the outsole hardness was clearly appeared that the harder outsole produces the higher ground reaction force. The bending test and the pronation test also showed proportional increments in the bending stiffness and the moment M_x according to the outsole hardness. So we could conclude that the results throughout various experiments were consistent so that mechanical properties extracted by the robot system could be used as valuable information in the shoe designing process. It is a new approach applying an industrial robot system to measuring multi- mechanical properties of shoes and it can be expected this measurement device as a substitution for several expensive measurement devices used in the shoe industry.

References

[1] F. C. Anderson and M. G. Pandy. "Dynamic Optimization of Human Walking", *Journal of Biomechanical Engineering*, 123, pp.381-389, 2001.

[2] A. Gefen, M.Megido-Ravid, Y. Itzchak, and M. Arcan. "Biomechanical Analysis of the Three-Dimensional Foot Structure During Gait: A Basic Tool for Clinical Applications", *Journal of Biomechanical Engineering,* 122, pp.630-639., 2000.

[3] B.M. Nigg,G. Eberle, and D. Frey. "Gait Analysis and Sport Shoe Construction", InE. Asmussen & K. Joergensen(Eds), *J. Biomechanics* VI-A, pp.303-309. 1978.

[4] Karin G. M. and Anton J. van den Bogert. "Direct Dynamics Simulation of The Impact Phase in Hell-Toe Running", *J. Biomechanics*, Vol 28, no. 6. pp.661-665. 1995.

[5] M. W. Spong and M. Vidyasagar. Robot Dynamics and Control, John Wiley & Sons. 1989.

[6] B. H. Lee and P. J. Song, "Study on Manufacturing of Mobile Robot System having Flexible Trajectory for Manless-Transportation", *J. of the Korean Academic Industrial Society,* v.4, no.3, pp.284-288, 2003.

[7] J. U. Cho, "A Dynamic Behavior of Rubber Component with Large Deformation", *J. of the Korean Academic Industrial Society,* v.6, no.6, pp.536-541, 2005.

Jong-Nyun Lee [Regular member]

- Aug. 1985 : Busan National Univ., Mechanical Engineering, MS.
- Aug.1992 : Univ. of Arizona, Mechanical Engineering, PhD.
- Aug. 1993 ~ Feb. 1995 : Agency Defence Development., Engineer.
- Mar. 1995 ~ current : Dongseo Univ., Dept. of Mechatronics, Professor.

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